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Geochemical Characteristics and Origin of Formation Water From the Upper Triassic Xujiahe Tight Sandstone in the Xiaoquan-Fenggu Structural Belt, Western Sichuan Depression, China

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Formation water represents an important driving force and carrier for the migration and accumulation of oil and gas; thus, research on its origin is a hot spot in petroleum geology. The Upper Triassic Xujiahe Formation in the Xiaoquan-Fenggu Structural Belt in the western Sichuan Depression, China, has developed thick tight sandstone gas reservoirs. However, previous studies have provided different conclusions on the origin of the formation water in the Xujiahe tight sandstone reservoir. In this paper, the origin of the formation water in the Xujiahe Formation was determined based on the latest major and minor elemental concentration data, hydrogen and oxygen isotopes data of formation water, and carbon and oxygen isotope data of carbonate cements. The results show that the salinity of the formation water of the Xujiahe Formation in the study area is generally greater than 50 g/L. The water type is mainly the $CaCl_2$ type, although a small proportion of $NaHCO_3$ type water with high salinity is observed, which is related to hydrocarbon expulsion by overpressure. Moreover, the formation water in the sandstone of the Xujiahe Formation is obviously rich in Br, which is related to membrane infiltration, overpressured hydrocarbon expulsion of shale and diagenesis of organic matter. The composition of Cl^- and Na^+ ions in the formation water in the Xujiahe tight sandstone reservoir is consistent with the seawater evaporation curve, which deviates significantly from the freshwater evaporation curve. The hydrogen and oxygen isotopes of condensate water in the Xujiahe Formation tight sandstone are similar to those of atmospheric precipitation water, while the hydrogen and oxygen isotopes of the formation water in the Xujiahe Formation show that it is of seawater origin. Therefore, to use hydrogen and oxygen isotopes to determine the origin of formation water, condensate water must be accurately differentiated from formation water. Otherwise, if the condensate water is misjudged as formation water, then incorrect conclusions will be drawn, e.g., that the formation water of the Xujiahe Formation originated from fresh water. Affected by organic carbon, the carbon isotope *Z* value of the carbonate cements in the Xujiahe Formation is low (mainly distributed between 110 and 130). A *Z* value of less than 120 does not indicate that the ancient water bodies formed by cements were fresh water or mixed water bodies. However, *Z* values greater than 120 correspond to a formation temperature lower than 80 C, which indicates that carbonate cement was not affected by organic carbon; thus, the *Z* value can reflect the origin of ancient water bodies. The results of this study indicate that the formation water of the Xujiahe tight sandstone in the study area is of seawater origin. The determination of the origin of the formation water and seawater of the Xujiahe Formation provides strong evidence for the determination of the marine sedimentary environment of the Xujiahe Formation in the study area, and can provide scientific guidance for the search for high-quality reservoirs.

Keywords: western sichuan depression, formation water chemistry, origin of formation waters, hydrogen and oxygen isotopes, carbonate cement, carbon and oxygen isotopes

INTRODUCTION

Formation water coexists with hydrocarbons underground in different forms and is an important driving force and carrier for hydrocarbon migration and accumulation. The Xujiahe Formation in the western Sichuan Depression contains abundant natural gas resources. However, considerable controversy remains over the origin of the formation water in the Xujiahe Formation (Lin and Pan, 1999; Wu et al., 2002; Yin et al., 2008; Wang et al., 2009; Shen et al., 2010). For example, some studies believe that the formation water of the Xujiahe Formation originated from a mixture of seawater and atmospheric precipitation based on hydrogen and oxygen isotope analyses of the formation water (Yin et al., 2008; Fan et al., 2020; Lin and Xiong, 1999). According to the analysis of the hydrogen and oxygen isotopes of the formation water, Shen et al. (2010) believes that the formation water of the Xujiahe Formation is mainly seawater, although a portion still retains the characteristics of atmospheric precipitation. From the perspective of sedimentation and tectonics, Wang et al. (2009) believed that the formation water of the Xu two member (From top to bottom, the Upper Triassic Xujiahe Formation developed the Xu five member (T_3x^5), Xu four member (T_3x^4), Xu three member (T_3x^3) and Xu two member (T_3x^2) in sequence) was originated from seawater and that the formation water of the Xu four member originated from atmospheric precipitation. Wu et al. (2002) used the Z value estimated by the carbon and oxygen isotopes of carbonate cement to distinguish the formation water of the Xu two member from seawater and the formation water of the Xu four member from seawater and freshwater. However, Zhou (2014) used the Z value and concluded that the formation water of the Xujiahe Formation originated from a mixed water body.

There are several reasons for the huge differences in the conclusions about the formation water genesis of the Xujiahe Formation in the western Sichuan Depression: 1) A single research method is used, such as hydrogen and oxygen isotopes or carbon and oxygen isotopes in carbonate cements, which increases the difficulty of guaranteeing the reliability of the conclusions (Li et al., 2020; Li, 2021; Lin and Pan, 2001; Yin et al., 2008; Shen et al., 2010; Wu et al., 2002; Zhou, 2014); 2) the influencing factors of hydrogen and oxygen isotopes in formation water have not been fully considered (e.g., not fully considering the effects of water-rock interactions, gas-water exchange, mixing, etc.) (Lin and Pan., 2001; Yin et al., 2008; Shen et al., 2010); 3) condensate water is not distinguished from formation water (Shen et al., 2010), which will lead to incorrect conclusions if condensate water is mistakenly used as formation water; and 4) directly using the Z value of carbonate cement as the basis for judging the origin of formation water is insufficient. For example, when the origin of the water body is directly determined based on a Z value greater than or less than 120, the influence of organic carbon on the carbon isotope of carbonate cement and the Z value cannot be considered (Wu et al., 2002). Moreover, previous studies on the origin of the formation water in the Xujiahe Formation in the study area did not fully consider the characteristics of the main ion content of the formation water. However, formation water will experience complex water-rock interactions, hydrocarbon generation, and mixing during and after deposition. Therefore, a large amount of original water body information is contained in the ion content.

The Western Sichuan Depression is a typical overpressure basin. The tight sandstones of the Xujiahe Formation are generally overpressured. There is no unified understanding of the cause of formation overpressure in the Xujiahe Formation (Leng et al., 2011; Wang P. et al., 2019). Generally, the overpressure of the formation is related to mechanical compaction, aquathermal pressuring, dehydration of clays, hydrocarbon generation, and cementation of the pore space (Wangen, 2001; Radwan et al., 2020; Santosh and Feng, 2020; Wang et al., 2020; Morozov et al., 2021). However, these factors will also affect the ion and salinity of the formation water, thereby affecting the identification of the origin of the formation water (Thyne et al., 2001; Lei et al., 2013; Zhao et al., 2020). In the existing study area, the formation water of Xujiahe Formation has not fully considered the influence of overpressure. In this paper,

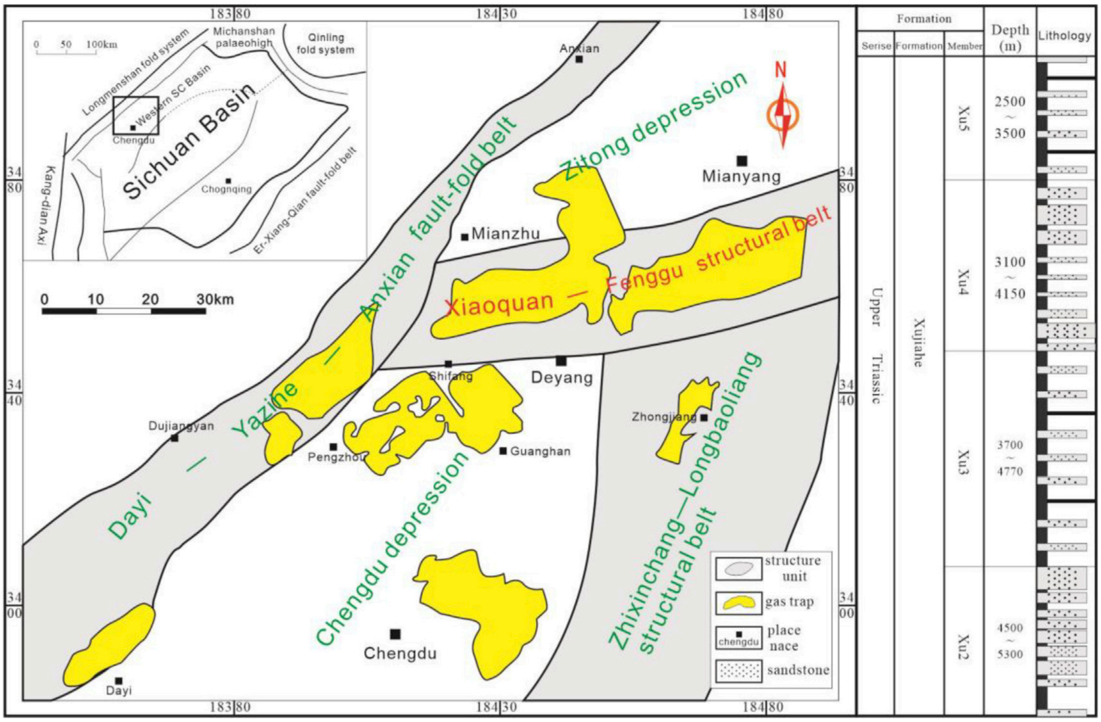

FIGURE 1 | Division of structural units and development of Xujiahe Formation in the middle part of the western Sichuan Depression.

we have conducted an in-depth discussion on the origin of the formation water in the Xujiahe Formation in the Xiaoquan-Fenggu Structural Belt in the western Sichuan Depression based on the latest formation water geochemical data.

GEOLOGICAL BACKGROUND

The western Sichuan Depression is located in the western part of the Sichuan Basin in China. It was developed based on the foreland basins in the western Sichuan Basin starting in the Late Triassic and represents the most developed area of continental natural gas in the Sichuan Basin (Xu et al., 2021). The western Sichuan Depression is a long strip zone extending in a NE-SW direction, and it is divided into north, middle, and south sections by the Mianzhu-Fenggu line and the Dayi-Chengdu line. The structural deformation strength increases from north to south, and the faults in the southern section are more developed. The middle section of the western Sichuan Depression is further divided into five structural belts (**Figure 1**): the Anxian-Yiaxian Fault Fold Belt, Zitong Sag, Xiaoquan-Fenggu Structural Belt, Zhixinchang-Longbaoliang Structural Belt, and Chengdu Depression. The study area is the Xiaoquan-Fenggu Structural Belt. The middle section of the Western Sichuan Depression is rich in natural gas resources, and two large gas fields with proven reserves greater than 300 × 108 m^3 have been discovered (Xinchang gas field and Luodai Gas Field); two medium-sized gas fields with proven reserves (100–300) × 108 m^3 have been discovered (Zhongba Gas Field and Xindu Gas Field); At the same time, more than ten gas-bearing structures such as Xiaoquan, Fenggu, and Majing have been developed.

The Upper Triassic Xujiahe Formation and continental Jurassic and Cretaceous deposits (continental deposits) in the study area are developed on the Middle Triassic marine sedimentary basement. The Jurassic and Cretaceous are terrestrial clastic deposits, but there are always disputes about the sedimentary environment of the Xujiahe Formation in marine, continental, and marine-continental transitional facies (Zhao and Zhang, 2011). Especially in recent years, more researches believe that the Xujiahe Formation is a marine deposit, and the dispute over the Xujiahe sedimentary environment has become a hot spot (Chen G. B. et al., 2021). In the Xujiahe Formation, the Xu three member, and Xu five member are dominated by shale while the Xu two member and Xu four member are dominated by tight sandstone reservoirs.

The Xujiahe Formation in the study area is an overpressured formation with a pressure coefficient ranging from 1.44 to 2.19. The reservoirs of the Xu4 member of the Xujia Formation show strong overpressure, with a pressure coefficient of 1.55–2.19, and an average pressure coefficient of 1.90; the pressure coefficient of the Xu2 member is slightly lower than that of the Xu4 member, with a pressure coefficient of 1.44–1.75 and an average pressure coefficient of 1.60 (Leng et al., 2011). There are controversies about the cause of overpressure in the Xujiahe Formation in the study area. Some researchers believe that it is the results of mechanical compaction and hydrocarbon generation (Leng et al., 2011), and some researchers believe that overpressure is

TABLE 1 | Statistics of the main ion content in the formation water of the Xujiahe Formation.

Formation	Cation concentration (g/L)				Anion concentration (g/L)		
	Na^+	Ca^{2+}	K^+	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}
T_3x^2	1.11~44.94 25.65 (198)	0.28~46.30 4.27 (198)	0.003~3.87 0.98 (198)	0.002~3.82 0.32 (198)	1.37~86.40 49.52 (198)	0.001~6.48 0.42 (198)	0.001~5.77 0.08 (198)
T_3x^4	2.34~46.37 20.53 (75)	0.02~14.02 4.55 (75)	0.05~4.31 0.58 (75)	0.01~1.04 0.37 (75)	3.59~84.67 40.84 (75)	0.001~1.46 0.34 (75)	0.001~1.37 0.08 (75)

The numbers above the underline represent the range of ion content; and the numbers under the underline represent the average value and the number of samples (in parentheses).

TABLE 2 | Major and trace element contents of the formation water from 28 samples in the Xujiahe Formation.

Sample	Formation	Ca^{2+}	Mg^{2+}	K^+	Na^+	HCO_3^-	Cl^-	SO_4^{2-}	Br^-	TDS
S1	T_3X^2	2,606.13	151.26	3,015.76	27,181.01	550.68	51,225.25	26.43	808.87	87.28
S2	T_3X^2	3,703.52	703.40	1,636.29	36,880.23	287.76	65,860.62	17.29	172.70	110.48
S3	T_3X^2	3,466.92	255.26	1,182.50	32,803.29	312.81	60,619.50	26.65	986.35	101.75
S4	T_3X^2	5,406.74	698.19	641.00	24,252.75	344.11	49,840.71	<10.00	667.11	84.10
S5	T_3X^2	9,973.00	225.00	1,138.12	44,935.63	228.00	85,563.52	<10.00	1844.25	145.31
S6	T_3X^2	7,108.00	183.00	849.00	38,152.14	972.00	70,281.78	<10.00	2,162.01	121.26
S7	T_3X^2	3,960.69	347.53	1,171.60	35,528.55	303.74	62,962.24	<10.00	922.90	106.38
S8	T_3X^2	6,572.21	187.00	662.00	35,110.78	388.00	68,065.63	<10.00	1,460.74	114.45
S9	T_3X^2	3,547.08	255.26	1,357.74	32,940.17	241.13	63,810.15	27.18	1,045.63	105.53
S10	T_3X^2	3,627.24	253.30	1,271.50	32,500.09	202.03	63,987.25	<10.00	1,010.56	105.00
S11	T_3X^2	6,408.02	583.06	1,579.80	36,917.70	516.20	69,432.77	<10.00	989.52	117.44
S12	T_3X^2	1938.36	146.00	1,203.19	29,017.10	551.20	64,375.51	<10.00	1,214.18	99.23
S13	T_3X^2	2,938.80	180.78	1,160.33	31,600.25	1,156.64	55,478.88	<10.00	1,135.63	94.53
S14	T_3X^2	7,773.01	3,820.02	876.27	34,246.10	416.06	75,193.13	61.89	1,573.25	126.39
S15	T_3X^2	95.10	10.20	136.52	3,060.81	633.81	4,170.28	<10.00	—	8.14
S16	T_3X^2	23.65	3.89	48.08	1,540.92	43.02	2,563.18	<10.00	—	4.22
S17	T_3X^2	323.09	6.72	54.30	2,324.31	215.00	4,162.78	<10.00	—	7.16
S18	T_3X^4	3,220.74	271.00	320.85	24,900.11	554.00	44,952.00	109.00	1,019.25	76.09
S19	T_3X^4	2,979.52	233.50	364.25	20,212.71	78.25	37,054.51	312.00	1,025.38	62.71
S20	T_3X^4	3,686.29	363.00	455.79	24,675.07	363.25	47,024.09	169.00	1,123.89	78.78
S21	T_3X^4	7,081.20	521.39	189.20	28,312.55	159.13	55,308.96	<10.00	1,201.06	95.07
S22	T_3X^4	4,348.34	406.00	394.31	24,548.57	314.26	47,945.77	118.00	1,057.71	80.13
S23	T_3X^4	3,914.48	824.18	268.50	29,225.83	191.84	41,378.4	94.66	453.50	77.41
S24	T_3X^4	3,837.51	15.51	799.22	26,864.38	79.57	51,754.55	25.52	1,019.96	88.41
S25	T_3X^4	2,217.49	82.47	1,073.25	23,684.59	309.61	50,625.63	<10.00	987.87	79.91
S26	T_3X^4	3,258.16	973.39	342.20	16,985.36	191.84	32,801.29	261.76	668.19	56.81
S27	T_3X^4	3,375.67	350.00	0.75	29,950.07	224.33	52,220.28	<10.00	788.74	88.72
S28	T_3X^4	378.15	397.18	315.25	21,315.91	124.15	39,175.88	<10.00	718.34	64.71

The S15, S16, and S17 samples are condensate water, and the other samples are formation water. All concentrations are given in mg/L except for TDS (g/L).

related to tectonic compression and mechanical compaction (Wang Z. et al., 2019). These studies have confirmed the important role of overpressure in the migration, accumulation and preservation of natural gas (Wang P. et al., 2019), especially the distribution of gas reservoirs is closely related to overpressure. The pressure relief zone next to the top interface of the overpressure bin is the most favorable enrichment zone for natural gas (Leng et al., 2011; Guo et al., 2020; Zhao et al., 2021).

DATABASES AND METHODS

To systematically study the geochemical characteristics of the formation water of the Xujiahe Formation in the study area, 273 groups of formation water data in the target layer were collected, including the main ion content (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}), salinity (TDS), pH value, etc. Among them, 198 groups were from the Xu two member and 75 groups were from the Xu four member. The main ion content test results are shown in **Table 1**.

In this paper, trace element tests were conducted on the formation water of the target layer. A total of 28 sets of formation water samples were obtained, including 17 sets from the Xu two member and 11 sets from the Xu four member. First, we tested the salinity and main ion content of 28 samples. The analysis of the salinity showed that three samples in the Xu two member had extremely low salinities at 4.22 g/L and 7.16 g/L and 8.14 g/L, respectively. According to the criterion of the water produced in the target layer, when the salinity of produced water was less than 10 g/L, it was considered condensate water, and when the salinity of produced water was greater than 10 g/L, it was considered formation water (Wang Z. et al., 2019). Therefore, the three low-salinity samples in the Xu two member were condensate water. The remaining 25 samples had high salinities at 56.18–145.31 g/L (**Table 2**), which were obviously formation water. Condensate water is the condensation of gaseous water in oil and gas reservoirs, and its major and trace elements cannot reflect the true information of formation water under burial conditions. Therefore, in this study, only 25 groups of formation waters with higher salinity were analyzed for trace elements. The testing work was completed by the Geological Laboratory of Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Field Branch. The test results of the samples are shown in **Table 2**.

Of the 25 formation water samples, 18 were selected for hydrogen and oxygen isotope testing. In addition, two out of three condensate water samples were selected for hydrogen and oxygen isotope testing, which were S15 and S16 respectively. A MAT-253 gas isotope mass spectrometer was used for the hydrogen and oxygen isotope analysis of 20 water samples. The test was completed at the Groundwater Mineral Water and Environmental Monitoring Center of the Ministry of Land and Resources of China. To explore the isotope relationship between formation water and atmospheric formation water in the study area, this study assessed 24 isotopic data samples for atmospheric formation water in the Sichuan Basin, of which 20 were from Lin and Pan (2001) and four were from Yin et al. (2008).

Based on the study of the occurrence state of carbonate cements and the symbiosis relationship of minerals under the analysis microscope, 17 sandstone samples from the Xu two member and 14 sandstone samples from the Xu four member were selected for the laser carbon and oxygen isotope test of the carbonate cements. The test was completed in the laboratory of Exploration and Development Research Institute of PetroChina Southwest Oil and Gas Branch. Under vacuum conditions, the coherent laser beam output by a helium-neon laser was focused by the microscope optical system (about 20 um) on the thin sample in the vacuum sample box, and the carbonate minerals in the delineated range of the thin sample were heated (the temperature exceeded 1,500 C), thereby producing CO_2. A gas isotope mass spectrometer (MAT-252) was used to determine the carbon and oxygen isotope values of CO_2. The isotope analysis results meet the PDB standard. The analysis accuracy of $\delta^{13}C$ and $\delta^{18}O$ was ±0.22‰(σ), and the spatial resolutions ranged between 20 and 50 um.

RESULTS

Formation Water Salinity

The 273 water salinity (TDS) produced by drilling in the Xujiahe Formation in the study area ranged from 0.048 g/L to 160.43 g/L. They include formation water and condensate water. Condensate water is the gaseous water in the gas reservoir, while the formation water is the liquid water body that actually exists in the formation. Formation water is in contact with oil and gas and reservoirs for a long time, so it can more accurately reflect the nature of the fluids inside the reservoir under geological conditions. This is also the reason why this study only studied the formation water of Xujiahe Formation with salinity greater than 10 g/L.

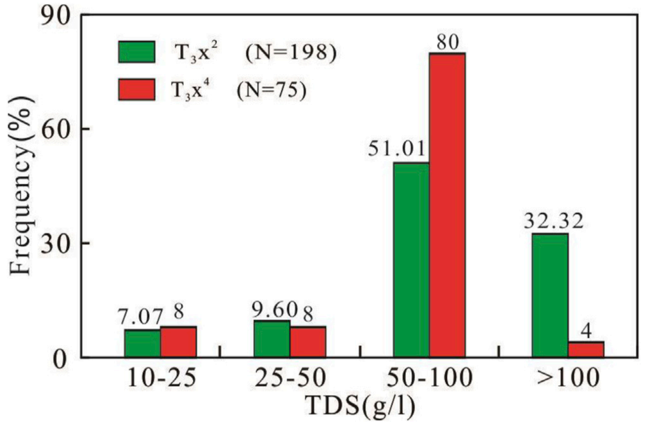

FIGURE 2 | Distribution characteristics of the formation water salinity of the Xujiahe Formation in the middle section of western Sichuan Depression.

The formation water salinity of the Xu two member ranges from 10.30 to 168.78 g/L, with an average of 85.63 g/L, and the formation water salinity of the Xu four member ranges from 10.78~162.63 g/L, with an average of 70.40 g/L. The formation water salinity of the Xujiahe Formation in the study area is usually greater than 50 g/L. Regardless of whether the sample is from the Xu two member or the Xu four member, the proportion of samples with a salinity higher than 50 g/L is greater than 83% (**Figure 2**). The proportion of samples with greater burial depth in the Xu two member with a salinity greater than 100 g/L is much higher than that of the Xu four member. **Figure 2** shows that the formation water salinity of the Xu four member is mainly distributed between 50 and 100 g/L. The salinity of formation water originating from the freshwater lake basin during the concentration process usually does not exceed the salinity of seawater (35 g/L). However, the formation water salinity of the Xujiahe Formation is generally much higher than that of seawater, indicating that the formation of the Xujiahe Formation water is more likely to originate from seawater.

Main Ion Characteristics

There are seven main kinds of the most common and high-content ions in formation water, namely, potassium ions (K^+), sodium ions (Na^+), calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), chloride ions (Cl^-), sulfate ions (SO_4^{2-}), and bicarbonate ions (HCO_3^-). These seven kinds of ions account for more than 90% of all dissolved salts, which are also the main research objects of this paper. From the statistical results of the main ion content of the Xujiahe Formation, the formation water cations of the Xu two and Xu four members are dominated by Na^+ and the anions are dominated by Cl^-. The contents of Na^+ and Cl^- are much higher than those of other ions. Moreover, the cation content satisfies $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ and the anion content satisfies $Cl^- > HCO_3^- > SO_4^{2-}$.

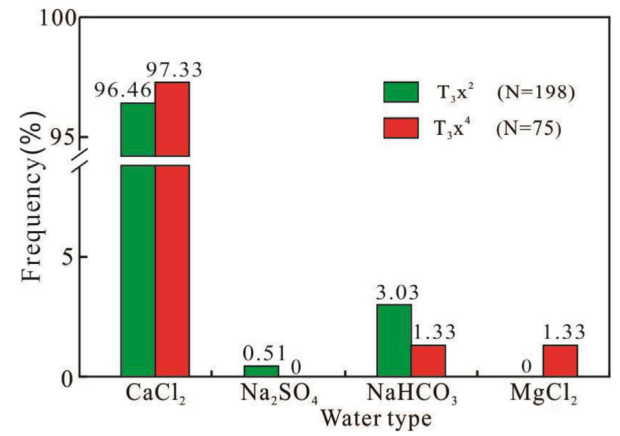

FIGURE 3 | Distribution characteristics of the formation water types of the Xujiahe Formation in the middle section of the western Sichuan Depression.

Formation Water Type

Figure 3 shows the classification of the formation water types in the study area according to the Surin formation water classification standards. The results show that $CaCl_2$-type water is the main type of Xu two and Xu four members, and a small amount of high salinity $NaHCO_3$-type water exists in the Xu two member. $CaCl_2$-type water shows that the formation has good sealing conditions, which is beneficial to the preservation of oil and gas. This result is consistent with the rich oil and gas resources of the Xujiahe Formation in the study area. The origin of high salinity $NaHCO_3$-type water can be summarized according to the following factors: 1) entrance of deep inorganic CO_2 into formation water; 2) the desulfurization effect; 3) dissolution of carbonate; 4) atmospheric water leaching; and 5) hydrocarbon expulsion under overpressure.

1) Deep inorganic CO_2, desulfurization, atmospheric water leaching and $NaHCO_3$-type water

Wang et al. (2013) studied the rare gas content and isotopes of He, Ne, and Ar in the tight sandstone gas of the Upper Triassic Xujiahe Formation in the western Sichuan Depression and confirmed that the Upper Triassic stratigraphic fluid in this area has no contribution from deep and mantle-derived materials. Therefore, the possibility of deep inorganic CO_2 entering the formation water to form $NaHCO_3$-type water can be denied.

Desulfurization and $NaHCO_3$ type water. In a closed reduction environment, the reduction of sulfate will produce HCO_3^-, which in turn will form $NaHCO_3$-type water with high salinity (Tan et al., 2012). The Xu two member of the study area lacks sulfate components; therefore, the formation of $NaHCO_3$-type water is less likely to be caused by sulfate reduction.

The dissolution of carbonate minerals can form HCO_3^- ions, so $NaHCO_3$ type water can also be seen in carbonate formations. However, the Xu2 member of the study area is composed of clastic rock deposits. In addition, the clastic particles are mainly quartz and feldspar, and the rock fragments are mainly composed of silt sand, with only a small amount of carbonate debris (Hu et al., 2006). The HCO_3^- ions formed by the dissolution of carbonate cuttings are very limited. Therefore, it is unlikely that the carbonate in the Xu2 member will dissolve to form $NaHCO_3$ type water.

Atmospheric water leaching and $NaHCO_3$ type water. In the shallow alternating zone of strong free water, the leaching of atmospheric water can also form $NaHCO_3$ water (Zhang et al., 2009); however, this type of $NaHCO_3$ water is usually low in salinity (TDS less than 15 g/L). However, the $NaHCO_3$-type water of the Xu two member has high salinity (30.66–69.53 mg/L) and a large burial depth (>4 500 m). Good sealing decreases the likelihood of leaching by atmospheric water. Overall, the formation of $NaHCO_3$-type water in the Xu two Formation of the study area is most directly related to the entry of organic origin CO_2 into the formation water.

2) Hydrocarbon expulsion under overpressure and $NaHCO_3$-type water

Generally, during the hydrocarbon generation process of source rocks, solid kerogen will be converted into liquid hydrocarbons, gases, and residues. Its volume expansion can reach 25%, which will cause internal overpressure. The overpressure inside the source rock allows the generated oil and gas to enter the reservoir through micropores or microfractures to achieve initial hydrocarbon migration. In the process of hydrocarbon generation, in addition to the formation of hydrocarbons, CO_2 and other materials are also generated. The generated CO_2 and hydrocarbons and other materials will enter the reservoir through the first migration under the action of overpressure. After entering the reservoir, CO_2 dissolves in the formation water and can form high-salinity $NaHCO_3$-type formation water. In many areas of China, this type of formation water has been found and appears to have good oil-bearing properties (Zhang et al., 2009). The six groups of $NaHCO_3$-type water in the second member of the study area came from Wells CG561, X3, X856, X851, CF63 and X10. The six wells all showed high natural gas production capacity (**Table 3**), which shows that the high salinity $NaHCO_3$ type water in the study area can also be a good indicator of oil and gas. Moreover, it has been further confirmed that high-salinity $NaHCO_3$-type water is related to the overpressure hydrocarbon expulsion of the source rock.

Gas Field Water Chemical Parameters

The gas field water chemical parameters can effectively reflect the sealing performance of the formation (Zhang D. J. et al., 2021); therefore, they are widely used in the study of oil and gas preservation conditions.

1) Sodium chlorine coefficient (rNa/rCl) [rNa/rCl coefficient]

If the sodium chloride coefficient of the formation water is less than 0.85, then the oil and gas preservation conditions are good,

TABLE 3 | Productivity of gas wells producing $NaHCO_3$-type water in the Xu two member.

Well name	Depth (m)	Test result (square/day)		
		Natural gas production	Water production	Open flow
CG561	4,932.45	26 900	—	27 581
X3	4,968.50	230 800	1.04	—
X856	4,838.20	585 300	3.34	—
X851	4,989.46	380 000	—	1,514 000
CF563	4,583.395	42 561	—	42879
X10	4,959.46	103 300	1.15	—

TABLE 4 | Statistics of the formation water chemical parameter results of the Xujiahe Formation in the study area.

Parameter	Minimum value	Maximum value	Average (number of samples)
rNa/rCl	0.03	0.80	0.27 (273)
$100\times rSO_4^{2-}/rCl^-$	0.01	2.65	0.28 (273)
rCl^-/rMg^{2+}	10.19	646.27	151.75 (273)
$(rCl^- - rNa)/rMg^{2+}$	7.50	550.71	109.08 (273)

and if the sodium chloride system is greater than 0.85, then the formation is significantly affected by infiltration water and the oil and gas preservation conditions are poor (Zeng et al., 2008). The sodium chloride coefficient of the formation water in the Xujiahe Formation in the study area is between 0.03 and 0.80, with an average value of 0.27 (**Table 4**), which fully indicates that the Xujiahe Formation has good oil and gas preservation conditions.

2) Desulfurization coefficient ($100\times rSO_4^{2-}/rCl^-$)

Under the closed condition of nonsulfate formations, the desulfurization coefficient is generally less than 3. If the desulfurization coefficient is greater than 3, then the formation sealing is worsened, which indicates that the water may be affected by the oxidation of the superficial formations (Zeng et al., 2008). The desulfurization coefficient of the formation water in the Xujiahe Formation in the study area is between 0.01 and 2.65, with an average value of 0.28 (**Table 4**), which indicates that the Xujiahe Formation has good sealing properties.

3) Magnesium chloride coefficient (rCl^-/rMg^{2+})[$rCl-/rMg^{2+}$ coefficient]

The larger the magnesium chloride coefficient, the better the sealing of the formation and the more conducive it is to the accumulation and preservation of oil and gas. Previous studies have found that the value of the chloride-magnesium coefficient of the formation water in gas-bearing areas is generally greater than 5 (Zeng et al., 2008). The chloride-magnesium coefficient of the formation water of the Xujiahe Formation in the study area is between 10.19 and 646.27, with an average value of 151.75 (**Table 4**), indicating that the Xujiahe Formation has good sealing properties.

4) Deterioration coefficient ($(rCl-rNa)/rMg^{2+}$)

The greater the metamorphic coefficient is, the better the stratum sealing. When the metamorphic coefficient is less than 0, the sealing condition of the formation water may be destroyed, and the formation water is affected by atmospheric precipitation (Zeng et al., 2008). **Table 4** shows that the metamorphic coefficient of the formation water in the Xujiahe Formation in the study area is between 7.50 and 550.71, with an average value of 109.08, indicating good sealing properties of the formation.

ANALYSIS OF THE ORIGIN OF THE FORMATION WATER

Analysis of Water Chemical Composition

The chemical composition of the current formation water is the result of the original formation water body, the later external water body and various physical and chemical effects. It is generally known that the chemical composition of formation water of different origins is obviously different. For formation water originating from seawater, its main ion characteristics conform to the change law of the seawater evaporation trajectory (SET) (Carpenter, 1978; Kharaka and Hanor., 2003; Birkle et al., 2013; Chen H. et al., 2021). However, the main ion characteristics of the formation water originating from atmospheric precipitation are consistent with the Freshwater Evaporation Trajectory (FET) curve (Lou, 1998). Therefore, according to the chemical composition of the formation water and the trend of the evaporation curve of different water bodies, the origin of the formation water, water-rock interactions, and the mixing effects can be effectively reflected.

1) Br-Cl and Br-Na

In the process of water evaporation and concentration, Br-associated dissolution and precipitation of minerals are very

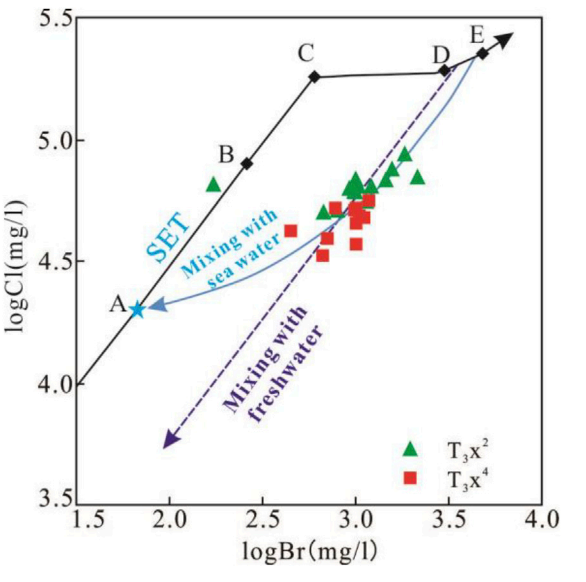

FIGURE 4 | Relationship between the logBr-logCl and SET of the formation water of the Xujiahe Formation in the middle part of the western Sichuan Depression. Notes: SET and the positions of points A, B, C, D, and E refer to Carpenter (1978). SET is the seawater evaporation curve. Point A represents normal seawater, point B represents the beginning of precipitation of gypsum, point C represents the beginning of precipitation of salt rock, point D represents the beginning of precipitation of magnesium sulfate, and point E represents the beginning of precipitation of potassium salt.

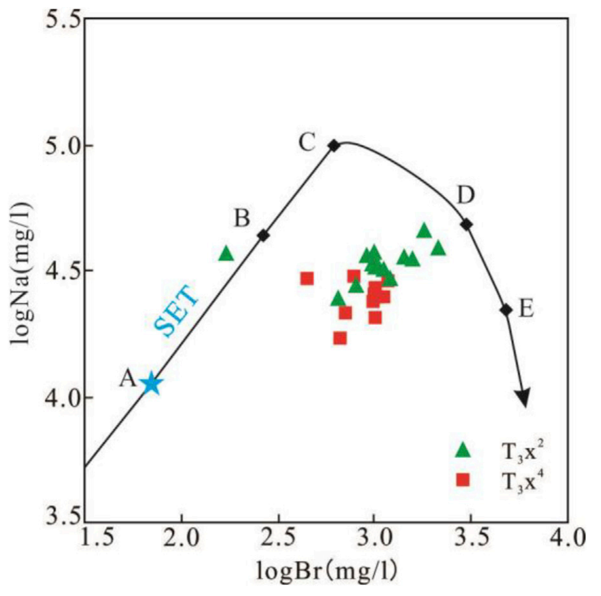

FIGURE 5 | Relationship between the logBr-logNa and SET of the formation water in the middle section of the western Sichuan Depression. Notes: SET and the positions of points A, B, C, D, and E refer to Carpenter (1978). The meanings of points A, B, C, D, and E are the same as in **Figure 4**.

limited compared to that of other components. However, the change characteristics of Br during the process of dilution, evaporation and mixing of the original water body are more obvious than those of other components; therefore, Br is easier to identify (Carpenter, 1978). Therefore, the origin of the formation water can be judged according to the characteristics of the seawater evaporation curve of Br- and other ions. In addition, compared with other major ions, Na^+ and Cl^- have the highest content in formation water; therefore, they involve relatively fewer water-rock effects and are more sensitive to the process of seawater evaporation. Therefore, the Br-Cl and Br-Na characteristics of the formation water combined with the evaporation curve of the water body are often used to reflect the origin of the formation water and the water-rock interaction.

From the logBr–logCl (**Figure 4**) and logBr–logNa (**Figure 5**) relationships, the formation water clearly deviates from the seawater evaporation curve, and its main body is located at the lower part of the seawater evaporation curve. If the Br content is used to trace the degree of evaporation of the formation water, then the main part of the formation water in the study area shown in **Figure 4** and **Figure 5** is seawater with high evaporation intensity. The main body of seawater concentrated by strong evaporation has reached the stage of salt rock precipitation (point C on SET). The formation water located in the lower part of the seawater evaporation curve (SET) in **Figure 4** is the result of the intense evaporation and concentration of high-salinity seawater being diluted by relatively low-salinity seawater or freshwater (Carpenter, 1978; Birkle et al., 2013; Zhang L. et al., 2021; Xue et al., 2021). The Br-Cl test results in **Figure 4** conform to the rule that the residual seawater from strong evaporation is diluted (or mixed) by the later low-salinity water. The residual seawater before mixing has reached the precipitation stage of magnesium sulfate (point D on SET), and the degree of evaporation and concentration of seawater is very high.

However, from the perspective of paleoclimate and paleoenvironment in the study area, it is impossible for the formation water of the Xujiahe Formation to reach such a high degree of evaporation because the mineral content in the formation does not support such a strong evaporation environment. A large number of studies have shown that the Sichuan Basin was a warm and humid tropical and subtropical environment during the Xujiahe Formation deposition period (Xu et al., 2011). During this period, the water body was in a weak evaporation environment, the evaporation concentration of the formation water was low, and it was impossible to realize the precipitation of a large amount of salt rock and magnesium sulfate. Salt rocks and sulfate minerals are not developed in the Xujiahe Formation, which indirectly indicates that the degree of evaporation of seawater in the study area is relatively low. On the other hand, the Leikoupo Formation underlying the Xujiahe Formation is a limited-evaporation platform sedimentary facies (Li et al., 2012), and its evaporation intensity is much higher than that of the Xujiahe Formation. However, even in the Leikoupo Formation, only gypsum or salt rocks are seen in evaporites. Therefore, it is impossible to form strong evaporative magnesium sulfate precipitation in the formation water of the Xujiahe Formation with low evaporation intensity.

To characterize the degree of seawater evaporation and concentration based on the Na and Cl contents, **Figures 4**, **5** show that the formation water Na and Cl of the Xujiahe Formation are distributed in the AB section of the seawater evaporation curve and the low evaporative concentration stage. This result is consistent with the paleoclimate, paleoenvironment and mineral characteristics of the Xujiahe Formation in the study area. Compared with the Na and Cl ion contents distributed in the A-B section of the seawater evaporation curve, the formation water of the Xujiahe Formation in the study area shows obvious Br-enrichment characteristics (**Figure 4**, **Figure 5**). The enrichment of Br in formation water is mainly related to evaporative concentration or the supply of organic matter sources (Edmunds, 1996). If the enrichment of Br is caused by strong evaporation, then the characteristics of the Br ion change should be consistent with the evaporation curve (Carpenter, 1978). Obviously, the enrichment of Br in the formation water of the study area is not the result of strong evaporative concentration.

2)Enrichment of Br in formation water caused by overpressure

The enrichment of Br in formation water is mainly related to the membrane infiltration and overpressured hydrocarbon expulsion of shale and diagenesis of organic matter. For the enrichment of Br caused by evaporation, the change in Br ions should be consistent with the evaporation curve (Carpenter, 1978; Birkle et al., 2013; Ji et al., 2021). Obviously, the Br enrichment of the formation water in the study area is not the result of evaporation.

The membrane infiltration and organic diagenesis of overpressured shale enrich Br in the formation water. The overpressured shale has a membrane percolation effect, which can make ions with a smaller radius pass through the semipermeable shale water film so that the residual fluid in the overpressured shale can be enriched with Ca, Br, and Cl. The Upper Triassic Xujiahe Formation Xu 1, Xu 3, and Xu five members mainly develop organic-rich shale. Undercompaction of shale during the deposition process will inevitably lead to overpressure. Previous research indicated that the Xujiahe Formation shale in the western Sichuan Depression was in a state of sedimentary overpressure as early as the middle of the Xujiahe Formation deposition (Leng et al., 2011). Then, the sedimentary overpressure of the shale of the Xujiahe Formation continued until the end of the Late Cretaceous. Therefore, long-term sustained overpressure facilitated the enrichment of Br in the shale of the Xujiahe Formation. At the same time, the organic matter in shale is rich in Br, and the release of Br into the formation water during the diagenesis process will significantly enrich the formation water in Br (Edmunds, 1996; Shen et al., 2010). The shale of the Xujiahe Formation in the study area is rich in organic matter. Therefore, both the membrane percolation of the overpressure shale in the early stage and the diagenesis of the rich organic matter in the shale will lead to the enrichment of Br in the formation water in the shale of the Xujiahe Formation.

The overpressure hydrocarbon expulsion of shale causes the enrichment of Br in sandstone formation water. Under the effect of shale overpressure and hydrocarbon expulsion, Br, which is enriched in shale formation water, enters the Xujiahe Formation sandstone through channels such as micropores and microcracks formed by overpressure. As a result, the formation water of the sandstone layers of the second and fourth members of Xu in the study area show abnormal Br enrichment (**Figure 4** and **Figure 5**). This finding indicates that Br cannot be used to effectively trace the origin of the formation water in the Xujiahe Formation.

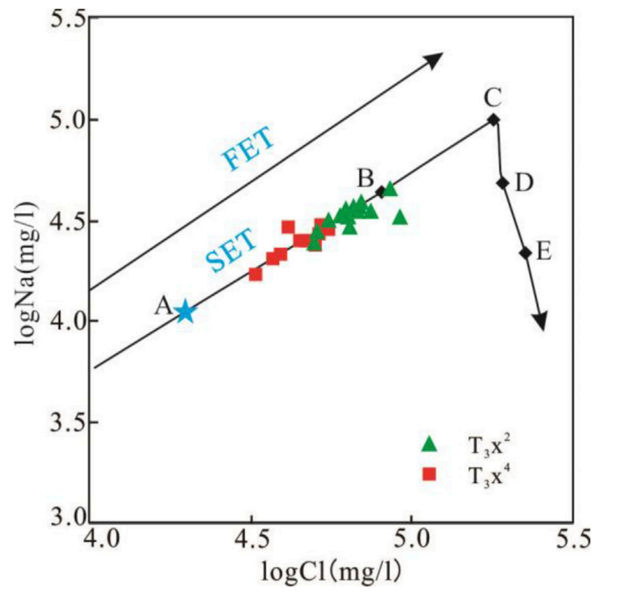

FIGURE 6 | Relationship between the logCl-logNa and SET and FET of the formation water of the Xujiahe Formation in the middle part of the western Sichuan Depression. Notes: SET and the positions of points A, B, C, D, and E refer to Carpenter (1978). The meanings of points A, B, C, D, and E are the same as in **Figure 4**.

3) Cl-Na

Cl and Br have many similar physical and chemical properties. A previously conducted seawater evaporation experiment showed that the content of Cl will always increase during the evaporation process, which is similar to Br (Carpenter, 1978). At the same time, Cl is the component with the highest content in formation water, and it is less affected by organic matter than Br and Cl. Therefore, the seawater evaporation curve of Cl is often used to analyze the formation and evolution of the formation water (Contia et al., 2000). Based on the relationship between Cl and Na (**Figure 6**), the characteristics of Cl and Na in the formation water of the Xujiahe Formation are consistent with the seawater evaporation curve.

All data points of the Xujiahe Formation are concentrated on the seawater evaporation curve, which fully shows that the formation water of the Xujiahe Formation has obvious seawater characteristics. Compared with the Xu two member, the Xu four member is closer to the sea point, which may be mainly related to its lower contents of Na^+ and Cl^- (**Table 2**). In the later geological process, salt rock dissolution has the greatest impact on the Na^+ and Cl^- contents. A large number of studies

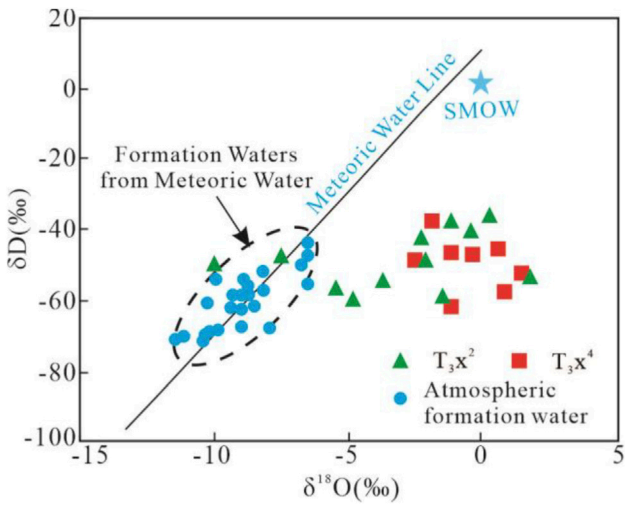

FIGURE 7 | Hydrogen and oxygen isotope characteristics of the formation water and atmospheric precipitation in the Xujiahe Formation in the middle part of the western Sichuan Depression.

have confirmed that the dissolution of salt rock will cause the data points to be distributed in the upper part of the seawater evaporation curve (Contia et al., 2000; Birkle et al., 2013; Lan et al., 2021). The distribution of Na+ and Cl-contents in formation water (**Figure 6**) indicates that they are not affected by the dissolution of salt rock, which is also related to the lack of salt rocks in the Xujiahe Formation and its upper strata in the study area. Therefore, the characteristics of Na^+ and Cl^- ions indicate that the formation water of the Xujiahe Formation originated from seawater.

Another view posits that the formation water of the Xujiahe Formation originated from fresh water (Wu et al., 2002; Wang et al., 2009; Zhou, 2014). Generally, the ion content characteristics of formation water originating from fresh water are usually consistent with the fresh water evaporation curve. The evaporation curve of Baiyangdian Lake in China is the commonly used reference standard for the evaporation and concentration of fresh water (Lou, 1998). In this study, the Baiyang Lake water evaporation curve was selected as the fresh water evaporation curve (FET) to analyze the relationship between formation water in the Xujiahe Formation and fresh water. The results show that the formation water of the Xujiahe Formation deviates significantly from the continental freshwater evaporation curve (**Figure 6**), which shows that there is no correlation between them. This conclusion also further demonstrates that the formation water of the Xujiahe Formation in the study area originated from seawater.

Analysis of the Hydrogen and Oxygen Isotope Characteristics of the Formation Water

Different sources of water have different hydrogen and oxygen isotopic compositions, and later water-rock interactions and gas-water exchange will also have a certain impact on the hydrogen and oxygen isotopes of the formation water (Kharaka and Hanor, 2003; Birkle et al., 2013; Lan et al., 2021; Nicula et al., 2021; Yang et al., 2021). Therefore, the hydrogen and oxygen isotopes of water bodies have become the most useful tools for studying the origin and evolution of the formation water. To better reflect the cause of the formation water in the Xujiahe Formation in the study area, in this study, we used previously reported formation water data on the origin of atmospheric precipitation in the Sichuan Basin (Lin and Pan, 2001; Yin et al., 2008). These data are distributed in the dotted ellipse area in **Figure 7**.

Regarding the hydrogen and oxygen isotope data of the formation water in the Xujiahe Formation in the study area, there are two sets of samples located within the range of atmospheric precipitation origin in the Sichuan Basin. However, this does not mean that part of the formation water in the study area originated from atmospheric precipitation. These two groups of samples are all condensate water samples, which are S15 and S16. Condensate water is gaseous water in gas reservoirs, and its ion content, salinity, and hydrogen and oxygen isotopes are essentially different; thus, they cannot reflect the geochemical characteristics and origin of the formation water. Therefore, these two groups of condensate water samples do not indicate that the formation water of the Xujiahe Formation in the study area originated from atmospheric precipitation. In the study of hydrogen and oxygen isotopes of the formation water, it is necessary to correctly distinguish between formation water and condensate water. Otherwise, if condensate water is studied as formation water, incorrect conclusions will be obtained (Shen et al., 2010).

The hydrogen and oxygen isotope values of the formation water caused by atmospheric precipitation are usually distributed near atmospheric precipitation or near a trend line that intersects with the atmospheric precipitation line (Kharaka and Hanor, 2003; Birkle et al., 2013). The formation water of the Xujiahe Formation in the study area is far from atmospheric precipitation. Moreover, the hydrogen and oxygen isotopes of the formation water have no obvious tendency to intersect the atmospheric precipitation line regardless of the Xu two or Xu four members. Therefore, the formation water of the Xujiahe Formation in the study area is unlikely to originate from atmospheric precipitation.

Water-rock interactions are also an important factor affecting the isotopes of formation water. Water-rock interactions will increase the oxygen isotopes of formation water, which is generally known as the positive drift of oxygen isotopes (Yin et al., 2008; Birkle et al., 2013). However, the positive drift characteristics of oxygen isotopes in the formation water of the Xujiahe Formation in the study area do not indicate that it originated from atmospheric precipitation. Water-rock interactions usually only increase oxygen isotopes and generally do not affect hydrogen isotopes (Kharaka and Hanor, 2003; Birkle et al., 2013; Jia et al., 2021). However, the difference in hydrogen isotopes in the formation water of the Xu two and Xu four members in the study area is relatively large. In addition, although water-rock interactions are the most important factor in formation water oxygen isotope drift, not all water-rock interactions can cause oxygen isotope drift. The water-rock interaction that can produce obvious oxygen isotope drift is mainly the diagenetic reaction related to carbonate minerals and clay minerals

(Kharaka and Hanor, 2003), especially carbonate minerals. In carbonate formations, strong water-rock interactions can increase oxygen isotopes by up to 10‰ (Birkle et al., 2013), while in clastic rock formations, water-rock interactions have relatively little effect on oxygen isotopes (Shi et al., 2012). Compared with the atmospheric precipitation line, the increase in the oxygen isotope value of the Xujiahe Formation is generally between five‰ and 10‰. It is difficult to achieve such a high oxygen isotope increase in the clastic strata of the Xujiahe Formation. Therefore, water-rock interactions cannot explain the origin of the formation water of the Xujiahe Formation in the study area from atmospheric precipitation.

Studies in the Gulf of Mexico Basin indicate that the clastic rock formation water in the basin originated from seawater. The typical characteristics of the hydrogen and oxygen isotopes of the formation water in these formations are as follows (Kharaka and Hanor, 2003): far away from the atmospheric precipitation line; a relatively similar oxygen isotope composition with seawater; and lower hydrogen isotope values than seawater, with the minimum reaching -70‰. The hydrogen isotopes of the formation water in the Xujiahe Formation in the study area range from -40‰ to -70‰, all of which are less than the hydrogen isotope value of seawater 0. Except for three samples in the Xu two member, which have low oxygen isotope values (approximately 5‰), the oxygen isotopes of the formation water of the Xu two and Xu four members are distributed between -2 and 2‰, which is similar to the oxygen isotopes of seawater. Since the test data are relatively close to the oxygen isotope value of seawater (0), the formation water originated from seawater.

There are three groups of samples with low oxygen isotopes in Xu two member, and they are distributed between atmospheric precipitation and seawater origin. This feature is consistent with the hydrogen and oxygen isotope properties of mixed water. However, further studies have confirmed that this feature is not the result of a mixed effect, and a mixing experiment of sea water and fresh water showed that the hydrogen and oxygen isotopes will change simultaneously during the mixing process, with the hydrogen isotope variation at approximately 3.7 times that of the oxygen isotope (Lin and Pan, 2001). Obviously, the low oxygen isotopes of these three groups of samples are not the result of mixing. Compared with other formation water samples of the Xu two member, these three samples all show light oxygen isotopes (approximately 2%). The exchange of oxygen isotopes between CO_2 and water under formation conditions will cause a negative drift in oxygen isotopes (Wu et al., 2002). The previous discussion has shown that CO_2 enters the high-salinity $NaHCO_3$ formation water of the Xu two member. Therefore, the three groups of the formation water samples with slightly lower oxygen isotopes should be the result of CO_2 entering the formation water and its exchange with water isotopes rather than the result of mixing between seawater and atmospheric precipitation.

Analysis of the Carbon and Oxygen Isotope Characteristics of Carbonate Cement

The use of carbon and oxygen isotopes of carbonate cements to calculate the paleosalinity Z value of water ($Z = 2.048\times(\delta^{13}C + 50)+0.498\times(\delta^{18}O+50)$ is an important basis for judging the origin of ancient water bodies (Keith and Weber, 1964). This method is widely used in the analysis of the formation environment of carbonate rocks (dolomite, limestone) and the identification of water properties in clastic rocks (Narayanan et al., 2007; Hofer et al., 2013). Generally, the Z value of marine carbonate minerals is greater than 120, the Z value of carbonate minerals of freshwater origin is less than 120, and the Z value of mixed water bodies is mainly distributed between 115 and 120 (Narayanan et al., 2007; Hofer et al., 2013). However, a large number of studies have confirmed that organic carbon will enter the formation water during the hydrocarbon generation process, which will cause the carbon isotopes of carbonate cement to be lighter. However, the source rocks of the Xujiahe Formation in the study area are well developed, and carbonate cements are susceptible to the influence of organic carbon (Liu et al., 2014). Obviously, if the Z value is used to determine the origin of ancient water bodies, then it is necessary to first determine whether carbonate cement is affected by organic carbon. This may also be the reason why different formation water origins can be obtained using the Z value.

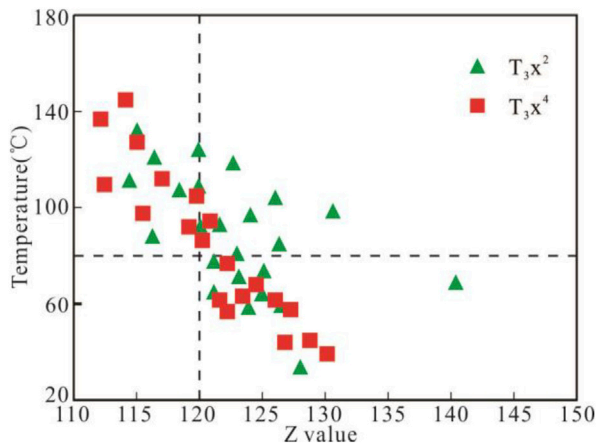

FIGURE 8 | Relationship between the *Z* value of carbonate cement and temperature in the target layer.

The coal-measure source rocks of the Xujiahe Formation in the western Sichuan Depression generally enter the hydrocarbon generation threshold at approximately 80 C (Wang et al., 2016). Therefore, for carbonate cements formed at a temperature higher than this temperature, the Z value may be lower due to the influence of organic carbon. The Z value of carbonate cement formed below 80 C can better represent the salinity of ancient fluids and the origin of water bodies.

The oxygen isotope of carbonate cement is closely related to temperature and represents an important paleotemperature calculation tool ($T = 16.9–4.38\ (\delta^{18}OC-\delta^{18}OW) + 0.10\ (\delta^{18}OC-\delta^{18}OW)^2$) (Shackleton, 1974). Therefore, the formation temperature of carbonate cement can be determined using the oxygen isotope value. **Figure 8** shows that the Z values of the carbonate cements in the Xujiahe Formation in the study are mainly distributed between 110 and 130. For samples with a Z value less than 120, the formation temperature is 80–150 C. If the

Z value reflects that the water body originally formed is atmospheric precipitation, then at least some samples with a formation temperature below 80 C will have a Z value less than 120. However, the Z values of samples with formation temperatures below 80 C are all greater than 120. When the paleogeographic temperature is 80–150 C, the Xujiahe Formation burial depth is between 1,500 and 4,000 m. These strata are unlikely to be affected by atmospheric precipitation. Therefore, samples with a low Z value formed at a temperature higher than 80 C do not reflect that the sedimentary ancient water bodies are freshwater. The lower Z value is mainly related to the lighter carbon isotope of carbonate cement caused by organic carbon. For samples with formation temperatures below 80 C, because they are less affected by organic carbon, they are more representative of the environment in which they are formed. The Z values of these samples are all greater than 120, which fully indicates that these carbonate cement deposits are seawater; that is, the ancient water bodies of the Xujiahe Formation originated from seawater. Obviously, to determine the origin of the Xujiahe Formation, it is necessary to first distinguish whether carbonate cement is affected by organic carbon.

CONCLUSION

1) In this paper, the origin of the formation water in the Xujiahe Formation was determined based on the latest formation water geochemical data. The results show that the salinity of the formation water of the Xujiahe Formation in the study area is generally greater than 50 g/L. The water type is mainly the $CaCl_2$ type, although a small proportion of $NaHCO_3$ type water with high salinity is observed, which is related to hydrocarbon expulsion by overpressure. Moreover, the formation water in the sandstone of the Xujiahe Formation is obviously rich in Br, which is related to membrane infiltration, overpressured hydrocarbon expulsion of shale and diagenesis of organic matter.
2) The composition of Cl^- and Na^+ ions in the formation water in tight sandstone is consistent with the seawater evaporation curve, which deviates significantly from the freshwater evaporation curve. The hydrogen and oxygen isotopes of condensate water in the Xujiahe Formation tight sandstone are similar to those of atmospheric precipitation water, while the hydrogen and oxygen isotopes of the formation water in the Xujiahe Formation show that it is of seawater origin. Therefore, to use hydrogen and oxygen isotopes to determine the origin of formation water, condensate water must be accurately differentiated from formation water. Otherwise, if the condensate water is misjudged as formation water, then incorrect conclusions will be drawn, e.g., that the formation water of the Xujiahe Formation originated from fresh water.
3) Affected by organic carbon, the carbon isotope *Z* value of the carbonate cements in the Xujiahe Formation is low (mainly distributed between 110 and 130). A *Z* value of less than 120 does not indicate that the ancient water bodies formed by cements were fresh water or mixed water bodies. However, *Z* values greater than 120 correspond to a formation temperature lower than 80 C, which indicates that carbonate cement was not affected by organic carbon; thus, the *Z* value can reflect the origin of ancient water bodies. The results of this study indicate that the formation water of the Xujiahe tight sandstone in the study area is of seawater origin.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary files, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

PW and SY contribute method and writting of this paper. ZS, TZ and WZ contribute experiments of this paper.

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