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REVIEW

Geochemical characteristics of carbonate rocks in a salinized lacustrine basin: a case study from Oligocene formation in the Qaidam Basin, northwestern China

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Abstract

Based on petrology, mineralogy, carbon and oxygen isotope composition, trace element composition, geochemical characteristics of carbonate rocks are systematically analyzed in the saline lacustrine basin environment in the Qaidam Basin, northwestern China. The results show that: (1) The carbon and oxygen isotopic compositions show carbonate rocks were deposited between open lake and closed lake environment; (2) the Sr/Ba ratio is greater than 1 with an average of 2.01; the Sr/Cu ratio is greater than 5 with an average of 109.04; the U/Th average value ratio is less than 1 with an average of 0.62. These data indicated the carbonate rocks deposited in an salinization, drought, and reducing lacustrine environments; (3) ΣREE values range from 39.41 to 162.67 ppm with an average of 87.67 ppm, and negative anomaly of Eu occurs in REE distribution patterns; and (4) lithologies of carbonate rocks are mainly composed of dark gray or black carbonates, commonly associated with salts deposition due to different lacustrine facies.

Keywords Geochemical characteristics · Salinized lacustrine basin · Carbonate rocks · Stable carbon and oxygen isotopes

Introduction

Lacustrine carbonate rocks refer to the carbonate rocks formed in the inland lake basins, including carbonate rocks deposited in fresh water (Zhao 2013), in brackish water–saline water and in salt lakes. The lacustrine carbonate rocks are not only regarded as important source rocks, but also as important reservoir rocks (Peng 2011; Zhou et al. 1991; Tuo et al. 1995; Tuo and Huang 1996). Numerous oil and gas reservoirs have been widely discovered in the lacustrine carbonate rocks.

Qaidam Basin, one of the continental petroliferous basins in northwestern China, is an important component of Tibetan Plateau (Fig. 1). The Qaidam basin is a typically foreland basin on the northeastern margin of the Tibet Plateau (Zhu 1986; Jia 2005). Based on drilling data, the Qaidam basin has undergone two complete Tectonic evolution, since the Mesozoic and these tectonic movements resulted in three sedimentary strata sequences. Depocenter of the basin in Paleogene was formed in the Western Qaidam Basin, then gradually migrated eastward. Depocenter of saline lacustrine sedimentary basins is not only controlled by tectonic evolution but also by the late tectonic pattern and distribution. Neogene stratigraphy is subdivided into six sets of bottom-up land Formation (Table 1).

Lacustrine carbonate rocks are obviously controlled by the changes in the paleoclimate, fossil water force and fossil water medium conditions. Paleoclimate influence is much greater in lakes than in the oceans (Xia et al. 2003; Zhao 2014). Due to location at the aggregation and intersection area in China, the climatic system in the Qaidam Basin, can sensitive to the Asian climate change, even to the global climate change (Mao et al. 2014). Lacustrine carbonate rocks was selected to study petrologic features and reservoir conditions in the Qaidam Basin to determine controlling factors and formation mechanism of lacustrine carbonate rock reservoirs.

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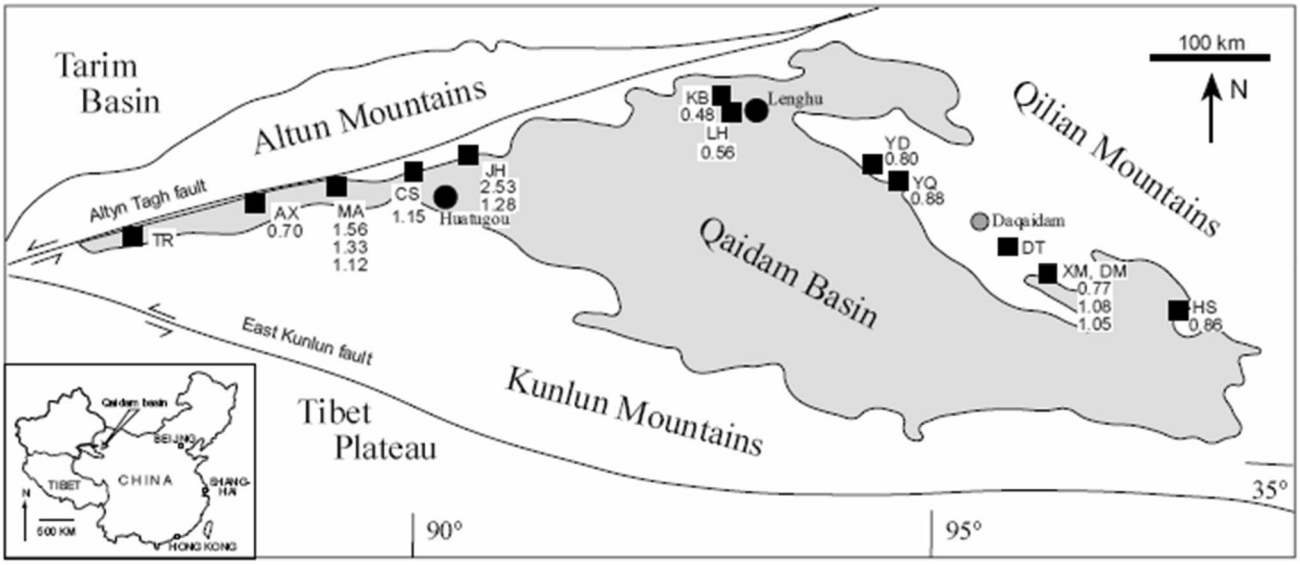

Fig. 1 Study objects Location map of Qaidam Basin

Table 1 Mesozoic and Cenozoic Chronostratigraphic framework in western Qaidam basin

Ara	Age	Epoch	Formation	Code
Cenozoic	Quaternary	Holocene	hubuxun	Q_4
		Pleistocene	Qigequan	Q_{1+3}
	Neogene	Pliocene	Shizigou	N_2^3
			Upper Youshashan	N_2^2
			Lower Youshashan	N_2^1
		Miocene	Upper Gancaigou	N_1
	Paleogene	Oligocene	Lower Gancaigou	E_3
		Eocene	Lulehe	E_{1+2}
Mesozoic	Cretaceous	Late Cretaceous		K_2
		Early Cretaceous	Quyagou	K_1
	Jurassic	Late Jurassic	Hongshigou	J_3
			Chaishiling	
		Mid Jurassic	Dameigou	J_2
			Xiaomeigou	
		Early Jurassic	Huxishan	J_1

Samples and methods

The core samples are selected from Yuejin area, Yingxi area, Ganchaigou area and Xianshuiquan area in the Qaidam Basin (Table 1) (Yin et al. 2007). The technical methods mainly include thin section observation, X-ray diffraction analysis, total rock mineral contents, scanning electron microscope (SEM), and electronic probe. All of above mentioned analysis and tests were carried out in the Key Laboratory of Reservoir Description, CNPC.

The thin section observation was conducted on thickness of 0.03 mm using the Zeiss Axio Scope A1 polarizing microscope.

The X-ray diffraction analysis were ground into powder with grain sizes less than 40 μm. The power was weighed to make a test piece by backpressure method, and the integrated intensities of diffraction peaks for individual minerals were measured. Total rock mineral contents in percentage were calculated, the instrument model was Empyrean. During the analysis, the working voltage was 40 kV, the current was 40 mA, the scanning speed was 2° (2θ)/min, and the sampling step width was 0.02° (2θ).

The scanning electron microscope were cut into cubes or irregular bulks with a 1 cm^3 volume. The fresh sections were selected as the observation surfaces, and the conductive metallic element Au was coated onto the surfaces. The conducting resin was used to fix the samples onto the sample holder, and the observation surfaces were connected with the sample holder for the electric charges conduction. In addition, the instrument model was FEI Quanta 450 FEG during the analysis with the working voltage of 20 kV and the electron incident flow of 3×10^{-10}–4×10^{-10} A.

The dolomite composition analysis was obtained by electronic probe, under an working voltage of 15 kV using a working current of 25 μA. The spot size was 5 μm, and the testing time at each probe point was about 2 h. The detected element composition included MgO, CaO, Na_2O, Al_2O_3, SiO_2, K_2O, MnO, FeO, SrO and BaO.

For stable carbon and oxygen isotopes, core samples and phosphate were mixed together in sample tube to react after vacuumizing for half an hour at 72℃. Liquid nitrogen and cold trap (about-196 °C) were used to collect carbon dioxide

gas. Purify it and make it enter the mass spectrometer analysis and testing, correction according to the standard sample (GBW04405) and the standard unit (V-PDB), the carbon and oxygen stable isotope error is no more than 0.1‰ based on repeating the test.

Results and discussion

Sedimentary characteristics

As the exploration deepens in each exploration phase, a lot of previous research achievements made one same conclusion: the Oligocene stratum is the most important hydrocarbon source rocks in the entire Qaidam Basin. Based on the analysis of 109 dark mudstones and carbonate rocks, it is indicated that the average organic carbon content ranges from 0.3 to 2% with an average of 0.77%. Most samples have moderate abundances of organic matter, and the hydrocarbon conversion rate is relatively high in salinization. Therefore, strong hydrocarbon generation capacity for oil source rocks occurs in each area of the Qaidam Basin.

In view of the overall color of rocks, lithology is dominated by dark colors such as dark gray or gray black, with no oxidation or weak oxidation colors. Although fine-grained terrigenous clastic stripes can be occasionally observed in strata, this cannot be considered as necessary and sufficient conditions to classify the lake basin as shore-shallow lacustrine due to relatively shallow water depth. The reason for this is that the contents of terrigenous clastics in the lacustrine facies carbonate rock strata mainly depend on the attenuation index of kinetic energy of river water with clastic particles flowing into the lake, i.e., in saline water, fine-grained clastic materials can be transported much farther, while coarse-grained clastic particles flowing into the lake are subject to bigger kinetic energy attenuation because of the resistance effect.

Some scholars once questioned whether the saline minerals development will make the lake basin dry up or water depth shallow in later period? This is not the case, because the saline minerals deposition mainly depends on whether saline minerals in the lake water approach saturation point, not depends on the lake water depth. Moreover, the abundance carried minerals flowing into the lake plays a decisive role. This inference can be basically supported by a simple laboratory experiment. Use a bowl fresh water (bowl diameter 10 cm, height 6 cm) to represent relatively shallow fresh water lake, and use a saline water basin (basin diameter 40 cm, height 20 cm) to represent relatively deep saline lake. Dissolve salt (NaCl) into saline water until the water is saturated, and then leave the bowl and the basin under sunshine for continuous evaporation. The experiment results indicate that no saline minerals precipitates can be found upon evaporation of fresh water from the bowl, whereas saline minerals are quickly precipitated at the beginning of the saline water evaporation from the basin although there is still much saline water left in the basin. The results shows that the saline minerals precipitation can also occur in semi-deep lacustrine or deep lacustrine facies provided that the saline minerals in lake water have reached their saturations, having nothing to do with the water lake depth,

Electron microprobe analysis about the actual drilling in 2017, the gypsum symbiosis was confirmed by energy spectrums of dozens of crystals with black mudstone containing calcite in strata (Fig. 2), and this proved that the saline minerals precipitation exits in deep water even without evaporation, drying up or exposure to surface.

Petrological characteristics

The whole rock mineral content analysis by XRD of drilling cores from Yuejin Area, Yingxi Area, Ganchaigou Area and Xianshuiquan Area in the Western Qaidam Basin, indicated that the carbonate contents (including dolomite and calcite) from such four areas were 69.8%, 54.6%, 45.0%, and 37.0%, respectively. The clastics contents were 11.8%, 19.2%, 27.8% and 30.6%, respectively. The shale content were 6.8%, 12.8%, 18.7% and 27.9%, respectively, and the authigenic minerals contents were, respectively, 11.7%, 13.4%, 8.6% and 4.6% (Fig. 3). The results revealed that the Yuejin area and Yingxi area had the highest carbonate contents (54.6% and 40.4% of dolomite, respectively); Xianshuiquan area and Ganchaigou area had the highest terrigenous clastics contents; Xianshuiquan area had the highest shale content; and Yingxi area had the highest saline minerals content. The rock components are closely related to the sedimentation environment. Long meandering river with sedimentary source is arrivalled in the east of the area-carrying abundant saline mineral solutes, such as Ca^{2+}, SO_4^{2-}, Na^+, Cl^-, Mg^{2+}, CO_3^{2-} and a little Ba^{2+}, Sr^{2+}. This process would make important contribution to precipitation of abundant saline minerals in the Yingxi area, or aggregation certain thickness salt bed, or mineral granules in the carbonate rocks (Huang et al. 2017). Due to the lake waves and fine-grained clastic particles and shale content are sedimented in lake, resulting in relatively high abundances of terrigenous clastics and shale contents in Ganchaigou area and Xianshuiquan area in the north. The Yuejin Area is a lake-bay area with relatively shallow water bodies and algae is developed and can easily break through the dynamic barrier formed by dolomite the hydration shell on the Mg^{2+} surface (Huang et al. 2016a; You et al. 2011), which is good for dolomitization and result in the highest contend of dolomite in Yuejin area (Table 2).

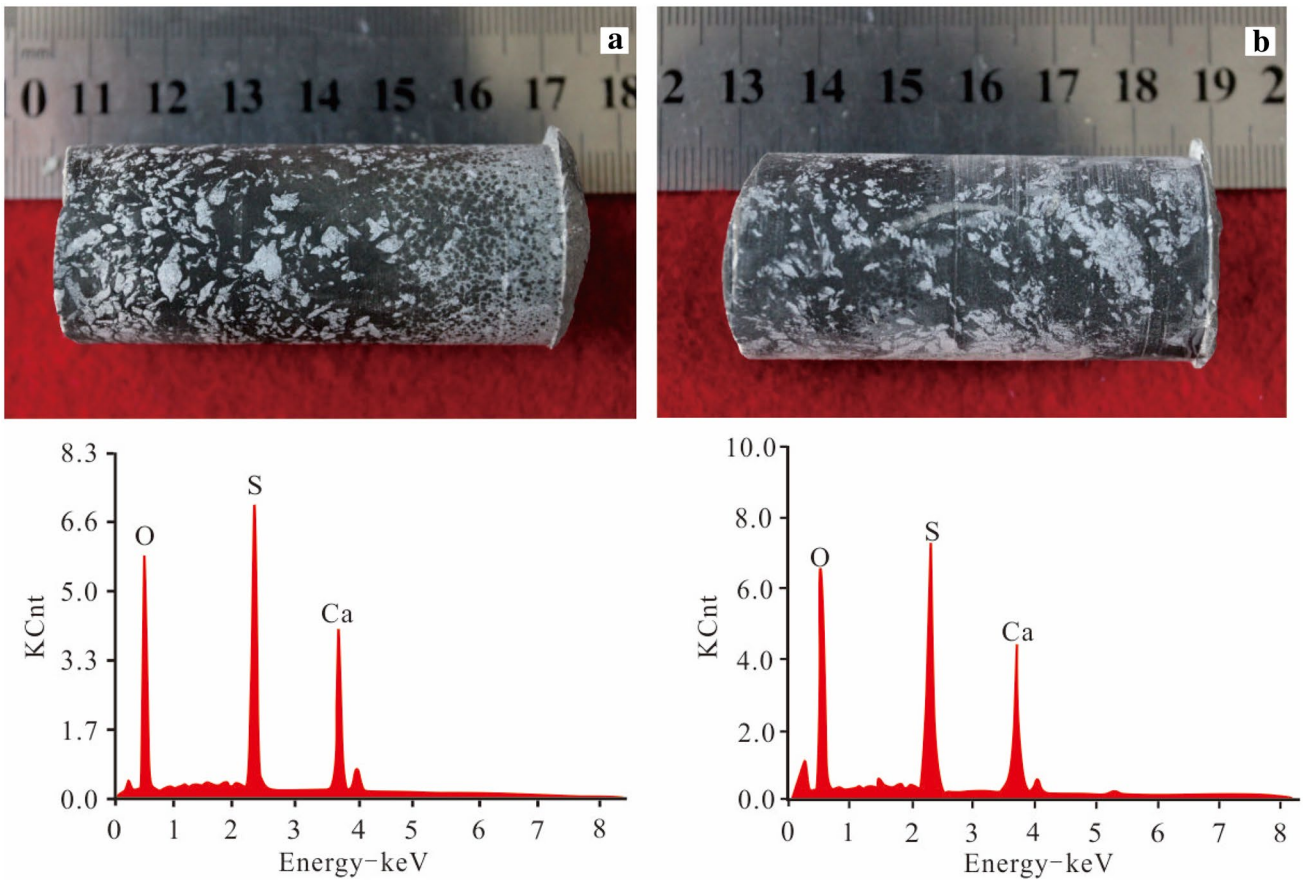

Fig. 2 Symbiosis of black containing calcite mudstone with gypsum of E_3^2 reservoirs of deep water deposits from Well S49-1 in the Yingxi area

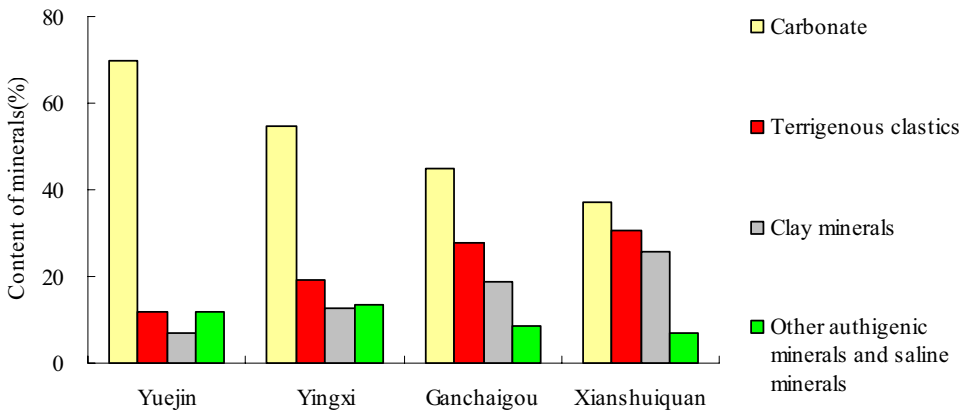

Fig. 3 Comparison of rock components of Oligocene reservoirs in the Western Qaidam Basin

Carbon and oxygen isotope analysis

In the continental lake, carbon and oxygen isotopes of protogenetic carbonates are important indicators for ancient environment and climate change. Previous studies have shown $\delta^{18}O$ and $\delta^{13}C$ in rock that the period is new and suffer feeblish late reformation are more closely related to the original sedimentary. For the samples after Mesozoic, $\delta^{18}O$ and $\delta^{13}C$ in carbonate rocks is more useful to study depositional environment. The carbon and oxygen isotopic composition in research area suffer from alteration faintly, so it can reflect original carbon and oxygen isotopic information during depositional stage in lake water.

The variation of carbon isotopic ratio in lacustrine carbonate sediments is controlled by inorganic carbon isotope composition in the lake water, and separately effect between the dissolved inorganic carbon (TDIC) and carbonate precipitation mineral. The inorganic carbon $\delta^{13}C$ dissolved in the

Table 2 Statistical table of the whole rock mineral content analysis by XRD of main reservoirs of Oligocene in the Qaidam Basin

Name of area	Sample no.	Depth (m)	Designation	Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Aragonite	Siderite	Magnesite
Yuejin area	YH101-5	2927.40	Algal dolomite containing calcite	4.9	0.6	3.2	19.5	0	13.3	6.7	0
	YH101-16	2928.85	Dolomite containing mud	13.3	1.1	4.9	6.4	0	0	0.6	0
	YH101-71	2943.05	Dolomite containing silt	7.7	0.6	3	5.7	0	0	0	0
	YH101-293	3160.40	Dolomite containing silt	7.3	0.4	2.4	6.6	0	0	7.4	0
	YH101-670	3208.64	Sandy dolomite containing calcite	8.1	0.3	4.4	6.7	0	0	5.1	0
	YH106-2	3281.70	Dolomite containing silt	10.6	1.7	4.4	11.3	0	3.7	6.1	2.6
	YH106-3	3294.20	Dolomite	4.6	0.2	2.2	7.5	0	0	7.0	0
	YH106-11	3366.10	Dolomite	4.0	0	1.8	16.7	0	0	0	0
	YH106-16	3358.40	Dolomite	6.6	0.3	2.9	6.6	0	0	0	0
	YH106-27	3381.90	Dolomite containing silt	9.6	0.5	3.4	11.1	0	0	0.6	0
	Average			7.7	0.6	3.3	9.8	0.0	1.7	3.4	0.3
Yingxi area	S3-1-3	4366.8	Dolomite	9.7	0.7	5.1	10	20.2	0	17.5	0
	S3-1-7	4369.35	Dolomite	13.8	0.7	8.2	4.5	0	0	13.1	0
	S3-1-23	4376.63	Dolomite	11.8	1.1	8.0	15.9	0	0	0	0
	S3-1-38	4371.15	Silty dolomite	11.7	1.7	12.6	6.9	0	0	0.2	0
	S41-6-1-10	3857.35	Dolomite containing silt	5.7	0.7	7.8	9.5	0	0	3.5	0
	S41-6-1-11	3857.95	Dolomite containing silt	12.1	1.3	11.3	7.6	38.2	0	11.7	0
	S41-6-1-12	3858.48	Saline dolomite containing silt	4.2	0.5	6.7	2.2	37.4	0	5.9	0.2
	S41-6-1-22	3867.12	Dolomite containing mud	6.1	1.1	5.2	5.9	0	0	0	0
	S38-1	2794.62	Argillaceous dolomite containing silt	14.8	0.9	6.5	8.4	16.2	0	0	0
	S38-11	3147.16	Dolomite containing calcite	8.8	1.0	9.1	18.3	0	0	0	0
	Average			9.9	1.0	8.1	8.9	11.2	0	5.2	0
Ganchaigou area	C6-1	1916.00	Carbonate rock containing silt	15.1	1.0	7.0	13.1	0	6.6	6.3	0
	C6-2	20100	Silty carbonate rock containing mud	21.9	1.1	8.9	12.6	0	4.6	0	0
	C6-3	2115.00	Carbonate rock containing silt	15.6	0.8	6.0	9.3	0	3.3	6.8	0
	C6-4	2214.00	Silty carbonate rock containing mud	23.4	1.4	6.9	15.4	0	7.9	0.2	0
	C6-5	22600	Silty carbonate rock containing mud	19.1	0.8	6.4	15.9	0	1.9	0	0
	C6-6	2347.00	Silty carbonate rock containing mud	17.1	2.7	9.2	14.9	0	4.0	6.8	0
	C6-7	2413.00	Silty carbonate rock containing mud	18.2	1.2	7.3	17.7	0	0	10.4	0
	C6-8	3667.00	Silty carbonate rock containing mud	16.7	0.6	8.0	12.2	0	0	10.1	0
	C6-10	3928.00	Silty carbonate rock containing mud	19.0	0.7	11.2	10.9	0	0	9.2	0
	Average			18.5	1.1	7.9	13.6	0	3.1	5.5	0

Table 2 (continued)

Name of area	Sample no.	Depth (m)	Designation	Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Aragonite	Siderite	Magnesite
Xianshuiquan area	X9-1	1532.95	Silty dolomite containing mud	17.7	0.9	7.5	4.5	0	2.8	8.4	0
	X9-2	1534.40	Sandy mudstone containing dolomite powder	23.7	1.7	6.3	7.3	0	2.6	1.0	0
	X9-3	1536.60	Sandy mudstone containing dolomite powder	22.7	0.9	7.1	12.4	0	2.5	0	0
	X9-4	1537.27	Dolomite	7.7	0.4	2.2	15.2	0	1.9	0	0
	X9-5	1538.67	Sandy mudstone containing calcite powder	18.3	1.1	7.2	20.6	0	1.9	1.1	0
	X9-6	1539.10	Sandy mudstone containing calcite powder	21.6	1.1	10	21.1	0	1.6	0.8	0
	X9-7	1540.80	Siltstone containing mud	33.6	2.1	11.5	14.8	0	1.8	0	0
	X9-8	1541.20	Dolomitic siltstone containing mud	26.4	6.0	6.9	11.4	0	2.0	0	0
	Average			21.5	1.8	7.3	13.4	0	2.1	1.4	0

Name of Area	Halite	Pyrite	Hematite	Analcite	Barite	Anhydrite	Anatase	Glauberite	Augite	Ankerite	Content of Shale content
Yuejin area	0	0	6.5	3.2	0	0	0	0	0	39.0	3.1
	0	4.0	2.3	2.3	0	0	0.5	0	0	51.8	12.9
	0	0	4.9	2.1	0	0	0	1.1	0	64.3	10.5
	0	4.2	3.5	1.9	0	2.6	0	0	0	56.3	7.3
	0.4	3.9	4.1	0	0	1.1	0	0	0	59.4	6.4
	0	0	5.0	1.4	0	3.1	0	0	0	44.3	5.8
	0	5.6	5.4	0	0	0.4	0	0	0	65.2	1.9
	0	5.6	4.5	0	0	9.9	0	0	0	56.6	0.9
	0.6	6.4	6.1	0.8	0	0.2	0	0	0	61.2	8.4
	0	7.0	4.8	1.3	0	0	0	0	3.1	48.3	10.3
	0.1	3.7	4.7	1.3	0.0	1.7	0.1	0.1	0.3	54.6	6.8

Table 2 (continued)

Name of Area	Halite	Pyrite	Hematite	Analcite	Barite	Anhydrite	Anatase	Glauberite	Augite	Ankerite	Content of Shale content
Yingxi area	0.6	2.9	0	0	0.4	0.6	0	3.1	0	20.1	9.0
	0.6	4.0	3.7	0	0	0	0.6	1.1	0	41.2	8.4
	2.1	4.3	3.2	0	0	0	0	0.8	0	43.3	9.5
	0.4	3.0	0	0	0	2.9	0	1.2	0	39.2	20.3
	1.2	2.9	3.6	0	0	10.7	0	1.3	0	42.4	10.7
	0.5	1.8	0	0	0	0.8	0	4.3	0	0	10.4
	0	3.8	0	0	0	16.1	0	14.0	0	0	9.0
	0.5	4.5	3.7	0	0	3.6	2.3	0	3.0	51.3	12.7
	0.6	2.4	0	0	0	4.1	0	2.8	0	17.5	25.8
	1.3	7.2	0	0	0	1.7	0	3.0	0	37.3	12.3
	0.8	3.7	1.4	0	0	4.1	0.3	3.2	0.3	29.2	12.8
Ganchaigou area	0	0	4.2	0	0	3.9	0	0	0	26.1	16.7
	0.4	3.6	2.2	1.7	0	1.0	0	0	2.5	16.7	22.7
	0	4.2	3.6	1.0	0	1.1	0	0	0	28.3	20
	0	3.6	2.7	1.3	0	2.9	0	0	0	15.4	19.0
	0.5	2.4	2.2	1.0	0	3.7	0	0	0	28.4	17.5
	0.5	3.2	2.3	0	0	3.0	0	0	0	17.6	18.8
	0.8	2.1	0	0.5	0	3.7	0	0	0	23.7	14.6
	0	4.1	0	0	0	4.0	0	0	0	29.0	15.3
	0.6	2.3	0	0.8	0	2.0	0	0	0	19.9	23.4
	0.3	2.8	1.9	0.7	0	2.8	0	0	0.3	22.8	18.7
Xianshuiquan area	0	0	2.7	3.0	0	0.7	0	0	0	33.7	20.9
	0.4	0	0	3.5	0	4.0	0	0	0	12.3	39.7
	0	1.9	0.5	3.7	0	0	0	0	0	19.3	31.6
	0	0	3.2	0	0	0	0	0	0	61.3	10.1
	0	2.4	0.6	5.1	0	1.0	0	0	0	0	42.6
	0	3.3	0	5.1	0	0	0	0	0	0	37.1
	0	0	0	3.9	0	4.0	0	0	0	7.2	22.9
	0	0	1.2	2.9	0	0.8	0	0	0	26.5	18.0
	0.1	1.0	1.0	3.4	0	1.3	0	0	0	20	27.9

lake water is related to the source of carbon, and separately effect between atmospheric CO_2 and dissolved carbon as a function of temperature.

The oxygen isotope change in lacustrine sedimentary system reflects hydrology balanced lakes status, namely the evaporation and injection change. Generally, evaporation makes the $\delta^{18}O$ in lake water heavier, since the lighter oxygen isotopic molecules escape from the lake surface preferentially, which makes oxygen isotope in carbonate settling in lake water heavier.

The range of $\delta^{13}C_{PDB}$ of lacustrine dolomite in Eocene Qaidam basin is between −4.5 and 0.2‰ with an average of −2.4‰. The range of $\delta^{18}O_{PDB}$ is between −6.1 and 0.4‰ with an average of −2.6‰. Previous research shows typical$\delta^{13}C_{PDB}$ lacustrine carbonate rocks is between −2 and 6‰, and for $\delta^{18}O_{PDB}$, it is between −4 and −8‰. Therefore, it is indicated that the carbon isotopic composition mainly deviates toward the negative and for oxygen isotopic composition toward the positive.

Carbon and oxygen isotope analysis on the carbonate rock in the research area, and compared the analysis results with open lakes (such as the Greifensee Lake in Switzerland, the Henderson Lake in the U.S., and the Huleh Lake in Israel), as well as closed lakes (such as the Great Salt Lake in the North America, and the Turkana Lake and the Natron-Magadi Lake in Africa), the comparison results indicate that the carbon and oxygen isotopic compositions of carbonate rock setting point in this area is located between open lake and closed lake (Fig. 4), which proves the inference of "semi-closed and semi-opened" confined lacustrine sedimentary environment.

Elemental analysis

Refer to analytical data of trace elements measured with ICP-MS method (Table 3), the Mn/Sr ratio (Wen et al. 2014; Zhou et al. 1997) can be used to evaluate whether the elemental compositions in the existing strata rocks are subject to diagenetic damage as a basis for sample selection with a good preserving effect, the average Mn/Sr ratio is 0.57, mostly less than 3, indicating that the tested samples have not been affected, or only been slightly affected by the diagenesis (Huang et al. 2016b). Therefore, their elemental compositions can reflect the original geochemical information during the sedimentation. Moreover, the correlation coefficient between the Ce abnormal value and the Eu abnormal value can be calculated to 0.02, and the correlation coefficient between the Ce abnormal value and ΣREE is 0.06. Neither of them shows significant correlation, which indicates that the tested samples are affected by the diagenesis

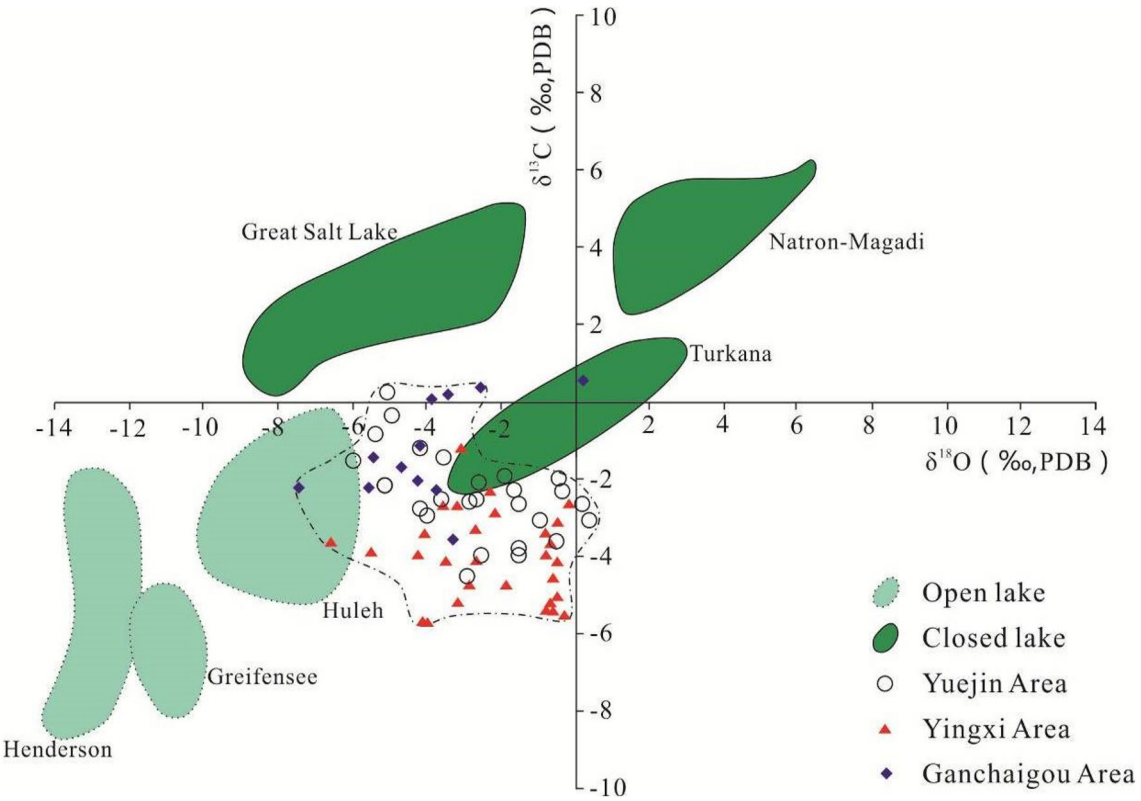

Fig. 4 Carbon and oxygen isotope composition of lacustrine carbonate rocks and analysis of sedimentary environment in Western Qaidam Basin

Table 3 Analysis of trace element geochemistry results list of the E_3^2 lacustrine dolomite in the Qaidam Basin

Sample no.	Depth (m)	Lithology	Li	Be	Sc	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Ga	Ge
S1-2-8	2758.19	Dolomite containing silt	30.21	1.07	4.21	1605.41	45.50	38.91	567.34	16.12	19.57	20.29	36.50	7.64	0.51
S1-2-11	2758.52	Dolomite containing mud	39.35	1.37	3.58	1780.34	53.62	40.40	498.44	9.67	21.07	25.45	56.51	9.31	0.63
S203-1	1502.70	Dolomite containing silt	67.58	1.65	8.52	2321.40	66.88	60.37	617.73	16.06	27.69	23.98	32.39	13.72	0.95
S203-3	4486.40	Dolomite containing silt	46.43	1.52	8.71	2444.84	81.43	61.64	461.54	30.12	31.11	26.98	162.31	16.59	1.09
S203-6	4495.35	Dolomite containing silt	35.10	1.08	3.38	906.30	31.85	34.88	480.89	11.82	13.88	14.05	3.01	5.68	0.33
S203-7	4496.90	Dolomite containing silt	95.55	1.91	9.63	3338.82	101.53	73.91	522.84	24.80	38.46	41.83	43.87	19.46	1.37
S203-8	4500.00	Silty dolomite	60.53	1.97	5.62	2442.57	73.31	54.68	637.75	24.60	28.96	29.80	51.95	13.17	0.90
S23-1	4034.90	Dolomite containing glauberite	52.37	1.65	6.74	2187.10	61.49	62.66	527.02	11.34	25.44	24.37	62.08	11.59	0.79
S23-3	4173.00	Dolomite containing calcite	15.80	0.68	4.82	1084.24	26.84	29.31	332.18	6.31	12.05	10.78	22.41	4.57	0.32
S25-1	4177.50	Dolomite containing calcite	13.45	0.59	2.45	581.88	31.74	38.41	414.28	8.92	10.27	6.15	50.04	3.76	0.23
S25-4	4216.80	Dolomite containing gypsum	26.59	1.26	6.02	1240.04	33.08	29.11	432.20	15.56	12.03	12.30	30.89	6.30	0.43
S25-6	4221.50	Dolomite	13.61	1.01	2.43	601.92	25.15	37.48	414.33	4.93	7.52	5.35	9.44	3.65	0.21
S30-1	4081.00	Dolomite containing silt	15.92	0.79	6.75	1498.20	35.93	38.06	477.86	11.04	15.90	11.35	31.35	6.85	0.39
S32X-6	4094.22	Dolomite containing calcite	24.85	0.70	0.85	1024.73	23.67	36.48	482.66	4.33	11.60	11.48	12.05	4.39	0.45
S32X-7	4097.74	Dolomite containing calcite	30.87	0.95	2.09	1103.61	30.07	31.02	420.56	8.38	14.12	12.45	19.28	5.56	0.58
S32X-8	4100.98	Silty dolomite containing mud	49.20	1.64	5.26	1616.63	52.93	44.72	679.77	7.92	20.11	20.55	30.85	9.88	1.12
S32X-9	4102.33	Argillaceous dolomite containing silt	35.86	1.62	9.16	2607.42	83.84	60.90	690.83	15.22	33.53	39.51	118.01	14.05	1.75
S32X-10	4112.53	Sandy limestone containing dolomite powder	36.86	1.30	8.91	1923.25	54.68	44.17	671.74	18.81	23.11	24.61	45.21	10.67	1.00
S32X-11	4117.04	Lime stone containing silt	38.13	1.45	10.28	2292.16	80.92	58.15	507.31	13.48	31.73	24.11	51.67	14.95	1.26
S32X-12	4121.50	Dolomite containing silt	20.14	1.04	4.36	1529.52	36.99	48.21	494.68	10.07	17.02	14.55	25.57	6.17	0.58
S32X-13	4127.93	Dolomite containing calcite	41.59	1.81	7.62	2177.19	79.91	86.49	661.27	12.53	30.36	25.11	61.72	14.29	1.09

Sample no.	Rb	Sr	Y	Zr	Nb	Mo	Cd	Sn	Cs	Ba	Hf	Ta	Pb	Bi	Th	U
S1-2-8	52.68	1187.82	10.64	58.96	5.03	2.33	0.06	1.31	4.32	450.31	1.81	0.42	13.97	0.23	4.99	2.64
S1-2-11	65.54	3410.48	13.05	75.99	5.47	2.34	0.08	1.55	5.59	1142.73	2.33	0.45	15.14	0.25	5.89	3.87
S203-1	96.92	675.05	17.05	93.09	7.46	3.19	0.06	2.15	10.25	373.52	2.70	0.56	18.91	0.29	7.77	3.70
S203-3	100.82	1722.24	16.19	93.88	7.59	3.94	0.63	2.33	10.61	1092.27	2.83	0.57	20.64	0.35	9.37	4.19
S203-6	37.07	3031.38	7.95	38.86	3.27	1.99	0.03	0.85	4.75	789.29	1.13	0.23	9.69	0.13	3.63	2.31
S203-7	150.63	243.76	23.88	128.90	10.59	5.82	0.06	3.31	14.97	376.62	3.90	0.83	24.84	0.47	13.27	6.57
S203-8	102.99	460.87	18.39	97.89	8.03	2.01	0.08	2.24	8.95	392.26	2.93	0.63	26.66	0.37	8.66	3.34
S23-1	90.44	841.17	15.03	86.31	7.16	1.04	0.10	1.78	7.44	512.31	2.59	0.56	30.28	0.29	7.36	2.83
S23-3	30.95	1841.98	7.48	71.61	3.38	2.58	0.06	0.85	2.45	1213.69	1.83	0.25	7.59	0.11	3.62	1.65
S25-1	18.26	1771.26	6.40	24.89	1.68	2.13	0.03	0.60	1.48	1077.57	0.68	0.14	3.15	0.08	1.56	1.53
S25-4	32.63	1666.25	11.17	64.95	5.01	7.51	0.08	1.20	4.58	1404.60	1.94	0.37	8.65	0.12	4.44	3.99
S25-6	25.62	2188.01	9.41	19.19	2.20	0.76	0.02	0.49	1.42	1333.58	0.56	0.23	5.25	0.08	2.19	1.56
S30-1	36.66	990.21	9.62	61.78	4.33	1.53	0.07	0.99	2.97	445.26	1.81	0.35	13.19	0.15	4.62	2.95

Table 3 (continued)

Sample no.	Rb	Sr	Y	Zr	Nb	Mo	Cd	Sn	Cs	Ba	Hf	Ta	Pb	Bi	Th	U
S32X-6	29.04	1061.46	7.36	30.52	4.07	2.25	0.03	0.91	2.82	599.97	0.87	0.33	7.27	0.10	2.04	1.73
S32X-7	32.70	2629.72	7.66	41.13	3.35	2.13	0.05	0.91	3.04	590.07	1.17	0.28	9.21	0.14	3.41	1.72
S32X-8	66.52	1539.85	14.59	67.92	5.01	5.16	0.05	3.29	6.54	782.59	2.03	0.40	10.13	0.19	6.20	4.41
S32X-9	82.83	546.94	20.53	115.35	8.02	6.87	0.21	2.58	8.69	539.78	3.45	0.66	25.15	0.40	9.92	9.56
S32X-10	66.10	1410.86	16.52	95.06	5.98	5.26	0.06	1.47	7.21	762.36	2.76	0.50	15.23	0.23	7.72	4.50
S32X-11	91.18	1755.76	17.09	90.42	6.59	6.28	0.06	2.24	9.86	821.41	2.63	0.52	17.00	0.30	7.64	4.93
S32X-12	41.67	603.86	10.10	89.66	5.12	3.10	0.06	1.00	3.31	227.55	2.58	0.40	12.53	0.19	5.17	2.84
S32X-13	95.78	1982.75	16.27	85.46	6.50	6.31	0.07	2.10	9.35	1134.32	2.56	0.50	16.67	0.29	7.58	4.46

The data of average UCC values of trace elements are cited from the research result data of Taylor and Mclenan

to a very limited extent, and the tested samples are able to represent the fluids geochemical characteristics during the sedimentation. It can be seen from the standardized spider web diagram (Fig. 5) of average upper continental crust (UCC) trace elements values (Taylor and Mclenan 1985) in dolomite obtained from the research area that Sr, Mo, Cs and Bi are subject to significant enrichment, and Nb, Sn and Ta contents are obviously lower than the average UCC values, Sr elements (in a high content) are the products sedimented at the saline lake basin, the celestite ($SrSO_4$) minerals presenting a high brightness can be obviously seen in the SEM back-scattered color images.

The Sr/Ba ratio is generally used for evaluating the sedimentation environment of lake water (Deng and Qian 1993), under the principle that the freshwater lake has less sulfate ions, so the sedimentations of Sr and Ba are unlikely to occuras the lake water gradually salinizes; The degree of mineralization gradually increases, the sedimentation of BaSO4 will occur firstly, followed gradually by sedimentation of SrSO4, therefore, have the higher the Sr/Ba ratio in the sediment, the higher the degree of salinization; the Sr content minimum value is 243.76 ppm. 21 samples obtained from in research area, the maximum value is 3410.48 ppm with an average of 1502.94 ppm; the Ba content ranges from 227.55 to 1404.60 ppm with an average of 764.86 ppm; the Sr/Ba ratio is greater than 1 with an average of 2.01. Therefore, it can be considered as typical saline lake sedimentation. Some scholars analysis on correlation between Sr/Ba ratio and elements B and Cl (the two indicating elements of salinity), obtained a no correlation conclusion, and a good positive correlation (Sun et al. 1997) between Sr/Ba ratio and carbonate content. Therefore, the sediment carbonate would affect the Sr/Ba ratio, so this ratio could not correctly reflect the original Sr/Ba ratio, such as Sr, paleosalinity of sedimentation environment might easily intrude into carbonate to replace a little Ca, the ratio was primarily controlled by Sr distribution coefficient in the carbonate. As a result, a little Sr existing would bring a certain error on paleosalinity estimate. For the research samples obtained from this area, an analysis on correlation between the Sr/Ba ratio measured with the ICP-MS method and the carbonate content measured by XRD (Fig. 6), indicates a relatively poor correlation (the correlation coefficient being only 0.18). The carbonate can only slightly affect the Sr/Ba ratio; therefore, it can be basically confirmed that using the Sr/Ba ratio as an indicator for a saline lake sedimentation environment in the research area is a relatively accurate method.

The Sr/Cu ratio is relatively sensitive to paleoclimate, and it is generally recognized that the Sr/Cu ratio is greater than the limit value 5 indicating an arid climate (Li and Zhou 2015). However, the Sr/Cu ratio calculated with the research samples is 5.83 ~ 408.92 with an average of 109.04, much higher than the limit value 5. Therefore,

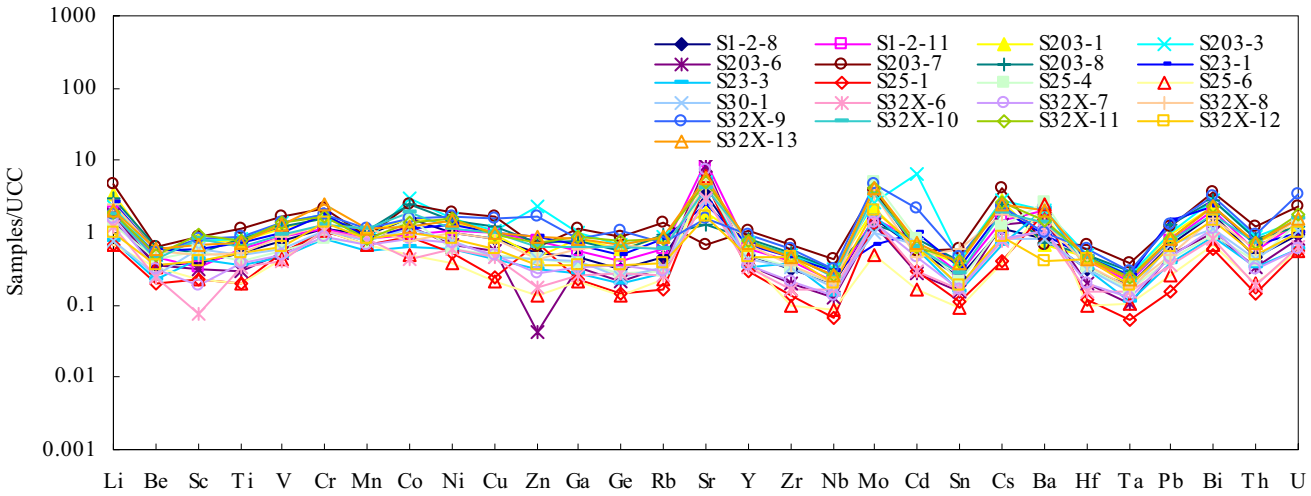

Fig. 5 Average standardized upper crust discrete race element's spider web of the E_3^2 lacustrine dolomites in Western Qaidam Basin

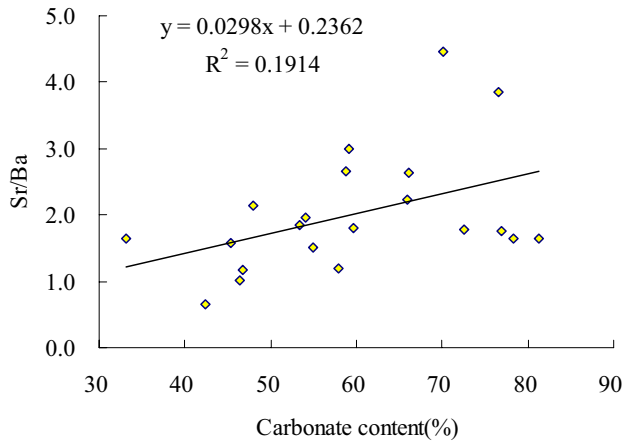

Fig. 6 Correlation between the carbonate content and Sr/Ba ratio of the E_3^2 reservoirs in Western Qaidam Basin

it indicates an arid climate, which is consistent with the evaporitic environment reflected by relatively developed saline minerals in the petrological characteristics. The U/Th ratio is able to reflect the oxygen-rich characteristics and oxygen-poor characteristics in the sedimentation environment. It is generally recognized that this ratio greater than 1 indicates an oxygen-rich environment, and this ratio less than 1 indicates an oxygen-poor environment. The U/Th ratio is 0.38 ~ 0.98, with an average of 0.62, completely lower than the limit value 1. Therefore, it indicates an oxygen-poor reducing environment. δ Ce is distributed in a range of 0.98 ~ 1.02 with an average of 1.01, basically with no anomaly, which indicates that the sedimentation occurs in the reducing sedimentation environment (Li and Zhou 2015).

Rare earth element

The analytical data obtained from the analysis on rare earth elements measured with the ICP-MS method (Table 4), total average quantity of the rare earth elements is 87.67 ppm (39.41 ~ 162.67 ppm), obtained from the lacustrine dolomite samples in the Qaidam Basin, between the chondrite ΣREE value (2.56 ppm) and average UCC ΣREE value (146.37 ppm) (Li and Zhou 2015). Generally, total quantity of the rare earth elements in the carbonate rocks accounts for a relatively low proportion in sedimentary rocks, mostly lower than 100 ppm (Wang 1989), some only being 20 ~ 30 ppm (Li and Zhou 2015). Hydrothermal dolomite also occupies a low content of rare earth elements. A few samples with extremely low quantity rare earth elements (such as 39.41 ppm) may have hydrothermal traces at some places (Kucera et al. 2009; Tang et al. 2013). Some samples with relatively high quantity of rare earth elements (such as 162.67 ppm) may be related to the mixed terrigenous clastics represented by fine-grained clay minerals, which in most cases enrich rare earth elements (Henderson 1984), thereby increasing the total rare earth elements quantity the entire rock to a certain extent. The rare earth elements distribution pattern diagram indicates a low–medium Eu negative anomaly (Fig. 7), and it is generally recognized that this is closely related to the interference by upper continental crus. It is affected by shale content mixed in the lacustrine dolomite to a certain extent, the Eu negative anomaly existence and the Eu positive anomaly missing in most samples indicate that the mantle-derived fluids have not involved the dolomite sedimentation in a large scale. Numerous previous research results have also proved that the research area is the penecontemporaneous metasomatic genesis (Cao et al. 2014; Yin et al. 2007; Sun et al. 2005), and the average

Table 4 Analysis of REE results list of the Eocene lacustrine dolomite in Western Qaidam Basin

Sample no.	Lithology	Depth (m)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho
S1-2-8	2758.19	Dolomite containing silt	15.61	32.07	3.61	14.25	2.57	0.51	2.21	0.36	1.95	0.38
S1-2-11	2758.52	Dolomite containing mud	18.78	38.05	4.42	16.88	3.03	0.67	2.79	0.47	2.46	0.48
S203-1	4502.70	Dolomite containing silt	23.29	47.45	5.51	20.84	3.72	0.78	3.35	0.57	2.94	0.57
S203-3	4486.40	Dolomite containing silt	25.32	50.55	5.95	22.47	3.87	0.81	3.30	0.56	2.91	0.57
S203-6	4495.35	Dolomite containing silt	10.52	21.50	2.39	9.51	1.71	0.36	1.48	0.24	1.29	0.25
S203-7	4496.90	Dolomite containing silt	33.72	68.49	7.68	30.65	5.24	1.05	4.82	0.80	4.29	0.82
S203-8	4500.00	Silty dolomite	27.03	53.70	6.30	23.00	4.15	0.86	3.80	0.65	3.42	0.67
S23-1	4034.90	Dolomite containing glauberite	21.72	42.68	5.01	18.75	3.34	0.70	3.03	0.52	2.72	0.54
S23-3	4173.00	Dolomite containing calcite	9.65	19.17	2.25	8.74	1.56	0.37	1.41	0.24	1.25	0.25
S25-1	4177.50	Dolomite containing calcite	8.01	16.19	1.90	7.36	1.45	0.36	1.36	0.23	1.12	0.21
S25-4	4216.80	Dolomite containing gypsum	13.91	27.27	3.22	12.56	2.38	0.53	2.13	0.35	1.88	0.37
S25-6	4221.50	Dolomite	11.33	21.37	2.44	9.97	2.01	0.48	1.94	0.33	1.63	0.31
S30-1	4081.00	Dolomite containing silt	12.66	24.81	3.06	11.29	2.05	0.42	1.79	0.29	1.61	0.32
S32X-6	4094.22	Dolomite containing calcite	12.25	23.06	2.62	10.46	1.72	0.36	1.47	0.23	1.27	0.25
S32X-7	4097.74	Dolomite containing calcite	10.36	20.28	2.40	8.39	1.64	0.34	1.44	0.23	1.25	0.24
S32X-8	4100.98	Silty dolomite containing mud	19.22	38.26	4.52	17.81	3.26	0.68	2.89	0.47	2.53	0.50
S32X-9	4102.33	Argillaceous dolomite containing silt	29.16	57.79	6.73	26.29	4.81	0.99	4.35	0.73	3.81	0.74
S32X-10	4112.53	Sandy limestone containing dolomite powder	20.88	42.79	4.83	19.23	3.47	0.80	3.26	0.55	2.87	0.56
S32X-11	4117.04	Lime stone containing silt	24.89	49.21	5.62	21.98	3.92	0.79	3.31	0.53	2.89	0.57
S32X-12	4121.50	Dolomite containing silt	14.13	27.96	3.32	12.95	2.28	0.47	2.08	0.35	1.82	0.36
S32X-13	4127.93	Dolomite containing calcite	22.78	43.80	5.29	21.24	3.59	0.81	3.27	0.56	2.88	0.57

Sample no.	Er	Tm	Yb	Lu	∑REE	LREE	HREE	LREE/HREE	LaN/YbN	LaN/SmN	GdN/YbN	δEu	δCe
S1-2-8	1.07	0.17	1.06	0.17	75.83	68.63	7.37	9.31	10.60	3.92	1.73	0.65	1.05
S1-2-11	1.37	0.21	1.32	0.21	90.93	81.83	9.31	8.79	10.19	4.00	1.75	0.70	1.02
S203-1	1.63	0.26	1.60	0.25	112.52	101.61	11.17	9.10	10.44	4.04	1.73	0.67	1.03
S203-3	1.64	0.26	1.62	0.25	119.83	108.97	11.12	9.79	11.19	4.23	1.68	0.70	1.01
S203-6	0.72	0.11	0.71	0.11	50.79	45.99	4.92	9.35	10.60	3.97	1.72	0.69	1.05
S203-7	2.36	0.38	2.37	0.37	162.67	146.84	16.21	9.06	10.21	4.15	1.68	0.64	1.04
S203-8	1.94	0.29	1.83	0.29	127.65	115.03	12.91	8.91	10.57	4.21	1.71	0.66	1.01
S23-1	1.55	0.24	1.49	0.24	102.29	92.19	10.33	8.92	10.44	4.20	1.68	0.67	1.00
S23-3	0.69	0.11	0.68	0.11	46.36	41.74	4.73	8.82	10.17	3.99	1.71	0.76	1.01
S25-1	0.58	0.09	0.55	0.09	39.41	35.27	4.22	8.35	10.45	3.55	2.05	0.79	1.02
S25-4	1.04	0.16	1.02	0.16	66.83	59.87	7.12	8.41	9.80	3.77	1.73	0.72	1.00
S25-6	0.82	0.13	0.77	0.12	53.51	47.60	6.04	7.88	10.55	3.64	2.08	0.75	1.00
S30-1	0.89	0.14	0.89	0.14	60.22	54.29	6.07	8.94	10.22	3.99	1.67	0.66	0.98
S32X-6	0.68	0.11	0.65	0.10	55.11	50.46	4.75	10.62	13.46	4.60	1.86	0.68	1.00
S32X-7	0.69	0.11	0.70	0.11	48.09	43.42	4.78	9.09	10.68	4.08	1.71	0.68	1.00
S32X-8	1.37	0.22	1.36	0.22	93.05	83.73	9.54	8.78	10.16	3.81	1.76	0.68	1.01
S32X-9	2.13	0.33	2.03	0.32	139.88	125.78	14.43	8.71	10.32	3.91	1.77	0.66	1.01
S32X-10	1.60	0.25	1.55	0.25	102.63	92.00	10.88	8.45	9.65	3.88	1.74	0.73	1.04
S32X-11	1.61	0.26	1.62	0.26	117.18	106.41	11.03	9.64	11.04	4.10	1.69	0.67	1.02
S32X-12	1.03	0.16	1.02	0.16	67.94	61.11	6.99	8.75	9.92	4.01	1.68	0.66	1.00
S32X-13	1.64	0.26	1.63	0.26	108.30	97.50	11.06	8.82	10.04	4.09	1.66	0.73	0.98

The standardized data of chondrite of rare earth elements are cited from the research results data of Sun and McDonough. ΣREE is the total content of rare earths; LREE/HREE is the ratio of light rare earths to heavy rare earths (LREE represents light rare earths, while HREE represents heavy rare earths); $(La/Yb)_N$, where N represents the ratio upon standardization of chondrite data; $\delta Eu = (Eu)_N/SQRT\ (Sm \times Gd)_N$; $\delta Ce = (Ce)_N/SQRT\ (La \times Pr)_N$, where N represents the value upon standardization of chondrite data

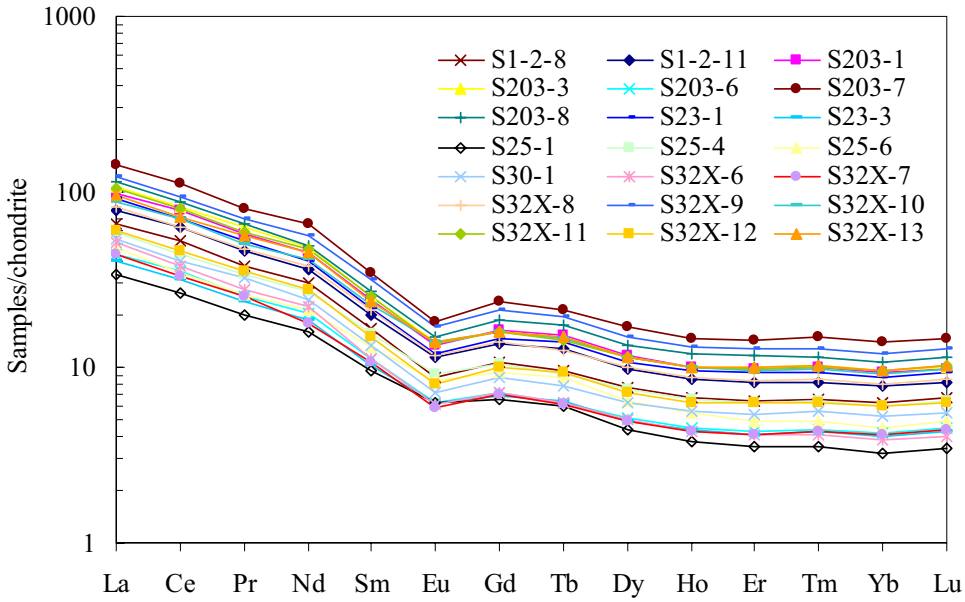

Fig. 7 REE distribution patterns of the E_3^2 lacustrine dolomites in Western Qaidam Basin

values of LREE/HREE, $(La/Yb)_N$, $(La/Sm)_N$ and $(Gd/Yb)_N$ are, respectively, 8.98, 10.51, 4.01 and 1.75. It is indicated that the light and heavy rare earths in the lacustrine dolomite are subject differentiation, and that the light rare earths more differentiated than the heavy rare earths. All distribution curves of rare earths are rightward, and heavy rare earths correspond to a relatively flat curve. This distribution model and characteristics reflect the mixed genesis characteristics, the rocks include multiple types of mineral compositions and multiple types of material sources.

Conclusions

Micritic lacustrine carbonate rocks are primarily developed in Oligocene E_3^2 in the Qaidam Basin; however, Yuejin area, Yingxi area, Ganchaigou area and Xianshuiquan area are subject to a certain difference in petrological characteristics: Yuejin area and Yingxi area have the highest carbonate contents, Xianshuiquan area and Ganchaigou area have the highest contents of terrigenous clastics, Xianshuiquan Area has the highest shale content, and Yingxi Area has the highest content of saline minerals. These petrographic characteristics are mainly controlled by the sedimentary environments.

Yingxi area is a semi-closed and semi-open lacustrine saline sedimentary environment, primarily influenced by: lithologic characteristics dominated by dark colors such as dark gray or black, and mixed with saline minerals sedimentation; palaeogeomorphologic characteristics prior to sedimentation in E_3^2; carbon and oxygen isotopes compositions; various trace elements such as Sr/Ba ratio, Sr/Cu ratio and U/Th ratio; distribution pattern of rare earth elements.

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