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# ТЕХНОЛОГИЯ СЕЙСМОРАЗВЕДКИ С ШИРОКИМ АЗИМУТОМ, ШИРОКОЙ ПОЛОСОЙ ЧАСТОТ И ВЫСОКОЙ ПЛОТНОСТЬЮ И ЕЕ ПРИМЕНЕНИЕ ДЛЯ ПРОГНОЗИРОВАНИЯ ЗОН ОСТАТОЧНЫХ ЗАПАСОВ НЕФТИ

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Данная статья посвящена описанию методики применения технологии сейсморазведки с широким азимутом, широкой полосой частот и высокой плотностью, благодаря внедрению которой завершена более подробная структурная интерпретация нефтяного месторождения К, а также выделен ряд микроструктур в периклинальных частях и выявлены потенциальные зоны остаточных запасов нефти на данном месторождении. Полученные полевые данные с широким азимутом и высокой плотностью, а также результаты широкополосной инверсии являются основными факторами, повышающими степень прогнозирования зон остаточных запасов нефти. Согласно комплексному анализу выявлено, что потенциальными зонами остаточных запасов нефти являются сводообразные структурные носы в периклинальных частях месторождения, малоамплитудные антиклинали в периклинальных частях месторождения, зоны литологического выклинивания. В результате данного исследования обеспечена техническая поддержка в определении потенциальных зон остаточных запасов нефти на данном месторождении и заложена основа для прогноза распределения зон остаточных запасов нефти на месторождениях-аналогах с высокой степенью выработки запасов и высокой обводненностью, вступивших в среднюю и позднюю стадии разработки.

*Сейсмические данные с широким азимутом, широкой полосой частот и высокой плотностью, мелкомасштабные разрывные нарушения, сводообразные структурные носы, малоамплитудные антиклинали, зоны литологического выклинивания, прогнозирование зон остаточных запасов нефти*

## WIDE-AZIMUTH, BROADBAND, AND HIGH-DENSITY SEISMIC TECHNOLOGY AND ITS APPLICATION FOR PREDICTION OF RESIDUAL OIL DISTRIBUTION

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The paper focuses on the wide-azimuth, broadband, and high-density (WBH) seismic data application methodology, which was used to complete a more detailed structural interpretation of the K oilfield, to identify a number of low-relief structures in its periclinal parts, and to detect the potential residual oil zones (ROZ) in the oilfield. The obtained wide-azimuth, high-density field data and the results of broadband inversion are the main factors that increase the degree of ROZ prediction. A comprehensive analysis has shown that potential ROZ are arched faulted-nose structures in the periclinal parts of the oilfield, low-relief anticlines in the periclinal parts of the oilfield, and lithologic pinchout zones. Technical support has been provided for identifying ROZ in the given oilfield, and the basis has been laid for predicting the residual oil distribution in analogous oilfields with high productivity and high water cut that are at the middle and late stages of development.

*Wide-azimuth, broadband, and high-density seismic data, small-scale faults, faulted-nose structures, low-relief anticlines, lithologic pinchout zones, prediction of residual oil zones*

## INTRODUCTION

The seismic exploration method with a seismic source as the main feature originated in the middle of the 19th century, and it still has the advantages of relatively low cost and high accuracy.

The history of continuous innovation and rapid improvement in the seismic exploration technology can be divided into the initial stage and five leap stages.

The initial period started in 1845, when R. Mallet used modeled seismic waves to measure the propagation velocity of elastic waves in the Earth's crust (Davison, 1921). This is the earliest record of scientific experiments in receiving seismic data simulated by artificial explosions. The earliest seismic technique used in


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petroleum exploration was refraction. In the 1930s the first leap stage was marked by the improvement from seismic refraction to reflection (Crutchley and Kopp, 2017). The second leap stage, which took place in the 1950s, was marked by the multiple coverage technology. The multiple coverage technology received reflected waves from the common reflection point underground at different receiver points. In the 1960s, the third leap stage was distinguished by the digital seismographs and digital processing technology. At that time, analog tape recording was replaced by digital tape recording, forming a complete technical system with computer-based digital recording, multiple coverage technology, and technology for digital processing of seismic data as a foundation, which greatly improved the recording accuracy and solved geological problems. In the early 1970s, the fourth leap stage was marked by the migration imaging technology (Bancroft, 2007; Jones et al., 2008). It has been recognized that migration imaging based on the wave equation can greatly reduce the distortion of the horizontal stacking to the stratum structure. However, it has not been able to achieve industrial application because of its limited computing power and lack of implementation methods. In the 1980s, the fifth leap stage was distinguished by the three-dimensional (3D) seismic exploration technology; it includes acquisition, processing, and interpretation. The 3D observation system, which is usually arranged by the area, extends one dimension to the two-dimensional method, providing more underground interface reflection points that cause an increase in the density of the recording track and fold number. So, the obtained information is sufficient for researchers to more accurately describe the structure of the underground heterogeneous medium and to make the interference wave better suppressed.

Before 2000, the narrow-azimuth observation system was generally adopted with 2–8 lines of array, and the fold numbers were usually 2–3 times in the transverse direction and 10–15 times in the longitudinal direction. The disadvantage is that the distribution of the azimuth is poor and the aspect ratio is low, so the obtained underground information is mainly distributed along the longitudinal survey line with less transverse information.

Oil and gas exploration methods are continuously improving and developing. Nowadays the requirements for technologies are becoming advanced. At the same time, seismic acquisition instruments have been developed, the number of field acquisition traces has increased, and the variety of high-precision 3D seismic methods has widened. The WBH seismic exploration technology has been proposed by the Bureau of Geophysical Prospecting, China National Petroleum Company (BGP, CNPC).

The prediction of residual oil distribution is one of the main factors for a detailed description of pay zones in oilfields that are in the middle and late stages of development. This is also the basis for the planning and implementation of the oilfield development project. Because of the vertical resolution limitations of conventional seismic data and the results of previous studies in the oilfield development, the use of seismic data for predicting the residual oil distribution is relatively limited. The implementation of the WBH seismic technology has solved the problems of reservoir characterization and identification of residual oil zones (ROZ) that might occur during the application of conventional seismic data.

In this paper we investigate the prediction and assessment of potential ROZ in the mature (K) oilfield using the seismological approach, including wide-azimuth seismic survey with high-density observations, high-resolution processing of the target object, detailed structural interpretation, broadband inversion, and analysis of the obtained static and dynamic data.

## ADVANTAGES OF WBH SEISMIC DATA

The WBH seismic technology refers to a high-density wide-azimuth seismic survey that can capture a broadband signal. The development of the application of this technology over more than ten years has created a complex integrated technical system for acquisition, processing, and interpretation of seismic data. This mainly includes the design of seismic survey methods, equipment for broadband acquisition, and a number of auxiliary technologies, such as the implementation of acquisition in the field data processing and complex studies (Ling, 2003; Wang et al., 2015; Zhang et al., 2015, 2018; Ni et al., 2017; Zeng et al., 2019; Chang et al., 2020). The observation azimuth refers to the angle between the line of the shot point and the receiver point, north, or longitudinal direction, and the width of the observation azimuth refers to the size of the fold area of the observation azimuth at the same CMP.

The aspect ratio of offset in a seismic observation system is used to express the azimuth of a 3D seismic observation system. When the aspect ratio of the array is less than 0.5, it is a narrow-azimuth seismic observation system. The value from 0.5 to 0.6 corresponds to the medium-azimuth seismic observation system; the value from 0.60 to 0.85, to the wide-azimuth one; and the value from 0.85 to 1.00, to an omnidirectional one, respectively (Ding et al., 2018).

As compared with the conventional narrow- and medium-azimuth observation systems, the wide-azimuth one has the following advantages: (a) the wide azimuth is conducive to attenuate regular noise, thereby improving the signal-to-noise ratio (SNR) and the resolution of seismic data. As the wide-azimuth observation has a longer lateral offset and a larger lateral fold number, noise attenuation techniques, such as three-dimensional f-k, can be used, which is more effective in the attenuation of regular noise and scattering noise; (b) the wide azimuth is beneficial for improvement of the 3D imaging accuracy of complex structures. Modern seismic exploration has two main characteristics: (a) the entire imaging process has gradually entered the stage of seismic wave inversion imaging, and (b) lithologic reservoirs are described. The seismic migration imaging technology based on the wave equation represents the highest achievement in seismic processing.

According to the different methods of implementation in the field, two types of high-density seismic exploration technologies have formed. The first one is the seismic exploration technology characterized by high-quality imaging of the density of traces with a small trace spacing. The key idea is to increase the receiver point and source density to improve the spatial sampling rate and resolution. The second type is the high-density seismic exploration technology with single-point reception of the digital combination. The principal idea is the single-point reception of the digital combination to improve the SNR, resolution, and fidelity.

The increase in the frequency bandwidth of seismic data is mainly to raise the low-frequency component. There are two main ways of improving the low-frequency component. First, to improve the acquisition technology of the low-frequency geophone and to increase the low-frequency energy of the original signal, which is the fundamental method. Second, during processing and interpretation, the various technologies are used to compensate for the low-frequency components. However, in this method it is usually difficult to change the SNR spectrum, especially if it is based on the single-trace technology.

The sampling rate is an important factor affecting the resolution, and the time interval determines the highest frequency signal that can be correctly restored. For the high-frequency signals, if the sampling is insufficient, aliasing will occur. So, the time sampling rate is closely related to the vertical resolution.

The influence of the spatial sampling rate on the seismic signal in the wave number domain is the same as the influence of the time sampling rate on the frequency. The spatial sampling rate is also called "the spatial acquisition density", which includes three aspects: shot density, trace density, and coverage density. Among these three parameters for measuring the spatial sampling density, the shot density and trace density are independent parameters, while the coverage density is a related parameter.

Owing to the continuous development of the WBH seismic technology, the SNR, resolution, and imaging accuracy of seismic data have greatly improved, especially with the development of the offset vector tile (OVT) processing and interpretation technology, low-frequency inversion, and other technologies. The application of WBH seismic data has also laid the foundation for the prediction of residual oil distribution.

## GEOLOGIC SETTING

The K oilfield is a typical mature oilfield in the Pre-Caspian region, characterized by high productivity and high water cut. The K oilfield is the anticline with a long axis (Fig. 1). The structure of the anticline with a long axis is complicated by two sets of faults, one of them striking in the E–W direction and the other in the NNE direction. The apparent throw of the faults varies within 5–60 m, and their extension is 2–15 km. The faults are divided into numerous structural blocks in the oilfield. The reservoirs are characterized by fine sandstones and siltstones with medium and high porosity and medium and high permeability.

Cenozoic, Mesozoic, and Paleozoic deposits have been exposed within the oilfield, where the Middle Jurassic sandstones are the most important productive pay zones.

After the Permian, the study area experienced four main stages: Permian–Triassic rift stage, Late Jurassic rift stage, late Eocene compression stage, and early Cenozoic compression stage. The last-mentioned stage is not very pronounced in the study area.

(1) The Permian–Triassic rift stage. In the Permian rifting period, under the tensile stress, the normal faults developed in the study area, and thick Permian–Triassic strata were deposited; the strong regional compression from Late Triassic to Early Jurassic led to regional uplift, resulting in the inversion of the rift system, the bending deformation of the stratum, erosion and loss of the stratum at the top of the Triassic, and the deposition of the Jurassic stratum;

(2) The late rift stage. From Late Jurassic to Early Cretaceous, the uplift related to strike-slip developed in the study area; some faults were reactivated; and NE–SW strike-slip faults formed, which made the structure in the study area more complex;

(3) The compression stage. From the Cenozoic to the present, the study area is basically in overall subsidence, which is less affected by the collision between the Eurasian and Arabian plates.

There are 12 sand formations in the K oilfield: J-5c, J-4c, J-3c, J-2c, J-1c, J-I, J-II, J-III, J-IV, J-V, J-VI, and J-VII. Five marker layers are mainly identified in the study area: calcareous sandstone of J-5c (unconformity), mudstone of the J-4c bottom, mudstone of the J-1c bottom, mudstone of the J-II bottom, and mudstone of the J-V top. The analysis showed that the mid-to-late Jurassic was in the period of structural uplift; the

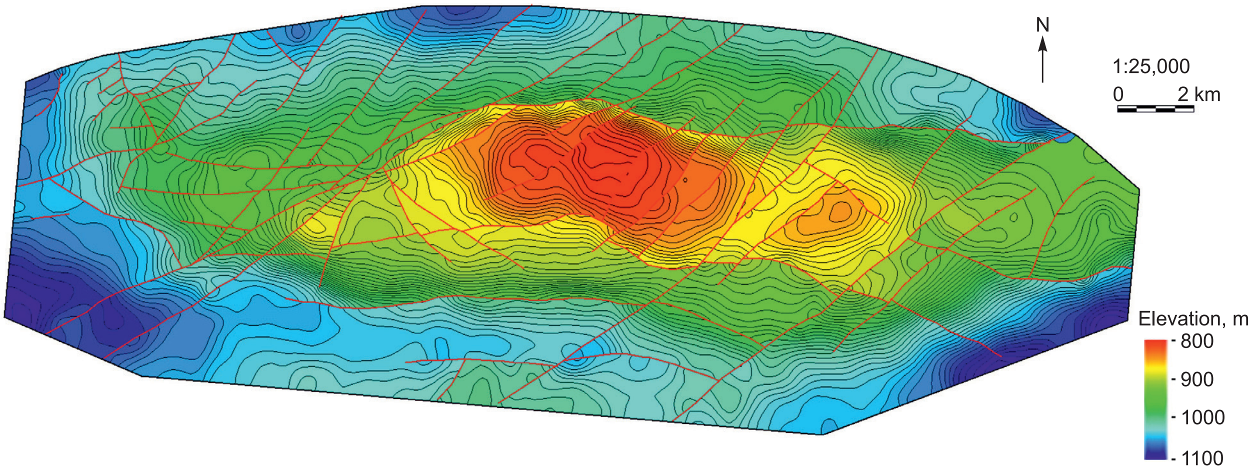



**Fig. 1. Structure map of the J-III layer in the K oilfield.**

middle–upper Jurassic strata J-5c~J-1c were denuded to varying degrees in the high part of the structure; and the lower strata J-I to J-VII were relatively complete (Fig. 2).

## RESEARCH METHODS

The WBH seismic technology is a new technology that has been developed to improve the accuracy of seismic surveys and plays an important role in improving the resolution and accuracy of seismic data. The following approaches have been formulated for the prediction and distribution of ROZ: wide-azimuth seismic

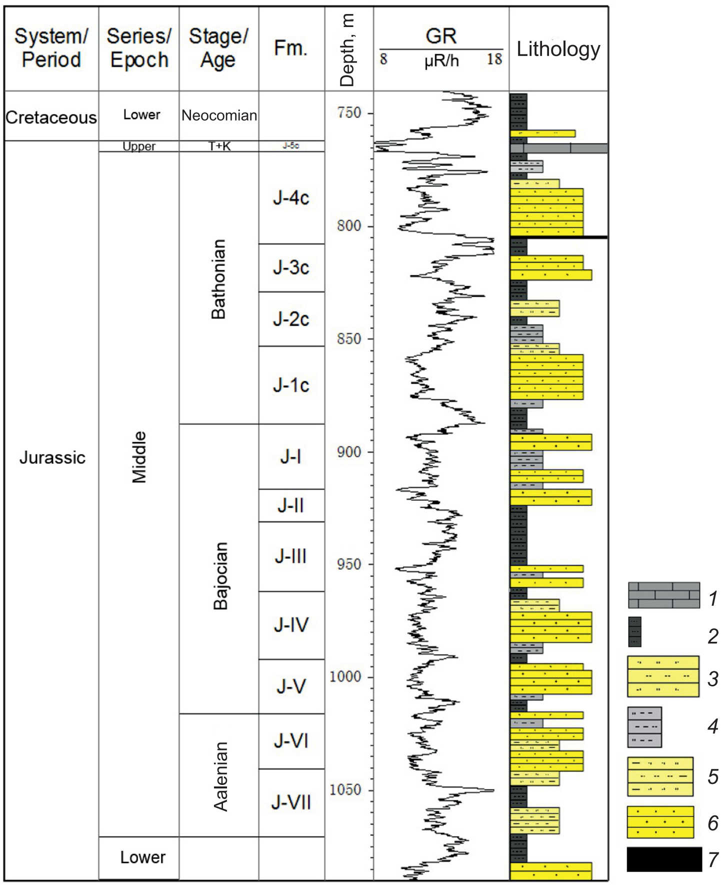



**Fig. 2. Lithologic stratigraphic column in the K oilfield.** ***1*** **– calcareous sandstone;** ***2*** **– mudstone;** ***3*** **– siltstone;** ***4*** **– silty mudstone;** ***5*** **– argillaceous siltstone;** ***6*** **– sandstone;** ***7*** **– coal seam.**

survey with high-density observations, high-resolution processing of the target object, detailed structural interpretation, broadband inversion, and analysis of the obtained static and dynamic data. All the work was done in the GeoEast software, developed by BGP company, CNPC.

### Wide-azimuth seismic survey with high-density observation

Conventional seismic exploration focuses on the study of structures and reservoirs. However, the wide-azimuth seismic survey focuses on analysis of structures, reservoirs, and fluids. The number of observation angles increases when the seismic survey with the wide-azimuth seismic technology is done. This results in the increased image accuracy of the structures, because wide-azimuth seismic data provide more abundant azimuth information. With the help of the basic theory of seismic anisotropy and the azimuth anisotropy information of wide-azimuth seismic data, the azimuth difference of seismic attributes, such as the traveltime, velocity, amplitude, frequency, and phase of a seismic wave propagating in underground media, can be better analyzed, and then the anisotropic characteristics of a stratum can be identified. The main advantages of high-density data are improved static correction accuracy, digital processing, and noise attenuation and increased spatial resolution of seismic data during processing. During a seismic survey with a high density of measurements, the coverage density increases from 10,000 times/km$^2$ to hundreds of thousands and even 1,000,000 times/km$^2$. Also, the fold increases significantly, as a result of which it is possible to carry out a full-fledged data sampling, which makes the image boundaries clearer (Table 1).

Table 1. **Parameters of wide-azimuth seismic survey with high-density observation**

| Source type | Vibrator |
|---|---|
| Sweep frequency | 1.5–110.0 Hz |
| Source point interval | 20 m |
| Source line interval | 100 m |
| Receiver line azimuth | 5° |
| Receiver point interval | 20 m |
| Receiver line interval | 100 m |
| Bin size | 10 × 10 |
| Maximum offset | 4072 m |
| Full fold number | 570 (15 × 38) |
| Source point area | 271 km$^2$ |
| Receiver point area | 270.8 km$^2$ |
| Source point density | 500 (sp/km$^2$) |
| Receiver point density | 500 (rp/km$^2$) |
| Sampling rate | 2 ms |
| Seismic trace length | 6000 ms |
| Aspect ratio | 0.81 |

The purpose of wide-azimuth observation is to obtain a 3D data volume with the observation azimuth width offset and a fold number as uniform as possible. In applications, there is sufficient far, middle, and near offset, and its distribution is relatively uniform only in the different observation directions of the shot point domain, the common receiver point domain, and the common middle point domain. Besides that, it is ensured that each observation direction has a fold number that meets the basic needs of imaging. That is why the fold number in each azimuth must be high enough, and the offset distribution of each azimuth is relatively uniform and reasonable, which is the true wide-azimuth observation. Therefore, wide-azimuth observation has to be combined with high-density observation, which will inevitably increase the cost of seismic acquisition. When implementing wide-azimuth observation, it is necessary to consider its economic feasibility and to combine the application of the high-efficiency acquisition technique.

### High-resolution processing of the target object

The target processing is divided into the following steps:

(1) First-arrival picking is carried out by the first-arrival fitting constraint method to improve the accuracy and efficiency of the first-arrival picking. The micrologging-constraint tomographic static correction is used to solve the problem of long-wavelength static correction in the work area to improve the imaging quality and to lay the foundation for the revision of the structure;

(2) Using the high-fidelity prestack denoising technique, the SNR of the data was improved, and low-frequency effective signals were kept efficiently;

(3) Using the broadband processing technology (low-frequency compensation and Q compensation), the seismic wavelet was compressed effectively, and the data frequency range was broadened;

(4) By the OVT domain prestack time migration technology, multiazimuth data volumes and spiral gathers were provided for interpretation and azimuth. Amplitude versus offset (AVO) analysis and identification of microfractures and fractures were carried out using a multidirectional data volume;

(5) The high-precision near-surface velocity model and well velocity were used for joint velocity modeling, and the accuracy of the velocity model was improved by grid tomography iteration, so as to improve the data imaging quality.

a

b

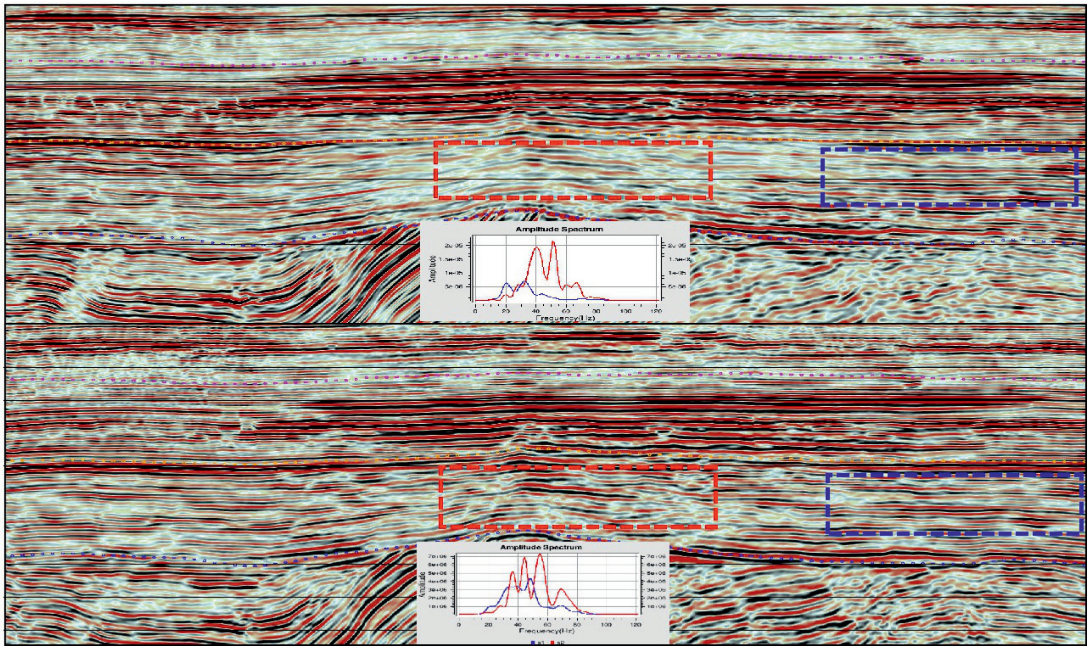


**Fig. 3. Comparison of the seismic sections.** ***a*** **– The seismic section before high-resolution processing of the target object;** ***b*** **– the seismic section after high-resolution processing of the target object.**

If all the above steps of the processing are carried out, this technology improves the frequency and amplitude of the seismic data, which is the basis for a detailed structural interpretation and prediction of reservoirs (Fig. 3). After high-resolution processing of the target, the resolution of the seismic data is increased, as a result of which the display of faults in the seismic data becomes clearer and the identification ability of seismic inversion for a thin reservoir is stronger.

### Detailed structural interpretation

Since wide-azimuth seismic data are characterized by a larger incident angle, the interpretation of azimuth information of wide-azimuth seismic data should be based on azimuthal anisotropy analysis and AVO analysis. By interpretation of seismic data based on the WBH seismic exploration technology, the small-scale faults were identified, which laid the foundation for detecting new traps in the periclinal parts of the oilfield and predicting the residual oil distribution zones. The main stages of detailed structural interpretation of seismic data are seismic calibration, interpretation of horizons and faults, analysis of seismic attributes, mapping, identification of traps, and prediction of hydrocarbon and residual oil distribution zones.

According to the principle of seismic wave propagation in the underground media, primarily the synthetic record corresponding to the established seismic model was calculated. After that the reasonable relationship between seismic responses and geologic features was verified, and the precision of reservoir prediction and reliability of identification of a thin sand bed were improved.

The next step of the work was the detailed interpretation of horizons and faults of all the study area. Then, according to the interpretation of the horizons and faults, the seismic attribute analysis was done. Seismic attribute analysis is a series of techniques including attribute extraction, attribute optimization, attribute fusion, and attribute interpretation on the basis of seismic data. This technique is useful for delineating sedimentary facies, characterizing the reservoir, and improving the application of seismic data in reservoir prediction, hydrocarbon detection, and identification and evaluation of stratigraphic lithologic traps.

### Broadband inversion

Thin bed identification by conventional seismic prediction methods is very difficult. Generally, the thin bed is the layer with a thickness less than one-eighth of wavelength. In developed oilfields with a high drilling well density grid, the prediction of thin layers is made by geostatistical inversion, characteristic logging curve inversion, and simulation. In blocks with scarce or uneven drilled well data, thin bed identification often depends on the amplitude or high-frequency attenuation of the seismic attribute combined with well data and can be predicted by broadband inversion as was carried out in the K oilfield.

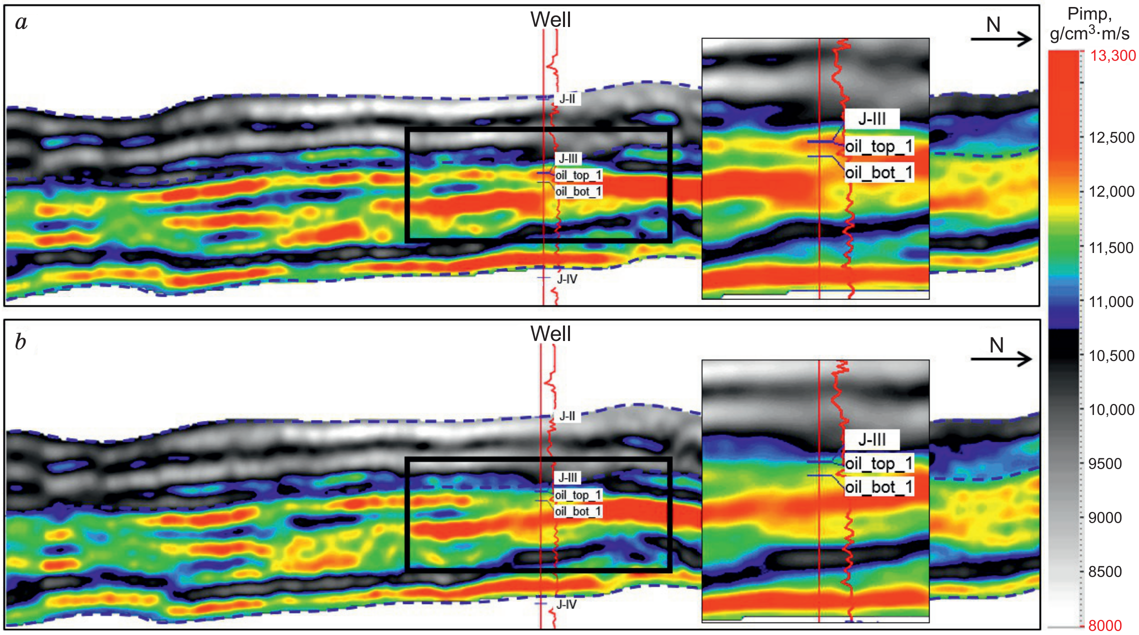



**Fig. 4. Comparison of the inversion sections. *a* – The conventional low-frequency inversion section (10–58 Hz); *b* – the broadband low-frequency inversion section (1.5–58.0 Hz).**

Broadband seismic energy excitation of low-frequency waves provides better access to low-frequency information (Ampilov et al., 2019). Based on this information, the vertical resolution is increased; the horizontal distribution of sand bodies can be determined more efficiently; and the oil and gas potential can be predicted. Thus, broadband seismic inversion has the following advantages: (a) insignificant influence of the number of wells and interpolation methods on the inversion result; (b) the vertical and horizontal geological information is more abundant; (c) improvement of the accuracy of inversion of seismic data (Fig. 4) (Ding et al., 2018; Ampilov et al., 2019).

### Analysis of static and dynamic data

Hydrocarbon comprehensive prediction is a kind of comprehensive fluid identification method which has combined drilling oil and gas display, formation testing, the change of lithologic and physical properties, and the difference in the corresponding seismic response to determine the fluid property. In addition to the methods described above for identification of reservoirs, the hydrocarbon prediction attribute was used. The principle of application of this attribute is as follows: When the seismic record passes through the oil- and gas-bearing stratum, the low-frequency energy of the seismic record will be relatively enhanced, while the high-frequency energy will be relatively weakened, which is called "low-frequency resonance, high-frequency attenuation." It can be used to determine the oil and gas abundance and to delineate the oil and gas range. The calculation results are robust, and the test results are highly accurate. First of all, spectrum analysis and comparison of known wells have to be carried out, where the selection of a time window is of vital importance. Then a large number of experiments should be carried out according to the actual situation to get better results.

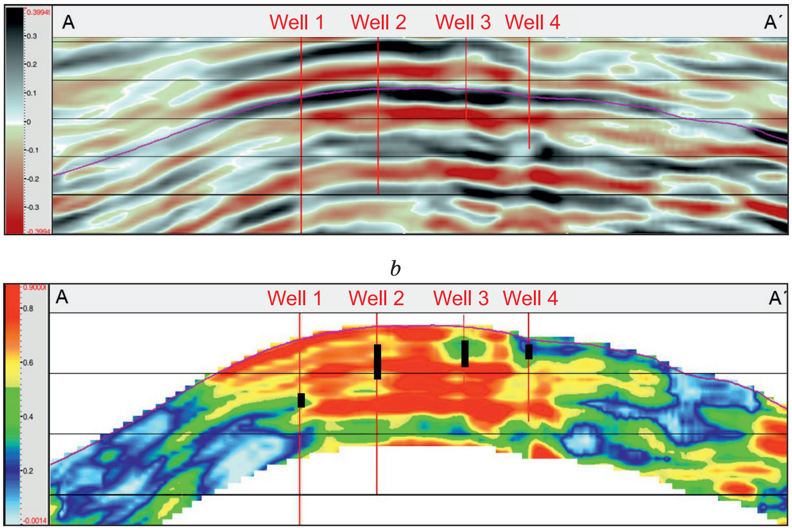
The method which has been applied to the seismic data of oil and gas detection is the technology of direct detection, such as static and dynamic data analysis. This technique has its advantages; under suitable conditions, different seismic geologic conditions need system analysis, test, and summary.

Static data refer to the data on the identified new traps that are unaffected by the development of the oilfield and include parameters, such as area, elevation (true vertical depth subsea level) and relief, etc. Dynamic data refer to complex data on the oilfield during development, namely, the current state of wells in potential areas. The results of the study are based on those of the above work and the integration of the analysis of static and dynamic data (Fig. 5), on the basis of which it is possible to predict the distribution of the potential ROZ.

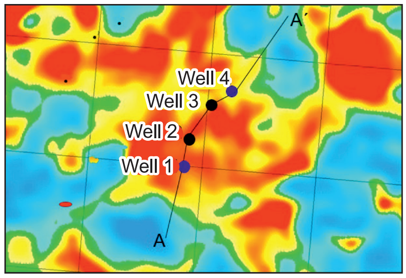
## RESULTS

In the research area of the oilfield, the Jurassic deposits are the most interesting in terms of oil and gas content. Therefore, the target objects of this study are productive deposits of the Jurassic System. Based on the *a*

*b*




*c*




*d*

| Well No. | Daily production, tons | Water cut, % |
|---|---|---|
| Well 1 | 4.7 | 92 |
| Well 2 | 7.8 | 85 |
| Well 3 | 5.3 | 90 |
| Well 4 | 1.5 | 97 |

**Fig. 5. Joint static and dynamic data on the oilfield. *a* – The well tie seismic section; *b* – the well tie section of the hydrocarbon detection attribute; *c* – the hydrocarbon detection attribute map; *d* – dynamic data on the wells.**

data of high-density wide-azimuth seismic exploration (Table 1), as well as high-resolution processing of the target object (Fig. 3), at the initial stage, seismic calibration was carried out (Fig. 6), as a result of which the markers were specified and the interpretation of the horizons and faults was conducted.

Based on seismic data in combination with dynamic reservoir data, a detailed interpretation of faults was carried out; low-relief structures and sand bodies were characterized in detail, which contributes to the identification of potential ROZ and the rational location of recommended wells in the oilfield.

## IDENTIFICATION OF SMALL-SCALE FAULTS

The identification of small-scale faults in the oilfield was carried out in several stages. To improve the display of faults on a seismic section, the attribute of structure-oriented filtering (SOF) was used. After that seismic attributes cubes were extracted, and then an analysis of the faults development was made based on OVT data after migration. As a result, the strike characteristics of the faults were established both vertically and horizontally. The technological process of SOF is shown in Fig. 7.

Structure-oriented filtering has the following advantages: (a) the signal-to-noise ratio improves; (b) the features of continuity and discontinuity of the seismic event become more clear; (c) the reliability of automatic tracking of a horizon improves. It is better to extract seismic attributes on the basis of seismic data after the application of SOF than to extract them directly from the original seismic data. As a result of implementation of SOF, the identification of previously unobvious faults on the seismic sections and detailed interpretation of small-scale faults were carried out (Fig. 8).

The results of application of SOF on seismic sections and multiattribute analysis are combined into a method of tracing the development of faults in the vertical and horizontal directions in the oilfield. The extraction of one seismic attribute is not enough for the detailed identification of small-scale faults. Therefore, in this study a comprehensive seismic multiattribute analysis of attributes, such as coherence, curvature, edge detection, and AI fault, was performed (Fig. 9). Analysis of slices of the seismic attributes allows for the conclusion that the coherence cube slice is capable of displaying the characteristics of the fault extension and their development horizontally in the oilfield. The edge detection cube slice more clearly reflects the characteristics of the distribution of large-scale faults and the AI fault, and the slices of the maximum positive curvature cubes make it possible to more clearly display the characteristics of extension of the local small-scale faults. As a result of comparison of the attributes, it is considered that the best method for identifying small-scale faults is the AI fault attribute (Fig. 9*d*). The basic method of the AI fault attribute is as follows: Owing to the construction of a series of 3D volume models, the current version has more than 1200 fault volume models with various fault properties and corresponding seismic forward modeling data. After the testing of the constructed deep neural network model, a fault prediction model was obtained. The module inputs 3D overlapped seismic data and directly predicts the formation of corresponding fault attribute data. This method belongs to attribute volume prediction. It

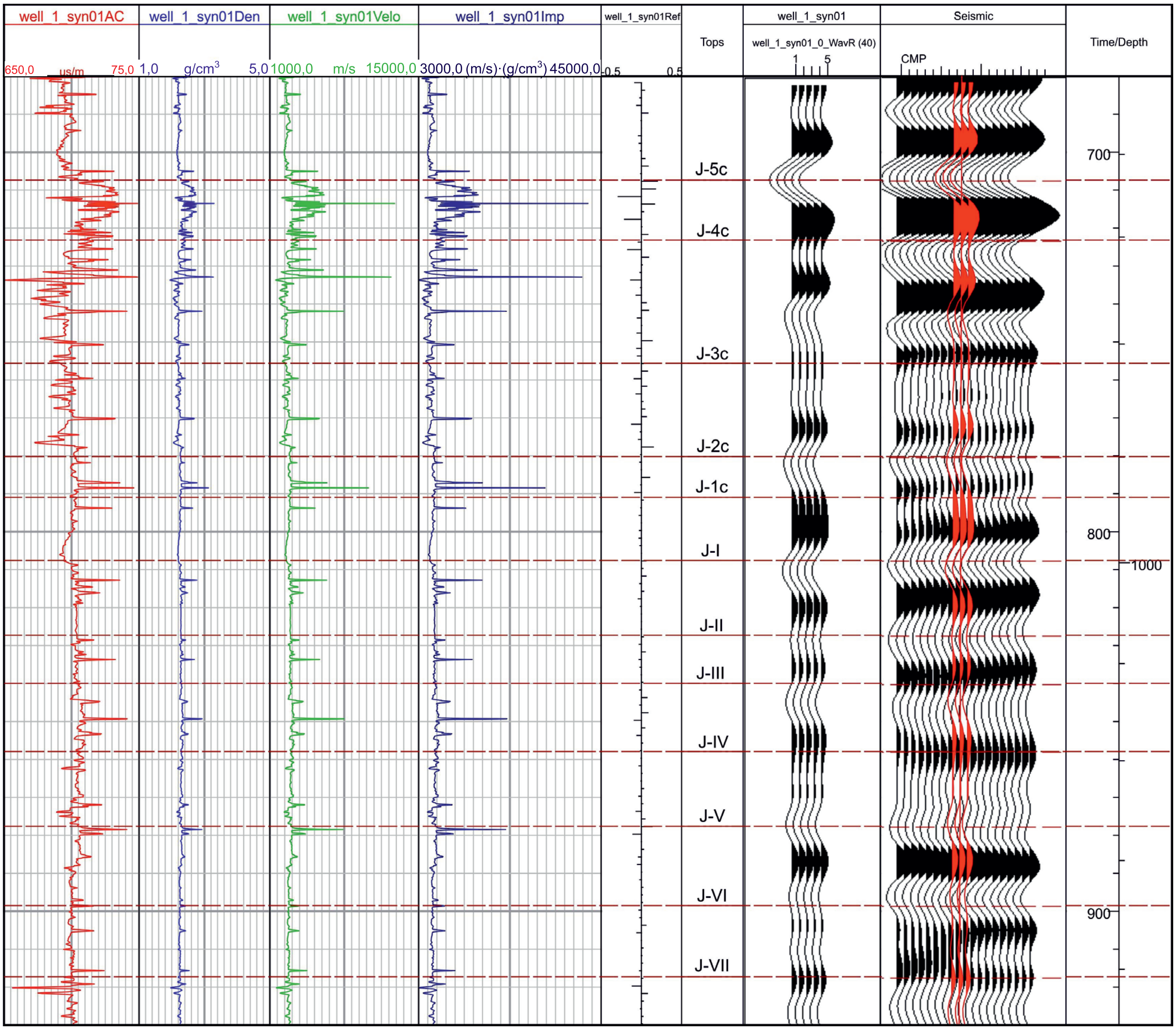



**Fig. 6. Seismic calibration.**

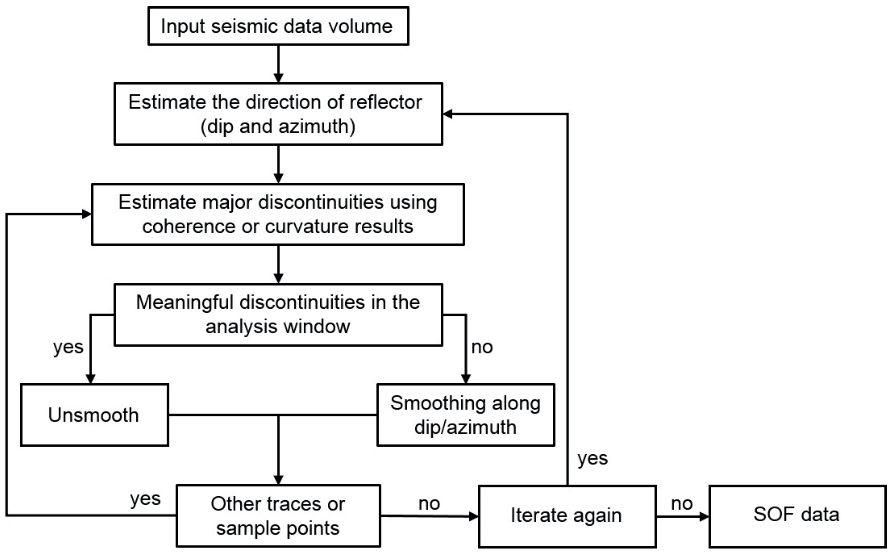



**Fig. 7. The technological process of structure-oriented filtering (SOF).**

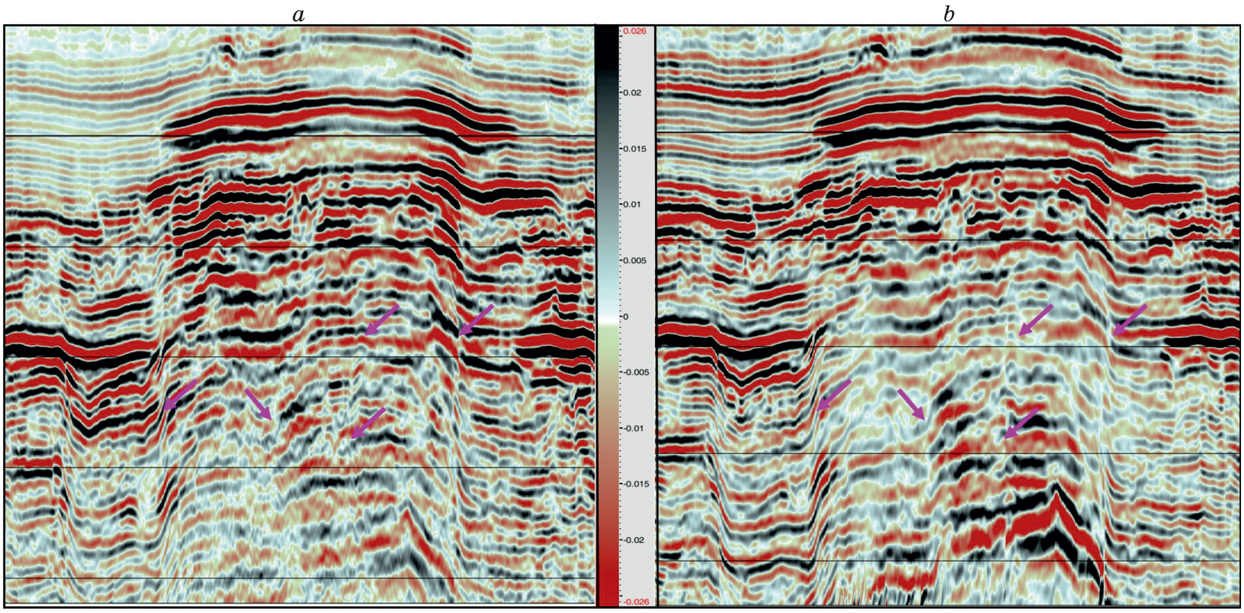



**Fig. 8. Comparison of the seismic sections.** ***a*** **– The seismic section before SOF application;** ***b*** **– the seismic section after SOF application.**

has obvious advantages in longitudinal section imaging, imaging of small-scale faults, and attenuation of the noise in deep layers. It improves the results of traditional coherence and curvature and may become a powerful tool for describing complex structures in fine exploration and efficient development.

The fault analysis based on the azimuth of OVT data after migration is one of the latest technologies for wide-azimuth and high-density seismic exploration (Xu et al., 2020; Zhang et al., 2020).

Wide-azimuth seismic data open up the opportunity of identifying anisotropic bodies with different orientations. When there is azimuth anisotropy, narrow-azimuth observation can only measure anisotropic response in one direction and cannot analyze in all directions [1°], while wide-azimuth observation can perform omnidirectional anisotropy response analysis to identify fault systems with different spatial distribution directions. To ensure the interpretability of seismic data after azimuthal stacking, all azimuthal stacking seismic data should have a certain number of folds.

The main advantage of the azimuth analysis of faults is the identification of small-scale faults of various strikes. When the chosen azimuth is perpendicular to the fault strike, the anisotropy is strong and new small-

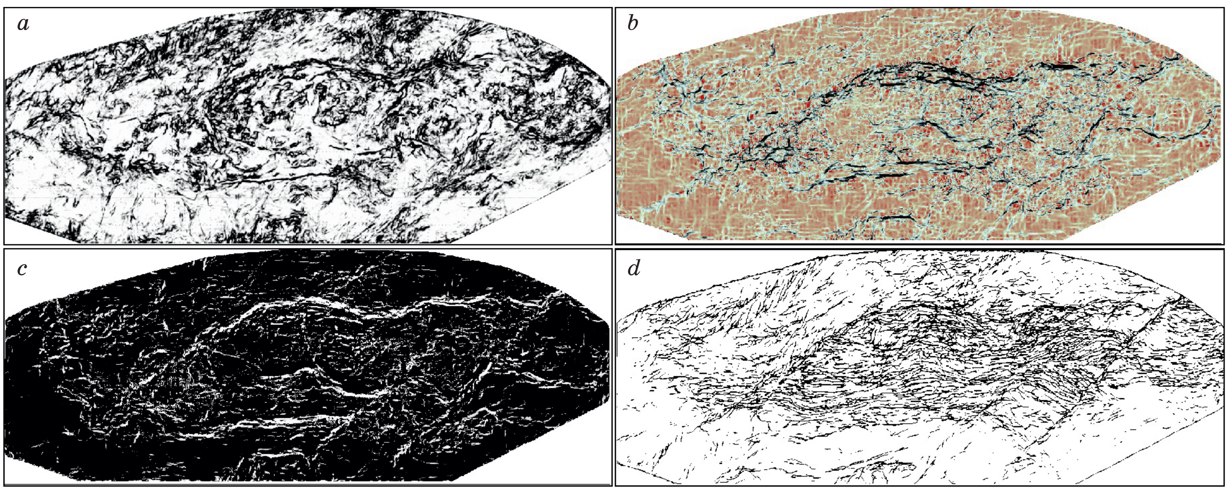



**Fig. 9. Identification of faults based on attribute analysis.** ***a*** **– Coherence;** ***b*** **– maximum curvature;** ***c*** **– edge detection;** ***d*** **– AI fault.**

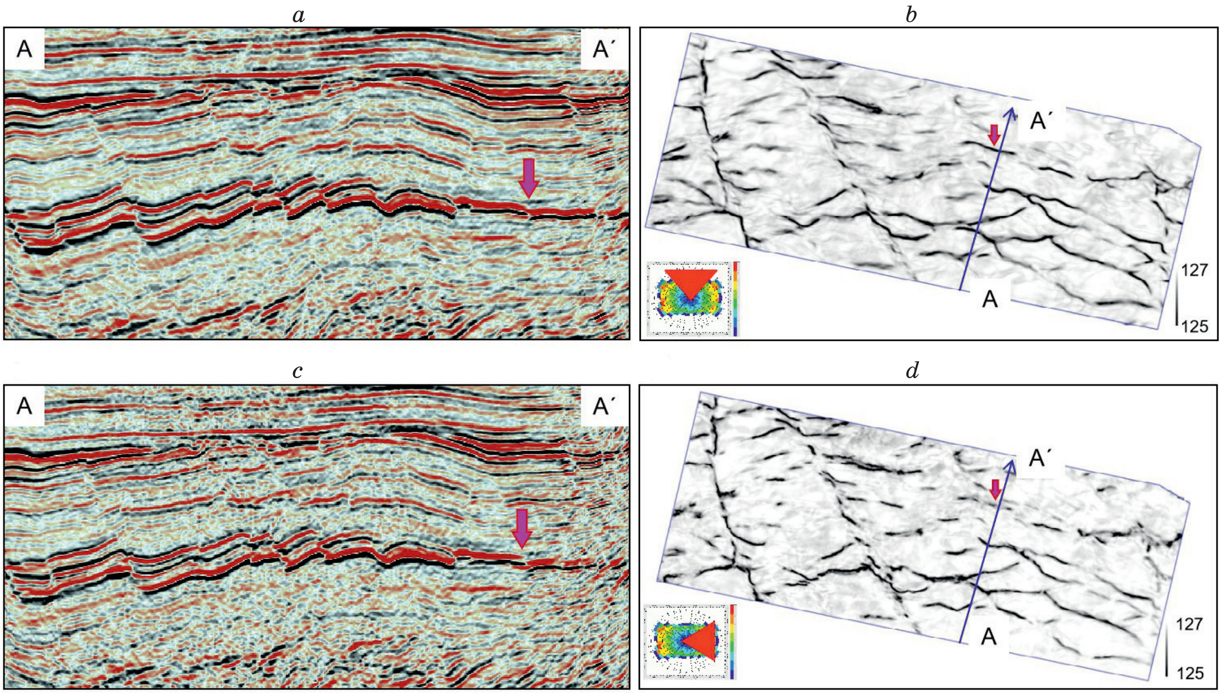



**Fig. 10. Fault identification based on azimuth analysis of offset vector tile (OVT) data after migration.**

*a* – The seismic section of anisotrophic azimuthal stacking after OVT migration (45-135); *b* – the coherence cube of anisotrophic azimuthal stacking after OVT migration (45-135); *c* – the seismic section of anisotrophic azimuthal stacking after OVT migration (-45-45); *d* – the coherence cube of anisotrophic azimuthal stacking after OVT migration (-45-45).

scale faults are found, or the continuity of the faults is displayed more clearly. When the chosen azimuth is along the strike of the faults, the anisotropy is weak, and small-scale faults are unclear, or the continuity of the faults is poor (Fig. 10) (Wang et al., 2017). Thus, the basic principle of azimuth selection is to ensure that each group of differently oriented fault systems has an azimuth perpendicular to strikes and that each azimuth has a specific SNR.

Within the K oilfield, as a result of the fault interpretation and the above works, according to the apparent heave slip, the extension in the area, and the control factors of the faults, the faults were subdivided into three categories: large-, medium-, and small-scale. Large-scale faults control the general morphology of the oilfield structure; medium-scale ones control the formation of oil and gas reservoirs and the location of the oil–water contact; and small-scale ones affect the development, water injection, and the distribution of residual oil.

## IDENTIFICATION OF LOW-RELIEF STRUCTURES IN THE PERICLINAL PARTS OF THE OILFIELD

Based on the detailed structural interpretation of seismic data, time and depth structural maps were created, from which new traps with a small area were identified (Fig. 11). Also, in the periclinal parts, low-relief structures were exposed that might be potential ROZ (Fig. 12). Thus, the potential oil area is much larger than the researchers presumed in previous years, which has radically changed the understanding of the hydrocarbon distribution areas in the K oilfield.

### Identification of thin reservoirs

Broadband seismic inversion is one of the latest technologies for identifying thin reservoirs (Xu et al., 2020; Zhang et al., 2020). On the basis of low-frequency information of broadband seismic inversion, work has been carried out more efficiently to determine the lateral boundaries of sand bodies and to predict the areas of petroleum zones. On the broadband inversion section, there are also thin productive reservoirs (Fig. 13) and lithologic pinchout zones (Fig. 14). For a comprehensive, complete, and objective identification of thin reservoirs, the analysis of sedimentary microfacies over the area and in wells along the sections was made. The

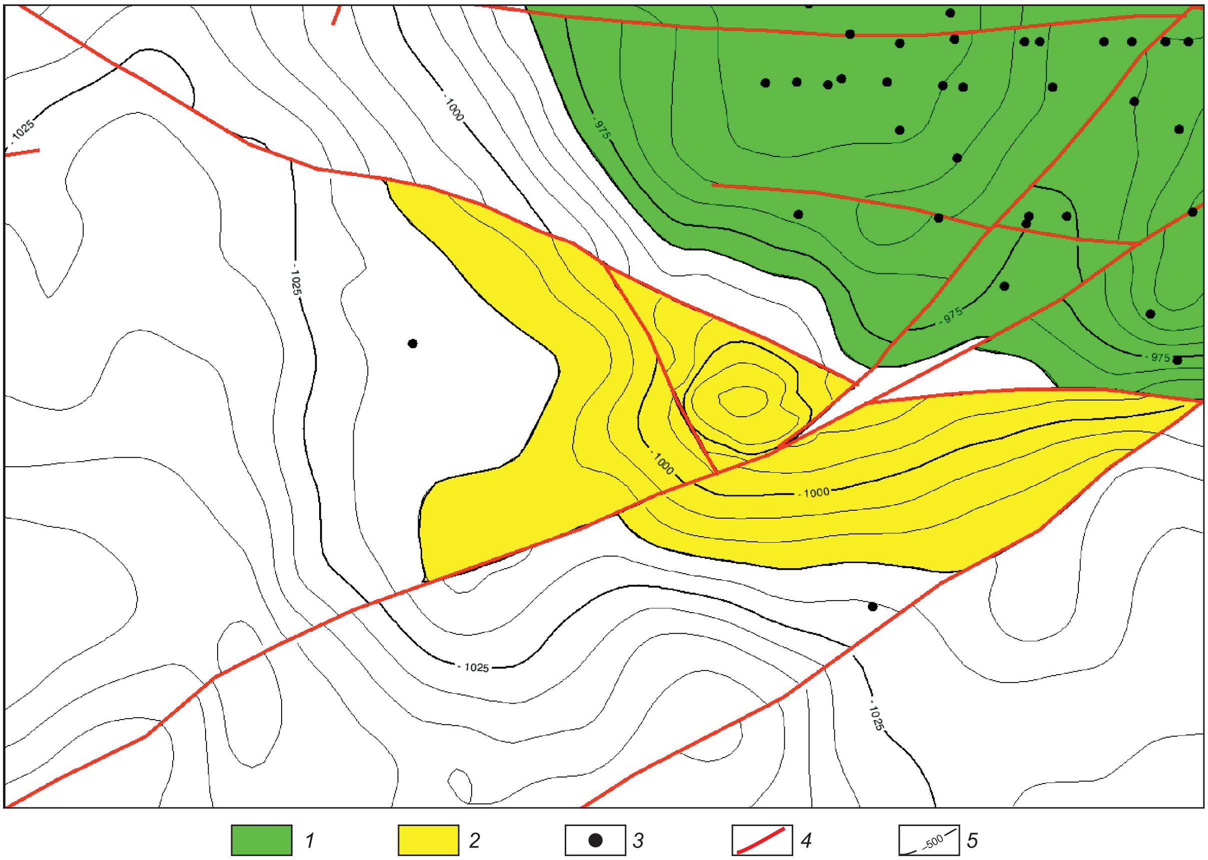



**Fig. 11. Local map of the identified trap.** ***1*** **– oil-bearing area;** ***2*** **– new trap;** ***3*** **– well;** ***4*** **– fault;** ***5*** **– contour.**


**Fig. 12. Local map of the identified low-relief structure. For the legend see Fig. 11.**

identification of sedimentary microfacies was carried out on the basis of cluster analysis of the waveforms, after which the correlation of sedimentary facies with logging facies was performed (Fig. 15).

It should be noted that the quality of the obtained seismic data made it possible to significantly clarify the structure of productive reservoirs and to effectively use modern techniques for recalculating resources and choosing the location of new appraisal and exploratory wells.

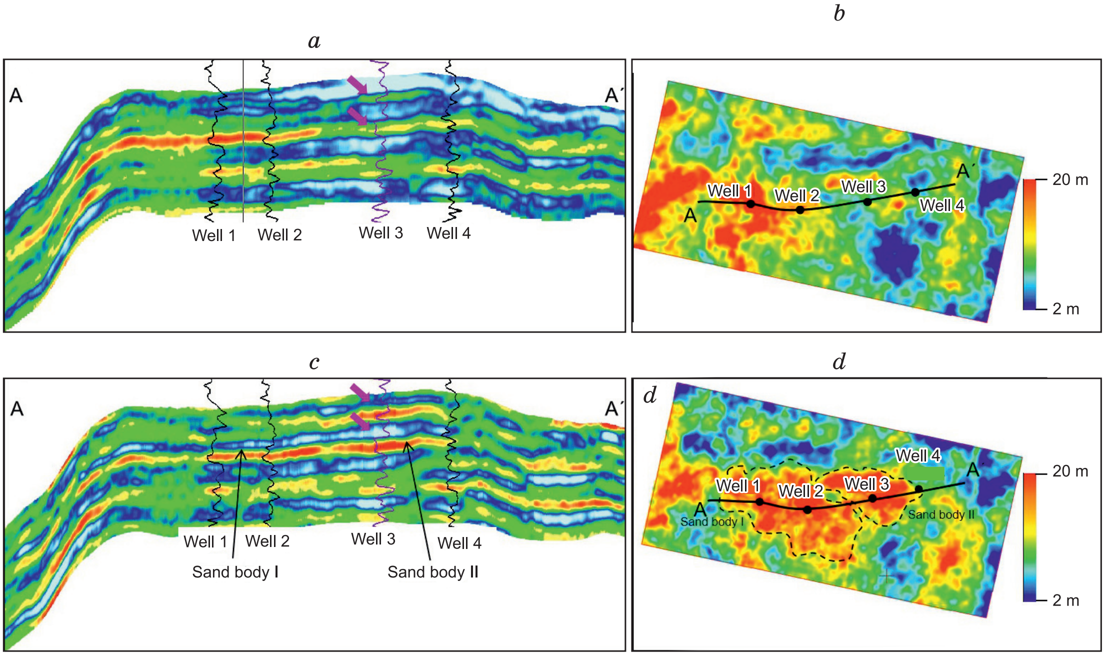


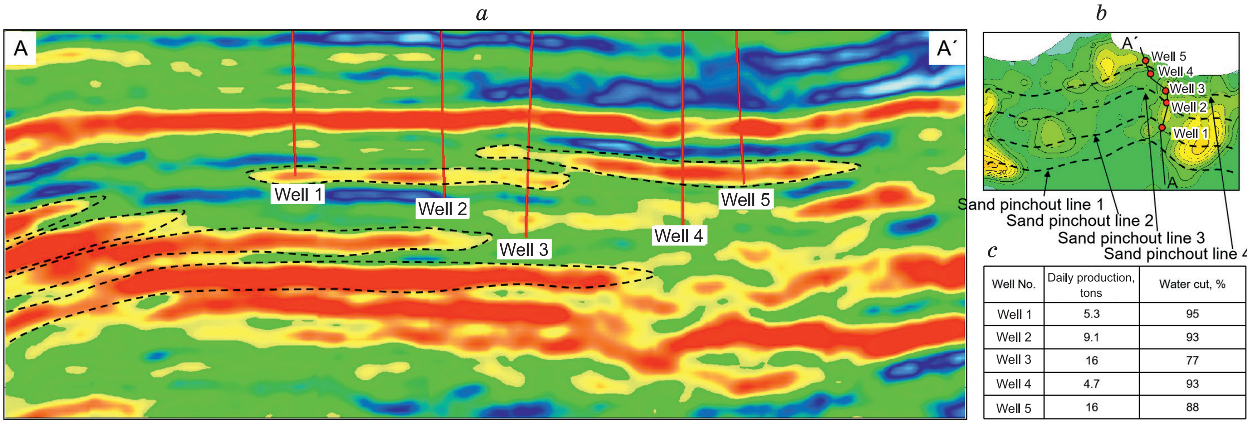

**Fig. 13. Identification of pay zones in the broadband inversion section.**

*a* – The seismic inversion section; *b* – the reservoir thickness map based on the data of the conventional seismic inversion; *c* – the broadband seismic inversion section; *d* – the reservoir thickness map based on the data of the broadband seismic inversion.

## Identification of the residual oil zones

As there are many production zones in the K oilfield, the dynamic production conditions of each zone were taken into account with seismic and geological studies, on the basis of which the data were generalized to search for potential ROZ. The research approach consists mainly of the static and dynamic data analysis, where static data are related to potential areas identified as a result of the seismic attribute analysis and broadband inversion and the dynamic data are related to reservoirs formed in areas with a low well density grid, low productivity, and low water cut after development in the oilfield.

Based on the analysis of seismic sections, inversion sections, and maps of pay zone thickness, as well as sections and maps of the hydrocarbon detection attribute in areas with a high well density grid, the following potential ROZ were identified in areas with a small number of drilled wells: (a) arched faulted-nose structures in the periclinal parts of the oilfield (Fig. 16); (b) low-relief anticlines in the periclinal parts of the oilfield (Fig. 17); (c) zones of lithologic pinchout (Fig. 18).




| Well No. | Daily production, tons | Water cut, % |
|---|---|---|
| Well 1 | 5.3 | 95 |
| Well 2 | 9.1 | 93 |
| Well 3 | 16 | 77 |
| Well 4 | 4.7 | 93 |
| Well 5 | 16 | 88 |

**Fig. 14. Identification of lithologic pinchout on the broadband inversion section. *a* – The seismic broadband inversion section; *b* – the local structural map; *c* – dynamic data on the wells.**

*a*

*b*

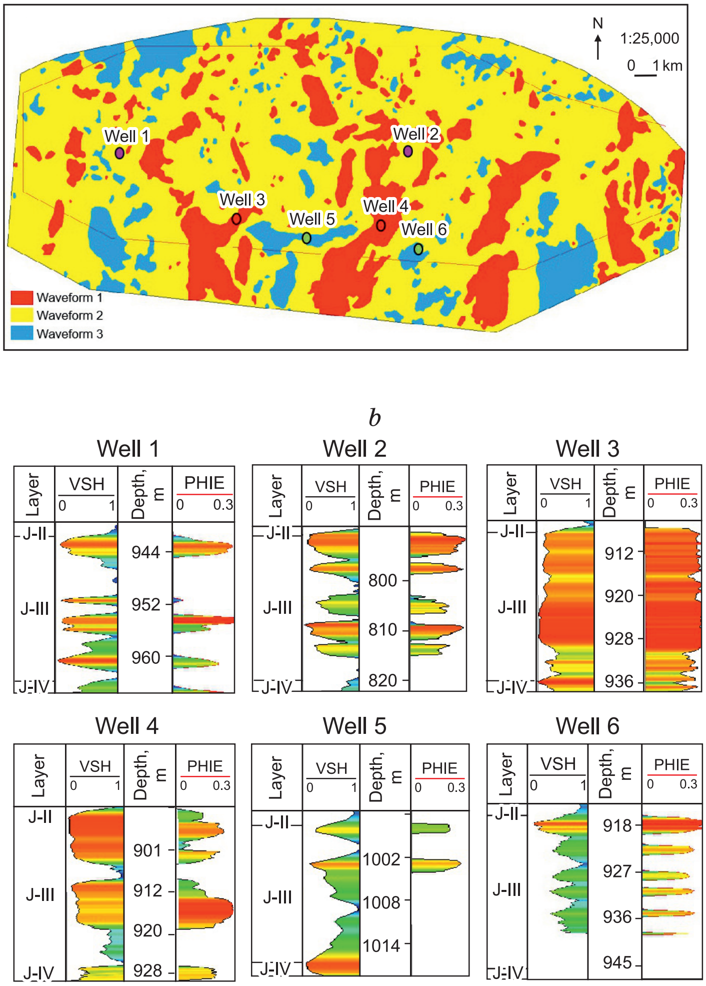



**Fig. 15. Prediction of thin reservoirs based on the identification of sedimentary microfacies and their correlation with log facies.**

*a* – Cluster analysis of the microfacies; *b* – log facies analysis.

Based on the results of seismic exploration and the dynamics of production in the K oilfield, five types of ROZ can be distinguished:

(a) Zones of the faulted-nose structure and crest of tectonic blocks with a low frequency and high amplitude;

(b) Zones of crests of low-relief structures with a low frequency and high amplitude;

(c) Zones of pinchout of sand bodies with low water cut in relatively high parts of the structures;

(d) Zones of pinchout of layers with low water cut in relatively high parts of the structures;

(e) Potential oil zones with low water cut and a lack of drilled wells.

## CONCLUSIONS

The WBH is one of the modern techniques in the seismic survey that focuses on analysis of structures, reservoirs, and fluids.

*a* *c*

*b* *d*

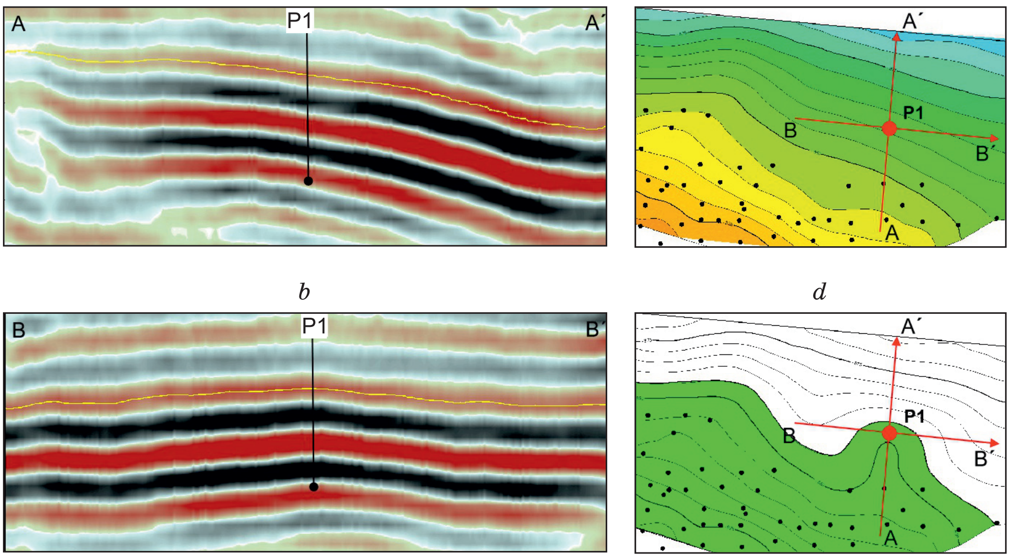



**Fig. 16. Identified faulted-nose structure in the periclinal part of the oilfield.**

*a* – The identified arched faulted-nose structure on the seismic section AA′; *b* – the identified arched faulted-nose structure on the seismic section BB′; *c* – the old local structural map; *d* – the identified arched faulted-nose structure on the local structural map as a result of the potential oil area was increased based on a detailed structural interpretation.

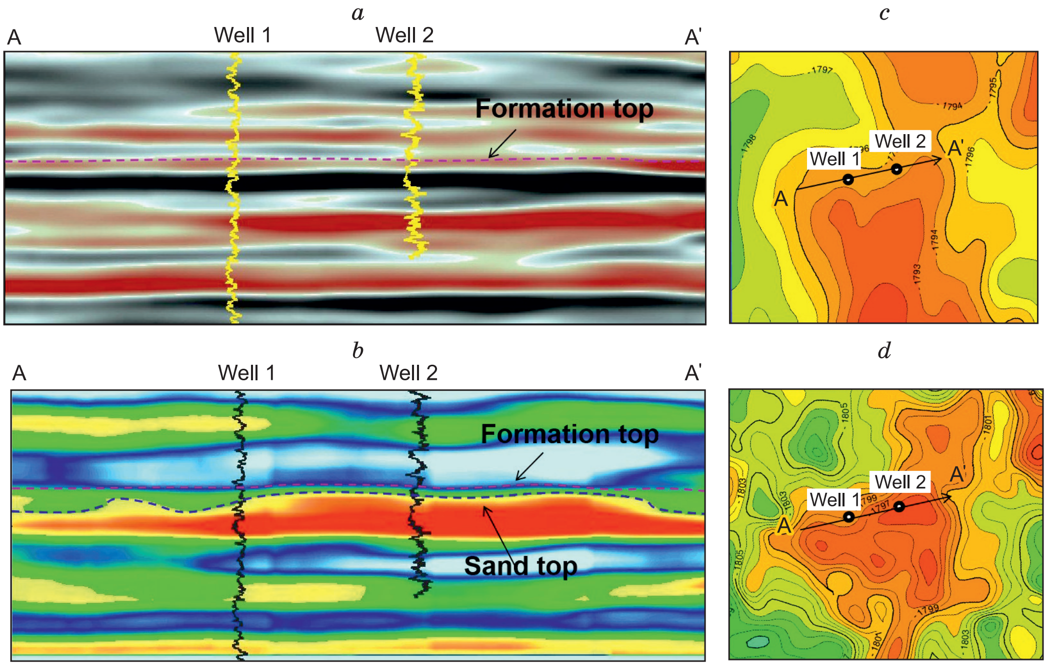



**Fig. 17. Identified low-relief anticline at the oilfield.**

*a* – The identified low-relief anticline on the seismic section; *b* – the identified low-relief anticline on the inversion section; *c* – the old local structural map; *d* – the local structural map of distribution of residual oil zones in the low-relief anticline.

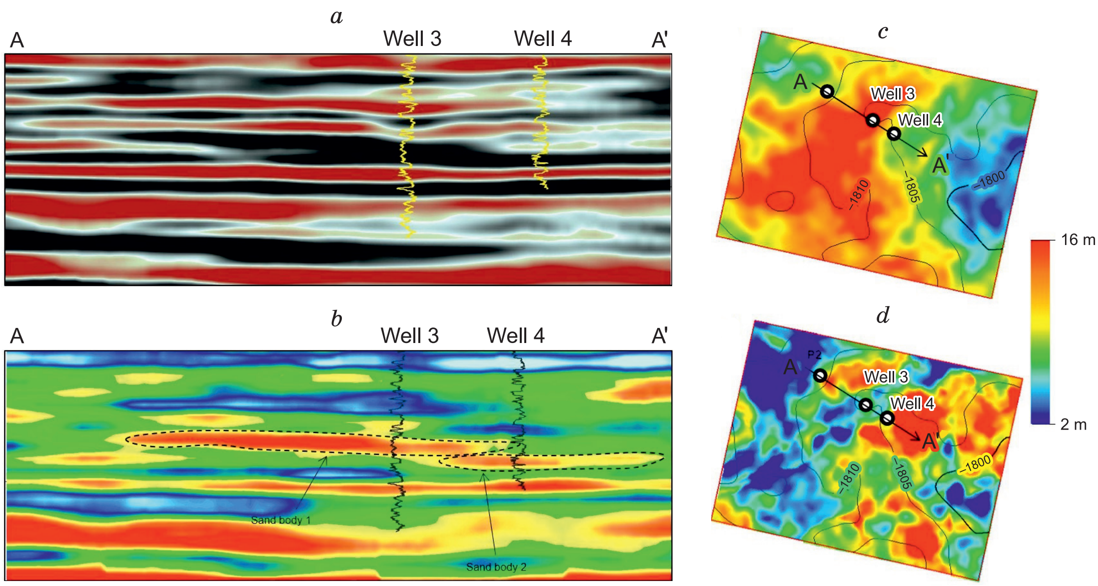



**Fig. 18. Lithologic pinchout zones.**

*a* – The identified lithologic pinchout zone on the seismic section; *b* – the identified lithologic pinchout zone on the inversion section; *c* – the local map of the reservoir thickness of sand body 1; *d* – the local map of the reservoir thickness of sand body 2.

The main advantages of high-density data are improved static correction accuracy, digital processing, and noise attenuation and increased spatial resolution of seismic data during processing. By increasing the frequency bandwidth of seismic data, mainly the low-frequency component can be increased based on improving the acquisition technique and equipment and methods of seismic data processing and interpretation.

As a result, with the application of WBH seismic data, the anisotropic characteristics of a stratum can be more obvious. Using the interpretation of seismic data, the small-scale faults, new structural traps, and pinchout zones in the periclinal parts of the oilfield can be identified. Based on the increase of vertical resolution, owing to the broadband inversion, the horizontal distribution of sand bodies can be determined more efficiently, and the oil and gas potential can be predicted.

By application of WBH seismic data, positive experience has been gained in prediction of ROZ. Comprehensive analysis of static and dynamic data shows that potential ROZ are arched faulted-nose structures in the periclinal parts of the oilfield, low-relief anticlines in the periclinal parts of the oilfield, and lithologic pinchout zones.

The results of the study can lay the foundation for studying the geologic structure of periclinal parts in mature oilfields, optimizing development, and assessing their potential.

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