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Thermal History Simulation Restoration of Burial History of Paleozoic Source Rocks in Western Margin of Ordos

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Abstract

The western margin of ordos basin as the main exploration area, because the thermal evolution process of source rocks in the western margin of the basin system research is not deep enough, seriously restricts the evaluation and exploration of oil and gas resources, regional exploration has not been a big breakthrough. In view of this, based on the restoration of burial history and thermal evolution history of source rocks, this paper analyzed and summarized the differences in thermal evolution of coal measure source rocks in Taiyuan Formation of different tectonic units in the study area by using PetroMod basin simulation software. The results show that the thermal evolution degree of organic matter in the source rocks in the western margin of Ordos presents a zonal distribution from south to north. On the whole, the thermal evolution degree of organic matter in source rocks of different horizons in Tianhuan depression is obviously higher than that in the Western margin thrust belt. The maximum Ro value of the source rocks in the Taiyuan Formation of the Western margin thrust belt of the Ordos Basin is 1.0% - 1.4%, and most of them have reached the late stage of mature oil and gas generation and gradually entered the early stage of high mature pyrolysis gas generation. The maximum Ro value of source rocks in the Taiyuan Formation in the west of Tianhuan depression is 1.4% - 2.0%, which reaches the high maturity stage of thermal cracking. This study can provide reference for oil and gas exploration and hydrocarbon accumulation research in the western margin of sedimentary basin.

Subject Areas

Petrochemistry

Keywords

Ordos Basin, Thermal Evolution, PetroMod, Ro

1. Introduction

Ordos Basin is a famous large Mesozoic petroliferous basin in western China [1], Rich oil and gas resources are in source rock reservoir of western margin of basin [2]. Before 2019, the gas test of horizontal well ZP1 drilled in the coal measure strata of Taiyuan Formation in the western margin of Ordos Basin was 26.48 $\times 10^4$ m^3/d. In 2021, the gas test production of shale gas horizontal well E102X in Wulalike Formation was 16.69 $\times 10^4$ m^3/d [3]. Previous studies on the organic matter abundance, maturity and geochemical indexes of source rocks were carried out by using the data of field outcrops and drilling core samples, and the geochemical characteristics and effectiveness of source rocks in the western margin of Ordos were basically clarified.

For a long time, the western Ordos Basin has been the main exploration area. Although many wells have obtained industrial gas flow, there has been no major breakthrough. At present, the research on the thermal evolution process of source rocks in the western margin of the basin is not deep enough, which seriously restricts the exploration and evaluation of oil and gas resources. In this paper, the western margin of Ordos Basin is taken as the main study area. Based on the full investigation of the geological background of the study area and the results of previous studies, the erosion amount of the key tectonic period is restored. Using PetroMod basin simulation software, on the basis of restoring the burial history of the basin, using the Easy%Ro model, combined with the related research methods of source rock evaluation, the thermal evolution process of source rocks in the western margin of Ordos Basin was restored, and the differences of thermal evolution of source rocks in different tectonic units were analyzed and summarized. This can provide reference for the study of oil and gas exploration and hydrocarbon accumulation in the western margin of Ordos Basin, and provide basic data support for the process of hydrocarbon accumulation in the study area.

2. Geological Settings

The Ordos Basin is one of the three major craton basins in China [4] and the second largest sedimentary basin in China. As an important oil and gas bearing basin in China, it is rich in multi-layer and multi-type mineral resources. Coal, oil and natural gas resources are widely distributed [5], and the scale reserves are large [6] [7] [8] [9].

The western margin of the Ordos Basin is located at the junction of the Ordos block, the Alashan ancient land and the Qinling-Qilian orogenic belt. It is also located at the junction of multiple tectonic units and is a hub connecting different tectonic units in eastern and western China (**Figure 1**) [10] [11] [12]. This special tectonic position makes it experienced multiple periods of tensile rifting, extrusion closure activities in different geological history periods [13].

The study area in this paper is located in the western margin of the thrust tectonic belt and the Western part of the Tianhuan depression. The area has experienced multiple complex tectonic evolution processes. The Western margin of the basin is affected by the thrust fold, the fold thrust is strong, the structural deformation is complex [14] [15], and the overall distribution is north-south [11] [16]. In the Cenozoic, the Himalayan tectonic movement caused the collision between the Indian plate and the Tibetan-Qinghai lithospheric plate, which led to the complication of folds and faults in the western margin, and the faults in the western margin thrust belt were extremely developed [2].

The thrust fold belt in the west margin of Ordos is an extremely important

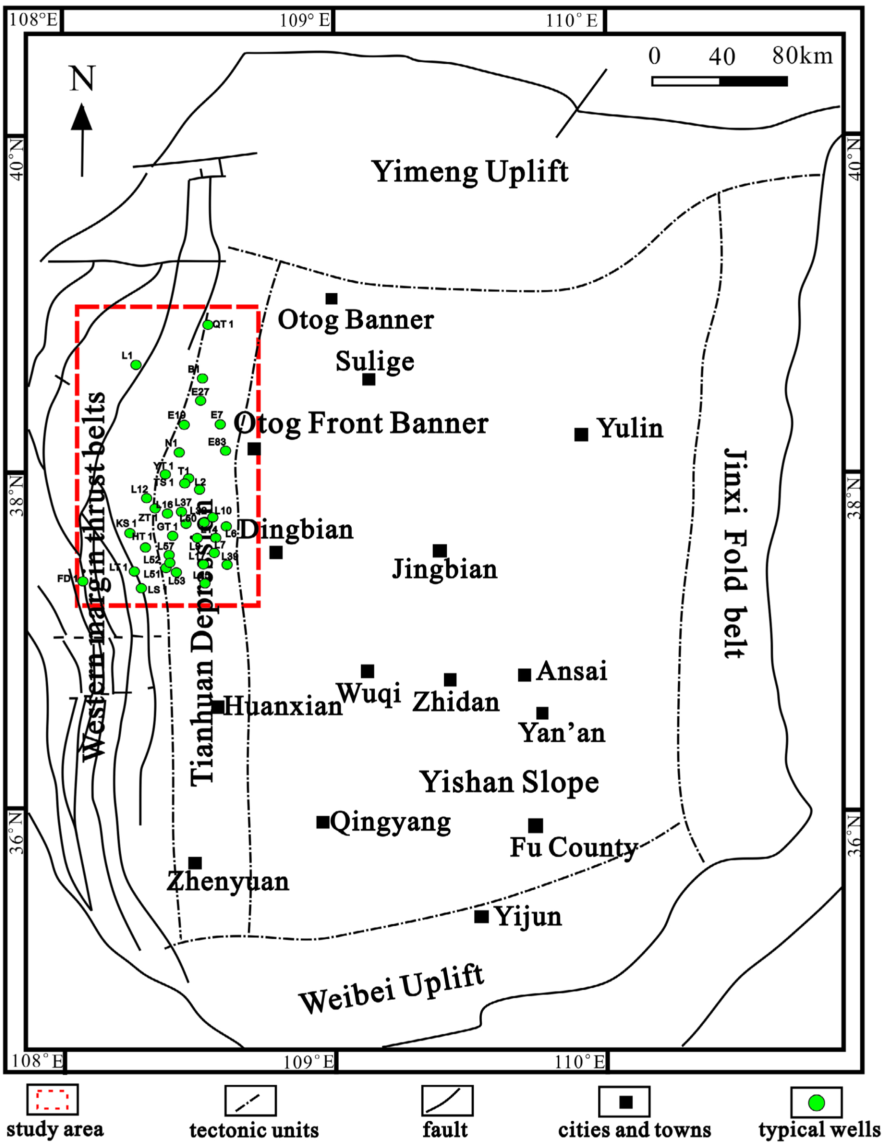

Figure 1. Structural location of western margin of Ordos Basin.

overthrust tectonic belt developed in Mesozoic era in China. It is transformed by multiple tectonic movements such as Indosinian movement, Yanshan movement and Himalayan movement. The structure is complex, the tectonic activity is strong, and the structure of Tianhuan depression is relatively stable [17]. The complex tectonic environment determines the complex, diverse and segmented tectonic characteristics of the western margin of the basin [18].

Three sets of source rocks are developed in the west margin of Ordos Basin from bottom to top, which are the grey mudstone of Uralik Formation of Middle-Upper Ordovician, coal measure source rocks of Taiyuan Formation and Shanxi Formation of Permian and Yanchang Formation of Triassic.

3. 1D Basin Modeling Method

The restoration of burial history, thermal evolution history and hydrocarbon generation history of source rocks in the western margin of Ordos Basin is an important aspect of oil and gas resource exploration and source rock evaluation [19] [20]. The hydrocarbon generation history of source rock thermal evolution determines the hydrocarbon generation evolution process of source rock, and has an important influence on the process of hydrocarbon generation, preservation and liquid oil cracking into gas [21]. The burial history of sedimentary basins controls the speed of basin deposition, the magnitude of uplift and denudation, and the formation and distribution of source rocks [22].

3.1. PetromMod

Basin simulation technology is based on the actual geological model, in time and space by the computer quantitative simulation of the formation and evolution of petroliferous basins [23]. It has been applied to quantitative and dynamic analysis of basins for more than thirty years. With the vigorous development of petroleum exploration and development, the application field is more and more extensive, and the technical method is more and more mature. It has played an important role in the tectonic-thermal evolution of the basin, the hydrocarbon generation and expulsion history of source rock, the dynamic process of migration and accumulation, and the prediction of oil and gas resources, revealing the essence of oil and gas law in the basin [24]. Based on the analysis of a large number of geological data and laboratory results, this paper uses the widely used basin simulation software system PetroMod 2016 to systematically simulate the burial history of strata and the mature evolution history of source rocks in the western margin of Ordos Basin, which provides a basis for the evaluation of oil and gas resources [25].

Vitrinite reflectance is the most commonly used and direct geochemical indicator of organic matter maturity [26]. Burnham et al.established a VITRIMAT model related to vitrinite reflectance and thermal maturity based on the Arrhenius first-order parallel reaction equation of chemical reaction activation energy distribution, and improved it to Easy % Ro model [27].

3.2. Simulation Parameter Selection

The basic parameters such as formation thickness, sedimentary age, lithology data, denudation thickness in critical period and organic geochemical parameters of source rocks are needed when using Petromod software system to establish the numerical simulation of typical well location in the western margin of Ordos. In addition, boundary condition parameters including sedimentary water interface temperature, paleo-water depth and terrestrial heat flow are needed to constrain the software calculation process [28] [29]. Other physical parameters such as density, porosity, permeability, compression coefficient, thermal conductivity of rock, specific heat and so on are calculated by arithmetic mean or geometric mean of pure lithology parameters by simulation software [30].

When using EASY % Ro method to simulate the thermal history, it is necessary to correct the thermal history according to the measured vitrinite reflectance value, and adjust the parameters to make it basically consistent with the measured value. Then the thermal evolution history and hydrocarbon generation history model of typical well source rock are established [22]. According to previous studies, the type of kerogen in the coal-bearing source rocks of Taiyuan Formation in this area is mainly type III humic type [31], and the type III kerogen kinetic model is selected for simulation. Through repeatedly adjusting the simulation parameters, the simulation results can be consistent with the actual geological conditions in the study area, and more reliable simulation results can be obtained.

3.2.1. Determination of Erosion Amount

Denudation thickness is one of the important parameters in basin simulation. The denudation thickness has a great influence on the burial history of strata and the thermal evolution history of source rocks.

In this paper, the mudstone acoustic time difference method is used to calculate the denudation amount, and the denudation amount of each well is comprehensively determined by referring to the previous estimation results of the denudation thickness of the Ordos Basin. Based on previous studies, it is believed that the western margin of the Ordos Basin has experienced five stages of uplift and denudation (**Table 1**), of which the first four denudations were weak, and the regional denudation in the late Cretaceous was the strongest [32] [33] [34].

Table 1. Determination of erosion amount.

Erosion Time	Erosion Quantity
Late O_3	0 - 200 m
Late T_3	150 - 250 m
Late J_1	80 - 100 m
Late J_3	120 - 180 m
Late K_2	500 - 600 m

The method of calculating the amount of strata denudation by acoustic time difference curve originated from the simple exponential model proposed by Athy (1930), that is, the exponential relationship between mudstone porosity and depth [33].

$$\phi = \phi_0 e^{-kD} \tag{1}$$

ϕ: rock porosity, %; ϕ_0: Surface rock porosity, %; k: exponential constant; D: Rock buried depth, m.

Ater Wyllie (1958) proposed the relationship between rock porosity (ϕ) and acoustic travel time (Δt) [35]:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_{\mathrm{f}} - \Delta t_{ma}} \tag{2}$$

Δt: the measured rock acoustic time difference, μs/m; Δt_{ma}: rock skeleton acoustic time difference, μs/m; Δt_f: acoustic time difference of pore fluid in rock, μs/m.

In combination with Equations (1) and (2), Magara pointed out that there is also a linear relationship between mudstone porosity and acoustic travel time, so the mudstone compaction equilibrium equation can be directly expressed by acoustic travel time:

$$\Delta t = \Delta t_0 e^{-CH} \tag{3}$$

Δt: Acoustic time difference of mudstone at depth H, μs/m; Δt_0: Acoustic time difference of mudstone extrapolated to the surface, μs/m; C: The slope of the normal compaction trend line; H: burial depth, m; The surface acoustic time difference of the western margin of Ordos Basin is generally taken 600 μs/m.

Combined with logging and mud logging data, 40 wells with complete data, mudstone development (pure mudstone or shale with thickness greater than 2 m) and small thickness of overlying strata were selected to read mudstone compaction curve. The Cretaceous thickness in the study area was calculated. Taking L14 and L10 as examples, the erosion amount data of Cretaceous (**Figure 2**) are calculated. The erosion thickness of L14 Cretaceous is 543 m, and that of L10 Cretaceous is 560 m. The results are in good agreement with the previous research results, and the calculation results of erosion amount are more reliable.

3.2.2. PWD Simulation

Paleo-water depth recovery is an important indicator of paleo-environmental research and basin analysis, and it is also a key boundary condition in the simulation of stratigraphic burial history and thermal evolution history of source rocks in sedimentary basins [36]. Reasonable prediction of paleo-water depth can improve the simulation accuracy of basin simulation. The sedimentary environment in the western margin of Ordos has the most serious influence on the ancient water depth. The ancient water depth of each sedimentary period is mainly based on the sedimentary facies of the period and the comprehensive prediction of the modern sedimentary water depth data of previous studies, and

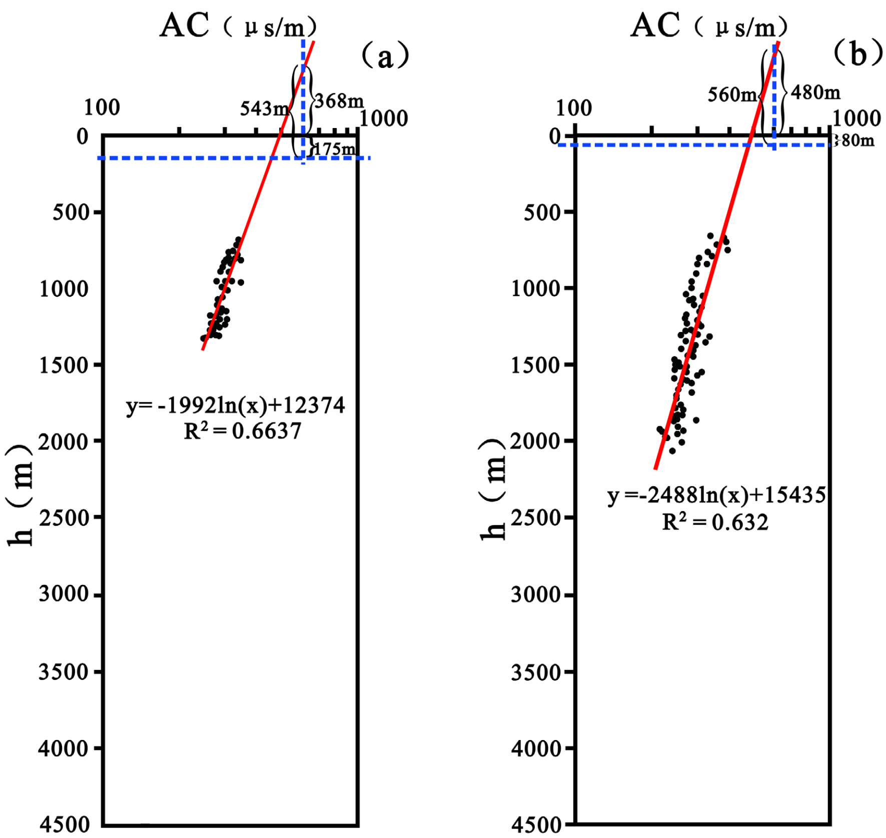

Figure 2. Restoration of eroded thickness; (a) L14, (b) L10.

Table 2. PWD of Ordos Basin in Different Periods [37].

Age	Facies	PWD/m
K^2~Q	Aeolian loess facies	0
T~K_2	Inland lake facies	0 - 20
C_2~P	Coastal plain facies	0 - 50
€~O	Coastal platform facies	50 - 200

the corresponding standard table of ancient water depth and sedimentary facies is established (Table 2) [35] [37] [38].

3.2.3. SWIT Simulation

The prediction of sedimentary water interface temperature is also one of the key boundary conditions in basin simulation. The prediction of sedimentary water interface temperature in the western margin of Ordos Basin mainly uses the global unified surface temperature temperature-time template (SWIT) provided by PetroMod software [35]. The regional geographical location of the western margin of the Ordos Basin is mainly located at 39·N latitude in the central Asia of the northern hemisphere. Input it into the software to generate a sedimentary water interface temperature template for the western margin of the Ordos Basin [30] [37] (Figure 3).

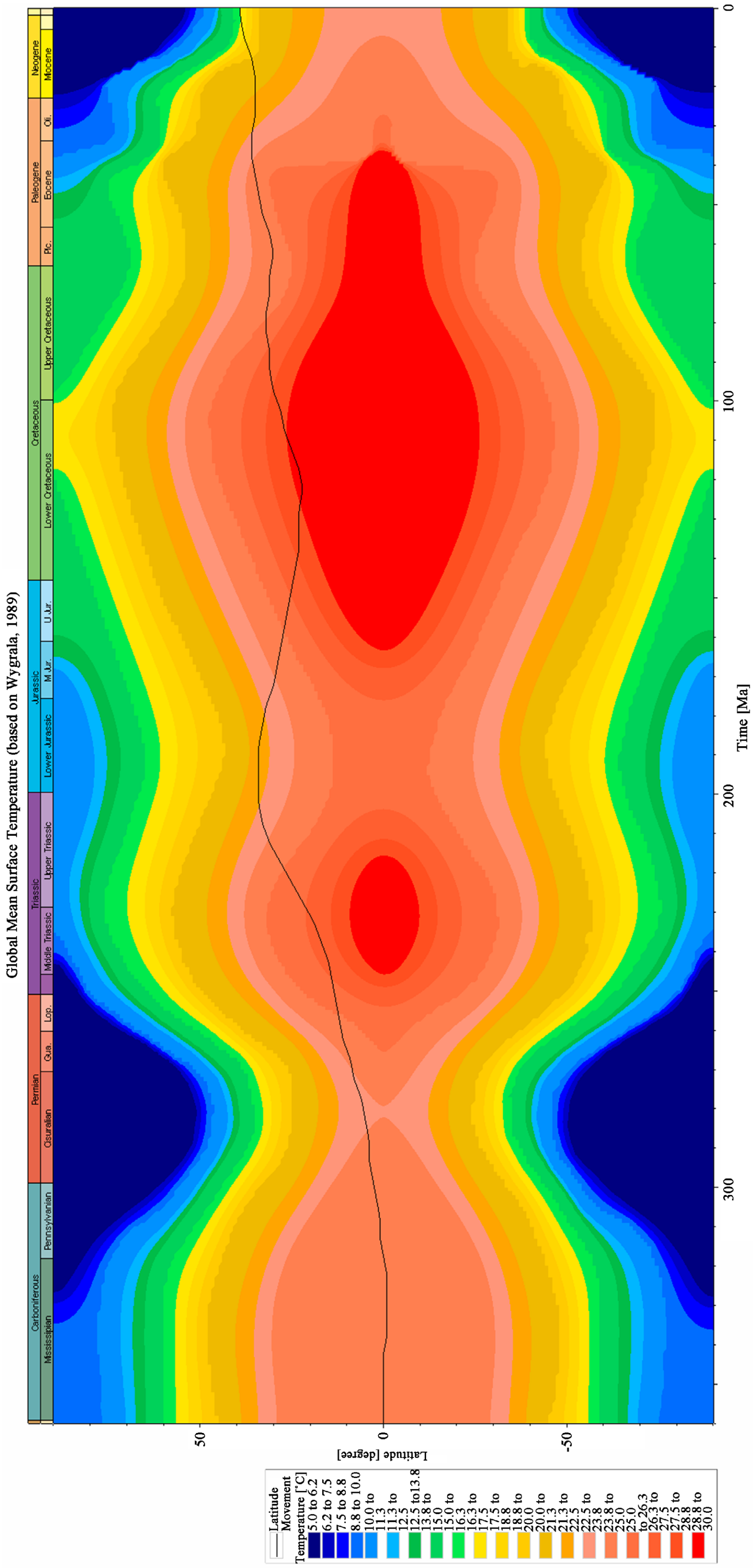

Figure 3. The global mean surface temperature.

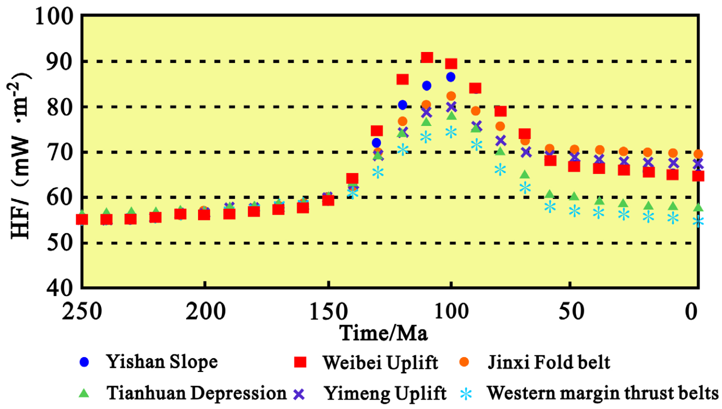

Figure 4. Evolution history of geothermal flow in Ordos basin [39].

3.2.4. Heat Flow Calculation

Selecting reasonable paleoheat flow value in basin simulation software plays a decisive role in the accuracy of simulation results. Combined with previous research results, it is shown that the current geothermal gradient and heat flow value of the thrust belt and Tianhuan sag in the western margin of Ordos Basin are lower than those of other structures. The selection of heat flow value in this area mainly refers to the research results of Zhanli Ren [35] [39] (**Figure 4**).

4. Results and Analysis

To verify the reliability of the established geological model of burial history and thermal evolution history of source rocks, and to avoid errors in the simulation of burial history. Taking Well FD1 and Well YT1 as examples, the vitrinite reflectance (Ro) value which can sensitively reflect the thermal evolution is selected as the calibration parameter of the simulation results. In the process of establishing the geological model, the measured vitrinite reflectance (Ro) value is input and the model is run for simulation verification.

In this paper, the vitrinite reflectance (Ro) value that can sensitively reflect the thermal evolution is selected as the calibration parameter of the simulation results to verify whether the established geological model is reliable (**Figure 5(b)**, **Figure 6(b)**) [39] [40] [41]. From the verification situation, a large number of single well formation Ro values are in good agreement with the current measured Ro values as calibration values, indicating that the selection of simulation parameters is more accurate and the model establishment is more reliable [42].

The burial history shows that FD1 well and YT1 well have the same tectonic uplift/subsidence history: both contain three major subsidence stages and three major uplift stages (**Figure 5(a)**, **Figure 6(a)**). They are: the first rapid sedimentary stage from Ordovician to late Triassic (450 - 210 Ma). The second slow burial stage from the early Early Permian to the middle and late Late Cretaceous (200 - 140 Ma), the strata experienced the maximum burial depth. The third burial stage is the late uplift burial stage from Cenozoic to present. Affected by the Yanshan movement, the first uplift event occurred at the end of the Late

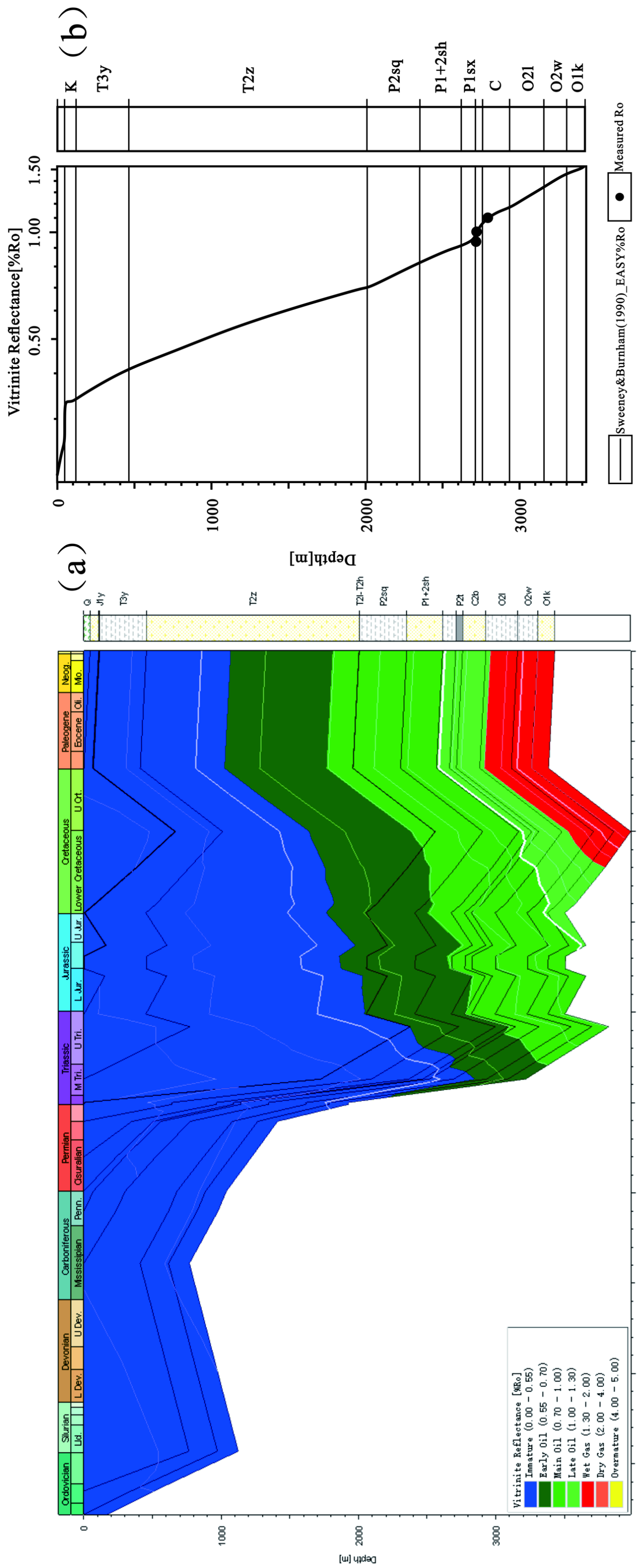

Figure 5. (a) 1D basin modeling of Well FD1 based on the best fifit between measured and modeled thermal indicators (b, Ro).

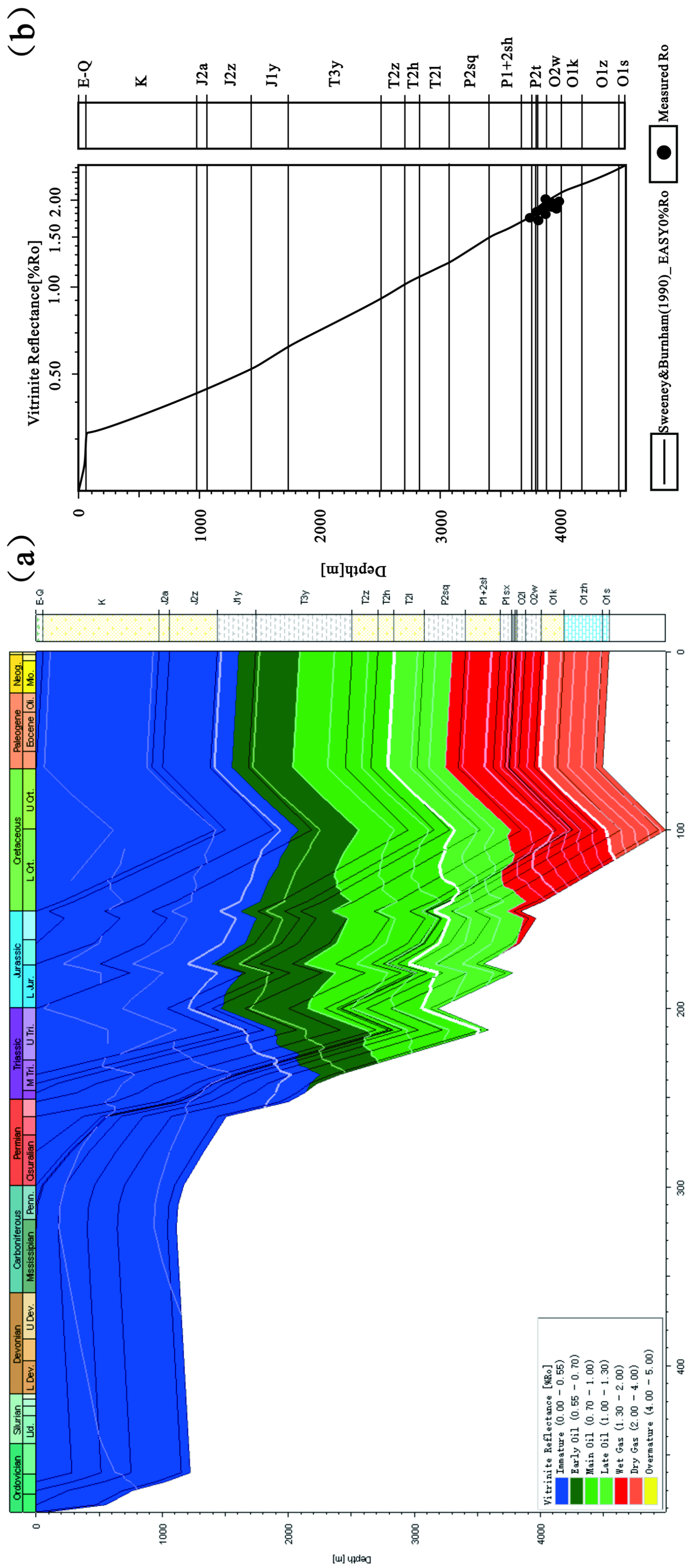

Figure 6. (a) 1D basin modeling of Well YT1 based on the best fifit between measured and modeled thermal indicators (b, Ro).

Triassic (212 Ma), and the denudation intensity was relatively weak, with a denudation thickness of 250 m. After Jurassic sedimentation, the main curtain of Yanshan movement caused the Late Jurassic Anding Formation to be denuded to form a second uplift event with a denuded thickness of 100 m. The third uplift occurred at the end of Cretaceous. The Yanshan late curtain tectonic movement uplifted the whole basin again, and the Cretaceous strata were strongly denuded with a thickness of 550 m.

Among them, the western margin thrust belt takes FD1 well as an example (**Figure 5(a)**). The maturity evolution history and hydrocarbon generation history of Paleozoic source rocks in this well can be described as follows: Permian Shanxi Formation + Taiyuan Formation source rocks: In the early Late Triassic, the Ro value reached 0.55% and began to enter the hydrocarbon generation threshold. In the middle and late Late Triassic, the Ro value reached 0.7% and began to enter the peak of oil generation and entered the main oil window. In the early and late Late Cretaceous, the Ro value reached 1.0% and began to enter the late stage of the main hydrocarbon generation stage. The source rocks of this group have not entered the gas generation stage. Ordovician Lashzhong Formation + Wulalike Formation source rocks: in the early Late Triassic Ro value reached 0.55% began to enter the hydrocarbon generation threshold; in the middle and late Triassic, the Ro value reached 0.7% and began to enter the peak oil generation period, entering the main oil window; in the middle and late period of Early Cretaceous, Ro value reached 1.0% and entered the late period of main hydrocarbon generation period; in the late Cretaceous Ro value reached 1.3%, began to enter a large number of moisture stage; after the Late Cretaceous, the thermal evolution of source rocks stopped due to uplift.

In the western part of Tianhuan sag, another structural part of the western margin of Ordos, taking well YT1 as an example (**Figure 6(a)**), the mature evolution history and hydrocarbon generation history of the source rocks in this well can be described as follows: Permian Shanxi Formation + Taiyuan Formation source rocks: in the early Late Triassic, the Ro value reached 0.55% and began to enter the hydrocarbon generation threshold, and the source rocks gradually matured. In the middle and late Late Triassic, the Ro value reached 0.7%, and began to enter the main oil generation window and began to enter the peak period of oil generation. In the early Cretaceous Ro value reached 1.0%, entering the late stage of the main hydrocarbon generation stage; the Ro value reached 1.2% in the middle and late Early Cretaceous, and began to enter the stage of high maturity (moisture generation). Ordovician Lashzhong Formation + Wulalike Formation source rocks: in the late Middle Triassic Ro value reached 0.55% began to enter the hydrocarbon generation threshold; in the middle of the late Triassic, the Ro value reached 0.7%, and began to enter the peak period of oil generation. In the early Cretaceous, the Ro value reached 1.0% and entered the late stage of main hydrocarbon generation. In the middle of the early Cretaceous, the Ro value reached 1.2%, and began to enter the stage of high mature moisture generation.

Combined with the evolution diagram of vitrinite reflectance of source rocks of Taiyuan Formation in 5 wells with time (**Figure 7**), it can be seen that before the early Late Triassic, the thermal evolution degree of the basin was low, and the source rocks of Taiyuan Formation were in the immature stage as a whole and did not have hydrocarbon generation capacity. The Ro value of the source rocks in the western margin of Ordos reached 0.55% in the early Late Triassic and entered the hydrocarbon generation threshold, which was in the stage of low maturity evolution. During the Yanshan cycle, the basin entered the stage of flexural differential subsidence after short-term overall uplift. During the uplift process, the structural characteristics changed significantly. The western margin of the basin was first uplifted and eroded, forming the tectonic evolution characteristics of the Yanchang Formation gradually uplifted and eroded from northeast to southwest. The strata experienced short-term uplift and denudation, and the evolution of source rocks stagnated, which delayed the time of source rocks entering the main oil window. With the increase of burial depth, in the early Jurassic (about 200 Ma ago), the source rocks of Taiyuan Formation gradually matured. The Ro value of the western margin thrust belt reached or exceeded 0.6% to enter the hydrocarbon generation threshold, and the Ro value near the Tianhuan sag reached or exceeded 0.8%, entering the main oil window and entering the peak oil generation period. The second episode of Yanshan movement occurred after the deposition of Anding Formation at the end of Late Jurassic. The main body of the basin rose and the strata were eroded. At the end of Late Jurassic (145 Ma ago), most of the source rocks of Taiyuan Formation entered the peak period of oil generation, and the overall evolution degree was low in the east and north, and high in the west and south. The overall Ro value of the western margin thrust belt reaches or exceeds 0.8%, and the Ro value near the Tianhuan sag reaches or exceeds 1.0%, and the range entering the peak hydrocarbon generation period is further expanded.

At the end of the Early Cretaceous (100 Ma ago), the thermal evolution of organic matter increased sharply. The Ro value of the western margin of the Taiyuan Formation thrust belt is mainly distributed between 0.8% - 1.4%, such as the Ro = 0.95% of FD1, which entered the stage of thermal catalytic hydrocarbon generation. The value of Ro is mainly distributed between 1.2% and 1.8% near the Tianhuan sag, such as Ro = 1.7% of YT1, which enters the stage of high maturity (moisture). At the same time, after experiencing the maximum burial depth at the end of the early Cretaceous, the strongest one-stage basin-wide uplift and denudation event occurred since the Triassic.Under the action of the late Yanshan tectonic movement, the basin was uplifted again, and the Cretaceous strata were denuded, which caused the strata to uplift, the hydrocarbon generation evolution of the source rocks to stagnate, and the degree of thermal evolution of the basin did not change much. At present, the thermal evolution degree of source rocks in Taiyuan Formation maintains the pattern at the end of Late Cretaceous, and the evolution degree increases slightly under the influence of

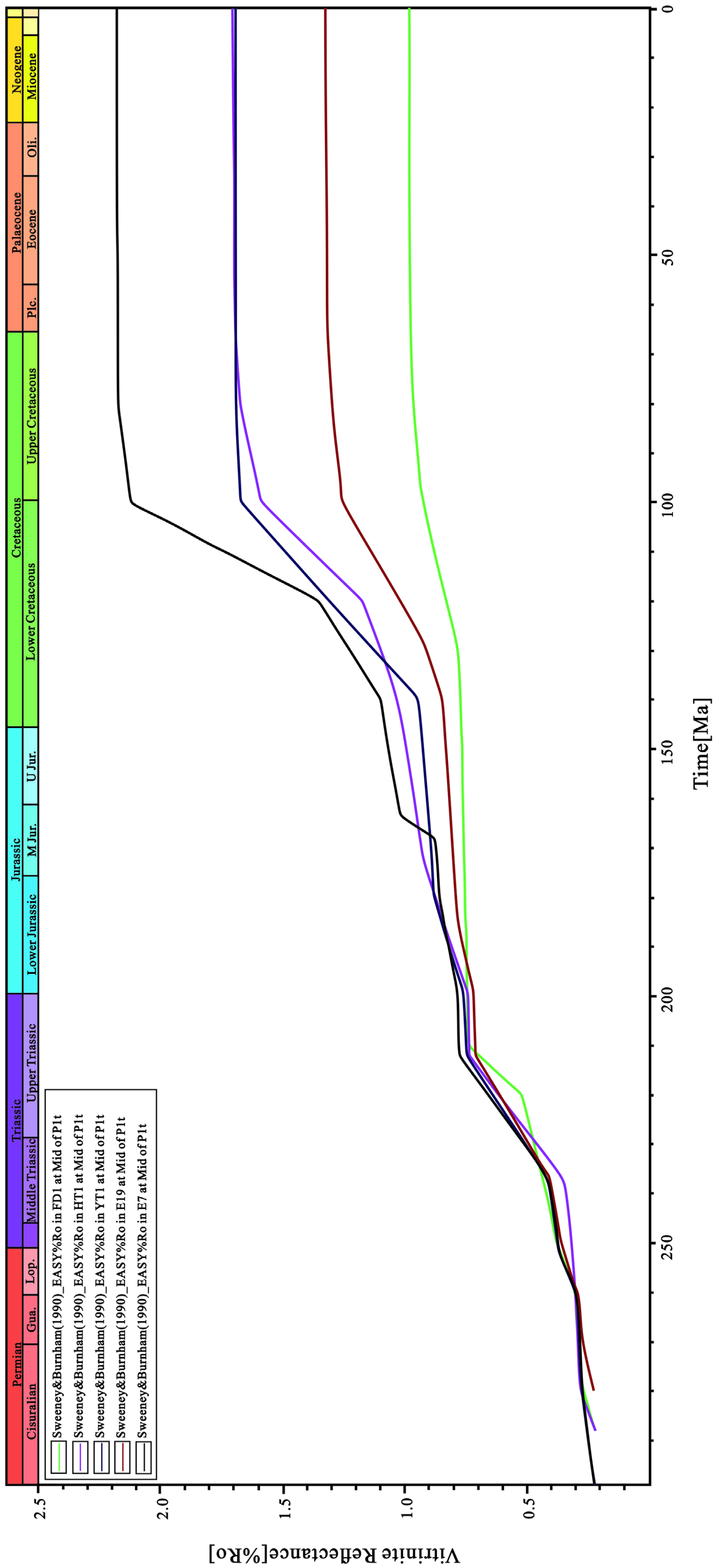

Figure 7. Vitrinite reflectance versus time.

superposition time effect. The Ro value of the western margin thrust belt is mainly distributed in 1.0% - 1.4%, reaching the late stage of mature oil and gas generation stage and gradually entering the early stage of high mature thermal cracking and moisture generation stage, and kerogen gas generation plays a major role. The value near the Tianhuan sag is mainly distributed between 1.4% - 2.0%, and in the late stage of high maturity (wet gas), crude oil cracking into gas is dominant.

5. Conclusions

1) Based on previous studies, the western margin of the Ordos Basin has experienced five stages of uplift and denudation, of which the first four denudations were weak. The erosion amount of Ordovician region is about 50 m; at the end of Late Triassic, the regional denudation is about 150 - 250 m; the denudation amount at the end of the early Jurassic is 80 - 100 m; late Jurassic unexfoliated amount is 120 - 180 m; the Late Cretaceous regional denudation is the most intense, the denudation thickness is 500 - 600 m.

2) The simulation results show that the period when the Ro value of Taiyuan Formation in the western margin of Ordos Basin reaches 0.55% and enters the hydrocarbon generation threshold is the early Late Triassic. On the whole, the thermal evolution degree of organic matter of source rocks in different layers of Tianhuan sag is obviously higher than that of source rocks in the western margin thrust belt. The maximum Ro value of source rocks in the thrust belt of the western margin of the basin is 1.0% - 1.4%, most of which have reached the late stage of mature oil and gas generation and gradually entered the early stage of high mature thermal cracking and moisture generation. The maximum Ro value of source rocks in the west of Tianhuan sag is 1.4% - 2.0%, which reaches the high mature stage of thermal cracking.

3) According to the results of single well simulation, based on the analysis of burial history and thermal history of source rocks, the thermal evolution degree of Paleozoic source rocks is analyzed in detail, and the exploration direction is clarified.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Cheng, K. (2020) Research on Tectonic Features and Hydrocarbon Accumulation in Majiatan Area of Ordos Basin. Xi'an Shiyou University, Xi'an.

[2] Fu, S.T., Fu, J.H., Xi, S.L., *et al.* (2022) Geological Characteristics of Ordovician Marine Shale Gas in the Ordos Basin and Its Prospects. *China Petroleum Exploration*, **26**, 33-44.

[3] Zhang, F.Q., Li, Y.N., Luo, J.L., *et al.* (2021) Microscopic Pore Structure Characteristics of Shale of Ordovician Wulalike Formation in Western Ordos Basin. *Lithologic Reservoirs*, **34**, 50-62.

[4] Zhao, W.Z., Wang, Z.C., Hu, S.Y., *et al.* (2012) Large-Scale Hydrocarbon Accumulation Factors and Characteristics of Marine Carbonate Reservoirs in Three Large Onshore Cratonic Basins in China. *Acta Petrolei Sinica*, **33**, 1-10.

[5] Zhao, J.L., Tan, C.Q., Liu, C.Y., *et al.* (2006) Enrichment Features of Oil, Gas, Coal and Uranium in Ordos Basin. *Acta Petrolei Sinica*, **27**, 58-63.

[6] Zhang, Y.N., Li, R.X., Xi, S.L., *et al.* (2022) Sedimentary Environments and Organic Matter Enrichment Mechanism of Ordovician Wwulalike Formation Shale, Western Ordos Basin. *Journal of Central South University* (*Science and Technology*), **53**, 3401-3417.

[7] Wu, D.X., Zhou, J.G., Wu, X.N., *et al.* (2018) Lithofacies and Palaeogeography of the Early-Middle Ordovician in the Western Ordos Basin. *Geological Journal of China Universities*, **24**, 747-760.

[8] Li, X.Y., Wei, Z.Y. and Chen, H.D. (2022) Genetic Analysis of Internal-Wave and Internal-Tide Deposits in Upper Ordovician Lashenzhong Formation, Western Ordos Basin. *Acta Geologica Sinica*, 1-17.

[9] Li, X.D. and Chen, H.Y. (2020) Analysis of Paleocurrent Direction and Identification of Ponded Turbidity Current Deposits in Deep Water Environment: A Case Study of the Upper Ordovician Lashenzhong Formation in Zhuozishan Area, Ordos Basin. *Acta Petrolei Sinica*, **41**, 1348-1365.

[10] Yu, W., Wang, F., Gong, L., *et al.* (2021) Sedimentary Environment Characteristics and Tectonic Implications of Yanghugou Formation in the Western Margin of Ordos Basin, China. *Journal of Chengdu University of Technology* (*Science & Technology Edition*), **48**, 691-7 04.

[11] Jiang, S.Y., Huang, W.H. and Zhang, Y.S. (2020) Geochemical Characteristics of Middle Ordovician in Western Margin of Ordos Basin and Its Implication on Paleoenvironment. *Geoscience*, **34**, 545-553.

[12] Yin, Z., Liu, Z.L. and Peng, N. (2019) Study on Sedimentary Faciess Features of the Upper Triassic Yanchang Formation, in the Western Margin, Ordos Basin. *Acta Sedimentologica Sinica*, **37**, 163-176.

[13] Zhu, S.Y., Liu, L., Wang, F., Hou, Y.D., *et al.* (2022) Genetic Mechanism and Depositional Processes of Sandy Sediments from the Carboniferous Yanghugou Formation along the Western Margin of the Ordos Basin and Its Adjacent Areas. *Acta Sedimentologica Sinica*, 1-23.

[14] Wu, C.Y., Jia, Y.N., Han, H.P., *et al.* (2015) Evaluation of Ordovician Source Rocks in Western Margin of Ordos Basin. *Xinjiang Petroleum Geology*, **36**, 180-185.

[15] Xi, S.L., Mo, W.L., Liu, X.S., *et al.* (2021) Shale Gas Exploration Potential of Ordovician Wulalike Formation in the Western Margin of Ordos Basin Case Study of Well Zhongping 1. *Natural Gas Geoscience*, **32**, 1235-1246.

[16] Li, X.D., Chen, H.Y. and Chen, H.D. (2019) Deep-Water Combined-Flow Deposits of the Upper Ordovician Lashenzhong Formation in Zhuozishan Are, Western Margin of Ordos Basin. *Advances in Earth Science*, **34**, 1301-1315.

[17] Guo, Y.Q., Wang, M.X., Guo, B.C., *et al.* (2020) Sedimentary System Characteristics and Paleographic Evolution of Upper Paleozoic of Northern West Margin, Ordos Basin. *Journal of Northwest University* (*Natural Science Edition*), **50**, 93-104.

[18] Wang, Z.W., Zhao, Y.G., Yin, Y.Y., *et al.* (2020) Seismic Prediction of "Sweet Spots" for Shale Gas. *Petroleum Geology and Engineering*, **34**, 37-41.

[19] Yin, Y.Y., Yao, Z.C., Guo, X.B., *et al.* (2022) Characteristics of Permian Concealed Structures in Western Margin of Ordos Basin and Its Significance for Oil and Gas Exploration. *Lithologic Reservoirs*, **34**, 79-88.

[20] Luo, W.B. (2016) Characteristics and Distributions of Chang 7 Source Rock in Ordos Basin. China University of Petroleum, Beijing.

[21] Jiang, Q., Zhu, C.Q., Qiu, N.S., *et al*. (2015) Paleo-Heat Flow and Thermal Evolution of the Lower Cambrian Qiongzhusi Shale in the Southern Sichuan Basin, SW China. *Natural Gas Geoscience*, **26**, 1563-1570.

[22] Qi, K., Ren, Z.L., Cui, J.P., *et al*. (2018) Thermal History Reconstruction of Mesozoic Source Rocks in Western of Suhongtu Depression, Inner Mongolia, Northern China. *Earth Science*, **43**, 1957-1971.

[23] Cui, J.W., Zhang, Z.Y., Liu, J.L., *et al*. (2021) Hydrocarbon Generation and Expulsion Quantification and Hydrocarbon Accumulation Contribution of Multiple Source Beds in Yanchang Formation, Ordos Basin. *Natural Gas Geoscience*, **32**, 1514-1531.

[24] Zhou, Y.S., Jia, C.S., Zhang, K.H., *et al*. (2021) Thermal Evolution History Reconstruction of Carboniferous Source Rocks on the Northeastern Margin of Junggar Basin Using TSM Basin Simulation Technology. *Petroleum Geology & Experiment*, **43**, 297-306.

[25] Liu, J.P., Jian, X.L., Wang, H.J., *et al*. (2020) Thermal Evolution History of Hydrocarbon Source Rock in the Zhongjiannan Basin, Western South China Sea. *Journal of Geology*, **44**, 157-162.

[26] Zheng, J.C., Li, B., Liu, Y.L., *et al*. (2018) Study on Thermal Evolution Modeling of Lower Cambrian Yuertusi Source Rock, Tarim Basin. *Petroleum Reservoir Evaluation and Development*, **8**, 7-12.

[27] Zhao, Y.H., Zhu, C.Q., Zhang, B.S., *et al*. (2022) Influence of Carboniferous-Permian Magmatic Activities on Thermal Evolution of Source Rocks in Tarim Basin. *Geology in China*, 1-15.

[28] Han, Y., Gao, X.Z., Zhou, F., *et al*. (2020) Thermal Evolution of Jurassic Source Rocks and Their Impact on Hydrocarbon Accumulation in the Northern Margin of Qaidam Basin, NW China. *Natural Gas Geoscience*, **31**, 358-369.

[29] Liu, J.D., Jiang, Y.W. and Zhang, W.H. (2018) Application of Basin Simulation Technology in Experimental Teaching for Source Rock Thermal Evolution. *Experimental Technology and Management*, **35**, 180-182.

[30] Wu, Y.J., Wang, S., He, L., *et al*. (2021) Research on the Burial History and the Thermal Evolution History of the Jurassic Coal-Measure Source Rocks in the Eastern Margin of Xiaocaohu Sag. *Northwestern Geology*, **54**, 180-191.

[31] Zhai, G.H. (2021) Study of Upper Paleozoic Hydrocarbon Source Rocks in Western Ordos Basin. Northwest University, Xi'an.

[32] Tao, C.Q., Li, Y., Ni, X.M., *et al*. (2022) Study of the Evolution Process of Coal Maturity in Upper Carboniferous Benxi Formation, Linxing Area. *Journal of China University of Mining & Technology*, **51**, 344-353.

[33] Weng, W.F., Wang, J.Q., Zhang, R.R., *et al*. (2011) Denudation Thickness Estimation of Sedimentary Formation in Ordos Basin by Acoustic Logging Information. *Xinjiang Petroleum Geology*, **32**, 143-146.

[34] Chen, R.Y., Luo, X.R., Chen, Z.K., *et al*. (2006) Estimation of Mesozoic Strata Denudation in Ordos Basin and Its Geological Significance. *Acta Geologica Sinica*, **80**, 685-693.

[35] Wang, B., Zhao, Y.Q., Luo, Y., *et al*. (2010) Thermal Evolution and Hydrocarbon Generation in the Caohu Sag of the Tarim Basin——Based on IES Basin Simulation Technology. *Petroleum Geology & Experiment*, **32**, 605-609.

[36] Liu, X., Shang, T., Tian, J.C., *et al*. (2021) Paleo-Sedimentary Environmental Conditions and Its Significance of Chang 4+5 Member of Triassic Yanchang Formation in the Zhenbei Area, Ordos Basin, NW China. *Acta Geologica Sinica*, **95**, 3501-3518.

[37] Tian, G. and Song, L.J. (2017) Thermal Evolution Modeling of Mesoproterozoic Source Rocks in the Ordos Basin. *Petroleum Geology & Experiment*, **39**, 520-526.

[38] Zhi, C.Y. (2021) Tectonic Evolution and Accumulation History Simulation in the Northern Depression of Wuwei Basin. Xi'an Shiyou University, Xi'an.

[39] Ren, Z.L., Qi, K., Li, J.B., *et al*. (2021) Thermodynamic Evolution and Hydrocarbon Accumulation in the Ordos Basin. *Oil & Gas Geology*, **42**, 1030-1042.

[40] Yu, Y.L. (2019) The Controling Effect of Tectonic Evolution on Source Rock Thermal Evolution in Xiaochaidan Area in Qaidam Basin. *Science Technology and Engineering*, **19**, 156-163.

[41] Zhao, G.P. (2016) Thermal Evolution Modeling of Neopaleozoic Source Rocks in Hangjinqi Region, Ordos Basin. *Petroleum Geology & Experiment*, **38**, 641-646.

[42] Li, C., Yuan, Q. and Zhang, M. (2017) Generative Potential of Carboniferous-Permian Coal-Bearing Source Rocks in Ordos Basin. *Open Journal of Yangtze Oil and Gas*, **2**, 260-272. https://doi.org/10.4236/ojogas.2017.24021