Integrated Fault Sealing Analysis Techniques Based on the FMI, OBN Seismic Data and Reservoir Performance and Its Application in K Oilfield

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Extended abstract

Accurate modelling of fault seal is crucial in understanding fluid flow and connectivity in mature fields. Numerous methods of modelling the sealing capacity of faults have been developed, such as lithological juxtapositions, SGR and PSSF. However, due to the uncertainty of structure, throw and lithology prediction, conventional methods are difficult to meet the needs of reservoir development. To improve the accuracy of fault seal analysis, a new method was proposed in this abstract. Integrated PSDM seismic data, well logging, and reservoir dynamic data, this new fault seal analysis method include 4 steps: 1) Horizons and faults update based on PSDM seismic data. In this step, more accurate structure model would be generated; 2) Integrated well logging and seismic motion inversion (SMI) for reservoir lithology modelling. In this step, the accuracy of lithology prediction results on both sides of the fault will be improved; 3) Fault seal analysis was run efficiently in 3D geological model by lithology juxtaposition and SGR. 4) Fault seal analysis QC and optimization by using reservoir dynamic data.

This method has been successfully applied to the K mature oilfield in Central Asia. The detailed faults interpretation was done based on new PSDM seismic data. The number of faults increased from 18 to 44, and the new structural model was improved obviously. The reservoir model based on the combination of well logging interpretation and seismic motion inversion (SMI) is not only consistent with drilled well, but also consistent with seismic inversion trend, which improves the accuracy of lithology prediction. Automatic fault seal analysis algorithm based on 3D geological model can efficiently generate the fault seal analysis results, and find potential areas. Fault seal analysis results can be validated and optimized by dynamic data from drilled wells. 6 potential faulted seal traps below conventional oil-water contract (OWC) were found in the slope area of oilfield. 3 wells have been drilled and confirmed 3 fault seal reservoirs with high oil production and much lower water-cut (6%) than conventional water- cut (96%) in the slope of K mature oilfield. It is proved that the method is beneficial for development in mature oil field.

This new fault seal analysis method integrated the information from PSDM seismic data, well logging, and reservoir performance data to improve the accuracy of faults model and lithology model, and generated a more reasonable fault seal analysis result. This allows more confidence in estimating the sealing or leaking capacity of faults and reduces risk of re-exploration and development in mature oil field.

Introduction

Approaches for modelling fault seal behavior have been adopted by the oil industry and used to predict locations of economic accumulations of oil and gas bound by faults or dependent on faults for migration. Lithological juxtaposition diagrams, referred to as Allan Maps, display the relative position of lithological units in the hanging wall and footwall of a fault (Allan, 1989). Sand-sand juxtapositions are indicative of areas where cross-fault flow is likely and juxtapositions against shales, or other low permeability lithology, indicate sealing parts of a fault.

Areas of sand-sand juxtaposition also act as barriers to cross-fault flow when the fault rock itself has a clay content sufficient to create an impermeable layer. This is because of the composition of the sequence that has been moved past that point by the fault. Quantitative techniques developed and adopted by the oil and gas industry include Shale Gouge Ratio (SGR) (Figure 1a), (Yielding et al., 1997), shale smear factor (SSF) (Figure 1b) (Lindsay et al., 1993), clay smear potential (CSP) (Figure 1c) (Fulljames et al., 1996), and probabilistic shale smear factor (PSSF) (Figure 1d), (Childs et al., 2007). Figure 1a-d gives the equations used and a graphical representation of each of these methods.

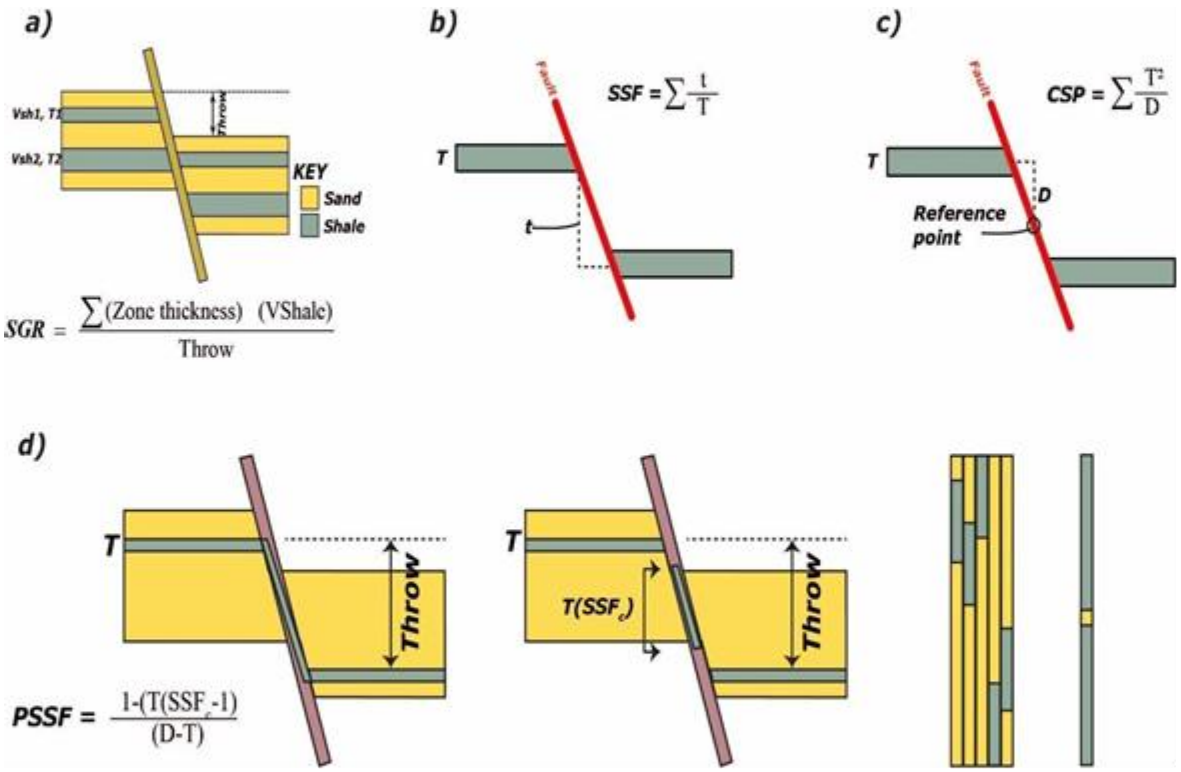

Figure 1. Seal proxies used in industry to estimate the likelihood of cross-fault hydrocarbon migration (C. Reilly, 2019). a) Shale gouge ratio (SGR); b) Shale Smear Factor (SSF); c) Clay smear potential (CSP); and d) Probabilistic shale smear factor (PSSF). For a full a description of each method, see references cited in the text.

The study area is located in the Ustyurt Basin of Central Asia. The structure is a long axis anticline complicated by faults in the east-west direction. The faults can be divided into three stages. The early east to west direction faults control the structural morphology, the North-East to south-west strike-slip faults control the oil and gas distribution, and the small faults associated with the two main faults affect the development of oil fields. The target layer of study is classic sediments in Cretaceous meandering river-delta environment. The single sand body thickness of the reservoir is 3m-16m, the reservoir porosity is 5% -24%, and the permeability is 0.1 md-1000md. K mature oilfield has been developed since 1972, with a production history of 40 years. At present, there are 3762 wells drilled, and the average water cut is 92%.

Data base

1 The main data base of this study includes four aspects:
2 280 new wells drilled in the last three years (from 2019-2021), of which 86 wells contain DST mid-course pressure test data;
3 3762 wells logging data since the year 1972 and log curves and log interpretation results;
4 New seismic acquisition of broadband azimuth high-density 3D seismic data in 2020, with PSTM and PSDM seismic processing;
5 Currently in production of 689 wells of production performance data, including production, water cut, wellhead and bottom-hole pressure, etc.

Method

In this paper, a new fault seal analysis method was proposed, this method include 4 steps: 1) Horizons and faults interpretation based on PSDM seismic data. In this step, more accurate structure model would be generated; 2) Integrated well logging and seismic motion inversion (SMI) for reservoir lithology modelling. In this step, the accuracy of lithology prediction results on both sides of the fault will be improved; 3) Fault seal analysis was run efficiently in 3D geological model by lithology juxtaposition and SGR. 4) Fault seal analysis QC and optimization by using reservoir dynamic data.

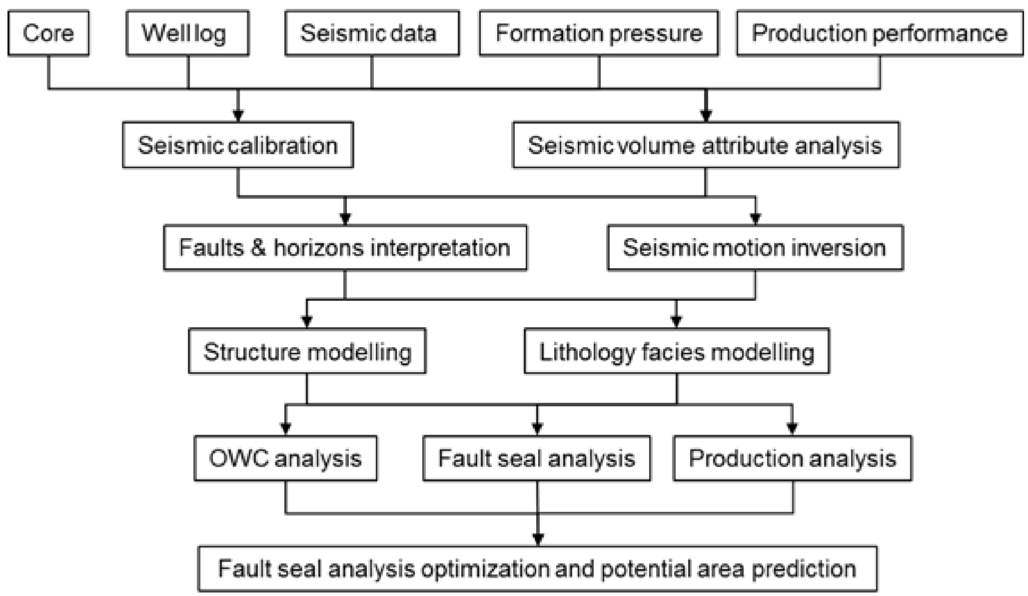

Fig.2 The workflow for Reservoir prediction based on the geological seismic waveform analysis

1) Horizons & faults interpretation and structure modelling

In this step, the most important point is fault clear identification and deliberate interpretation. A series of seismic attributes such as coherence, variance and curvature will be used for fault identification based on the PSDM seismic data. Deep learning faults interpretation technology will be used to interpret faults based on the optimization of seismic attributes analysis. In recent years, with the coming of the era of big data, the technology of fault recognition based on deep learning has become a research hot spot in the field of artificial intelligence, and it's still evolving. Fault identification is of great significance in seismic exploration and development, especially for small faults, which are difficult to be identified directly in seismic profiles, and for the recoverable reserves of exploration areas at the late stage or stage of oilfield exploration, capacity building is of great significance. All faults will be QC in 3D visualization. On the basis of fault and horizon interpretation, new structure model was generated.

2) Seismic motion inversion (SMI) and reservoir lithology modelling

The analysis of seismic waveform and logging curve of actual data shows that the logging curve corresponding to similar waveform shows higher similarity in wider frequency band, therefore, high-resolution Inversion is realized by using high-frequency logging information driven by the transverse similarity of Seismic waveform, and the method of seismic motion inversion (SMI) is established. First, the singular value decomposition is used to perform a dynamic clustering analysis of the wave forms of the seismic traces next to the well, and the mapping relationship between the structure of the seismic wave forms and the structure of the logging curves is established, the sample sets of logging curves with different types of waveform structures (representing different types of seismic facies) are generated, and then the distribution of the sample sets corresponding to different types of waveform structures is analyzed, Bayesian inversion frameworks for different types of seismic facies are established, and then the common parts of the sample sets are selected as initial models for iterative inversion under different Bayesian frameworks, taking the optimal cut-off frequency of the sample set as the constraint condition, the inversion results with high resolution are obtained.

Seismic motion inversion (SMI) was carried out under the constraint of seismic facies. Seismic motion inversion (SMI) can integrate the advantages of seismic data with horizontal high resolutions and the advantages of well data with vertical high resolutions, so the Seismic motion inversion (SMI) results are more accurate. On the basis of structure model and seismic motion inversion, new reservoir lithology modelling was generated. This lithology model will be QC by both previous drilled wells and newly drilled wells. After QC, lithology model was used for lithology juxtaposition analysis between different sides of fault.

3) Fault seal analysis

Fault seal analysis was carried out in a Geo East - Trap 3D software. Trap 3D fault sealing software identification method mainly includes 5 steps. 1) firstly, depth domain slices are generated from the depth domain geological model containing faults. 2) through the lithology juxtaposition rule, the computer automatically discriminates the lithology docking relation of both sides of each fault one by one; 3) the number of single sand body can be identified through the adjacent slice relation, and the plugging area can be identified through the lithology docking relation; 4) the plugging area can be effectively supplemented by Shale Smear Factor (SSF). 5) output the result of different plugging coefficient.

Firstly, the lithology juxtaposition method was used to preliminary estimate the fault seal analysis coefficient in the 3D geological model. And then the Shale gouge ratio (SGR) method was used to update the fault seal analysis coefficient.

4) Fault seal analysis QC and optimization by using reservoir dynamic data.

The depth slice of the model and the cross model section can be used to QC the results of fault seal analysis in static model. The difference of oil-water contacts, production pressure, water cut between different sides of the fault can be used to QC the results of fault seal analysis from the perspective of reservoir performance view. To match the prediction results with the dynamic evidence of reservoir production, fault seal analysis need to optimize the cut-off value permeability of lithology.

5) Potential area prediction and new wells proposal

Finally, on the basis of fault sealing analysis, and integrated the structure, reservoir prediction results, the potential area was predicted and new wells was proposed.
The principle of determining potential area mainly includes the following five aspects. 1) the meandering river area blocked by the NE-SW controlled reservoir faults; 2) the lithologic reservoir is well developed near the potential area, and the OWC of the newly drilled wells is not consistent; 3) the DST pressure test results of the newly drilled wells are complicated, and there are oil-bearing high-pressure wells at the bottom; 4) the obvious faults can be seen on the newly acquired seismic profile; 5) the obvious oil-bearing characteristics of"Low frequency, strong amplitude" can be seen in the fault-blocked area at the low location.

Application

The new sealing analysis method based on PSDM seismic, well logging and reservoir performance has been successfully applied in K oilfield.

1) Horizons & faults interpretation and structure modelling

Six Horizons have been interpreted based on the PSDM seismic data. (Fig.3).A series of minor faults were explained based on the PSDM seismic data and seismic attributes (Fig.3, Fig.4).Structure model was established and updated based on fault and horizon interpretation. Compare with previous fault model with only 18 faults, the new updated fault model was more elaborate with 44 faults. (Fig.4).

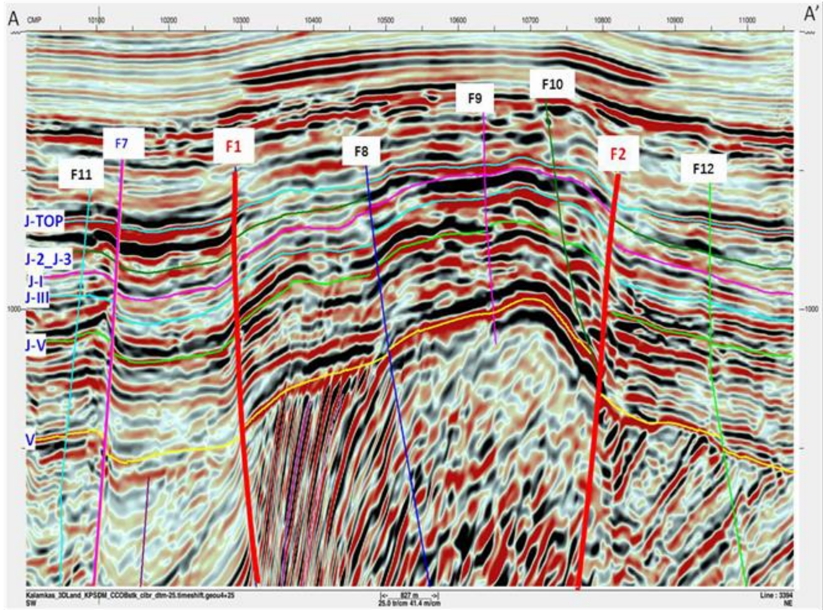

Fig.3 Fault interpretation updated based on PSDM seismic data. (F1 and F2 were previous faults, new minor faults F7 to F12 were interpreted in this study.)

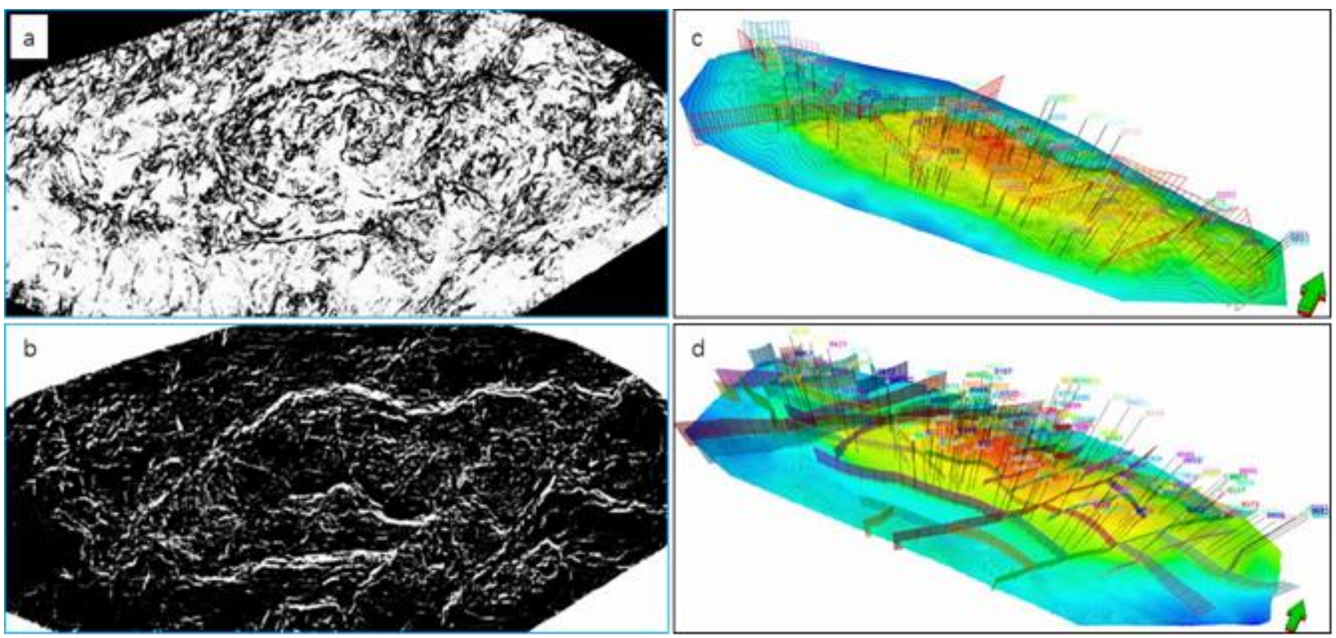

Fig.4 Fault model updated based on PSDM seismic data. a- Coherence from previous seismic data (It is difficult to identify faults), B-new coherence from new PSDM seismic data (It can identify faults more clearly); C - Previous fault model with only 18 faults, d- updated fault model with 44 faults.

2) Seismic motion inversion (SMI) and reservoir lithology modelling

Seismic inversion volume can clearly display lithology distribution and matched with wells. (Fig.5a, Fig.5c). Reservoir lithology model was established based on the seismic motion inversion results. (Fig.5b, Fig. 5d). Lithology model was used for lithology juxtaposition analysis and SGR analysis between different sides of fault.

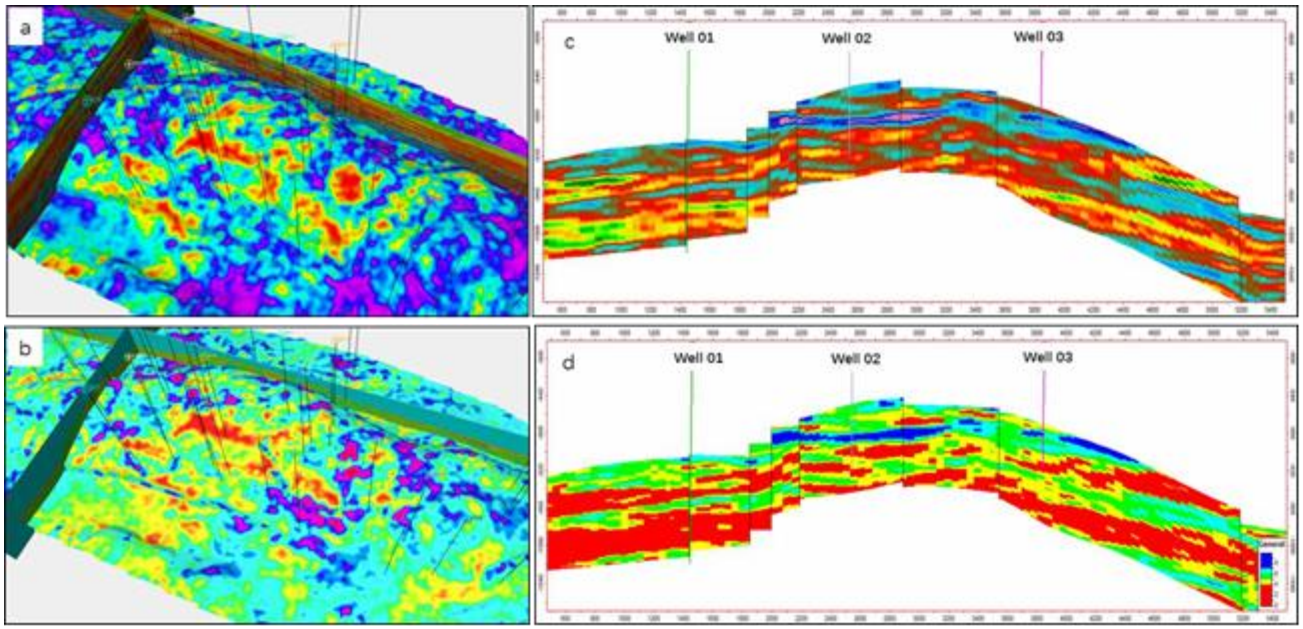

Fig.5 Lithology model updated based on seismic inversion: a-seismic inversion volume can clearly display lithology distribution and matched with wells, b-lithology model, lithology distribution is consistent with seismic inversion, c-seismic inversion section with faults, d- lithology model section with faults show the lithology distribution is consistent with seismic inversion.

3) Fault seal analysis and QC

Lithology juxtaposition method and shale gouge ratio (SGR) method were used to estimate the fault seal analysis coefficient (Fig. 6b, Fig7a) based on the 3D geological model (Fig.6a). From the prediction results, the potential area of fault sealing can be easily identified. In the area where the well has been drilled, these potential areas can be verified and QC by the well. The difference of oil-water contacts, production pressure, water cut between different sides of the fault can be used to QC the results of fault seal analysis (Fig.6c, Fig.6d).

Different fault blocks of fault sealing have different characteristics oil-water contacts, production pressure, water cut and different production perform.

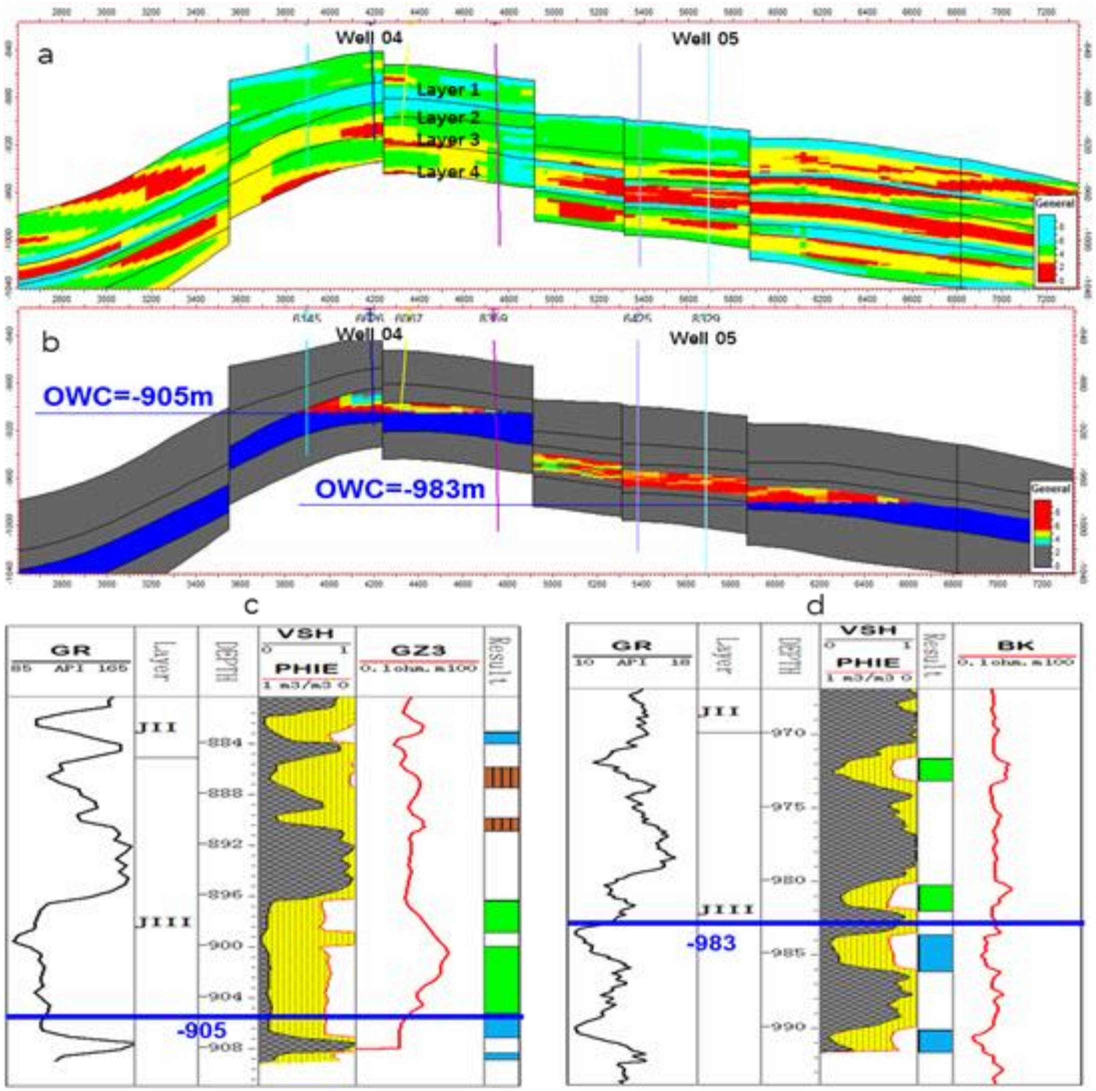

Fig.6.Fault seal analysis of layer 3 based on 3D geological model, and verified by drilled wells. a – 3D geological model with faults and lithology distribution. b-fault seal analysis of the layer 3, find 2 potential areas, c-potential area 1 was confirmed by well04, OWC is -905m, d-potential area 2 was confirmed by well05, OWC is -983m.

4) New potential areas were discovered based on the fault seal analysis

A series of new potential areas were discovered in the structural slope area. Take the JIII sub formation for example, 7 new potential areas were discovered (Fig7a).

These potential areas also can be confirmed by seismic data with obvious low seismic frequency and strong seismic amplitude (oil seismic respond) (Fig.7b, Fig.7c).

In 2021, three new wells (N11, N12, and N13) have been drilled. All 3wells discovered industrial oil with high production (210bbl/d-689bbl/d) and low water cut (5%-14%). (Fig.7a, Fig.7d).

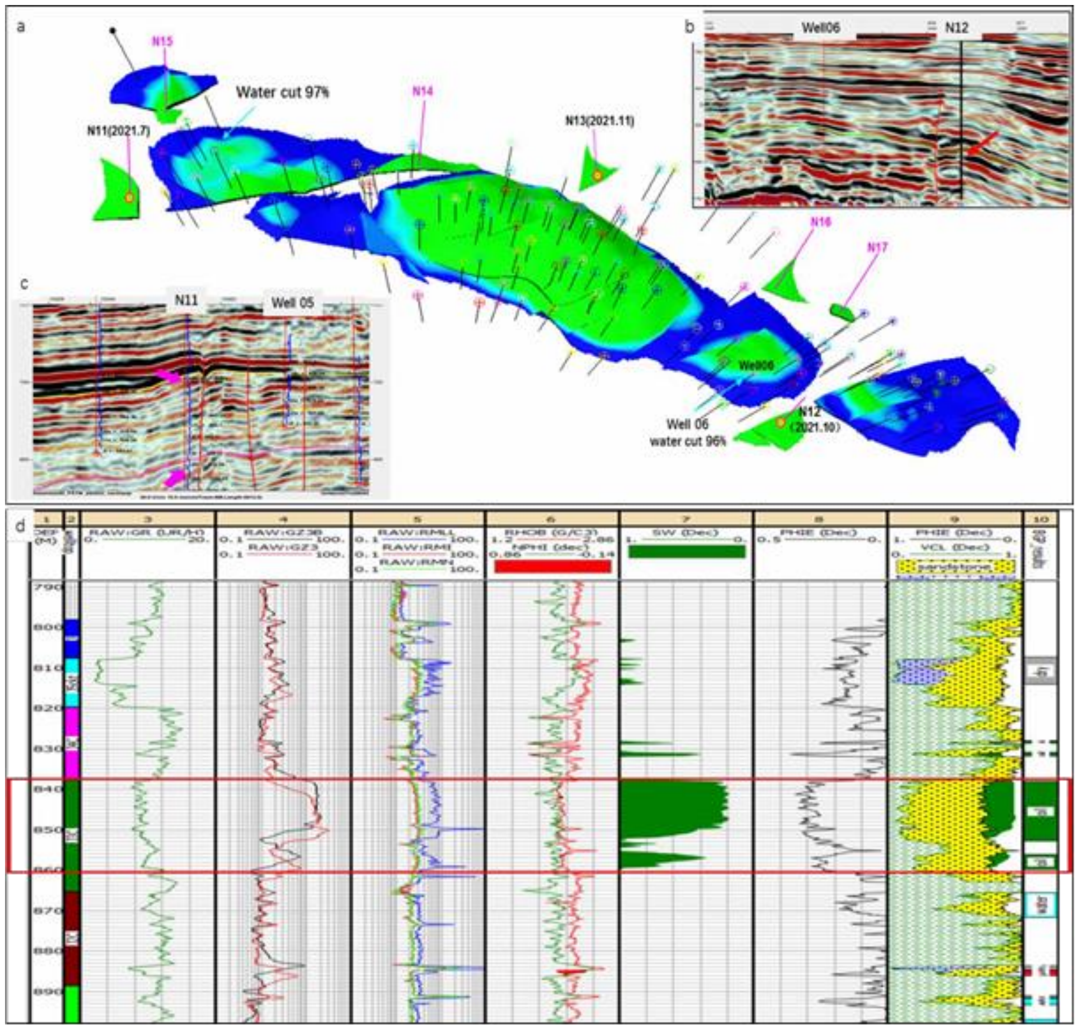

Fig.7 Fault seal analysis result in K oilfield and confirmed by new wells. a- Fault seal analysis result and 6 new wells were proposed in potential areas; b- PSDM seismic section cross well N12 from NW to SE, shows that well N12 is located in a new fault block at a lower position with obvious low seismic frequency and strong seismic amplitude (oil seismic respond). However, well 06 with higher OWC and the water cut has reached 96%; c to e -new wells logging results with pure oil layers in lower fault blocks confirmed the fault seal analysis result.

Conclusions

In order to improve the accuracy of fault seal analysis, a new method was proposed in this abstract. Integrated PSDM seismic data, well logging, and reservoir dynamic data.

This method has been successfully applied to the K mature oilfield in Central Asia. 7 potential faulted seal traps below conventional oil-water contract (OWC) were found in the slope area of oilfield. 3 wells have been drilled and confirmed these fault seal reservoirs with high oil production and much lower water-cut (6%) in the slope of K mature oilfield. It is proved that the method is beneficial for development in mature oil field.

This new fault seal analysis method integrated the information from PSDM seismic data, well logging, and reservoir performance data to improve the accuracy of faults model and lithology model, and generated a more reasonable fault seal analysis result. This allows more confidence in estimating the sealing or leaking capacity of faults and reduces risk of re-exploration and development in mature oil field.

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