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Characteristics of Tectonic Stress Field and Its Influence on Reservoir in Kelasu Structural Belt

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Abstract: *The sandstone reservoir quality and productivity of Cretaceous Bashijiqike Formation in Kelasu structural belt of Kuqa Depression in Tarim Basin are obviously controlled by stress. Through the multi-scale characterization of field outcrops, logging, cores and microcosms, it is clear that the Cretaceous reservoir was controlled by the regional and local stress fields caused by the uplift in the south Tianshan mountain. Combined with numerical simulation, the influence of tectonic stress field on reservoir is discussed. The results show that there are three main effects of canopy, stress meso and strike slip in the process of dual tectonic stress field. The canopy effect and stress surface effect have constructive effects on the reservoir, forming favorable combination of reservoir and cap, slowing down vertical compaction and horizontal extrusion, protecting primary pores and forming effective fractures of a certain scale. Under the influence of the distribution of Paleogene salt lake, some structural torsion occurred at the salt lake boundary, and local compaction occurred in the torsion area, resulting in insufficient natural gas injection in the accumulation process, and the early water could not be effectively displaced. Therefore, in the process of well placement and reservoir transformation, the distribution law of tectonic stress field should be clarified to ensure high and stable production of gas Wells.*

Key Word*: Cretaceous; Bashijqike Formation; Kelasu structural belt; Reservoir quality; Characteristic of stress field.*

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I. Introduction

Kelasu structural belt is located in the middle of Kuqa depression of Tarim basin (Fig. 1). Since 2008, Keshen 2 well has been tested in 6000m sandstone reservoir under salt to obtain high-yield industrial airflow, and a number of large and medium-sized gas reservoirs, such as Keshen 2, Keshen 5 and Keshen 8, have been discovered. The amount of natural gas resources has exceeded one trillion cubic meters, forming a large-scale ultra-deep scale natural gas reservoir. The burial depth of subsalt reservoirs in Kelasu structural belt is generally 6000-8000m, which belongs to low porosity, low permeability and ultra-low permeability reservoirs. However, there are high production gas wells with a daily gas output of 500,000 cubic meters or even more than 100 cubic meters. Under the background of sand body deposition and large-scale stable distribution, tectonic stress field is the most fundamental factor affecting the difference of reservoir quality and productivity. At present, domestic and foreign scholars have done a certain degree of research on the stress field of Kuqa depression. According to the difference of stress environment, Tang Yangang et al. divided the Kelasu structural belt into oblique extrusion stress zone and transverse extrusion stress zone, and put forward the influence of stress environment on reservoir quality. Based on the field outcrop data and finite element numerical simulation, Zheng Chunfang et al. determined that the direction of the maximum principal compressive stress in the late Himalayan period of Kuqa depression was near the north-south direction. Zhang Zhongpei et al. studied the ancient stress field using the joint and shear fracture characteristics. Zhang Mingli et al. used rock acoustic emission to determine the tectonic time. Lei Ganglin et al. established the influence of in-situ stress field on fracture development characteristics based on finite element numerical simulation. Previous studies mainly focused on regional tectonic stress simulation, paleo-stress field and the relationship between stress and fractures. With the improvement of exploration degree, there are obvious differences in reservoir quality and natural gas production in the same sedimentary facies zone. There are few studies on the relationship between stress and reservoir quality at home and abroad. For example, Wells KS203 and KS209 of Keshen 2 gas reservoir belong to the structural axis and are only 1700m apart. Under the same test altitude, test thickness and work system, the daily gas output of KS203 is more than 200,000 square meters, and the daily water output of well KS209 is 10 square meters. Wells KS506 and KS508 in Keshen 5 gas reservoir are located in the high part of the structural axis, with low test yields, while wells located in the two wings generally achieve high yields. Under the condition of phased reservoir, the heterogeneous distribution of stress field has a great influence on the reservoir. Therefore, based on the multi-scale analysis of field outcrop, imaging logging, core and reservoir microstructure, this paper focuses on the analysis of regional and local stress field characteristics, and makes clear that the Cretaceous Bashijiqike formation subsalt ultra-deep sandstone reservoir in Kelasu structural belt is under the joint action of dual stress field. It is clear that the tectonic stress field produces canopy, stress meso and strike-slip effect on the subsalt reservoir. It provides a reasonable basis for well placement and reservoir transformation of high yield Wells in Kelasu structural belt.

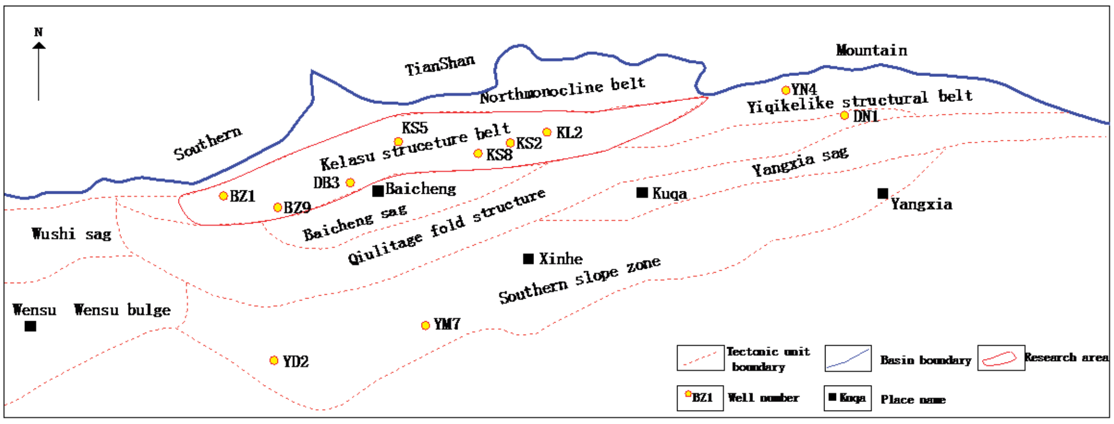

Fig.1 Location of Kelasu Structural belt in Kuqa depression.

II. Regional geological survey

The Kelasu structural belt in the study area is located in the middle of Kuqa depression in the northern margin of Tarim Basin. The vertical strata show a three-layer structure. According to the existence of salt layer, it can be divided into upper salt layer (Quaternary Xiyu formation, Neogene Kuqa formation, Kangcun formation, Jidike formation, Paleogene Suweiyi formation), salt layer (Paleogene Kumgelemu group), and lower salt layer (Cretaceous Bashijiqike formation, Baxigai formation, and Shushanhe formation) from top to bottom. The salt layer is a high quality regional cap layer in this area, with wide distribution and large thickness. According to the actual drilling data, the thickness of the salt layer uncovered by drilling has exceeded 4000m. The subsalt Cretaceous Bashijiqike Formation is the main target layer, with a burial depth of 6000-8000m. It is a braided river delta and fan delta front deposition, with a large longitudinal overlapping range of sand body thickness of 280-320m, and its lithology is brown fine sandstone, siltstone and mudstone. During the Himalayan movement period, the cuneiform thrust with huge scale developed under the salt under the joint influence of the two sets of detachment layers at the top and bottom. Under the influence of the Mesozoic Yanshan Movement and Cenozoic Himayala movement, the thrust imbricate anticlines with 6-8 rows of high dip Angle and large fault distance and high and steep structures of fault anticlines developed in the thrust body.

III. Characteristics of tectonic stress field in Kelasu structural belt

3.1 Characteristics of regional stress field

3.1.1 Stress direction of regional stress field

Through the measurement of the field Kuqa River profile and Kizilenuergou profile in the study area (Table 1), it is found that various stress sensing data are widely developed in the study area, such as conjugate joints, fault rub, occurrence of folded wings and axial cleavage occurrence, etc. The occurrence of the strata on the two wings was measured, and the measured data were projected on Wu's network. The occurrence and axial plane of the β axis of the fold pivot were calculated on the region by using GEOrient program. The direction perpendicular to the axial plane of each fold was the direction of the maximum principal compressive stress of the tectonic stress field on the region during the formation of the fold. Therefore, the regional tectonic stress field fractions determined by the occurrence of fold axial plane can be obtained. Fault scratch is a common small linear structure on the fault plane. The tectonic stress field can be quantitatively analyzed according to the direction of the scratch on the cross section. In order to analyze the regional stress field based on the development of joint and shear fracture, the direction of the acute Angle bisector of conjugate shear joints can indicate the direction of the maximum principal stress in the regional tectonic stress field under the condition of restoring the stratum level.

According to the above three indicators of the direction of regional tectonic stress field, in the Kizilenuergou and Yiqikelike areas, the rub marks and conjugate joints indicating the structural stress of NW-SE tectonic stress only developed in the N1j formation, indicating that the structure of NW-SE stress should be later than the deposition time of N1j formation, and it should belong to the Pliocene and later tectonic movement. This conclusion is consistent with the direction of tectonic stress obtained by Zhang Zhongpei et al. (2004) based on shear joint data in Kuqa-Kizi area during Pliocene and later. Therefore, it can be concluded that the NW-SE compressive stress state occurred in the Kezi-Yiqikelike area after Pliocene. After Pliocene, the Yangxia area showed the same compressive stress state, but the direction was different from that of the above area, which was NNE-SSW direction. In Kuqa river-Yiqikelike area, NNW-SSE tectonic stress indicators are widely developed in T, J, K and E strata. However, there is no development in N and Q strata, indicating that the tectonic activity in this period should be no later than N1j, but later than the deposition of E strata. Therefore, the tectonic stress state in this region during Miocene should be NNW-SSE extrusion.

Table 1 Statistics of field in-situ stress characteristics in Kelasu tectonic belt.

Measuring point location	strata	Occurrence method of strata on two wings of fold			Method of occurrence of scratches		Conjugate joint formation method	
		Data number	β axis dip direction(°)	β axis average dip Angle (°)	Data number	Mean dominant bearing(°)	Data number	Giving directions(°)
Kuqa river	J-K	54	260-278	18	2	356	44	351
Kizilenuergou	T-J	32	245-270	25	5	314	27	348
Yiqikelike	E-N_{1j}	22	75	6	4	318	46	13
Yangxia	J-K_{2sh}	28	281	8	3	7	28(Pt granite)	45

3.1.2 Stress distribution characteristics of regional stress field

Due to the difficulty of regional stress measurement, this paper mainly based on the discrete element stress numerical simulation under seismic geological analytical calibration, through rock mechanics experiments to determine the elastic modulus E, shear modulus G and other parameters.

At present, the methods of calculating rock mechanical parameters mainly include uniaxial compression test, triaxial compression test and logging data calculation.The rock mechanical parameters obtained from uniaxial and triaxial compression tests are usually called static parameters, and the rock mechanical parameters calculated from logging data are called dynamic parameters. According to the mechanism of formation, occurrence and action of stress in underground strata, especially in terms of stress amplitude, loading speed and rock deformation caused by stress, it is closer to the condition of rock static test. Therefore, static rock mechanics parameters are usually used in in-situ stress calculation and practical engineering. Based on the calculation results of uniaxial compression test, triaxial compression test and logging data in the Keshen gas field, taking into account the differences in mechanical properties of salt layer, upper salt layer and lower salt layer, combined with the experimental analysis results, the comprehensive value is obtained (Table 2). Through the area depth method and the balance section, the structural shortening in the Keshen area was determined to be 10km. In order to ensure that the experimental results were as similar as possible to the actual geological body stress distribution characteristics, 10 structural sections were selected from west to east for the numerical simulation experiment after seismic geological analysis. After adjusting the experimental extrusion velocity repeatedly, the similarity between the simulated model and the actual structural geological body is over 90%. According to the stress and strain values on the top surface of the reservoir, the strain distribution map on the top surface of the Cretaceous Bashijiqike Formation is formed.

Table 2 Particulate property of discrete element simulation element.

	Particle radius（*m*）	Shear modulus*(Pa)*	Young's modulus*(Pa)*
Salt layer	40，60	8.0E8	1.9E9
Surrounding rock	40，60	2.9E9	6.9E9
Basement	40，60	3.2E9	7.6E9

On the plane, the stress in Keshen and Dabei areas of the Kelasu tectonic belt is gradually increasing from north to south. In Keshen area, the deformation is intense. The north-south extrusion stress generated by the uplift of the southern Tianshan Mountains is transformed into the dynamic fault distance of the fault anticline in the wedge thrust body developing upward along the fault, the greater the fold deformation strength, the stronger the meso-surface effect, and the smaller the compression stress of the reservoir. From north to south, due to the gradual weakening of the extrusion stress, the degree of structural deformation is reduced, and the overall high extrusion stress is maintained. In the Dabei area, the stress characteristics from north to south are similar to those of Keshen area. The difference is that the tectonic deformation ability of Dabei area is weak, and the overall extrusion environment of Dabei area is obviously higher than that of Keshen area(Fig. 2).

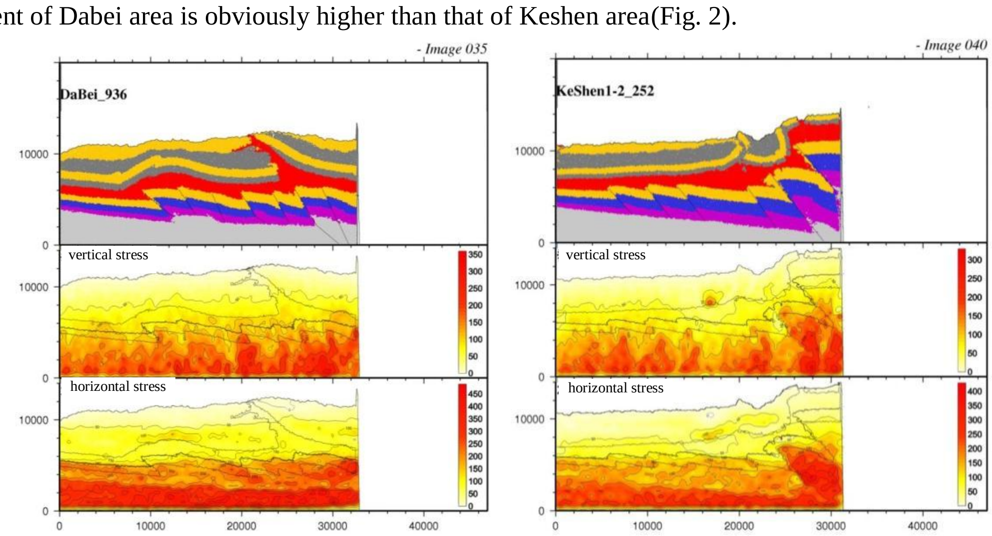

Fig. 2 Stress profile of Kelasu structural belt simulated by discrete element method
(Left: Dabei area; Right: Keshen District)

3.2 Characteristics of local stress field

Regionally, the compressive stress field is generally low in the north and high in the south, and there are obvious differences in stress distribution among and even within structures. Taking the Keshen section of Kelasu structural belt as an example, according to the statistical results of the testing ground stress data of the drilled tensile section, in general, within the same structure, the stress difference in the high-curvature area of the structural axis is small, generally within 25-30Mpa, followed by the structural saddle and west wing, with the stress difference between 28-35Mpa. The compressive stress on the east wing of the structure is the strongest, and the stress difference reaches 35-45Mpa. The stress distribution between structures is also obviously different. The horizontal stress difference in the tensile section of Keshen 8 and Keshen 24 gas reservoirs is 20-24Mpa. Keshen 6 and Keshen 9 gas reservoirs are next, with the stress difference distribution in 22-28Mpa, while Keshen 1, Keshen 2 and Keshen 13 gas reservoirs are relatively poor, with the stress difference mainly concentrated in 24-30Mpa(Fig.3). Perhaps because Keshen 24 and Keshen 8 belong to burst structures, the development of backthrust faults offset part of the extrusion stress. The larger the fault distance is, the stronger the derived tensile stress is, and the greater the reservoir protection is.

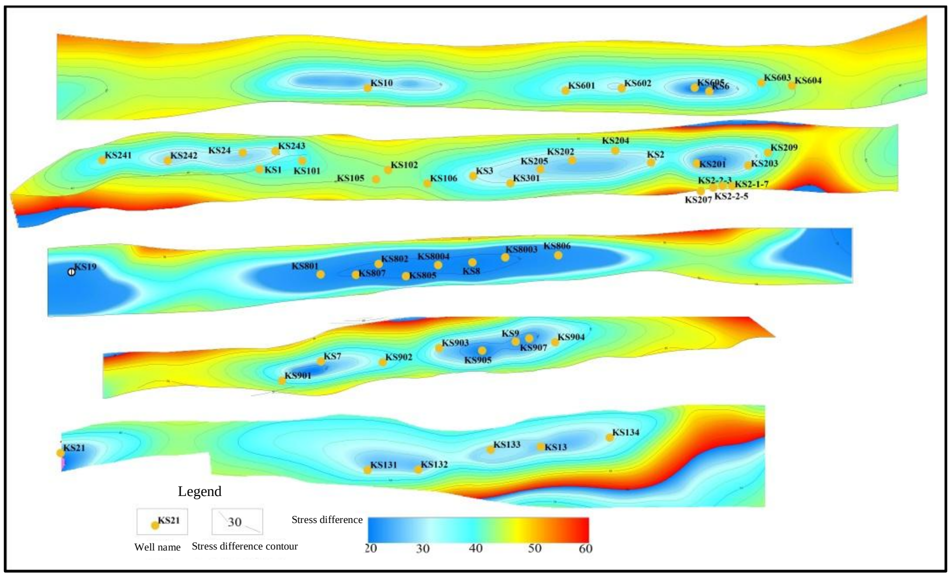

Fig. 3 Plane distribution of stress difference in Keshen area of Kelasu structural belt.

IV. The influence of tectonic stress field on reservoir

The reservoir quality of Bashijiqike formation is controlled by both regional and local stress field in Kelasu structural belt. The regional stress field formed a series of high and steep structures of subsalt fault anticlines, and the regional stress field adjusted the local shape of the structures formed in the later stage, thus affecting the quality of reservoirs. In general, the dual stress field mainly forms three kinds of effects on the subsalt reservoir: "roof canopy", "middle surface" and "strike slip".

4.1 Effects of canopy

Due to the strong uplift and extrusion of the southern Tianshan Mountains, the brittle and plastic strata have undergone stratified deformation. Fault and fold structures are formed in the brittle strata, and a large number of plastic paste rock formations are filled in the accommodating space beneath them, which together form a kind of structural assemblage with the appearance of ridge in profile(Fig.4). At present, several oil-bearing structures such as Kela 2, Keshen 2, Keshen 8, Dabei and Bozi have been discovered. The exploration practice shows that although the thrust deformation of Kuqa depression is strong and the Cretaceous buried deep is large, the zone still has excellent petroleum geological conditions.The strong thrust provides a favorable place for the enrichment of natural gas, and the roof effect formed by the roof structure provides a protective effect for the accumulation of natural gas. The main effects of roof and canopy effect on gas accumulation under salt are as follows. Firstly, the canopy structure promotes the development of thrust structures in the subsalt tectonic layer, forming weak zones of tectonic stress, and providing space for the development of faults in the subsalt tectonic layer. In the thickening part of salt rock, large fault distance faults can be formed in the subsalt structural layer, forming the top slip zone, and the faults in the subsalt structural layer are mostly slipped in the salt layer, forming the thrust structure in rows and belts. Secondly, the roof structure protected the Cretaceous reservoir in the deep layer under salt, and the stress equalization formed by the roof structure and the compressive stress in the South Tianshan Mountains formed a large area of sandstone pore zone in the deep layer under salt, which became the main place for capturing oil and gas. Thirdly, the top canopy structure became the key to the accumulation of Cretaceous reservoirs under salt in Kuqa depression. Due to the upper sealing and lateral block of the pastes, the traps mainly dominated by faulted anticlings developed in rows under salt in Kuqa foreland thrust belt, which protected the strongly charged natural gas and accelerated the accumulation of natural gas.

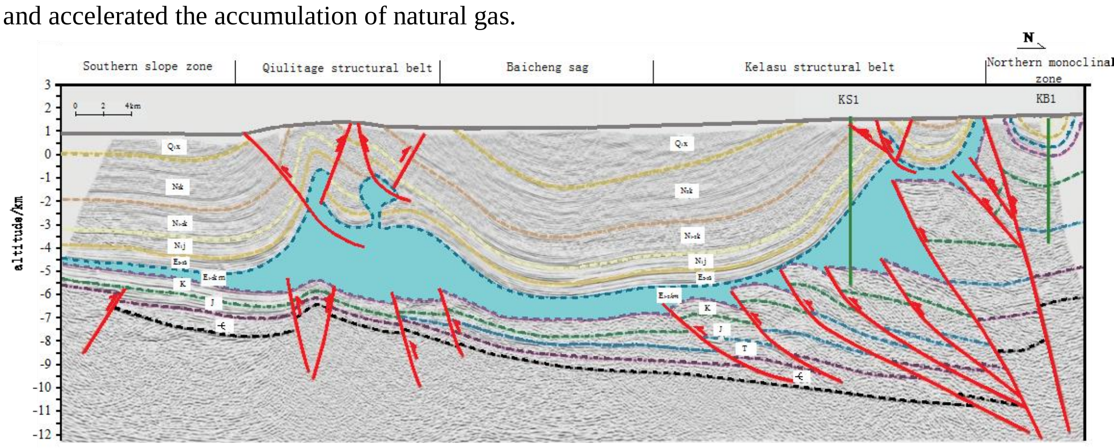

Fig.4 South-north seismic structure profile of Kelasu structural belt.

4.2 Stress neutralization effect

Under the effect of roof and canopy, a series of high and steep thrust imbrication structures were produced under the thick paste salt formation, and the meso-surface effect was produced in the structure. In other words, a zero-strain surface (reservoir segment) with neither tension nor compression is formed in the anticlinal fold structure, above which is the derived tensile stress (strain) area, and below which is the extrusion stress (strain) area. The larger the fault distance, the stronger the structural deformation and the more obvious the meso-plane effect. Different from the classic Ramsay middle plane, the stress in the subsalt Cretaceous sandstone reservoirs in the Kelasu structural zone is not uniformly distributed, and there are obvious differences in the plane and vertical direction. According to the differences of reservoir physical properties, resistivity, acoustic time difference, drilling time, imaging fracture, in-situ stress and other characteristics, the vertical section can be divided into tensile section, transition section and pressure torsion section from top to bottom. Among them, the tensile and transitional sections have good reservoir quality, high fracture effectiveness and strong vertical communication ability, which are the main contribution areas of natural gas reserves and production, accounting for more than 80% of the total natural gas resources. At present, a variety of high quality reservoir prediction methods have been established, such as structural arch rise Angle, two wing Angle and structural principal curvature, which have been widely used in the optimization of drilling depth and test interval.

4.3 Strike slip effect

Under the influence of the extent of the Paleogene salt lake, the strike-slip fault slip caused by the boundary effect of the salt lake caused the upwarping phenomenon of the Keshen6, Keshen2, Keshen9 and Keshen13 structures in the east wing, and the upwarping phenomenon was weakened from the north to the south. For example, KS203 and KS209 in Kesen 2 gas reservoir were only 1.7km away from each other, and the two Wells were tested at similar altitude, test interval and far from the confirmed gas-water interface. The daily gas production of well KS203 was higher than 200,000 square meters, while that of well KS209 was 10 square meters and 2000 square meters.In addition, well KS203 still produces more than 200,000 square meters of natural gas per day after well KS209 is tested and water is found, and there is no obvious fracture in the earthquake, indicating that there is a local tight zone between well KS203 and KS209. According to the results of water analysis, the water type and water quality of well KS209 are similar to the bottom water. Through the analysis of water chemical phase diagram, it is believed that the water body of well KS209 is locally dense, and the natural gas cannot be effectively charged in the accumulation process, resulting in local sealed water. The similar situation also includes well KS904 in Keshen 9 gas reservoir and well KS13 in Keshen 13 gas reservoir. Well Keshen 904 is also located in the east wing of Keshen 9 structure. The daily gas output is more than 200,000 square meters. The daily water output gradually decreases from 30 square meters to more than 10 square meters within a year. In the southernmost gas reservoir Keshen 13, Wells Keshen 131 and Keshen 134 are located in the west wing and east wing of the structure, respectively. The two Wells are also tested at similar elevations and depths. The conventional well completion test of KS131 well has achieved high production of air flow of nearly 400,000 square meters per day, while the conventional well completion test of KS134 well has not produced gas. Only after the large-scale acid pressure transformation can the daily gas production be similar to that of KS131. Wells KS209, KS904 and KS134 are located in the east wing of the three structures. The difference is that well Keshen 209 is located in an obvious updip zone with completely compact reservoirs. In well Keshen904, only a small amount of sealed water exists. Well Keshen 131 is far away from the updip zone, but it is still affected to a certain extent, and the reservoir has a large degree of compaction and poor physical properties.

V. Conclusion

The regional stress field of the Kelasu structural belt was judged to be NNW-SSE compressive stress environment based on conjugate joints, fault scratches and two-wing occurrence method, and the stress gradually increased from north to south.

The reservoir of Cretaceous Bashijiqike Formation in Kelasu structural belt is controlled by both regional and local stress fields. Among them, the regional stress field is mainly constructive, producing roof and canopy effect, middle and surface effect, which is beneficial to reservoir protection. The local stress field is dominated by destructive regulation, and the strike-slip effect produces deformation, bending and upwarping of local structures, leading to the deterioration of the quality of some affected reservoirs and even local compaction.

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