Journal of Petroleum Exploration and Production Technology (2019) 9:2441–2447
https://doi.org/10.1007/s13202-019-0676-z

ORIGINAL PAPER - EXPLORATION GEOLOGY

The characteristics and hydrocarbon-generation model of Paleogene–Neogene System saline lacustrine facies source rocks in the Western Qaidam Basin, China

Zhe Chen[1,2] · Chunsheng Zhang[2]

Received: 15 July 2018 / Accepted: 6 May 2019 / Published online: 14 May 2019

Abstract
To further understand the characteristics and hydrocarbon-generation model of Paleogene–Neogene System salt-lake facies source rocks in the Western Qaidam Basin, selecting argillaceous source rock samples from the Lower Ganchaigou Formation, the Upper Ganchaigou Formation, and the Upper Youshashan Formation in the Western Qaidam Basin, relevant experimental studies have been carried out, including pyrolysis of rocks, analysis of soluble components, and simulation of hydrocarbon generation and expulsion. According to the analysis of the experimental results, the selected sample thermal evolution degree stays in the low-mature–immature stage and shows good hydrocarbon-generation ability. There was a positive correlation between chloroform bitumen "A," moderate salt content and carbonate content, and cumulative liquid hydrocarbon production. The hydrocarbon-generation peaks of the Paleogene–Neogene salt-lake facies source rocks in the Western Qaidam Basin are significantly advanced compared to the traditional model. The result clearly defines the hydrocarbon-generation model of Paleogene–Neogene salt-lake facies source rocks in the study area, which is important to direct the oil and gas exploration in the Western Qaidam Basin.

Keywords Hydrocarbon source rock · Hydrocarbon-generation evolution · Characteristic · Western Qaidam Basin

Introduction

Detrital lacustrine facies have good conditions for oil and gas generation and accumulation. In terms of oil production conditions, the deep waters of the deep lake and semi-deep lakes are deep and are in a reducing or weak reducing environment, suitable for the preservation of organic matter and conversion to hydrocarbons. It is a good oil-producing environment, and all kinds of sand bodies developed in the lake phase are also good reservoirs of oil and gas (Jin et al. 2008; Shi et al. 2013).

The western part of the Qaidam Basin (hereinafter as the "Western Qaidam Basin") mainly develops the Paleogene–Neogene E_3^1–N_2^1 saline lacustrine facies source rocks. The source rocks have obvious changes in the longitudinal distribution, and there are different deposition centers in different stages in the horizontal direction. The Paleogene–Neogene source rocks in the Chaixi area are different from the marine lagoons or the general freshwater lakes (Peng 2004). The hydrocarbon-forming parent material is special, deposited in a high-salinity environment, and the gray-matter content is high. The abundance of organic matter is not too high overall, but the efficiency of hydrocarbon generation and discharge is high (Fu et al. 2016; Song et al. 2018; Zhang et al. 2018; Du et al. 2019).

Current research shows that for this set of saline lacustrine facies source rocks (Hu 2012), the researches on the hydrocarbon generation and expulsion efficiency, hydrocarbon-generation potential, and hydrocarbon-generation mode are still not intensive enough, thus restricting our understanding and evaluation on the saline lacustrine facies source rocks and hydrocarbon-rich depression in the Western Qaidam Basin. Through hydrocarbon-generation simulation experiments, this paper discusses the characteristics of Western Qaidam Basin saline lacustrine facies source rocks and their

✉ Chunsheng Zhang
zcs129@126.com

1 Key Laboratory of Exploration Technologies for Oil and Gas Resources (Yangtze University), Ministry of Education, Wuhan 430100, China

2 School of Geosciences, Yangtze University, Wuhan 430100, China

hydrocarbon-generation modes, so as to provide support for oil and gas exploration in the Western Qaidam Basin.

Regional geological background

The Western Qaidam Basin is located in the western part of the Qaidam Basin (Fig. 1) and mainly consists of tectonic units such as the Southwest Qaidam rift, the Mangya depression, and the Da Fengshan uplift, with an area of approximately 3×10^4 km^2 (He et al. 2011). The Qaidam Basin is located in the northern latitude dry climatic zone in the Tertiary. The water source only comes from the transient flood-type river, surrounded by the Kunlun Mountains, the Altun Mountains, the Qilian Mountains, and other mountain ranges. The evaporation is greater than the recharge, resulting in the salinization of the lake, forming an inland closure (Ye and Zhu 2006). Previous studies have shown that the tectonic movement in the Mangya depression area in the western part of the basin has led to a continuous decline. The area of the lake basin is the largest in the Oligocene–Miocene, and the paleo-salinity is 15–16‰. In the late Oligocene, the Indian plate continued to squeeze into the Eurasian plate, causing the Qinghai–Tibet Plateau to rise continuously, causing the sedimentary center of the Qaidam Basin to continue to move eastward, eventually being isolated from the humid climate of the ocean, causing the lake to continue to be salty and the paleo-salt gradually rising (He et al. 2011). In the Cenozoic stratum, from bottom-up there mainly are Lulehe formation (E_{1+2}), the lower segment of the lower Ganchaigou formation (E_3^1), the upper segment of the lower Ganchaigou formation (E_3^2), the upper Ganchaigou formation (N_1), the lower Youshashan formation (N_2^1), the upper Youshashan formation (N_2^2), Shizigou formation (N_2^1), and Qigequan formation (Q_{1+2}) (Dang et al. 2004; Zhu et al. 2005; Jiang et al. 2009).

Sample selection and experimental methods

The following are the principles for sample selection: ① The source rock samples must be representative. The selected source rock samples must not only represent the position of the source rock in the study area, but also enable the experimental results to represent the differences in hydrocarbon-generation behavior, hydrocarbon-generation processes, and hydrocarbon-generation products of different source rocks; ② the organic matter maturity of the source rock samples requires that the selected source rocks must not undergo significant hydrocarbon generation and discharge, ensuring that the organic matter maturity of the selected source rocks is still in the immature or low-maturity stage, ensuring the simulation results. It covers the whole process of thermal evolution of organic matter and then studies the hydrocarbon evolution characteristics and hydrocarbon properties of organic matter in different stratifications and different source rocks. Therefore, from the Western Qaidam Basin, we collected the rock core samples from Liang 3 Well, Hongdi 107 Well, Lvcan 1 Well and You 14 Well, respectively; the positions covered the Lower Paleogene–Neogene lower Ganchaigou formation, and the Upper Paleogene–Neogene upper Ganchaigou formation and upper Youshashan formation.

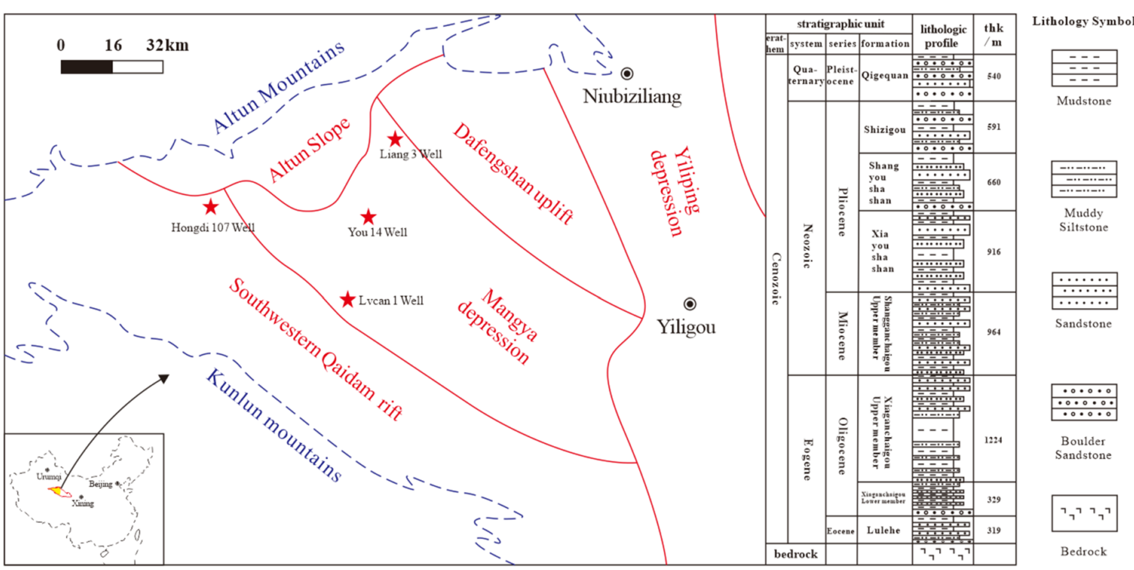

Fig. 1 Location of Western Qaidam Basin and characteristics of stratigraphic development

The experiment uses a closed system under water-added conditions. The experimental process is as follows: The thermal simulation experiment was carried out in a fully enclosed environment. The heating method was a water bath, and the heating method was gradually warmed up. A total of six temperature points were selected. For each of 200, 250, 300, 350, 400, and 450 °C, a 72-h thermal simulation was performed for each set thermostat. The specific experimental operation process is as follows: First, the ground source rock is selected to be placed in a high-temperature reaction vessel about 100 mesh, and is continuously replaced with helium gas to a vacuum; then, the sealed high-temperature reactor is heated. The six constant temperature points selected in this thermal simulation cover the hydrocarbon-generation process of low-mature, mature, and high-mature stages of source rocks, which can reflect the hydrocarbon-generation characteristics of the source rock organic matter in these three stages (Zhang et al. 2013). After completing the temperature setting process for each set temperature, the gas is collected by the gas collecting device, the solid residue sample is taken out, and the inner wall of the high-temperature reaction vessel is repeatedly rinsed and extracted with chloroform to obtain the discharged liquid hydrocarbons (Wu et al. 2015). The solid residue sample was subjected to chloroform Soxhlet extraction to obtain chloroform pitch "A," and then, the extract was subjected to group component separation to obtain saturated hydrocarbon, aromatic hydrocarbon, non-hydrocarbon, and asphaltene content, respectively.

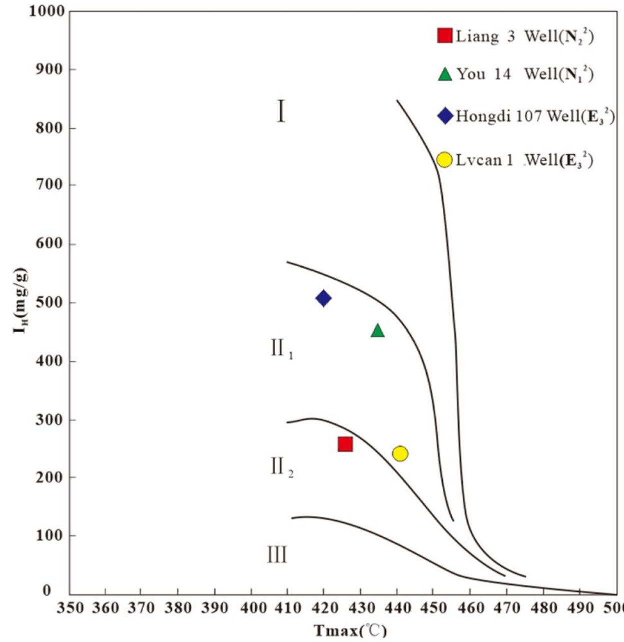

Fig. 2 Classification of organic matter based on hydrogen index and hydrogen index and hydrocarbon pyrolysis peak temperature

Experimental results

Pyrolysis characteristics of source rocks

The pyrolysis analysis of source rocks shows that the organic matter types of the source rock samples were analyzed based on the hydrogen index (I_H) and the pyrolysis temperature (Fig. 2), and the organic matter types of all samples are type II, among which, for the You 14 Well and the Lvcan 1 Well in the upper segment of upper Ganchaigou formation (N_1^2), and the Hongdi 107 Well in the upper segment of lower Ganchaigou formation (E_3^2), the organic matter types of their source rock samples are more like type II_1, for the upper Youshashan formation (N_2^2) Liang 3 Well, the organic matter type of its source rock sample is more like type II_2. The Lvcan 1 Well source rocks are at a low-maturity stage, while You 14 Well, Hongdi 107 Well, and Liang 3 Well source rocks are at the immature stage.

The pyrolysis data analysis shows (Table 1) that the pyrolysis parameters of samples of different positions in the Western Qaidam Basin are different. According to the organic matter abundance evaluation criteria from the previous studies (Zhang et al. 2013), the source rocks of the upper segment of lower Ganchaigou formation (E_3^2) Lvcan 1 Well and Hongdi 107 Well are good- and very-good-level source rocks; the source rocks of upper Ganchaigou formation (N_1^2) You 14 Well are good-level source rocks; the source rocks of upper Youshashan formation (N_2^2) Liang 3 Well are very-poor-level source rocks.

Characteristics of soluble components in source rocks

The study of soluble components (Table 2) shows that the wells of higher total hydrocarbon content are the You 14 Well and the Lvcan 1 Well; the total hydrocarbon content of Liang 3 Well and Hongdi 107 Well is less; and the chloroform bitumen "A" shows the same characteristics, the contents of You 14 Well and Lvcan 1 Well are higher, while the contents of Liang 3 Well and Hongdi 107 Well are less, and the carbonate content in the samples is less different.

Evolutionary characteristics of thermal simulation of source rocks

The amount and efficiency of hydrocarbon expulsion from hydrocarbon source rocks play an important role in hydrocarbon accumulation. Analysis of the thermal simulation results of source rock samples shows that the output of liquid hydrocarbons from different samples of the Western Qaidam Basin first increases and then decreases with the increasing of temperature (Fig. 3a). The peak of the output of expulsed liquid hydrocarbon appears at 300 °C, for the output of expulsed liquid hydrocarbon per unit weight of each sample, Lvcan 1 Well is the highest, Hongdi 107 Well is the second, and Liang 3 Well is the smallest. The thermal simulation data show that the unit weight of liquid

Table 1 Pyrolysis analysis data of Paleogene–Neogene-simulated samples in the Western Qaidam Basin

Well	Position	Depth (m)	Lithology	T_{MAX} (°C)	S_1 (mg/g)	S_2 (mg/g)	PG (mg/g)	TOC (%)	I_H (mg/g)	Ro (%)
Liang 3	N_2^2	1584.5	Gray mudstone	426	0.31	1.29	1.60	0.50	258	0.47
You 14	N_1^2	2125.5	Gray mudstone	431	0.43	4.15	4.58	0.92	451	0.45
Hongdi 107	E_3^2	2045.03	Gray mudstone	420	0.41	6.04	6.45	1.19	507	0.49
Lvcan 1	E_3^2	4310.5	Dark-gray calcium mudstone	441	1.59	2.27	3.86	0.94	241	0.68

Table 2 Analytical data of soluble components of Paleogene–Neogene-simulated samples in the Western Qaidam Basin

Well	Position	Chloroform bitumen "A" (mg/g rock)	Total hydrocarbon (mg/g rock)	Saturated hydrocarbon (%)	Aromatic hydrocarbon (%)	Non-hydrocarbon (%)	Asphaltene (%)	Carbonate (%)	Saltness (mg/kg)
Liang 3	N_2^2	0.17	0.08	40.93	7.30	48.78	2.99	12.23	3095.08
You 14	N_1^2	0.98	0.64	59.08	5.73	29.96	5.23	22.57	2433.47
Hongdi 107	E_3^2	0.05	0.02	32.95	8.86	50.29	7.90	20.38	1912.36
Lvcan 1	E_3^2	1.01	0.48	37.11	10.57	44.38	7.93	20.86	269.25

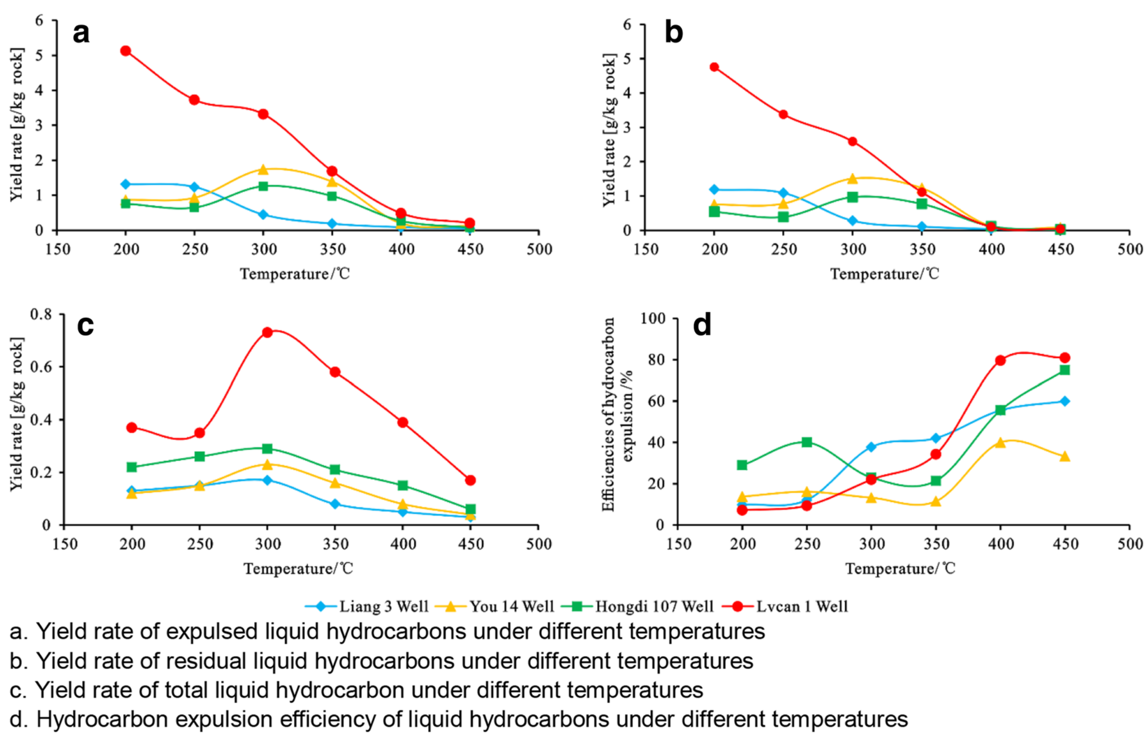

Fig. 3 Thermal simulation of hydrocarbon expulsion of Paleogene–Neogene source rocks in the Western Qaidam Basin. **a** Yield rate of expulsed liquid hydrocarbons under different temperatures. **b** Yield rate of residual liquid hydrocarbons under different temperatures. **c** Yield rate of total liquid hydrocarbon under different temperatures. **d** Hydrocarbon expulsion efficiency of liquid hydrocarbons under different temperatures

hydrocarbons expulsed from the source rocks in the upper segment of the lower Ganchaigou formation (E_3^2) Lvcan 1 Well and Hongdi 107 Well is higher than that of the upper Ganchaigou formation (N_1^2) You 14 Well and upper Youshashan formation (N_2^2) Liang 3 Well, but the upper Youshashan formation (N_2^2) Liang 3 Well has higher hydrocarbon expulsion efficiency.

The thermal simulation results of source rock samples show that the yield rate of residual hydrocarbon is obviously higher than that of the expulsed liquid hydrocarbon at each temperature stage, especially in the lower temperature stage. The yield rate of liquid hydrocarbon in different samples showed two evolutionary characteristics with the increasing of temperature (Fig. 3b). The first is the samples of Lvcan 1 Well and Liang 3 Well, when the initial temperature of simulation is at 200 °C, the yield rate of residual liquid hydrocarbon reaches the maximum; as the temperature gradually increases, the yield rate significantly reduces; the second, when the temperature increases from 200 to 300 °C, the maximum liquid hydrocarbon yield rate has been reached, and then, the yield rate gradually decreases with the increasing of temperature. Since the yield rate of residual liquid hydrocarbon in the simulation samples is much greater than the yield rate of expulsed liquid hydrocarbon, the change in the yield of total liquid hydrocarbons is basically similar to that of the residual hydrocarbons (Fig. 3c). The hydrocarbon expulsion efficiency of liquid hydrocarbons in all positions increases with the increasing of temperatures (Fig. 3d).

Analysis and discussion

Controlling factors of hydrocarbon-generation amount in source rocks

The level of organic carbon and the cumulative output of total liquid hydrocarbons determine the hydrocarbon-generation capability of the parent hydrocarbons of organic matter. The relationship between the organic carbon content of hydrocarbon source rocks and the cumulative output per unit rock of liquid hydrocarbons is shown in Fig. 4a. There is no significant positive correlation between the cumulative output per unit rock of liquid hydrocarbons and the organic carbon content, and the level of organic carbon cannot

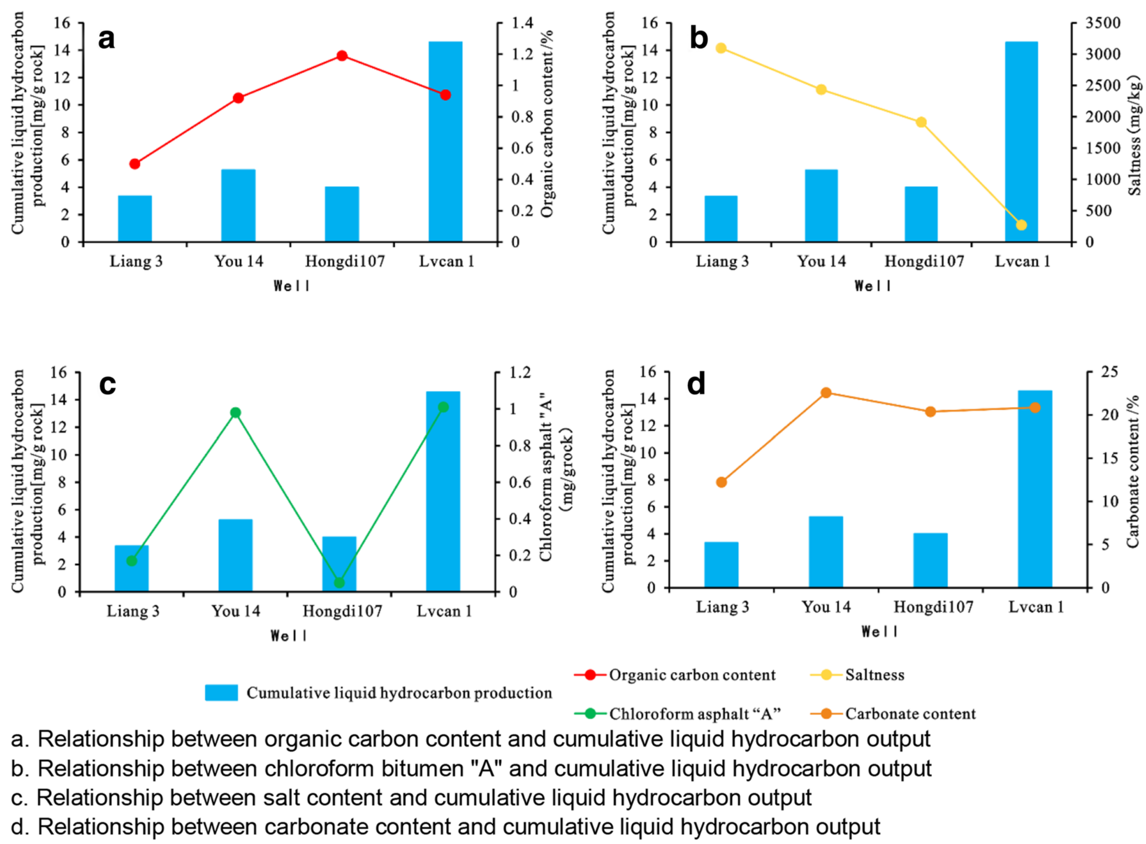

Fig. 4 Thermal simulation of hydrocarbon generation and hydrocarbon expulsion of Paleogene–Neogene source rocks in the Western Qaidam Basin. **a** Relationship between organic carbon content and cumulative liquid hydrocarbon output. **b** Relationship between chloroform bitumen "A" and cumulative liquid hydrocarbon output. **c** Relationship between salt content and cumulative liquid hydrocarbon output. **d** Relationship between carbonate content and cumulative liquid hydrocarbon output

completely determine the hydrocarbon-generation capacity of source rocks. There is a good positive correlation between chloroform bitumen "A" and the cumulative output of liquid hydrocarbons. It is shown that as the content of chloroform bitumen "A" increases, the cumulative output of simulated liquid hydrocarbons in source rock also increases (Fig. 4b).

The salt content of the source rock samples indicates (Table 2) that the source rocks of Liang 3 Well were formed in the environment where the salinity of the water body was relatively the highest, and the source rocks of Lvcan 1 Well were formed in the environment where the salinity of the water body was relatively the lowest. The study of salt content and output of liquid hydrocarbons shows that (Fig. 4c) the output of liquid hydrocarbons in the source rock of the Liang 3 Well with the highest salinity is the lowest, while the unit liquid hydrocarbon source rocks with the highest cumulative output is the source rock from the Lvcan 1 Well with the lowest salinity. The salt content and accumulative liquid hydrocarbon output of You 14 Well and Hongdi 107 Well indicate that the cumulative liquid hydrocarbon output and salinity of You 14 Well are higher than that of the Hongdi 107 Well. Therefore, for wells under extremely high salt content, the capability of liquid hydrocarbon generation is weak. In a moderate salinity range, higher salt content is conductive for the source rocks to generate hydrocarbons.

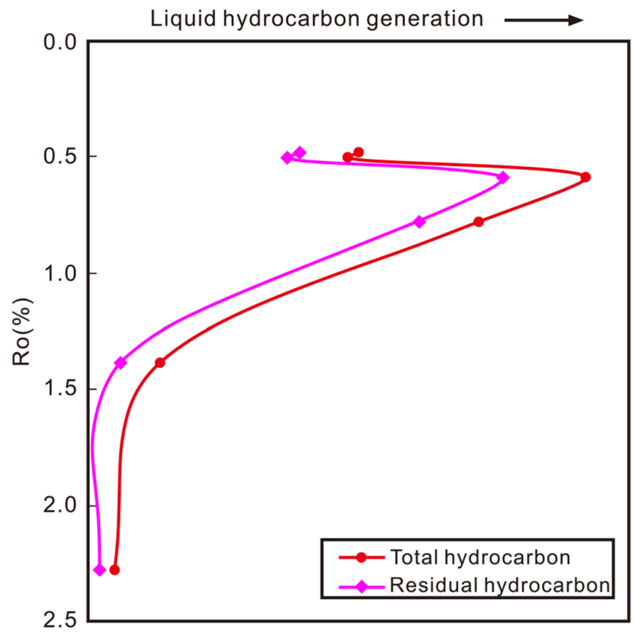

Fig. 5 Hydrocarbon-generation mode of the Paleogene–Neogene source rocks in the Western Qaidam Basin

Preliminary discussion on hydrocarbon-generation mode of source rocks

Comprehensive research shows that in the low-mature stage of thermal evolution (before 350 °C), the total hydrocarbon generation and hydrocarbon expulsion of liquid hydrocarbons all reach the peaks, and the total hydrocarbon yield rate reaches 0.45–3.32 mg/g at 300 °C and the yield rate of expulsed hydrocarbon reaches 0.17–0.73 mg/g rocks, showing good hydrocarbon-generation capacity. Its maturity range of source rocks is narrow, Ro is mainly between 0.5–0.8%; and when Ro is about 0.6%, the hydrocarbon generation of hydrocarbon source rocks reaches a peak (Fig. 5). After the maturity increased to 1.3%, the amount of hydrocarbon generation decreased dramatically. Compared with the traditional hydrocarbon-generation mode, the hydrocarbon-generation peak obviously appears earlier. This result plays an important role in guiding the exploration of oil and gas in the Western Qaidam Basin.

Conclusions

The study of the Paleogene–Neogene System saline lacustrine facies source rocks in the Western Qaidam Basin shows that the Lvcan 1 Well in the upper segment of upper Ganchaigou formation is in the low-mature evolutionary stage, the You 14 Well in the upper segment of upper Ganchaigou formation, the Hongdi 107 Well in the upper segment of lower Ganchaigou formation, and the Liang 3 Well in the upper Youshashan formation are in the immature evolutionary stages. The residual liquid hydrocarbon yields of the four groups showed two evolution characteristics with increasing temperature. One is that the yield of residual liquid hydrocarbons decreases with increasing temperature; the other is residual liquid with increasing temperature. The hydrocarbon yield increases first and then decreases; the hydrocarbon expulsion efficiency of each sample generally increases with the increase in temperature. In a moderate salinity range, higher salt content is conductive for the source rocks to generate hydrocarbons; meanwhile, its hydrocarbon-generation capacity is related to the carbonate content; for the Western Qaidam Basin Paleogene–Neogene saline lacustrine facies sources rocks, their hydrocarbon-generation peaks obviously appear earlier, and this simulation result has guiding significance for the exploration in the Western Qaidam Basin, and has expanded the exploration zones and strata systems in the Western Qaidam Basin.

Acknowledgements This study was jointly supported by the National Science and Technology Major Project of China (No.

2011ZX05001-002-007). Special thanks go to journal editor and reviewers for the insightful suggestions to improve the manuscript.

References

Dang YQ, Yin CM, Zhao DS (2004) Sedimentary facies of the Paleogene and Neogene in western Qaidam Basin. J Palaeogeogr 6(3):297–306

Du YS, Fan QS, Gao DL et al (2019) Evaluation of boron isotopes in halite as an indicator of the salinity of Qarhan Paleolake water in the Eastern Qaidam Basin, Western China. Geosci Front 10(01):253–262

Fu ST, Ma DD, Chen Y, Zhang GQ, Wu KY (2016) New advance of petroleum and gas exploration in Qaidam Basin. Acta Pet Sin 37(S1):1–10

He JX, Duan Y, Zhang XL, Wu BX, Xv L (2011) Study on hydrocarbon generation conditions of saline lacustrine source rocks of the upper unit of the Upper Ganchaigou Formation in Western Qaidam Basin. Miner Resour Geol 25(03):242–247

Hu YW (2012) Geochemical characteristics of crude oils and oil source correlation from GaSiKuLe Oilfield of Qaidam Basin. Master thesis, Yangtze University, Wuhan, China

Jiang XQ, Lv ZL, Sun BN, Liu CY, Fang LH (2009) Evaluation of hydrocarbon source rocks in Xiaoliangshan Sag, Western Qaidam Basin. Nat Gas Geosci 20(03):405–410

Jin Q, Zhu GY, Wang J (2008) Deposition and distribution of high-potential source rocks in saline lacustrine environment. J China Univ Pet (Ed Nat Sci) 32(4):19–23

Peng DH (2004) Geochemical characteristics and mechanism of hydrocarbon-generating for source rocks from the Tertiary Salty Lacustrine Facies in the West Region of the Qaidam Basin. Ph.D. Thesis, Guangzhou Institute of Geo-chemistry, Guangzhou, China

Shi H, Liu Z, Lian LD, Mao YK, Zhang QX, Yang QZ, Wu J (2013) Enrichment regularity of lithologic reservoirs in plateau saline Lacustrine Basin: taking the Southwestern Qaidam Basin for example. Nat Gas Geosci 24(04):701–711

Song BW, Zhang KX, Zhang L et al (2018) Qaidam Basin paleosols reflect climate and weathering intensity on the northeastern Tibetan Plateau during the Early Eocene Climatic Optimum. Palaeogeogr Palaeoclimatol Palaeoecol 512:6–22

Wu YZ, Duan Y, Xu L et al (2015) Distribution characteristics of dark mudstone and analysis of hydrocarbon potential of Chang 9 in Huanxian-Zhengning. Xinjiang Geol 33(03):388–392

Ye AJ, Zhu YM (2006) Geochemical and sedimentary features of tertiary saline lacustrine source rocks in Qaidm Basin. Oceanol Limnol Sin 37(5):472–480

Zhang MF, Zou HL, Feng BZ, Zhang XJ, Wu CJ, Chen R, Tuo JC (2013) The isomeric composition of the phenyl-polyaromatic hydrocarbons and its implications for thermal evolution of organic matter: a case study of source rocks in Western Qaidam Basin. Nat Gas Geosci 24(05):975–981

Zhang B, He YY, Chen Y et al (2018) Formation mechanism of excellent saline lacustrine source rocks in western Qaidam Basin. Shiyou Xuebao Acta Pet Sin 39(6):674–685

Zhu Y, Weng H, Su A et al (2005) Geochemical characteristics of Tertiary saline lacustrine oils in the Western Qaidam Basin, northwest China. Appl Geochem 20(10):1875–1889