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Characteristics and Main Controlling Factors of the Cretaceous Supra-deep and Low-resistivity Gas Stratum in Kelasu Structural Belt

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Abstract: *The ultra-deep sandstone reservoirs of the Cretaceous Bashkiqike Formation in Kelasu structural belt are generally characterized by low resistivity, even lower than the regional standard water resistivity, which makes it more difficult to identify the reservoirs with medium and high resistivity. Therefore, through the comprehensive study of logging, seismic and core analysis data, the three-dimensional distribution characteristics of the low-resistivity gas stratum are clarified, and the low-resistivity gas stratum is divided into thick layer concentration type and thin layer dispersion type according to its development location, and the control factors of the two types of low-resistivity stratum are explored. The results show that the distribution of low-resistivity gas reservoirs is influenced by the low-stress environment and the salt content of reservoirs. The low-resistivity gas layer with thick layer concentration is mainly affected by the stress neutralization plane. The derived tensile stress can offset the compressional stress and effectively protect the pores. The resistivity of overlying strata is relatively low and generally distributed in the depth range of 150 meters below the unconformity surface. The dispersed thin layer is mainly affected by the brine with high saturation in the pores of the reservoir. The better the physical property is, the stronger the electrical conductivity is and the lower the resistivity is. Generally, the dispersed thin layer is distributed in the position with porosity greater than 8%.*
Keywords: Low-resistivity gas stratum, Kelasu structural belt, Cretaceous Bashijiqike formation, Ultra-deep reservoir, Main controlling factor

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I. Introduction

In recent years, the exploration of the Cretaceous ultra-deep reservoirs in the Kelasu tectonic belt in the middle of Kuqa Depression in Tarim Basin has found many large and medium-sized gas reservoirs, such as Keshen 2, Keshen 5 and Keshen 8. The ultra-deep reservoir in the Kelasu tectonic belt has a deep burial depth of more than 6,000 meters, high production rate of single well and open flow of more than 300,000 cubic meters. Strong extrusion stress, the resistance rate overall demonstrated high resistance characteristics of deep lateral resistivity value in 30-100 Ω·m. In 2008, the discovery of Well Keshen 2 in Keshen 2 gas reservoir produced more than 400,000 cubic meters of gas a day. In the reservoir section of 6617-6618 meters, a suspicious fluid layer with resistivity inversion appeared, which was later confirmed by tests to be a low-resistivity and high-yield gas layer, which did not attract much attention at that time. With the improvement of exploration degree, low-resistivity gas layer characterized by salt frost in core and logging as water layer appears in blocks of Keshen 9, Keshen 13, Keshen 24 and so on, which seriously affects the process of fluid identification and gas reservoir evaluation, and the exploration and development of low-resistivity gas layer is also paid more and more attention. The so-called low resistivity stratum refers to those hydrocarbon fluids with certain industrial value, but with low logging resistivity. Low resistivity reservoirs are common in eastern China. In the process of early exploration, a pattern has been formed to distinguish the gas layer from the water layer, that is, to judge the fluid property by resistivity logging after identifying it as a reservoir. In Kelasu areas, the resistivity in high gas production formation is usually between 12 and 20 Ω·m. The resistivity in water yield formation and pure water yield formation is usually less than 10 Ω·m, especially below 4 Ω·m. But in the later it is found that the gas production rate of gas reservoirs, with the resistivity of lower than 4 Ω·m, even lower than 2 Ω·M, is similar to normal resistance area, or even higher, which is in contrast with the traditional understanding of "gas reservoir always with high resistivity". The resistivity in high gas production formation is even lower than average regional water layer resistivity.

At present, low-resistivity reservoirs are widely studied at home and abroad, which are generally affected by low amplitude, high content of bound water, sand-mud interbed, micro-pore development or mud invasion. Schlumberger company established the evaluation technology for low porosity, low permeability, low resistance formation characteristics. R. Aguilera et al. combined the capillary pressure curve with the Pickett chart to study the flow unit and identify the reservoir flow properties. R.P. Baron and A.J. Pearce evaluated the reservoir characteristics of a low resistivity field in Hyde Field, England, using production logging and well test data[1-4]. Paul F.Worthington proposed the famous Worthington low-resistance identification evaluation flowchart which is widely used in practical production. In the Ordos Basin, Liu Wenbin et al. used the chart established by combining rock analysis and logging interpretation to identify low-resistivity tight gas layer[5]. Yan Yuan-zi et al. established the difference ratio of equivalent modulus of elasticity method to identify the low-resistivity gas layer in the southeast of Ordos Basin. Sima Liqiang et al. conducted the research on the formation mechanism of low-resistivity gas layer in Xujiahe Formation in Guang 'an area. There are few published reports on low-resistivity studies in Tarim Oilfield. Low-resistivity gas layers are widely developed in the Kelasu structural belt in Kuqa Depression[6-9], and the resistivity values are even significantly lower than the regional marker water layers, and the main controlling factors can not be completely identified by using the above experience and methods. In recent ten years[10-11], great progress has been made in the structure, deposition and reservoir of the Kelsu area, but the research on the low-resistivity gas layer of the ultra-deep reservoir is still blank. The research on the low-resistivity stratum of other oil and gas fields at home and abroad cannot be directly applied to the ultra-deep reservoir of Kelasu. Oil-base mud is always used in drilling in Kuqa area. Ruling out the effect of mud invasion, by means of well logging, mud logging, seismic, core analysis data of comprehensive research, the low resistance reservoir distribution characteristic of three-dimensional space has been clear. The low-resistivity reservoir is divided into thick layer of centralized and thin layer dispersible according to its development, which controlled by the two types of low resistivity gas controlling factors. The results show that the distribution of low-resistivity reservoirs is influenced by the low-stress environment and the salt content of reservoirs. The low-resistivity layer with thick layer concentration is mainly affected by the neutral plane effect of stress. The derived tensile stress can offset the extrusion stress and effectively protect the pores. The overall resistivity is relatively low and generally distributed in 150 meters below the unconformity surface. The dispersed thin layer is mainly affected by the brine with high saturation in the pores of the reservoir. The better the physical property is, the stronger the electrical conductivity is and the lower the resistivity is. Generally, the dispersed thin layer is distributed in the position with porosity greater than 8%.

II. Regional geological characteristics

The study area is located in the central part of Kuqa Depression, Tarim Basin, western China. The sandstone reservoir of Bashkiqike formation of cretaceous is the major exploration stratum, which belongs to the front subfacies of fan delta. The thickness of the strata is 280-320 meters, which is mainly brown fine sandstone and middle sandstone, with a small amount of mudstone intercalations locally. The reservoir is covered with a set of thick paleogene gypsum salt rock with a thickness of 400-4000 meters, which is a set of high quality regional cap rocks. The reservoir is buried at a depth of 6000m to 8000m, and the effective porosity is generally distributed at 4% to 8%. The porosity of places with good local physical properties can reach more than 10%, and the effective permeability is generally at 0.035-0.5md. In places where local fractures are developed, the effective permeability reaches more than 1mD. As a whole, it belongs to a set of ultra-low porosity medium and low permeability reservoirs.

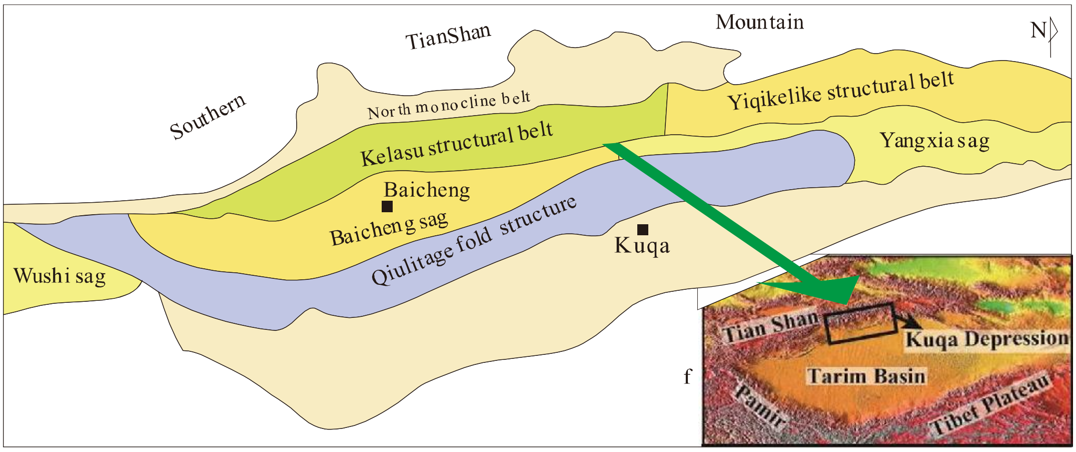

Fig. 1 Location map of Kelasu structural belt

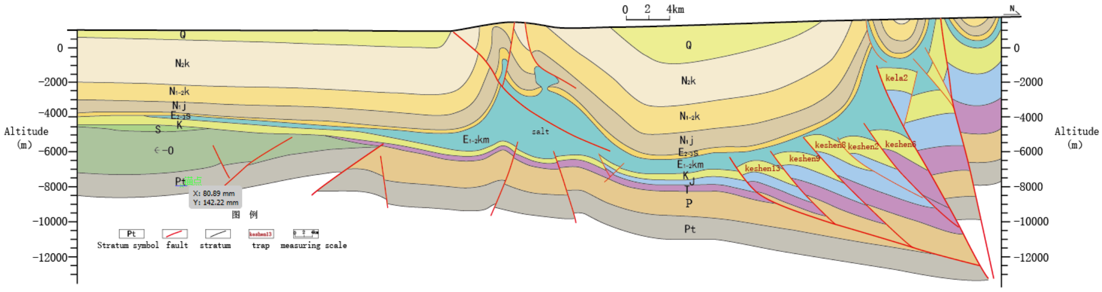

Fig. 2 Geologic analytic model of Kelasu structural belt

III. Development characteristics and distribution of low resistivity gas layer

3.1 Logging response of gas and water layer

After long-term water-rock reaction, the formation water has high chlorine ion content and formation water salinity. Theoretically, from top to bottom, the closer to the water layer, the lower the gas saturation and the higher the water saturation. However, in the Kelas structural belt, the difference of resistivity in the pure gas layer is obvious, which increases obviously from top to bottom. There are also local low-resistivity abnormal areas in the local high-resistance area, but the range is limited, generally ranging from 2 m to 10 m. Water layer resistivity is in commonly from 4 Ω.m to 40 Ω·m, but gas reservoir resistivity difference is larger, from the 2 Ω.m to 200 Ω·m. According to fluid properties and well logging response, cretaceous reservoirs in Kelasu structural belt are divided into four types, which are low-resistivity gas layer, high-resistivity gas layer, low-resistivity water layer and high-resistivity water layer.

The logging curve characteristics of low-resistivity gas layer are low natural gamma ray value, generally less than 60 API, bigger acoustic time difference, generally greater than 65 ms/ft, porosity generally greater than 8%, relatively low resistivity values, generally less than 10 Ω·M, along with the increase of mud resistivity relative rise instead, array induction amplitude difference curve.

The logging curve characteristics of high-resistivity gas layer are low natural gamma ray value, generally less than 70 API, bigger acoustic time difference, generally greater than 75 ms/ft, porosity generally greater than 4%, the resistivity value generally 30 Ω·m - 100 Ω·m.

The logging curve characteristics of low-resistivity water layer are low natural gamma ray value, generally less than 73 API, bigger acoustic time difference, generally greater than 68 ms/ft, porosity generally 4% to 8%, relatively low resistivity values, generally less than 4 Ω·m.

The logging curve characteristics of high-resistivity water layer are low natural gamma ray value, generally less than 81 API, acoustic time generally greater than 80 ms/ft, generally porosity is 4% to 6%, resistivity value generally 30 Ω·m - 100Ω·m.

3.2 Distribution and characteristics of low-resistivity gas layer

Through the analysis of well logging, logging, testing and pilot production data of 42 Wells in 9 blocks including Keshen 2, Keshen 5 and Keshen 13, etc., the distribution of low-resistivity gas layer is universal on the plane. In the vertical direction, it is mainly distributed more than 200m away from the plane of unconformity, and its distribution range is related to the structure type. In general, the thickness of the abrupt type structure with higher steep-fault anticline is larger, and the larger the tectonic amplitude is, the greater the thickness of the low-resistance gas layer is. The ranges of gas reservoirs in Keshen 2, Keshen 9 and Keshen 13 range from 300 meters to 400 meters, the thickness of low-resistivity gas layer is from 80 meters to 120 meters, the thickness of gas reservoirs in Keshen 5 and Keshen 8 range from 400 meters to 550 meters, and the thickness of low-resistivity layer is from 100 meters to 150 meters.

3.3 Type of low-resistivity stratum development

Based on the analysis of the development location, logging, testing, physical properties and other aspects of the low-resistivity stratum in The Wells of Keshen 134, Keshen 242 and Bozi 9, according to the development location, the low-resistivity stratum can be divided into thick layer concentrated type and thin layer dispersed type.

Thick layer of centralized low-resistance gas stratum is mainly developed within the distance of 150 meters below the unconformity surface, and the thickness of the stratum is always between 50 meters to 150 meters. Large sets of alternating layers of sandstone, fine sandstone are developed, and mudstone interlayer is less. The segment resistivity curve performance for baseline characteristics, on the vertical curve shape is often a significant rise in ladder shaped, deep lateral resistivity value is in commonly 4 Ω·m to 30 Ω·m, depth of resistivity inversion phenomenon is not obvious. The effective porosity is 6% to 10%, and the median value is generally 6.8%. The effective fractures in this section are extremely well developed and highly effective, which can improve the matrix seepage capacity by more than 50 to 200 times, and test the open flow rate of more than 300,000 to 2 million cubic meters.

The thin dispersed low-resistivity layer is mainly developed between 100 and 200 meters below the unconformity surface, and the development thickness is usually between 5 meters and 20 meters. The development location is related to the effective porosity. According to the statistics of 27 Wells in Crassus area, this kind of low-resistivity stratum is usually developed in the position where the effective porosity is greater than 8%. The higher the effective porosity is, the more obvious the low-resistivity stratum is. Within the scope of the specific performance in the normal resistivity are often suddenly reduce the phenomenon, the resistivity from 5 Ω·m ~ 20 Ω·m suddenly dropped to 2 Ω·m ~ 8 Ω·m, resistivity apparent depth inversion. The core of this set of low-resistivity stratum has water and moisture sense, and obvious salt frost can be seen. The magnetic logging is usually shown as water layer, comprehensively characterized as water layer or gas-bearing water layer, and the open flow of the test is over 500,000 cubic meters.

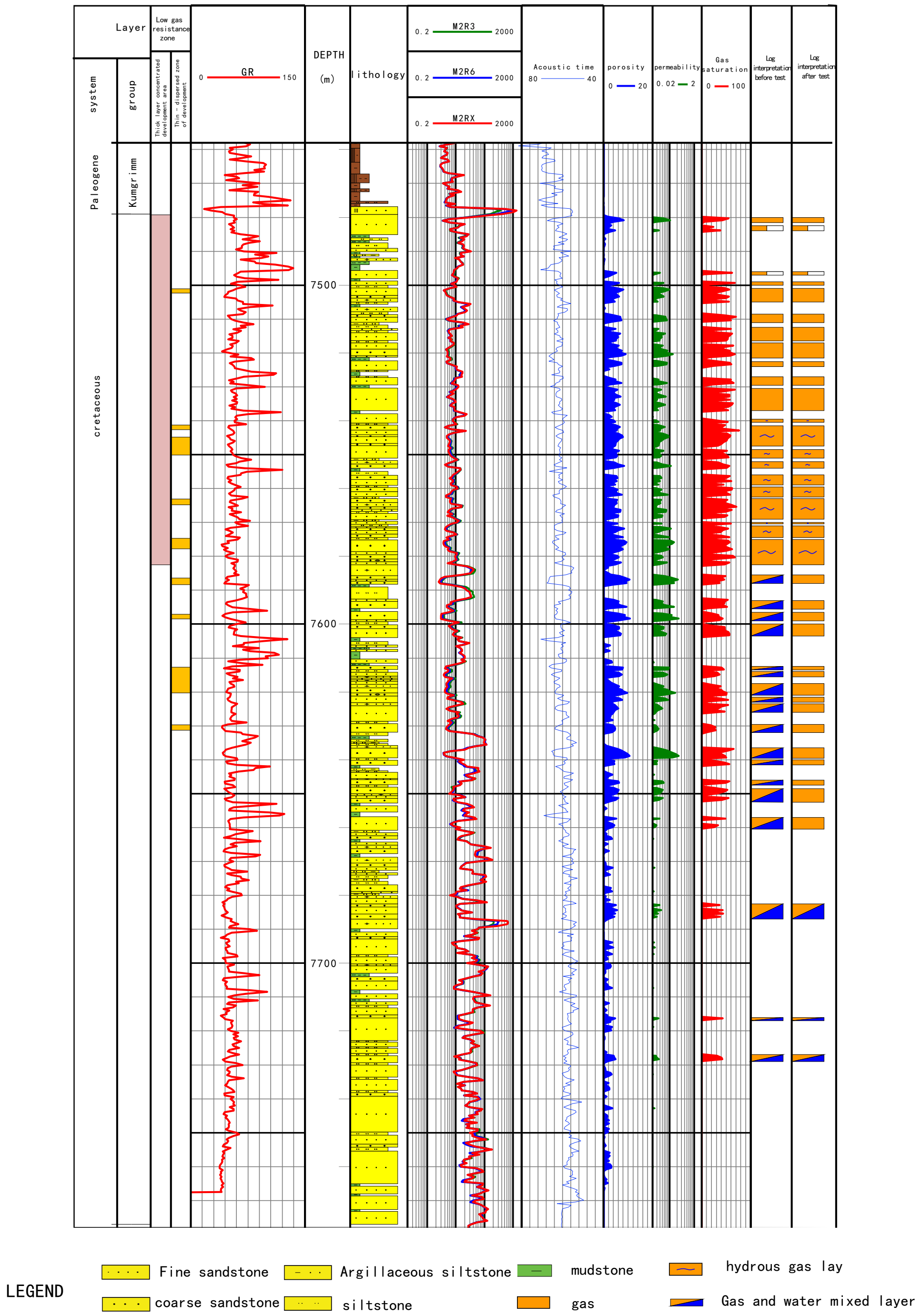

Fig. 3 Typical curve of low-resistivity stratum in Keshen area

IV. Discussion on the main controlling factors of low- resistivity gas layer

4.1 Neutral plane effect in stress

A series of imbricated and wedge-shaped thrust structure formed under the salt formation with the effect of the uplift of the southern Tianshan and the two sets of slip layer which are thick gypsum rock layers and coal layers of Jurassic. The "neutral plane in the stress effect" was produced in the process of deformation. Ling-ling shi et al. divided the gas reservoir stress in Keshen 5 reservior into extensional section, transition section and press section according to reservoir microscopic characteristics, such as tectonic belt. Among them, the transition section with normal compaction can represents the real transition section of the reservoir characteristics, the resistivity in 6-15 Ω.m, thickness of 50 meters to 100 meters. Extensional section is always with effective protection of reservoir property and high longitudinal tension crack development effectiveness which affected by derived pull tensile stress. The resistivity of extensional section is usually in 1-8 Ω·m, and thickness of extensional section is between 50 meters to 100 meters. A forecasting technique of extensional section reservoir thickness was established by Peng Zhou et al. based on finite element numerical simulation prediction method of reservoir thickness, according to the different structure types of different thickness. Particles orientation phenomenon is obvious in press section affected by strong compressional stress. The reservoir is tight and there is almost no effective reservoir in this section with the resistivity in 50-200 Ω·m. Therefore, the stress environment affects the reservoir quality in the range of pure gas layer. From top to bottom, from the derived tensile stress environment to the strong compressive stress environment, the reservoir physical properties gradually become worse, and the resistivity based on the difference in the stress environment forms an obvious three-stage characteristics. Therefore, the change of the resistivity of ultra-deep reservoirs under salt in Kelasu generally reflects the change of the stress environment, and the thick concentrated low-resistivity reservoirs mainly reflect the stress derived environment of the tension section.

4.2 Anisotropic distribution of salt in reservoir

4.2.1 The source of the salt

The cretaceous reservoirs in the Kelasu structural belt are covered with huge thick paste salt rock, which permeates for a long time in the historical sedimentary period and forms saturated brine in the pore bound water of the reservoir. Based on the core chlorine salt analysis data of 35 Wells, it is shown that the closer the distance is to the paleo-Cretaceous unconformity, the higher the chlorine salt content is, which indicates that the salt mainly comes from the upper stratum, and the high chlorine ion content is not the mark of water layer.

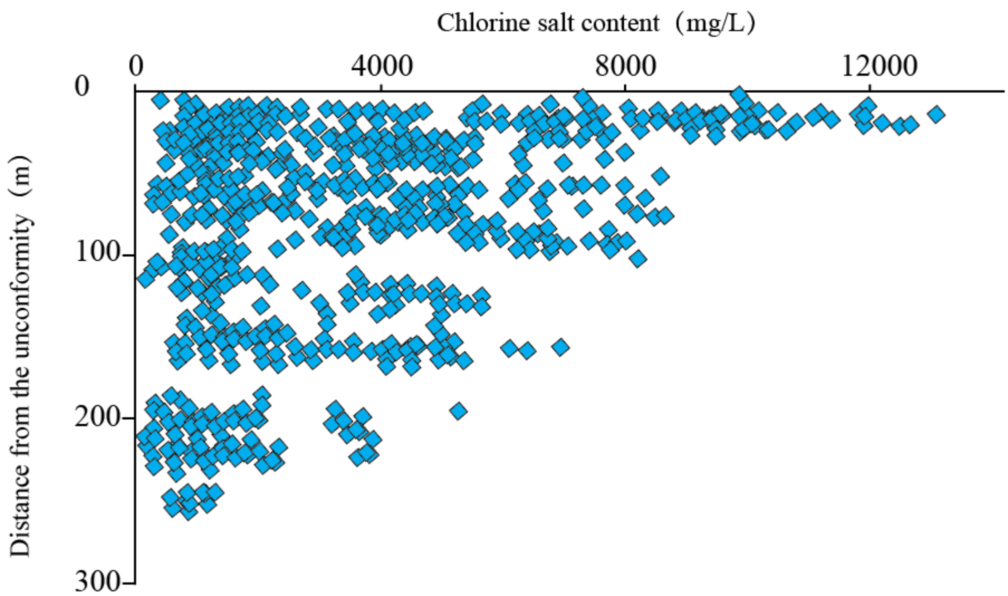

Fig. 4 Relationship between chlorine content and distance from the unconformity surface

4.2.2 The state of salt in a reservoir

Pure salt resistivity value is extremely high. On the reservoir development several kilometers of cream gypsum formation, extremely pure salt layer development, pure salt layers deep lateral resistivity is in commonly 1500 Ω·m above. In a pre-salt reservoir, the position with more salt will have a lower resistivity, indicating a stronger electrical conductivity. Salt in the reservoir should be confined water in pores, forming saturated brine. In general, the bound water consists of adsorbed thin film stagnant water on the surface of rock particles and capillary stagnant water in the pores of the capillary.

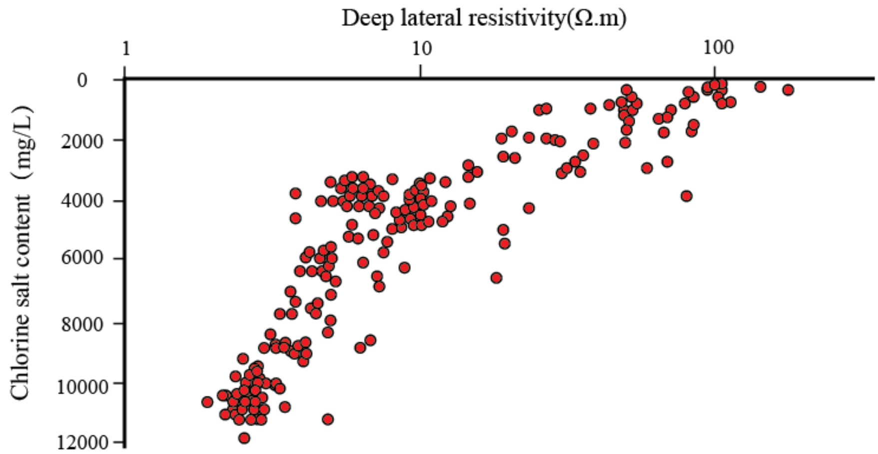

Fig. 5 Diagram of chlorine content and resistivity

The reservoirs with low resistivity values in this area tend to be medium sandstone with relatively coarse grain size. According to the investigation of Basins in Sichuan, Ordos and Caidamu, the smaller the porosity is, the higher the bound water content will be, and theoretically, the higher the salt content should be. In the Kelasu area of Tarim Basin, the actual drilling situation is on the contrary which shows that the higher porosity, the lower resistivity and the higher salinity should be. Therefore, the concept of water content is introduced, that is, water content = water saturation * effective porosity. According to coring data statistics of the reservoir, the larger the particle size is, the greater the porosity is, and the smaller the water saturation is, but the greater the water content is. The reservoir has high water saturation, but no water is found in the test, which proves to be bound water. For example, water saturation of medium sandstone with relatively high porosity is mostly below 40%, and water saturation of fine siltstone with relatively low porosity is mostly above 50%. Reservoirs with low resistivity in this area tend to be medium sandstone with relatively coarse grain size. In other words, the lower the resistivity is, the lower the water saturation is. The reservoir space is mainly residual intergranular pore and secondary solution pores and fine throat. Pore throat sorting is poorer and the rock surface is rough. The capillary pressure is always high. Oil and gas water displacement is not thoroughly. A large number of small pore and micro pore was dominated by formation water, resulting in a lot of formation water residue. With the increase of reservoir physical property, reservoir space increase resulting in formation water residue increased, causing the reservoir resistivity fall further, and under the influence of stress and effect of resistivity reduce further.

V. Conclusion

The low-resistivity gas layer of the Cretaceous Bashkiqike formation in Kelasu can be divided into thick layer concentration type and thin layer dispersion type according to its development location. Among them, the thick concentrated low-resistivity layer is controlled by the surface effect in stress, and the thin dispersed low-resistivity layer is controlled by the heterogeneous effect of salt contained in the reservoir.

Salt in the reservoir is mainly caused by the infiltration of paleogene brine, and it is mainly concentrated in the tensional and transitional reservoirs in the middle and upper part of the reservoir. In the same block, with the increase of depth, the resistivity of the gas layer is significantly increased under the influence of stress. On the other hand, there is a negative correlation between resistivity and reservoir physical property. Under different tectonic setting and sedimentary environment, the genesis type of low resistivity and the characteristics of gas layer are different.

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