Advances in Geo-Energy Research

Vol. 6, No. 5, p. 402-414, 2022

Original article

Potential resources of conventional, tight, and shale oil and gas from Paleogene Wenchang Formation source rocks in the Huizhou Depression

Tao Hu[1,2], Guanyun Wu[1,2], Zhi Xu[1,2], Xiongqi Pang[1,2]*, Yang Liu[1,2], Sa Yu[3]*

[1] *State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, P. R. China*

[2] *College of Geosciences, China University of Petroleum, Beijing 102249, P. R. China*

[3] *Shenzhen Branch of China National Offshore Oil Corporation (CNOOC) Limited, Shenzhen 518000, P. R. China*

Keywords:
Hydrocarbon generation
hydrocarbon expulsion
resource potential
Wenchang Formation
Huizhou Depression

Cited as:
Hu, T., Wu, G., Xu, Z., Pang, X., Liu, Y., Yu, S. Potential resources of conventional, tight, and shale oil and gas from Paleogene Wenchang Formation source rocks in the Huizhou Depression. Advances in Geo-Energy Research, 2022, 6(5): 402-414.
https://doi.org/10.46690/ager.2022.05.05

Abstract:
Conventional and tight unconventional oil and gas resources in the Huizhou Depression have shown broad exploration prospects, which mainly originate from Wenchang Formation source rocks. Thus far, studies on Wenchang Formation source rocks mainly focused on the geochemical characteristics and conventional petroleum resource evaluation; however, the correlation of conventional, tight, and shale oil and gas, and their resources are still unknown. In fact, the formation of conventional, tight, and shale oil and gas are intrinsically related, which allows for a more objective evaluation to consider the three types of oil and gas resources simultaneously in the whole dynamic process of both hydrocarbon generation and expulsion, as well as reservoir tightness history. In this work, based on geological and geochemical analyses, the improved hydrocarbon generation potential method was utilized to establish a hydrocarbon generation and expulsion model of the Wenchang Formation source rocks. Then, combined with the reservoir tightness history, the conventional, tight, and shale oil and gas resources were evaluated. The results show that the Wenchang Formation source rocks are distributed in the whole depressions, with a thickness of 50-1850 m and an average total organic carbon content of 2.2%. The organic matter is mainly type II and is mature-high maturity. The Wenchang Formation source rocks reached hydrocarbon generation threshold and expulsion threshold at a vitrinite reflectivity of 0.43% and 0.65%, respectively, and the reservoir evolved completely tight at 2.3 Ma. Overall, the Lower and Upper Wenchang Formation contain a large amount of conventional, tight, and shale oil and gas resources.

1. Introduction

With the advancement of global oil and gas exploration and development, increasing attention has been paid to offshore oil and gas resources (Shi et al., 2020). Since 2000, the global offshore oil and gas proven reserves have entered a period of rapid growth. In 2013 alone, 124 new oil and gas fields were discovered, with annual new oil and gas proven reserves of 4.77×10^8 t and 7.90×10^8 m^3, respectively, accounting for 77% of the global oil and gas proven reserves in that year. Offshore oil and gas have become a key area for global exploration and development. China, with a vast marine area, has abundant offshore oil and gas resources (Jiang et al., 2015). By the end of 2018, 239.05×10^8 t of geological oil resources had been discovered, and 52.92×10^8 t of oil reserves had been confirmed, which are mainly distributed in the Pearl River Mouth Basin, Bohai Bay Basin and Beibuwan Basin. In addition, a total of 20.85×10^{12} m^3 of geological gas resources had been discovered by then, and 1.44×10^{12} m^3 of gas reserves had been confirmed, which are mainly distributed in the Pearl River Mouth Basin, Bohai Bay Basin, Southeast Hainan Basin, and Yinggehai Basin (Xie et al., 2020). At

Yandy Scientific Press

*Corresponding author.
E-mail address: thu@cup.edu.cn (T. Hu); wuguanyun1997@163.com (G. Wu); 2019215045@student.cup.edu.cn (Z. Xu); pangxq@cup.edu.cn (X. Pang); 18291943384@163.com (Y. Liu); yusa@cnooc.com.cn (S. Yu).

Received April 30, 2022; revised May 29, 2022; accepted June 18, 2022; available online June 26, 2022.

present, the overall degree of exploration of China's offshore oil and gas resources is relatively low, with proven rates of oil and gas at 22% and 7%, respectively, while those of the Pearl River Mouth Basin are merely 14% and 6%, respectively.

The Pearl River Mouth Basin is a typical passive continental margin rift basin developed on a complex basement (Shi et al., 2009), which is an important offshore hydrocarbon-rich exploration area in China (Shi et al., 2020). Since the 1970s, the cumulative production of oil and gas has exceeded 30×10^8 t of oil equivalent in this area. The Huizhou Depression is a hydrocarbon-rich depression in the middle of the Zhu I Sub-basin in the Pearl River Mouth Basin, consisting of four half-grabens and two low uplifts with widely developed source rocks (Xu et al., 2012). Different types of conversion zones are developed in the Huizhou Depression, which have a significant influence on the segmentation and zoning of rift basin structure. The sedimentary center migrates along the strike, which is favorable for oil and gas accumulation (Shi et al., 2009). Recently, significant breakthroughs have been achieved in petroleum exploration in the Huizhou Depression, such as the discovery of medium-high condensate reservoir in the shallow Huizhou 21 structure in southwestern Huizhou Depression. This structure is surrounded by sag with good oil source conditions, so it is an important compound oil and gas accumulation zone. In addition, a breakthrough has been made in the exploration of condensate gas in buried hills and shallow water areas in the Huizhou 26-6 structure, and its proven oil and gas reserves are up to 5×10^7 t (Jia et al., 2021; Liu et al., 2021). All the above data indicate that the Huizhou Depression has good oil and gas exploration potential. Previous studies have shown that, if abundant conventional oil and gas resources are discovered in the shallow layers of a petroliferous basin, there will be much more abundant tight and shale oil and gas resources in the deep layers (Pang et al., 2021a; Hu et al., 2022a; Ma et al., 2022). The Wenchang Formation (E_2w) is the key source rock of the Huizhou Depression, which mainly developed deep lacustrine mudstone, and the organic matter mainly originates from aquatic algae (Jiang et al., 2015), showing great hydrocarbon generation potential. Fluvial deltas, braided deltas and fan deltas were formed in the margin of Huizhou Depression, creating various reservoirs and trap types for oil and gas accumulation. At present, to ensure the benefits of offshore petroleum exploration, conventional oil and gas resources are still the main object of offshore petroleum exploration in China. However, with the deepening of petroleum exploration, conventional large tectonic and lithologic traps are decreasing, and the exploration targets are shifting to deep and unconventional fields (Li et al., 2021). Clarifying the hydrocarbon generation and expulsion characteristics of source rocks in the E_2w and evaluating the conventional, tight, and shale oil and gas resources will provide important guidance for the overall deployment of petroleum exploration.

Previous studies have proposed a variety of methods for evaluating the hydrocarbon generation and expulsion of source rocks, such as the simulation experiment method, chemical dynamics method, and material balance method. The simulation experiment method simulates the thermal evolution and hydrocarbon generation process of organic matter under natural conditions by increasing the temperature in a closed, semi-closed or open system; meanwhile, the chemical kinetic method establishes a hydrocarbon generation model through kerogen thermal degradation chemical reaction, combined with kerogen activation energy, frequency factor, and paleo-thermal simulations to calculate hydrocarbon generated from organic matter. However, these methods have two key problems: (1) simulation experiments and artificial subjective factors have great influences on the accuracy of parameter determination; (2) they investigate the hydrocarbon expulsion process from the perspective of migration and accumulation mechanism, which considers more controlling factors, but ignores the contribution of low-mature to immature oil for petroleum accumulation (Hu et al., 2015). To solve the above problems, some scholars proposed the hydrocarbon generation potential method based on the mass balance principle. This method can establish the hydrocarbon generation and expulsion model of source rocks by using total organic carbon and pyrolysis data that can be quickly obtained from a statistical point of view, and then evaluates the amount of hydrocarbon generation and expulsion of source rocks (Pang et al., 2005; Peng et al., 2016). However, it still retains the following three weaknesses: (1) the model of hydrocarbon generation and expulsion is established by judging the envelope of the sample pyrolysis dataset, which is highly artificial and subjective; (2) the amount of hydrocarbon generation (Qg) cannot reflect the amount of generated hydrocarbons, and certain errors exist in evaluating the amount of oil and gas resources; (3) there is an error in the recovery of original organic carbon, and the rock volume reduction during the hydrocarbon generation and expulsion process is not considered, either. To solve these problems, by combing the data-driven model and Monte Carlo simulation, Li et al. (2021) proposed an improved hydrocarbon generation potential method, which will be used for evaluation in this study.

Previous studies targeting the oil and gas resource evaluation methods often focused at a certain type of oil and gas resource. For example, the exploration trend extrapolation method was proposed to predict conventional oil and gas resources by analyzing the discovered oil and gas resource amounts using statistical methods (Sun et al., 2020). The estimated ultimate recovery method was proposed to evaluate tight oil and gas resource by utilizing the regional drilling well amount and oil and gas yields of a single well (Male and Duncan, 2022). The small cell volumetric method divides the evaluation area into many calculation units and calculates the amount of resources in each grid one by one according to the effective thickness, effective porosity and oil saturation of the reservoir, which is applicable to shale petroleum resource evaluation (Guo et al., 2013). In fact, from the perspective of "whole petroleum system", different types of hydrocarbon resources are formed by matching the evolution of hydrocarbon generation, retention and expulsion of source rocks with the evolution of reservoir density (Jia, 2017; Pang et al., 2022). For instance, hydrocarbons generated in the early stage of the source rock may accumulate before the reservoir becomes dense, forming conventional oil and gas; hydrocarbons generated from the source rock accumulating

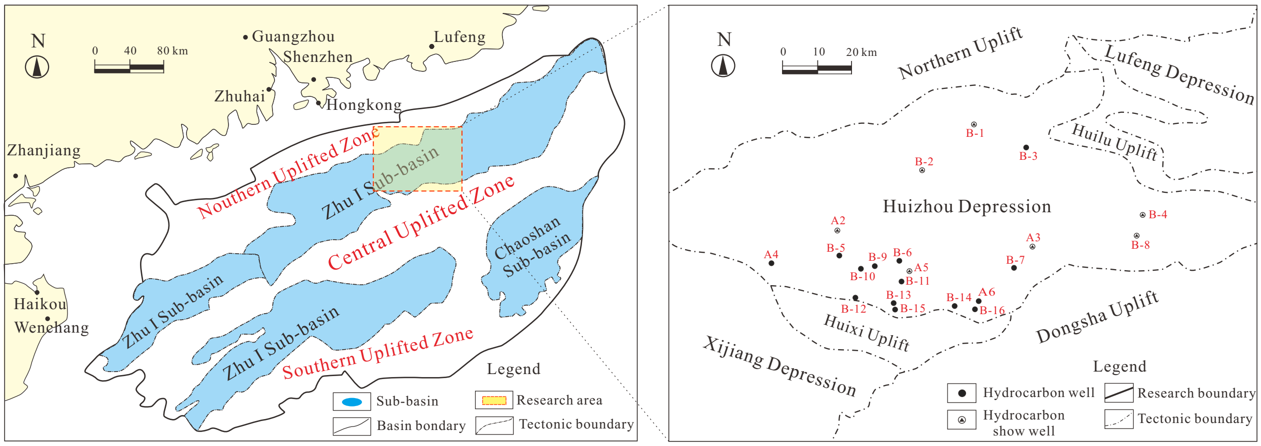

Fig. 1. Geographical location map of Huizhou Depression.

after the reservoir became dense form tight oil and gas; the generated hydrocarbons are trapped in the source rock, forming shale oil and gas (Hu et al., 2022a). Therefore, the conventional, tight and shale oil and gas formed by the same set of source rocks in petroliferous basins are intrinsically related. Previous studies rarely considered the genetic correlation between conventional, tight and shale petroleum, hence they failed to evaluate the amount of their resources from the overall evolutionary process by matching the evolution of hydrocarbon generation, retention and expulsion of source rocks and the evolution of reservoir density.

Based on the detailed analysis of the geological and geochemical characteristics of E_2w source rocks in the Huizhou Depression, this study selected the improved hydrocarbon generation potential method to establish the hydrocarbon generation and expulsion model of source rocks (Li et al., 2020). Furthermore, by improving the restoration of original hydrocarbon generation potential of source rocks, the history of the hydrocarbon generation and expulsion of source rocks was revealed, and the potential of conventional, tight, and shale oil and gas resources were further evaluated based on the history of tight reservoir evolution. The results are of guiding significance to the overall deployment of oil and gas exploration in the Huizhou Depression.

2. Geological setting

The Pearl River Mouth Basin is located in the southern margin of the South China Continent, in the north of South China Sea (Robison et al., 1998), where the Eurasian, Indian and Pacific plates meet. On the whole, it has the characteristics of “north and south sub belt, east and west sub block”, and there are five first-order tectonic units, named as northern uplift belt, northern depression belt, central uplift belt, southern depression belt and southern uplift belt from north to south (Guo et al., 2022). The Zhu I Sub-basin is the first-order structural belt in the north of Pearl River Mouth Basin, and the Huizhou Depression is located in the middle of the Zhu I Sub-basin (Cao et al., 2020), covering an area of about 1×10^4 km^2, which is a sublevel negative tectonic unit in the depression (Fig. 1). During the Cenozoic evolution of the Huizhou Depression, many tectonic movements occurred, such as Shenhu movement, Zhuqiong movement, Nanhai movement, and Dongsha movement, and many regional unconformities were developed (Shi et al., 2020). The basement of the Huizhou Depression is pre-Paleogene igneous rock, and the strata from bottom to bottom are successively E_2w, Enping Formation, Zhuhai Formation, Zhujiang Formation, Hanjiang Formation, Yuehai Formation, and Wanshan Formation. Among them, the Paleogene E_2w has typical lacustrine facies, fan-delta facies, braided river delta facies, and near-shore underwater fan facies, with the lithology being mainly a set of thick dark mudstone that are the main source rocks (Wang et al., 2019) (Fig. 2). During the sedimentary period of the Lower E_2w, the sedimentation center was located in Huizhou 26 Sag in the southwest, and the semi-deep to deep lacustrine source rocks were developed. The lacustrine basin reached the maximum during the fourth sedimentary period of the E_2w, and is dominated by dark mudstone; during the sedimentary period of the Upper E_2w, the sedimentation center migrated from SW to NW, and the lake basin contracted, which was a shallow to semi-deep lake deposit (Jiang et al., 2012).

3. Sample acquisition

A total of 34 mudstone cores and 32 mudstone debris were obtained from five exploration wells, A5, B-7, B-11, B-13 and B-16. The total organic carbon (TOC) content, pyrolysis and vitrinite reflectance (Ro) were determined. The TOC content was determined by a CS-230HC carbon and sulfur analyzer. Firstly, the sample was crushed to 80-100 mesh size. Secondly, the carbonate minerals were removed with dilute hydrochloric acid solution and heated in a water bath until the carbonate minerals were completely dissolved. Then, the sample was washed with distilled water and dried for 7 hours. Finally, the treated samples were placed in the instrument for combustion and the determination of organic carbon content in the rock. The Rock-Eval II instrument was used for the pyrolysis measurements. The samples were first crushed to about 100 mesh size, and then 100 g of samples were weighed and put into the instrument for combustion and the measurement of parameters. A Zeiss microscope equipped

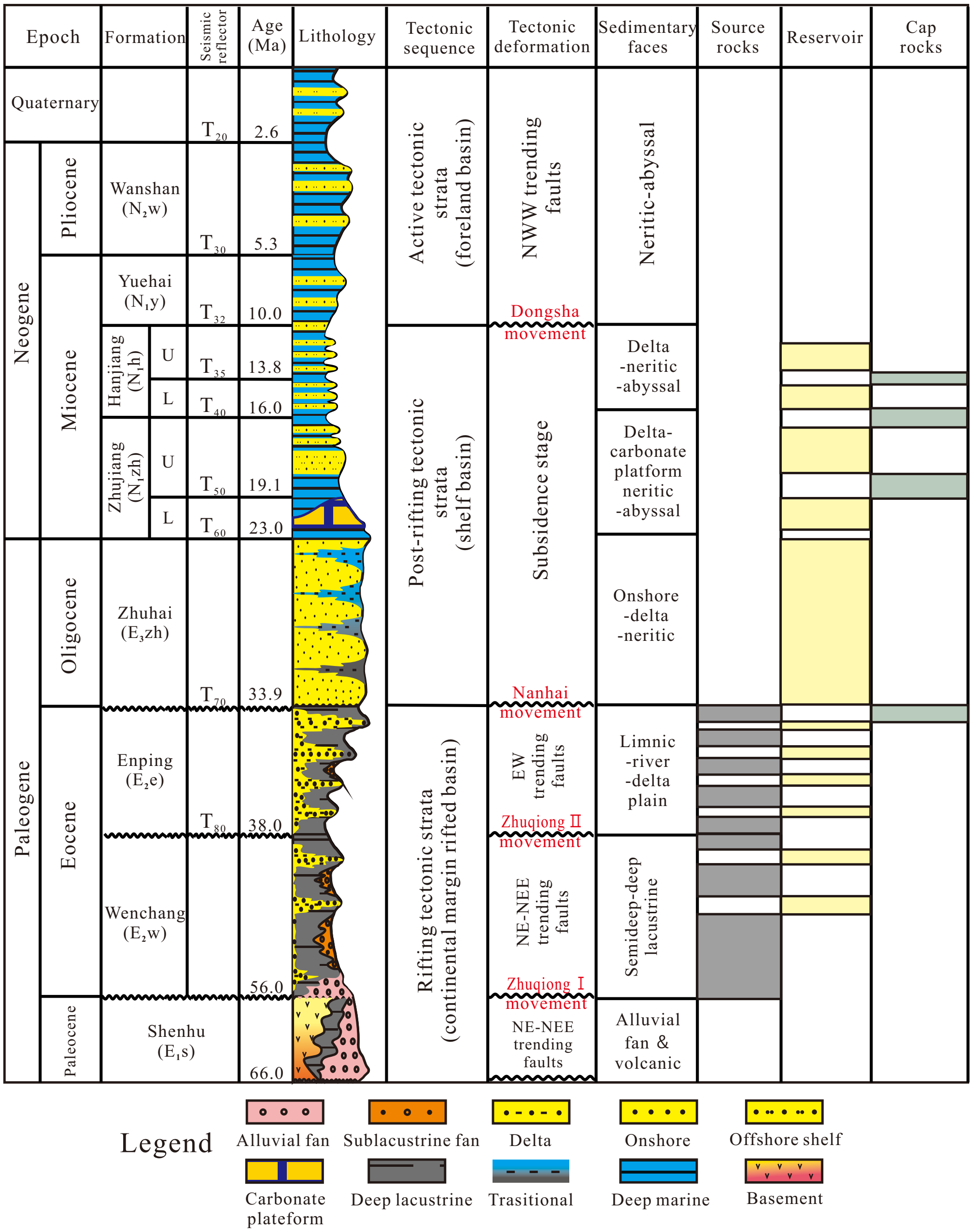

Fig. 2. Stratigraphic histogram of Pearl River Mouth Basin.

with a CRAIC photometer instrument was used to measure Ro, and the experimental process was consistent with Hu et al. (2022b).

Due to the few exploration wells drilled into E_2w source rocks in the Huizhou Depression, it is difficult to establish the hydrocarbon generation and expulsion model of E_2w source rocks based on the existing data of total organic carbon, pyrolysis and vitrinite reflectance analysis. To solve this problem, the relevant data of source rocks of E_2w in the southern Lufeng area with similar tectonic background, consistent sedimentary environment and same organic matter type were combined. The improved hydrocarbon generation potential method was used to establish the hydrocarbon generation and expulsion model, and recover the hydrocarbon generation, retention and expulsion history of E_2w source rocks. Finally, combined with the tight evolution history of E_2w sandstone reservoirs, the conventional, tight, and shale oil and gas resources were evaluated (Fig. 3).

4. Results

4.1 Geological and geochemical characteristics

4.1.1 Analysis of test data validity

Mudstone debris samples are susceptible to borehole wall falling, reservoir hydrocarbon or drilling mud pollution; therefore, too low maximum pyrolysis peak temperature (Tmax) (< 400 °C), for instance, may indicate the contamination of

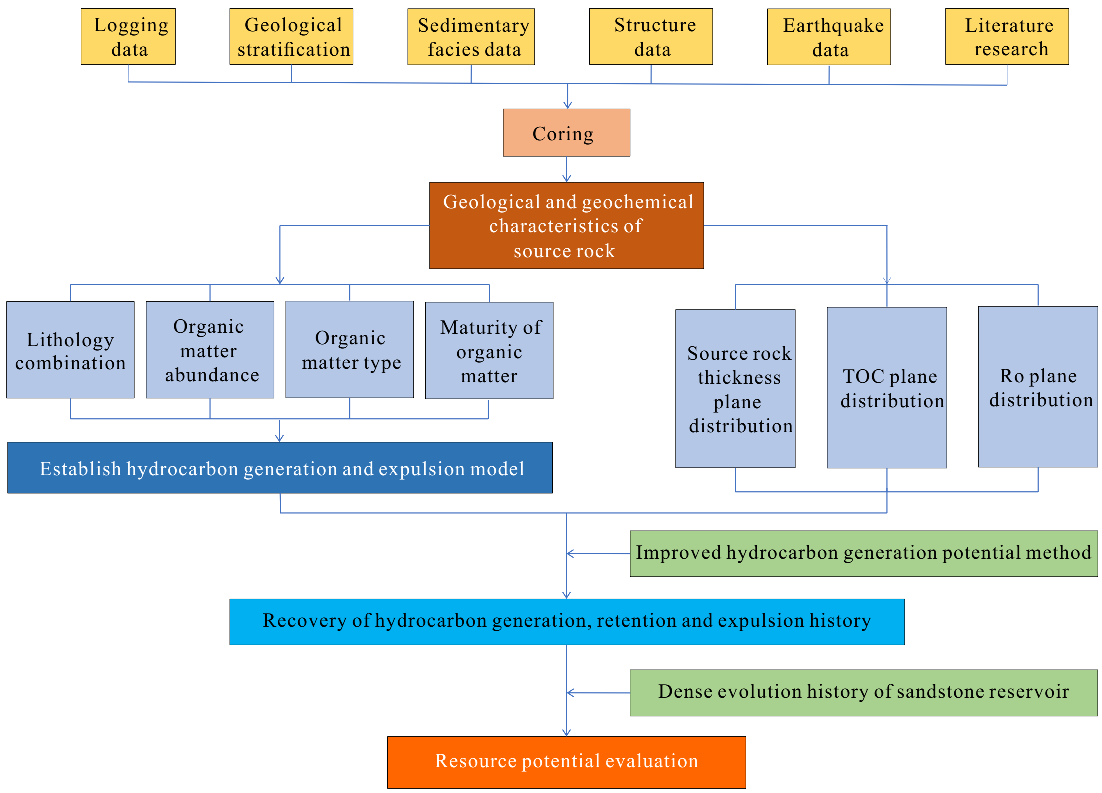

Fig. 3. Technology roadmap.

the core with oil-based mud (Katz and Lin, 2021). Thus, the validity of the analytical test data of the sample should be evaluated when using the data. Herein, this was performed using the pyrolysis Tmax and yield index (PI) plots (Fig. 4(a)). The results show that the Tmax values of 19 samples were less than 400 °C, ranging from 366 to 383 °C, indicating the occurrence of significant hydrocarbon migration or oil-based mud contamination in these samples, which were removed in subsequent analysis.

4.1.2 Lithology and thickness distribution

The source rocks of E_2w in the Huizhou Depression are mainly gray black mudstone, and there are coal seams on the top of E_2w in some areas. The thickness of source rocks in the Lower E_2w ranges from 0.61 to 1,853.06 m, with an average of 513.69 m, which is thin in the north and thick in the south. The source rocks in Huizhou 26 Sag in the southeast are the thickest with a value of up to 1,853.06 m (Fig. 5(a)). Meanwhile, the thickness of the Upper E_2w source rocks ranges from 0.64 to 1,405.31 m, with an average of 386.12 m, which gradually decreases from west to east. The thickness of the western source rocks is more than 500 m on the whole, and the thickest source rocks in the northwestern part of A4 well are up to 1,400 m thick (Fig. 5(b)).

4.1.3 Organic matter abundance

The assays of TOC, pyrolysis hydrocarbon yield (S_2) and hydrocarbon generation potential (S_1+S_2) can be used to evaluate the abundance of organic matter in source rocks. The TOC of source rocks in E_2w ranges from 0.4% to 5.5%, with an average of 2.2%; S_2 ranges from 0.8-33.2 mg/g, with an average of 6.9 mg/g; and S_1+S_2 ranges from 0.9 to 36.7 mg/g, with an average of 8.3 mg/g. The cross plot of TOC-S_2 (Fig. 4(b)) and TOC-(S_1+S_2) (Fig. 4(c)) shows that the E_2w is mainly composed of high-quality source rocks (Peters and Cassa, 1994), of which good, very good and excellent source rocks account for 34%, 38.3% and 10.6%, respectively.

As can be seen from the plane distribution map, the TOC of source rocks in different locations varies to some extent. The TOC of source rocks in the Lower E_2w ranges from 0.16% to 5.95%, decreasing gradually from south to north. Most of them are high-quality source rocks in the middle and south, with the highest organic matter content in the Huizhou 26 Sag and Xijiang 30 Sag (Fig. 6(a)). The TOC of source rocks in the Upper E_2w ranges from 0 to 4.06%, with high TOC in the east and low TOC in the west, and the highest TOC in the northwest of well A4 (Fig. 6(b)).

4.1.4 Organic type

The TOC-S_2 cross plot and hydrogen index (HI)-Tmax cross plot were used to evaluate the types of organic matter (Tissot and Welte, 1984; Peters and Cassa, 1994). The TOC-S_2 crossplot shows that the source rocks of E_2w are mainly type II kerogen and type III kerogen, of which type II_1 and type II_2 account for 25.5% and 29.8%, respectively, type III kerogen accounts for 42.6%, and type I kerogen only accounts for 2.1% (Fig. 4(b)). The HI-Tmax cross plot shows that the source rocks of E_2w are all type I and type II kerogen, excluding type III kerogen, of which type I, II_1 and II_2 kerogen account for 34%, 53.2% and 12.8%, respectively (Fig. 4(d)).

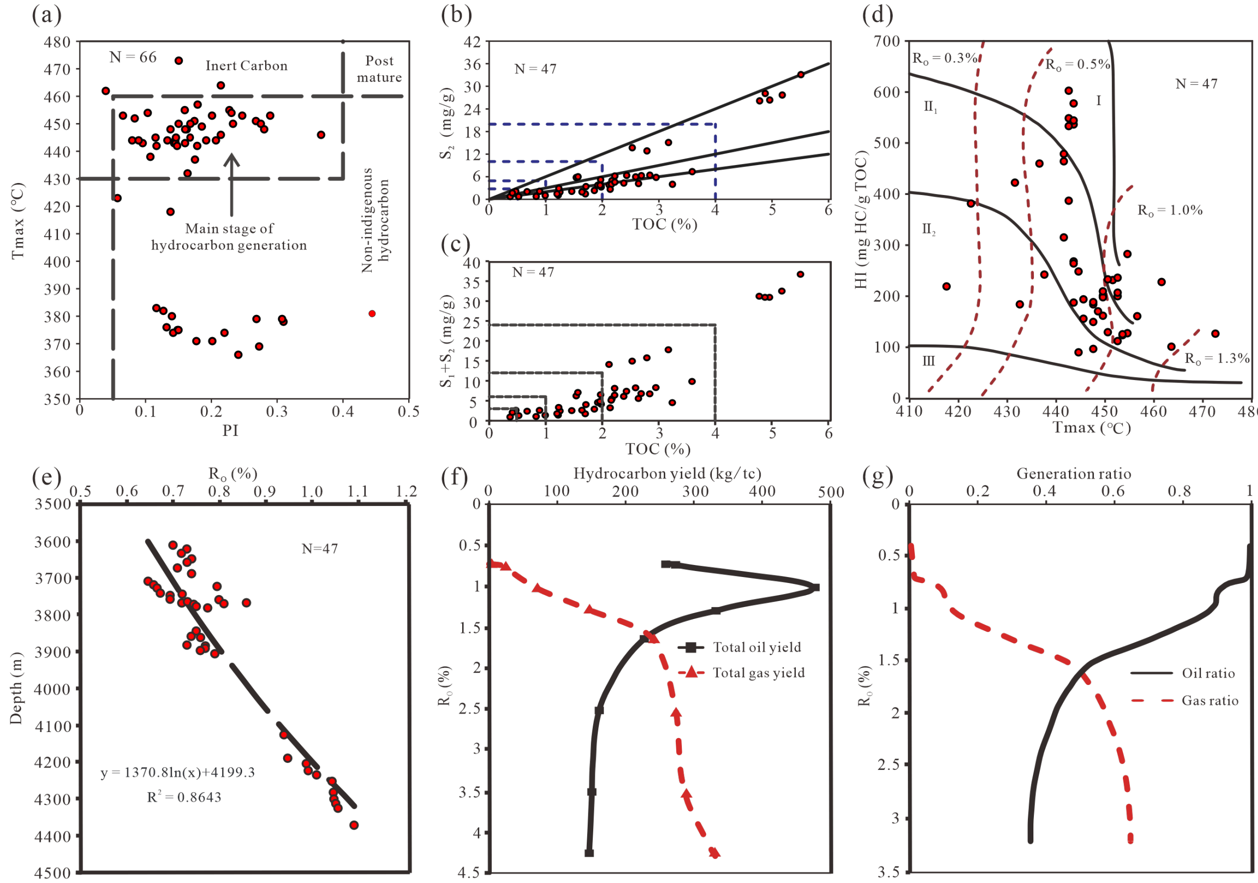

Fig. 4. (a) Tmax and PI diagram of source rocks in the E_2w, (b) TOC-S_2 crossplot of source rocks in the E_2w, (c) TOC-(S_1+S_2) crossplot of source rocks in the E_2w, (d) HI-Tmax crossplot of source rocks in the E_2w, (e) Cross plot of measured R_O and depth of source rocks in the E_2w, (f) Hydrocarbon generation kinetics model under hot pressure simulation of source rocks in the E_2w (Shi et al., 2021), (g) Hydrocarbon generation ratio diagram for different maturities. HC = hydrocarbon.

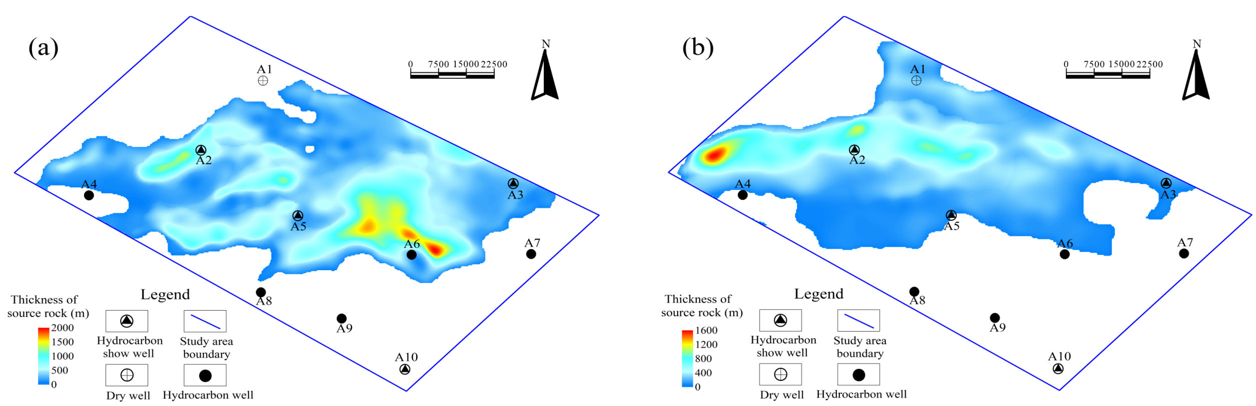

Fig. 5. (a) Plane distribution map of the thickness of effective source rocks of the Lower E_2w, (b) Plane distribution map of the thickness of effective source rocks of the Upper E_2w.

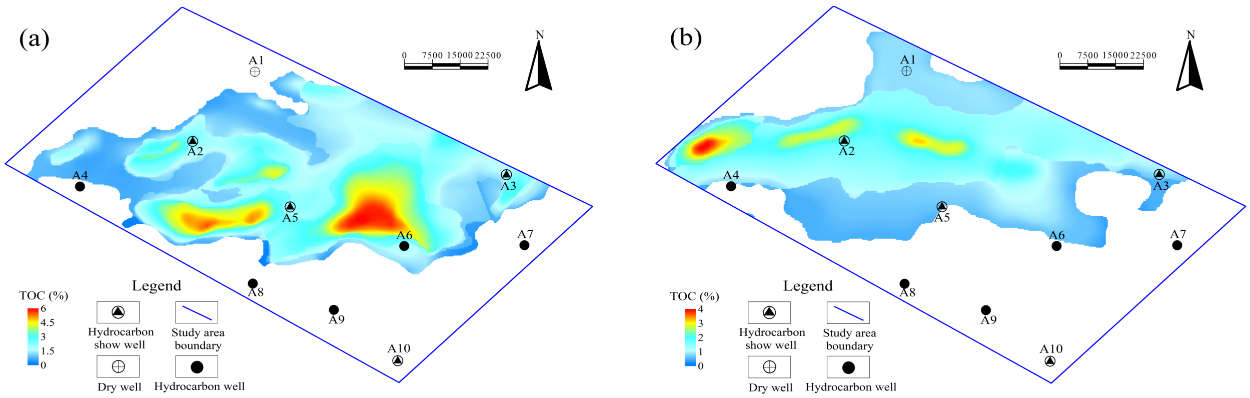

Fig. 6. (a) TOC plane distribution map of the Lower E_2w source rocks, (b) TOC plane distribution map of the Upper E_2w source rocks.

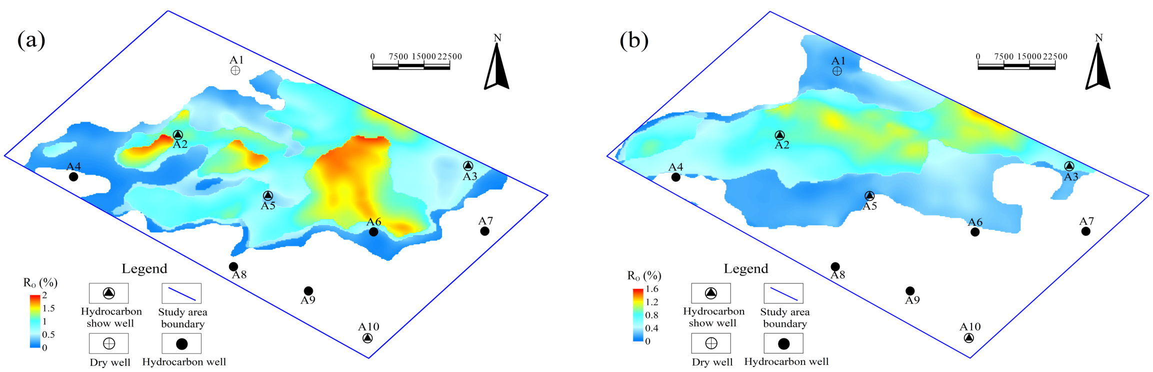

Fig. 7. (a) Plane distribution map of the R_O of source rocks in the Lower E_2w, (b) Plane distribution map of the R_O of source rocks in the Upper E_2w.

There are great differences in the type of organic matter evaluated by the two plates above, which is mainly because the source rocks of E_2w in the Huizhou Depression have a large burial depth and high thermal maturity. The source rocks have undergone a significant process of hydrocarbon generation and expulsion, hence it is difficult to accurately evaluate the types of original organic matter using the current hydrogen index. The latter considers the influence of maturity and is more credible than the former. Therefore, the source rocks of E_2w can be considered as mainly type II kerogen.

4.1.5 Maturity

The kerogen R_O and Tmax are commonly used parameters to evaluate maturity (Tissot et al., 1987; Peters and Cassa, 1994). The Tmax of source rocks in the E_2w ranges from 418 to 473 °C, with an average of 447 °C, among which the Tmax of 85% of samples is greater than 440°C (Fig. 4(d)); the R_O of source rocks in the E_2w ranges from 0.65% to 1.09%, with an average of 0.81% (Fig. 4(e)). The above data show that the source rocks of the E_2w are in the middle and late stages of oil generation window and are generating hydrocarbon on a large scale.

As can be seen in the plane distribution map, the R_O of Lower E_2w source rocks ranges from 0.21 to 2.08%, with an average of 0.97%, the middle part is high and the edge is low, and the whole area is in the mature stage. Among them, the maturity of the northern part of well A6 is higher, namely, highly mature to over-mature ($R_O > 1.2\%$) (Fig. 7(a)). The R_O of source rocks in the Upper E_2w ranges from 0.17% to 1.57%, with an average of 0.67%, and gradually increasing from west to east. The maturity of source rocks in the northeast is the highest, generally entering the maturity–high maturity stage ($R_O > 1\%$) (Fig. 7(b)).

4.2 Hydrocarbon generation and expulsion

4.2.1 Characteristics

The hydrocarbon generation and expulsion model of source rocks in the E_2w was established by using the improved hydrocarbon generation potential method (Li et al., 2020) (Fig. 8). The results show that the source rocks of the E_2w enter the hydrocarbon generation threshold (HGT) and hydrocarbon expulsion threshold (HET) when the R_O is 0.43% and 0.65%, respectively. After entering HGT and HET, the hydrocarbon generation rate (R_G) and hydrocarbon expulsion rate (R_E) of source rocks gradually increase. With the increasing degree of thermal evolution, the rate of increase of R_G and R_E is initially fast and then becomes slow. The source rocks of the

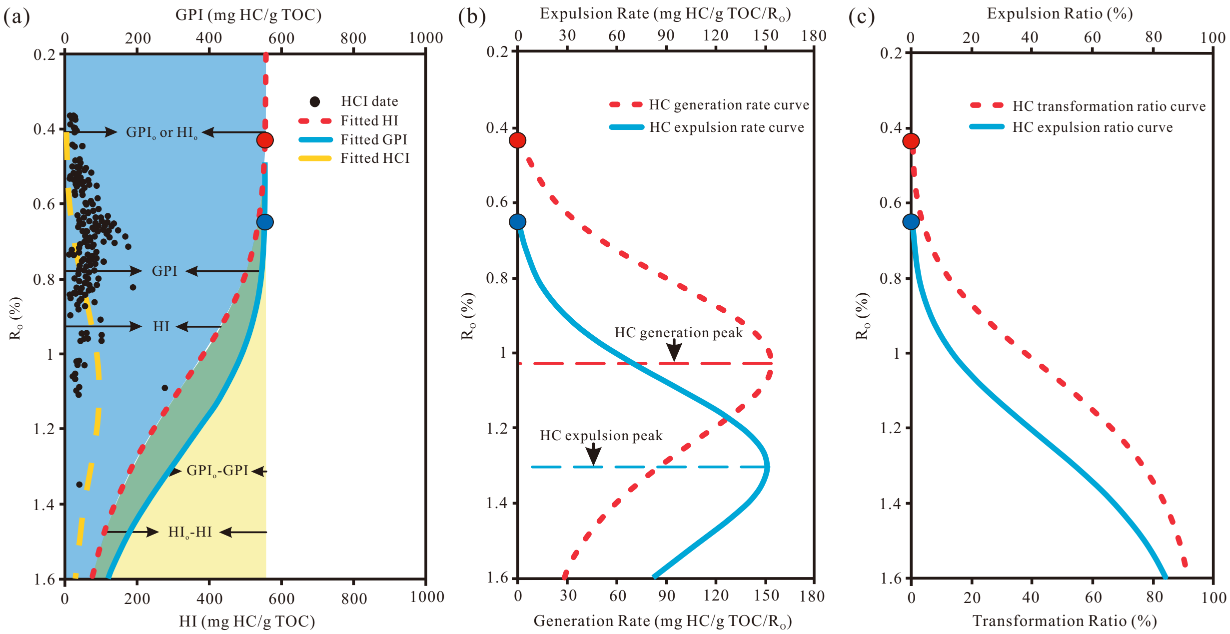

Fig. 8. Hydrocarbon generation and expulsion model of source rocks in the E_2w. HCI = hydrocarbon index; GPI = hydrocarbon generation potential index; GPI_O = original hydrocarbon generation potential index; HI_O = original hydrogen index.

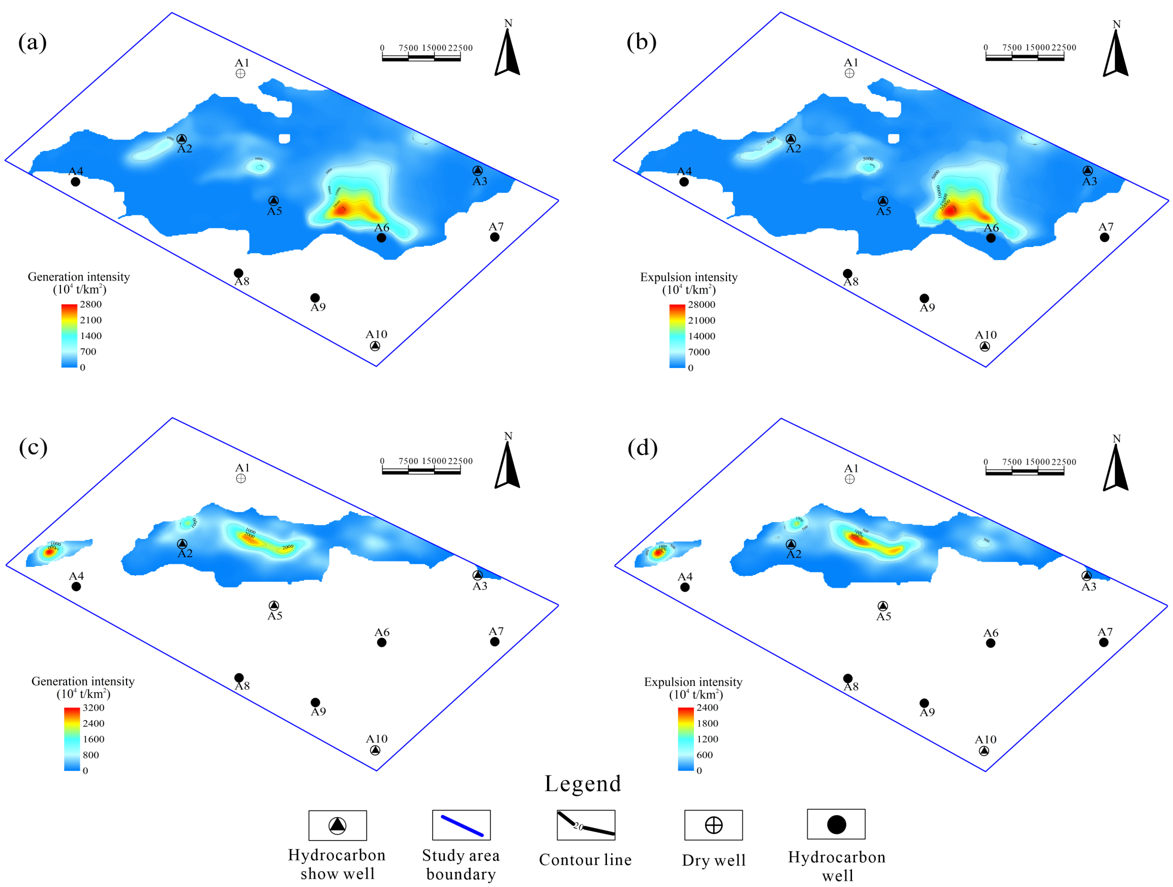

Fig. 9. (a) Plane contour map of the cumulative hydrocarbon generation intensity of source rocks in the Lower E_2w, (b) Plane contour map of the cumulative expulsion intensity of source rocks in the Lower E_2w, (c) Plane contour map of the cumulative hydrocarbon generation intensity of source rocks in the Upper E_2w, (d) Plane contour map of the cumulative expulsion intensity of source rocks in the Upper E_2w.

E_2w reach the peak of hydrocarbon generation and expulsion when the R_O is 1.02% and 1.30%, respectively. At this time, the R_G and R_E of source rocks reach the maximum, and then decrease with the increase of thermal evolution degree. During the whole process, the hydrocarbon expulsion ratio (E_R) of source rocks increases from 0 to 84.10%. Before the source rock enters the HET, the hydrocarbon is mainly retained in the source rock as adsorption phase, and only a very small amount of it is discharged as water soluble phase and free phase. After the source rock has entered the HET, it meets its own needs and begins to discharge a large amount of hydrocarbon in the free phase (Pang et al., 2005).

4.2.2 Hydrocarbon generation and expulsion history

The hydrocarbon generation potential curves of source rocks reflect the hydrocarbon generation and expulsion characteristics of source rocks at different burial depths, which is a comprehensive reflection of the effects of various geological factors. Firstly, based on the burial history of source rocks, the hydrocarbon generation and expulsion characteristics of source rocks in each burial period are obtained according to the hydrocarbon generation potential curves. Secondly, the R_O corresponding to HET is used to determine the range of effective hydrocarbon expulsion in each burial period, calculate the hydrocarbon expulsion intensity, and study the change of hydrocarbon expulsion center. Then, according to the hydrocarbon generation potential method, the stratigraphic stripping method is employed to determine the geological history maturity evolution of source rocks and the planar distribution of hydrocarbon transformation ratio (T_R) and E_R in each period. Finally, based on the data of source rock thickness and TOC plane distribution, the cumulative hydrocarbon generation and expulsion intensity, and the amount of hydrocarbon generation and expulsion during the main hydrocarbon expulsion period of source rocks in the Lower and Upper E_2w in the Huizhou Depression are calculated (Fig. 9), and the hydrocarbon expulsion history is restored. The source rocks of E_2w in the Huizhou Depression are mainly type II kerogen. Based on the previous results of hydrocarbon generation thermal simulation experiments on type II kerogen for this area (Shi et al., 2021), the oil and gas generation ratio under different thermal maturity were obtained (Fig. 4(f) and 4(g)). Subsequently, the cumulative oil discharge intensity, cumulative exhaust intensity, oil discharge and gas discharge of source rocks in the E_2w in different periods were acquired.

The results show that the hydrocarbon generation, expulsion, oil discharge and gas discharge of the Lower E_2w in the Huizhou Depression are 381.29×10^8, 369.38×10^8, 215.65×10^8 and 153.72×10^8 t, respectively. Meanwhile, the hydrocarbon generation, expulsion, oil discharge and gas discharge of the Upper E_2w are 25.12×10^8, 20.58×10^8, 17.53×10^8 and 3.04×10^8 t, respectively.

According to the burial history of E_2w in the Huizhou Depression, the hydrocarbon generation and expulsion history of source rocks was recovered (Fig. 10). The results show that the Lower and Upper E_2w entered the HGT (R_O = 0.43%) at 12.6 and 11.1 Ma, respectively, and the source rocks began to generate hydrocarbon but did not expel hydrocarbon. With the increase of burial depth, the lower Wenchang and the Upper E_2w entered the HET (R_O = 0.65%) at 5.1 and 2.3 Ma, respectively, and the oil and gas began to be discharged into the reservoir as free phase, forming oil and gas accumulation. Until now, the source rocks of E_2w have been continuously subsiding and increasing in maturity. The Lower E_2w has reached the maximum rate of the hydrocarbon generation and expulsion, accounting for 43.72% and 22.32%, respectively, indicating that the Lower E_2w has higher T_R and E_R, while the Upper E_2w has reached the maximum rate of the hydrocarbon generation and expulsion, accounting for only 12.01% and 0.12%. The hydrocarbon generation center of the Lower E_2w source rocks is located in the Huizhou 26 Sag (Fig. 9(a)). The source rocks of the Upper E_2w have two hydrocarbon generating centers, located in Xijiang 2 Sag and Xijiang 24 Sag, respectively (Fig. 9(c)). The hydrocarbon expulsion centers of the Lower and Upper E_2w are consistent with their respective hydrocarbon generation centers. Because the Lower E_2w source rocks are deeply buried and enter the HGT and HET earlier, the intensity of hydrocarbon generation and expulsion is much higher than that of the Upper E_2w source rocks.

4.3 Petroleum resource potentialn

4.3.1 Conventional oil and gas

After being discharged from the source rock, conventional petroleum is driven by buoyancy to migrate in a series of transport systems, and is mainly enriched in the positive structure at the top and edge of the paleo-uplift or the upper part of the basin (Zou et al., 2012). The physical properties of conventional reservoirs are beneficial, whereas the porosity gradually decreases with the increase of burial depth. When the porosity decreases to 12%, the reservoir reaches the density limit (Jia et al., 2012; Pang et al., 2021b), thus, a conventional reservoir has a porosity limit of 12%. According to the porosity evolution history diagram of E_2w (Fig. 10), the reservoir of E_2w reached the density limit at about 2.3 Ma, that is, the hydrocarbon produced in the reservoir before 2.3 Ma is conventional oil and gas. Based on the study of hydrocarbon expulsion history, the conventional petroleum resources in the Huizhou Depression of Pearl River Mouth Basin are calculated by the genetic method. The hydrocarbon accumulation coefficient (Kma) is one of the key parameters used to calculate the resource amount by the genetic method, which is affected by various geological factors; the product of accumulation coefficient and hydrocarbon expulsion amount is the resource amount of the hydrocarbon accumulation system (Zhu et al., 2007). By analyzing the geological conditions of the Huizhou Depression, previous hydrocarbon accumulation coefficient values can be divided into four stages, which are respectively the Wenchang-Enping Formation sedimentary period (oil: 13%, gas: 12 ‰), the Zhuhai-Zhujiang group under the period of deposition (oil: 10%, gas: 10 ‰), the Zhujiang group up to Hanjiang group sedimentary period (oil: 9%, gas: 8 ‰) and the Yuehai group to present (oil: 7%, gas: 6‰) (Shi et al., 2009). Since it is not clear when petroleum migration and accumulation occurred in this area, the average value

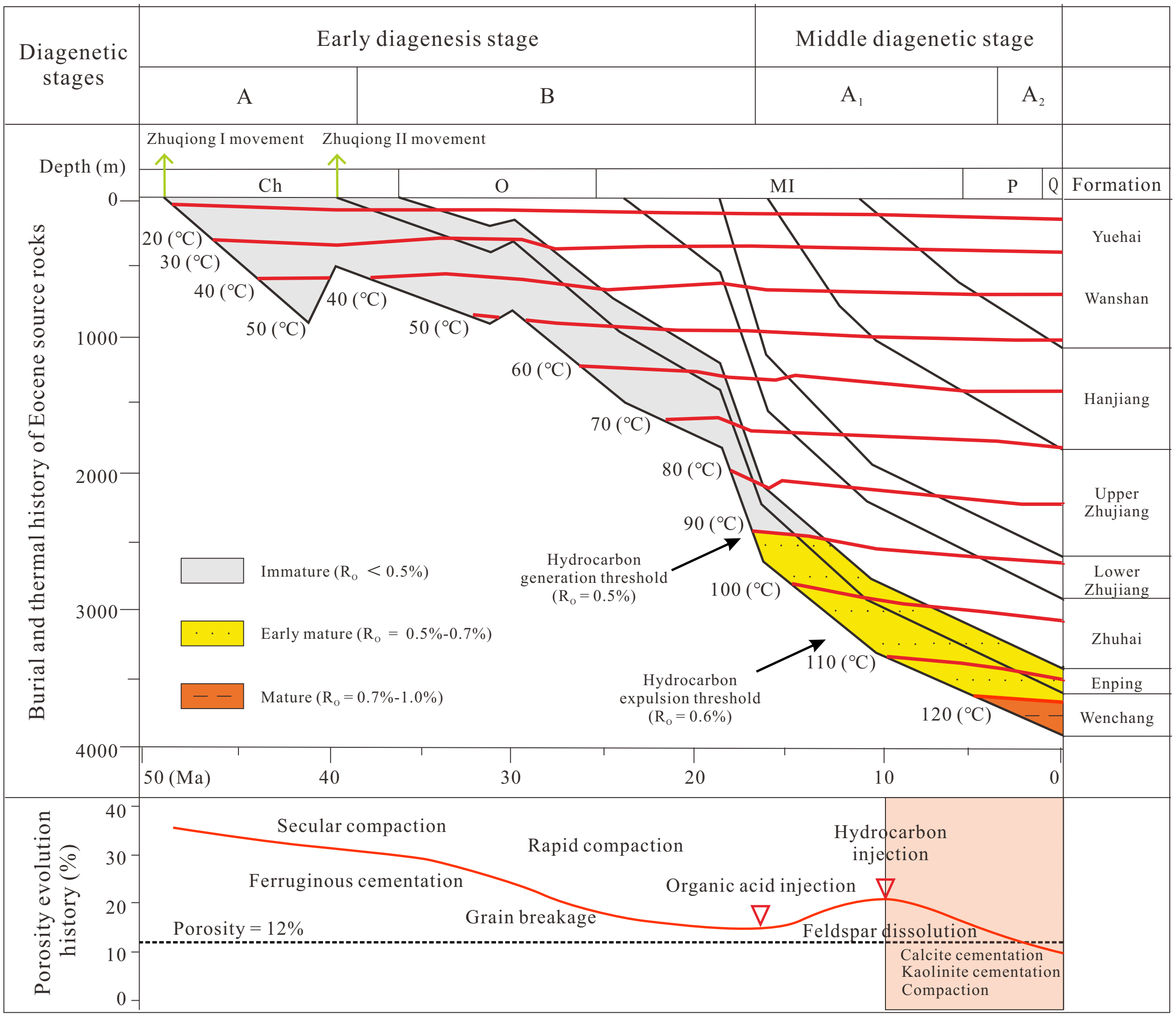

Fig. 10. Burial history and reservoir porosity evolution of Huizhou Depression, Pearl River Mouth Basin (Peng et al., 2016).

of the above four stages was adopted in this study, and the accumulation coefficients of petroleum were 9.75% and 9‰, respectively.

The amount of hydrocarbon expulsion before 2.3 Ma of the Lower E_2w source rocks is multiplied by the oil generation ratio and the oil Kma to obtain the conventional oil resources, and by the gas generation ratio and gas Kma to obtain the conventional gas resources; the same procedure is applied for the Upper E_2w. The results show that the conventional oil and gas resources of the Lower E_2w in the Huizhou Depression are 2.73×10^8 t and 0.18×10^8 m^3, respectively, and those of the Upper E_2w are 1.08×10^8 t and 0.02×10^8 m^3, respectively.

4.3.2 Tight oil and gas

In recent years, with the progress of petroleum exploration methods, continental lacustrine tight petroleum has become a popular but challenging issue in the exploration and development of unconventional petroleum resources in China (Wang et al., 2015). Non-buoyancy plays a leading role in the process of tight petroleum migration and accumulation, and petroleum reservoirs are mainly located in negative tectonic units or sag centers of basins. Tight reservoirs have low porosity, their permeability is generally less than 1 mD, and their pore structure has strong heterogeneity and poor connectivity. According to the porosity evolution history diagram of the E_2w (Fig. 10), the petroleum discharged from the source rocks from 2.3 Ma up to the present are all tight petroleum, and the reservoir densification occurs in the process of continuous petroleum charging. Therefore, there are two types of tight oil reservoirs: accumulation before compaction and accumulation after compaction.

According to the amount of hydrocarbon expulsion of source rocks in the E_2w after 2.3 Ma, the oil generation ratio and gas generation ratio are respectively multiplied, and then the Kma of oil and gas are respectively multiplied (9.75% and 9‰). The tight oil and gas resources of the Lower E_2w are 18.29×10^8 t and 1.20×10^8 m^3, respectively, and those of the Upper E_2w are 0.63×10^8 t and 0.01×10^8 m^3, respectively.

4.3.3 Shale oil and gas

With the continuous progress of science and technology, shale oil and gas has become a trending field affecting the patterns of oil and gas exploration and development (Hu et al., 2021). Shale is composed of fine debris, clay and organic matter with a particle size of less than 0.0039 mm, which is a kind of sedimentary rock with lamellar or lamellar bedding that is easy to fracture (Zou et al., 2010). Shale oil and gas are usually self-generated and self-stored (Zhang et al., 2018). Different from conventional and tight oil and gas, which are mainly free hydrocarbons, shale oil and gas consist mainly of adsorbed hydrocarbons and kerogen dissolved hydrocarbons, and are characterized by hydrocarbon generation and the retention of organic matter in the source rock. Shale comprises both source rock and reservoir, so the difference between the hydrocarbon generation and expulsion of E_2w is the corresponding shale oil and gas reserves.

By multiplying the Lower and Upper E_2w shale oil and gas reserves by the oil and the gas generation ratio, the Lower E_2w shale oil and gas resources are 7.02×10^8 t and 5.00×10^8 m^3, respectively, and the Upper E_2w shale oil and gas resources are 3.87×10^8 t and 0.67×10^8 m^3, respectively.

4.3.4 Comparison of previous results

Based on the above analysis, the accumulative hydrocarbon generation amount of E_2w source rocks in the Huizhou Depression is 406.52×10^8 t, the accumulative hydrocarbon expulsion amount is 389.95×10^8 t, and the total resource amount is 40.71×10^8 t. Among them, the Lower E_2w is 34.43×10^8 t, and the conventional, tight, and shale oil and gas resources are 2.91×10^8, 19.50×10^8 and 12.02×10^8 t, accounting for 8.46%, 56.63% and 34.90%, respectively, with the largest proportion of tight petroleum resources. The Upper E_2w has 6.28×10^8 t of resources, while the conventional, tight, and shale oil and gas resources are 1.10×10^8, 0.64×10^8 and 4.54×10^8 t, accounting for 17.48%, 10.16% and 72.35%, respectively. In contrast, the resource amount of Lower E_2w is significantly greater than that of the Upper E_2w, in which the tight oil and gas resources in the Lower E_2w occupy the largest proportion, while the shale oil and gas resources of the Upper E_2w occupy the largest proportion. The reason for the difference is mainly related to the higher maturity of the Lower E_2w source rocks.

Previous studies have evaluated the oil and gas resources of E_2w in the Huizhou Depression. Compared with the evaluation result (29.08×10^8 t) of the E_2w oil and gas resources by basin simulation in the Huizhou Depression by the China National Offshore Oil Corporation (CNOOC), the evaluation result of this study is about 1.4 times greater for two main reasons: (1) the improved hydrocarbon generation potential method was adopted in this study, which is evaluated from the aspects of generation, expulsion, migration and accumulation, as well as the immature oil and low-maturity oil during hydrocarbon generation and expulsion; (2) the improved hydrocarbon generation potential method restores the original TOC of source rocks in the E_2w. Meanwhile, Li (2013) conducted a petroleum resource evaluation in the Huizhou Depression, and the results showed that the total resource amount of E_2w is 59.25×10^8 t, of which the Lower E_2w is 42.40×10^8 t, and the Upper E_2w is 16.85×10^8 t. There are two reasons for the difference between these research results: (1) with the continuous improvement of exploration, the understanding of Huizhou Depression has been further deepened, and new research achievements in structure, sedimentation and reservoir formation have been made, which were used as the evaluation basis in our study; (2) Li (2013) used the organic carbon method to evaluate the resource amount, and obtained the key parameter hydrocarbon expulsion coefficient through a thermal simulation experiment, but the accuracy of the result was limited due to the small number of samples. In this study, the hydrocarbon generation potential method was utilized for resource evaluation, which is based on the material balance principle and the hydrocarbon expulsion threshold theory. By establishing hydrocarbon generation and expulsion models in the burial evolution of the target interval, the coupling relationship between hydrocarbon generation, residual hydrocarbon, expulsion hydrocarbon and critical conditions for hydrocarbon expulsion of source rocks was revealed, the quantitative characterization of the hydrocarbon generation and expulsion process, as well as the hydrocarbon generation and expulsion efficiency were accomplished, and the oil and gas resources were evaluated (Pang et al., 2005). To sum up, the results of this study are more scientific and reliable compared to previous attempts.

5. Conclusions

1) The source rocks of E_2w in the Huizhou Depression have a wide distribution area, large thickness, and high abundance. The organic matter is mainly type II, with a small amount of type I. The thermal evolution degree has reached the mature-high-maturity evolution stage, which is realized in a set of highly superior source rocks.
2) The source rocks of E_2w in the Huizhou Depression reach the HGT and HET when the R_O is 0.43% and 0.65%, respectively. Thus far, the Lower E_2w source rocks have reached 381.29×10^8 t of hydrocarbon generation, 369.38×10^8 t of hydrocarbon expulsion, 215.65×10^8 t of oil expulsion, and 153.72×10^8 t of gas expulsion. Meanwhile, the hydrocarbon generation, hydrocarbon expulsion, oil expulsion, and gas expulsion of the Upper E_2w have reached 25.12×10^8 , 20.58×10^8 , 17.53×10^8 and 3.04×10^8 t, respectively.
3) The tight oil and gas reserves of the Lower E_2w in the Huizhou Depression are the largest, the resources are 18.29×10^8 t and 1.20×10^8 m^3, respectively, accounting for 56.63% of the total resources. The shale oil and gas reserves of the Upper E_2w are the largest, with 3.87×10^8 t and 0.67×10^8 m^3 respectively, accounting for 72.35% of the total resources.

Acknowledgement

This study was supported by the research project of CNOOC (Shenzhen) (No. SCKY-2020-SZ-21). We gratefully acknowledge the CNOOC (Shenzhen) for providing data used in this study and permission to publish the results.

Conflict of interest

The authors declare no competing interest.

References

Cao, X., Zhong, D., Liu, J., et al. Coupling between diagenetic environment and porosity evolution—A quantitative study of the Zhuhai Formation in the Huizhou Sag, Pearl River Mouth Basin, South China Sea. Minerals, 2020, 10(2): 170.

Guo, B., Yu, F., Wang, Y., et al. Quantitative prediction of palaeo-uplift reservoir control and favorable reservoir formation zones in Lufeng Depression. Advances in Geo-Energy Research, 2022, 6(5): 426-437.

Guo, Q., Chen, N., Wu, X., et al. Method for assessment of tight oil resources. China Petroleum Exploration, 2013, 18(2): 67-76. (in Chinese)

Hu, T., Pang, X., Jiang, F., et al. Movable oil content evaluation of lacustrine organic-rich shales: Methods and a novel quantitative evaluation model. Earth-Science Reviews, 2021, 214: 103545.

Hu, T., Pang, X., Jiang, F., et al. Dynamic continuous hydrocarbon accumulation (DCHA): Existing theories and a new unified accumulation model. Earth-Science Reviews, 2022a, 232: 104109.

Hu, T., Pang, X., Xu, T., et al. Identifying the key source rocks in heterogeneous saline lacustrine shales: Paleogene shales in the Dongpu depression, Bohai Bay Basin, eastern China. AAPG Bulletin, 2022b, 106(6): 1325-1356.

Hu, T., Pang, X., Yu, S., et al. Hydrocarbon generation and expulsion characteristics of Lower Permian P_1f source rocks in the Fengcheng area, northwest margin, Junggar Basin, NW China: Implications for tight oil accumulation potential assessment. Geological Journal, 2015, 51(6): 880-900.

Jia, C. Breakthrough and significance of unconventional oil and gas to classical petroleum geology theory. Petroleum Exploration and Development, 2017, 44(1): 1-10.

Jia, C., Zou, C., Li, J., et al. Assessment crlteria, main types, basic features and resource prospects of the tight oil in China. Acta Petrolei Sinica, 2012, 33(3): 343-350. (in Chinese)

Jia, P., Zhang, X., Chen, W., et al. Tectonic evolution of Huizhou 21 buried hill and its control over deep oil accumulations in the Huizhou Sag of Pearl River Mouth Basin. Marine Geology Frontiers, 2021, 37(12): 27-37. (in Chinese)

Jiang, H., Pang, X., Shi, H., et al. Source rock characteristics and hydrocarbon expulsion potential of the Middle Eocene Wenchang formation in the Huizhou depression, Pearl River Mouth basin, south China sea. Marine and Petroleum Geology, 2015, 67: 635-652.

Jiang, Z., Zhu, J., Deng, H., et al. Petroleum system and hydrocarbon accumulation characteristics in the Wenchang and Enping formations in the Huizhou Sag, Pearl River Mouth Basin, China. Energy Exploration & Exploitation, 2012, 30(3): 351-371.

Katz, B. J., Lin, F. Consideration of the limitations of thermal maturity with respect to vitrinite reflectance, $T_{\max}$, and other proxies. AAPG Bulletin, 2021, 105(4): 695-720.

Li, C., Pang, X., Huo, Z., et al. A revised method for reconstructing the hydrocarbon generation and expulsion history and evaluating the hydrocarbon resource potential: Example from the first member of the Qingshankou Formation in the Northern Songliao Basin, Northeast China. Marine and Petroleum Geology, 2020, 121: 104577.

Li, J., Yang, Z., Wu, S., et al. Key issues and development direction of petroleum geology research on source rock strata in China. Advances in Geo-Energy Research, 2021, 5(2): 121-126.

Li, S. Petroleum resources ecaluation of the hydrocarbon-rich generation depression with sparse wells—A case study from the Huizhou Depression, Pearl River Mouth Basin. Wuhan, China University of Geosciences, 2013. (in Chinese)

Liu, J., Xu, G., Wen, H., et al. Main factors controlling the formation of buried hill-Paleogene reservoirs in 26-6 structure of Huizhou, Pearl River Mouth Basin. Natural Gas Industry, 2021, 41(11): 54-63. (in Chinese)

Ma, K., Pang, H., Zhang, L., et al. Hydrocarbon dynamic field division and its relevance to oil and gas exploration for Paleogene reservoir in Lufeng Depression. Advances in Geo-Energy Research, 2022, 6(5): 415-425.

Male, F., Duncan, I. J. The paradox of increasing initial oil production but faster decline rates in fracking the Bakken Shale: Implications for long term productivity of tight oil plays. Journal of Petroleum Science and Engineering, 2022, 208: 109406.

Pang, X., Li, M., Li, S., et al. Geochemistry of petroleum systems in the Niuzhuang South Slope of Bohai Bay Basin: Part 3. Estimating hydrocarbon expulsion from the Shahejie formation. Organic Geochemistry, 2005, 36(4): 497-510.

Pang, X., Jia, C., Wang, W., et al. Buoyance-driven hydrocarbon accumulation depth and its implication for unconventional resource prediction. Geoscience Frontiers, 2021a, 12(4): 101133.

Pang, X., Shao, X., Li, M., et al. Correlation and difference between conventional and unconventional reservoirs and their unified genetic classification. Gondwana Research, 2021b, 97: 73-100.

Pang, X., Hu, T., Larter, S., et al. Hydrocarbon accumulation depth limit and implications for potential resources prediction. Gondwana Research, 2022, 103: 389-400.

Peng, J., Pang, X., Shi, H., et al. Hydrocarbon generation and expulsion characteristics of Eocene source rocks in the Huilu area, northern Pearl River Mouth basin, South China Sea: Implications for tight oil potential. Marine and Petroleum Geology, 2016, 72: 463-487.

Peters, K. E., Cassa, M. R. Applied source rock geochemistry, in the Petroleum System-From Source to Trap, edited by L. B. Magoon and W. G. Dow, American Association of Petroleum Geologists, Tulsa, pp. 93-120, 1994.

Robison, C. R., Elrod, L. W., Bissada, K. K. Petroleum generation, migration, and entrapment in the Zhu I depression, Pearl River Mouth basin, South China Sea. International Journal of Coal Geology, 1998, 37(1-2): 155-178.

Shi, H., Du, J., Mei, L., et al. Huizhou movement and its significance in Pearl River Mouth Basin, China. Petroleum Exploration and Development, 2020, 47(3): 483-498.

Shi, H., Zhu, J., Jiang, Z., et al. Hydrocarbon resources reassessment in Zhu I depression, Pearl River Mouth basin. China Offshore Oil and Gas, 2009, 21(1): 9-14. (in Chinese)

Shi, Y., Liu, J., Wen, H., et al. Thermo-compression simulation experiment and gas generation potential analysis of Huizhou 26-6 source rocks in the Pearl River Mouth basin. Marine Geology Frontiers, 2021, 37(11): 53-59. (in Chinese)

Sun, F., Zhang, K., Han, S., et al. Analysis of petroleum play and resources evaluation in the North Ustyurt Basin. Journal of Northeast Petroleum University, 2020, 44(6): 43-52. (in Chinese)

Tissot, B. P., Pelet, R., Ungerer, P. H. Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. AAPG Bulletin, 1987, 71(12): 1445-1466.

Tissot, B. P., Welte, D. H. Petroleum Formation and Occurrence. Berlin, Germany, Springer-Verlag, 1984.

Wang, M., Sherwood, N., Li, Z., et al. Shale oil occurring between salt intervals in the Dongpu Depression, Bohai Bay Basin, China. International Journal of Coal Geology, 2015, 152: 100-112.

Wang, X., He, S., Wu, J. Tectonic controls on lacustrine source rock occurrence in the Huizhou Sag, Pearl River Mouth Basin, China. International Geology Review, 2019, 62(1): 72-93.

Xie, Y., Gao, Y. Recent domestic exploration progress and direction of CNOOC. China Petroleum Exploration, 2020, 25(1): 20-30.

Xu, S., Li, S., Yuan, C. Resource potential of water-soluble gas in the Palaeogene Huizhou Sag, Pearl River Mouth Basin. Petroleum Exploration and Development, 2012, 39(2): 194-201.

Zhang, P., Lu, S., Li, J., et al. Permeability evaluation on oil-window shale based on hydraulic flow unit: A new approach. Advances in Geo-Energy Research, 2018, 2(1): 1-13.

Zhu, H., Pang, X., Jiang, Z., et al. Studying methods and application of the hydrocarbon accumulation coefficient. Earth Science—Journal of China University of Geosciences, 2007, 32(2): 260-266. (in Chinese)

Zou, C., Dong, D., Wang, S., et al. Geological characteristics and resource potential of shale gas in China. Petroleum Exploration and Development, 2010, 37(6): 641-653.

Zou, C., Zhu, R., Wu, S., et al. Types, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: Taking tight oil and tight gas in China as an instance. Acta Petrolei Sinica, 2012, 33(2): 173-187. (in Chinese)