Characteristics and origin of the Fengcheng Formation water in Mahu depression and its significance to hydrocarbon migration and accumulation

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Abstract. Formation water is the power and carrier of oil and gas generation, migration and accumulation, which has important significance for oil and gas migration, accumulation and preservation. The groundwater characteristics and genetic mechanism of the Permian Fengcheng Formation in Mahu sag are mainly studied through the chemical composition, isotope test, inclusion temperature measurement and salinity analysis. The study shows that the formation water of Fengcheng Formation in Mahu sag has special hydrochemical characteristics of high salinity, high HCO\textsubscript{3} concentration, low Ca\textsuperscript{2+}, Mg\textsuperscript{2+} concentration and high pH value NaHCO\textsubscript{3} water type. The characteristics of inclusion temperature measurement, carbon and oxygen isotope, strontium isotope and boron isotope show that the Fengcheng Formation fluid has deep hydrothermal source, and volcanism contributes significantly to its CO\textsubscript{2} source. The source of deep hydrothermal solution, volcanism and a large amount of hydrocarbon generation and expulsion from source rocks may be the main reasons for high HCO\textsubscript{3} content in formation water. The Fengcheng Formation in Mahu sag is an alkalized lake deposit. The highest alkalization degree of water in the study area may be distributed in the southwest slope of Mahu lake. From the evolution stage of the alkali lake, the first member of the wind is the initial stage of the formation of the alkali lake, corresponding to the late stage of the high water level of the lake, and the water salinity is low; the second member of the wind is the strong alkali forming stage, corresponding to the Lake recession period, the water surface drops, the water body is strongly concentrated, and the salinity is high; the third member of the wind is the fading period of the alkali lake, corresponding to the early stage of the lake advance, the water salinity gradually decreases. On the whole, the groundwater mineralization degree of Fengcheng Formation in Mahu depression is high, and the formation sealing property is relatively good. The side near the edge of the basin is affected by the infiltration of atmospheric water, which results in the decrease of mineralization degree and the appearance of Na\textsubscript{2}SO\textsubscript{4} type water. The water head decreases gradually from Mahu sag to northwest margin, and the
gradient of water head near Wuerhe in the north section is relatively strong, which is not conducive to hydrocarbon accumulation and preservation. Baikouquan and Karamay areas are low potential areas, and the water head gradient becomes gentle, which is conducive to oil and gas accumulation.

Key words: Characteristics of formation water; genetic analysis; significance of oil and gas; Fengcheng Formation; Mahu depression

1. Introduction

The hydrogeological and geochemical properties of groundwater are closely related to the migration and accumulation of oil and gas and the destruction and preservation of reservoirs, which have important indicative significance for the migration, accumulation of hydrocarbon. The Junggar basin is characterized by a large number of hydrocarbon reservoirs, large variation in groundwater mineralization, multiple water types and complex characteristics, and a lack of in-depth understanding of the genesis and source of groundwater, especially the chemical characteristics and genesis of groundwater of the Permian Fengcheng Formation in the Mahu Sag need to be studied urgently. By collecting typical well cores and formation water samples of the Fengcheng Formation, thin section observation and sample analysis and test, combined with structural and sedimentary reservoir characteristics analysis of the study area, the source of chemical, chemical feature and dynamic characteristic fluid of groundwater in the Mahu Depression was analyzed, and the groundwater types and genetic mechanism were discussed.

The Fengcheng Formation (P1f) in the Mahu Sag is divided into three sections from bottom to top, namely the first section (P1f1), the second section (P1f2) and the third section (P1f3). Lithology includes clastic rock, dolomitic rock and volcanic rock, reflecting the characteristics of mixed deposition. A total of 37 core samples were collected from 8 Wells of the Fengcheng Formation in this study, including the Feng 15 Well, Fengnan 1, Feng 5 Well, Feng 26 Well, Feng 8 Well, Fengnan 7 well, Xia 40 and Aike 1 Well. The samples were mainly concentrated in the eastern and southeastern Wuerhe Regions. Carbon and oxygen isotopes and strontium isotopes were mainly selected from carbonate samples for analysis, mainly dolomite rock and argillaceous dolomite rocks. Boron analysis mainly selects searlesite rich samples, such as strip-enriched dolomite rock and tuff. Fluid inclusion analysis is mainly selected from carbonate and salt minerals. For one or two-phase saline solution inclusions, the salinity of the solution can be obtained by measuring the freezing point of the inclusions according to the principle of decreasing the freezing point of dilute solution and the known phase diagram of the saline system. At the same time, the formation hydrochemical analysis data of this area are also widely collected. For the relatively new exploration Wells such as the Maye 1, timely on-site sampling is carried out for ion and salinity analysis of water.

2. Experimental analysis and results

2.1. Fluid-inclusion analysis

(1) Uniform temperature of inclusions

The inclusions of the Fengcheng Formation in Mahu Sag were analyzed by temperature measurement, the results show that the homogeneous temperature distribution of the inclusions is very wide, and the homogeneous temperature of the fluid inclusions in the three layers is quite different (Fig.1). The uniform temperature of the first section (P1f1) is mainly distributed in 140°C to 180°C, followed by 100°C to 140°C, the second section (P1f2) is distributed in the range of 40°C to 200°C, with two peaks, namely 60°C to 100°C and 140°C to 180°C. The third section (P1f3) were mainly distributed in 60°C to 100°C and 160°C to 180°C. From the first section to the third section, the average temperature peak of inclusions decreases gradually. The fluid of the Fengcheng formation may have the property of lower formation fluid source, which is related to
the active hydrothermal activity in the early Permian.

(2) Salinity determination of fluid inclusion

Because the salt composition of diagenetic ore-forming fluid is complex, usually NaCl is the main component, so the salinity is represented by the equivalent component of NaCl \[w(\text{NaCl,eq})\%\]. The salinity of the first section \((P_{1f})\) is relatively low, generally lower than 12%, mainly concentrated between 4% to 6% and 8% to 10%. The second section \((P_{1f2})\) has a wide range of salinity distribution, which is dominated by high salinity. The peak value is 22% to 24%, followed by 6% to 10% and 16% to 18%. The salinity of the third section is is next to that of the second section, and the peak value is mainly distributed at 18% to 20%, followed by 6% to 8% and 22% to 24% (Fig. 1). From the stratification, the salinity rises first and then drops from the first to the third section, presenting a low-high-low variation trend. The salinity was highest in the second section, corresponding to the intense period of alkali lake development.

2.2 Geochemical analysis

(1) Carbon and oxygen isotope analysis

The value of \(\delta^{13}C\) (PDB) of the Permian Fengcheng formation in the Mahu Depression ranges from -1.542‰ to 5.754‰, with an average value of 3.129‰. The carboniferous \(\delta^{13}C\) (PDB) values range from -17.9‰ to 2.312‰, with an average value of -7.588‰. Compared with the Carboniferous, the carbon isotopes of the Fengcheng formation are significantly overweight, which indicates that they are significantly influenced by deep hydrothermal fluids. The carboniferous carbon isotopes are obviously light, which indicates that they are strongly influenced by atmospheric water (Fig. 2). According to the ancient salinity index formula \[Z=2.048\times(\delta^{13}C+50)+0.498\times(\delta^{18}O+50)\] [3-5]. Z values of the Fengcheng formation in Mahu Sag are all greater than 120, indicating that carbonate cements were formed in the Marine sedimentary environment. The Z value of carboniferous is generally less than 120, reflecting the formation of carbonate cements in the freshwater diagenetic environment (Fig. 2). The Z value of the paleosalinity index of the Fengcheng formation is very different from that of the carboniferous, indicating that the carbonate cements were formed in the sedimentary environment with high salinity and were weakly affected by the infiltration of atmospheric water. The Z value of the second section \((P_{1f2})\) was relatively the highest, corresponding to the intense period of alkali lake development. The value \(\delta^{18}O\) (PDB) of the Fengcheng formation is distributed in the range of -11.866‰ to 2.494‰, and the lower value \(\delta^{18}O\) is formed in the hydrothermal fluid with high temperature. Meanwhile, the negative drift of the value \(\delta^{18}O\) is caused by the influence of atmospheric precipitation due to the isotope exchange between diagenetic fluid and atmospheric fresh water (Fig. 2). The difference of carbon and oxygen isotopes between the first section, the second section and the third wind are not obvious.
Fig. 2 Diagram of Carbon and oxygen isotopes between the Fengcheng Formation in Mahu Depression and the Carboniferous of the Northwest Margin(left) and Diagram of Z value and carbon isotopes (right)

(2) Strontium isotope analysis
The composition of strontium isotope in rocks is mainly controlled by shell source and mantle source. The average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in shell source ratio is 0.7119, mantle source is low with average of 0.7035$^6$. Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio reflects the marking characteristics of substances from different sources. According to the strontium isotope test data, the strontium isotope ratio of the samples measured in the Fengcheng formation in Mahu Sag is 0.705833 to 0.710084, which is between the strontium of mantle source and strontium of shell source, indicating that it is influenced by both mantle source and shell source, among which the mantle source has a greater influence and may be affected by deep hydrothermal solution. Longitudinally, with the increase of buried depth, the strontium isotope showed a tendency of decrease, and there is no obvious difference in each layer segment.

(3) Boron isotope analysis
The Fengcheng formation in Mahu Sag of Junggar Basin was deposited in the volcano-Alkaline lake evaporation environment and borosilicate minerals developed. The source of boron was related to volcanic hydrothermal activity. Boron is a very active and volatile magmatic emanative element, which often forms volatile, melting and soluble complex and migrates and accumulates. The source of boron in boron-rich minerals is often associated with hot springs or volcanism. Boron is abundant in the stratigraphic water of Fengcheng formation in Mahu area surrounding. The Fengcheng area in the Northwest margin in Junggar Basin is 1.73mg/L to 1619.12mg/L, with an average of 662.43mg/L. The Wuerhe area is 2.59mg/L to 2330.95mg/L, with an average of 314.31mg/L. It is much higher than other blocks and other strata in the basin. The distribution range of $\delta^{11}\text{B}$ value in the Permian Fengcheng formation of Mahu Sag is 0.33‰ to 2.13‰, with an average value of 1.08‰. Therefore, it is speculated that the boron element in this area is from the deep heat source, and the fraction of boron isotopes is affected by the salt lake evaporation$^7$.

3. Genesis of stratigraphic water in the Fengcheng formation
The formation water of the Fengcheng formation in Mahu Sag has the special hydrochemical characteristics of NaHCO$_3$ water type with high salinity, high HCO$_3^-$ low concentration of Ca$^{2+}$, Mg$^{2+}$ and high concentration of pH value, which is similar to the chemical composition of alkaline lake brine. The salinity of the formation water is significantly higher than that of other groups of the Permian, with an average of 56.85g/L, among which nearly half of the samples are as high as the salinity of modern seawater with Salinity of 35 g/L. Ion of Na$^+$, K$^+$, Cl$^-$, SO$_4^{2-}$, CO$_3^{2-}$, HCO$_3^-$ are the main component of alkaline lake brines and Ca$^{2+}$, Mg$^{2+}$ are low. The correlation between formation water salinity and Cl$^-$ content in Fengcheng formation is relatively poor, especially the formation water with high salinity. With the increase of salinity, the increase of Cl$^-$ concentration was not obvious, while the concentration of HCO$_3^-$ increased significantly, indicating that the high salinity of formation water in Fengcheng formation mainly came from the abnormally high contribution of HCO$_3^-$. 

The high concentration of CO$_2$ in the deep layer rises into the groundwater, resulting in the increase of CO$_3^{2-}$ content in the water, in which part of CO$_3^{2-}$ combines with the Ca$^{2+}$, Mg$^{2+}$ in the water to form CaCO$_3$ and CaMg(CO$_3$)$_2$ precipitation, resulting in the greatly reduced content of Ca$^{2+}$, Mg$^{2+}$ in the water, and the content of Na$^+$ and K$^+$ takes the absolute advantage. The high concentration of HCO$_3^-$ in the study area is mainly distributed near the fault zone. The carbon and oxygen isotopes and strontium isotopes analysis of inclusions indicate that the fluids of the Fengcheng formation have deep hydrothermal sources, and the volcanism contributes significantly to the source of CO$_2$. In addition, the boron content in high-salinity formation water in the deep Permian carboniferous is abnormally high, which is mainly distributed in Wuerhe to Fengcheng area, which is speculated to be closely related to the deep strata connected with faults. In the Fengcheng formation of the Mahu Sag, high quality hydrocarbon source rocks are developed, with high maturity of organic matter. The mature organic matter of hydrocarbon generation layer generates and expels a large amount of hydrocarbon, and CO$_2$ gas dissolves in water, increasing HCO$_3^-$ in aqueous solution, which may be another main reason for the high HCO$_3^-$ content in formation water. The Fengcheng formation in Mahu Sag is an alkalized lake with closed environment, arid climate, intense evaporation and high concentration and salinity of formation water. Volcanic action and a large amount of hydrocarbon generation and expulsion from source rocks provide abundant CO$_2$. CO$_2$ gas dissolves in water and forms high concentration of HCO$_3^-$, which increases pH value and makes lake water become unique alkalinity. The highest degree of alkalinity of water in the study area may be distributed in the southwest slope area of the Mahu depression.

The evolution of alkali lakes usually includes the complete sequence of alkali preparation, strong alkali formation and weak alkali formation, and the sedimentary evolution is no exception in the Fengcheng formation$^{[8]}$. According to the formation water chemical characteristics and inclusions analysis and test results, the formation water salinity of the first Section is low, while that of the Second section and the Third Section is high. Among them, the Cl$^-$ concentration of the Second section is high, while the HCO$_3^-$ concentration of the Third Section is relatively high. High Cl$^-$ concentration indicates the highest concentration of formation water. The salinity of the first section is relatively lowest, the salinity of the second section is higher, and the salinity of the third section is slightly lower than that of the second section (Fig.3). The difference of formation hydrochemistry in each member of the Fengcheng formation reflects different evolutionary stages. Combined with the characteristics that alkaline minerals mainly develop in the second stage, it can be inferred that the first Section is the initial stage of alkaline lake formation, corresponding to the late stage of the high stage of lake-intake, and the water salinity is relatively low. The second Section stage is a strong alkali-forming stage, corresponding to the lakeback stage, water surface drops and water body is strongly concentrated, salinity is high, and a large number of alkaline minerals are developed. The third Section stage is the subsiding stage of alkaline lake, corresponding to the early lacustrine stage, in which the salinity of water decreases gradually and the content of alkaline minerals decreases gradually. Therefore, the second Section stage is the most intense stage of the development of alkaline lake.
3. Salinity, Cl⁻, HCO₃⁻ variation with depth in each member of the Fengcheng formation in the study area

4. The effect of formation water on hydrocarbon migration and accumulation

The Permian system of Junggar Basin is deeply buried, with relatively good stratigraphic closure and high groundwater mineralization. The average salinity of groundwater in the Fengcheng formation of Permian is over 50g/L, among which the salinity of Mahu 16 Well (4424m~4437m) is 241.871 g/L, which is the highest in the whole region. Local surface water permeates along the fault, resulting in the decrease of salinity and Na₂SO₄ water. The preservation conditions of oil and gas are destroyed and the oil quality becomes thicker. For example, the salinity of Ke 78 well is 6.58 g/L (3347~3335 m), and the crude oil density is 0.9495 g/cm³. Adjacent to the edge of the basin, Wells with relatively shallow burial depth are greatly affected by atmospheric water, and the condition of oil and gas preservation is poor. With the increase of buried depth, the condition of oil and gas preservation becomes better gradually, and the heavy oil is mainly distributed in the Middle and upper Permian.

On the plane, high salinity type of NaHCO₃ water is present in the mahu area of Baikou Quan-Wuerhe-Fengcheng area, with a salinity of over 200g/L, mainly concentrated in the
Fengcheng Formation (Fig.4). The side near the edge of the basin was affected by atmospheric water infiltration, and most of them were NaHCO₃ or Na₂SO₄ water with low salinity, while the rest areas were mostly CaCl₂ water, with good oil and gas preservation conditions. The Permian system as a whole shows overpressure, with the formation pressure coefficient between 0.74 and 2.14. The pressure coefficient increases gradually with the increase of buried depth. The head decreases gradually from The Mahu depression to the northwest margin of the Junggar Basin, among which the head gradient near Wuerhe in the north section is large and the hydrodynamic action is relatively strong, which is not conducive to the accumulation and preservation of oil and gas. The karamay, Che-Guai and Baikouquan areas are a low potential area, and the water head gradient becomes slow, which is favorable for oil and gas accumulation (Fig.4).

5. Conclusions
(1) The Fengcheng Formation in Mahu Depression is an alkalized lake deposition, and the formation water has the special hydrochemical characteristics of NaHCO₃ water type with high salinity, high HCO₃⁻ and low concentration of Ca²⁺, Mg²⁺ and high concentration of pH. The formation water is significantly contributed by deep hydrothermal and volcanic sources of CO₂, and the high alkalinization degree of water is distributed in the southwest slope area of Mahu depression.

(2) From the first section to the third section of the Fengcheng formation, the salinity first rose and then decreased, showing a low-high-relatively low change trend. The second section sedimentary period is the most intense stage of alkaline lake development.

(3) Under the influence of atmospheric water infiltration near the edge of the basin, the salinity decreased, Na₂SO₄ water appeared, the preservation conditions of oil and gas were destroyed, and the oil quality became thicker. The head decreases gradually from The Mahu depression to the northwest margin, among which the head gradient near Wuerhe area in the north section is large and the hydrodynamic action is relatively strong, which is not conducive to the accumulation and preservation of oil and gas. The karamay and Baikouquan area is a low potential area, and the water head gradient slows down, which is favorable for oil and gas accumulation.

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