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Hydrocarbon Generation and Expulsion Histories of the Upper Permian Longtan Formation in the Eastern Sichuan Basin, Southwest China

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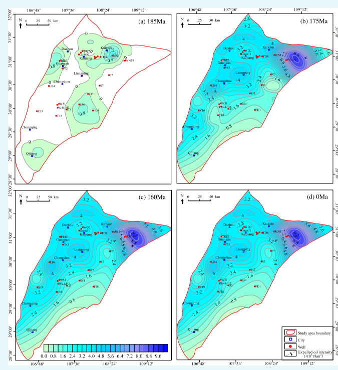
ABSTRACT: The Upper Permian Longtan Formation is the main source rock of the Lower Triassic Jialingjiang Formation in the Eastern Sichuan Basin, Southwest China. However, studies of its maturity evolution and oil generation and expulsion histories are lacking, which are not conducive to the accumulation dynamics of the Jialingjiang Formation in the Eastern Sichuan Basin. Based on the study of tectono-thermal history and geochemical parameter data of the source rock, this paper uses basin modeling technology to simulate the maturity evolution and hydrocarbon generation and expulsion histories of the Upper Permian Longtan Formation in the Eastern Sichuan Basin. The results show that the Longtan Formation source rock in the Eastern Sichuan Basin entered the oil generation threshold at the middle stage of the Early Jurassic and reached the high-maturity stage in the north and central regions at the late stage of the Early Jurassic, and the maturity did not increase after the late stage of the Middle Jurassic. The source rock had the characteristic of "one-stage oil generation and one-stage oil expulsion"; the corresponding period of high oil expulsion was 182−174 Ma (the late stage of the Early Jurassic), which was later than the formation time of the trap of the Jialingjiang Formation, possibly providing oil sources for the paleo-oil reservoirs of the Jialingjiang Formation. The results are of great significance to the gas accumulation process and exploration decision-making in the Eastern Sichuan Basin.



1. INTRODUCTION

With the continuous progress of oil and gas geological theory and exploration technology, global oil and gas exploration gradually moves from shallow to deep, from land to sea, and from conventional to unconventional.[1] As the most promising clean energy, natural gas plays an irreplaceable role in the new era of coping with global climate change and vigorously developing low-carbon energy. A large number of oil and gas exploration practices show that the discovered large- and medium-sized gas fields are closely related to the distribution of source rocks and have obvious characteristics of near-source distribution, that is, the geological idea of "source control theory".[2] For example, the Kela 2 gas fields discovered in the Tarim Basin,[3] the Jingbian,[4] Sulige,[5] and Yulin[6] gas fields discovered in the Ordos Basin are basically located in the hydrocarbon generation center and its periphery. As the primary condition for oil and gas reservoir formation, the quality of source rock and its hydrocarbon generation and expulsion histories are of great significance for the evaluation of oil and gas resources and the study of reservoir formation dynamics.[7−9] Sichuan Basin has the largest natural gas resources in China (Figure 1), and its output is also the largest in China. The output in 2021 reached 539.58 × 10^8 m^3, accounting for about 25% of China's natural gas production. However, it is a large superimposed basin developed on the Upper Yangtze Carton, which has undergone multiple tectonic movements since the Sinian;[10] thus, the accumulation process is complex. It is urgent to clarify the conditions of source rocks and the hydrocarbon generation and expulsion histories, so as to provide an important basis for the determination of the main accumulation period and the reconstruction of the accumulation history.

For research on the hydrocarbon generation and expulsion histories of source rocks, traditional research methods have mainly focused on the qualitative research in geology and geochemistry,[11−13] but in recent years, with the development of computer technology, more and more attention has been paid to quantitative and dynamic research methods.[14−16] At present, basin modeling is an important technology to quantitatively study the hydrocarbon generation and expulsion histories of source rocks. This technology can conduct numerical

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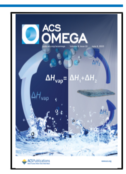

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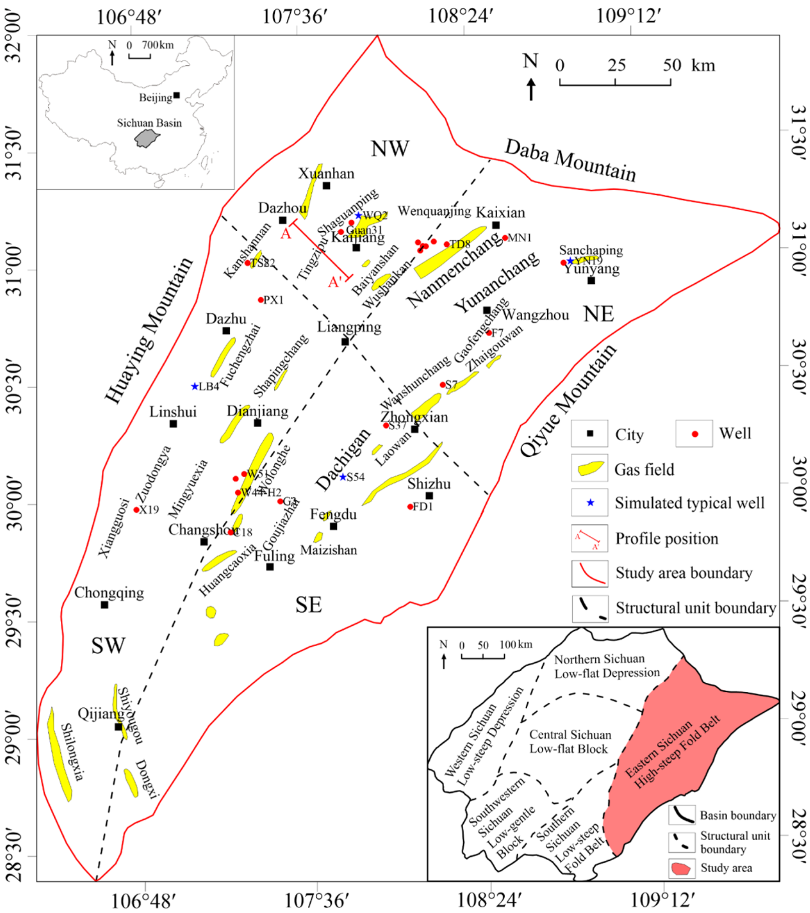

Figure 1. Structural unit division and position of the Eastern Sichuan Basin. NW, Northwest structural area; NE, Northeast structural area; SW, Southwest structural area; SE, Southeast structural area.

simulations and quantitative analyses on the formation and evolution of basins and the generation and expulsion processes of oil and gas and provide important parameters for the dynamics of oil and gas accumulation.[17,18] Among them, the BasinMod software provided by Platte River Associates Inc. is one of the more advanced basin modeling software programs. The software can easily realize the single well, profile, and stratum simulations of various basins. It has been widely used in the evaluation of oil and gas resources in major basins worldwide and has effectively guided the petroleum geological exploration of relevant basins.[19−22]

The first drilling well in the Lower Triassic Jialingjiang Formation of the Eastern Sichuan Basin began in 1937. After that, natural gas reservoirs in the Jialingjiang Formation were found on those structures, such as Shiyougou (1939), Wolonghe (1959), Shuanglong (1975), Fuchengzhai (1977), Huangcaoxia (1981), and Dachiganjing (1983). By the end of 2017, 33 natural gas reservoirs and gas-bearing structures were discovered in the Jialingjiang Formation in the Eastern Sichuan Basin, and 126 gas wells were obtained, with total proven gas reserves of 418.21×10^8 m^3 and a cumulative gas production of 296.80×10^8 m.[23] Therefore, the Eastern Sichuan Basin is an important production area in the Sichuan Basin, and the Jialingjiang Formation is an important production layer in the study area. The natural gas of the Jialingjiang Formation in the Eastern Sichuan Basin mainly came from the cracking of paleo-oil reservoirs, and the oil source of paleo-oil reservoirs was mainly the Upper Permian Longtan Formation in the Eastern Sichuan Basin.[23,24] However, previous studies on the Longtan Formation mainly focused on the static characteristics of the source rock, such as organic matter abundance, kerogen type, and maturity.[25,26] Dynamic evaluation of maturity, generation, and expulsion histories of the source rock is limited, which restricts the determination of the main reservoir forming period and the reconstruction of the hydrocarbon accumulation history of the Jialingjiang Formation in the Eastern Sichuan Basin. Therefore, it is necessary to restore the generation and expulsion histories of the Longtan Formation. In the paper, based on the tectono-thermal history and geochemical parameter data of source rock, the maturity, oil generation, and expulsion histories of the Longtan Formation in the Eastern Sichuan Basin were modeled by using basin modeling technology. The results are of great significance to the gas accumulation process and exploration decision-making in the Eastern Sichuan Basin.

2. GEOLOGICAL SETTINGS

The Eastern Sichuan Basin locates in the east of the Sichuan Basin, which is surrounded by the Huaying Mountain to the east, the Qiyue Mountain to the west, the Daba Mountain to the south, and Chongqing-Qijiang to the north. It belongs to the middle-uplift and high-steep fault fold belt of the paleocline in the Eastern Sichuan Basin, with an area of 2.7×10^4 km^2 (Figure 1).[27] Affected by the Jinning, Caledonian, Indosinian, Yanshan, and Himalayan Movements, the study area has experienced the basement formation stage of the Yangtze platform during the Middle-Late Proterozoic, the Cratonic depression stage during

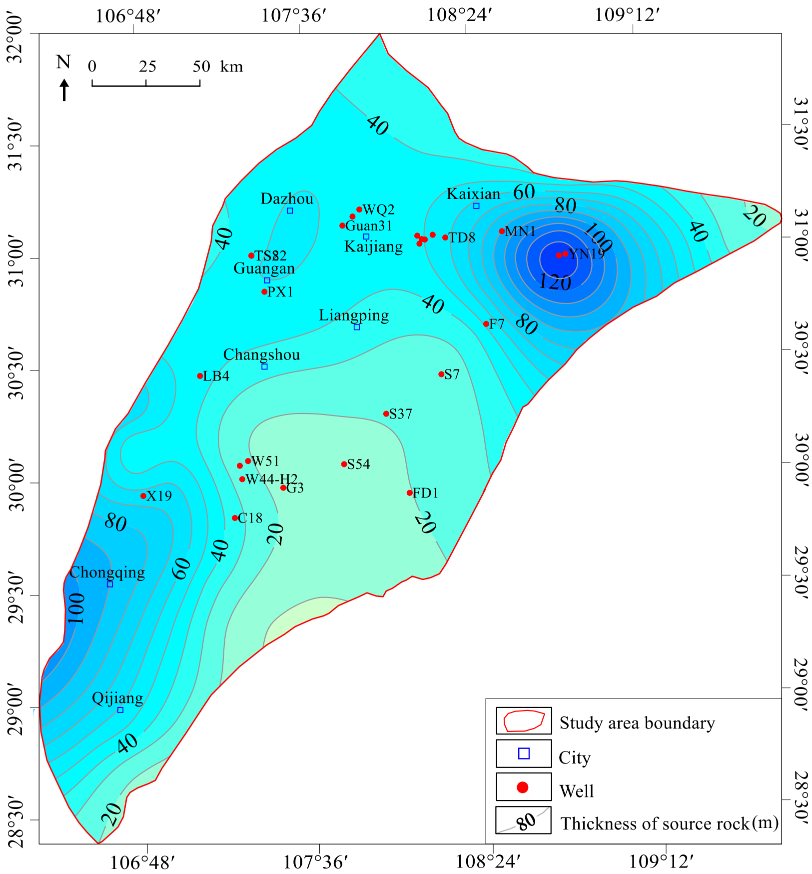

Figure 2. Thickness distribution of source rock of the Longtan Formation in the Eastern Sichuan Basin.

the Early Paleozoic, the Cratonic rifting stage during the Late Paleozoic to the Middle Triassic, and the Foreland Basin stage since the Late Triassic.[25] The source rocks in the Eastern Sichuan Basin have many layers and wide distribution areas, mainly including the Cambrian, Ordovician, Silurian, Lower Permian, and Upper Permian Longtan Formations.[25,28] The sedimentary environment of the Longtan Formation in the Eastern Sichuan Basin transitioned from fluvial facies to deep-water shelf facies, mainly developed mudstone, sandstone, and thin coal seams.[25] The source rock of the Longtan Formation is mainly mudstone,[24] and its thickness ranges from 50 to 120 m, with a maximum thickness of 130 m (Figure 2). The total organic carbon content (TOC) is generally greater than 2.0% (Figure 3) and the vitrinite reflectance (R_o) is between 1.5 and 3.5%, which is in the over-maturity stage.[23]

The present geothermal field and tectono-thermal history are the basis for studying the maturity, generation, and expulsion histories of source rocks.[29−31] The Eastern Sichuan Basin is a relatively "cold" area in the Sichuan Basin, with a geothermal gradient mainly between 16 and 23 °C/km and the terrestrial heat flow mainly between 45 and 65 mW/m^2, showing the low-temperature characteristics of the present geothermal field in a structurally stable area. The distribution of the geothermal gradient and terrestrial heat flow is characterized by high values in the west and south and low values in the east and north.[32] The tectono-thermal history of the Eastern Sichuan Basin shows the dual action characteristics of uplift and erosion and basin cooling effects. Since the Triassic, the geothermal gradient and heat flow have continuously decreased, the geothermal gradient has decreased from 30−38 to 20−23 °C/km, and the heat flow has reduced from 70−85 to 50−55 mW/m^2. The uplift and erosion began from the Early Cretaceous to the Late Cretaceous, with erosion amounts of 2.0−3.7 km.[32]

3. METHODS AND PARAMETERS

3.1. Methods. The maturity history is to analyze the hydrocarbon generation process of main source rocks in a region and its impact on the development and migration evolution of hydrocarbon kitchen, which is based on the present geothermal field and tectono-thermal history.[33−35] The maturity history of source rocks determines the hydrocarbon generation and expulsion processes. Based on the study of maturity history and further combined with the geochemical parameters of source rocks, it is possible to analyze the amounts and hydrocarbon generation and expulsion histories and then study the process of oil and gas accumulation.[12,35,36] This paper uses BasinMod software (including BasinMod 1D, BasinView, and BasinFlow software) provided by Platte River Associates Inc. to restore the maturity, oil generation, and expulsion histories of the Longtan Formation in the Eastern Sichuan Basin.

Based on tectono-thermal history, geochemical and geological parameters, the maturity, oil generation, and expulsion histories of typical wells in each structural zone were modeled by using Basinmod 1D software. Then, the three-dimensional geological model of the Eastern Sichuan Basin was established by using the thickness of each stratum and source rocks; the maturity, oil generation, and expulsion histories of the Longtan Formation in the Eastern Sichuan Basin during the critical period were modeled by using the BasinView software. During the simulation, the Easy%R$_o$ model was used to simulate the

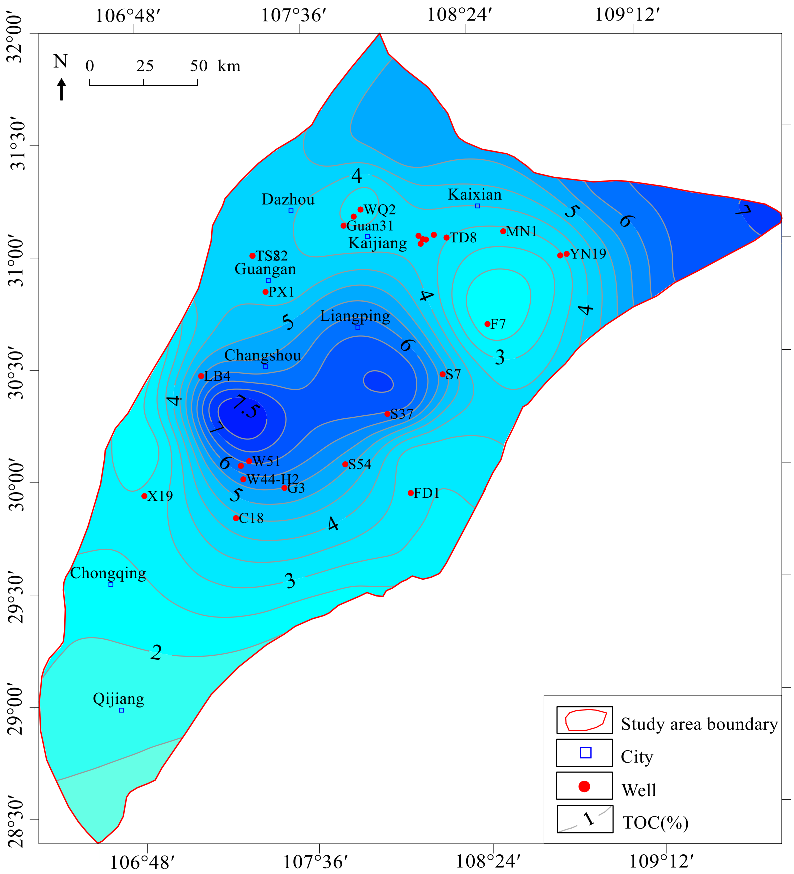

Figure 3. TOC of source rock of the Longtan Formation in the Eastern Sichuan Basin.

generated hydrocarbon,[37] and the critical saturation model was used to simulate the expelled hydrocarbon.[14]

3.2. Parameters. The basic parameters include geological, geochemical, and thermal parameters of source rocks. Among them, geological parameters include stratum thickness, erosion amount, stratum stratification, and lithology.[13] The thickness and erosion amount of each stratum and geochemical parameters of source rocks are from PetroChina Southwest Oil and Gas Field Company. The actual measured values of single well drilling are used for stratum stratification, and the initial porosity and compaction coefficient are obtained by Sclater and Christie.[38] The rock thermal conductivity,[39] heat production rate,[40] and thermal history[13,32] are based on previous research results. The present temperature and paleosurface temperature in our modeling are set to (15 °C) over the geologic time. The end ages of the strata are as follows: 140 Ma for the Jurassic (J); 195 Ma for the Upper Triassic Xujiahe Formation (T_3x); 208 Ma for the Middle Triassic Leikoupo Formation (T_2l); 210 Ma for the Lower Triassic Jialingjiang Formation (T_1j); 220 Ma for the Lower Triassic Feixianguan Formation (T_1f); 230 Ma for the Upper Permian Changxing Formation (P_2ch); 240 Ma for the Upper Permian Longtan Formation (P_2l); and 263 Ma for the Lower Permian (P_1).[41] The key geological historical periods for modeling include the middle stage of the Early Jurassic (185 Ma), the late stage of the Early Jurassic (175 Ma), the late stage of the Middle Jurassic (160 Ma), and the present day (0 Ma).

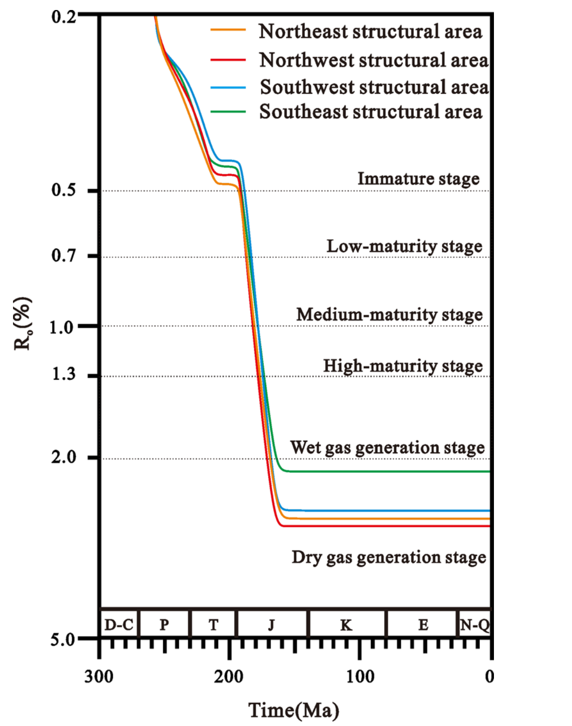

Figure 4. Maturity evolution of typical wells in different structural units in the Eastern Sichuan Basin. D−C, Devonian−Carboniferous; P, Permian; T, Triassic; J, Jurassic; K, Cretaceous; E, Paleogene; N−Q, Neogene−Quaternary.

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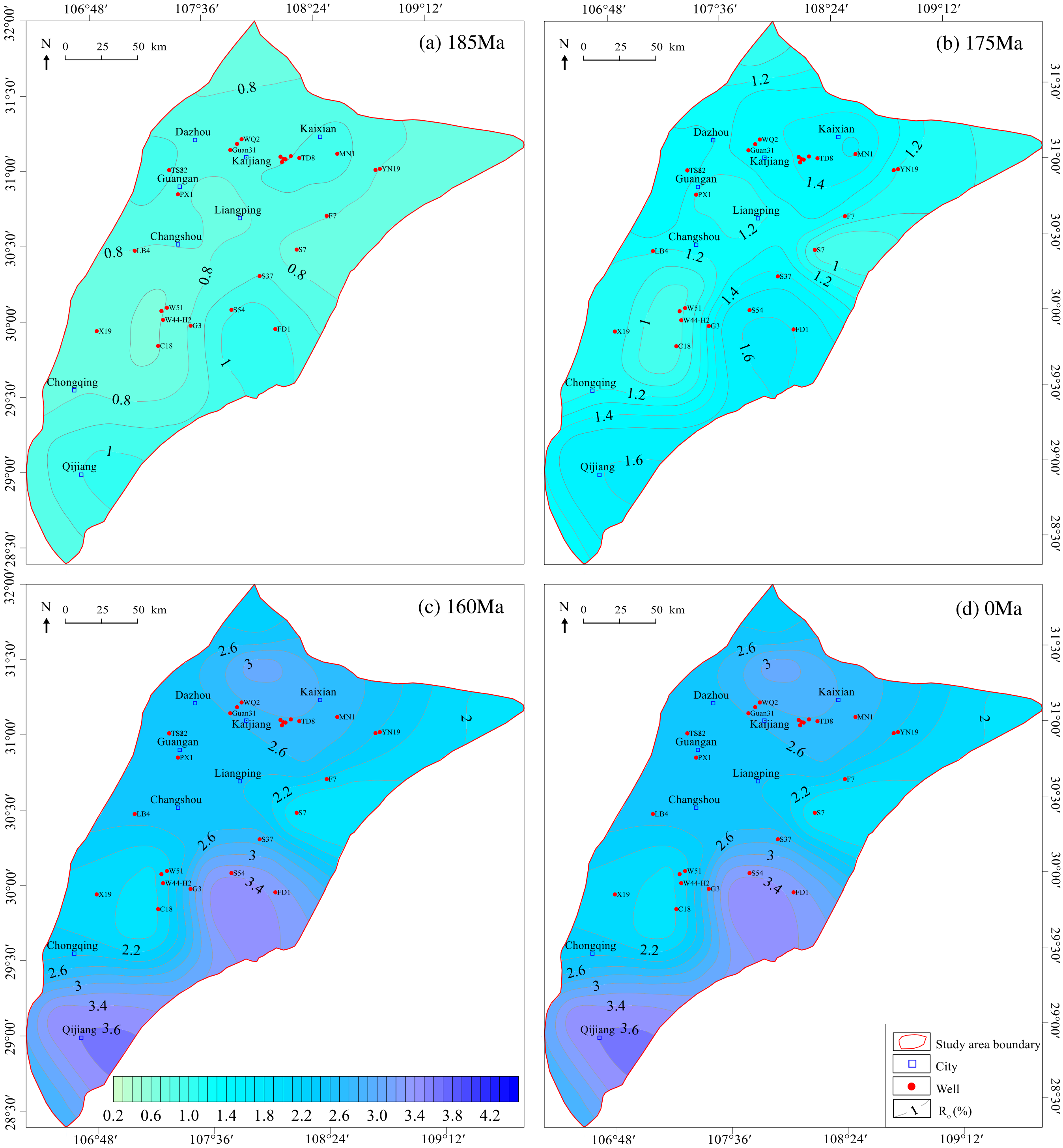

Figure 5. Maturity evolution of the top surface of source rock of the Longtan Formation in the Eastern Sichuan Basin. (a) 185 Ma, middle stage of the Early Jurassic; (b) 175 Ma, late stage of the Early Jurassic; (c) 160 Ma, late stage of the Middle Jurassic; and (d) 0 Ma, present day.

4. RESULTS

4.1. Maturity Evolution of Source Rock. *4.1.1. Maturity Evolution of Source Rock in Typical Wells.* In this paper, 18 wells in four different structural areas of the northwest, northeast, southwest, and southeast regions in the Eastern Sichuan Basin were selected to simulate the maturity history of source rock in typical wells. The measured vitrinite reflectance and maturity modeling values were used for fitting correction. The degree of fitting was high, indicating that the modeling results of maturity could reflect the maturity evolution process in the actual geological history period, suggesting the reliability of this modeling. The maturity evolution stages of source rocks are divided into five stages: the immature stage (R_o < 0.5%), low-maturity stage (0.5% ≤ R_o < 0.7%), medium-maturity stage (0.7% ≤ R_o < 1.0%), high-maturity stage (1.0% ≤ R_o < 1.3%), and over-maturity stage (R_o ≥ 1.3%). The over-maturity stage is divided into the wet gas generation stage (1.3% ≤ R_o < 2.0%) and dry gas generation stage (R_o ≥ 2.0%).[35]

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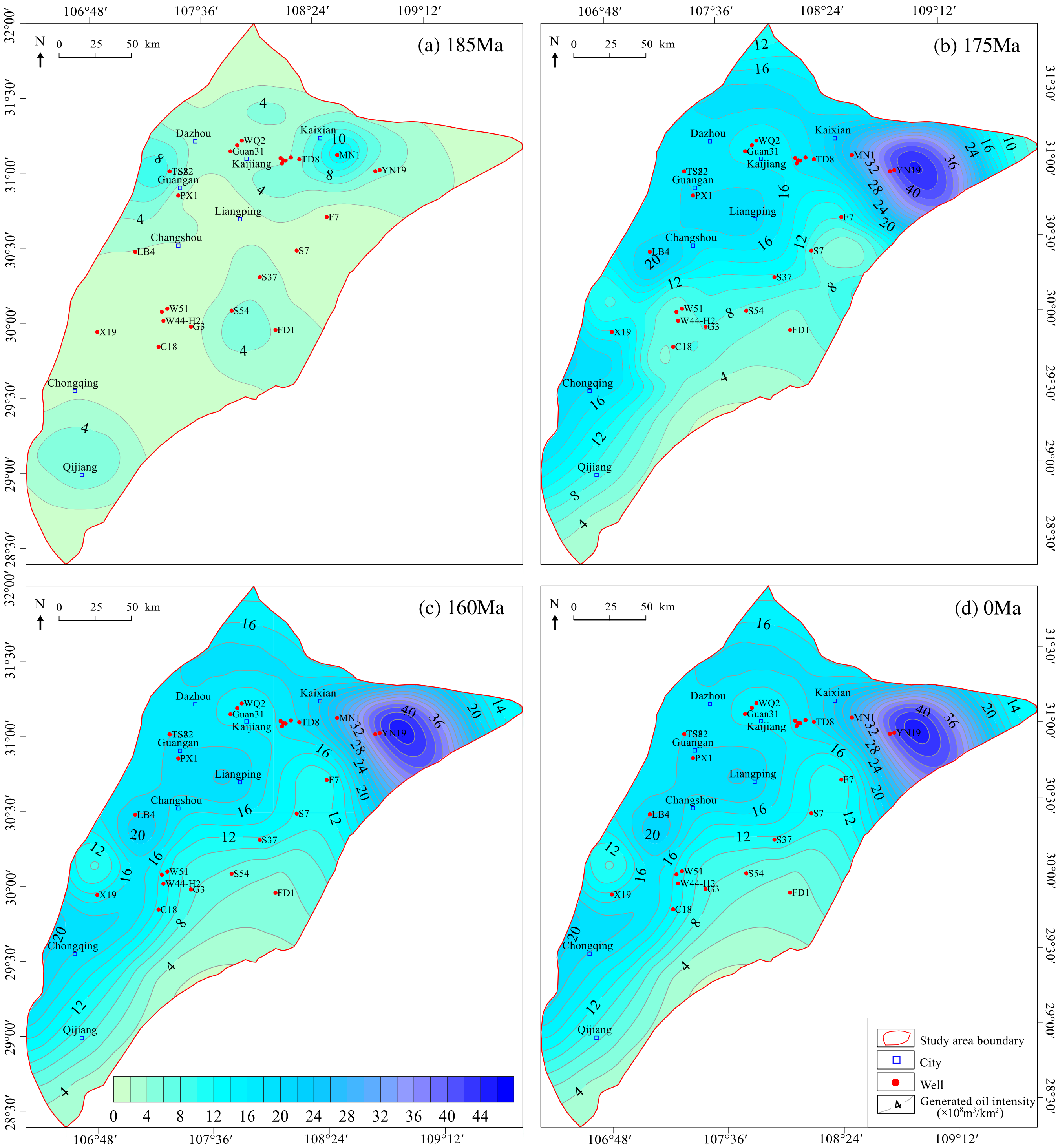

Figure 6. Oil generation intensity of source rock of the Longtan Formation in the Eastern Sichuan Basin. (a) 185 Ma, middle stage of the Early Jurassic; (b) 175 Ma, late stage of the Early Jurassic; (c) 160 Ma, late stage of the Middle Jurassic; and (d) 0 Ma, present day.

The simulation results indicate that the source rock of the Longtan Formation in the Eastern Sichuan Basin is currently in the over-maturity stage. There is a difference between the north and the south, and the maturity in the north is slightly greater than that in the south. The maturity evolution process shows that during the deposition period of the Jialingjiang Formation, the maturity of the top boundary of the Longtan Formation source rock increased rapidly, but the evolution speed slowed down before entering the oil generation threshold. The maturity increased rapidly again in the Early Jurassic and entered the wet gas generation stage at the late stage of the Early Jurassic, the dry gas generation stage at the late stage of the Middle Jurassic, and then the maturity remained constant. There are some differences in the maturity evolution histories of typical wells on the surface, mainly due to the differences in the sedimentary burial depth and paleo-heat flow value of the Middle and Upper Triassic, resulting in the rapid thermal evolution degree of the northeast and some wells, and the thermal evolution degree of the north was greater than that of the south (Figure 4).

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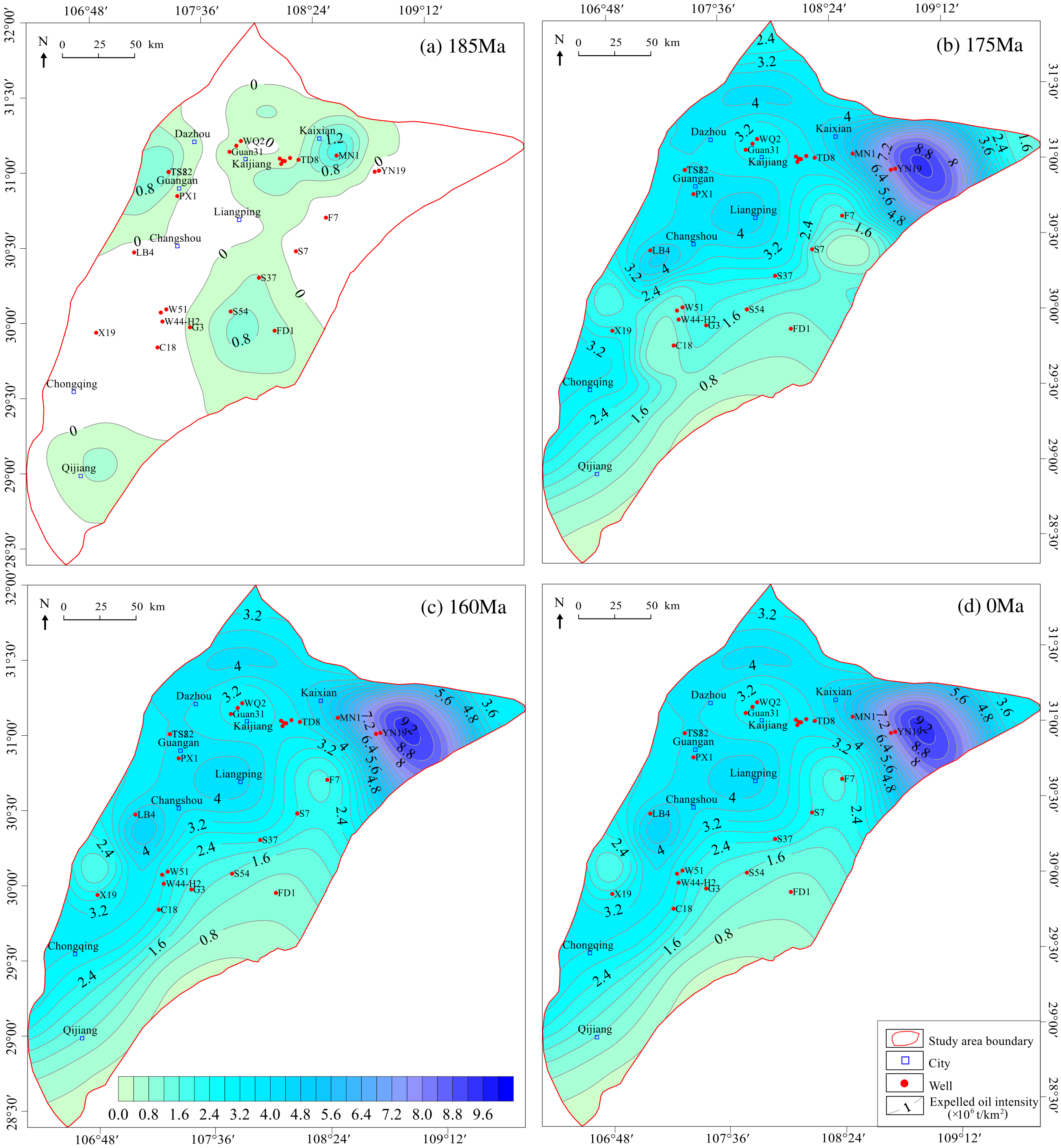

Figure 7. Oil expulsion intensity of source rock of the Longtan Formation in the Eastern Sichuan Basin. (a) 185 Ma, middle stage of the Early Jurassic; (b) 175 Ma, late stage of the Early Jurassic; (c) 160 Ma, late stage of the Middle Jurassic; and (d) 0 Ma, present day.

4.1.2. Maturity Evolution of Source Rock of the Longtan Formation. According to the characteristics of tectonic evolution and the thermal history of the sedimentary basin, Basinview software was used to simulate the maturity evolution history of the top surface of the Longtan Formation in the Eastern Sichuan Basin at the middle stage of the Early Jurassic (185 Ma), the late stage of the Early Jurassic (175 Ma), the late stage of the Middle Jurassic (160 Ma), and the present day (0 Ma) (Figure 5).

The simulation results reveal that at the middle stage of the Early Jurassic, the entire area of the source rock of the Longtan Formation entered the oil generation threshold and reached the medium-maturity stage (Figure 5a). At the late stage of the Early Jurassic, the maturity further increased, reaching the high-maturity stage in the north and central regions, which generated a large amount of oil, and wet gas generation stage in the south, with the maximum maturity attaining 1.6% (Figure 5b). At the late stage of the Middle Jurassic, the maturity of source rock continued to increase and the whole region reached the dry gas

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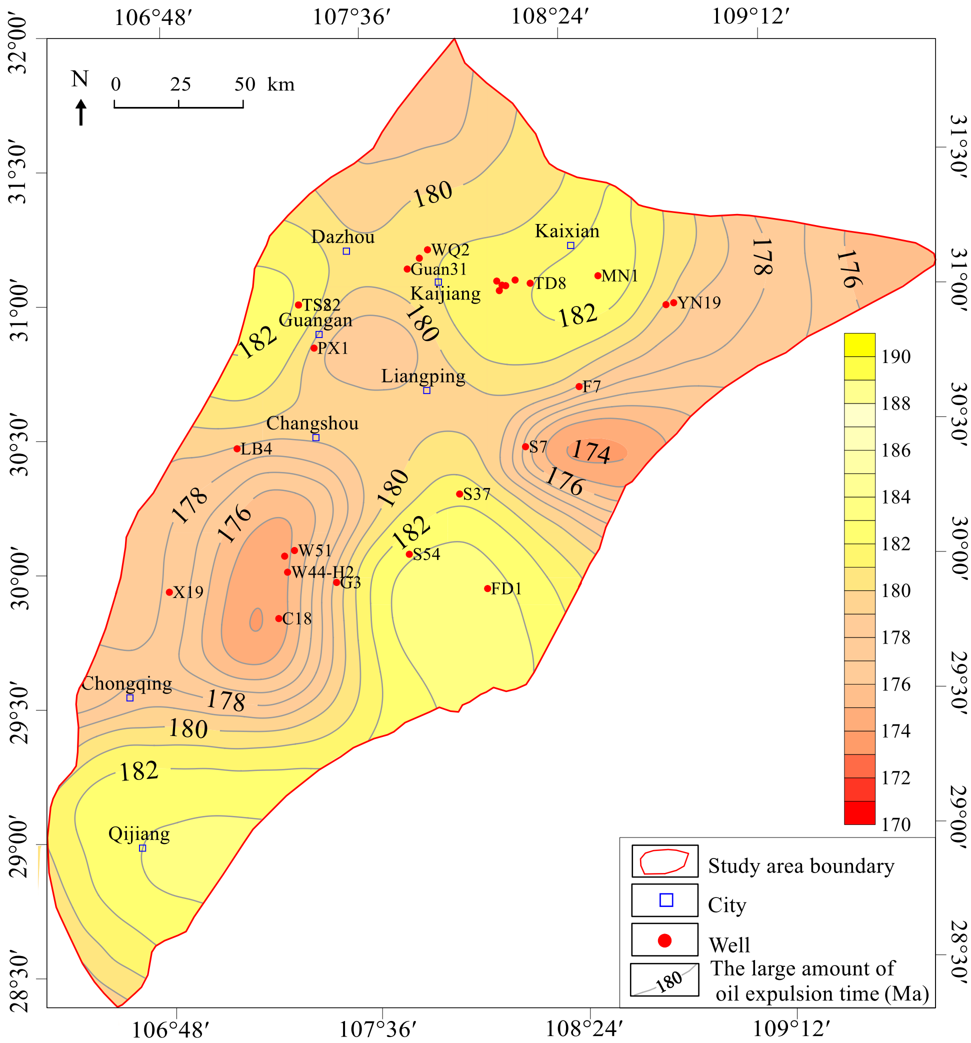

Figure 8. Large amount of oil expulsion time from the top surface of the source rock of the Longtan Formation in the Eastern Sichuan Basin.

generation stage, with the highest maturity in the south, greater than 3.0% (Figure 5c). The maturity has not increased since then (Figure 5d).

4.2. Oil Generation and Expulsion Histories. On the basis of the study of tectono-thermal histories and maturity evolution histories, and combined with geochemical parameters of source rock, the oil generation and expulsion histories of the Upper Permian Longtan Formation in the Eastern Sichuan Basin were simulated by using Basinmod 1D and BasinFlow software (Figures 6 and 7).

4.2.1. Oil Generation History. The simulation results indicate that the Longtan Formation source rock in the Eastern Sichuan Basin generally generated oil at the middle stage of the Early Jurassic, and the oil generation intensity was large in the north, with a maximum of 12×10^8 m^3/km^2, and small in the center (Figure 6a). At the late stage of the Early Jurassic, a large amount of oil was generated in the whole region, and the oil generation intensity was the largest in the northeast, with a maximum of 42 $\times 10^8$ m^3/km^2, and relatively small in the south (Figure 6b). At the late stage of the Middle Jurassic, the oil generation intensity increased slightly in the center and had little change in other areas (Figure 6c). The source rock in the whole region did not generate oil after this period (Figure 6d).

4.2.2. Oil Expulsion History. The simulation results suggest that the Longtan Formation source rock in the Eastern Sichuan Basin began to expel oil in the north and southeast at the middle stage of the Early Jurassic, and the oil expulsion intensity was relatively large in the north, with a maximum of 1.2×10^6 t/km^2 (Figure 7a). At the late stage of the Early Jurassic, a large amount of oil was expelled in the whole area, and the oil expulsion intensity was the largest in the northeast, with a maximum of 9.2 $\times 10^6$ t/km^2, and relatively small in the south (Figure 7b). At the late stage of the Middle Jurassic, the oil expulsion intensity increased slightly in the center and changed little in other areas (Figure 7c). Since then, the source rock no longer expelled oil (Figure 7d).

5. DISCUSSION

5.1. Reliability Analysis of Simulation Results. Basin modeling technology integrates information such as geology, geophysics, geochemistry, and tectono-thermal history to establish geological models that are consistent with or similar to reality.[15,29,30] Simulation calculations are conducted using models such as Easy%R_o model[37] and critical saturation model[14] to reproduce the entire process of hydrocarbon generation and expulsion from mature source rocks. The calculation results are closely related to the accuracy of a given geological, geophysical, geochemical, and tectono-thermal history. In this paper, the latest research results of PetroChina Southwest Oil and Gas Field Company have been used in the simulation. The Easy%R_o

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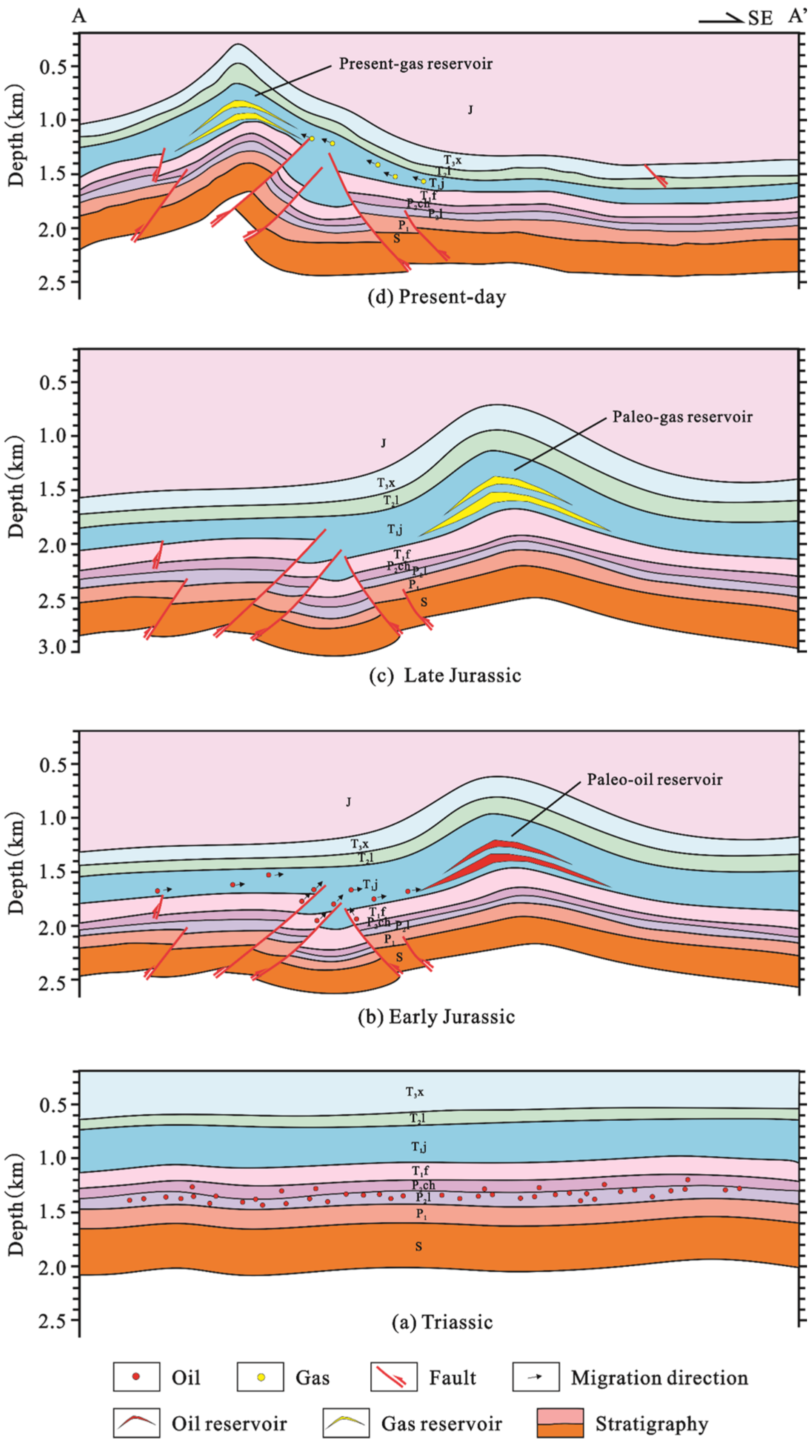

Figure 9. Gas accumulation process of the Jialingjiang Formation in the Eastern Sichuan Basin. S, Silurian; P_1, Lower Permian; P_2l, Upper Permian Longtan Formation; P_2ch, Upper Permian Changxing Formation; T_1f, Lower Triassic Feixianguan Formation; T_1j, Lower Triassic Jialingjiang Formation; T_2l, Middle Triassic Leikoupo Formation; T_3x, Upper Triassic Xujiahe Formation; J, Jurassic.

model has also been used since the 1990s and has been recognized by everyone. The critical saturation model is also the default for basin modeling software, and its critical saturation value can be adjusted based on research in different basins. The values in this paper are set based on the results of thermal simulation experiment of hydrocarbon generation in the Sichuan Basin. Therefore, the modeling results in the paper are reliable.

5.2. Relationship between Maturity Evolution and Tectonic Movement. Tectonic movement has an obvious control effect on the maturity evolution of source rocks. In the basin, it is mainly manifested in the control of later tectonic movement on the maturity of previously preserved source rocks, mainly regulating the paleogeothermal field in the source rock development area.[42,43] The Longtan Formation source rock in the Eastern Sichuan Basin experienced two stages of rapid increase in thermal maturity. The first stage of rapid maturity

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increase was the depositional period of the Jialingjiang Formation, which was mainly affected by the deep heat flow brought by the upwelling of the Emeishan mantle plume,[32] accelerating the maturity evolution of the source rock. Until the depositional period of the Xujiahe Formation, the marine face transformed into a continental face,[44] the high peak of heat flow disappeared,[32] and thus, the maturity evolution speed of the Longtan Formation source rock decreased and did not enter the oil generation threshold. The second stage of rapid maturity increase was the depositional period of the Jurassic, mainly due to the continuous increase of depositional buried depth,[41] causing the formation temperature to increase continuously and leading to the rapid maturity increase of source rock and the rapid entry into the oil generation threshold (Figure 5a). In the late stage of the Early Jurassic, the maturity further increased, and the northern and central parts were at a high-maturity stage, which was a large amount of oil generation stage (Figure 5b). In the late stage of the Middle Jurassic, with the increase of burial depth, the maturity continued to increase, and the whole area was in the dry gas generation stage. Due to the large thickness of the source rock in the south, the high organic carbon content of the source rock in the east, and the deep burial depth and high formation temperature, the southern and eastern regions experienced rapid maturation and evolution, with the highest maturity exceeding 3.0% (Figure 5c). Subsequently, due to the continuous influence of the Yanshan−Himalaya Movement, uplift and erosion occurred in the Eastern Sichuan Basin and the Cretaceous and Jurassic strata in some areas suffered substantial denudation,[10] resulting in the maturity of the source rock that has not increased since then.

5.3. Relationship between Hydrocarbon Generation and Expulsion Histories and Hydrocarbon Accumulation. The maturity evolution, hydrocarbon generation, and expulsion histories of source rocks are closely related to hydrocarbon accumulation.[8,29] Organic matter can only degrade and generate hydrocarbons when it reaches a certain degree of thermal evolution. Good matching between hydrocarbon generation and expulsion periods and trap formation periods is conducive to the migration and accumulation of oil and gas, leading to the formation of oil and gas reservoirs with industrial value.[45,46] The Longtan Formation source rock in the Eastern Sichuan Basin had the characteristic of "one-stage oil generation and one-stage oil expulsion"; the corresponding period of high oil expulsion was 182−174 Ma (the late stage of the Early Jurassic) (Figure 8), while the formation time of the trap of the Jialingjiang Formation was the early stage of the Early Jurassic;[23,24] hence, the main oil expulsion time was later than the formation time of the trap of the Jialingjiang Formation, which could provide oil sources for the paleo-oil reservoirs of the Jialingjiang Formation.

In addition, the source control theory emphasizes that "the oil and gas fields are distributed around the oil generation center and strictly controlled by the oil generation area". This theory is an important theory to guide oil and gas exploration in China's continental petroliferous basins.[47] After calculating statistics on the distribution characteristics of oil and gas reservoirs in China's petroliferous basins, Pang et al. propose that more than 95% of oil and gas reservoirs (number and reserves) are distributed in and around the main hydrocarbon expulsion range of source rocks or within a radius twice the hydrocarbon expulsion intensity of source rocks.[48] According to this theory, the source rock of the Longtan Formation can effectively supply oil to the paleo-structural high points of the Jialingjiang Formation to form paleo-oil reservoirs. When the reservoir temperature reached 160 °C, the paleo-oil reservoirs broke down to form paleo-gas reservoirs. Due to the later structural adjustments, the paleo-gas reservoirs can supply gas to the surrounding structures, forming the distribution characteristics of current gas-bearing structures (Figure 9). Therefore, for natural gas exploration of the Jialingjiang Formation, large-scale natural gas reservoirs around paleo-oil reservoirs can be considered.

6. CONCLUSIONS

(1) The source rock of the Upper Permian Longtan Formation in the Eastern Sichuan Basin entered the oil generation threshold and reached the medium-maturity stage at the middle stage of the Early Jurassic. At the late stage of the Early Jurassic, the maturity further increased, reaching the high-maturity stage in the north and central regions, which generated a large amount of oil. At the late stage of the Middle Jurassic, the whole region reached the dry gas generation stage. In addition, the maturity has not increased since then.

(2) The Longtan Formation source rock generally generated oil at the middle stage of the Early Jurassic. At the late stage of the Early Jurassic, a large amount of oil was generated in the whole region, and the maximum oil generation intensity was 42×10^8 m^3/km^2 in the northeast. At the late stage of the Middle Jurassic, the oil generation intensity increased slightly. Since then, the source rock has not generated oil.

(3) The Longtan Formation source rock began to expel oil in the north and southeast at the middle stage of the Early Jurassic. At the late stage of the Early Jurassic, a large amount of oil was expelled in the whole area, and the oil expulsion intensity was the largest in the northeast, with the maximum reaching 9.2×10^6 t/km^2. At the late stage of the Middle Jurassic, the oil expulsion intensity increased slightly. Since then, the source rock has no longer expelled oil. Based on the oil generation and expulsion histories, it is clear that the corresponding period of high oil expulsion was 182−174 Ma (the late stage of the Early Jurassic), which was later than the formation time of the trap of the Jialingjiang Formation, possibly providing oil sources for the paleo-oil reservoirs of the Jialingjiang Formation.

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Notes

The authors declare no competing financial interest.
The authors declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of the manuscript entitled.

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