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## Evaluation of reservoir environment by chemical properties of reservoir water—A case study of Chang 6 reservoir in Ansai oilfield, Ordos Basin, China

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### ABSTRACT

The Ordos Basin is the largest continental multi-energy mineral basin in China, which is rich in coal, oil and gas, and uranium resources. The exploitation of mineral resources is closely related to reservoir water. The chemical properties of reservoir water are very important for reservoir evaluation and are significant indicators of the sealing of reservoir oil and gas resources. Therefore, the caprock of the Chang 6 reservoir in the Yanchang Formation was evaluated. The authors tested and analyzed the chemical characteristics of water samples selected from 30 wells in the Chang 6 reservoir of Ansai Oilfield in the Ordos Basin. The results show that the Chang 6 reservoir water in Ansai Oilfield is dominated by calcium-chloride water type with a sodium chloride coefficient of generally less than 0.5. The chloride magnesium coefficients are between 33.7 and 925.5, most of which are greater than 200. The desulfurization coefficients range from 0.21 to 13.4, with an average of 2.227. The carbonate balance coefficients are mainly concentrated below 0.01, with an average of 0.008. The calcium and magnesium coefficients are between 0.08 and 0.003, with an average of 0.01. Combined with the characteristics of the four-corner layout of the reservoir water, the above results show that the graphics are basically consistent. The study indicates that the Chang 6 reservoir in Ansai Oilfield in the Ordos Basin is a favorable block for oil and gas storage with good sealing properties, great preservation conditions of oil and gas, and high pore connectivity.

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### 1. Introduction

Research on the chemical properties of reservoir water is extremely important for evaluating and predicting oil and gas reservoirs. In a reservoir fluid system, reservoir water is indispensable. Mainly stored in pores and fractures, reservoir water is an important part of oil and gas and the main power source for the migration and accumulation of oil. Different from other water, reservoir water is closely related to the formation of oil and gas accumulations and the paleoclimate

and sedimentary environment of accumulations (Liu GD and Zhang HF, 2009). Recently, increasing global attention has been paid to the chemical information of produced water. In 2011, Schlumberger showed that the nature of oilfield water contained rich information and could significantly affect the economic benefits of oilfields (Abdou M et al., 2011). The different pH of oilfield water can significantly corrode and damage the drilling and production equipments (Jones T et al., 2006; Vazquez O et al., 2015). For example, ions in produced water from four Cretaceous oilfields in the North Sea of Denmark are related to corrosion and scaling (Sofie N et al., 2020). In addition, the composition of oilfield water varies in different oilfields and also varies greatly within the same oilfield, and the interaction is complex, impeding the development of oilfields (Vazquez O et al., 2015; Schovsbo NH and Holmslykke, HD, 2016; Schovsbo NH et al., 2017,

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2018; McMahan PB et al., 2018). The nature of oilfield water affects the wettability of reservoirs (Shi BH et al., 2012; Xue YQ et al., 2007; Xie Q et al., 2015; Masalmeh SK et al., 2014) and also significantly influences oil-salt-rock interaction (Dubey S and Doe P, 1993; Brady PV and Thyne G, 2016; Mahani H et al., 2017; Song Y et al., 2017). Low salinity promotes enhanced oil recovery (EOR) (Austad T et al., 2012; Standnes DC and Austad T, 2000), and  $\text{Cl}^-$  can trace the source of reservoir water (McCartney RA et al., 2005; Houston SJ et al., 2006; Vazquez O et al., 2015). The research on oilfield water in China mainly focuses on evaluating the reservoir preservation environment and equipment destruction mechanism, especially the reservoir preservation environment (Yao ZJ et al., 2021; Wang R et al., 2021; Zhang L et al., 2021). As an important oil and gas producing area, the Ordos Basin is mainly affected by the types and sources of reservoir water, which controls the preservation environment, and the sources are diverse and related to the structure and sand body (Qi YL et al., 2014; Li JH et al., 2009; Lou ZH et al., 2009; Dou WT et al., 2010; Tan W et al., 2011; Ma HY et al., 2013; Qi YL et al., 2013; Liang JW et al., 2013; Li JH et al., 2014), which also plays an important role in the development of reservoir pores (Wang CY et al., 2014; Zhou X et al., 2016; Dai JY et al., 2012; Yuan YF et al., 2013; Guo M et al., 2009; Zhang W et al., 2017; Zhang ZB., al., 2017). Nearly 150 formation water data of the Chang 7 reservoir have been collected by predecessors. Because formation water is prone to contamination by fracturing fluids, acidizing fluids, or other residual fluids during drilling and production testing, abnormal data exist. To ensure the reliability and representativeness of the data, the abnormal data were excluded. Finally, 136 data were selected for statistics and analysis. According to the analysis results, six kinds of ions, ( $\text{K}^+ + \text{Na}^+$ ),  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ , and  $\text{SO}_4^{4-}$ , occupy more than 90% of the total amount of formation water ions in the Chang 7 reservoir. The most abundant ion is  $\text{Cl}^-$ , followed by ( $\text{K}^+ + \text{Na}^+$ ) and  $\text{Ca}^{2+}$  (Qi YL et al., 2014). In these studies, Sulin classification was adopted to evaluate the formation of water in the oilfields. However, using Sulin's classification method, the cyclability of formation water is not considered (Qi YL et al., 2014). Therefore, the single use of this classification method has certain limitations.

In this paper, the authors adopted Sulin chemical ion characteristic value, classification, the oilfield water characteristic index, and the four-corner layout to comprehensively evaluate the formation water of the central and southern Ansai Oilfield in the Ordos Basin. The study revealed the chemical characteristics of the Chang 6 reservoir water and the relationship between the oil and gas providing a basis for oilfield exploration and reservoir evaluation work.

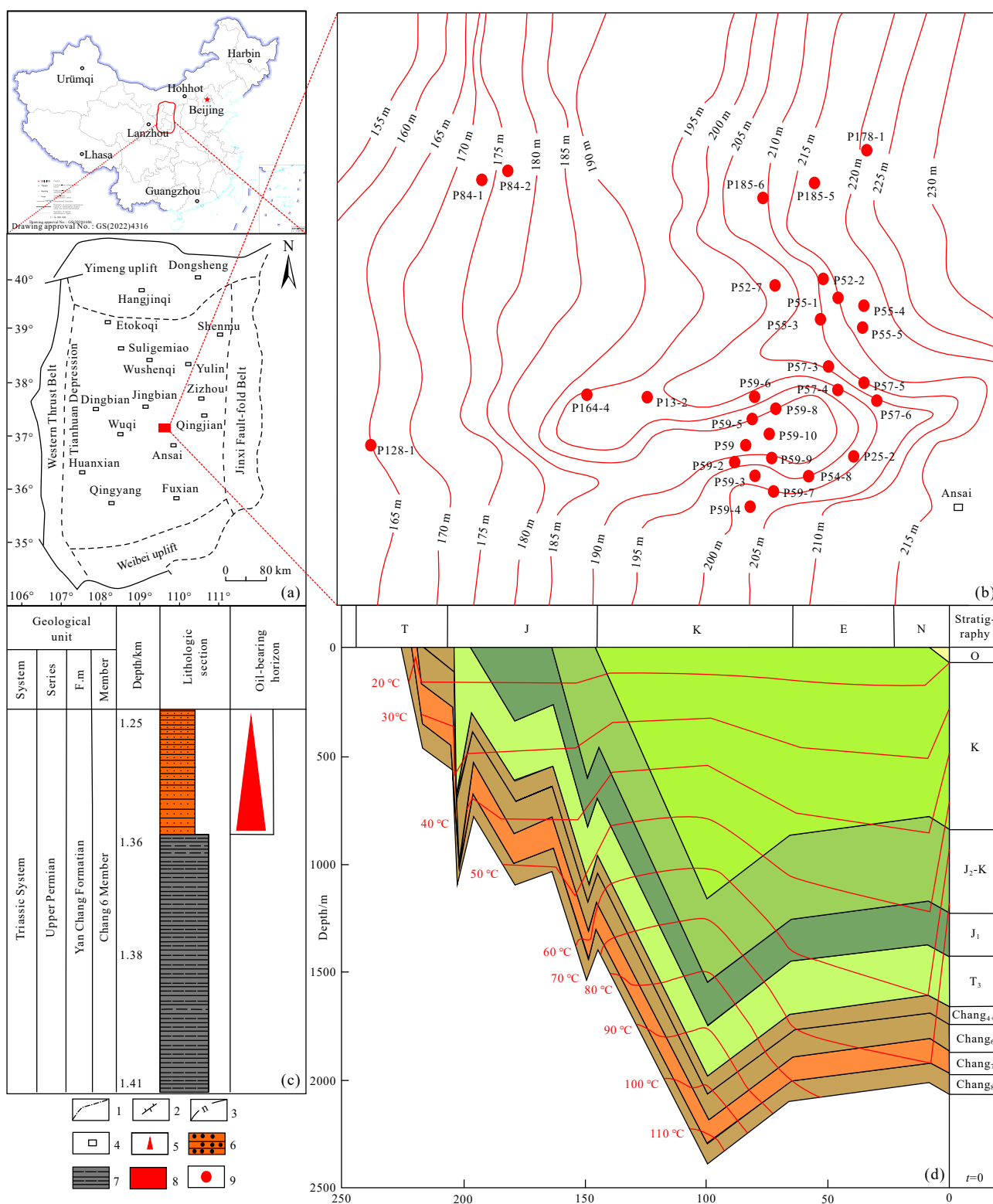
## 2. Geological background

The Ordos Basin is located on the western margin of the North China Plate. It is a sedimentary cratonic basin with weak structural deformation, multi-cycle evolution, and

multiple sedimentary types. It was formed on a stable Archean basement. The basin is about 250000 km<sup>2</sup> (Zhang ZB et al., 2017). The basin is divided into six structural units, including the western margin thrust belt, Tianhuan depression, northern Shaanxi slope, western Shanxi flexure belt, Yimeng uplift, and Weibei uplift (Sun NL et al., 2017) (Fig. 1a). Influenced by the Yanshan and Himalayan movements, the Ordos Basin was denuded from the Cretaceous to the Quaternary. In the Late Middle Jurassic–Late Jurassic, the source rocks of the Chang 7 reservoir were buried at 1500–2000 m, the paleogeothermal temperature reached 60°C–80°C, and hydrocarbon was generated. In the middle and late stages of the Early Cretaceous, the source rocks of the Chang 7 reservoir were buried at 2000–2500 m, the paleotemperature was 80°C–130°C, and a large amount of hydrocarbon was generated (Fig. 1d). The Yanchang Formation is the main formation for oil and gas exploitation in the Ordos Basin. It is divided into 10 reservoirs (Chang 10 reservoir–Chang 1 reservoir) from bottom to top. It is not only a set of important oil- and gas-bearing strata but also the northern continental stratigraphic section of the Triassic strata (Dai JY et al., 2012). The structure of study area is located in the south-central part of the northern Shaanxi slope in the Ordos Basin and above the Ansai-Zichang Delta, and it is high in the southeast and low in the northwest (Li ET et al., 2004). The delta deposits were developed from reservoir 6 to Chang 4+5 (Figs. 1b, c). During the high-tide period of the construction, large-scale swamp development occurred in the late Chang 4+5 reservoirs, the distribution and combination characteristics of the source, reservoir, and caprock were controlled by the sedimentary geological background, and no faults were found. The structural appearance of the Chang 6 reservoir is consistent with the regional structural appearance of the northern Shaanxi slope. The lithology is mainly dark gray mudstone, dark gray argillaceous sandstone, light gray fine sandstone, and light gray siltstone. The sand body has a large thickness, single-layer thickness, wide distribution area, and good continuity. The rock layers are superimposed on each other, providing a good space for oil and gas storage.

## 3. Samples and methods

Compared with other blocks in Ansai County, the northwest block has a high exploitation degree but a low research degree of reservoir water. To ensure that the water samples are the original reservoir water samples, the authors selected the area which has not been developed by water injection and has been in production for a long time as the study area. During drilling, the drilling fluid has been completely extracted to avoid the pollution of the original reservoir water by external water as much as possible. A total of 30 water samples from the Chang 6 reservoir were collected from 30 wells in the study area. The water samples were put into disposable clean sample bottles and sent to the laboratory for indoor treatment. The samples were left for a



**Fig. 1.** a–Secondary structural unit (modified from Zhang ZB et al., 2017; Shi BH et al., 2012); b–isothickness map of the sand body in the study area (unit: m); c–lithologic bar chart of Chang 6 members; d–burial and thermal histories in the Ordos Basin (Shi BH et al., 2012). 1–secondary structural unit; 2–fault; 3–isopachy line of the sand body; 4–place name; 5–oil-bearing horizon; 6–sandstone; 7–mudstone; 8–research area; 9–well.

while. After the oil and water were separated, the water samples were taken. The pH values and Total Dissolved Solid (TDS) indexes of the water samples were measured with a portable HANNA multi-parameter water quality meter in the field, and the stability of hydrochemical indexes, such as

positive ion and anion, were analyzed and tested with an inductively coupled plasma mass spectrometer (ELEMENT2), an ion chromatography (ICS-1100) and an atomic absorption spectrometer (CE3500). The test results and ion characteristic parameters are shown in Table 1.

**Table 1. Types and salinity of water ions in Chang 6 reservoir of Ansai Oilfield.**

Well No.	Cation			Anion				pH	TDS (g/L)	Coefficient of sodium chloride	Magnesium chloride coefficient	Calcium magnesium coefficient	Coefficient of desulfurization	Carbonate equilibrium coefficient
	Na <sup>+</sup> +K <sup>+</sup> (mg/L)	Ca <sup>2+</sup> (mg/L)	Mg <sup>2+</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	SO <sub>4</sub> <sup>-2</sup> (mg/L)	CO <sub>3</sub> <sup>-2</sup> (mg/L)	HCO <sub>3</sub> <sup>-2</sup> (mg/L)							
P25-2	10103	26753	130	62878	256	17	344		100.48	0.161	483.677	0.005	0.407	0.013
P52-2	11414	24613	130	60662	1026		157		98.00	0.188	466.631	0.005	1.691	0.006
P52-7	11520	23650	65	59326	513		134		95.21	0.194	912.708	0.003	0.865	0.006
P54-8	9162	11343	65	33760	769		85		55.18	0.271	519.385	0.006	2.278	0.007
P55-4	14012	18276	346	53494	1825		165	5.9	88.118	0.262	154.607	0.019	3.412	0.009
P55-5	12177	14754	58	44222	913		243	6.5	72.37	0.275	762.448	0.004	2.065	0.016
P55-3	9000	18943	173	47075	913		237	5.8	76.34	0.191	272.110	0.009	1.939	0.013
P55-1	12283	16601	92	47431	1369		217	5.8–6.0	77.99	0.259	515.554	0.006	2.886	0.013
P57-3	9194	22045	195	53101	769		115		85.42	0.173	272.313	0.009	1.448	0.005
P57-4	9869	19905	65	50303	256		204		80.60	0.196	773.892	0.003	0.509	0.010
P57-5	5655	12012	49	29851	256		117		47.94	0.189	609.204	0.004	0.858	0.010
P57-6	11410	25041	130	61791	513		157		99.04	0.185	475.315	0.005	0.830	0.006
P59	11937	23757	65	60155	513		138		96.56	0.198	925.462	0.003	0.853	0.006
P59-2	14519	22473	1817	61269	8207		182		108.47	0.237	33.720	0.081	13.395	0.008
P59-3	12871	22366	195	59528	513	8	102		95.58	0.216	305.272	0.009	0.862	0.005
P59-4	13288	24185	130	63288	385	21	101		101.40	0.210	486.831	0.005	0.608	0.005
P59-5	11095	25255	260	60921	2052		170		99.75	0.182	234.312	0.010	3.368	0.007
P59-6	10638	25255	130	61269	128		151		99.57	0.174	471.300	0.005	0.209	0.006
P59-7	15254	18781	357	56743	1282	8	138		92.56	0.269	158.944	0.019	2.259	0.008
P59-8	12206	23971	104	61164	256	125	159		97.99	0.200	588.115	0.004	0.419	0.012
P59-9	10099	24827	130	58658	1539		119		95.37	0.172	451.215	0.005	2.624	0.005
P59-10	10935	23971	519	59528	1539		187		96.68	0.184	114.697	0.022	2.585	0.008
P84-1	7736	21189	65	49339	256	8	106		78.70	0.157	759.062	0.003	0.519	0.005
P128-1	9377	22473	260	54307	769		153		87.34	0.173	208.873	0.012	1.416	0.007
P164-4	9702	23864	195	57251	513		182		91.71	0.169	293.595	0.008	0.896	0.008
P13-2	9824	25469	65	59361	1282	8	125		96.13	0.165	913.246	0.003	2.160	0.005
P185-6	15333	18086	173	54207	2510		124	6	90.43	0.283	313.335	0.010	4.630	0.007
P84-1	5105	13800	182	32375	479		140	6.4–6.5	52.08	0.158	177.885	0.013	1.480	0.010
P178-1	6266	11994	231	30135	1825		113	5.5–5.8	50.56	0.208	130.455	0.019	6.056	0.009
P185-5	14751	19038	115	55277	1825	112	103	7	91.22	0.267	480.670	0.006	3.302	0.011
Max	15333	26753	1817	63288	8207	125	344	7	108.47	0.283	925.462	0.081	13.395	0.016
Min	5105	11343	49	29851	128	8	85	5.5	47.94	0.157	33.720	0.003	0.209	0.005
average	10891	20823	216	53289	1175	38	156	6.15	86.63	0.206	442.161	0.010	2.228	0.008

#### 4. Characteristics of the reservoir water in the Chang 6 reservoir

Reservoir water refers to the groundwater related to the oil and gas structure in a certain layer in the oilfield area and mainly includes oil-layer water and non-oil-layer water. The sources and causes of reservoir water are extremely complex. Generally, there are four main sources: Sedimentary water, infiltration water, transformed water, and deep water (Liu GD and Zhang HF, 2009). The research on the properties of reservoir water mainly covers the salinity, the composition of salt ions, and the type of reservoir water.

##### 4.1. Characteristics of the salinity of the reservoir water in the Chang 6 reservoir

The chemical composition and salinity of reservoir water

are closely related to where it originates from and how it is influenced when it enters the underground environment. Reservoir water formed by many aspects of physical, chemical, and biological transformations is usually significantly different. However, reservoir water formed in the same or similar environment has very similar properties and composition. For example, in oilfields, the reservoir water mainly comes from sedimentary water and organic water (Liu GD and Zhang HF, 2009) and can be classified into five types according to salinity degrees (Table 2; Guo JH et al., 2006; Hu XL et al., 2008; Chen XZ et al., 2008; Man HM et al., 2009).

Statistical analysis (Table 1) and histogram (Fig. 2) of the reservoir water in the study area show that the salinity values of the 30 wells range from 47.94 g/L to 108.47 g/L, with an average of 86.63 g/L, indicating that the reservoir water type in the study area is brine. Liang XW et al. (2012) calculated

that the paleosalinity value of boron element in clay minerals in the Yichang Formation was 4.43%, showing the property of a saline-brine lake. This result is consistent with that of previous studies on reservoir water in the Chang 6 in the basin. The pH values of the Chang 6 reservoir water in the study area range from 7 to 5.5, with an average of 6.15, indicating that it is mainly weak acid.

4.2. Characteristics of the chemical ion contents of the formation water in the Chang 6 reservoir

The cations of the Chang 6 reservoir water in Ansai Oilfield mainly include  $Ca^{2+}$ ,  $Na^+$ ,  $K^+$  and  $Mg^{2+}$ . The anions contain  $Cl^-$ ,  $SO_4^{2-}$ ,  $CO_3^{2-}$  and  $HCO_3^-$ . The abundance of cations and anions have the characteristics of  $\rho(Ca^{2+}) > \rho(Na^+ + K^+) > \rho(Mg^{2+})$  and  $\rho(Cl^-) > \rho(SO_4^{2-}) > \rho(HCO_3^-) > \rho(CO_3^{2-})$ .  $Na^+$ ,  $K^+$ ,  $Ca^{2+}$ ,  $Cl^-$  and  $SO_4^{2-}$  are the main salt ions

in the formation water in this area as shown in Fig. 3. Fig 3a shows the three-terminal diagram of the cations, and Fig. 3b shows the three-terminal diagram of the major anions.

4.3. Types of the reservoir water

So far, although many supplementary classification schemes and modifications have been made to natural water, most of them are based on the relationship between the content and composition of the two groups of anions and cations, namely,  $Cl^-$ ,  $SO_4^{2-}$ ,  $HCO_3^-$  and  $Mg^{2+}$ ,  $Ca^{2+}$ ,  $Na^+$ ,  $K^+$ . Among various classifications, the Sulin classification is the most concise and has been adopted by most countries in the world (Liu GD and Zhang HF, 2009). In this paper, the Sulin classification is also adopted (Table 3).

According to the sample analysis results of the 30 wells in the study area, the range of  $r_{Na^+}/r_{Cl^-}$  is 0.17 to 0.24 in the study

Table 2. Mineralization classification of reservoir water.

Formation water type	Freshwater	Brackish water	Saltwater	Saline	Brine
TDS ( $\rho/gL^{-1}$ )	<1	$1 \leq \rho \leq 3$	$3 \leq \rho \leq 10$	$10 \leq \rho \leq 50$	$\geq 50$
Research area		47.94–86.63			

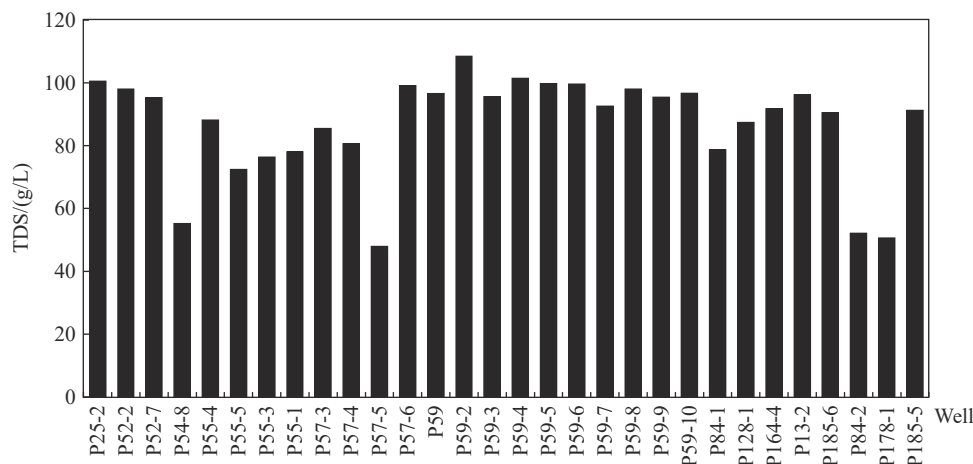


Fig. 2. Salinity distribution histogram of the Chang 6 reservoir in Ansai Oilfield.

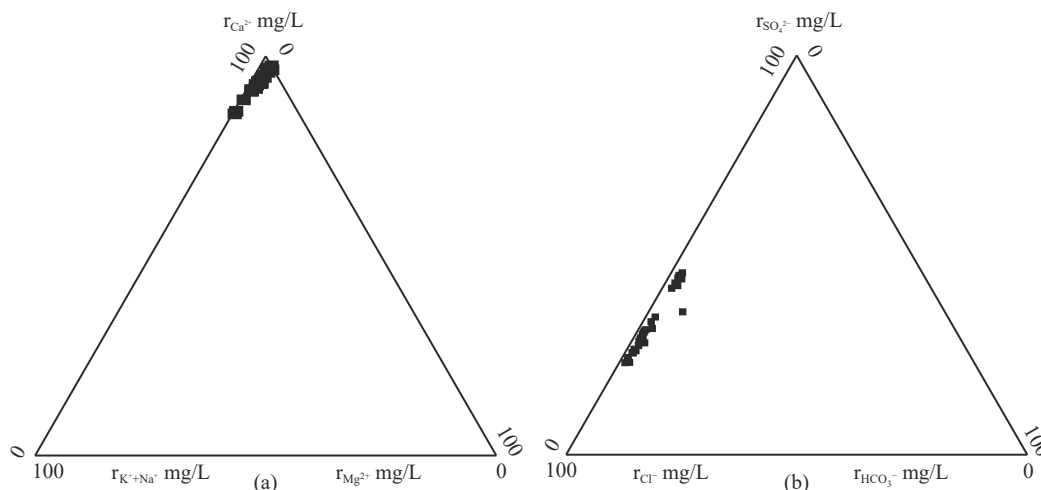


Fig. 3. Triangle diagram of water anion content in Chang 6 reservoir in Ansai Oilfield. a- $r_{Ca^{2+}}$ ,  $r_{K^+ + Na^+}$  and  $r_{Mg^{2+}}$  tri-terminal diagram of major cation; b- $r_{SO_4^{2-}}$ ,  $r_{Cl^-}$  and  $r_{HCO_3^-}$  tri-terminal diagram of major anions.

**Table 3. Sulin genetic classifications of the natural water (after Liu GD and Zhang HF, 2009).**

Water type		Genetic factor (concentration ratio)		
		Na <sup>+</sup> / Cl <sup>-</sup>	(Na <sup>+</sup> - Cl <sup>-</sup> )/ SO <sub>4</sub> <sup>2-</sup>	(Cl <sup>-</sup> - Na <sup>+</sup> )/ Mg <sup>2+</sup>
Continental Water	Ulfate-Sodium Type	>1	<1	<0
	Sodium Bicarbonate Type	>1	>1	<0
Seawater	Chloride-Magnesium Type	<1	<0	<1
Deep Water	Chloride-Calcium Type	<1	<0	<1
Research area	Average Value	0.20	-36.08	246.71

area, with an average of 0.2, all less than 1. The  $r_{Na^+-Cl^-}/r_{SO_4^{2-}}$  range from -93.33 to -5.84, with an average of -36.08, all less than 0.  $(Cl^- - Na^+)/Mg^{2+}$  range from 34.83 to 609.20, with an average of 246.71, all greater than 1. The above results indicate that the water in the study area is of the deep calcium chloride type. Sulin believes that the groundwater in an exposed geological structure is of the sodium sulfate type, most of the groundwater without infiltrated atmospheric water is of the calcium chloride type, and the groundwater between the above two kinds is of the magnesium chloride type. Based on this opinion, the Chang 6 reservoir may not be infiltrated by atmospheric water, and the reservoir water is of the deep calcium chloride type. The reason is that the Yanchang reservoir is a low-porosity and low-permeability reservoir. The reservoir is in a closed space, and its transverse and longitudinal connectivity with the outside world is bad. Therefore, the reservoir in hydration cannot be destroyed by hydrodynamic force, and the external fluid cannot be led into the reservoir, thus, the reservoir has good storage conditions. The authors analyzed the correlations of TDS with the cations  $K^+ + Na^+$ ,  $Ca^{2+}$ , and  $Mg^{2+}$  and the correlations of TDS with the anions  $Cl^-$ ,  $SO_4^{2-}$ , and  $HCO_3^-$ . The results show that  $Ca^{2+}$  and  $Cl^-$  are highly correlated with TDS, and the correlation coefficients  $R^2$  are 0.8133 and 0.9853 (Figs. 4b, c), which are close to 1. The correlation value ( $R^2$ ) is 0.5541 (Fig. 4a), followed by that between TDS and  $K^+ + Na^+$ . The cross-correlations of TDS with  $Mg^{2+}$ ,  $SO_4^{2-}$ , and  $HCO_3^-$  (Figs. 4d–f) also indicate that the Chang 6 reservoir water is mainly of the calcium chloride type, and the Chang 6 reservoir is a favorable oil and gas reservoir.

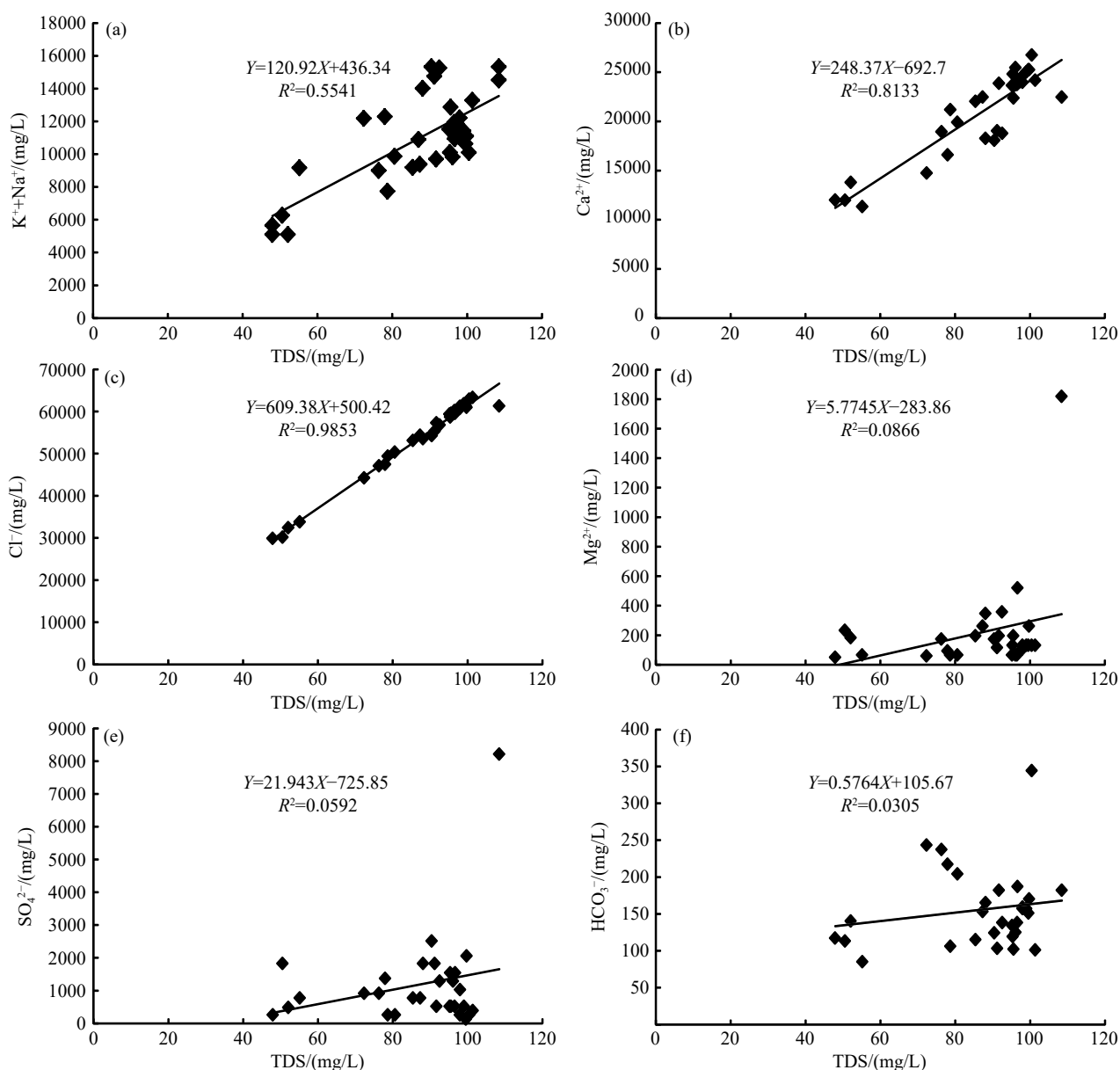
## 5. Discussions

The sealing performance and redox conditions of oil and gas reservoirs are usually evaluated using the parameters of the chemical properties of the reservoir water, such as sodium chloride coefficient, desulfurization coefficient, chloride magnesium coefficient, magnesium calcium coefficient, reservoir water the four-corner layout, and carbonate balance coefficient. It can reflect the sealing properties of caprocks of the oil layer and the quality of oil, providing a basis for evaluating oil and gas fields (Lou ZH et al., 2009). Therefore, the authors used these hydrochemical parameters to evaluate the chemical indicators of the Chang 6 reservoir water, revealing the preservation environment of the Chang 6 reservoir and providing a reference for evaluating the oil and gas fields in Ansai Oilfield in the Ordos Basin.

### 5.1. Evaluation and analysis of the reservoir by sodium chloride and chloride magnesium coefficients

Sodium chloride coefficient ( $r_{Na^+/Cl^-}$ ) is important for indicating the quality of reservoir sealing, the metamorphism degree of reservoir water, and the activity of reservoir water. A low sodium chloride coefficient and a high metamorphism degree of reservoir water reflect good conditions for preserving oil and gas; a small ratio of the sodium chloride coefficient reflects that the reservoir is a reductive environment and conducive to oil and gas preservation (Yang XH, 2009). Bethke CM et al. (1991) believed that when the sodium chloride coefficient is greater than 0.75, the properties of sealing reservoir water are poor, indicating that the reservoir is significantly affected by external environmental water and not conducive to hydrocarbon accumulation (Bethke CM et al., 1991); when the sodium chloride coefficient is less than 0.75, the reservoir has a good water sealing condition; when it is less than 0.5, a stagnant environment can be formed, and the reservoir is a great zone for hydrocarbon accumulation (Liang XW et al., 2012; Luo, ZD 2014). The chloride magnesium coefficient ( $r_{Cl^-/Mg^{2+}}$ ) is an important indicator of concentration metamorphism and cation adsorption and exchange. A larger chloride magnesium coefficient indicates better properties of sealing reservoir water, a longer sealing time, and a higher concentration and metamorphism, which show that the reservoir can be used as a favorable space for oil and gas accumulation and preservation. Studies have shown that the chloride magnesium coefficients of the reservoir water in gas-bearing areas are generally greater than 5 (Hu XL et al., 2008; Liang XW et al., 2012; Zhang XF et al., 2015).

The statistical results of the reservoir water parameters of the 30 wells in the study area (Fig. 5) show that the maximum and minimum sodium chloride coefficients are 0.2 and 0.16, respectively. All the sodium chloride coefficients are less than 0.5 (Fig. 5a), indicating that the Chang 6 reservoir water is in a stagnant environment and mainly composed of residual seawater sealed in ancient times. The reservoir is not affected by the permeable water of the external and is a favorable trap environment for oil and gas storage. By analyzing the chloride magnesium coefficients (Fig. 5b), the range of chloride magnesium coefficients in the Chang 6 oil layer of the Yanchang reservoirs is 33.7 to 925.5. The chloride magnesium coefficients of 24 wells are above 200, and only a few wellheads have relatively small values. The minimum value is 33.7 for well No P185-5. These results indicate that



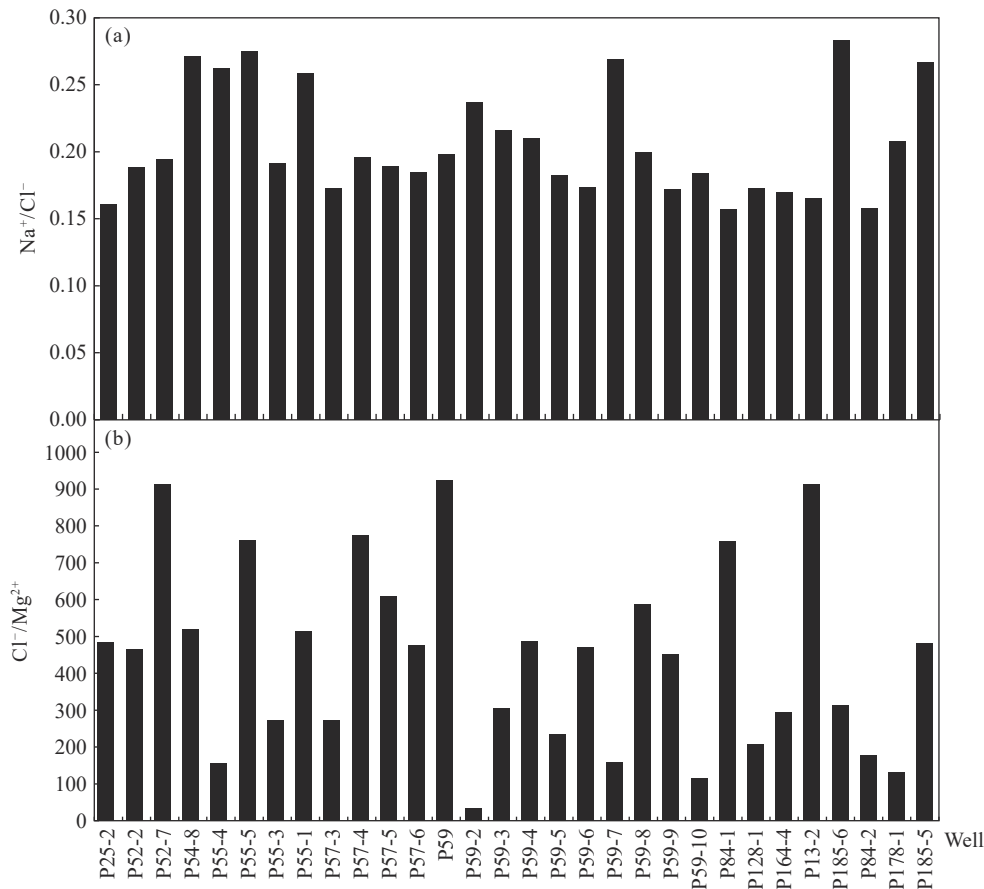
**Fig. 4.** Correlation diagram between the content of cation and anion in water and salinity in Chang 6 reservoir in Ansai Oilfield. a– $K^+ + Na^+$  correlates with TDS; b– $Ca^{2+}$  correlates with TDS; c– $Cl^-$  correlates with TDS; d– $Mg^{2+}$  correlates with TDS; e– $SO_4^{2-}$  correlates with TDS; f– $HCO_3^-$  correlates with TDS.

most wells in the study area have good properties for sealing reservoir water, a long storage time, and a high degree of concentration metamorphism, and they are favorable blocks for oil and gas storage. In summary, the Chang 6 Reservoir of Ansai Oilfield has favorable traps and good sealing conditions.

### 5.2. Evaluation and analysis of the reservoir by desulfurization and carbonate balance coefficients

The desulfurization coefficient ( $100 \times r_{SO_4^{2-}/Cl^-}$ ) is an important index indicating the oxidation and reduction degrees of groundwater. A lower desulfurization coefficient indicates a stronger reduction effect and a reservoir more conducive to preserving oil and gas. Melimans KR (1987) believed that due to oil and gas, reservoir water sulphate may

decrease, and the bicarbonate content may increase, decreasing the desulfurization coefficient. The desulfurization coefficient of reservoir water is positively correlated with the carbonate content. A smaller desulfurization coefficient implies a longer distance between the reservoir water and the oil and gas reservoir. Therefore, the desulfurization coefficient can be used to determine whether the geological body is close to the oil-gas-water interface. The sulfate content in calcium chloride-type water is very small and generally less than 2%. A large amount of sulfate is not conducive to protecting oil and gas reservoirs and even has a destructive effect. A sulfate radical content of greater than 5% means that the oil and gas reservoirs have been destroyed (Guo JH et al., 2006; Liang XW et al., 2012; Zhang XF et al., 2015). The carbonate balance coefficient ( $r_{HCO_3^- + CO_3^{2-}/Ca^{2+}}$ ) can indicate the nature and direction of oil and gas and the



**Fig. 5.** Distribution histogram showing (a) the sodium-chlorine and (b) the chlorine-magnesium coefficients of formation water in the Chang 6 reservoir.

decarbonization degree. The smaller the value of this coefficient, the closer the geological body is to the oil and gas reservoir, and the better the preservation conditions of the region (Hu XL et al., 2008; Liang XW et al., 2012; Zhang XF et al., 2015).

The desulfurization coefficients of the Chang 6 reservoir water in the study area are between 0.21 to 13.4, with a maximum value of 13.4 and an average of only 2.227 (Fig. 6a), indicating that the reservoir water is very close to the oil-water interface, and the oil and gas preservation conditions are good. The carbonate balance coefficients of the Chang 6 reservoir water range from 0.02 to 0.005, with an average of 0.008 (Fig. 6b), indicating good properties of the oil and gas in this reservoir, which is also confirmed by the high-quality crude oil produced in the study area. These two sets of parameters show that the Chang 6 reservoir is very close to the oil-water interface, has great oil and gas preservation conditions, and has good oil and gas properties.

### 5.3. Evaluation and analysis of the reservoir by the four-corner layout of the formation and calcium-magnesium coefficient

In the four-corner layout of reservoir water, four stable parameters, the concentrations of  $\text{K}^+ + \text{Na}^+$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ , and total TDS, are used as four vertices, and the area and shape of the quadrilateral surrounded by them are used to characterize

certain water samples. These characteristics are used to judge the reservoir connection between wells (Bethke CM et al., 1991; Melimans KR, 1987). The analysis results show that the four-corner layouts of the 12 wellheads of the Chang 6 reservoir selected from different well sites have the same trends in the four parameters (the areas and shapes of the shaded figures are very similar), indicating good well-to-well connectivity in the study area (Fig. 7). A low calcium-magnesium coefficient ( $r_{\text{Mg}^{2+}/\text{Ca}^{2+}}$ ) is related to the development of secondary pores. In addition, the dolomitization and dissolution of calcite can change the physical properties of the reservoir and reduce the calcium-magnesium coefficient of the reservoir water. According to previous studies, the calcium-magnesium coefficients of the reservoir water in gas-bearing areas are generally less than 0.30 (Hu XL et al., 2008; Liang XW et al., 2012; Zhang XF et al., 2015; Xu GS et al., 1999). Through statistical analysis of the 30 wells in the study area (Fig. 8), the calcium-magnesium coefficients ( $r_{\text{Mg}^{2+}/\text{Ca}^{2+}}$ ) of the Chang 6 reservoir in the Yanchang Formation range of 0.08 and 0.003, with an average of 0.01, indicating that the Chang 6 reservoir has been reformed by multiple diageneses. The secondary pores in the group are well-developed, forming a good corresponding relationship with the low calcium-magnesium coefficients of the formation water. This phenomenon also reflects that the pores of the Chang 6 reservoir are mainly formed by later reformation, making the

Chang 6 reservoir develop well. Therefore, the primary pores of the Chang 6 reservoir in the study area have been developed, and good connectivity has been created between wells.

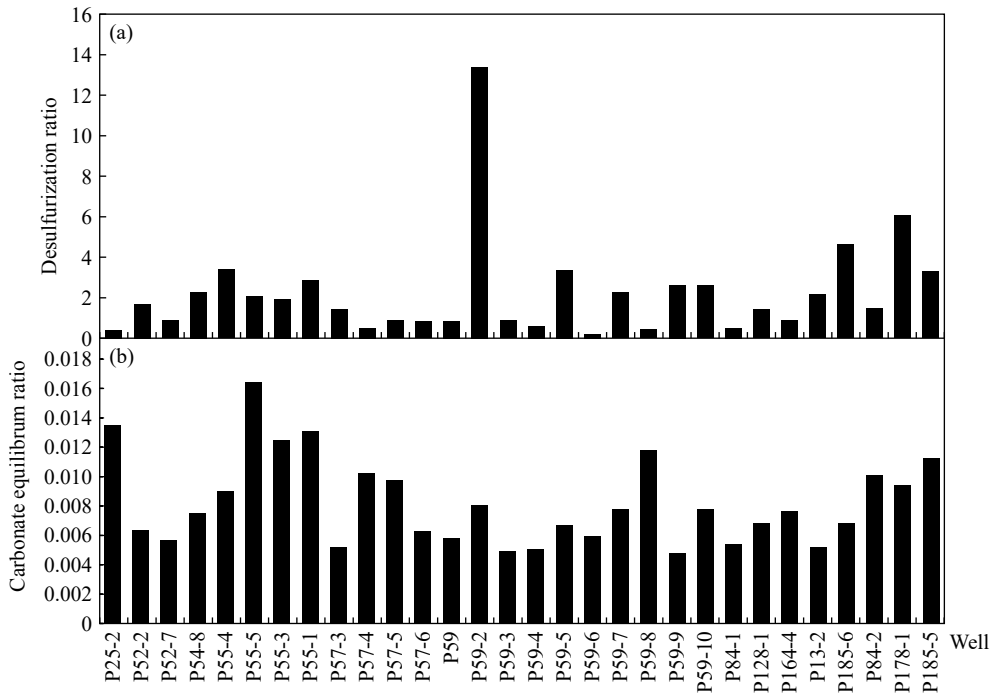


Fig. 6. Distribution histogram showing the desulfurization coefficients (a) and carbonate equilibrium coefficients of formation water (b) in the Chang 6 reservoir in Ansai Oilfield.

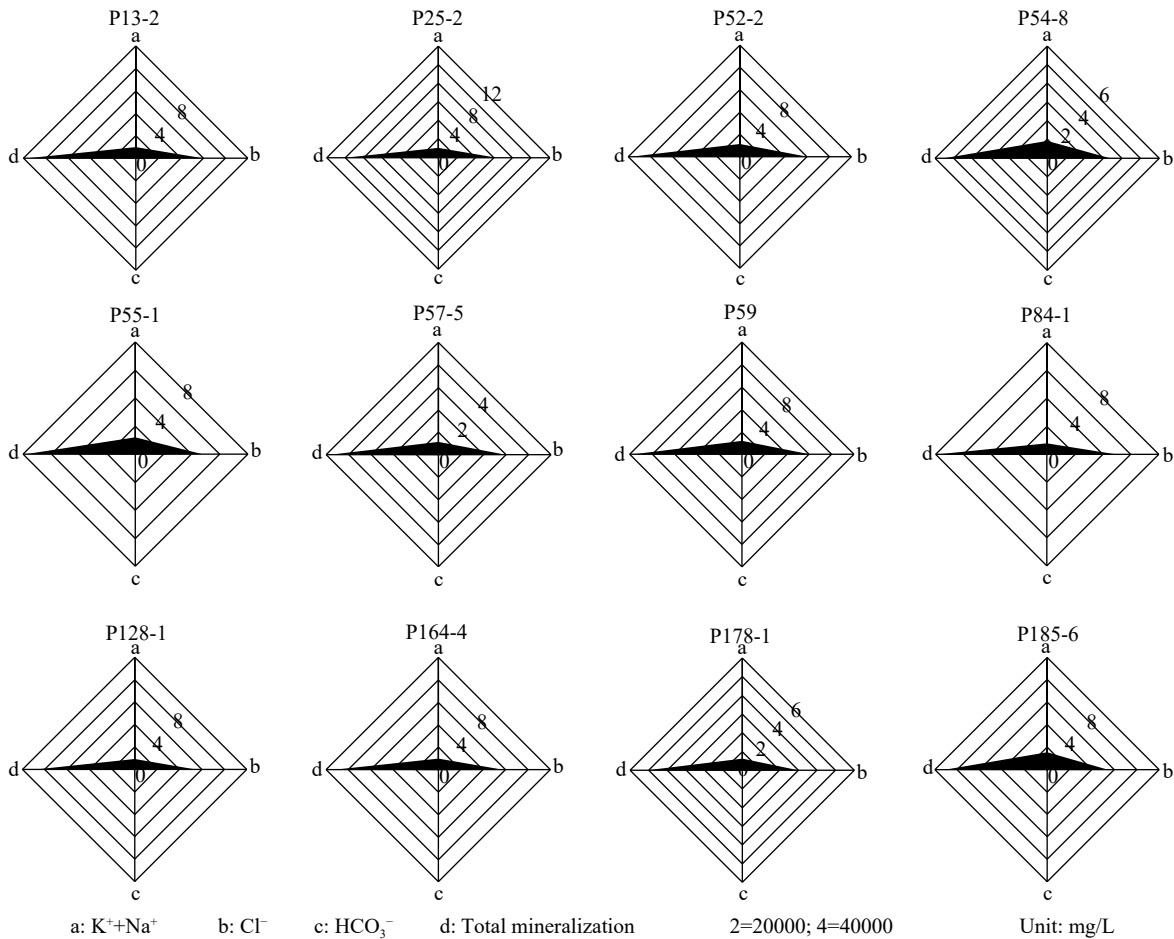
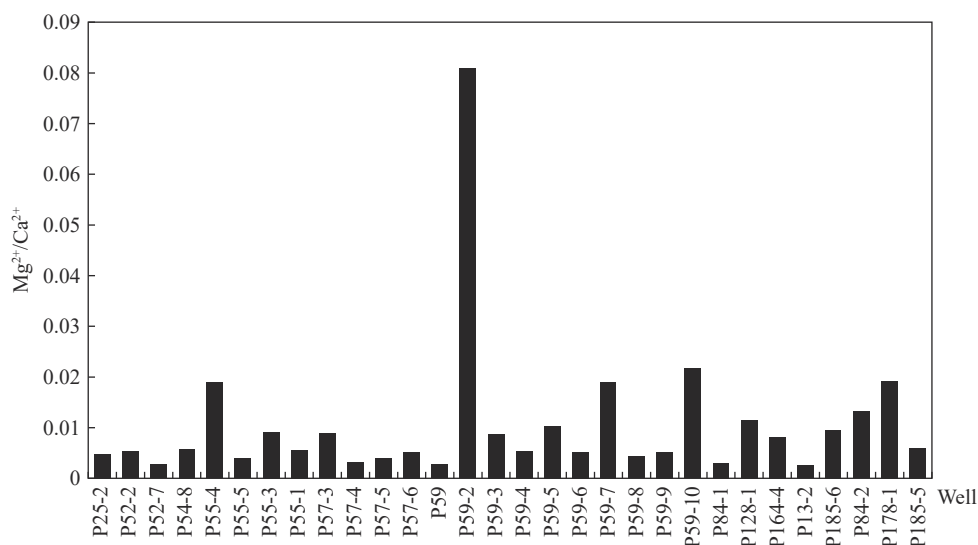


Fig. 7. Four-angle layout of 12 Wells in Chang 6 reservoir in Ansai Oilfield.



**Fig. 8.** Distribution histogram showing the calcium-magnesium coefficients of formation water in the Chang 6 reservoir in Ansai Oilfield .

## 6. Conclusions

(i) By analyzing the chemical characteristics of the Chang 6 reservoir water in the Ansai oilfield, the authors found that  $\text{Na}^+ + \text{K}^+$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$ , and  $\text{SO}_4^{2-}$  are the main salt ions. The  $\text{Cl}^-$  and  $\text{Ca}^{2+}$  have the highest contents, playing a key role in water type and salinity and leading to high salinity and brine-type properties of this reservoir.

(ii) The authors performed comprehensive analyses of the sodium chloride coefficient, the chloride magnesium coefficient, the desulfurization coefficient, the carbonate balance coefficient, the calcium-magnesium coefficient, and the four-corner map solution on the Chang 6 reservoir water in Ansai Oilfield. The results show that the sealing conditions of the Chang 6 reservoir in Ansai Oilfield are good. The Chang 6 reservoir is a reductive environment, with highly developed secondary pores and good connectivity between wells, providing a favorable space for oil and gas storage. Therefore, it is a good reservoir.

(iii) Additionally using various hydrochemical parameters of the Chang 6 reservoir water in Ansai Oilfield can effectively overcome the limitations of Sulin's classification method for formation water in some specific examples. The effective combination and comprehensive interpretation of the two can accurately improve the reliability of predicting favorable reservoirs and provide a reliable basis for oil and gas exploration.

### CRedit authorship contribution statement

Zhi-bo Zhang and Teng-rui Jin conceived of the presented idea. Hao-ming, Liu Ying Xu, and Di-fei Zhao contributed to sample preparation. Wei-cheng Jiang and Dan-ling Chen verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

### Declaration of competing interest

The authors declare no competing financial interest.

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