Indian Journal of Geo Marine Sciences
Vol. 47 (10), October 2018, pp. 2042-2048

Comprehensive prediction of fractures distribution: A case study of Badaowan Formation of Baka Oilfield, Turban-Hami Basin, China

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Received 09 November 2017; revised 04 May 2018

Development of fractures have important influence on migration and accumulation of the hydrocarbon. Taking the Badaowan Formation of Baka Oilfield, Turban-Hami Basin as an example, Comprehensive prediction of fractures by weighting assessment was performed based on three fracture prediction method. Fractures are influenced by two tectonic movements. The main orientation of fractures lie in NWW (280°±10°), NNE (20°±10°) and NNW (330°±10°). Fractures of NWW and NNE are better validity because of its consistence or seam at small angles with present maximum principal stress, less filled degree and larger aperture. Comprehensive prediction of the fractures distribution shows that the fractures are mainly developed in Ke20~Ke23 well area, the high point of the footwall of the KEKEYA fault, Ke22 ~Ke19 well area, Ke34 well area, the area of south of Ke21,the area of west of Ke26, Ke32 well area and Ke24 well area. The comprehensive prediction technology effectively improves the accuracy and reliability of fracture distribution.

[**Keywords**: Fracture; Comprehensive Prediction; Badaowan Formation; Baka Oilfield]

Introduction

Fractured zones in tight sandstone reservoirs represent primary targets for oil and gas exploration. Fractures created by tectonic activities act as the main passages and storage spaces for hydrocarbons in such reservoirs[1]. Baka Oilfield is located in the Taibei Depression within the Turban-Hami basin. Since the 1950s, the Bureau of Geophysical Prospecting, Yumen Petroleum Administration Bureau and other former exploration departments had undertaken a series of exploration activities in the Baka area and its surroundings, including geophysical prospecting, drilling, evaluation of hydrocarbon traps, etc. Later, Tuha Oilfield has carried out systematic geological research and drilling in this area since 2000 and extracted commercial hydrocarbon flow from the Jurassic System in wells Ke19 and Ke20 successively. Among the seven wells drilled in 2009, 5 wells were found to produce commercial hydrocarbon flow from a total of 8 formations. Previous exploration results suggest that fractures are relatively developed in the Badaowan Formation in the Baka area and they have a considerable influence on hydrocarbon migration and storage. The permeability of the reservoir matrix is 0.41 mD, but it reached 14.3 mD in the early stage of exploration and development. Moreover, the well production has declined rapidly with time. These demonstrate that fractures are a critical factor influencing oil and gas production capacity[2]. This study investigated the characteristics of fractures in the Badaowan Formation and then predicted the patterns of fracture development and distribution. The results are expected to provide guidance on hydrocarbon exploration and development in the future[3].

Materials and Methods

Baka Oilfield is situated in the KEKEYA tectonic belt, west of the hilly area of the Taibei Depression within the Turban-Hami Basin. The KEKEYA tectonic belt has a NWW trend and the major part of the study area sits on the hanging wall of the KEKEYA fault. Jurassic Formation in Baka Oilfield forms an anticline with a roughly E-W trending long axis. Both limbs of the anticline are cut by faults and the southern limb dips more steeply by the northern limb. A section across the area shows that the anticline has developed above high and steep thrust faults, including master faults and secondary ones. The master faults largely strike NWW-SEE and have played a decisive role in the formation and evolution of local geological structures. Later formed secondary faults strike NE-SW and cut the anticline, thus complicating local tectonic setting (Fig. 1).

The Jurassic Badaowan Formation of Baka Oilfield, composed primarily of sandstone of varying grain sizes, was deposited on the delta of a braided river. Hydrocarbons primarily occur in intragranular and intergranular dissolution pores and fractures in fine- to medium-grained sandstone. The porosity of this formation varies generally between 2% and 6%, with an average of 4.56%. Its permeability is generally between 0.005~5×10^{-3} um^2, averaging at 0.38×10^{-3} um^2, and has a low correlation with porosity. Such low porosity and permeability, together with significant heterogeneity, make it a typical tight reservoir. This formation is highly heterogeneous. Fractured core samples taken from this formation were found to have good hydrocarbon potential during drilling, implying a significant positive effect of fractures on hydrocarbon production.

In this comprehensive method, methods such as the fractal theory, the theory of rock damage degree and seismic monitoring are used first. The results produced by the three prediction methods were normalized and their grey relational coefficients, correlation coefficients, and weighting coefficients were calculated, yielding the values for the master levels of the three methods. Then, the values were multiplied by the corresponding weighting coefficient, and calculating the sum of the products yielded the final weight values predicted by the comprehensive fracture evaluation (Fig. 2). A comprehensive evaluation index was obtained and then used to predict fracture development and distribution.

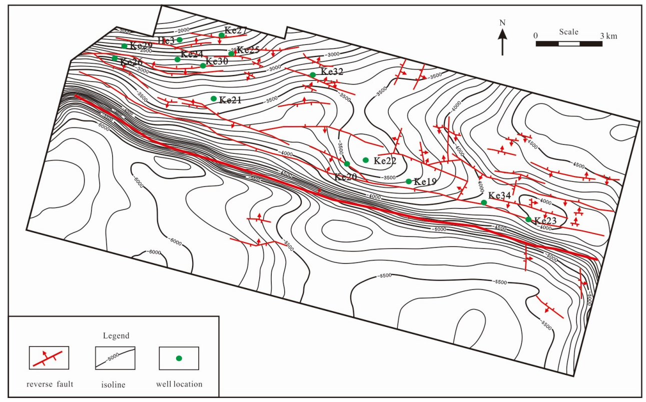


Fig. 1 — Top structure of the Jurassic Badaowan Formation of Baka Oilfield

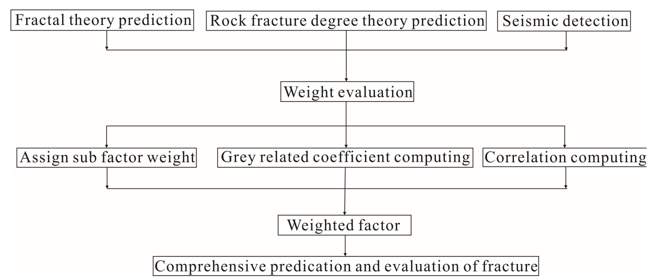


Fig. 2 — Comprehensive evaluate flow table of fracture based on weight theory

Types and characteristics of fractures

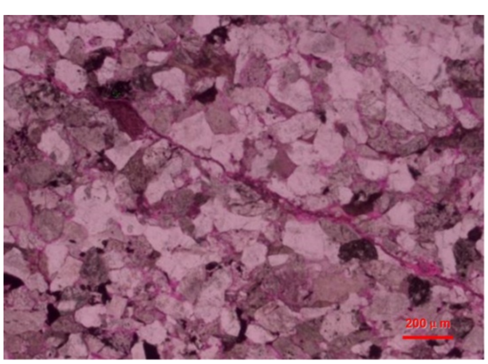
Fractures in the Badaowan Formation in this area can be divided into three types according to their geological origin: tectonic fractures (Fig. 3a-2c), diagenetically induced fractures, and microfractures (Fig. 3d-2e). Tectonic fractures, the main fracture type, widely occur across different rocks of this formation. Statistics on their dip angles show that high-angle fractures with a dip angle higher than 75° (including vertical fractures) account for about 60% of the total number of these tectonic fractures, while the rest, around 40%, are low-angle oblique fractures dipping 45°-75°. High-angle fractures, mostly shear fractures, are characterized by flat and regular surfaces, stable orientation, obvious striations, and mineral fillings. Low-angle fractures are primarily shear or tensile fractures. Only 25% of the tectonic fractures are filled fully or partially with minerals. The fracture fillings include calcite and tiny amounts of siliceous, argillaceous, and carbonaceous fillings. Microfractures range from 0.1 to 0.15 mm in displacement, have smooth surfaces, and usually cut sand grains. Petrographic thin sections reveal that the microfractures account for 18% of the total areal porosity of this formation and most of them are not filled with minerals. This suggests that the microfractures are fairly effective and make an important contribution to the reservoir's permeability. These fractures with varying characteristics intersect each other and constitute an extensive fracture network[4], which has effectively controlled the distribution of reservoir in the Badaowan Formation.

An analysis of fractures in cores and interpretation of formation micro-imaging (FMI) logs suggest that the displacements of most fractures were smaller than 1 mm, except for a small number of tensile fractures with displacements of more than 1 mm. About 85% of the fractures were 5 to 15 cm deep. A few large vertical fractures were found to cut through the cores. Fracture densities of the cores were fairly low,

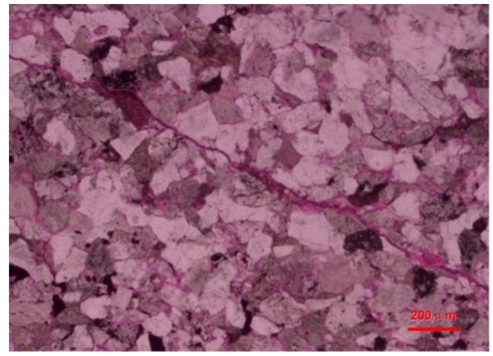
a. Low angle shearing cracks, Ke22, 4008.55m～4008.74m

b. High angle shearing cracks, Ke21, 3394.62m～3394.75m

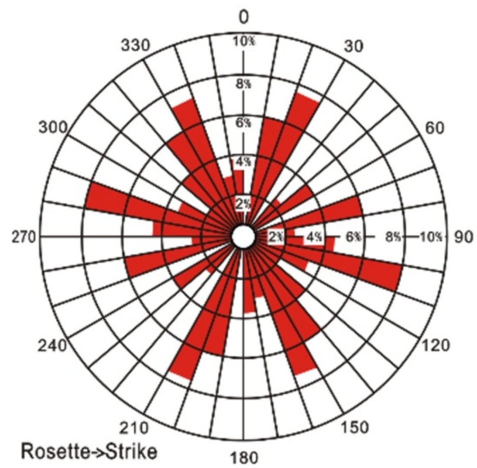
c. Tension fractures, Ke21, 3401.52m～3401.74m



d. Ke191, 3537.7m, Dissolved pores between grains, structural fractures



e. Ke19, 3397.22m, Intragranular and dissolved pores between grains、microcrack



f. rose diagram of fracture strike

Fig. 3 — Fracture developed characteristic of the Jurassic Badaowan Formation of Baka Oilfield

generally between 0.2 and 0.3 fractures per meter. As fracture depth and density are often affected by fracture orientation and core sampling, the data obtained was then corrected based on the results of geological survey and the spatial distribution of fracture spacing in similar outcrop areas [5]. According to the results, the fracture spacing in this area is between 0.4 and 0.6 m, with an average of 0.5 m, and the horizontal fracture lengths fall within the range of 3-5 m.

Interpretation of FMI logs and microseismic data (Fig. 3f) reveals that the fractures in the Badaowan Formation of Baka Oilfield spread predominantly in the NWW (280°±10°), NNE (20°±10°), and NNW (330°±10°) directions, followed by the NEE (80°±10°) direction. Based on the spatial relationship between fractures, results of testing on fracture fillings as well as regional geological setting and previous findings [6], we can infer that these fractures were mostly generated by tectonic forces associated with the middle-to-late stage of the Yanshanian movement and the Himalayan orogeny. During the middle-to-late stage of the Yanshanian Movement, tectonic compression in the NW direction resulted in NNW and NWW trending conjugate shear fractures and a small number of NW trending tensile fractures. During the Himalayan orogeny, tectonic compression in the SN direction created NNE and NEE trending conjugate shear fractures and NE trending associated fractures. The NNW and NNE trending fractures, which are approximately parallel, or at a small angle, to the current maximum horizontal principal stress (nearly SN), exhibit low filling ratios and large displacements and are therefore considered the most effective fractures in this formation.

Results and Discussion

Prediction of fracture distribution has been a hot and difficult topic for research on reservoirs. Experts and scholars have done a lot of work on this topic from the perspectives of geophysics, geology, rock mechanics, nonlinearity, etc.[7,8,9,10,11,12]. Fracture prediction through single approach is usually incapable of delivering satisfactory results due to its limitations, but using a combination of multiple approaches can greatly improve the reliability and accuracy of prediction. Given the actual situation of the study area, this study used the nonlinear fractal theory, seismic monitoring and the theory of rock damage degree to predict fractures in the Badaowan Formation, separately. Later, comprehensive prediction and assessment were performed by combining the results produced by the three methods.

Prediction of fracture distribution based on the fractal theory

Faults and fractures in the same stress field represent fractures that differ in the degree of damage and relative displacement and they satisfy the fractal theory. So it is feasible to quantify the relationship between faults and fractures in rock cores using their fractal characteristics and then qualitatively predict crack development from the relationship obtained. This provides a new approach to studying fracture distribution in reservoirs [13].

In Baka Oilfield, the predominant orientations of fractures in the wells penetrating the Badaowan Formation are highly consistent with the predominant orientations of faults near the wells, suggesting statistical self-similarity in orientations of fractures (including faults) (Fig. 4). By use of the box coverage method, the maps showing the faults in the Badaowan Formation were meshed at various scales and the corresponding fractal dimensions were calculated. Then the quantitative relationship between fault capacity and fracture capacity was derived from the results. In theory, fractures are more developed in regions with larger fractal dimensions. The fracture prediction based on the fractal theory (Fig. 5) shows that fractal dimensions greater than 1.4 were distributed in wells Ke22, Ke19, Ke23, and Ke24 as well as the regions south of wells Ke20, Ke21, and Ke26. The cores from these regions and FMI logs all expose well-developed fractures there, and the well test suggested good hydrocarbon potential. Fracture dimensions smaller than 1.1 were concentrated in wells Ke27 and Ke29, which showed poor hydrocarbon potential during well test. The results of prediction using this method are fairly consistent with the actual production performance and therefore considered reliable.

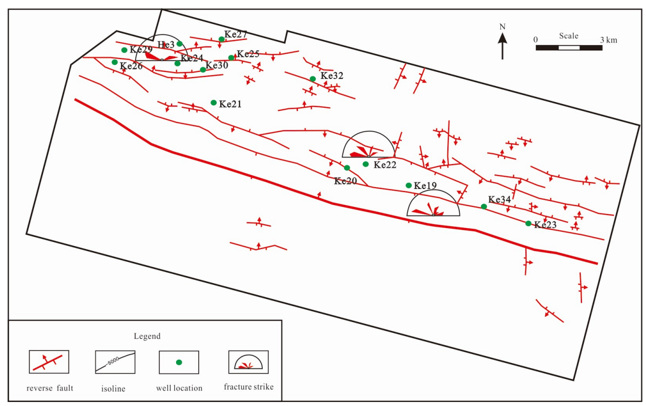


Fig. 4 — Fault and fracture azimuth of Badaowan Formation of Baka Oilfield

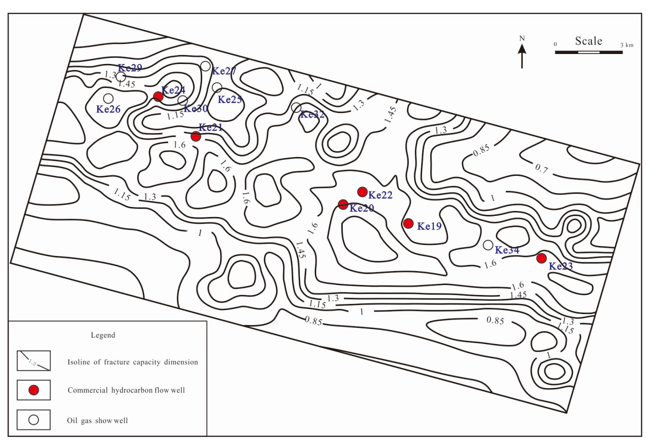


Fig. 5 — Fracture capacity dimension horizontal distribution of Badaowan Formation of Baka Oilfield

Prediction of fracture distribution by seismic monitoring

Seismic detection of fractures is a fracture prediction method that uses geophysical data [14,15]. It is performed on horizontal slices of three-dimensional seismic data blocks. In faulted and fractured zones caused by tectonic deformation, optimal positions for fracture development vary widely in curvature. These positions correspond to low coherences in the slices of coherence cubes.

The results of fracture detection based on curvature data (Fig. 6) reveal that, horizontally, the fractures in the Badaowan Formation were largely distributed along the main faults in a discontinuous zonal pattern, and the fractured zones were mainly located in wells Ke23, Ke34, Ke19, and Ke24, between Ke22 and Ke20, the periphery of well Ke32, the region south of well Ke26, well Ke21 and the region south of it. The southern and northeastern parts of the study area exhibited poor development of fractures.

Prediction of fracture distribution based on the theory of rock damage degree

Fracture prediction based on the theory of rock damage degree mainly involves inversion of paleotectonic stress fields[16]. In this method, the degrees of damage of rocks, η, are measured through stress-strain simulation based on paleotectonic features in different tectonic stage combined with the mechanical properties of the rocks. Then fracture distribution can be predicted by relating η to the level of fracture development[17].

After the Badaowan Formation was deposited, the KEKEYA tectonic belt experienced tectonic deformation during the Yanshanian movement and the Himalayan orogeny. It was found that the Yanshanian movement exerted limited effect on this belt and did not create noticeable folds or nappes there. The Himalayan orogeny was identified as the key driver behind the formation and development of structures in the study area and fractures in the Badaowan Formation primarily developed in this period. A reasonable geological model was constructed based on these tectonic causes and regional geological setting and used in subsequent inversion of paleotectonic stress field. The degrees of rock damage were then calculated from the results of inversion and corresponding levels of fracture development were determined (Table 1). Later, the levels of fracture development, fracture types and orientations were predicted using a comprehensive method. Fig. 7 presents the results of the prediction.

Level-I fractured zones mainly occurred in wells Ke22, Ke27, and Ke30 and the areas south of the belt Ke26-Ke20-Ke22-Ke23. Overall, these zones were distributed in a zonal pattern along the KEKEYA fault and the northern KEKEYA fault. A few structural high locations and convex zones also displayed Level-I fracture development. Level-I fractured zones had high coefficients of damage, ranging from 1.363 to 1.558. Level-II fractured zones were mainly located in the vicinity of Level-I

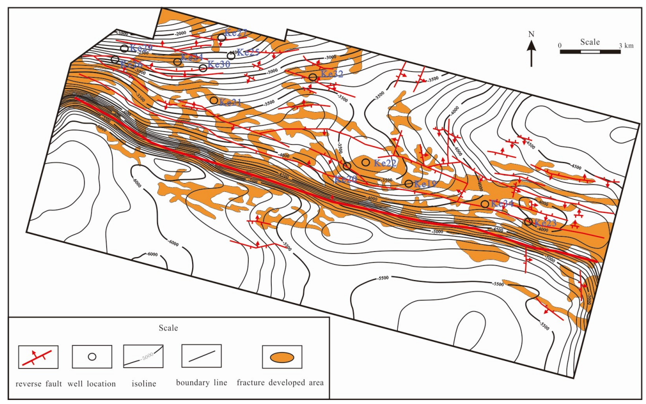


Fig. 6 — Fracture seismic prediction of Badaowan Formation of Baka Oilfield

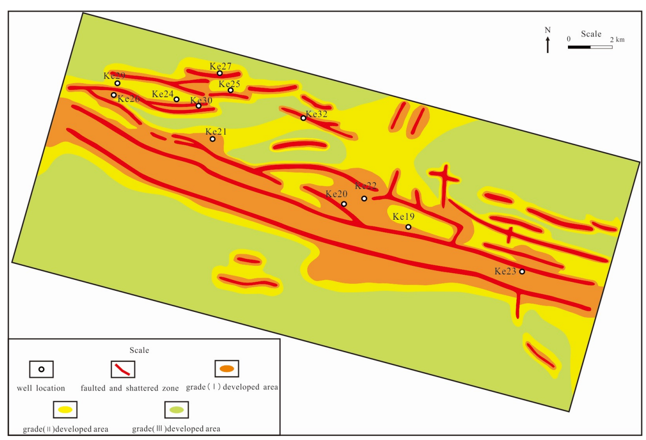


Fig. 7 — Fracture type and azimuth of Badaowan Formation of Baka Oilfield

Table 1 — η value standard table of rock mass fracture prediction

Value（η）	Rock fracture degree	Fracture developed degree
≤1.071	Failure less developed area	III
1.071~1.363	Failure more developed area	II
1.363~1.558	Failure developed area	I
≥1.558	Failure zone	Fracture zone

Table 2 — Weight assignment table of fracture comprehensive rate

Master control grade	Seismic detection	Rock fracture degree theory prediction	Fractal theory prediction	Assign
Grade Ⅰ	Fracture developed area	Grade Ⅰ fracture developed area	Fracture developed area	3
Grade Ⅱ	Fracture undeveloped area	Grade Ⅱ fracture developed area	Fracture more developed area	2 (1.5)
Grade Ⅲ		Grade Ⅲ fracture developed area	Fracture undeveloped area	1

fractured zones and far from the faults; their damage coefficients are between 1.071 and 1.363.

Comprehensive prediction of fracture development

Weight assessment of the prediction results presented above was conducted. A comprehensive evaluation index was obtained and then used to predict fracture development and distribution. This comprehensive prediction method can effectively overcome the limitations of prediction by any single approach and improve the accuracy of fracture prediction and evaluation.

First, values were assigned to the three prediction methods (Table 2); a higher value indicates a higher master level. Two types of master factors, types I and II, were set for the results of seismic detection of fractures and the corresponding values were 3 and 1.5. Three types of master factors, types I, II, and III, were determined for the results obtained based on the theory of rock damage degree; the corresponding values were 3, 2, and 1. Three types of master factors were set for the results of prediction based on the fractal theory: types I, II, and III, which corresponded to values 3, 2, and 1. After data normalization, the grey relational coefficients, correlation coefficients, and weighting coefficients of the three methods were calculated through grey relational analysis. The results show that the correlation coefficients between the series and subseries were $r_{i,\ 0}$= (0.3514, 0.6324, 0.3036). Then the weighting coefficients of the three methods were obtained: a_i= (0.29, 0.39, 0.42). Multiplying the values for master levels of the three methods by the weighting coefficients and calculating the sums of the products gave the final weights predicted by the comprehensive method.

The results of the comprehensive prediction of fracture distribution (Fig. 8) reveal that zones with weights greater than 2.5 were Level-I fractured zones and they occurred in wells Ke34, Ke32, and Ke24, the region between wells Ke22-Ke19, the region south of well Ke21, the area west of well Ke26, as well as structural high points of the region between Ke20-Ke23 and the KEKEYA fault's footwall. These zones were largely distributed between the two master faults

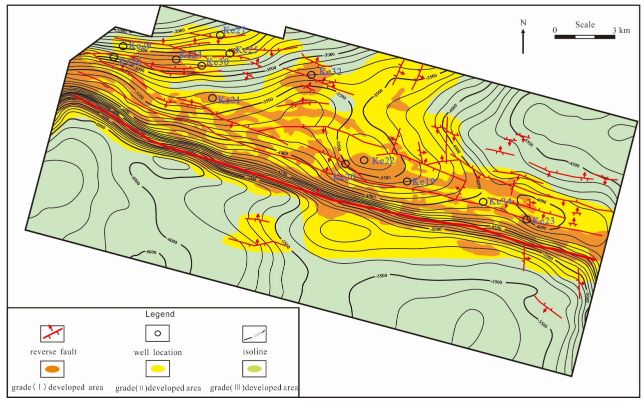


Fig. 8 — Comprehensive prediction figure of fracture distribution of Badaowan Formation of Baka Oilfield

and around the surrounding secondary faults. Zones with weight values of 2.0-2.5 were classified as Level-II fractured zones, including the northern part of the study area, the western sloping region, and the central portion of the hanging walls of faults. These zones were generally in the vicinity of Level-I fractured zones, but they had a wider distribution than the latter. Regions with weight values less than 2 were classified as Level-III fractured zones. They were distributed primarily in the northeaster and southern parts of the study area, including the vast area on the footwall of the KEKEYA fault and the flat area on its hanging wall.

A comparison of the results of comprehensive prediction with the actual production performance shows that wells Ke19-2, Ke24, Ke21, and Ke19, which were drilled in Level-I fractured zones, had good hydrocarbon potential during well testing. During testing of well Ke21 in the Badaowan Formation at depths of 3397 to 3432 m. daily oil production of 5.15 t and daily gas production of 2.8×10^4 m^3 were achieved. Wells Ke25, Ke27 and Ke29 in Level-II fractured zones delivered poor results in the testing. The test of well Ke27 performed in the Badaowan Formation at depths of 2673-2686 m reveals a low daily oil production of 0.08 t. These results confirm that distribution of fractures has a significant effect on the accumulation and distribution of hydrocarbons in the Badaowan Formation of Baka Oilfield.

Conclusions

The main types of fracture in the Badaowan Formation of Baka Oilfield include tectonic fractures (Fig. 2a-2c), diagenetically induced fractures, and microfractures. High-angle and low-angle shear fractures of tectonic origin are the dominant fractures; they are characterized by small displacements, low depths, small density, large spacing, low filling ratios, and high effectiveness.

Development of fractures in this formation was governed by two tectonic events. The predominant fracture orientations include the NWW (280°±10°), NNE (20°±10°), and NNW (330°±10°) directions, followed by the NEE (80°±10°) direction. The NNW and NNE trending fractures are approximately parallel, or at a small angle, to the current maximum horizontal principal stress (nearly SN). With low filling ratios and large displacements, these fractures played an important role in improving the permeability of the reservoirs.

The prediction results produced by the comprehensive method suggest that fractured zones were mainly distributed in wells Ke34, Ke32, and Ke24, the region between wells Ke22-Ke19, the region south of well Ke21, the area west of well Ke26, as well as structural high positions of the region between wells Ke20-Ke23 and the footwall of the KEKEYA fault. The research methods have important guiding significance for deepening fracture prediction.

Acknowledgments

This study was supported by the Applied Basic Research Programs of Sichuan Province (serial number:2017JY0176).

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