Quantitative prediction of sub-seismic faults and their impact on waterflood performance: Bozhong 34 oilfield case study

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A R T I C L E   I N F O
Keywords:
Sub-seismic faults
Fractal geometry theory
3-D geo-mechanical simulation
Quantitative prediction
Remaining oil

A B S T R A C T
Sub-seismic faults are the key factors that control the reservoir quality, hydrocarbon accumulation, and water injection development. In this paper, we developed a method to predict the number, size, orientation and location of sub-seismic faults based on the analysis of fault fractal growth patterns and three-dimensional (3-D) geo-mechanical simulation. This work also discussed the influence of sub-seismic faults on water injection development and remaining oil distribution from analyzing the dynamic oilfield development data. In the methodology developed in this study, the geometrical features of large-scale seismic faults were thoroughly explained based on 3-D seismic data. Based on fractal geometry theory, the number, length and throw of the sub-seismic faults were predicted by extrapolating the power law distribution of seismic fault parameters. According to the distribution of seismic faults, we established the 3-D geo-mechanical model and simulated the disturbed stress field near the seismic fault zone during faulting. By combining the simulation results with the failure criterion, the preferred failure orientation grids and maximum Coulomb shear stress grids were then established. Using these two grids and the parameters of sub-seismic faults constrained by the power-law distribution, we determined the stochastic model to predict the distribution of sub-seismic faults. This work shows that the distribution of sub-seismic faults can be effectively predicted by the combination of fractal theory and 3-D geo-mechanical simulation. Both key parameters in a typical waterflood process, namely the residual oil saturation and the performance of water injection, can be impacted by the size (throw) and the orientation of sub-seismic faults.

1. Introduction

Faults are one of the significant characteristics of a sedimentary basin which usually control the formation and evolution of the basin, the migration and accumulation of hydrocarbons as well as the quality of the reservoirs (Kim et al., 2004; Gudmundsson et al., 2010; Zeng and Liu, 2010; Ferrill et al., 2014; Peacock et al., 2017). Faults can be categorized based on their size and the identification methods into large-scale, medium-scale, and small-scale faults (Fig. 1) (Gauthier and Lake, 1993; Casini et al., 2011; Rotevatn and Fossen, 2011; Laubach et al., 2014). Large-scale faults can be identified by two- or three-dimensional seismic data, i.e., seismic faults (Maerten et al., 2006; Lohr et al., 2008; Rotevatn and Fossen, 2011). Small-scale faults usually refer to shear fractures that can be identified through cores or imaging logs (Zeng et al., 2013; Sanderson and Nixon, 2015). On the other hand, medium-scale faults may not be identified from seismic or logging data, and they are often referred to as sub-seismic faults (Gauthier and Lake, 1993; Damsleth et al., 1998; Casini et al., 2011; Rotevatn and Fossen, 2011). The boundary between seismic faults and sub-seismic faults is difficult to identify because the depth and lithology may affect the resolution of seismic and logging data (Gauthier and Lake, 1993; Ackermann and Schlische, 1997; Walsh et al., 1998; Steen and Arild, 1999; Fossen and Jonny, 2000; Maerten et al., 2006; Lohr et al., 2008).

Currently, there is no effective method to identify the sub-seismic
faults even though they have great impacts on the reservoir quality, hydrocarbon accumulation and water injection performance (Damsleth et al., 1998; Rotevatn and Fossen, 2011). Many studies proved that the quantity of sub-seismic faults in a reservoir is far greater than the number of seismic faults (Damsleth et al., 1998; Maerten et al., 2006). The presence of these sub-seismic faults can substantially increase the porosity and permeability of tight reservoirs, making them to be fractured reservoirs, such as the mudstone reservoir of Bristol, UK (Cosgrove, 2001), the Devonian hornstone reservoir in Parkland oilfield, Canada (Packard et al., 2001), and the Triassic pure fractured-tight sandstone reservoir of Dongpu depression, Bohai bay basin, China (Zeng et al., 2013). In addition, when affected by cataclasis, clay smearing, juxtaposition change between sand and clay layers during faulting, and late cementation, the permeability of sub-seismic faults drops sharply, turning them into barriers for the fluid flow in high porosity reservoirs (Fossen and Bale, 2007; Fossen, 2010; Schueller et al., 2013; Meng et al., 2014; Fu et al., 2015; Gong et al., 2017; Luo et al., 2018). In this scenario, they hence damage the lateral continuity and connectivity, and further compromise the water flooding performance. In either case, the sub-seismic faults can strongly control the subsurface fluid flow. Therefore, an accurate prediction of the geometry, development intensity, and location of the sub-seismic faults can provide a reliable geological model for numerical simulation, which can lead to successful deployment of well patterns, exploration, and development plans (Gauthier and Lake, 1993; Maerten et al., 2006).

Many studies show that a fracture system has a power-law distribution (i.e. self-similarity) over a wide range of scales. Therefore, according to fractal theory, the number of sub-seismic faults can be predicted by the fine extrapolation of the power-law distribution of seismic faults parameters (Gauthier and Lake, 1993; Odling, 1997; Marrett et al., 1999; Ortega and Marrett, 2006; Maerten et al., 2006; Gong et al., 2012; Strijker et al., 2012; Hooker et al., 2013, 2014; Wang et al., 2018). However, this method cannot predict the location and orientation of sub-seismic faults. The 3-D geomechanical simulation can simulate the stress disturbance near a fault during the fault-creating process. The failure orientations, locations, and density can then be predicted considering the rock failure criteria. In this paper, we predicted the number, length, throw, orientation and location of sub-seismic faults of the Bozhong 34 Oilfield by combining the fractal growth patterns and 3-D geomechanical simulation. We also discussed the influence of sub-seismic faults on water injection performance and remaining oil distribution according to the dynamic data from the field development and numerical simulation.

2. Geological setting

Bozhong 34 oilfield locates in the Huanghekuang sag in the south of Bohai Bay basin, China (Fig. 2). The overall structure of the oil field is a faulted anticline in NE-SW trending. E-W trending faults and NE-SW trending faults coexist in the studied area (Fig. 3) (Xu et al., 2015). Based on their orientations, crosscutting and abutting relationships, and the characteristics of tectonic evolution, the nearly E-W trending faults are younger than the NE-SW trending faults. The Paleogene Kongdian Formation (Ek), Shahejie Formation (Es), Dongying Formation (Ed), Neogene Gantao Formation (Ng), Minghuazhen Formation (Nm), and Quaternary Pingyuan Formation (Qp) developed vertically in sequence (bottom to top) in the Bozhong 34 oil field (Fig. 3) (Jiang and Pang, 2011). The oil-bearing formation is the Dongying Formation and Shahejie Formation, among which the second Member of Dongying Formation (Ed2) and the second Member of Shahejie Formation (Es2) are the major pay zone (Fig. 3).

The burial depth of the second Member of Shahejie Formation (Es2) is between 3200 m and 3400 m. The bed thickness ranges from 94.6 m to 116.9 m. The sedimentary microfacies is dominated by the main channel and branch channel of fan delta. The fan bodies are large and widely distributed. The lithology is characterized as fine-medium grained arenose and lithic arkose with medium sorting. The porosity is between 11.2% and 17.1% with an average value of 13.1%. The permeability is between 8.9 mD and 449 mD, and the average value is 46.4 mD.

Bozhong 34 oil field started its operation and production in June 1990. And now there are 21 production wells and 5 injection wells in the study area. There is not available technique to effectively identify the small faults in this area due to the inadequate resolution of the seismic data induced by ultra-deep burial depth. Especially, the information about the distribution of sub-seismic faults and their relationship with the remaining oil is still inadequate. Therefore, the quantitative prediction of sub-seismic faults and remaining oil enrichment in Bozhong 34 oilfield is of great significance to resolve production problems and adjust well patterns. The Bozhong 34–2 oilfield is treated as the research target in this case study since it hosts the major production wells in the field (Fig. 3). However, in an effort to obtain more information, all faults in the study area were investigated.

3. Methodology

3.1. Fault fractal growth model

Many studies show that faults and fractures have fractal features. Self-similarity is also found in the process of rock failure. Fractal geometry is widely applied to predict the sub-seismic faults and fractures (Gauthier and Lake, 1993; Marrett et al., 1999; Ortega and Marrett, 2006; Maerten et al., 2006; Fu et al., 2007; Gong et al., 2012). The fault fractal growth model was firstly proposed by King (1983). He concluded that the geometry of the fault is finite in 3-D space; the ideal fault plane is elliptical; the displacement at the center point of the fault is the largest; the displacement gradually decreases from center to the periphery and decreases to zero at the tip line (Fig. 4a and b); the maximum throw and length of faults in the same region follow power law distribution (Fig. 4c).
\[ D = b_1 \times L^{C_1} \]  
Where \( D \) is the maximum fault throw, \( L \) is the fault length, \( b_1 \) is a constant, and \( C_1 \) is the power exponent representing the slope of the linear relationship between fault throw and length in the log-log coordinate. Fault size frequency is also subject to a power law distribution (Fig. 4d):

\[ N_L = b_2 \times S^{-C_2} \]  
Where \( N_L \) is the number of faults with size greater than \( S \), \( b_2 \) is a
constant, $S$ is fault size (length, throw, etc.), $C_2$ is the power exponent which represents the slope of linear relationship between frequency and size in the log-log coordinate. Based on this model, we can extrapolate the number and their corresponding size of faults of any scale.

Due to the truncation and censoring effects, the fault size distribution usually seems to follow a log-normal distribution by showing concave shape on both sides, and a straight line in the center segment (Fig. 5). However, according to the studies conducted on fault size-frequency distribution at different scales, the fault size frequency curves should present a power-law distribution rather than a log-normal distribution over a wide range of scales (Gauthier and Lake, 1993; Odling, 1997). For example, Odling (1997) studied the fracture system of the sandstones in western Norway at different scales (Fig. 5a). Although the fracture trace-length mimics a log-normal distribution under a single resolution, they obey a unique power-law distribution with the same exponent of $-2.1$ when considering all the data. Based on this law, we can establish the relationship between fault size and frequency using the middle straight segment of the fault size frequency distribution obtained from seismic data, and then extrapolate the number and size of sub-seismic faults (Fig. 5b).

### 3.2. Seismic data analysis

Depth data is needed in the 3-D geo-mechanical simulation, so the seismic data is time-depth converted. A detailed interpretation of the geometry and characteristics of seismic faults are required to establish the fault fractal growth model. For this purpose, we carefully examined and determined the fault length, maximum fault throw, and the occurrence of each fault. We also constrained the displacement distribution of each fault surface. And then these data and seismic horizon data were imported into the Trap Tester software to build the 3-D geological model. Since faults usually exist above and below the target interval, we imported the whole data of each fault into the model to obtain more accurate simulation results.

### 3.3. 3-D geo-mechanical model

In the process of 3-D geo-mechanical simulation, it is assumed that the formation is homogeneous, isotropic, and linear-elastic material. The mechanical parameters of the rocks are obtained by triaxial rock mechanical experiments. The Boundary Element Method (BEM) is adopted in the simulation. In the BEM method, the boundary surface is discretized while the surrounding materials are not (Maerten et al., 2006). The simulated fault is discretized into triangular elements with specific displacements. This triangular elements in BEM is especially suitable for simulating complex surfaces, such as the curved fault plane with irregular tip lines.

The 3-D geo-mechanical model is controlled by local boundary condition and regional load. The local boundary condition is defined by the displacements of each fault surface. The regional loads can be stresses or strains. Note that, since the studied area experienced multiple tectonic events, each phase had a specific stress field with specific direction and size, which require different sets of boundary conditions. Based on rock mechanical parameters and boundary conditions, the disturbed stress field in any part of the rock mass can be calculated. Then, combined with the failure criterion, the predicted failure strike and density can be obtained. The predicted fault strike is estimated through the Coulomb failure criterion (Maerten et al., 2006), given by:

$$\tan(2\theta) = \pm 1/\mu$$

Where $\theta$ is the angle between failure surface and the maximum principal stress $\sigma_1$ and $\mu$ is the coefficient of internal friction. In 3-D geo-mechanical simulation, we assume that the strata are homogeneous elastomers, and the entire strata have the same rock mechanical parameters. According to the Coulomb shear failure criterion, the probability of a shear failure at a point depends on the shear stress of the potential fault surfaces. The shear stress on this surface is called the maximum Coulomb shear stress (MCSS) (Maerten et al., 2006). Therefore, MCSS value can be used to represent the probability of relative failure at a certain point. The larger the MCSS value is, the
greater the chance that failure occurs. The MCSS can be calculated by:

\[
MCSS = \frac{\sigma_2 - \sigma_1}{2}\sqrt{1 + \mu^2} - \mu \frac{\sigma_2 + \sigma_1}{2}
\]

(4)

where \(\sigma_1\) and \(\sigma_2\) are the maximum and minimum principal stresses respectively, and \(\mu\) is the coefficient of internal friction.

3.4. Stochastic modeling of sub-seismic fault

The occurrence and density of sub-seismic faults can be constrained by the 3-D geo-mechanical simulation results. And well data can provide some useful information about sub-seismic faults distribution, but the location of the sub-seismic fault is still unknown. In this paper, the marked-point process stochastic technique was used to determine the location and orientation of sub-seismic faults. The length and number of sub-seismic faults are determined according to the fault-fractal growth model as given in Equation (2). The fault throw of sub-seismic fault is determined by the relationship between fault length and fault throw (Equation (1)). The development positions of sub-seismic faults were determined according to the distribution of the maximum Coulomb shear stress. The orientations of sub-seismic faults were determined by the azimuth of disturbed stress and the Coulomb failure criterion.

4. Case study

In the following case study, we interpreted the horizon and faults using the 3-D seismic data and summarized the length and maximum throw of each faults. We established the relationship between fault length and the maximum throw as well as the fault length fractal growth model for each set of fault systems based on Equations (1) and (2) (Fig. 6). The actual fault model in the study area is as follows:

The maximum fault throw and length relationship model for the NE-SW trending fault system:

\[
D = 0.0056 \times L^{1.2241}, \quad R^2 = 0.9121
\]

(5)

The fault length cumulative frequency distribution model for the NE-SW trending fault system:

\[
N_L = 15865 \times L^{-0.982}, \quad R^2 = 0.9926
\]

(6)

The maximum fault throw and length relationship model for the nearly E-W trending fault system:

\[
D = 0.0025 \times L^{1.3714}, \quad R^2 = 0.9251
\]

(7)

The fault length cumulative frequency distribution model for the nearly E-W trending fault system:

\[
N_L = 722037 \times L^{-1.547}, \quad R^2 = 0.9952
\]

(8)

where \(D\) is the maximum fault throw, \(L\) is the fault length, \(N_L\) is the number of faults with fault length longer than \(L\), \(R\) is the correlation coefficient.

From Fig. 6a and b, the fault length and maximum throw of both sets of fault systems show good power-law distribution in log-log...
The fault length cumulative frequency distribution is quite close to a log-normal distribution (Fig. 6c and d), but it presents a linear relationship (power-law distribution) at the center of the data. This is due to the limitation of seismic resolution and boundary effect. Therefore, it is necessary to define two truncations on both sides of the curvature to fit the best power law distribution. The left truncation should match with the minimum resolution of 3-D seismic data. The right truncation, on the other hand, is difficult to determine since it is related to the length of faults being beyond the target area. In this study, it is set to the point where the curvature deviates from the central straight line (Fig. 6c and d). According to the established fault length cumulative frequency distribution model and the relationship between fault length and maximum throw, we extrapolated the number of sub-seismic faults, and the length and throw of each sub-seismic fault (Table 1).

The rock mechanical parameters are obtained from triaxial experiments conducted on six core plug samples from B1 well (Table 2). The interpreted seismic faults and strata data were input into the Trap Tester software for the 3-D geo-mechanical simulation. There are two sets of fault systems in the study area. We simulated the two stages of the disturbed stress field when they formed. Since all the faults in the study area are normal faults, according to Anderson’s model, we assumed that the direction of the minimum principal stress was perpendicular to the fault strikes (that is 145.5° and 182.2° respectively). The magnitude of the applied strain was determined according to the extension amount of each period being 0.021 and 0.014 respectively. The preferred failure orientations and the maximum Coulomb shear stresses were then calculated with Equation (3) and Equation (4) (Fig. 7).

Finally, the distribution of sub-seismic faults is quantitatively predicted using the marked-point process stochastic technique (Fig. 8). The locations of the sub-seismic faults were constrained based on the distribution of the maximum Coulomb shear stress (Fig. 7). The larger the MCSS value of a grid point is, the greater probability of sub-seismic fault located there. The strikes of the sub-seismic fault were determined by the preferred failure orientation of the point which the center of the sub-seismic fault located. The length of each predicted sub-seismic fault was estimated according to the inverse function of the fault length cumulative frequency relationship (Equations (6) and (8)). The maximum throw of sub-seismic fault was obtained according to the relationship model between the maximum fault throw and the fault length (Equations (5) and (7)).

5. Discussion
5.1. Impact of the size of sub-seismic faults on waterflooding response time

The existence of sub-seismic faults and fractures significantly further complicates the reservoir heterogeneous (Rotevatn and Fossen, 2011; Gao et al., 2015). We use the response time to evaluate the effect of sub-seismic faults on the water flooding development. Response time refers to the time from the beginning of water injection to the time at which the production well has an obvious increase in output, which can be construed from the dynamic production curves. The throws of sub-seismic faults are calculated from Equations (5) and (7). To eliminate the effect of well spacing on the response time of different production wells, we also calculated the response time per unit distance (1000 m). According to the statistical relationship between sub-seismic fault

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Table 1
Prediction results of length, throw and number of sub-seismic faults.

<table>
<thead>
<tr>
<th>NE-SW trending faults</th>
<th>E-W trending faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>Throw (m)</td>
</tr>
<tr>
<td>900–800</td>
<td>23.1–20.0</td>
</tr>
<tr>
<td>800–700</td>
<td>20.0–17.0</td>
</tr>
<tr>
<td>700–600</td>
<td>17.0–14.1</td>
</tr>
<tr>
<td>600–500</td>
<td>14.1–11.3</td>
</tr>
<tr>
<td>500–400</td>
<td>11.3–8.6</td>
</tr>
<tr>
<td>400–300</td>
<td>8.6–6.0</td>
</tr>
</tbody>
</table>

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Fig. 6. Fractal model for fault growth of the second Member of Shahejie Formation (Es2) in Bozhong 34 oilfield.
throw and the response time, it is observed that the larger the sub-seismic fault is, the greater the response time and the ratio between response time and well spacing are (Fig. 9). This phenomenon is more distinct when the sub-seismic fault throw is larger than 6.5 m, where a significant positive correlation between response time and fault throw can be observed. The larger the sub-seismic fault throw, the more likely it will create a network of sealing sub-seismic faults. Thus, they can become effective barriers to water flood front and causing longer flood response times. Even though the sub-seismic fault did not completely break the single sand body, affected by the cataclasis, clay smearing and late cementation, the permeability in the direction normal to the fault strike drops sharply, which also prolongs the response time.

5.2. Influence of sub-seismic faults on waterflood flow path

The existence of the sub-seismic faults also leads to a more tortuous flow of the injected water, which complicates the distribution of residual oil (Fig. 10). For instance, from the analysis of dynamic injection/production relationships, the water injection in well P3 is supposed to work on the production of well B4. Well B6 was completed recently and not yet to be deployed for production. Because the well B6 is not at the injection/production line of well P3 and well B4, if the reservoir between well P3 and well B4 is homogeneous and isotropic, the well B6 should be saturated with oil. However, the well B6 shows serious water flood even ahead of its production. This can be explained by the influence of sub-seismic faults. According to the prediction of sub-seismic faults (Fig. 8), there develops one sub-seismic fault between well P3 and well B4. This sub-seismic fault acts as a seepage barrier, which deviates the direction of injected water and accelerate the water breakthrough time at well B6.

5.3. Impact of sub-seismic faults on waterflood front advancement and remaining oil saturation

The influence of sub-seismic faults on water flooding development and remaining oil distribution depends on the relationship between the strikes of sub-seismic faults and the directions of injection/production lines. According to the numerical simulation (Fig. 11), when the sub-seismic fault is normal to or intersected with the direction of injection/production lines at a high angle, there is a clear pressure gradient difference between the two sides of the faults: the pressure gradient drops sharply from the side of injection well to the side of production well. While the pressure gradient drops gradually when there is no sub-seismic fault or the sub-seismic faults are parallel to the injection/production lines.

When the sub-seismic faults are parallel to the directions of injection/production lines, the injected water flow quickly along the damage zones, shortening the response time. For instance, the existence of several sub-seismic faults parallel to the injection/production line of well P1 and well B9 makes the injected water from well P1 detectable in well B9 only in two months. However, the relatively low permeability

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Table 2

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
<th>Failure load (kN)</th>
<th>Confining pressure (MPa)</th>
<th>Axial stress (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Shear parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1-1</td>
<td>25.38</td>
<td>53.18</td>
<td>0</td>
<td>42.06</td>
<td>0</td>
<td>73.41</td>
<td>34.52</td>
<td>0.244 Cohesion</td>
</tr>
<tr>
<td></td>
<td>B1-2</td>
<td>25.48</td>
<td>50.09</td>
<td>0</td>
<td>47.52</td>
<td>0.209</td>
<td>35.27</td>
<td>0.106 Internal friction angle</td>
</tr>
<tr>
<td></td>
<td>B1-3</td>
<td>25.44</td>
<td>53.37</td>
<td>5</td>
<td>121.3</td>
<td>0.132</td>
<td>41.8</td>
<td>0.131 φ = 55.21°</td>
</tr>
<tr>
<td></td>
<td>B1-4</td>
<td>25.46</td>
<td>56.18</td>
<td>10</td>
<td>145.35</td>
<td>0.106</td>
<td>41.53</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>B1-5</td>
<td>25.48</td>
<td>50.09</td>
<td>15</td>
<td>125.15</td>
<td>0.106</td>
<td>41.53</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>B1-6</td>
<td>25.46</td>
<td>54.56</td>
<td>20</td>
<td>175.4</td>
<td>0.222</td>
<td>52.11</td>
<td>0.222</td>
</tr>
</tbody>
</table>
areas of both sides of the sub-seismic faults tend to form remaining oil distribution. Therefore, when the sub-seismic faults are normal to the injection/production line, the remaining oil of the production well side is relatively rich. When the sub-seismic fault is parallel to the direction of injection/production line, both sides of the sub-seismic fault are rich in remaining oil. Combined with the sub-seismic fault simulation, we predicted the flooded areas in the second Member of Shahejie Formation (Fig. 12). In sum, three flooded areas are identified, i.e. P1, B10–P2 and P3–B4 flooded areas, which are consistent with the results from drilling reports.

6. Conclusion

Sub-seismic faults control the reservoir quality, hydrocarbon accumulation and water injection development. A quantitative prediction method was developed to predict the number, size, occurrence and location of these sub-seismic faults based on the analysis of fault fractal growth patterns and 3-D geo-mechanical simulation. The number, length and throw of the sub-seismic faults were predicted by extrapolating the power law distribution of seismic fault parameters explained from 3-D seismic data. The occurrence and location of the sub-seismic faults was constrained based on a stochastic model deduced from the disturbed stress field near the seismic fault zone during faulting. This work shows that the distribution of sub-seismic faults can be effectively predicted by the combination of fractal theory and 3-D geo-mechanical simulation.

Sub-seismic faults play an important role in the reservoir connectivity, water injection development, and thus the distribution of remaining oil. The influence of the sub-seismic faults depends on the size of these faults and the relationships between their strikes and the directions of the injection/production lines. The large sub-seismic faults will tend to break the single sand body and worsen the lateral
Fig. 12. Prediction of water flooding scenarios in the second Member of Shahejie Formation (Es2) in Bozhong 34–2 oil field.

connectivity of the reservoir. When the sub-seismic faults are perpendicular to or intersected at a high angle with the direction of injection/production line, the injected water will change direction and flow along the sub-seismic faults due to the seepage barrier function of sub-seismic faults, which complicates the distribution of residual oil. When the sub-seismic faults are parallel to the directions of injection/production lines, the injected water flows quickly along the strikes of sub-seismic faults, shortens the effective time which leads to more remaining oil.

Acknowledgement

The authors would like to acknowledge the Research Institute of Petroleum Exploration and Development of PetroChina for providing Trap Tester software. This work is financially supported by the National Natural Science Foundation of China (grant nos. 41502124, U1562214 and 41572116), the Young Innovative Talents Training Program for Universities in Heilongjiang Province (grant no. UNPYSCT-2018043), the Natural Science Foundation of Heilongjiang Province (grant nos. QC2018043 and 41471837-8-13145), the China Postdoctoral Science Foundation (grant nos. 2016M63908 and 2015M581423) and Cultivating Fund of Northeast Petroleum University (grant nos. SCXHB201705 and 2017PYQZL-14).

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