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Research Article

Geochemistry of Formation Water and Implications for Ultradeep Tight Sandstone of DK Gas Field in Kuqa Depression

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Formation water is produced during gas well production, which can seriously affect gas well productivity, especially in deep and ultradeep tight sandstone gas reservoirs. In this paper, we have studied the formation water production and geochemical properties of the ultradeep tight sandstone gas reservoir in the Cretaceous Bashijiqike Formation of the DK gas field in the Kuqa Depression. The results indicate that the formation water can be classified as condensate water, gas-water transition zone water, mixed water, and isolated formation water, all of which are acidic and of $CaCl_2$ type, with increasing salinity or chloride ion content. Sodium/chloride ratio ($\rho Na^+/\rho Cl^-$), metamorphic coefficient ($\rho(Cl^- - Na^+)/\rho(Mg^{2+})$), desulfurization coefficient ($100 \times \rho(SO_4^{2-})/\rho(Cl^-)$), and trace elements concentration parameters show that the formation water was formed in a closed and reductive environment and experienced strong water-rock interaction. The formation water may have been influenced by early seawater, but it is not significant and is more likely to have been influenced by water seepage from the overlying gypsum strata. The Sr, H, and O isotopes reveal that the different types of formation water have good homology and are not affected by atmospheric precipitation, which is propitious to the preservation of natural gas.

1. Introduction

Unconventional oil and gas are currently the focus of exploration and development, such as shale oil and gas and tight sandstone oil and gas, and their efficient development is the key to achieving energy independence in the United States [1–7]. Formation water is an important type of geological fluid that coexists with petroleum and natural gas in sedimentary basins and is also an important medium affecting the migration, accumulation, and destruction of hydrocarbons in conventional and unconventional oil and gas reservoirs [8–12]. The chemical composition and isotope of the formation water can provide insights into the geological environment and the water-rock reaction in reservoirs and is even of predictive value for the formulation of effective water avoidance measures in the course of the development of unconventional reservoirs [12–14]. As theory and technology advance, the exploration and development of oil and gas are developing rapidly towards deep and ultradeep [15, 16]. Tarim Basin is the largest oil-bearing basin in China, and the oil and natural gas resources buried over 6000 m account for about 83% and 64% of the total hydrocarbon resources, respectively; however, the discovery rate of ultradeep oil and gas is extremely low [17]. The burial depth of tight sandstone gas reservoirs in the Cretaceous Bashijiqike (Kb) Formation in Kuqa Depression of Tarim Basin is generally greater than 6000 m, with the maximum burial depth up to 9400 m, which is the main development range of ultradeep tight gas resources in Tarim Basin. The distribution of gas and water in tight sandstone reservoirs is complex, and water is common in the development process. Formation water production has a devastating effect on the efficient development of gas reservoirs, which may lead to water locking at the least or water invasion and flooding at the worst. The deep tight sandstone gas in DK gas field of Kuqa Depression has reached the stage of large-scale development and utilization (Figure 1). However, in the course of development, the gas-water distribution relationship is complicated, the relatively high part of the structure is a water layer or gas-water layer, and the phenomenon of rapid water occurrence during production poses a great threat to the stable production of gas wells [1, 18]. In tight sandstone reservoirs, formation water occurs in different states in tight reservoir space, which is an indispensable part of gas reservoir fluid system. However, there is a lack of systematic investigation of the production characteristics and geochemical properties of formation water. Therefore, this paper investigates the occurrence state and geochemical characteristics of formation water in ultradeep tight sandstone gas reservoir of DK gas field in Kuqa Depression, revealing the characteristics of formation water in different production processes and discussing its origin and source, for the sake of providing geological basis for the adjustment of development plan and improvement of development efficiency in natural gas development. The research results can also serve as a reference for the development of deep tight sandstone gas in other areas.

2. Materials and Methods

In this investigation, more than 300 formation water data were collected from Tarim Oilfield Company, including the content of chlorine (Cl^-), as well as the daily data of gas and water production, which corresponding to the water samples. X-ray diffraction data of 24 Cretaceous Bashijiqike Formation tight sandstone samples were also collected for the analysis of rock composition. Meanwhile, 36 water samples were collected that were not contaminated with drilling fluid, meaning that potentially contaminated water samples had been removed during the analysis of the formation water. All of these samples were tested for both conventional ions and trace elements, and 22 of them were analyzed for strontium and hydrogen and oxygen isotopes.

The obtained formation water samples were treated as follows: (i) all water samples were set aside for 10 days prior to initial physical purification. (ii) The clarified liquid was extracted from the upper part of the container for high-speed centrifuge analysis. The centrifuge speed was 10000 r/min, and the time of each centrifuge was 20 minutes. (iii) The centrifugal liquid was filtered by a needle cartridge filter film filter with an aperture of 0.45 μm. Filtrates were collected, and a series of geochemical tests were carried out (Figure 2(a)). (iv) High analytical purity trichloromethane (99.0% purity) was used to extract filtrate of formation water when hydrogen and oxygen isotopes are analyzed in formation water (Figure 2(b)), and the impurities in water were physically adsorbed by dry, analytically pure activated carbon, and then the water samples can be used for isotope analysis.

Conventional ion analysis of water mainly includes K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-. Most of the elements can be detected by ion chromatography, the instrument is DIONEX-500 ion chromatograph, and the detection limit and error are 10 ppm and ±2‰, respectively. HCO_3^- or CO_3^{2-} was detected by METROHM automatic titration instrument. Trace elements were analyzed by inductively coupled plasma emission spectrometry (ICP-AES) with NexION300D plasma mass spectrometer. The detection limit and error were 0.002 PPM and ±5‰, respectively. The MAT253 stable isotope mass spectrometer produced by Thermo Finnigan company in Germany was used for hydrogen (H) and oxygen (O) isotope test, and the measurement error was ±0.2‰. The oxygen isotopes were determined by carbon dioxide water balance and the hydrogen isotopes by zinc reduction. The strontium isotopic composition ($^{87}Sr/^{86}Sr$) was measured according to GB/T17672-1999 "Determination method of Lead, Strontium, and neodymium isotopes in Rocks". The mass spectrometer model was PHOENIX with a detection error of less than 0.00002.

3. Results and Discussion

3.1. Production Type of Formation Water. In tight sandstone reservoirs, the microscopic occurrence characteristics of formation water are mainly connected with the intensity of gas charging and the microscopic pore throat structure of the reservoirs, which has been studied extensively by predecessors [4, 19, 21, 22]. Generally, the occurrence state of formation water in tight gas sandstone reservoirs can be classified as four types: free water, capillary water, bound water, and adsorbed water [21, 22]. Free water occurs in a large pore, so it is possible to complete the gas-water displacement at a small displacement pressure. Capillary water occurs in medium and small pores and throats and is controlled by large capillary forces, which is residual water formed by unsaturated gas charging. Irreducible water is controlled by small pores or throats, so that it is difficult to migrate even at large displacement pressures. Adsorbed water occurs on the surface of macroporous framework particles and is mainly controlled by adsorption. This is the microscopic occurrence of formation water, but it is not the same as the water produced during natural gas production. In the process of production, free water is the easiest to produce. Capillary water, bound water, and adsorbed water can be counter-dissolved in natural gas to form condensates or taken out in the process of strong gas flows.

These different occurrence states of formation water gradually turn into produced formation water during natural gas production. Based on the formation water production characteristics, well-produced gas water can be divided into four types: condensate water, mixed water, gas-water transition zone water, and isolated formation water. Condensate water refers to the water that coexists with natural gas in the form of gaseous or misty droplets at high temperatures and pressures in the formation. When it is extracted into the wellbore or the surface, the pressure and temperature

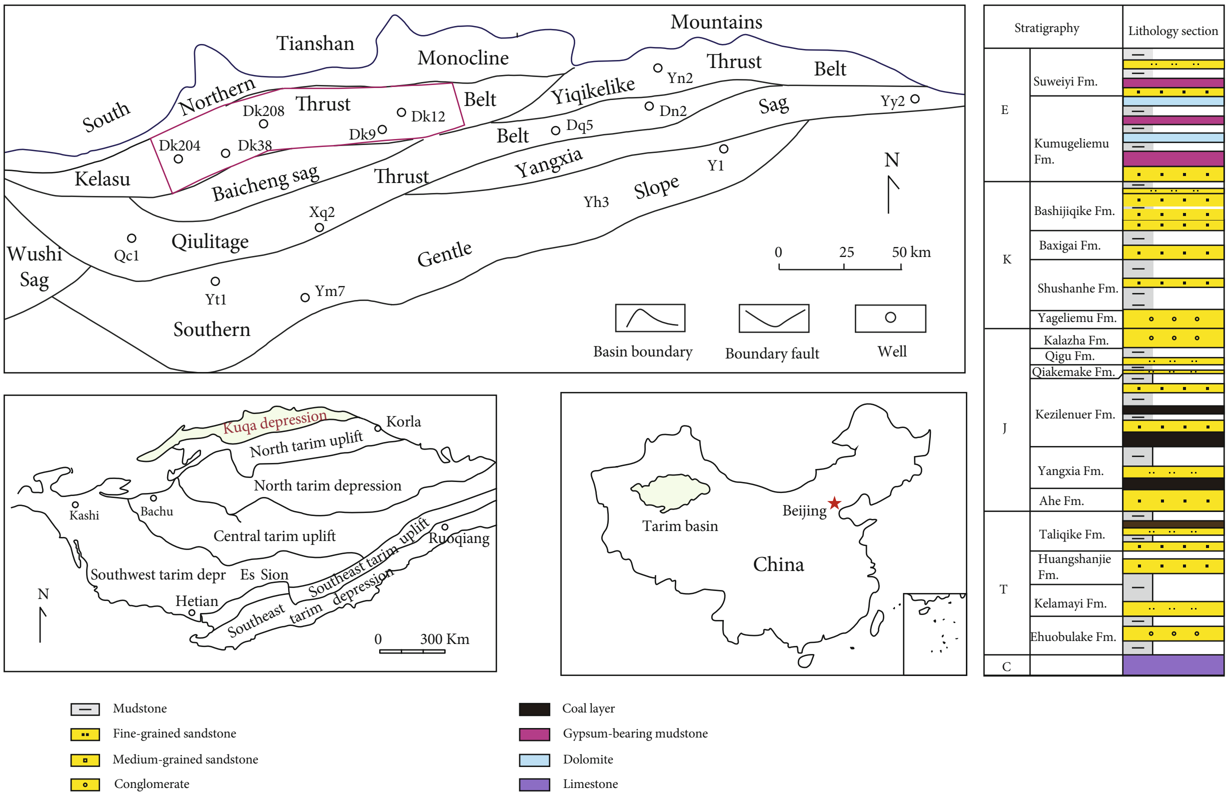
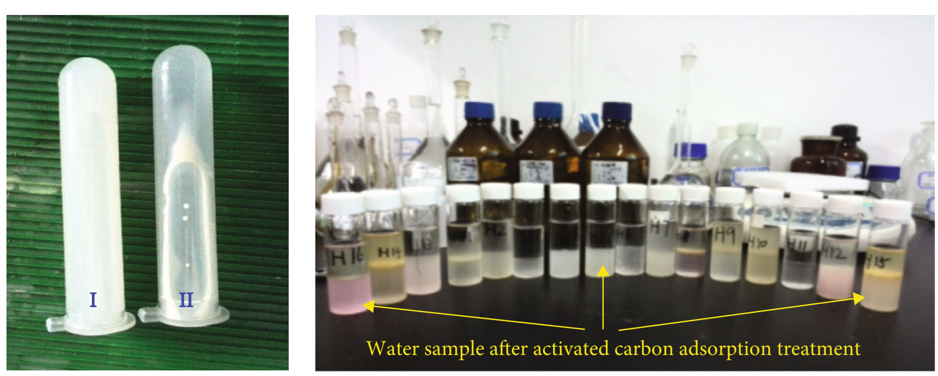


Figure 1: The location of the study area (red wire frame) in Kuqa Depression (After [1, 19, 20]).



(a) (b)

Figure 2: Treated formation water samples. (aI) Sample before centrifugation; (aII) Samples after centrifugation. (b) Water samples for hydrogen and oxygen isotope analysis.

decreased and condensed into liquid state. Condensate water is water vapor and usually contains some dissolved salts [8]. Isolated formation water refers to the edge water, bottom water, or free water that is not charged by natural gas in the reservoir. During the development process of gas reservoir, it can be produced together with natural gas by the reason of the connection between faults and fractures, or it can become the dominant fluid type during the later stages of gas reservoir exploitation. Transition zone water refers to the water in the gas-water transition layer formed by the free water in the tight reservoir that has not been completely displaced by natural gas. It may also be produced by percolation in adjacent areas. Mixed water refers to water in different occurrence states (condensate water, capillary water, adsorption water, etc.) and free water in gas reservoir, water mixed with transitional zone water, or isolated formation water, which are mixed and produced together in the process of production. Mixed water is characterized by a variety of sources. In the process of production, natural gas and free water can be produced together with other forms of water. The products of these four types of reservoir water in the production process have certain production characteristics.

Different types of formation water have different production characteristics, taking the production ratio of formation water to natural gas in the production process of DK 205 well as an example to illustrate the change with production time (Figure 3). The DK 205 well is located in the middle of Kelasu structural zone in Kuqa Depression. After acidizing test in the 5932-6045 m section of Cretaceous Bashijiqike Formation in 2008, the well has a daily output of 34.8×10^4 m^3 of natural gas and 5.96 m^3 of oil and entered the development and production stage. During production between November 2010 and March 2016, formation water samples were systematically collected and analyzed for chlorine (Cl^-) content. The analysis showed that the early water production was low, with a water to gas ratio of less than 0.07, and the Cl^- in formation water was generally less than 5000 mg/L, mostly condensate water, until July 16, 2012. Cl^- was then gradually increased, indicating that water with high Cl^- content was mixed into the produced water, and the type of water produced changed from condensate water to mixed water, which continued until April 2013. After that, the water-gas ratio rose rapidly, water production increased significantly, and the Cl^- rose to about 120000-150000 mg/L and was basically stable, showing the production characteristics of isolated formation water (Figure 3).

Transition zone water is mobile water that remains in tight sandstone reservoirs due to incomplete gas charging, and it percolates with the gas during gas exploitation. For the output characteristics of water in the transition zone, production water is higher, and the salinity/chlorine content is higher, but lower than that of isolated formation water. The Cl^- content in formation water changed little over time. In the process of the gradual increase of the production water-gas ratio, the content of Cl^- in formation water basically remained unchanged. For example, the production water-gas ratio of Well DK208 continued to rise, but the content of Cl^- was stable at about 90000 mg/L (Figure 3(c)). On the basis of the production characteristics of formation water and water-gas ratio data, the formation water samples obtained in this study can be classified as four types (Table 1).

A large number of production data were collected from oil field, including the chloride ion content of the formation water and the water-to-gas ratio in the corresponding production. The discriminant charts of different types of formation water were established based on the characteristics of single well formation water production (Figures 3 and 4). When water-gas ratio is very low in the production, and the content of chloride ion of formation water is also very low, which was mainly condensate water. The boundary of the research area can be defined as the content of chloride ion (<5000 mg/L) and the water-gas ratio ($<0.1\ m^3/10^4\ m^3$). With the growth of water-gas ratio, the content of chloride ion in the formation water varies considerably and is mainly characterized by mixed formation water. At this stage, the reason for the large variation of the content of chloride ion in formation water is the difference of mixing ratio of different types of formation water (Figures 3(a) and 4). The boundary of mixed water can be defined as the content of chloride ion (5000~120000 mg/L), the water-gas ratio ($0.1{\sim}0.35\ m^3/10^4\ m^3$). After that, the water-gas ratio of the production continues to increase and the water yield is already very high, which should be isolated formation water or water in the gas-water transition zone. According to the basic principle of water-rock reaction in reservoir, isolated formation water has sufficient water-rock contact, strong regional mobility of formation water, diagenesis and evaporation concentration of formation water are intense, and the content of chloride ion (or salinity) of formation water should be the highest. In the gas-water transition zone, the coexistence of gas and water in tight reservoirs inhibits water-rock reaction and evaporation and concentration of formation water to a certain extent, and the content of chloride ion (or salinity) of formation water decreases slightly. Therefore, the characteristic of isolated formation water layer can be defined as the content of chloride ion (>120000 mg/L) and the water-gas ratio ($>0.35\ m^3/10^4\ m^3$) (Figures 3(a) and 4). While in the gas-water transition zone, the content of chloride ion (60000~12000 mg/L) and the water-gas ratio ($>0.35\ m^3/10^4\ m^3$) are its significant features (Figures 3(c) and 4).

3.2. Composition of Major Ions and pH Values. In the tight sandstone reservoir of Bashijiqike Formation in Kuqa Depression, the main cations of formation water include Na^+, K^+, Ca^{2+}, and Mg^{2+}, among which Na^+ content is the highest, followed by Ca^{2+}, K^+, and Mg^{2+}, and the contents of the four cations are very different, with an obvious trend of concentration to a certain end of Na^+ (Table 1). The content of Na^+ in condensate water is the lowest, with available means of 689.8 mg/L, and that in isolated formation water is the highest, ranging from 72289 to 109806 mg/L (averaged as 87207.8 mg/L), followed by water in gas-water transition zone and mixed water (Table 1). In other words, Na^+ and sodium salts with high solubility tend to be enriched in formation water, while calcium salts and magnesium salts with low solubility precipitate out.

The Cl^- is the dominated major anion due to its tendency to form strong electrolyte, followed by SO_4^{2-} (Table 1). The maximum value of Cl^- content is 182940 mg/L in isolated formation water, and the minimum value of Cl^- is 24 mg/L in condensate water. The difference is also reflected in the content of Total Dissolved Solids (TDS). The average TDS of condensate water, mixed water, gas-water transition zone water, and isolated formation water is 2392.8 mg/L, 17834.7 mg/L, 154149.4 mg/L, and 264194.2 mg/L, respectively (Table 1). The weakest dissolving ability of substances is condensate water, while isolated formation water is the strongest, and water in transition zone is inhibited by natural gas charging, which its dissolving ability is reduced.

According to the classification method of formation water by Sulin [23], the formation water with different production characteristics is $CaCl_2$ type, but the condensate water and the mixed water are obviously affected by secondary action and cannot represent the type of formation water under geological conditions. This preliminarily shows that the tight sandstone reservoir fluid of Bashijiqike Formation has good sealing ability, which facilitates the later preservation of natural gas. The pH values of formation water samples in the research area ranged from 3.7 to 7.4, with an average of 5.3 (Table 1). It can be found that the pH

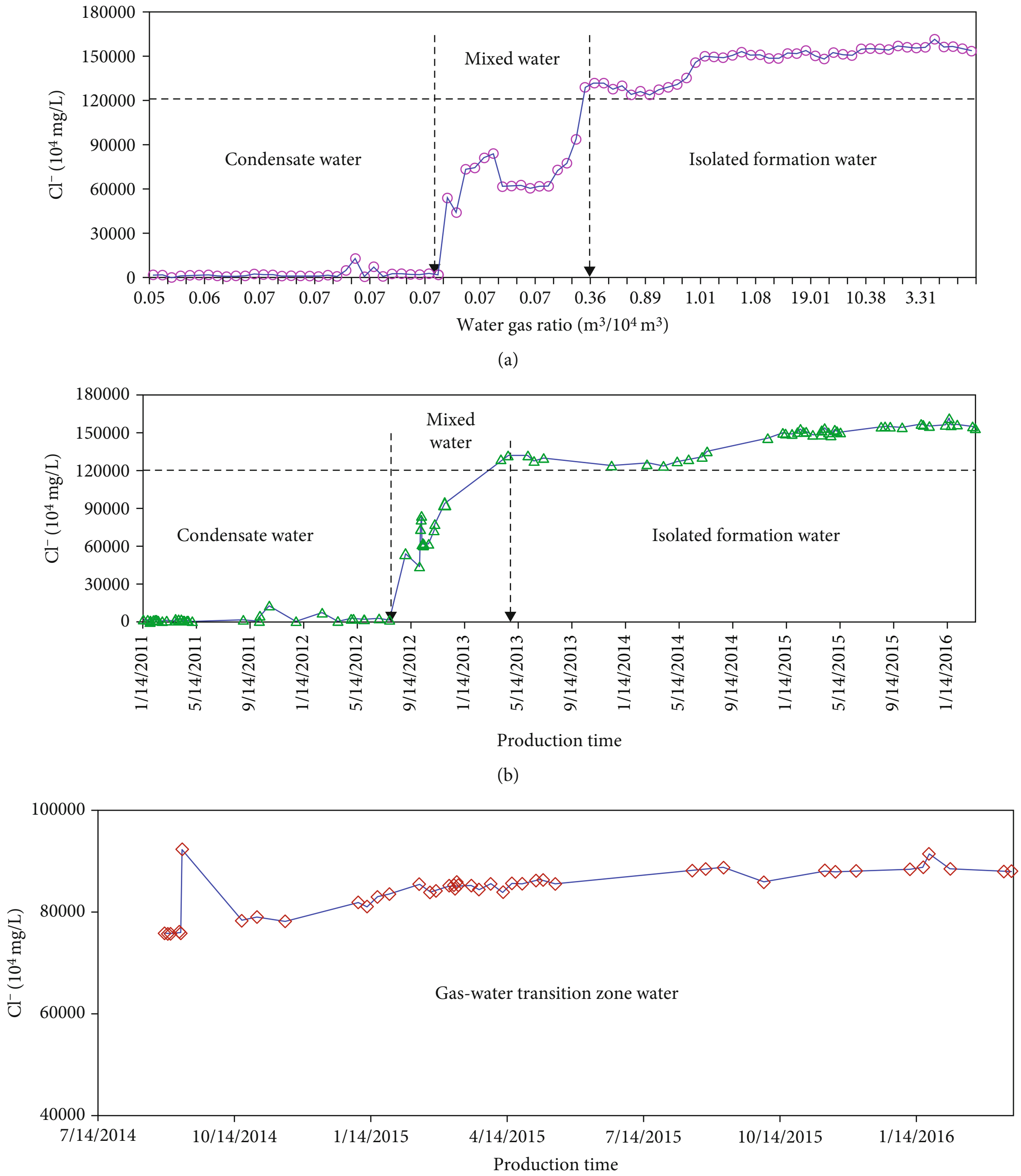


FIGURE 3: The content of Cl^- varies with water/gas ratio and production time in Well DK 205 (a and b) and Well DK 208 (c) in Kuqa Depression (Data from Tarim Oilfield).

values distribution of formation water has little difference, mainly acidic water (pH lower than 7.0), and only a few samples with pH value greater than 7.0 are alkaline.

3.3. Origin of Formation Water. Formation water in the reservoir is not always the result of diagenetic evolution of the original sedimentary water, but may also be affected by the intrusion of meteoric precipitation and formation water from other sources. A variety of geochemical parameters can be used to analyze the origin of formation water.

3.3.1. Parameter Discrimination of Major Ions. The content of Na^+ and Cl^- has obvious linear correlation, and the data points with high values are located between the halite dissolution line and the sea water evaporation line, or even some of the formation water values plot on or close to the line of evaporated seawater (Figure 5). As for the sedimentary environment of Bashijiqike Formation in Kuqa Depression, previous studies on calcareous nannofossil assemblage and sedimentation suggest that obvious transgression occurred during the late Cretaceous, but the sedimentary environment is relatively closed, the type of water

Table 1: The ion concentrations and pH values of different type formation water samples analyzed.

Sample ID	Type	Cl^- (mg/L)	SO_4^{2-} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	TDS (mg/L)	pH
K-1	Condensate water	2200	10	171	23	1135	65	3603	3.7
K-2		181	16	9	0	127	2449	2782	7.0
K-3		3553	36	51	0	2965	547	7309	6.6
K-4		31	5	0	0	28	696	1157	7.0
K-5		972	11	78	12	446	46	1565	3.9
K-6		2646	0	196	19	1312	153	4326	4.5
K-7		271	92	6	2	168	90	629	7.3
K-8		24	2	3	0	11	27	68	7.4
K-9		33	31	4	1	16	13	96	5.0
K-10	Mixed water	4614	33	334	48	2386	186	7601	4.0
K-11		10437	239	771	95	5152	615	17309	4.0
K-12		6130	37	642	96	3205	803	11050	4.7
K-13		6277	87	449	54	3712	306	10885	4.3
K-14		20381		1555	236	9588	772	32532	3.7
K-15		15413	736	263	21	9834	1193	27631	6.4
K-16	Isolated formation water	156190	2350	14083	1264	85380	3549	262816	5.4
K-17		138145	290	8502	845	78562	3145	229503	4.8
K-18		181840	1950	19973	1342	95390	4284	304779	4.2
K-19		147630	0	10946	689	81820	3155	244240	3.8
K-20		182940	0	9237	631	109806	5184	310593	3.8
K-21		143171	595	12152	775	72289	4252	233234	5.0
K-22	Transition zone water	83145	790	7163	737	46147	1624	139606	6.9
K-23		92710	0	9308	650	48641	4872	156373	4.6
K-24		111710	275	8876	661	61970	3124	186691	5.6
K-25		116500	665	10335	697	62142	3773	194112	6.9
K-26		70460	1825	10435	712	33297	3520	120249	4.2
K-27		51935	705	2938	160	29162	2664	87564	7.2
K-28		86405	385	8702	1185	43943	5656	146276	4.4
K-29		105510	2870	9976	1350	51302	5698	176706	4.8
K-30		106470	2130	9888	668	57065	3547	179768	6.8

The content of HCO_3^- and CO_3^{2-} are very low and the detection error is large, so they are not listed. TDS: total dissolved solids.

is saline water, and the paleoclimate is mainly characterized by drought and high temperature [24–26]. So, the current formation water may have been influenced to some extent by the early seawater.

The sodium/chloride ratio ($\rho Na^+/\rho Cl^-$) can reflect the degree of concentrated metamorphism of formation water and the hydro geochemical environment of the reservoir [28, 29]. The $\rho Na^+/\rho Cl^-$ ratios of different types of formation water are obviously different, and the parameter value of condensate water varies widely (Figure 6), which cannot reflect the formation water situation. The $\rho Na^+/\rho Cl^-$ ratio of the other types of formation water is distributed in the range of 0.47 and 0.64, with available means of 0.54, demonstrating that the formation water environment is highly reductive and conducive to the preservation of natural gas.

The metamorphic coefficient ($\rho(Cl^- - Na^+)/\rho(Mg^{2+})$) is used to demonstrate the metamorphic concentration degree of formation water. If the value is small (generally less than 0), it suggests that the closed preservation condition of formation water has been destroyed [9, 30]. On the contrary, the more concentrated and the deeper the metamorphism, with larger the parameter value, the better the sealing degree and the stronger the water-rock interaction, which is more propitious to the preservation of oil and gas [30]. The metamorphic coefficient of mixed water, gas-water transition zone water, and isolated formation water ranges from 30.4 to 263.2, averaged as 76.1 (Figure 7). This forecasts that the metamorphism of formation water in the research area is strong, which is propitious to the preservation of natural gas.

The desulfurization coefficient ($100 \times \rho(SO_4^{2-})/\rho(Cl^-)$) is used to characterize the degree of desulfurization acid action of formation water [9, 31]. When the desulfurization coefficient is less than 1.0, it usually illustrates that the formation water is well-sealed, and that the water-rock environment has undergone a thorough reduction. Instead, it is considered that the reduction degree is incomplete and may be affected by shallow surface oxidation. The desulfurization coefficient of mixed water, gas-water transition zone

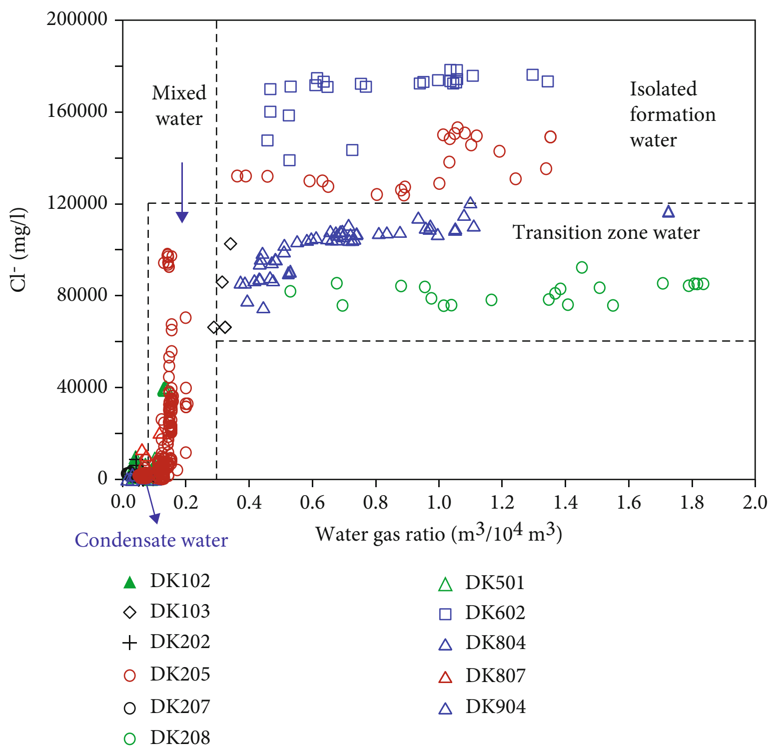


Figure 4: The identification chart of formation water types with production of water gas ratio and chloride content.

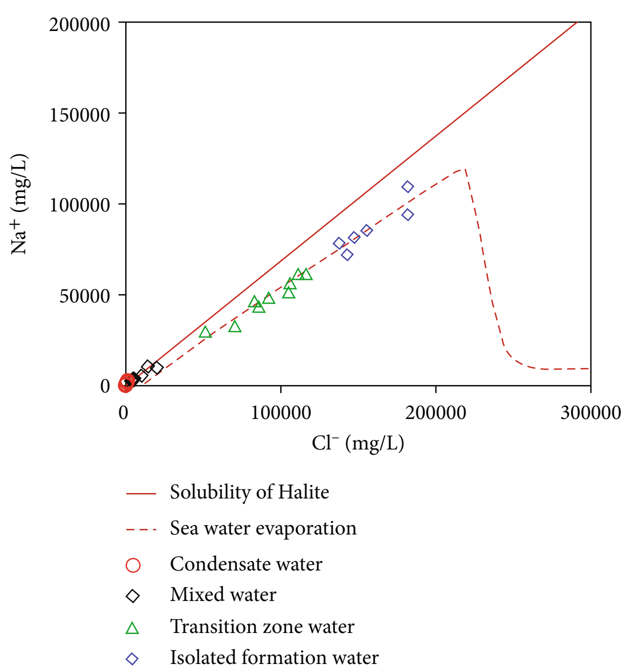


Figure 5: Cross–plot of Na^{+} vs. Cl^{-} with theoretical evaporation and dissolution trends [27] of the collected formation water samples in Kuqa Depression.

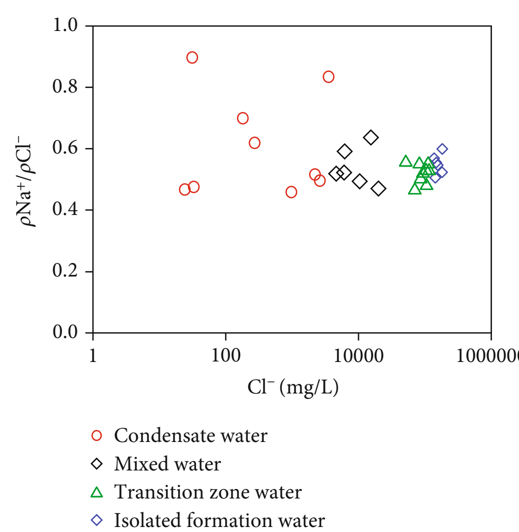


Figure 6: Distribution of sodium/chloride ratios of formation water in Kuqa Depression.

water, and isolated formation water is in the range of 0.5-7.5, averaging as 2.1 (Figure 7). Most of the desulfurization coefficients were significantly higher than 1.0, demonstrating that the desulfurization of formation water is not complete and the water-rock interaction is not strong and is not affected by atmospheric precipitation (<0) [9]. Overall, the formation water in the research area has a good sealing ability, and the water-rock interaction is strong, without peroxide. Above Bashijiqike Formation is the Cretaceous Kumugeliemu Group (E_{1-2}km) (Figure 1(d)), which is mainly comprised of thick layered gypsum salt deposits with strong plastic flow ability and not easy to be penetrated by faults. It is recognized as a good regional cap rock [17, 18], which should be an important reason for the good sealing conditions of Cretaceous deep formation water in

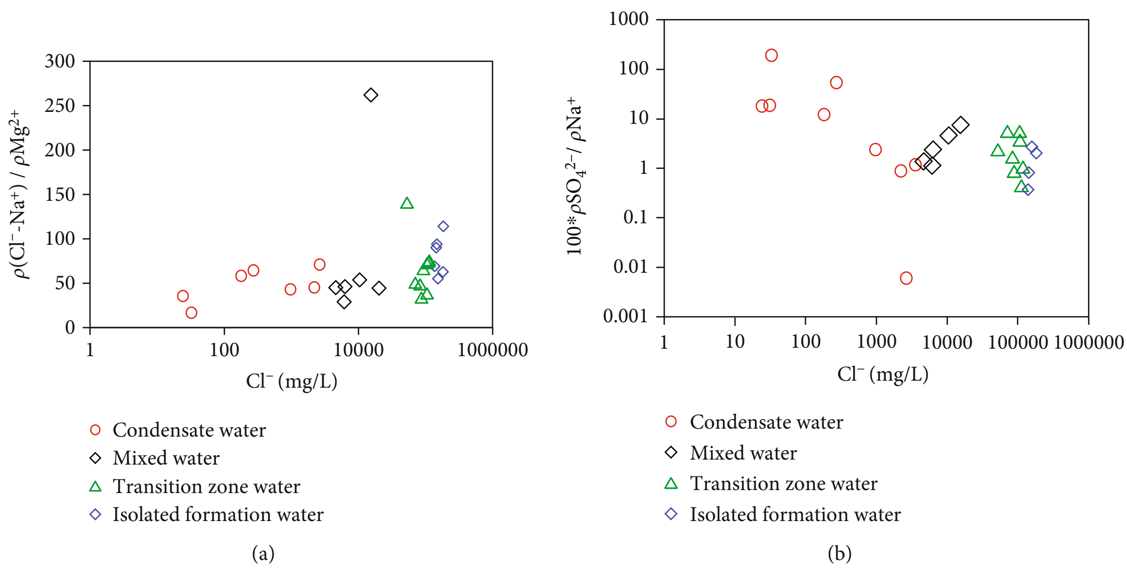


Figure 7: Distribution of metamorphic coefficient and desulfurization coefficient of formation water in Kuqa Depression.

Kuqa Depression. The high value of the desulfurization coefficient may be due to the influence of SO_4^{2-} in the overlying gypsum strata on the formation water in the Bashijiqike Formation.

3.3.2. Identification of Trace Elements and their Isotopes. Formation water contains not only a large number of major ions but also a variety of trace elements. In this study, we analyzed common trace elements such as Sr, Rb, B, and Ba, with the concentrations range from 0.1 to 561.2 mg/L, 0.1 to 9.4 mg/L, 1.3 to 59.6 mg/L, and 0 to 16.0 mg/L (Table 2). The analysis shows that the content of trace elements increases gradually from condensate water, to mixed water, and then to transitional zone water and isolated formation water, and the contents of each element in transitional zone water and isolated formation water are similar (Figure 8). Condensate water also has a similar positive correlation with Cl^- concentration, but individual sample points are deviate from the trend line (Figure 8), forecasting that different elements have different chemical activities and different capacities to evaporate into condensate water.

Previous studies have found that certain trace elements give a good indication for the source of formation water. For example, high Sr content mainly develops in highly concentrated marine formation water or occurs in gypsum rock, and B is mainly in the concentration of condensed gypsum rock formation water or marine mudstone [13, 32]. The contents of these elements are generally higher than those in seawater and marine sediments, primarily referring to isolated formation water and transitional zone water (Table 2 and Figure 8). It can be inferred that the formation water of Bashijiqike Formation was influenced by the overlying gypsum rock formation water of Kumugeliemu Group. Small amounts of anhydrite have been found in some sandstone samples, (Table 3), which may be a sign of fluid infiltration in the overlying strata. What is more, trace elements have high industrial value, and the formation water of some oil and gas fields can reach industrial grade, which is a resource with potential development value and has attracted high attention of the industry [21]. Analysis of the distribution of trace elements in deep formation water in the Kuqa Depression shows that they are significantly enriched in transition zone water and isolated formation water, which are the main objects of trace element extraction.

3.3.3. Strontium Isotopes. There are four natural stable isotopes of strontium (Sr), ^{88}Sr (82.58%), ^{87}Sr (7.00%), ^{86}Sr (9.86%), and ^{84}Sr (0.56%), which do not produce obvious isotopic fractionation in chemical and biological processes. And the ratio of $^{87}Sr/^{86}Sr$ ratio is almost constant in the same geological period and in the same water area, not affected by fractionation or by mineral precipitation [33]. Therefore, the isotopic composition of strontium can be used as an effective tracer to determine the source of formation water. The analysis shows that $^{87}Sr/^{86}Sr$ ratios of formation water are in a relatively narrow field between 0.7104 and 0.7129 in the study area (Table 2 and Figure 9). Due to the weak effect of strontium isotope fractionation, the distribution interval of strontium isotope values between different types of formation water is consistent with each other (Figure 9), implying that different types of formation water have good homology. Since the Precambrian, the $^{87}Sr/^{86}Sr$ ratios are in a fairly narrow field of seawater between 0.7070 and 0.7092 [34, 35]. The $^{87}Sr/^{86}Sr$ ratios of the formation water samples in the research area are all higher than this range (Table 2 and Figure 9), indicating that the formation water cannot be completely derived from seawater.

3.3.4. Hydrogen and Oxygen Isotope Discrimination. The stable isotopes of hydrogen (H) and oxygen (O) in formation water mainly refer to ^2H (D) and ^{18}O, whose natural average abundance is 0.0156% and 0.2%, respectively [13]. Due to the effect of evaporative fractionation or water-rock interaction during burial, the hydrogen and oxygen stable isotopes

Table 2: The trace element concentrations, stable isotopes of Sr, H, and O of different type formation water samples analyzed.

Sample ID	Type	Mn (mg/L)	B (mg/L)	Ba (mg/L)	Rb (mg/L)	Sr (mg/L)	$^{87}Sr/^{86}Sr$	δ^2H	$\delta^{18}O$
K-1	Condensate water	0.6	2.1	2.0	0.1	5.0			
K-2		0.1	1.4	0.0	0.5	0.2			
K-3		0.2	4.0	0.0	0.4	1.6	0.7109	-68.5	-6.7
K-4		0.1	1.3	0.0	0.1	0.3	0.7115	-64.3	-6.9
K-5		0.9	2.8	3.8	0.1	1.6	0.7123	-65.1	-7.1
K-6		2.8	3.1	0.9	0.3	6.1			
K-7		0.7	4.5	0.1	0.1	1.6	0.7129	-45.9	-4.5
K-8		0.8	7.4	0.1	0.1	1.8	0.7121	-45.2	-3.8
K-9		0.4	7.2	0.4	0.0	0.1			
K-10	Mixed water	1.1	3.6	2.0	0.3	14.9			
K-11		2.9	4.8	0.9	0.8	36.4	0.7119	-74.3	-8.4
K-12		2.1	3.6	0.8	0.5	15.4	0.7121	-64.9	-7.4
K-13		1.3	4.6	0.3	0.5	17.5	0.7117	-68.0	-6.3
K-14		21.3	8.2	5.8	2.2	94.1	0.7118	-67.0	-9.7
K-15		0.3	8.8	0.1	1.3	7.8	0.7105	-69.4	-6.8
K-16	Isolated formation water	9.6	25.4	2.6	7.2	326.6			
K-17		14.9	29.2	2.4	8.4	430.3	0.7122	-64.3	-7.2
K-18		14.7	13.6	4.7	7.3	510.8			
K-19		16.3	17.9	2.6	8.6	561.2	0.7110	-64.9	-6.6
K-20		86.7	28.0	1.7	9.4	418.9	0.7120	-61.4	-7.3
K-21		71.7	17.0	2.5	6.5	363.0	0.7129	-55.7	-4.3
K-22	Transition zone water	3.8	59.6	2.2	4.4	331.2			
K-23		63.7	24.4	2.5	6.3	285.2	0.7104	-66.2	-6.3
K-24		44.4	48.8	3.8	8.3	426.7	0.7120	-55.1	-5.8
K-25		14.1	42.5	3.3	9.2	464.3			
K-26		194.5	21.5	16.0	8.4	330.5			
K-27		17.3	42.0	7.2	4.0	146.5	0.7128	-52.8	-4.8
K-28		404.6	54.8	3.4	8.4	402.4	0.7104	-64.9	-6.4
K-29		25.6	32.7	9.5	8.7	377.6			
K-30		8.0	39.1	5.1	8.2	414.8			

will be altered, such as the mixing of atmospheric precipitation and reactions of formation water with limestone and/or dolomitization of calcium carbonates [14, 36]. The hydrogen and oxygen stable isotopes of atmospheric precipitation are usually lighter, while those of closed formation water are heavier, which increases with the increase of strength water-rock interaction [13, 36]. Water-rock reaction can increase the $\delta^{18}O$ value of formation water, so it can be used to indicate the intensity of water-rock reaction, and then reflect the sealing of formation environment and the preservation conditions of oil and gas. For the collected formation water samples, δ^2H and $\delta^{18}O$ values do not show regular variation in relation to formation water type (Figure 10 and Table 2), which shows that the isotopes mainly reflect the formation water origin and have little relationship with their occurrence state in the gas reservoirs. Most of the data points are distributed on the right side of the Global Meteoric Water Line (GMWL) [37] (Figure 10), illustrating that the formation water is mainly affected by water-rock reaction, and the formation conditions are conducive to the preservation of natural gas.

3.4. Inspirations for Ultradeep Tight Sandstone Gas Reservoirs

3.4.1. Inspiration for Formation Water Production. Combined with the characteristics of trace elements and stable isotopes of hydrogen and oxygen in the formation water, this suggests that the formation water was dominated by sedimentation, diagenesis, and burial evolution, without the influence of atmospheric fresh water, and that the effects of early seawater were less pronounced. Different types of formation water have good homology, and geochemical parameters reflect good formation sealing, which facilitates the preservation of natural gas in the ultradeep tight gas reservoirs of the Cretaceous Bashijiqike Formation in the Kuqa Depression. The formation water can be judged by the Cl^- content, TDS and, trace element concentration of the formation water during gas well production. The effect

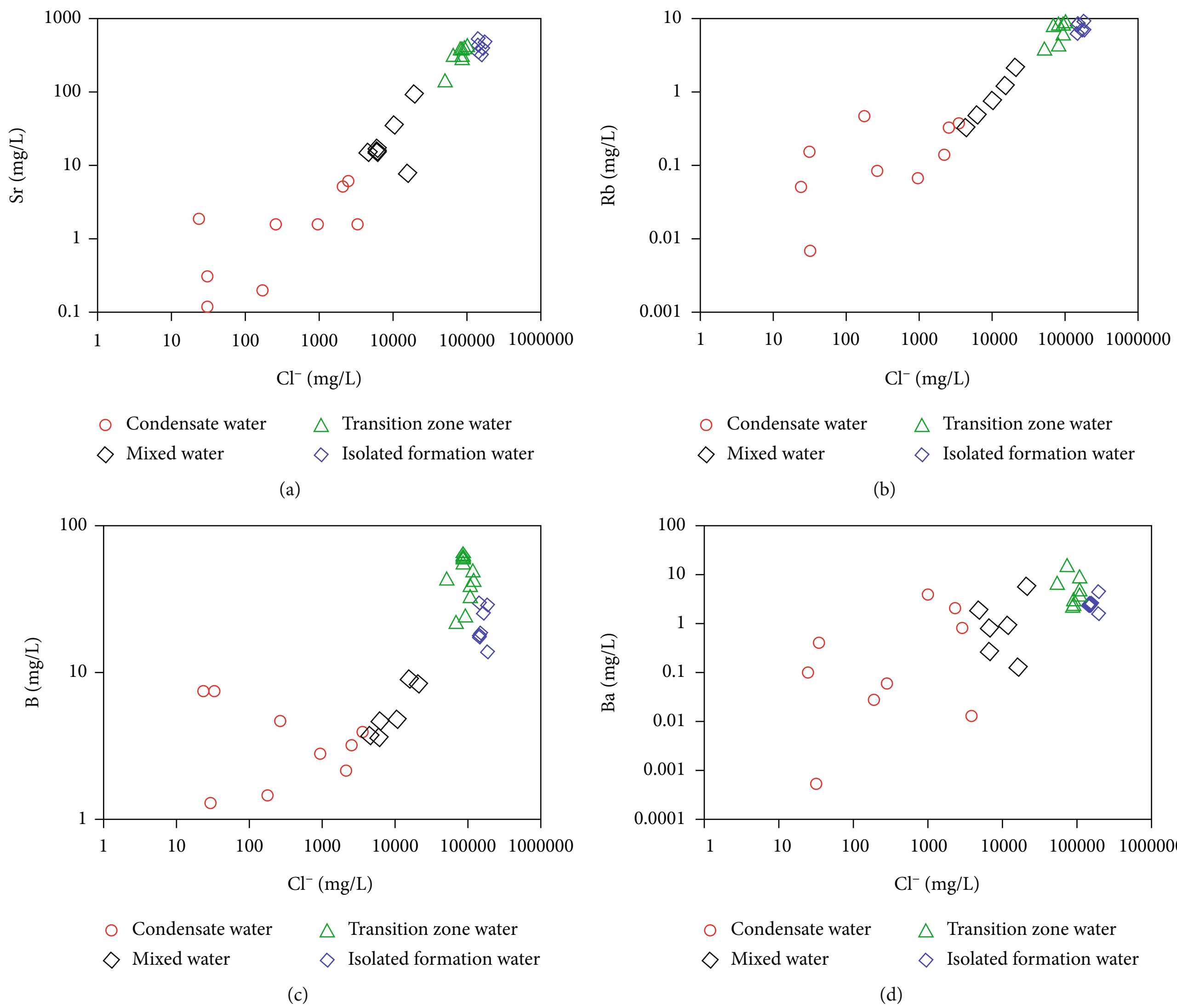


Figure 8: Relationship between Sr, Rb, B, Ba, and Cl^- content of the collected formation water samples in Kuqa Depression.

of the condensate production on the gas well is negligible, and it has very low concentrations of major and trace elements. Mixed water production requires a high level of vigilance, indicating that water production will enter a phase of rapid increase. A significant amount of formation water percolates and is produced in the reservoir, which can cause severe damage to the tight reservoir and affect the production and economic benefits of the gas well. Therefore, the production plan should be adjusted in time. The production of transitional water indicates that the tight reservoir is not fully charged with natural gas, forming a gas-water transition zone. During production, natural gas is produced together with large amounts of formation water for a long time. The development of such reservoirs requires the treatment of large quantities of formation water with relatively high concentrations of primary and trace ions. Direct discharge obviously causes environmental pollution, and industrial extraction and application of important ions can be considered to maximize economic benefits.

3.4.2. Inspiration for Fluid Evolution. Carbonate cements are the main cements in tight sandstone reservoirs of Bashijiqike Formation in Kuqa Depression, and their formation has an important effect on the densification process, micropore structure, gas and water distribution, and production of the reservoir [19, 38, 39]. The carbonate cements in Bashijiqike Formation tight sandstone include calcite and dolomite. The content of calcite ranges from 1% to 15%, with a mean of 3.8%, and that of dolomite ranges from 0 to 13%, with an average of 4.2%; the average content of dolomite is slightly higher than that of calcite (Table 3). The relative content of magnesium (Mg^{2+}) and calcium (Ca^{2+}) can be used to reflect the dissolution and precipitation of dolomite and calcite [12, 40]. The content of Ca^{2+} increases gradually with the growth of Cl^- content, but tends to be stable when it reaches a certain high value, and the data points of transition zone water and isolated formation water plot on or close to the trend line of $CaCl_2$ dissolution (Figure 11(a)). However, the Mg^{2+} content remained remarkably low, below the

Table 3: X-ray diffraction experimental results of tight sandstone samples of Cretaceous Bashijiqike Formation in Kuqa Depression.

Sample ID	Depth/m	Clay	Quartz	Potassium feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Anhydrite
DK-1	6345.21	6	57	6	14	1	13	—	3
DK-2	6348.17	4	49	10	18	1	6	—	12
DK-3	6408.50	5	54	10	21	10	0	—	—
DK-4	6427.45	4	51	8	22	15	0	—	—
DK-5	6487.05	3	48	9	30	3	7	—	—
DK-6	6353.66	5	60	9	16	6	4	—	—
DK-7	6485.85	2	49	8	27	2	12	—	—
DK-8	5971.93	5	55	3	30	7	0	—	—
DK-9	6765.05	3	65	8	20	4	0	—	—
DK-10	6797.82	3	69	7	16	2	3	—	—
DK-11	6931.70	7	48	11	26	1	7	—	—
DK-12	7086.44	3	55	6	28	2	6	—	—
DK-13	7085.35	5	51	8	28	6	2	—	—
DK-14	7091.02	3	55	5	30	2	5	—	—
DK-15	6801.74	5	57	8	22	2	6	—	—
DK-16	6806.94	5	57	8	24	1	5	—	—
DK-17	6737.78	4	57	8	19	1	9	—	2
DK-18	6717.59	3	65	7	17	2	4	—	2
DK-19	6957.16	2	49	12	28	5	2	—	2
DK-20	6964.52	4	51	14	25	1	2	1	2
DK-21	6419.85	12	59	7	16	5	1	—	—
DK-22	6424.56	12	65	5	11	7	0	—	—
DK-23	6507.60	11	58	8	19	3	1	—	—
DK-24	6735.39	2	63	3	22	1	5	—	4

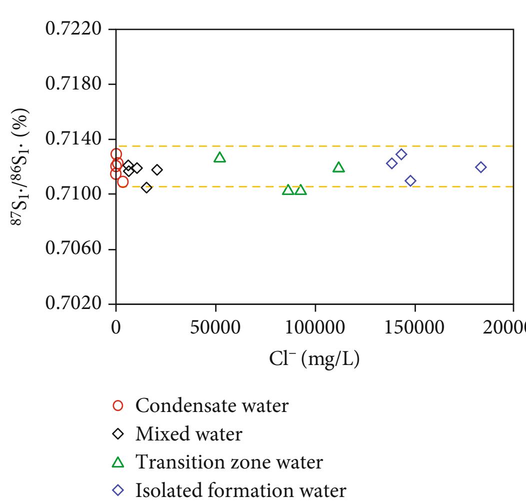


Figure 9: Distribution of strontium isotope in different types of the collected formation water samples in Kuqa Depression.

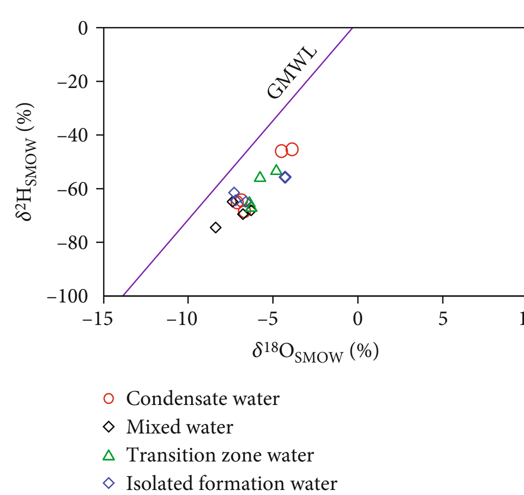


Figure 10: Hydrogen and oxygen isotopic composition of the collected formation water samples in Kuqa Depression. The Global Meteoric Water Line (GMWL: $\delta^2H = 8 \times \delta^{18}O + 10‰$) is taken from Craig [37].

evaporation trend line of sea water (Figure 11(b)). Bozau et al., [40] systematically analyzed the geochemical characteristics of formation water in many basins in Western and Middle Europe, Russia, and America and found that Mg^{2+} content was mostly lower than the sea water evaporation line, and the accumulation of Ca^{2+} or the deficiency of Mg^{2+} is mainly affected by albitization or dolomitization.

For the formation water of Kuqa Depression, we hypothesize that dolomitization plays a more important role in controlling Mg^{2+} concentration. Compared with the high concentration of Ca^{2+}, the solubility of calcite is higher than that of dolomite, or the activity of Ca^{2+} is higher

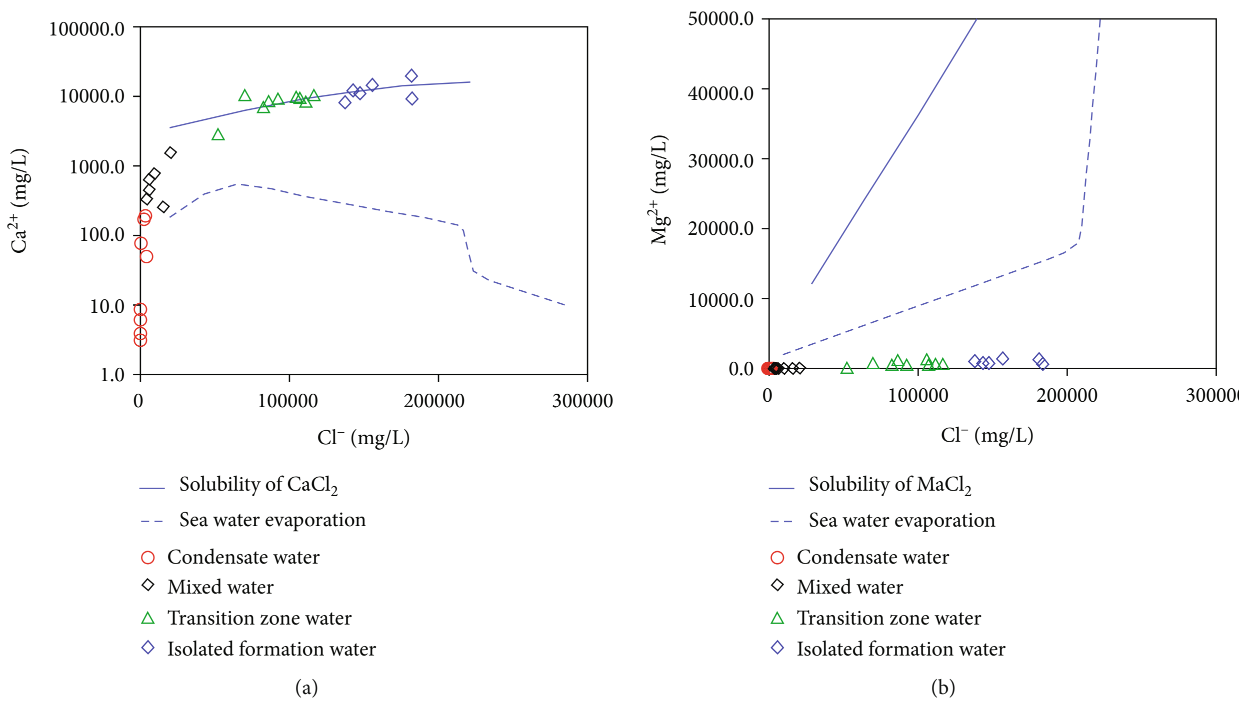


Figure 11: Cross–plot of Ca^{2+} (a) and Mg^{2+} (b) vs. Cl^- with theoretical evaporation and dissolution trends [27] of the collected formation water samples in Kuqa Depression.

than that of Mg^{2+} in Bashijiqike Formation with high temperature and pressure. The formation of these cements is mainly connected with carboxylic acids and CO_2 formed during the thermal evolution of source rocks [38, 39], and the organic-inorganic interaction between organic fluids and rocks is the main mechanism.

In the process of natural gas charging, when all the movable water in the reservoir can be discharged, pure gas reservoirs could be formed. Only bound water or immovable water exists in the reservoir. Meanwhile, water exists in the gas reservoir with the dissolved state and forming condensate water when it is mined to the surface. When the natural gas charging is insufficient, the natural gas, bound water, and part of movable water coexist in the reservoir, which is the gas-water transition zone. During the development process, natural gas and movable water are produced together. When there is no natural gas filling in the reservoir, the reservoir space is saturated with primordial formation water, such as gas reservoir edge water and bottom water. The mixed water does not exist in the formation state, but is formed by the mixture of condensate water and transition water and condensate water and isolated formation water in the process of gas reservoir development. The geochemical characteristics of formation water at present reflected that the salinity of formation water was mainly controlled by water-rock reaction. From the investigation of fluid inclusions in carbonate cements, the salinity of paleofluid in Bashijiqike Formation sandstone reservoir was low, and the salinity of the fluid inclusions increased rapidly and tended to the maximum with the fast burial depth of the formation since 5 Ma [41]. It indicated that the salinity of formation water, fluid temperature and pressure increased rapidly after 5 Ma. Meanwhile, it was the key period for the fluid charging and reservoir densification [39, 41]. The mobility of formation water will be weakened by reservoir densification and gas charging, and it could inhibit the water-rock reaction. Therefore, the rapid increase of formation water salinity is mainly driven by the rise of formation temperature. With the densification of reservoir and the continuous charging of natural gas, the effect of inhibiting water-rock reaction is gradually significant, and the variation of formation water salinity tends to be gentle. And this is an important reason that the occurrence of the geochemical characteristics of isolated formation water and transitional zone formation water.

4. Conclusions

(1) The formation water of Cretaceous Bashijiqike Formation tight sandstone gas reservoir in Kuqa Depression can be divided into condensate water, gas-water transition zone water, mixed water, and isolated formation water, and different types of formation water have regular production characteristics and geochemical characteristics

(2) The difference of formation water salinity (Cl^- content) is mainly affected by formation water type, not by external factors such as atmospheric precipitation and overburden water leakage, and the four types of formation water have good homology

(3) The formation water chemical parameters reflect that the tight reservoir of Bashijiqike Formation in Kuqa Depression has experienced strong water-

rock reaction and is in a closed environment, which is propitious to the preservation of natural gas

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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