

Article

Thermal Evolution and Hydrocarbon Generation History of Upper Cretaceous Qingshankou Formation in Central Depression of Songliao Basin

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Abstract

The Songliao Basin is an important Meso-Cenozoic terrestrial petroliferous basin in China. The hydrocarbon source rocks of the Upper Cretaceous Qingshankou Formation in the Central Depression possess favorable oil-generating conditions and huge hydrocarbon resource potential. This paper systematically analyzes the geochemical characteristics and simulates the thermal evolution history of Upper Cretaceous source rocks in the study area. The results show that the total organic carbon (TOC) content of Qingshankou Formation source rocks reaches up to 4.6925%. Organic matter is predominantly Type I and Type II₁, representing high-quality hydrocarbon source rocks. Thermal history simulation reveals two evolutionary stages: rapid temperature rise from the Early Cretaceous to the Late Cretaceous, and gradual cooling from the Late Cretaceous to the present day. Continuous temperature increase occurred during the depositional period of the Qingshankou to Mingshui Formations, with the maximum paleotemperature up to 180 °C. Paleotemperature has gradually decreased since the late depositional stage of the Mingshui Formation. The average TOC content of the 1st Member of Qingshankou Formation is 3.88%, classified as high-quality source rock. It reached the hydrocarbon generation threshold at approximately 82 Ma and is currently at the high-mature stage. The average TOC content of the 2nd and 3rd Members is 1.31%, also high-quality source rock. These strata entered the hydrocarbon generation threshold at about 80 Ma with relatively low vitrinite reflectance (Ro), belonging to the medium-mature and high-mature stage. Since the deposition of the Qingshankou Formation, the major hydrocarbon generation period of Cretaceous source rocks in the Central Depression ranged from 75 Ma to 80 Ma. The maximum oil generation rate is 28 mg/(g·TOC·Ma), and the cumulative oil generation capacity peaks at 220 mg/(g·TOC). The maximum gas generation rate reaches 5.5 mg/(g·TOC·Ma), with a maximum cumulative gas yield of 40 mg/(g·TOC).

Keywords: Songliao Basin; Central Depression; Qingshankou Formation; hydrocarbon source rock; geochemical characteristics; thermal evolution history

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1. Introduction

The Songliao Basin ranks among the largest Meso-Cenozoic terrestrial sedimentary basins in China and hosts abundant hydrocarbon resources [1]. Shale oil, a hot target for unconventional hydrocarbon exploration and development, has achieved remarkable exploration breakthroughs in this basin [2]. Gulong shale oil is mainly distributed in the Upper Cretaceous Nenjiang and Qingshankou Formations. The 1st Member and lower 2nd Member of the Qingshankou Formation serve as the primary exploration targets, categorized as pure shale-type shale oil [3,4]. Stable industrial oil production has been obtained from multiple drilling wells in Qijia-Gulong Sag, Central Depression. Source rocks here feature high maturity and superior shale oil quality, making this area the core priority for shale oil development in Daqing Oilfield [5–8].

Previous studies have extensively investigated structural features, sedimentary systems, reservoirs, source rocks, oil-source correlation, and the geothermal field in the Central Depression [9–13]. The 1st Member of Qingshankou Formation develops distinct laminated assemblages, and lamination diversity is closely correlated with oil-bearing property [14]. Rapid temperature elevation after deposition creates a favorable thermal regime that accelerates thermal maturation of Gulong shale oil [2]. Massive micron-scale pores and fractures are developed within shale reservoirs with favorable storage capacity [15]. Major oil-bearing intervals are capped and sealed by high-quality roof and floor strata, and high breakthrough pressure is concentrated in the central sag [16]. Prediction models linking reservoir parameters including porosity, clay content, water saturation, and permeability with logging data have been established, improving accuracy and efficiency of lithology identification verified by adjacent wells [17]. Studies on viscoelastic anisotropic wavefield simulation and response characteristics provide theoretical support for seismic exploration of Gulong shale oil [18].

Currently, Gulong shale oil exploration has stepped into large-scale reserve expansion and efficient production construction. Compared with other structural units, Gulong Sag is characterized by maximum burial depth, high thermal maturity, and premium shale oil quality. In 2023, the proven geological reserves of shale oil in Guye-1 Block reached 204 million tons, forming the largest single-block shale oil reserve in China. The discovery of the Gulong shale oil field subverts the traditional cognition that shale only generates but cannot store hydrocarbons, and breaks the conventional exploration pattern targeting tight sandstone interlayers as favorable zones. It marks the first major breakthrough in the exploration and development of pure shale-type shale oil in China, and demonstrates promising prospects of medium-high mature terrestrial shale oil in China. Nevertheless, systematic research on geochemical features and thermal evolution of Qingshankou Formation source rocks remains insufficient, restricting further shale oil exploration progress. As the fundamental material for hydrocarbon accumulation, source rock geochemistry and thermal evolution reconstruction are indispensable for hydrocarbon resource assessment and remain core research topics in petroleum geology [19–26]. In this study, organic geochemical methods are adopted to evaluate organic matter abundance, kerogen type, and thermal maturity [27,28]. Basin modeling and the EasyRo method are applied to reconstruct thermal evolution history, determine maximum geothermal gradient, peak paleotemperature, and hydrocarbon generation process. The research findings possess important theoretical and practical significance for local shale oil exploration.

2. Regional Geological Setting

The Songliao Basin is a large-scale Mesozoic–Cenozoic continental petroliferous basin in northeastern China. Geographically, it spans from 119°40' E to 128°24' E in longi-

tude and from 42°25' N to 49°23' N in latitude, covering Heilongjiang, Jilin, and Liaoning provinces as well as the Inner Mongolia Autonomous Region. The basin extends in a north-northeast (NNE) direction, with a length of approximately 750 km, a width of 330–370 km, and a total area of 260,000 km².

The Songliao Basin is subdivided into six first-order tectonic units: the Western Slope Zone, Southwest Uplift Zone, Southeast Uplift Zone, Northeast Uplift Zone, North Plunge Zone, and Central Depression Zone (Figure 1) [13]. The Central Depression Zone is the primary hydrocarbon-producing province of the basin, which contains second-order tectonic units such as the Gulong Sag, Daqing Placanticline, Sanzhao Sag, and Chaoyanggou Terrace.

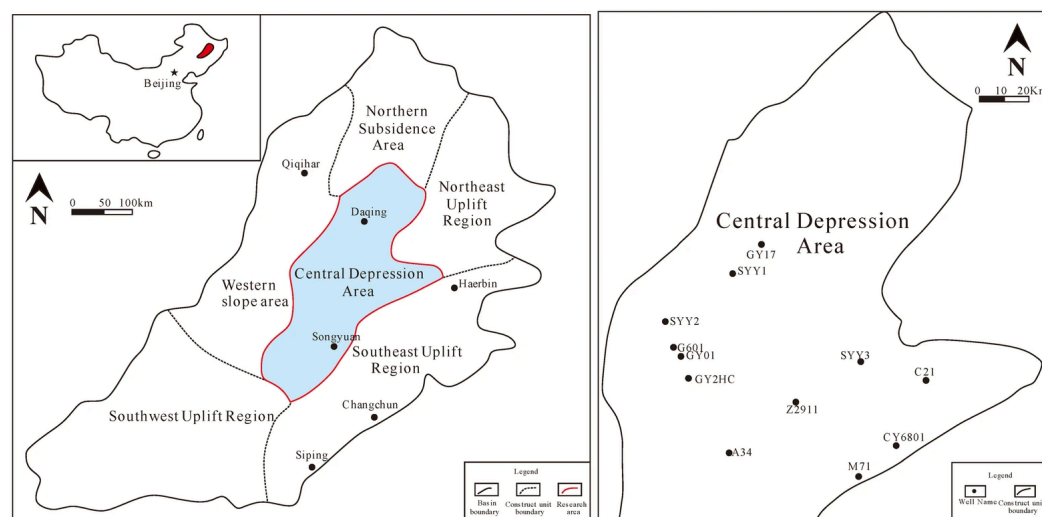


Figure 1. Tectonic location of the Central Depression in the Songliao Basin.

The Songliao Basin has undergone three evolutionary stages: the rifting stage, the depression stage, and the inversion stage. During the depression stage, two large-scale lacustrine transgression events occurred, forming extensive deep to semi-deep lake facies in the central part of the basin. These events led to the deposition of two important sets of hydrocarbon source rocks, the Qingshankou Formation and the Nenjiang Formation, which constitute the primary source rock intervals for shale oil enrichment (Figure 2). The Qingshankou Formation is the main interval for shale development. It is dominated by organic-rich gray to dark gray mudstone and shale with large thickness, wide distribution, high organic matter abundance, and excellent hydrocarbon generation potential, making it the primary target interval for shale oil exploration and development in the basin [29–31].

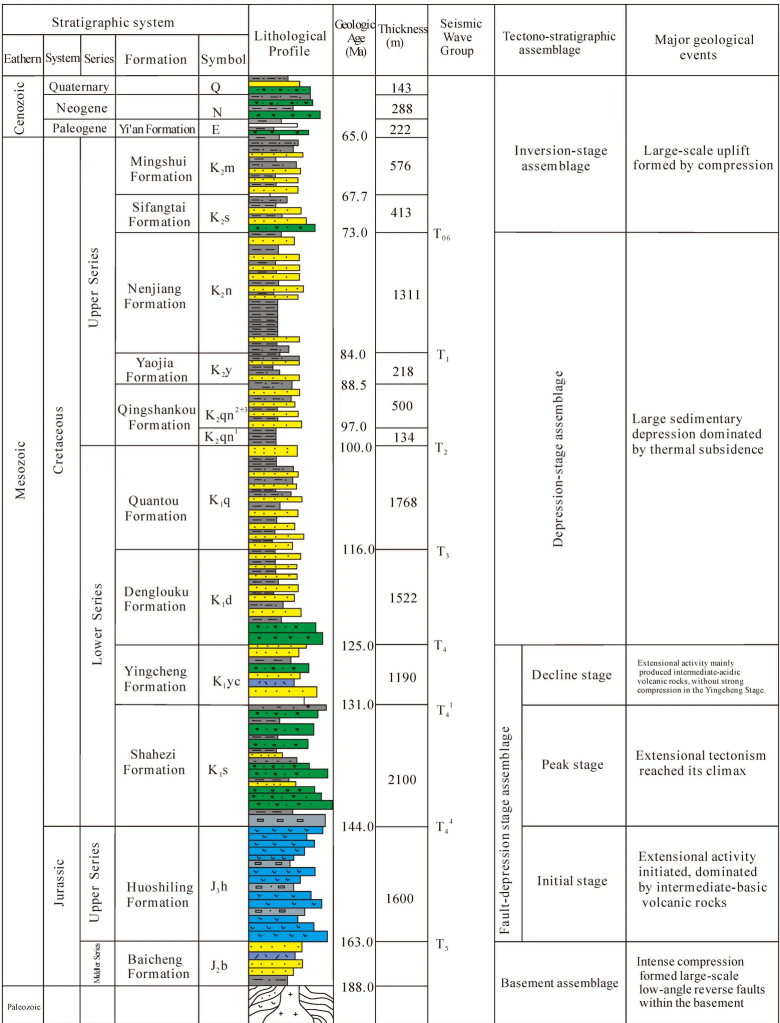


Figure 2. Stratigraphic column of the Central Depression in the Songliao Basin.

3. Data and Methods

In this work, all of the analyzed source rock samples from the K_2qn^{2+3} and K_2qn^1 formations were collected from the Central Depression in the Songliao Basin. The samples from 12 wells with depths from 211 m to 2370 m consist of 414 mudstone samples and were used for Rock-Eval pyrolysis and the determination of total organic carbon content (%), chloroform bitumen “A” (%), kerogen carbon isotope “ $\delta^{13}CPDB$ ”, total reduced sulphur, and vitrinite reflectance (Ro%). All mudstone samples were pulverized to 100 mesh in preparation for those experiments.

Vitrinite reflectance (Ro) measurements were performed at the State Key Laboratory of Continental Dynamics, Department of Geology, Northwest UniversityXi’an, China. For each sample, more than 30 indigenous vitrinite particles were measured under oil immersion following the procedure. Instrument calibration was performed using a certified reflectance standard prior to measurement. Only unaltered indigenous vitrinite particles with smooth polished surfaces and without evidence of oxidation, contamination, or recycling were selected for reflectance measurements.

Rock-Eval/TOC was conducted in an OGE-II Oil and Gas Evaluation Workstation at the State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, and provided the measurements of TOC (wt%), Tmax, S1, and S2. The temperature was set to 300 °C for 3 min, and heating was then conducted at 25 °C/min to 600 °C. All laboratory analyses were calibrated against international certified reference mate-

rials. Procedural blanks and duplicate samples were included in each analytical batch for quality control. The absolute measurement error for total organic carbon (TOC) was maintained within ± 0.1 wt%, and the relative standard deviation (RSD) of replicate measurements for Rock-Eval pyrolysis parameters was below 5%. Tmax represents the temperature that corresponds to the maximum generation rate of hydrocarbons from kerogen cracking. S1 represents any free hydrocarbons. S2 represents the amount of hydrocarbons that are expelled from kerogen cracking. Prior to TOC analysis, carbonate minerals were removed using dilute hydrochloric acid where necessary to eliminate the influence of inorganic carbon. TOC and Rock-Eval pyrolysis analyses were calibrated using certified reference materials according to the manufacturer's analytical procedures (Vinci Technologies, Rueil-Malmaison, France). Instrument calibration was routinely verified before analysis, and analytical precision was better than $\pm 2\%$. Some parameters are then generated from the Rock-Eval pyrolysis techniques: Hydrogen index [HI = $(S2/TOC) \times 100$, mgHC/g TOC] is the normalized S2 value (S2/TOC), indicating the potential of kerogen in a rock to generate petroleum [32,33]. The TRS of source rocks is measured using a LECO CS-230 analyzer (LECO Corporation, St. Joseph, MI, USA). The results are listed in the Supplementary Materials, Table S1.

Kerogens separated from mudstones were used for observations and testing by a DLAPLAN biological microscope (Leica Microsystems, Wetzlar, Germany). They were also used for thin sections in preparation for vitrinite reflectance (Ro%) determinations and were placed under reflected light in a ZEISS Axio Microscope (Carl Zeiss AG, Oberkochen, Germany). The number of valid measurement points was determined based on the count of identifiable vitrinite particles. The vitrinite reflectance measurement system used a TIDAS PMT IV photometer and MSP200 testing software (J&M Analytik AG, Esslingen, Germany). The detailed methods, experimental conditions, and algorithm for selecting the appropriate values were optimized. The results are shown in Table 1. To more accurately assess organic matter types and depositional conditions, kerogen carbon isotope ($\delta^{13}\text{CPDB}$) analyses were conducted with a MAT-251 Stable Isotope Mass Spectrometer (Finnigan MAT, Bremen, Germany). The analysis was calibrated against the VPDB reference standard, with an analytical precision of better than 0.1 ‰. The chloroform bitumen "A" was determined by the Soxhlet extraction method. The rock samples were crushed to 0.09 mm powder, extracted with chloroform continuously for 72 h, and then dried to calculate the content of soluble organic matter in unit rock. Approximately 50 g of powdered rock sample was used for each extraction. Chloroform extraction was performed under identical laboratory conditions, and procedural blanks were included in each analytical batch to monitor possible contamination. Duplicate analyses indicated an analytical reproducibility better than $\pm 5\%$.

Table 1. Organic matter abundance of source rocks in Songliao Basin.

Horizon	w(TOC)/%	(S ₁ + S ₂)/(mg·g ⁻¹)	Chloroform Bitumen "A" (%)	Evaluation Results
K ₂ qn ²⁺³	$\frac{0.09 \sim 4.54}{1.31 (192)}$	$\frac{0.02 \sim 44.78}{8.04 (192)}$	$\frac{0.02 \sim 0.5}{0.23 (8)}$	Good
K ₂ qn ¹	$\frac{0.08 \sim 12.11}{3.88 (222)}$	$\frac{0.03 \sim 84.47}{25.45 (222)}$	$\frac{0.01 \sim 1.42}{0.41 (45)}$	High-quality

The thermal burial history modeling was constructed using the method introduced by Lopatin [34], which was modified and calibrated using vitrinite reflectance measurements, stratigraphic sequences, and geologic time in million [35]. Sweeney and Burnham (1990) put forward a vitrinite maturation model (Easy% Ro), which was widely applied

to predict the levels of thermal maturity evolution history [36]. To elucidate the spatial differences in thermal evolution across distinct tectonic positions within the Central Depression, one-dimensional (1D) basin modeling was conducted for Wells G3, G1, and A1, located in the northern, central, and southern sectors of the depression, respectively. The model comprehensively incorporates stratigraphic thickness, sedimentation rate, denudation thickness, paleogeothermal gradient, and the evolutionary history of regional heat flow. The initial heat flow was constrained by the Early Cretaceous rifting setting of the Songliao Basin, whereas subsequent heat flow variations were reconstructed by integrating regional tectonic evolution and the present-day geothermal field. These three modeling profiles respectively capture the burial and thermal evolution characteristics of different locations across the Central Depression.

4. Results and Discussion

4.1. Organic Matter Abundance

Organic matter abundance in source rocks is one of the most fundamental indicators for evaluating source rocks, an important basis for hydrocarbon formation, and also a key index for measuring the production and distribution scale of petroliferous basins [37–39]. Total organic carbon (TOC) content and hydrocarbon generation potential index ($S_1 + S_2$) are commonly used indicators for comprehensive assessment of organic matter abundance in source rocks [40–42]. At high maturity levels, S_1 values should be interpreted cautiously because free hydrocarbons measured by Rock-Eval pyrolysis may include both indigenous retained hydrocarbons and migrated hydrocarbons. Therefore, S_1 was not used independently as an indicator of retained oil potential in this study. Instead, hydrocarbon generation potential was evaluated mainly based on the integrated interpretation of TOC, S_2 , HI, kerogen type, and thermal maturity. Although no artificial correction was applied to S_1 values, abnormal values were evaluated by comparing S_1 with TOC, S_2 , and HI parameters. Therefore, S_1 was considered only as a supplementary parameter rather than a quantitative indicator of retained oil. In this study, we systematically collected and compiled geochemical test data of 414 samples from 12 key drilling wells in the Central Depression (Table 1).

The test results show that the TOC content of source rocks in the 1st Member of Upper Cretaceous Qingshankou Formation ranges from 0.08% to 12.11% with an average of 3.88%, chloroform bitumen “A” ranges from 0.03% to 1.42% with an average of 0.41%, and $S_1 + S_2$ ranges from 0.03 mg/g to 84.47 mg/g with an average of 25.45 mg/g, indicating high-quality source rocks. The TOC content of source rocks in the 2nd and 3rd Members of Qingshankou Formation ranges from 0.09% to 4.54% with an average of 1.31%, chloroform bitumen “A” ranges from 0.02% to 0.5% with an average of 0.23%, and $S_1 + S_2$ ranges from 0.02 mg/g to 44.78 mg/g with an average of 8.04 mg/g, indicating good source rocks (Table 1). The measured TOC and pyrolysis parameters represent the present-day preserved organic matter characteristics rather than the original source rock potential. Considering that the Qingshankou Formation in the Central Depression has reached the high-maturity stage ($R_o = 1.26$ – 1.38%), a considerable proportion of reactive organic matter has already undergone hydrocarbon generation and expulsion. Therefore, the present-day TOC and S_2 values may underestimate the original hydrocarbon-generating potential. However, the relatively high residual TOC values (average TOC of 3.88% for K_2qn^1 and 1.31% for K_2qn^{2+3}) indicate that abundant organic matter was preserved after thermal evolution, suggesting that the Qingshankou Formation originally possessed excellent source-rock quality.

4.2. Organic Matter Type

Kerogen is the main component of organic matter, and its type is closely related to the parent material source of organic matter. The organic matter types of source rocks are generally divided into Type I, Type II, and Type III. Different organic matter types not only differ in hydrocarbon generation capacity, but also have different characteristics of generated hydrocarbon components [43–47]. Based on the H/C and O/C atomic ratios and the relationship between pyrolysis Tmax and HI of source rocks in the Qingshankou Formation of the Central Depression, Songliao Basin, the organic matter of the 1st Member of Qingshankou Formation is dominated by Type I, while that of the 2nd and 3rd Members is dominated by Type I and Type II (Figure 3).

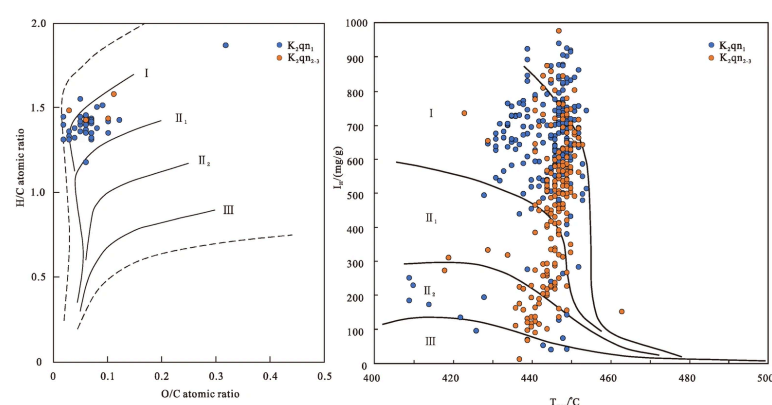


Figure 3. H/C versus O/C atomic ratio diagram of kerogen in source rocks, Songliao Basin.

In addition, kerogen carbon isotopes are stable during stratigraphic evolution and can reflect the original material composition of organic matter. Therefore, the organic matter type can be inferred from the characteristic range of kerogen carbon isotopes [43]. Type I kerogen derived from algae has relatively light carbon isotope composition, generally less than -28‰ . Type III kerogen from terrestrial higher plants has relatively heavy carbon isotope composition, generally greater than -25‰ . Type II kerogen has carbon isotope values between these two ranges. The results of kerogen carbon isotope analysis show that the organic matter of the 1st Member of the Qingshankou Formation in the Songliao Basin is predominantly Type I, while that of the 2nd and 3rd Members is Type I and Type II (Figure 4).

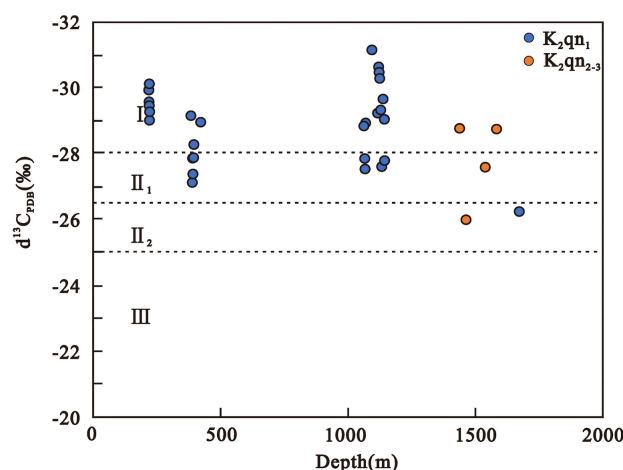


Figure 4. Relationship between $\delta^{13}\text{CPDB}$ (‰) and Depth of Source Rocks in the Songliao Basin.

4.3. Organic Matter Maturity

Vitrinite reflectance (R_o) and rock pyrolysis peak temperature (T_{max}) constitute the optimal parameter combination for reflecting maturity and thermal evolution history, and are also key indicators for evaluating hydrocarbon generation capacity [48–52]. Based on 68 vitrinite reflectance data from 4 wells, the vitrinite reflectance (R_o) of the 1st Member of Qingshankou Formation in the study area ranges from 0.78% to 1.67% with an average of 1.38%, and the T_{max} values range from 422 °C to 452 °C, indicating that it is mainly in the high-mature stage. The vitrinite reflectance (R_o) of the 2nd and 3rd Members of Qingshankou Formation ranges from 0.68% to 1.63% with an average of 1.26%, and the T_{max} values range from 433 °C to 457 °C, mainly in the medium-high mature stage (Figure 5).

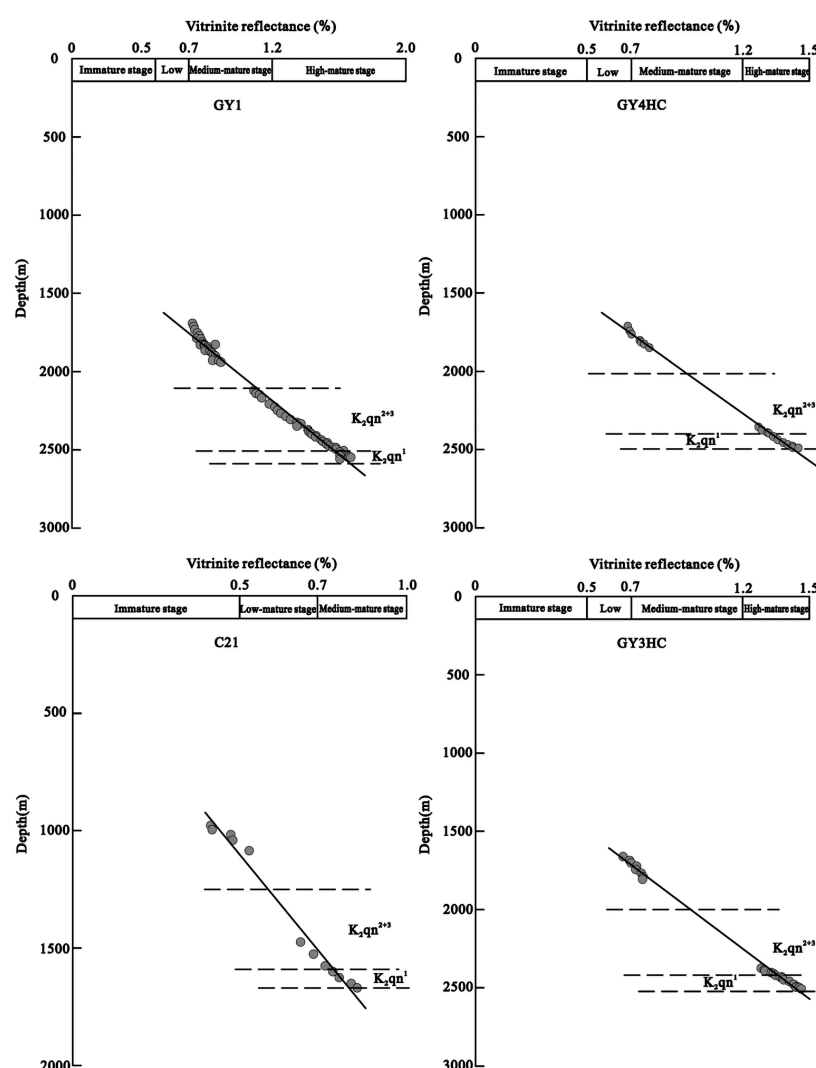


Figure 5. Relationship between vitrinite reflectance (R_o) and depth in the Central Depression of the Songliao Basin.

5. Thermal History Simulation

5.1. Uplift and Cooling History

The application of the fission track method in tectonic uplift and thermal history of sedimentary basins has achieved numerous results [53–57]. Apatite fission track thermal history simulation shows that the Qingshankou Formation has experienced two major thermal evolution stages since its deposition: the continuous subsidence and heating

stage from 91 Ma to 65 Ma, and the uplift and cooling stage since 65 Ma (Figure 6). The heating rate was relatively fast during the 91–65 Ma continuous subsidence and heating stage, indicating a rapid subsidence rate. The cooling rate since 65 Ma has been relatively slow, indicating a slow uplift rate. Overall observation reveals that the Central Depression of the Songliao Basin reached its maximum burial depth at 65 Ma, when the paleotemperature peaked and the thermal evolution degree of source rocks reached the maximum. Subsequently, uplift occurred, temperature decreased, and hydrocarbon generation weakened.

5.2. Thermal History Simulation

Although the Easy%Ro model was originally developed based on vitrinite maturation kinetics, it has been extensively applied in thermal evolution studies of numerous petroliferous basins in China owing to its capacity to comprehensively account for time–temperature effects. Accordingly, the Easy%Ro modeling results are not treated as the sole basis for thermal history interpretation in this study. Instead, the thermal history is comprehensively reconstructed by integrating apatite fission track (AFT) constraints, measured vitrinite reflectance (Ro) data, and the regional tectonic subsidence history [36,58]. Through single-well simulation, the theoretically calculated Ro values are fitted with measured data, and geological model parameters are adjusted until the best fit between theoretical and measured Ro trends is achieved. Therefore, this method can be used to invert paleogeothermal gradient values [49,58].

Although the Easy%Ro model is intrinsically sensitive to organic matter type and heating rate, the simulation results in this study are not solely derived from Ro inversion; instead, they are constrained by multiple independent geological lines of evidence.

First, apatite fission track (AFT) modeling indicates that the study area underwent a pronounced cooling phase after ca. 65 Ma, which is consistent with the peak paleotemperatures at the end of the Late Cretaceous and the subsequent cooling trend recovered from Easy%Ro modeling.

Second, modeling results from three wells at different structural positions consistently show three evolutionary stages: sustained heating following the deposition of the Qingshankou Formation, maximum temperatures attained at the end of the Mingshui Formation deposition, and a cooling stage initiated in the Cenozoic. This thermal evolutionary pattern is in good agreement with the geological setting of rapid subsidence and tectonic inversion in the Songliao Basin during the Late Cretaceous.

Accordingly, we conclude that the Easy%Ro model can reliably reconstruct the first-order thermal evolution trend in the study area, although uncertainties remain in specific Ro values due to variations in organic matter type.

The present-day geothermal gradient in the Central Depression of the Songliao Basin is 42 °C/km [59], and the erosion thickness at the end of the Late Cretaceous ranges from 300 m to 500 m [60]. In this thermal history simulation, stratigraphic thickness, stratigraphic age, geothermal field parameters, and erosion thickness at key periods were taken as important constraints. Combined with measured vitrinite reflectance values, the PetroMod simulation software and the Easy%Ro method were applied to simulate the thermal history of three drilling wells at different locations in the study area: Well G3, Well G1, and Well A1. The simulated Ro values are in good agreement with the measured Ro values, indicating reliable results.

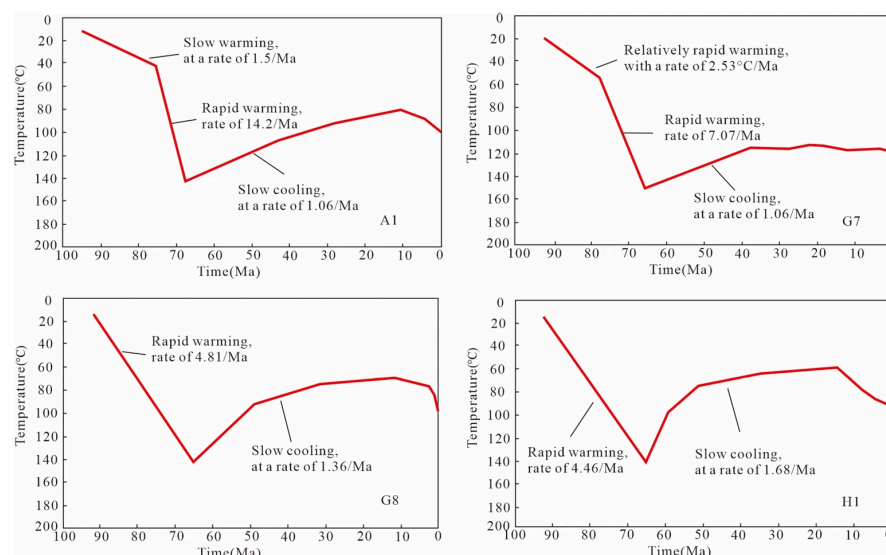


Figure 6. Apatite fission track thermal history simulation map of the Central Depression, Songliao Basin (modified from Xu, 2025 [60]).

The Qingshankou Formation in the Central Depression of the Songliao Basin has mainly experienced two thermal evolution stages since its deposition: the rapid temperature rise stage in the Late Cretaceous (100–65 Ma) and the slow cooling stage from the Paleogene to Quaternary (since 65 Ma) (Figure 6). The simulation results show that there are certain differences in thermal evolution history among different parts. Well G3 is located in the northern part of the Central Depression. Its thermal evolution history indicates that the source rocks of the 1st Member of Qingshankou Formation entered the hydrocarbon generation threshold at 78 Ma, with R_o reaching 0.5% and paleotemperature exceeding 90 °C. The present-day vitrinite reflectance reaches 1.0%, indicating it is in the peak hydrocarbon generation stage. The source rocks of the 2nd and 3rd Members of Qingshankou Formation entered the hydrocarbon generation threshold at 76 Ma, with R_o reaching 0.5% and paleotemperature exceeding 90 °C. The present-day vitrinite reflectance of the lower part of the 2nd and 3rd Members reaches 1.0%, indicating the peak hydrocarbon generation stage, while that of the upper part reaches 0.7%, indicating the medium-mature stage (Figure 7).

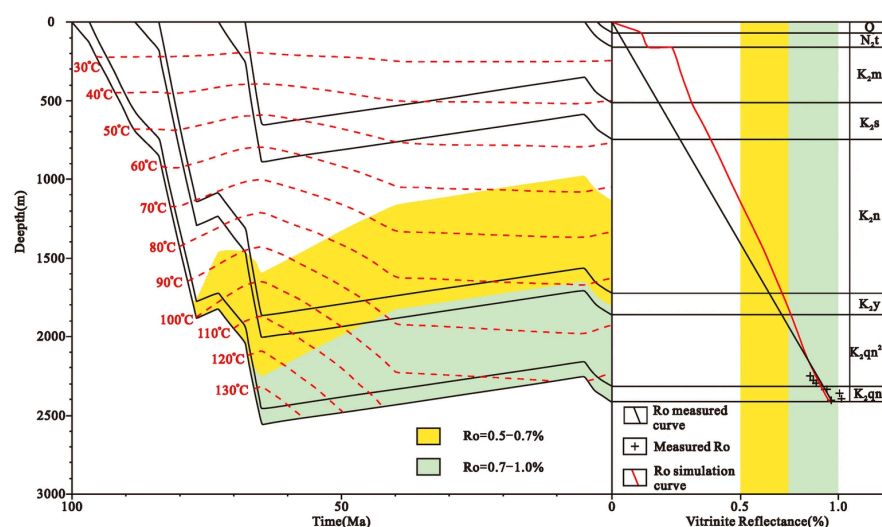


Figure 7. Thermal history simulation map of Well G3 in the northern part of the Central Depression, Songliao Basin.

Well G1 is located in the central part of the depression. Its thermal evolution history shows that the source rocks of the 1st Member of Qingshankou Formation entered the hydrocarbon generation threshold at 82 Ma, with Ro reaching 0.5% and paleotemperature exceeding 90 °C. It entered the peak hydrocarbon generation stage at 68 Ma, with vitrinite reflectance reaching 1.0% and paleotemperature exceeding 140 °C. The present-day vitrinite reflectance reaches 1.3%, indicating the high-mature stage. The source rocks of the 2nd and 3rd Members of Qingshankou Formation entered the hydrocarbon generation threshold at 81 Ma, with Ro reaching 0.5% and paleotemperature exceeding 90 °C. They entered the peak hydrocarbon generation stage at 67 Ma, with vitrinite reflectance reaching 1.0% and paleotemperature exceeding 140 °C. The present-day vitrinite reflectance of the lower part of the 2nd and 3rd Members reaches 1.3%, indicating the high-mature stage, while that of the upper part reaches 1.0%, indicating the medium-mature stage (Figure 8).

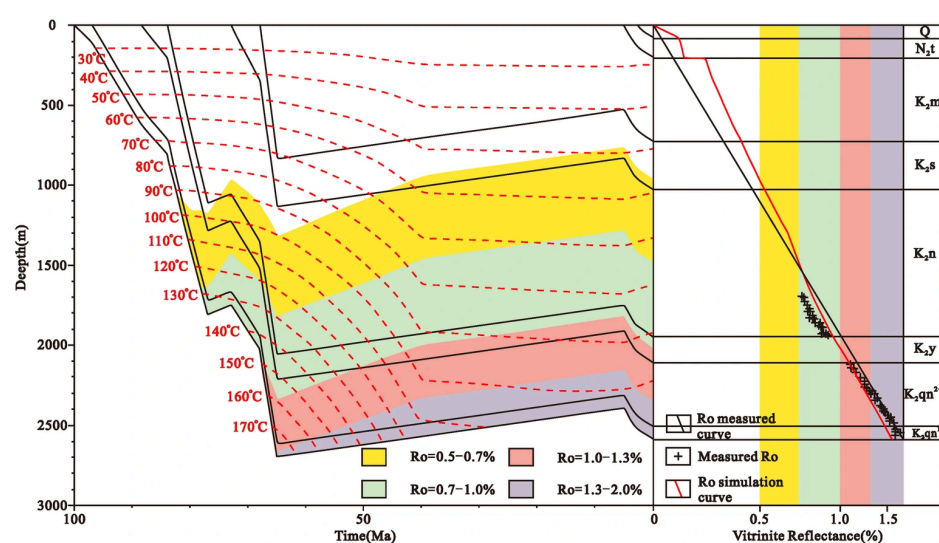


Figure 8. Thermal history simulation map of Well G1 in the central part of the Central Depression, Songliao Basin.

A1 is located in the southern part of the Central Depression. Its thermal evolution history indicates that the source rocks of the 1st Member of Qingshankou Formation entered the hydrocarbon generation threshold at 82 Ma, with Ro reaching 0.5% and paleotemperature exceeding 90 °C. It entered the peak hydrocarbon generation stage at 72 Ma, with vitrinite reflectance reaching 1.0% and paleotemperature exceeding 140 °C. The present-day vitrinite reflectance reaches 1.0%, indicating the medium-mature stage. The source rocks of the 2nd and 3rd Members of Qingshankou Formation entered the hydrocarbon generation threshold at 81.8 Ma, with Ro reaching 0.5% and paleotemperature exceeding 90 °C. They entered the peak hydrocarbon generation stage at 67 Ma, with vitrinite reflectance reaching 1.0% and paleotemperature exceeding 140 °C. The present-day vitrinite reflectance of the lower part of the 2nd and 3rd Members reaches 1.0%, indicating the peak hydrocarbon generation stage, while that of the upper part reaches 0.7%, indicating the medium-mature stage (Figure 9).

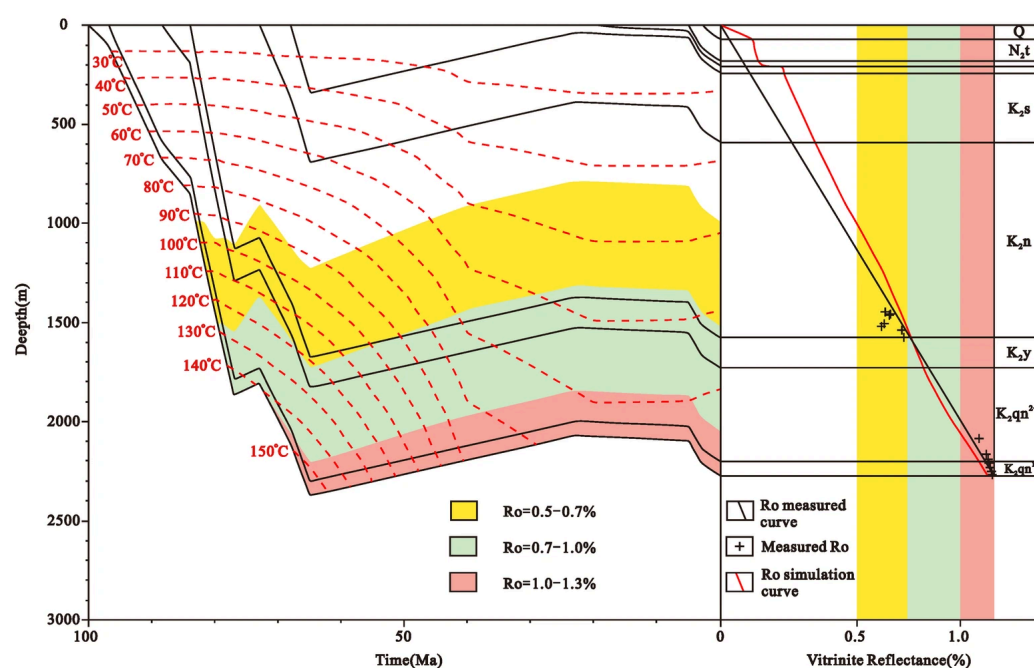


Figure 9. Thermal history simulation map of Well A1 in the southern part of the Central Depression, Songliao Basin.

The simulation results of hydrocarbon generation and cumulative hydrocarbon generation for Wells G3 and A1 are presented in Figures 10 and 11. The modeled results indicate that hydrocarbon generation of the Qingshankou Formation generally initiated during approximately 80–75 Ma, after which hydrocarbon generation intensified rapidly. The principal hydrocarbon generation interval occurred during approximately 75–65 Ma, whereas the maximum hydrocarbon generation rate was reached during the late stage of this interval.

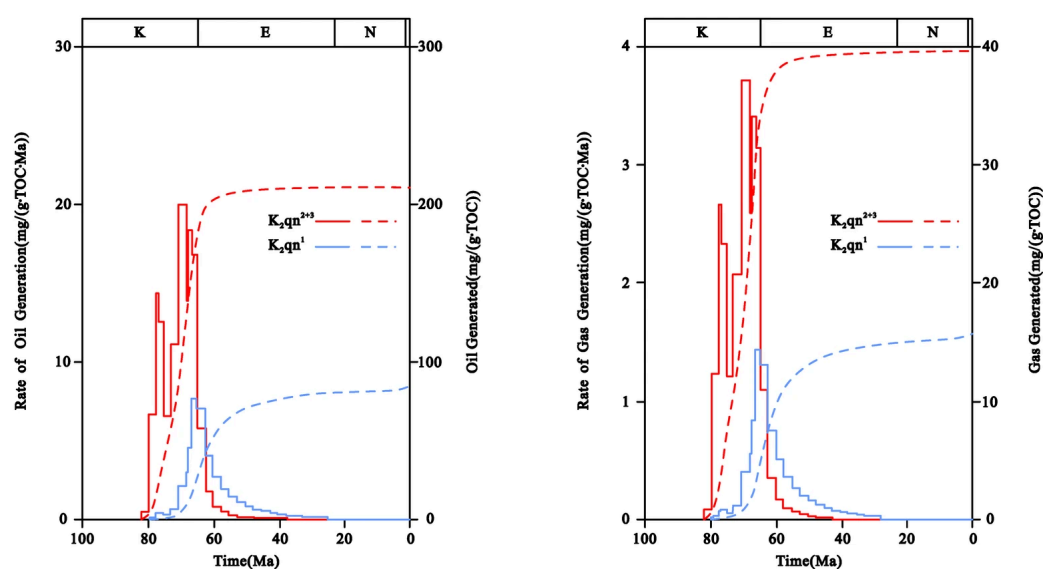


Figure 10. Evolution history of hydrocarbon generation rate and cumulative production of Well G3 in the Central Depression, Songliao Basin. Solid lines represent hydrocarbon generation rates; dotted lines represent cumulative hydrocarbon generation amounts.

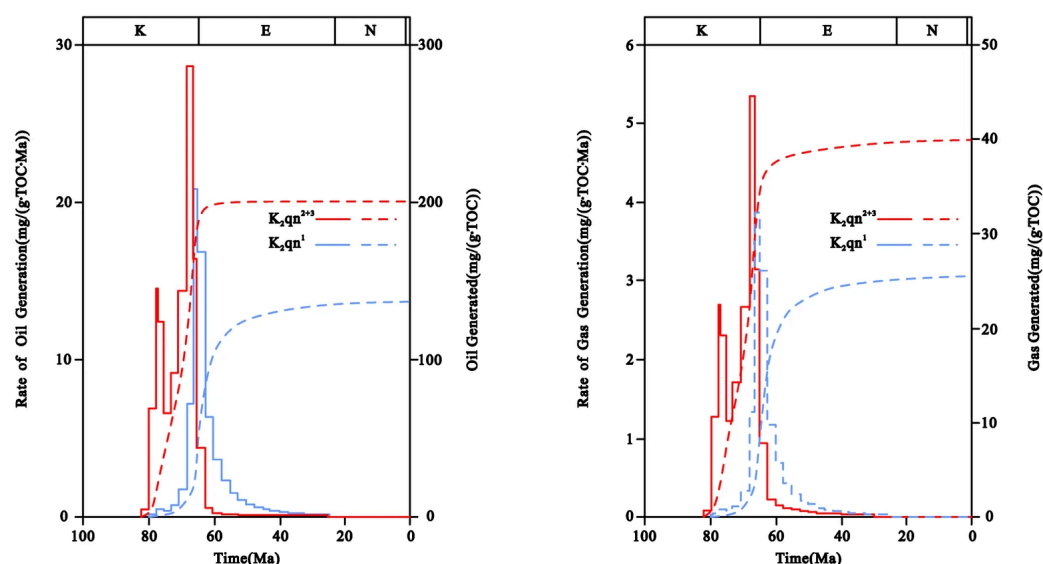


Figure 11. Evolution history of hydrocarbon generation rate and cumulative production of Well A1 in the Central Depression, Songliao Basin. * Solid lines represent hydrocarbon generation rates; dotted lines represent cumulative hydrocarbon generation amounts.

For the source rocks of the 2nd and 3rd Members of the Qingshankou Formation in Well G3, oil generation began at approximately 80–75 Ma, and the principal oil generation interval occurred during 75–65 Ma. The maximum oil generation rate reached approximately 23 mg/(g·TOC·Ma) at 65–67 Ma, while cumulative oil generation gradually increased and finally stabilized at approximately 140 mg/(g·TOC). Gas generation followed a similar evolutionary trend, with the maximum gas generation rate reaching approximately 4 mg/(g·TOC·Ma) during 65–67 Ma, and cumulative gas generation eventually reaching approximately 26 mg/(g·TOC). For the 1st Member of the Qingshankou Formation in Well G3, hydrocarbon generation also initiated during approximately 80–75 Ma, followed by rapid hydrocarbon generation during 75–65 Ma. The maximum oil generation rate occurred at approximately 69 Ma, reaching 28 mg/(g·TOC·Ma), whereas cumulative oil generation continued to increase after the peak generation stage before gradually approaching a stable value of approximately 200 mg/(g·TOC). The maximum gas generation rate reached approximately 5.5 mg/(g·TOC·Ma) during 78–80 Ma, and cumulative gas generation finally stabilized at approximately 40 mg/(g·TOC) (Figure 10).

The hydrocarbon generation history of Well A1 exhibits a similar evolutionary pattern. For the 2nd and 3rd Members, hydrocarbon generation initiated during approximately 80–75 Ma, the principal hydrocarbon generation interval occurred during 75–65 Ma, and the maximum oil generation rate reached approximately 8 mg/(g·TOC·Ma) during 65–67 Ma, with cumulative oil generation stabilizing at approximately 80 mg/(g·TOC). For the 1st Member, hydrocarbon generation also began during approximately 80–75 Ma, the maximum oil generation rate occurred at approximately 69 Ma, reaching approximately 20 mg/(g·TOC·Ma), and cumulative oil generation gradually increased after the peak generation stage before approaching a maximum value of approximately 220 mg/(g·TOC). The maximum gas generation rate occurred during 78–80 Ma, reaching approximately 3.7 mg/(g·TOC·Ma), and cumulative gas generation eventually stabilized at approximately 40 mg/(g·TOC) (Figure 11).

6. Discussion

To evaluate the lateral heterogeneity of thermal evolution within the Central Depression of the Songliao Basin, one-dimensional basin modeling was performed for

wells G3, G1, and A1, which represent the northern, central, and southern parts of the study area, respectively. The geological and thermal parameters used in the simulations are summarized in Table 2, including well location, present-day burial depth of the Qingshankou Formation, maximum burial depth, estimated erosion thickness, geothermal gradient, and key thermal constraints.

Table 2. Geological and thermal parameters used for burial history reconstruction of wells G3, G1, and A1.

Parameter	Well G3 (Northern)	Well G1 (Central)	Well A1 (Southern)
Tectonic position	Northern part of the Central Depression	Central part of the Central Depression	Southern part of the Central Depression
Maximum burial depth (m)	2400	2600	2300
Maximum paleotemperature (°C)	130	170	150
Maximum vitrinite reflectance (Ro, %)	1.0	2.0	1.3

The modeled maturity histories reveal significant spatial variations in the thermal evolution of the Qingshankou Formation among the three wells (Figures 7–9). Although all wells exhibit a similar first-order thermal evolution pattern characterized by progressive heating during the Late Cretaceous followed by cooling since the end of the Cretaceous, the timing and magnitude of thermal maturation differ due to variations in burial history and tectonic position. The modeled Ro values of the Qingshankou Formation range from 1.3% to 2.0%, indicating different degrees of organic matter maturation across the Central Depression. The maturity differences among wells are primarily attributed to heterogeneous burial histories. The central part of the depression generally experienced greater subsidence and thicker sediment accumulation, resulting in deeper burial and longer residence time under elevated temperature conditions. Consequently, the source rocks in the central depression experienced more intense thermal maturation compared with those located in marginal areas. In contrast, wells located closer to structural margins were more strongly influenced by reduced burial thickness and earlier uplift, which limited the duration of high-temperature exposure and resulted in relatively lower maturity levels. In addition to burial effects, post-depositional tectonic modification also played an important role in controlling the spatial distribution of thermal maturity. The Songliao Basin experienced Late Cretaceous tectonic inversion after the main subsidence stage, and differential uplift and erosion modified the preservation of maximum burial conditions in different structural positions. Variations in basement morphology and fault activity may have further influenced local heat transfer efficiency, resulting in heterogeneous thermal histories across the basin. However, no significant evidence for large-scale thermal anomalies was identified in the present study, suggesting that differential burial and tectonic evolution were the dominant factors controlling the observed maturity variations.

Therefore, the thermal evolution of the Qingshankou Formation in the Central Depression was controlled by the combined effects of regional basin-scale thermal evolution and local structural differences. The reconstructed thermal histories indicate that although the entire study area experienced a comparable Late Cretaceous heating–Cenozoic cooling evolution, the intensity of organic matter maturation varied spatially due to differences in burial depth, erosion history, and tectonic setting.

The thermal evolution of source rocks not only controls organic matter maturation and hydrocarbon generation, but also potentially influences the physical and mechanical properties of shale reservoirs. Previous studies have demonstrated that rapid temperature increase and high-temperature exposure may induce thermal stress accumulation, mineral expansion mismatch, and microfracturing within rocks, thereby modifying pore structures and fluid migration pathways [61]. Therefore, the reconstructed thermal history of the Qingshankou Formation provides important implications not only for hydrocarbon generation but also for shale reservoir evolution. The thermal modeling results indicate that the Qingshankou Formation experienced rapid temperature increase during the Late Cretaceous, with maximum palaeotemperatures reaching approximately 180 °C. Such high-temperature conditions significantly exceeded the temperature range commonly associated with organic matter maturation. During this process, thermal stress generated by differential expansion of minerals and organic matter transformation may have contributed to the development of micro-scale fractures and pore modification within the shale matrix. In addition, thermal cracking of kerogen and the generation of hydrocarbons could have further promoted the formation of secondary pores, which is consistent with the general understanding that organic-rich shale reservoirs commonly experience coupled evolution of organic matter transformation and pore development during maturation. However, the quantitative contribution of thermal stress to reservoir modification remains uncertain in the Qingshankou Formation because direct evidence, such as microfracture characterization, pore-scale imaging, or mechanical property measurements, is not available in this study. Therefore, thermal effects are considered as a potential factor influencing reservoir quality rather than the sole control mechanism. The development of favorable shale oil reservoirs in the Central Depression likely resulted from the coupling of multiple geological processes, including high-quality organic matter accumulation, progressive thermal maturation, hydrocarbon generation, pore evolution, and preservation conditions.

Given that the Qingshankou Formation source rocks in the study area are currently at the moderate to high maturity stage, direct evaluation of original organic matter abundance based on present-day TOC values may result in underestimation. In recent years, multiple TOC restoration approaches (e.g., the Espitalié method and the Jarvie method) have been proposed for mature to overmature source rocks, which are established based on H/C atomic ratios, Rock-Eval parameters, and mass balance principles.

Nevertheless, all these methods rely on critical parameters including original organic matter type, maturity evolution pathways, and initial hydrogen index (HI) values, whereas robust constraints from complete immature end-member samples are currently lacking in the study area. Accordingly, quantitative TOC restoration was not performed in this study. Instead, a comprehensive assessment was conducted by integrating present-day TOC data with organic matter type, maturity characteristics, and thermal history evolution.

The source rocks in the Central Depression of the Songliao Basin have mainly experienced three stages of tectonic evolution since their deposition: the rifting stage from the Late Jurassic to Early Cretaceous, the depression stage from the late Early Cretaceous to Late Cretaceous, and the tectonic inversion stage from the Sifangtai Formation and Mingshui Formation to the Cenozoic [62]. The reconstruction results of single-well burial history and thermal history for each well in the Central Depression of the Songliao Basin (Figures 12 and 13) show that the Cretaceous source rocks in the Central Depression have mainly experienced two thermal evolution stages since their deposition: the rapid temperature rise stage from early Early Cretaceous to late Early Cretaceous, and the slow cooling stage from late Early Cretaceous to present day.

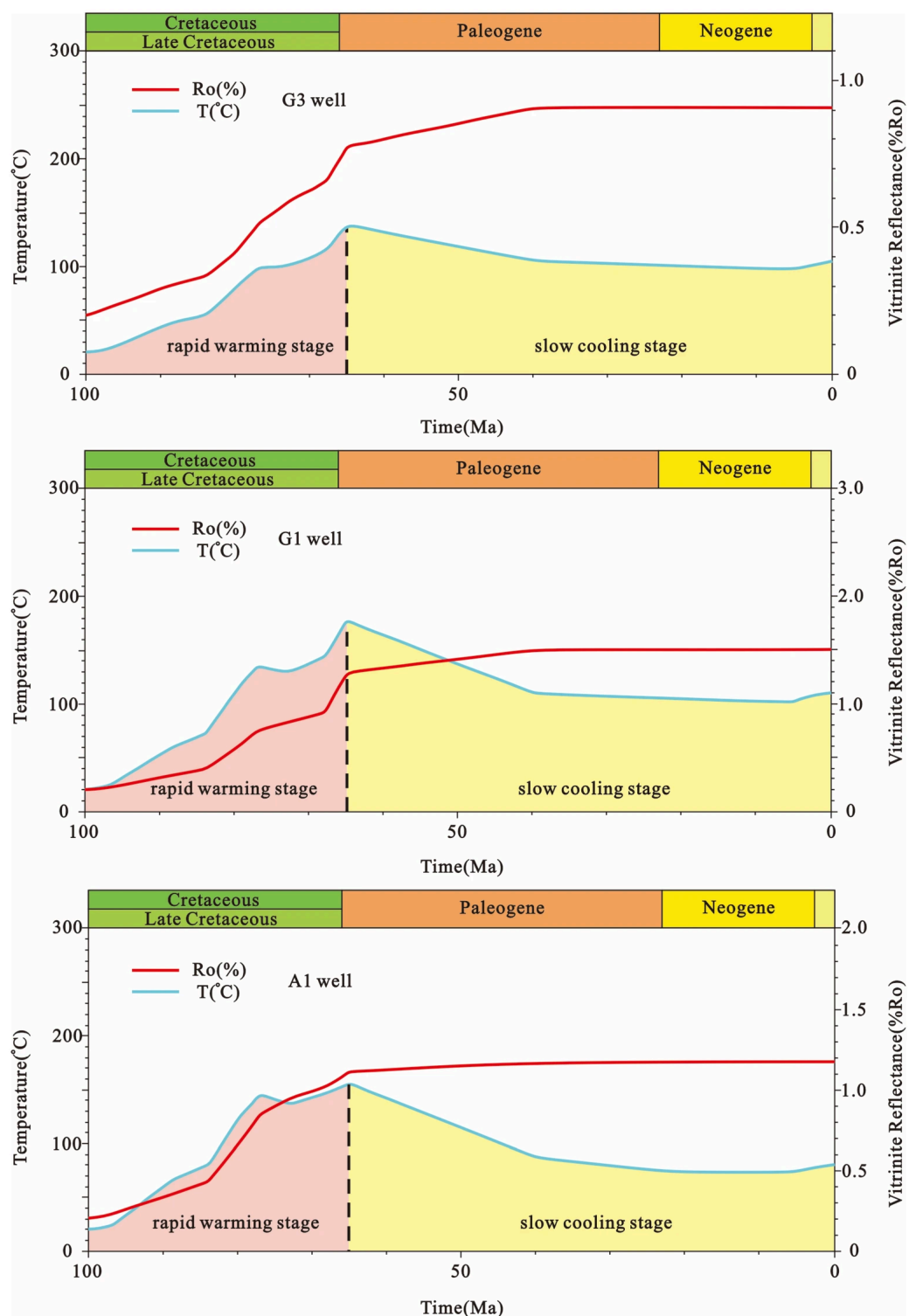


Figure 12. Relationship diagram of organic matter maturity, temperature, and time for Well G3, Well G1, and Well A1 in the Central Depression, Songliao Basin.

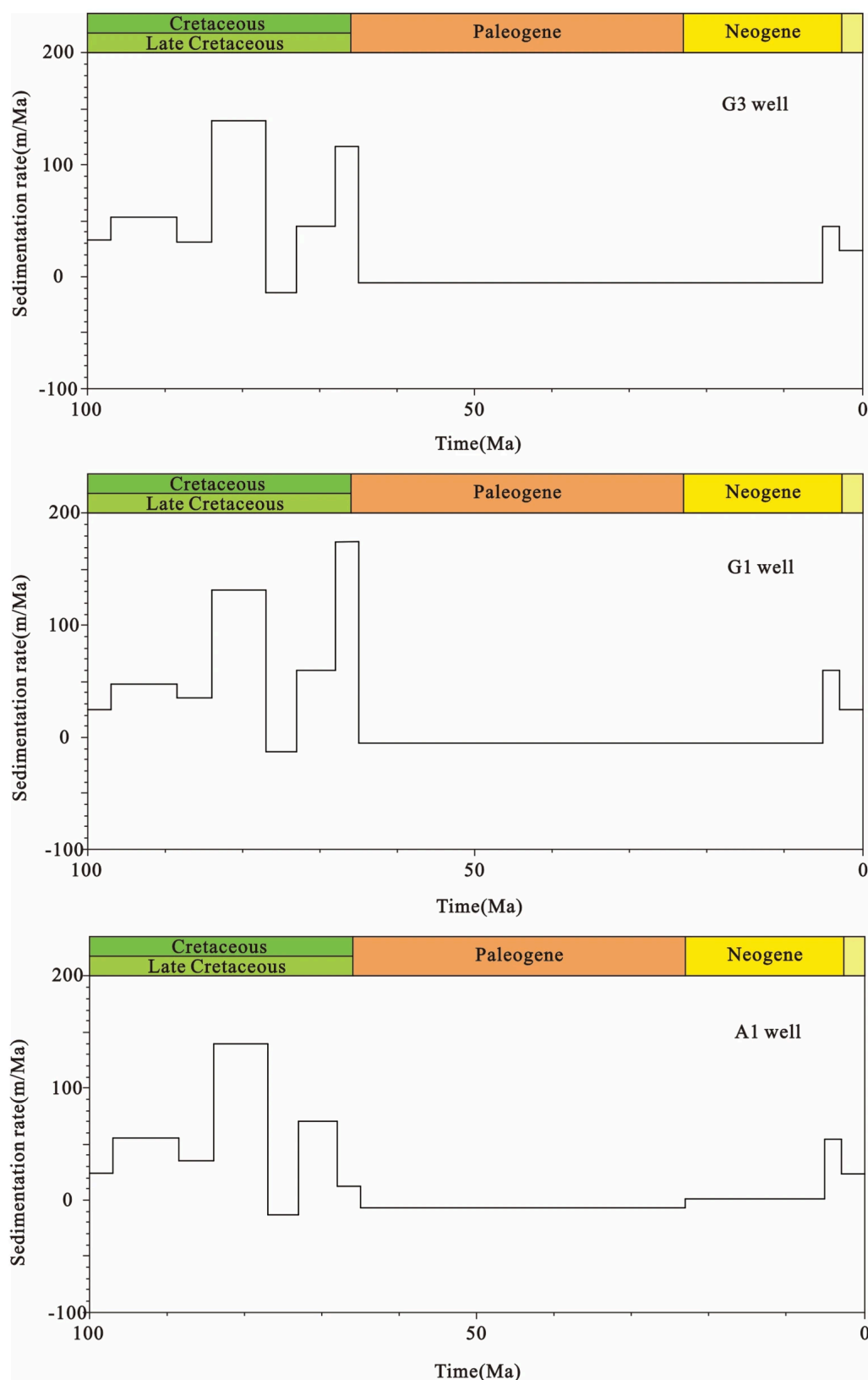


Figure 13. Sedimentation rate evolution of Well G3, Well G1, and Well A1 in the Central Depression of the Songliao Basin.

The Central Depression was in the rifting development stage during the Early Cretaceous, with the maximum paleotemperature reaching 100 °C. By the depositional period of the Nenjiang Formation, the strata were generally in a continuous burial state,

and the paleotemperature continued to rise. During the Late Cretaceous, the Central Depression entered the depression stage, with overall depression and subsidence, continuous sinking of the lake basin, increasing sedimentation rate, and rising paleotemperature. During the depositional period of the Nenjiang Formation, the maximum sedimentation rate of the basin reached 150 m/Ma, and the paleotemperature continued to increase. At the end of the Nenjiang Formation deposition, the strata changed from extensional subsidence to compressional uplift, the sedimentation rate decreased significantly, and the paleotemperature decreased at the same time, leading the strata to enter a cooling stage in a short period. After the deposition of the Nenjiang Formation, the basin experienced multiple episodes of episodic compressional stress, which caused the reactivation and thrusting of early-formed synsedimentary normal faults, resulting in folding of depression strata and formation of shallow structural traps. Uplift, erosion, and tectonic inversion occurred, forming a large number of faults in the basin. During the depositional stage from the Sifangtai Formation to the Mingshui Formation, the activity intensity of sag-controlling faults gradually weakened, while the crust remained in a state of continuous subsidence, and the sedimentation rate still maintained a high level, with the maximum reaching 170 m/Ma. The paleotemperature continued to increase and reached the maximum value of 180 °C at 65 Ma (Figures 12 and 13). Until the end of the Mingshui Formation deposition, tectonic activity was weak, the sedimentation rate gradually decreased, the strata were basically finalized, and the paleotemperature and geothermal gradient continued to decrease. The three-stage complex tectonic evolution process of the Central Depression provided important conditions for the enrichment of hydrocarbon resources, and the rapid subsidence process during the depression stage provided favorable geological conditions for the development of source rocks.

Since the Neogene, with the weakening of regional tectonic activity, the rifting stage ended, magmatic activity significantly decreased, the upwelling efficiency of deep heat sources decreased, and paleo-heat flow values gradually declined. The basin as a whole entered the depression development stage, the lithosphere gradually thickened, the geothermal field entered the cooling stage, and the overall paleotemperature showed a downward trend.

7. Conclusions

- (1) The Cretaceous source rocks in the Central Depression of the Songliao Basin generally have high organic matter abundance. The average TOC content of the 2nd and 3rd Members of Qingshankou Formation is 1.31%, with organic matter of Type I. The R_o values range from 0.682% to 1.263%, mainly representing medium-mature and high-mature source rocks. The average TOC content of the 1st Member of Qingshankou Formation is 3.88%, with organic matter mainly of Type I and Type II₁. The R_o values range from 0.429% to 1.382%, mainly representing medium-mature and high-mature source rocks. The Qingshankou Formation retains relatively high residual organic matter abundance, indicating favorable original hydrocarbon generation potential.
- (2) Although the three wells experienced a similar regional thermal evolution pattern characterized by Late Cretaceous heating and subsequent cooling, significant differences in maturity evolution existed due to heterogeneous burial histories and structural settings. The Central Depression of the Songliao Basin has experienced three tectonic stages. Among them, the depression stage during the deposition of the Qingshankou Formation and Nenjiang Formation was the main subsidence and basin-forming stage of the basin, with the maximum sedimentation rate reaching 150 m/Ma. The paleotemperature continued to increase from the initial simulation

period to the end of the Nenjiang Formation deposition. Compression occurred in the basin at the end of the Nenjiang Formation deposition, causing a slight decrease in paleotemperature. Thereafter, until the depositional period of the Mingshui Formation, the sedimentation rate increased again, with the maximum reaching 170 m/Ma, and the paleotemperature also continued to rise, reaching a maximum of 180 °C. From the end of the Mingshui Formation deposition to the present day, the sedimentation rate has gradually stabilized, and the paleotemperature has gradually decreased and tended to be stable.

- (3) The main hydrocarbon generation period of Cretaceous source rocks in the Central Depression of the Songliao Basin was 75–80 Ma. The maximum cumulative oil production of source rocks in the 2nd and 3rd Members of Qingshankou Formation is 140 mg/(g·TOC), and the maximum cumulative gas production is 26 mg/(g·TOC). The maximum cumulative oil production of the 1st Member of Qingshankou Formation is 220 mg/(g·TOC), and the maximum cumulative gas production is 40 mg/(g·TOC). Since the end of the Cretaceous, with the slow progress of thermal subsidence, the hydrocarbon generation potential of source rocks has gradually weakened.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/doi/10.3390/pr14152396>, Table S1: Basic geochemical properties, Rock-Eval pyrolysis, and kerogen isotope data of the studied source rocks.

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