frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 25 January 2023
DOI 10.3389/feart.2022.1097806

Prediction of hydrocarbon source rock distribution using logging curves: A case study of Es_3^2 source rock in Nanpu Sag, Huanghua depression, Bohai Bay Basin

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SPECIALTY SECTION
This article was submitted to Geochemistry, a section of the journal Frontiers in Earth Science

RECEIVED 14 November 2022
ACCEPTED 02 December 2022
PUBLISHED 25 January 2023

CITATION
Guo Q, Jiang S, Wang J, Zhou Q, Gao Y, Ye L and Yin J (2023), Prediction of hydrocarbon source rock distribution using logging curves: A case study of Es_3^2 source rock in Nanpu Sag, Huanghua depression, Bohai Bay Basin. *Front. Earth Sci.* 10:1097806. doi: 10.3389/feart.2022.1097806

The Es_3 is the main hydrocarbon source rock system in the Nanpu Sag. Finally, the TOC and hydrocarbon potential of each sub depression of Es_3were predicted. The study shows that the hydrocarbon source rocks of Es_3^2 and Es_3^4 sections are mainly of type II_2 and type II_1 respectively, with good organic matter type and high maturity. Biomarker compound parameters indicate that the Es_3^2 section hydrocarbon source rocks developed in a semi-saline, low to medium terrestrial source organic matter supplied reduction environment with a high algal contribution; the Es_3^4 section hydrocarbon source rocks formed in a freshwater, low terrestrial source supplied reduction environment with a medium-high algal contribution. The multiple linear regression method is more effective than the ΔlgR method in predicting hydrocarbon source rocks in the Nanpu Sag, and the prediction accuracy is higher; the correlation between TOC and $S_1 + S_2$ is the best in the model for predicting hydrocarbon potential. The TOC and hydrocarbon potential of the hydrocarbon source rocks in Es_3^1 are generally low; the high value area of TOC and hydrocarbon potential of the hydrocarbon source rocks in Es_3^2 is partly between the No. 1 tectonic zone and No. 5 tectonic zone in Linque sub depression, and the TOC and hydrocarbon potential of the hydrocarbon source rocks in Liunan sub depression are larger; the high value area of TOC and hydrocarbon potential of the hydrocarbon source rocks in Es_3^4 is mainly concentrated in Shichang sub depression.

KEYWORDS

TOC, hydrocarbon source rock evaluation, hydrocarbon generation potential, Nanpu Sag, Es_3

1 Introduction

Under the guidance of the geological theory of complex oil and gas accumulation and hydrocarbon formation (Hu, 1982; Guo, 2006; Fu et al., 2021; Liang et al., 2021; Pan et al., 2022), with the in-depth research of fine 3D seismic and comprehensive geology (Zhao and Chi, 2000; Zhou et al., 2005; Guo et al., 2021), the concepts of oil and gas-rich depressions with full-concave oil-bearing theory, oil and gas-bearing system and complex hydrocarbon generation system have been put forward successively (Magoon and Dow, 1994; Chen et al., 2000; Zhao et al., 2002; Zhao et al., 2004; Meng et al., 2008; Lin et al., 2022), which have great guiding significance for oil and gas exploration in Bohai Bay Basin. The Nanpu Sag is an important fault-type oil and gas-rich depression in the Bohai Bay Basin, mainly located in the low part of the depression and in the lithologic stratigraphic traps in the slope area (Zhao et al., 2008; Sun et al., 2015; Dang et al., 2016). Hydrocarbon source rocks are the material basis for hydrocarbon formation and determine the hydrocarbon production capacity (Cheng et al., 2021; Han et al., 2016; Kang, 2021; Meng et al., 2022). A correct understanding of hydrocarbon source rock characteristics and spreading pattern is the basis and key to hydrocarbon exploration (Huang et al., 2017).

A large number of scholars have studied hydrocarbon source rocks in major basins in China, Among them, Zou et al. (2010) simulated the maturity evolution and hydrocarbon production and discharge processes of hydrocarbon source rocks in the Bohai Bay Basin based on the sedimentary and tectonic development history of hydrocarbon source rocks combined with geochemical and thermal parameters; Lu et al. (2017) used the material balance method to quantitatively analyze hydrocarbon expulsion from source rocks in the Songliao Basin, and used the "over-pressure" module of PetroMod software to evaluate the over-pressure history of source rocks; Zhang et al. (2017) used constant water pressure and high water pressure experiments to simulate the pyrolysis of carbonaceous mudstones drilled in the Liaohe Basin, and the results showed that the number of hydrocarbon discharges had a significant contribution to the production of liquid hydrocarbons from hydrocarbon source rocks; Liu et al. (2017) established the evaluation method for hydrocarbon generating substances of marine carbonate source rocks by studying the matching relationship between the hydrocarbon source rocks in Tarim Basin and the oil and gas reservoirs in Tahe Oilfield; Pang et al. (2020) used the pyrolytic hydrocarbon generation potential index method and single-factor regression analysis to characterize the hydrocarbon generation and discharge of hydrocarbon source rocks in the Sichuan Basin and a quantitative model for the probability of reservoir formation under controlled systems; Tang et al. (2021)established evaluation criteria and hydrocarbon generation models for alkaline lacustrine hydrocarbon source rocks in the Mahu Depression of the Dzungar Basin. (Song et al., 2021).quantified the potential of different resource types in the Tsaidam Basin based on the geochemical and petrological characteristics of hydrocarbon source rocks combined with the buoyancy-driven hydrocarbon formation depth (BHAD) and the lower limit of movable resource abundance.

In recent years, some scholars have evaluated hydrocarbon source rocks in the Nanpu Sag, mainly including hydrocarbon source rock development sections, geochemistry and hydrocarbon production and discharge characteristics. (Guo et al., 2013). used a basin and hydrocarbon-bearing system modelling approach to study the hydrocarbon transport history of the Nanpu Sag, suggesting that hydrocarbon source rocks are mainly developed in Ed_3 of the Dongying Formation, Es_1 and Es_3 of the Shahejie Formation; Gang et al. (2021) conducted rock pyrolysis, gas chromatography-mass spectrometry, elemental geochemistry organic and inorganic analyses on several samples showing that the Es_3 section has higher organic carbon content than the Ed_3 and Es_1 sections, and the hydrocarbon source rocks have the highest hydrocarbon generation potential, with the Ed_3 and Es_1 section hydrocarbon source rocks being of type II_1-II_2, and the Es_3 section hydrocarbon source rocks being dominated by type II_2-III chevrons. (Pei et al., 2016). studied the genesis of oil reservoirs in four tectonic zones in the Nanpu Sag, pointing out that the hydrocarbon source rocks in the Ed_3 and Es_1 sections were deposited in a freshwater anoxic environment, and the hydrocarbon source rocks in the Es_3 section were deposited in a high salinity, anoxic interval, with a large contribution from terrestrial organic matter (TOM); Wei and Sun. (2017) concluded that the thickest effective hydrocarbon source rocks in the Ed_3 section are located in the Linque and Liunan sub depressions based on hydrocarbon source rock evaluation characteristic parameters and the oil source comparison method, and that the Caofeidian sub depression has greater exploration potential. (Wang et al., 2021). and (Zhu et al., 2013) considered the initial hydrogen index and conversion ratio during hydrocarbon source rock evolution based on the measured rock-eval pyrolysis data, which more realistically reflected the hydrocarbon generation and discharge history of hydrocarbon source rocks. For the study of the hydrocarbon source rocks in the Es_3sub-section of the Nanpu Sag, (Zuo et al., 2010), concluded that two hydrocarbon source foci developed early in the Es_3^2 of the Bohai Bay Basin, and that the Nanpu Sag was one of the main hydrocarbon source foci that evolved with geological evolution; Zhu et al. (2013) concluded that Es_3^4 is a high quality hydrocarbon source rock with an effective hydrocarbon source rock thickness of approximately 250 m through detailed comparative analysis of oil shale and crude oil biomarkers and isotopic signatures.

Although the evaluation of the key hydrocarbon source rock formations in the Nanpu Sag is based on certain research, the sub-sections of Es_3 with hydrocarbon generation potential are

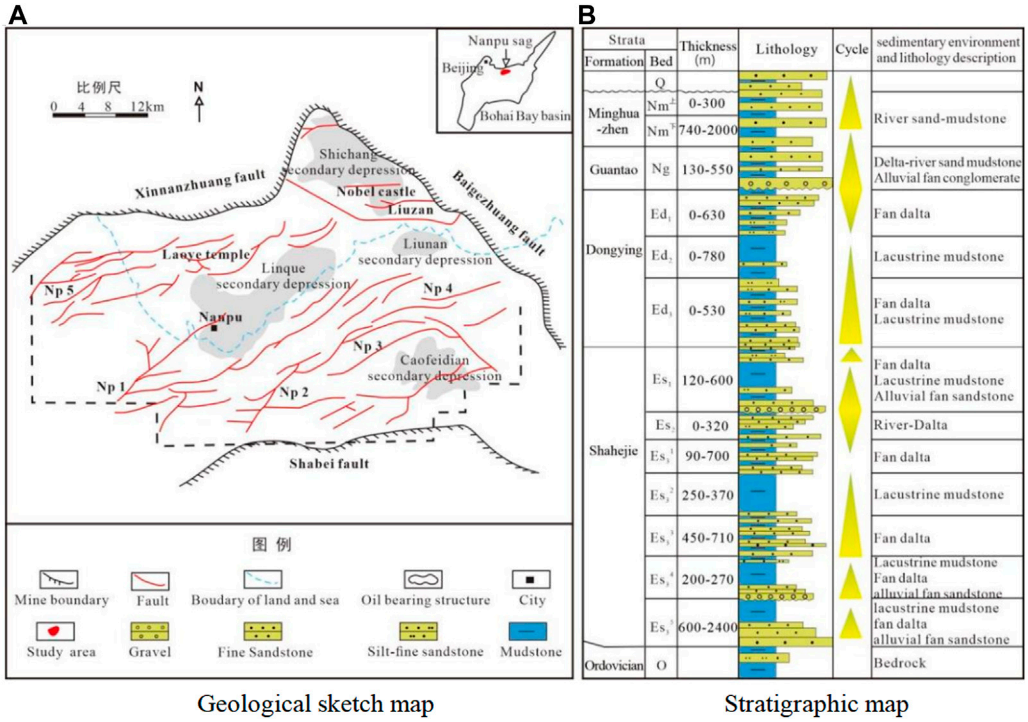


FIGURE 1
Structural and comprehensive geological histogram of the study area. **(A)** Geological sketch map **(B)** Stratigraphic map.

not studied in detail enough, resulting in a lack of clarity on the genesis type and resource potential of the tight oil system, which limits the further exploration of tight oil, therefore, the comprehensive evaluation system of hydrocarbon source rocks in each sub-section Es_3 of needs to be improved. In this paper, the hydrocarbon source rocks in the Es_3 section of the Nanpu Sag were evaluated and studied through a large number of sample analysis and testing experiments; a quantitative TOC prediction model for the Es_3 section was established based on the logging curves using the improved ΔlgR method and multiple linear regression method, and the key wells were selected to compare the predicted and measured TOC values. It also establishes a model for predicting the hydrocarbon generation potential of the Es_3 section hydrocarbon source rocks; finally, the organic carbon and hydrocarbon generation potential of each sub-section of Es_3 in the study area are predicted. It has important theoretical and application values for the evaluation of hydrocarbon resources and the next exploration direction in the Nanpu Sag.

2 Geological overview

The Nanpu Sag is located in the northeastern part of the Huanghua depression in the Bohai Bay basin. It has a tectonic pattern of northern fault and southern superstructure developed through the application of block faulting in the Middle and Cenozoic eras on the base of the North China Platform, covering an area of about 1930 km^2 (Li et al., 2010; Xu et al., 2010). The depression is mainly developed on the Southwest Zhuang, Baige Zhuang and Shabei boundary faults (Wang et al., 2020), and can be divided into four hydrocarbon bearing depressions, namely the Caofeidian sub depression, the Linque sub depression, the Liunan sub depression and the Shichang sub depression, and eight major tectonic zones, namely the Nanpu1-5, Laoyemiao, Gaoshangpu and Liuzan. The Caofeidian sub depression is located in the southern part of the Nanpu3 structure, the Linque sub depression is located in the southern part of the Laoyemiao structure, the Liunan sub depression is in the central part of the Nanpu4 and Liuzan structures, and the Shichang sub depression is located in the northern part of the Gaoshangpu structure (Cheng et al., 2022). The Nanpu Sag is characterized by a complex fracture system consisting of fractures of different levels and different time periods, and the fractures and their subdivisions form a complex fracture system (Figure 1A). The sedimentary rocks of the Nanpu Sag are up to 8000 m thick and consist of the Shahejie Formation (Es) and Dongying Formation (Ed) of the Palaeocene and the Minghuazhen Formation (Nm) and Tantao Formation (Ng) of the

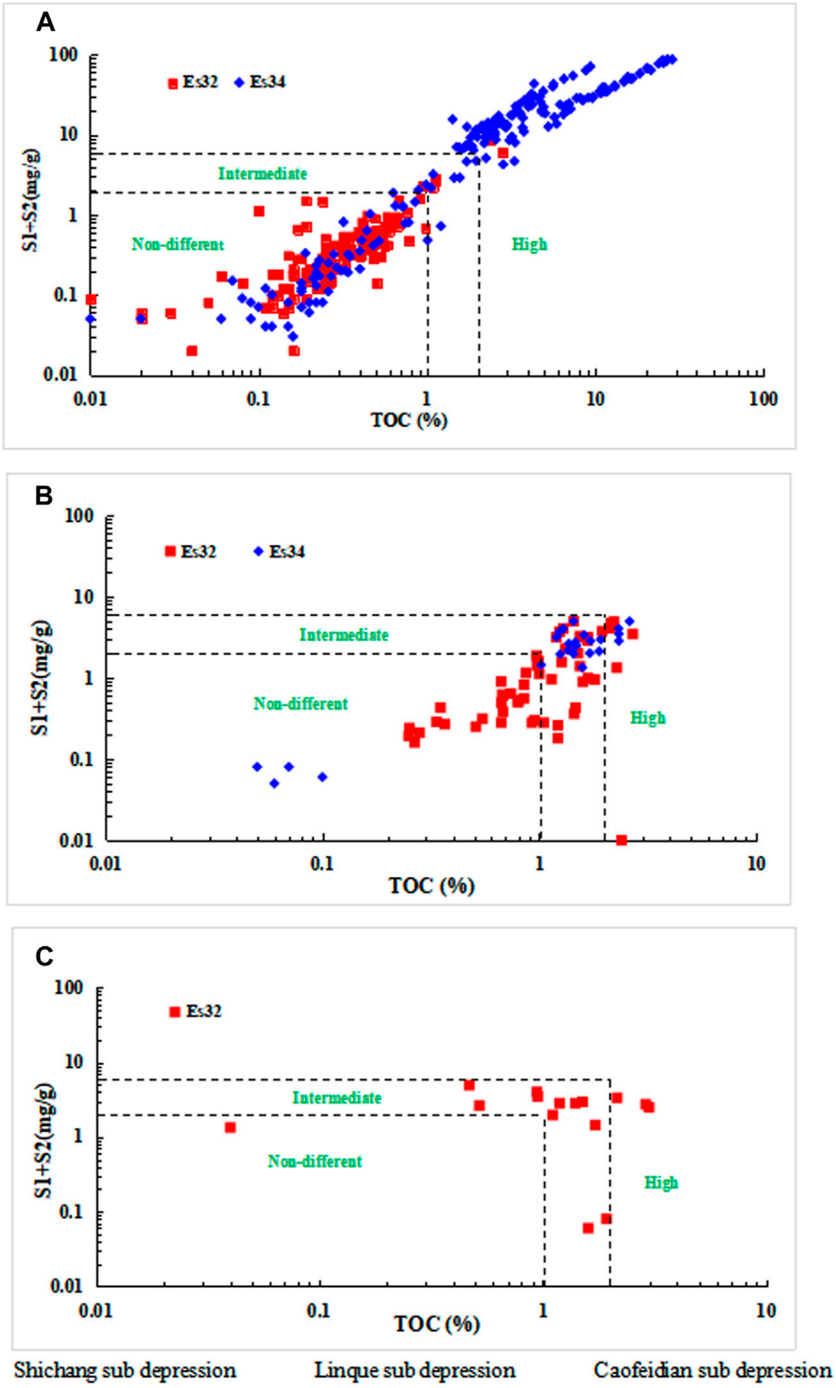
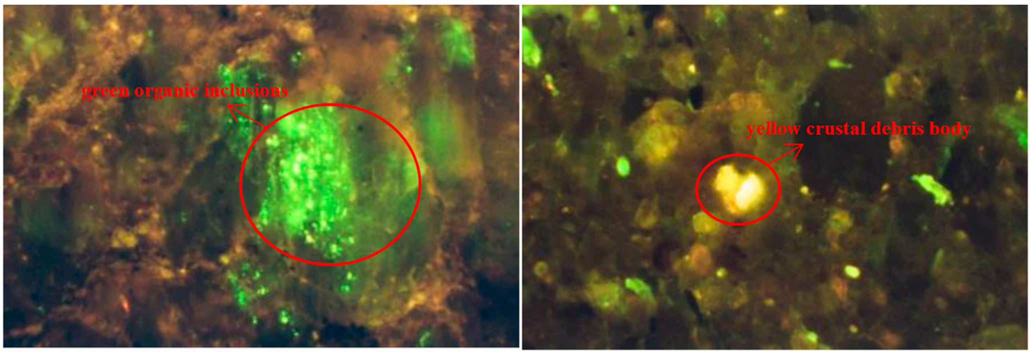


FIGURE 2
Statistical distribution map of organic matter abundance of Es_3 source rocks in different sub depressions of Nanpu Sag. **(A)** Shichang sub depression. **(B)** Linque sub depression. **(C)** Caofeidian sub depression.

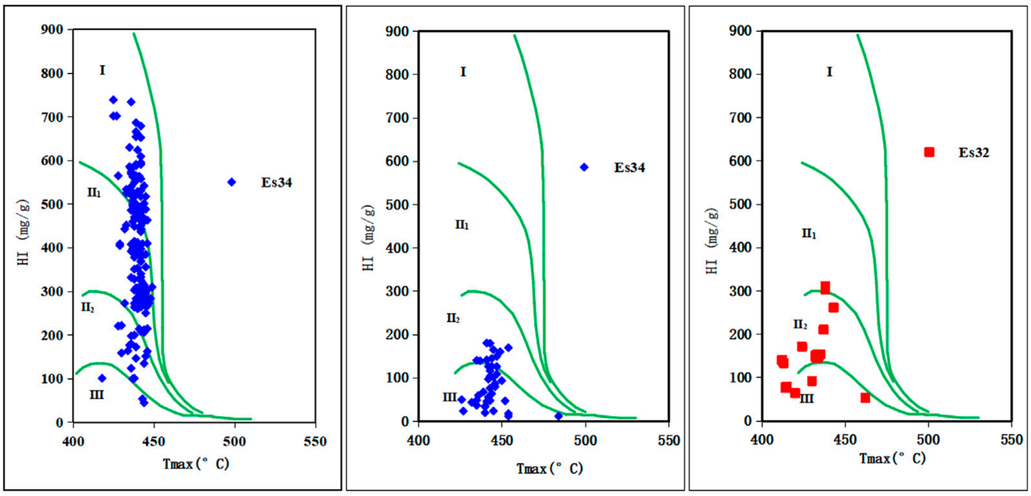
Neoproterozoic (Chen et al., 2020). The Shahejie Formation stratigraphy can be divided into Es_1, Es_2, and Es_3. Among them, the Es_3 section is a shallow lake-deep lake, fan delta and alluvial fan deposition, which shows a complete secondary cycle of coarse lower, medium and fine upper, with a total thickness of 600–2000 m and an overall upward thinning. It is divided into five sub-sections (Es_3^5, Es_3^4, Es_3^3, Es_3^2, and Es_3^1) based on lithology from the bottom up (Figure 1B).



(A) Nanpu280, Es_3^2, 4011.87m green organic inclusions

(B) Liu15, Es_3^4, 4520.12m yellow crustal debris body

FIGURE 3
Group of maceral photographs of Es_3 source rocks in Nanpu Sag. **(A)** Nanpu280, Es_3^2, 4011.87 m green organic inclusions. **(B)** Liu15, Es_3^4, 4520.12 m yellow crustal debris body.



(A) Shichang sub depression (B) Linque sub depression (C) Caofeidian sub depression

FIGURE 4
Classification of organic matter types of Es_3 source rocks in different sub depressions of Nanpu Sag. **(A)** Shichang sub depression. **(B)** Linque sub depression. **(C)** Caofeidian sub depression.

3 Hydrocarbon source rock evaluation

Three sets of hydrocarbon source rocks, Es_3^1, Es_3^2, and Es_3^4, are developed in the Es_3 section of the Nanpu Sag, of which Es_3^2 and Es_3^4 are the main hydrocarbon source rocks. This study focuses on the evaluation of the effective hydrocarbon source rocks in the Es_3^2 and Es_3^4 sections of the Shichang, Linque and Caofeidian sub depressions.

3.1 Organic matter abundance

Organic matter abundance refers to the enrichment of organic matter per unit mass of rock. Indicators that effectively reflect the organic matter abundance of hydrocarbon source rocks include organic carbon (TOC), hydrocarbon generating potential (S1+S2), chloroform bitumen "A" and total hydrocarbon (HC), *etc.* (Bojang and Xiongqi, 2014). According to the organic matter abundance

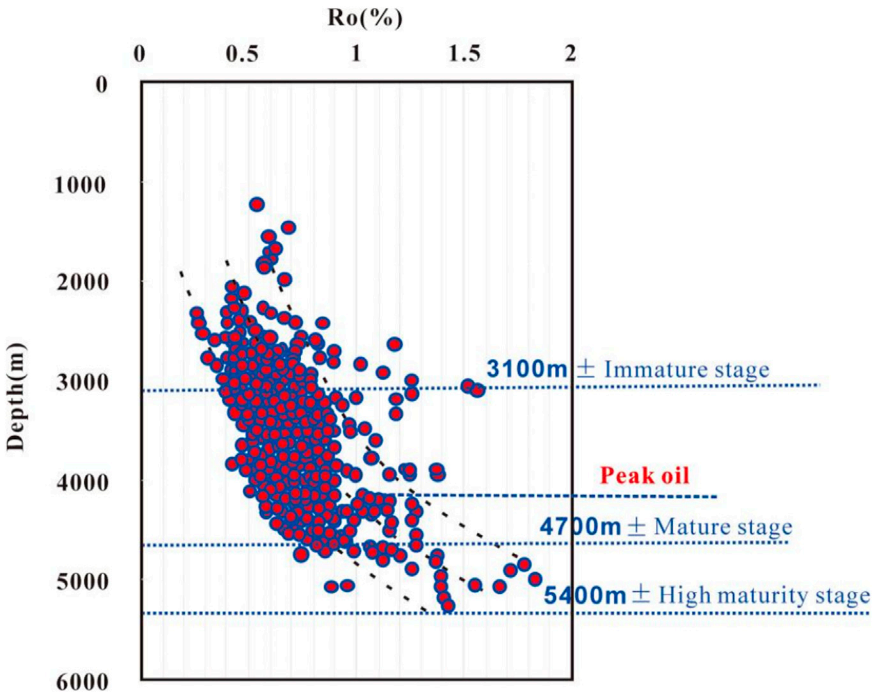


FIGURE 5
Relationship between R_o and depth of source rocks in Nanpu Sag.

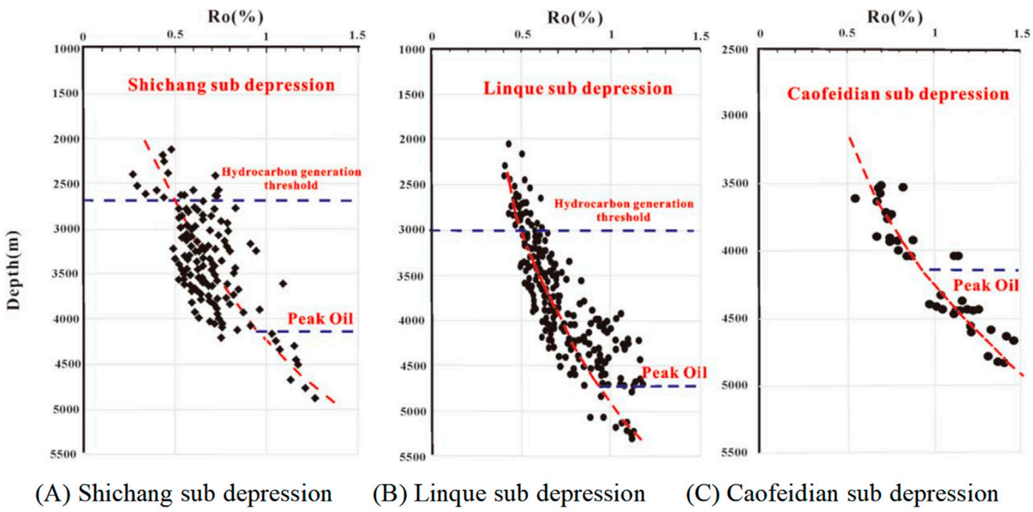


FIGURE 6
Relationship between R_o and depth of Es_3 source rocks in different sub-depressions of Nanpu Sag. **(A)** Shichang sub depression. **(B)** Linque sub depression. **(C)** Caofeidian sub depression.

distribution map, the organic carbon content of Es_3^2 is 0.12%–2.82%, with an average value of 0.41%; the hydrocarbon potential value is 0.10–9.21 mg/g, with an average value of 0.67 mg/g; the hydrocarbon source rock abundance of Es_3^2 is a poor hydrocarbon source rock, not the main hydrocarbon source rock section in Shichang sub depression. The organic carbon content of Es_3^4 is 0.21%–35.18%, with an average value of 4.13%. The organic carbon content of Es_3^4 ranges from 0.21% to 35.18%,

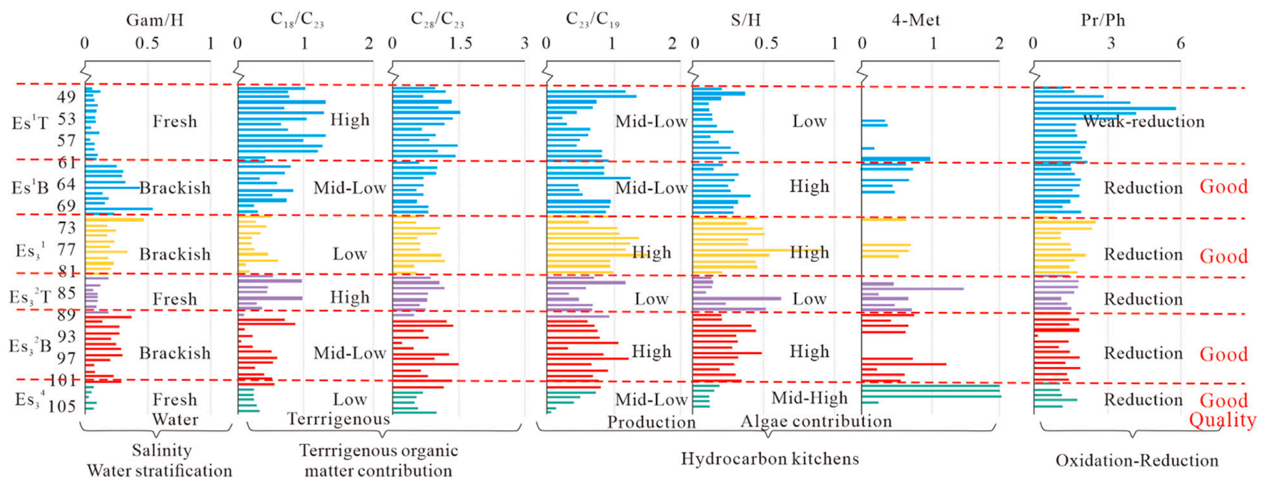


FIGURE 7
Characteristics of organic geochemical parameters of Es_3 source rocks of Nanpu Sag.

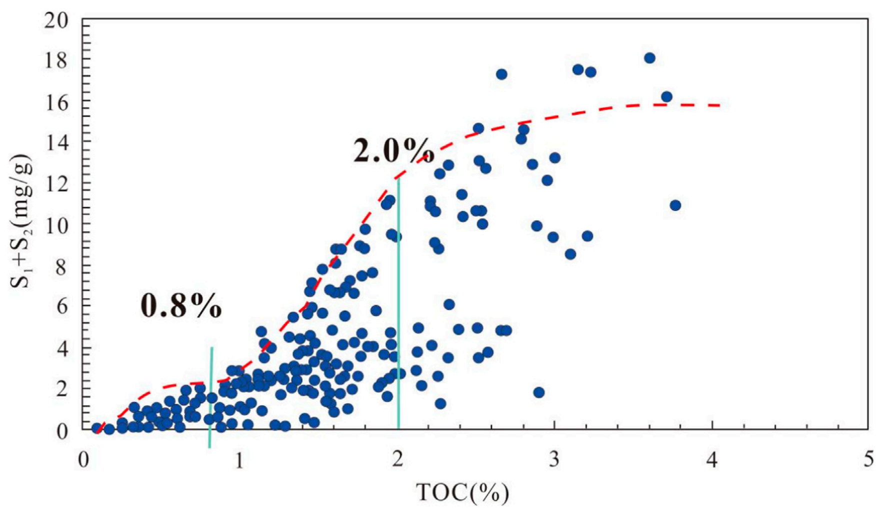


FIGURE 8
Relationship between $S_1 + S_2$ and TOC of Es_3 source rocks in Nanpu Sag.

with an average value of 4.13%; the hydrocarbon potential values are distributed from 0.20 to 105.1 mg/g, with an average value of 15.81 mg/g; Es_3^4 is the main hydrocarbon source rock section in Shichang sub depression (Figure 2A). The organic carbon content of section Es_3^2 in Linque Sub-pavement ranges from 0.25% to 2.71%, with a mean value of 1.16%; the hydrocarbon potential values are distributed from 0.18 to 4.97 mg/g, with a mean value of 1.46 mg/g. The organic carbon content of section Es_3^2 in Caofeidian sub depression ranges from 0.47% to 2.99%, with a mean value of 1.43%; the hydrocarbon potential values range from 0.56 to 9.92 mg/g, with a mean value of 3.46 mg/g; Es_3^2 section hydrocarbon source rocks are the main hydrocarbon source rock section of Linque and Caofeidian sub depression (Figures 2B,C).

3.2 Organic matter types

The organic matter type is one of the main indicators for classifying organic phases and evaluating the hydrocarbon generation potential of organic matter (Lu et al.,2012). The data collected show the following characteristics of the organic

TABLE 1 Identification criteria of Es_3 source rocks in Nanpu Sag.

Sub depression	Layer	Effective hydrocarbon source rock			High quality hydrocarbon source rocks		
		TOC (%)	S1+S2 (mg/g)	Ro (%)	TOC (%)	S1+S2 (mg/g)	Ro (%)
Shichang	Es_3	>.8	>2	>0.5	>2.0	>6	>.7
Linque		>.8	>2	>0.5	>2.0	>6	>.7
Caofeidian		>.8	>2	>0.5	>2.0	>6	>.7

microfraction: the specular group is generally low in content, grey in oil-immersion reflected light, and the specular bodies do not fluoresce; the inert group is slight in content, with grey-white filamentous bodies predominating in oil-immersion reflected light; the crustacean group has mainly laminar algal bodies, microsporidia yellow (Figure 3A), fluorescent microsporidia, mostly occurring as flat rings and worms, a few greenish-yellow fluorescent, striped thin-walled keratophores; mineral asphalt matrixmostly disperse, crustacean; very few fluorescent bodies with strong green fluorescence (Figure 3B). In this study, the main method of pyrolysis analysis was used to classify the organic matter types of hydrocarbon source rocks in the Nanpu Sag. The hydrogen index HI of hydrocarbon source rock pyrolysis can classify the type of organic matter. The temperature Tmax corresponding to the appearance of the P_2 peak during pyrolysis can determine the maturity of organic matter, and the organic matter type of hydrocarbon source rock can be judged by making an intersection diagram between the hydrogen index and Tmax. The rock pyrolysis analysis shows that the best organic matter type is found in the Es_3^4 section of the Shichang sub depression (Figures 4A,B), dominated by type I~II_2, with the least terrestrial supply; the hydrocarbon source rocks in the Linque and Caofeidian sub depression Es_3^2 sections have more contribution from higher plants (Figure 4C), and the organic matter type is dominated by type II_2~III mixed cheese roots.

3.3 Organic matter maturity

The abundance of organic matter determines the amount of hydrocarbon producing material base of the hydrocarbon source rock, the type of organic matter determines the hydrocarbon producing potential of the hydrocarbon source rock, and the ability to produce oil or gas is closely related to the degree of thermal evolution of the organic matter (Xia et al., 2019). The Specular body reflectance (Ro) is currently the most common method for determining the maturity of organic matter. According to the measured data (Figure 5), the Specular body reflectance (Ro) of hydrocarbon source rocks in the Nanpu Sag is mainly distributed in the range of 0.25%–1.75%. Ro is distributed in the depth range of 2000–5500 m, and the relationship with depth is not very clear, even the shallow part is higher than the deep part of Ro. This is mainly due to the influence of the igneous rocks prevalent in the Nanpu Sag. Leaving aside the anomalies influenced by igneous rocks, the conventional peak oil generation should correspond to a depth of roughly 4200 m, with the angry phase being deeper. According to the trend of Ro, the immature stage is not indicated, and the boundary between the low and mature stages is roughly around 3100 m depth.

The reflectance data of the specular bodies were analyzed by different sub depression sub-tectonic zones, in different tectonic zones of the Nanpu Sag, there are some differences in the rate of increase of Ro with increasing depth of the strata. The hydrocarbon source rocks in the Es_3^4 section of the Shichang sub depression are all in the mature stage, with a hydrocarbon generation limit of about 2700 m and a peak oil generation at about 4200 m (Figure 6A). The hydrocarbon source rocks in the Es_3^2 section of the Linque sub depression are in the mature stage, with a hydrocarbon generation limit of about 3000 m and a peak oil generation at about 4700 m (Figure 6B). The hydrocarbon source rocks of section Es_3^2 in Caofeidian sub depression have entered the mature stage, with hydrocarbon generation threshold less than 3500 m and oil generation peak at 4200 m (Figure 6C).

3.4 Biomarker characteristics

Biomarker compounds are derived from organisms that have lived (especially lipid-like compounds) and are complex molecular fossils. The parameters basilane/phytane (Pr/Ph), sterane/hoxane (S/H), C_{19} tricyclic terpene/C_{23} tricyclic terpene (C_{19}/C_{23}TT), C_{20} tricyclic terpene/C_{23} tricyclic terpene (C_{20}/C_{23}TT), C_{27}/C_{29} rule sterane parameters, gammacerane index (gammacerane/αβ-C_{30}holo) and 4-methyl sterane (4MSI) were selected as the seven parameters are used to distinguish the organic geochemical characteristics of the hydrocarbon source rocks in each sub-section of theEs_3. The study shows (Figure 7) that there are significant differences between the Es_3^2 and Es_3^4 sections mainly in terms of water properties and biogenic composition. The mean Pr/Ph value of the hydrocarbon source rocks in the Es_3^2 section is 1.8, the weakly reduced water environment, the mean Gam/H index is 0.22, the mean C_{27}/C_{29} sterane value is 0.85, the mean C_{19}/C_{23} and C_{20}/C_{23} tricyclic terpene parameters are 0.39 and 0.93 respectively; the mean S/H value is 0.31. The developmental environment is generally a reduced environment with semi-saline, low to medium terrestrial organic

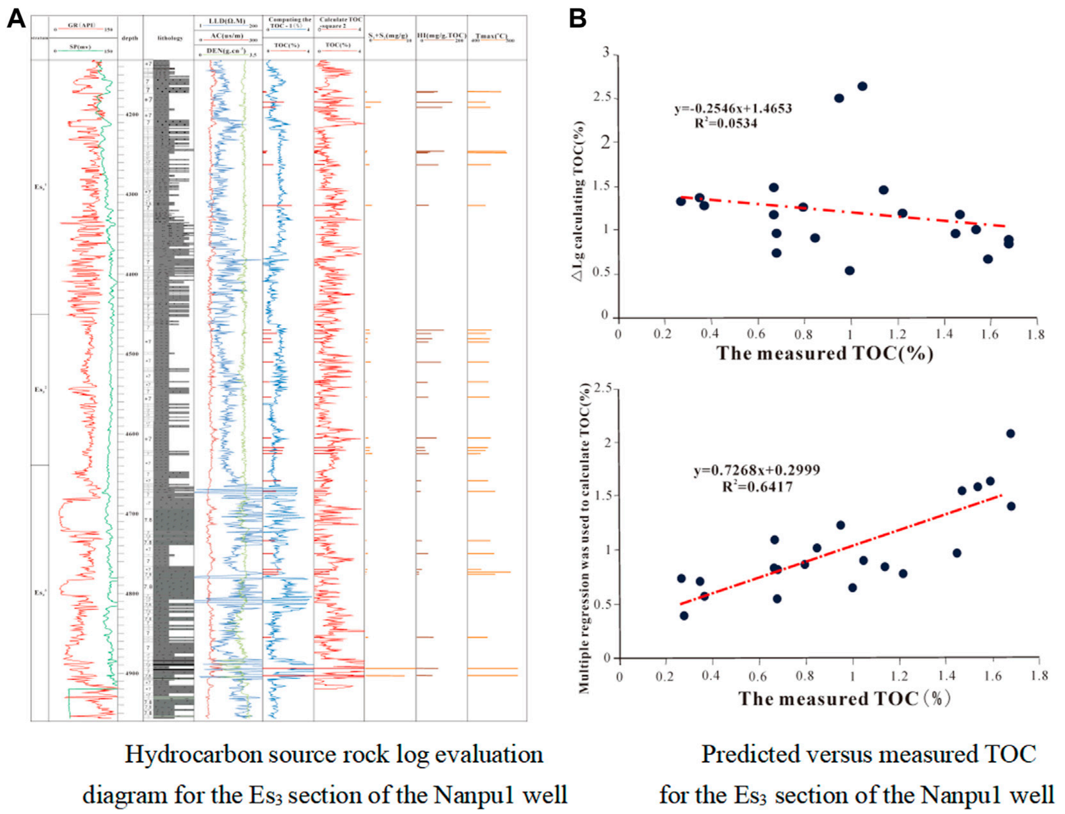


FIGURE 9
The diagram of logging evaluation and relationship between prediction and measured of Es_3 source rock in well Nanpu1. **(A)** Hydrocarbon source rock log evaluation diagram for the Es_3 section of the Nanpu1 well. **(B)** Predicted versus measured TOC for the Es_3 section of the Nanpu1 well.

matter supply and a large contribution from algae. Es_3^4 section hydrocarbon rock Pr/Ph mean 1.2, weak reduction-reduction water environment, Gam/H index mean 0.05, C_{27}/C_{29} sterane mean 0.43, C_{19}/C_{23} and C_{20}/C_{23} tricyclic terpene parameter means 0.23 and 0.56 respectively; S/H mean 0.13. Although organic matter productivity was not prominent, the contribution of methanogens was evident and generally formed in a freshwater, low terrestrial supply reduction environment with a medium-high algal contribution.

4 Hydrocarbon generation potential prediction model

4.1 Effective hydrocarbon source rock identification

The identification of effective hydrocarbon source rocks is mainly evaluated in terms of organic matter abundance, organic matter type and maturity of hydrocarbon source rocks, which require the three conditions of being rich in organic matter, having reached maturity stage and being able to discharge hydrocarbons effectively at the same time (Hou et al.,2015). The inflection point where the hydrocarbon production potential (S_1 + S_2) changes with the abundance of hydrocarbon source rocks will produce obvious inflection points (Figure 8). The inflection point where the hydrocarbon production potential increases significantly is usually taken as the discriminatory limit for effective hydrocarbon source rocks, while the inflection point where the hydrocarbon production potential no longer increases significantly is taken as the discriminatory limit for high-quality hydrocarbon source rocks. The parameters for identifying hydrocarbon source rocks in the Es_3 section were determined by subdividing the Nanpu Sag, and the criteria for identifying hydrocarbon source rocks in the study area were established (Table 1). The lower limit of hydrocarbon source rock abundance in the Es_3 section is TOC >0.8%, and the lower limit of high quality hydrocarbon source rock abundance is TOC >2.0%.

4.2 TOC prediction model

The main methods for quantitative evaluation of hydrocarbon source rocks based on logging data are ΔlgR method, multiple linear regression method and CNN neural

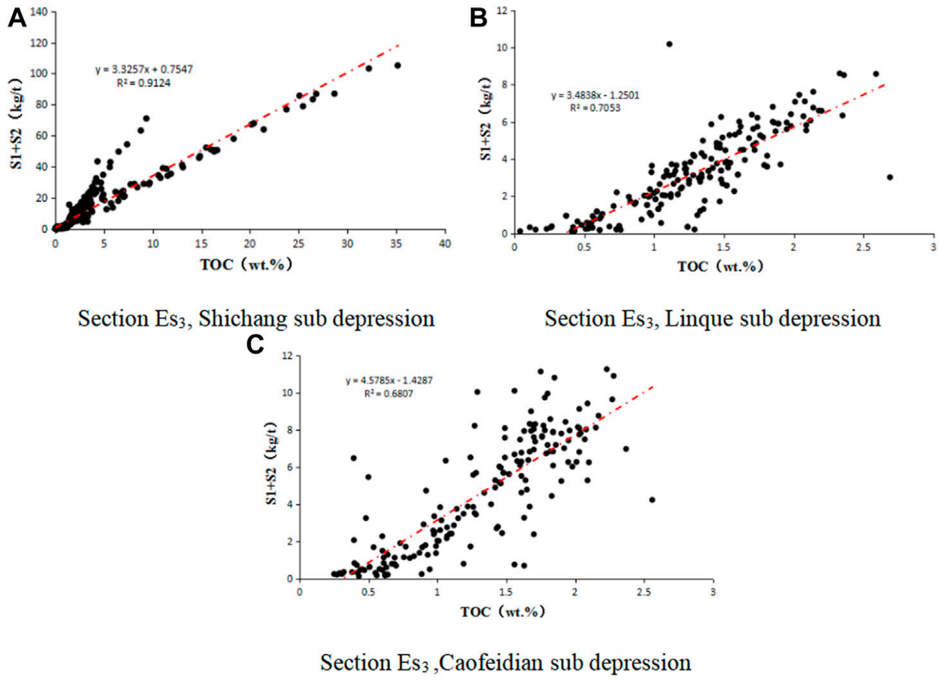


FIGURE 10
Cross plot of measured TOC and S_1+S_2 of Es_3 source rocks in different sub depressions of Nanpu Sag. **(A)** Section Es_3, Shichang sub depression. **(B)** Section Es_3, Linque sub depression. **(C)** Section Es_3 , Caofeidian sub depression.

network method, *etc.* Although the CNN neural network method has greater advantages in solving non-linear complex problems, it is difficult to express them in expressions. Currently, multiple linear regression and ΔlgR methods are widely used in the quantitative prediction and evaluation of hydrocarbon source rocks.

1) ΔlgR

The ΔlgR method was originally proposed by Passey et al. Based on the theory of qualitative identification of hydrocarbon source rocks by natural gamma curves, two curves of sonic time difference and resistivity are applied, and when the rocks are fine-grained and non-hydrocarbon source rocks, these two logging curves overlap together to show the baseline, and the difference in magnitude between the two curves is the ΔlgR value. The model can effectively eliminate the porosity on the logging response value of organic carbon content The effect of Eq:

$$\Delta \log R = \log(R/R_b) + x \times (\Delta t - \Delta t_b)$$

The ΔlgR method was used to predict the TOC content of hydrocarbon source rocks using the equation.

$$TOC = (\Delta \log R) \times 10^{2.297-0.1688Ro}$$

To avoid the uncertainty that arises when manually superimposing the acoustic and resistivity curves, the ΔlgR equation is deformed as follows.

$$TOC = a \times \lg R + b \times \Delta t + c$$

where R is the resistivity, R baseline is the resistivity of the non-hydrocarbon source rock section, Δt is the acoustic time difference, Δt baseline is the acoustic time difference of the non-hydrocarbon source rock section, x is the coefficient, R_o is the organic matter maturity index, and the values of a, b and c can be obtained by analysis of samples from the study area and fitting with least squares.

Considering that the lithological combination and maturity of hydrocarbon source rocks under different sedimentary phase zones in different areas of the Nanpu Sag may cause differences in logging response, in order to improve the TOC logging prediction model in the study area, the actual hydrocarbon source rock sample points and logging parameters were counted in the Linque sub depression, Caofeidian sub depression and Shichang sub depression respectively, and regression analysis was carried out according to the above equation to obtain the TOC prediction models for different sub depressions Es_3 sections in turn, although there are some differences in the prediction models in different areas, the

TABLE 2 Prediction model of hydrocarbon generation potential of Es_3 source rocks of Nanpu Sag.

Sub depression	Layer	S1+S2 quantitative forecasting model	Correlation coefficient
Shichang	Es_3	S1+S2=3.3257*TOC+0.7547	0.912
Linque		S1+S2=3.4828*TOC-1.2501	0.705
Caofeidian		S1+S2=4.5785*TOC-1.4287	0.681

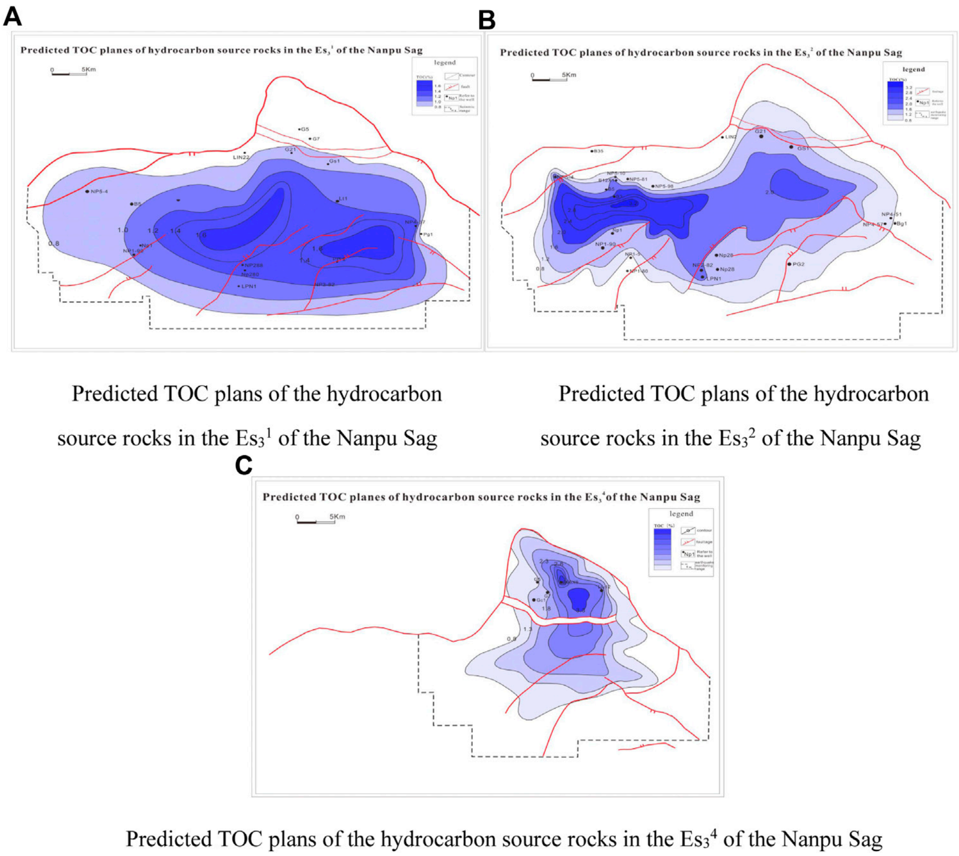


FIGURE 11
TOC planimetry of Es_3 source rocks in different sub depressions of Nanpu Sag. **(A)** TOC planimetry of the hydrocarbon source rocks in the Es_3^1 sub depression. **(B)** TOC planimetry of the hydrocarbon source rocks in the Es_3^2 sub depression. **(C)** TOC planimetry of the hydrocarbon source rocks in the Es_3^4 sub depression.

correlation coefficient of the ΔlgR method TOC prediction model for the Nanpu Sag is generally around 0.65.

2) Multiple linear regression

Multiple linear regression is to take hydrocarbon source rock TOC as the dependent variable and multiple logging parameters that correlate well with TOC as independent variables to establish multiple regression equations, and determine the best TOC quantitative prediction model through multiple regression analysis. The hydrocarbon source rocks in the Es_3 section of the Nanpu Sag are characterized by high natural gamma, high acoustic time difference, high resistivity and low density in the logging curve response. The high gamma of hydrocarbon source rocks is due to the small particle size and large specific surface area of hydrocarbon source rocks, which adsorb more radioactive element uranium; the high resistivity is due to the presence of organic matter with poor electrical conductivity in high quality hydrocarbon source rocks, resulting in a large resistivity; the high acoustic time difference value between

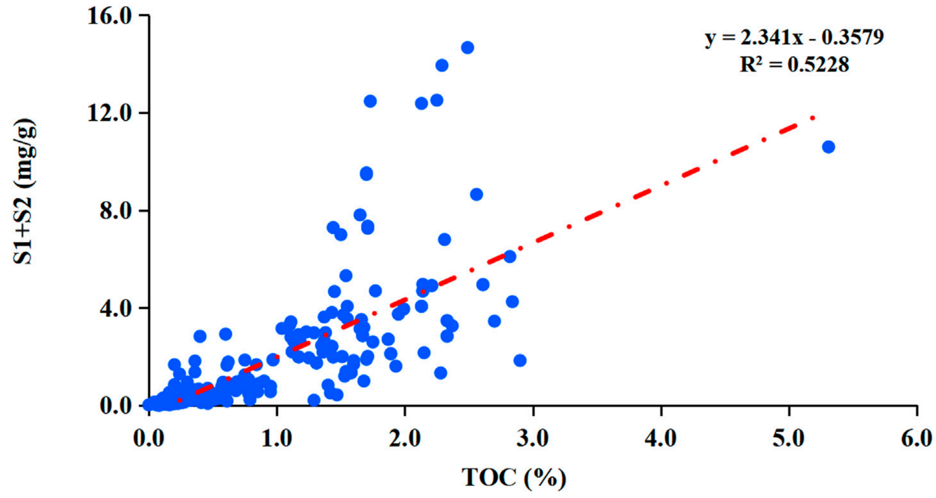


FIGURE 12
Linear diagram of TOC and $S_1 + S_2$ of Es_3 source rocks of Nanpu Sag.

organic matter and oil and gas in hydrocarbon source rocks is larger than the rock skeleton will cause the increase of acoustic time difference (AC) in the formation; the density of organic matter in hydrocarbon source rocks (1.1–1.4 g/cm ^{3}) is much lower than that of quartz and clay, so the density logging values (DEN) show low values. Based on the measured TOC of hydrocarbon source rocks in the Nanpu Sag and the five logging parameters, GR, AC, RT, DEN, and SP, using data analysis tools, a multiple regression model was constructed.

$$TOC = a \times GR + b \times AC + c \times RT + d \times DEN + e \times SP + f$$

Where: a, b, c, d and e are constants; f is the random error.

To improve the accuracy of the prediction formulae, the measured TOC data and corresponding logging parameters in the study area were statistically grouped separately according to different blocks.

To verify the accuracy of the two methods, a single well with more geochemical analysis data was selected to compare the predicted TOC values with the measured TOC values. The Nanpu1 well is located near the SW1 tectonic zone in the Linque sub depression. The well has more organic carbon analysis data in the Es_3 section and the logging data is of good quality. The organic carbon logging response model (Figure 9A) shows that the measured organic carbon distribution in the Es_3^1 and Es_3^2 sections of the Nanpu1 well ranges from 0.35% to 1.68%, with an average value of 0.97%. The interpretation of the logs showed that the correlation coefficient between TOC and measured TOC calculated by the ΔlgR model was 0.23, while the correlation coefficient between TOC and measured TOC calculated by the multiple linear regression model was 0.801. It can be seen visually (Figure 9B) that the comparison between the predicted TOC and measured TOC by the multiple linear regression method also revealed a better agreement between the two, indicating that the multiple linear regression The comparison between the TOC predicted by the multiple linear regression method and the measured TOC also reveals a better agreement between the two, indicating that the multiple linear regression method is better than the ΔlgR method in predicting the hydrocarbon source rocks in the Es_3 section of the Nangpu1 well in the Linque sub depression, with a higher prediction accuracy.

4.3 Hydrocarbon generation potential prediction model

In this study, the total organic carbon content (TOC) and rock pyrolysis hydrocarbon potential (S_1+S_2) of the measured hydrocarbon source rock samples from the Es_3 section of Shichang, Linque and Caofeidian sub depression were calculated and correlation analysis was performed to predict the hydrocarbon potential of the Es_3 hydrocarbon source rock.

As can be seen from the rendezvous plot (Figure 10), the measured geochemical parameters TOC of Es_3 hydrocarbon source rock samples in the study area show a good positive correlation with S1 + S2, with the best correlation between TOC and S1 + S2 in the Shichang sub depression and the next best correlation in the Linque sub depression. The correlation coefficients are 0.912, 0.705, and 0.681 for Shichang.

Linque and Caofeidian respectively. The multiple regression method of logging parameters can predict the TOC of hydrocarbon source rocks in the study area more accurately, so the predicted TOC can be used to predict the hydrocarbon generation potential again, and the model for predicting the hydrocarbon generation potential is as follows.

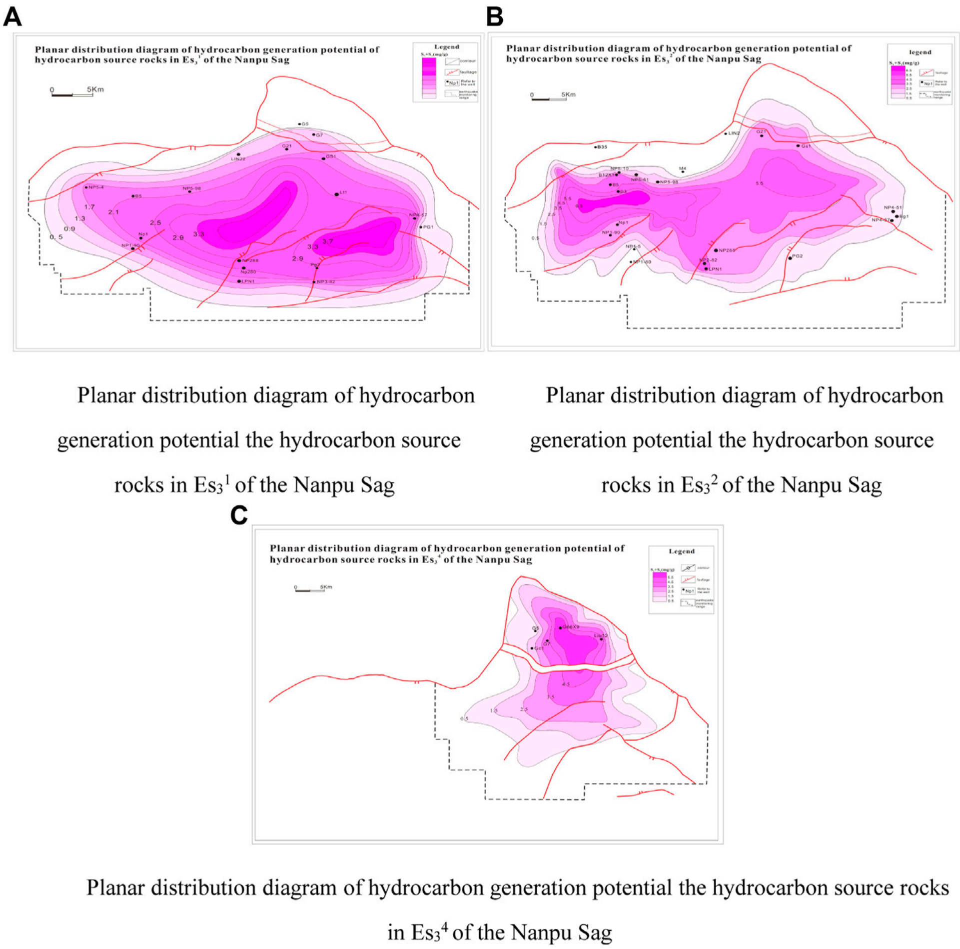


FIGURE 13
Plane prediction map hydrocarbon generation potential of Es_3 source rocks of Nanpu Sag. **(A)** Plan view of the hydrocarbon potential of the $Es_3{}^1$ sub-section. **(B)** Plan view of the hydrocarbon potential of the $Es_3{}^2$ sub-section. **(C)** Plan view of the hydrocarbon potential of the $Es_3{}^4$ sub-section.

$$S_1 + S_2 = \mathrm{a} \times TOC + \mathrm{b}$$

Where: a is a constant; b is a random error. a and b values can be obtained by analysing samples from the study area with a linear fit, and the final model for predicting the hydrocarbon generating potential of the Es_3 section of the Nanpu Sag is obtained (Table 2).

5 Predicted planar distribution of hydrocarbon source rocks

5.1 Predicted organic carbon planes

The prediction of total organic carbon in hydrocarbon source rocks in the study area is mainly based on the method of point-controlled pits and pits-controlled surface. Firstly, the predicted wells controlling each sub depression were selected and the median of the predicted TOC curve of a single well was calculated as the TOC value of that well. The trend of TOC between wells is combined with the trend of TOC between wells to control the internal spreading of each tectonic zone and sub depression. Finally, the TOC of each tectonic zone and sub depression is linked with the sedimentary phase spread to produce a TOC contour map for that section of the formation.

TOC values for hydrocarbon source rocks in the $Es_3{}^1$ section are generally not high, with predicted TOC greater than 2.0% area, and only relatively high areas exist in the Linque sub depression and Caofeidian sub depressions, with overall TOC between 1.4% and 1.6% (Figure 11A). The TOC in the No. 5 tectonic zone ranges from 0.8% to 1.0%; in the slope area between No. 1 and No. 3 tectonic zone, the TOC ranges from 0.8% to 1.2%, gradually decreasing from the Linque sub depression to the slope; the TOC in the Liunan sub depression is around 1.0%; and the TOC in the Shichang sub depression is generally low, basically not reaching the lower limit of 0.8% effective hydrocarbon source rock.

The high value hydrocarbon source rocks of Es_3^2 section are mainly concentrated between the No. 5 and No. 1 tectonic zones in the Linque sub depression and the Liunan sub depression (Figure 11B). The high TOC values in the Linque sub depression trend nearly east-west, with TOC ranging from 2.0% to 3.2%; the Linque sub depression TOC ranging from 1.6% to 2.0%; the Shichang sub depression TOC values ranging from 0.8% to 1.2%; and the Caofeidian sub depression TOC values ranging from 0.8% to 1.2%.

The area of high TOC values for hydrocarbon source rocks in the Es_3^4 section is mainly concentrated in the Shichang sub depression (Figure 11C), with average values ranging from 1.3% to 4.3%, with the highest TOC of 35% in well G66x9; the overall TOC is slightly lower in the Linque sub depression area, ranging from 1.3% to 2.0%.

5.2 Hydrocarbon potential plane projection

The regression of the single well measured and predicted TOC against the single well S_1 +S_2 was used to establish the hydrocarbon source rock relationship for the Es_3 section (Figure 12). The linear relationship was combined with the TOC prediction results to predict the hydrocarbon potential of each layer and then combined with the single well control to obtain a hydrocarbon potential plan.

The hydrocarbon source rocks in the Es_3^1 section have relatively low hydrocarbon generation potential, with S_1 + S_2 at a maximum of 4.0 mg/g, mainly concentrated in the Linque sub depression and Caofeidian sub depression (Figure 13A). The north-west oriented hydrocarbon source rocks are relatively high between the No. 2 and No. 3 structures in the Linque sub depression, with S_1 + S_2 at 3.0–4.0 mg/g; the S_1 + S_2 in the Caofeidian sub depression is 3.0–4.0 mg/g, and the high value area is obviously controlled by faults and spreads in an east-west direction; the S_1 + S_2 in the No. 5 tectonic zone is between 0.5 and 2.5 mg/g, and the hydrocarbon generation potential has a trend of low in the west and high in the east; the S_1 + S_2 in the Liunan sub depression is 0.5–2.5 mg/g, and the S_1 + S_2 in the Liunan sub depression is 0.5–2.5 mg/g. S_1 + S_2 is between 0.5 and 2.5 mg/g, and the hydrocarbon potential gradually decreases from southwest to northeast.

Es_3^2 section hydrocarbon source rocks S_1 + S_2 reach 3.5 mg/g in the vicinity of Linque sub depression, Liunan sub depression and No. 2 tectonic zone (Figure 13B). Among them, the east-west trending high hydrocarbon potential zone is developed between the No. 5 tectonic zone and No. 1 tectonic zone in Linque sub depression, with S_1 + S_2 between 5.5 and 6.5 mg/g; S_1 + S_2 in Liunan sub depression is between 5.5 and 6.0 mg/g; Caofeidian sub depression has low hydrocarbon potential, with S_1+S_2 between 1.5 and 3.5 mg/g.

The high hydrocarbon potential of the Es_3^4 section is mainly concentrated in the Shichang sub depression, with S_1 + S_2 ranging from 5.5 to 6.0 mg/g in the central sub depression area, including up to 36.0 mg/g in well G66x9 S_1 + S_2. The hydrocarbon potential decreases to the south, with S_1 +S_2 ranging from 2.5 to 4.5 mg/g in the Liunan sub depression area (Figure 13C).

6 Conclusion

1) The lower limit of hydrocarbon source rock abundance in the Es_3 section is TOC >0.8%; the lower limit of high quality hydrocarbon source rock abundance is TOC >2.0%; by establishing a quantitative TOC prediction model and selecting a single well with more geochemical analysis data to compare the predicted TOC with the measured TOC values, it is found that the multiple linear regression method is more effective than the ΔlgR method in predicting hydrocarbon source rocks in the Nanpu Sag. The results show that the multiple linear regression method is more effective and more accurate than the ΔlgR method in predicting hydrocarbon source rocks in the Nanpu Depression.
2) Total organic carbon content (TOC) and rock pyrolysis hydrocarbon potential (S_1 + S_2) were calculated for the core samples from Shichang, Linque and Caofeidian sub depressions, respectively, and correlation analysis was performed to establish a hydrocarbon potential prediction model. The best correlation between TOC and S_1 + S_2 was found in Shichang sub depression, and the second best correlation was found in Linque sub depression.
3) The TOC values and hydrocarbon potential of the hydrocarbon source rocks in section Es_3^1 are generally low, mainly concentrated in the Linque and Caofeidian sub depressions; the high TOC values and hydrocarbon potential of the hydrocarbon source rocks in section Es_3^2 are partly between the No. 5 and No. 1 tectonic zones in the Linque sub depression, and the TOC values and hydrocarbon potential of the Liunan sub depression as a whole are high; the high TOC values and hydrocarbon potential of the hydrocarbon source rocks in section Es_3^4 are mainly concentrated in the Shichang sub depression. The Es_3 section hydrocarbon source rocks have high TOC values and hydrocarbon potential mainly in the Shichang sub depression.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

QG: Methodology and validation; SJ: Supervision, review and editing; QZ: Methodology and software; YG: Sample collection and experimentation; JW: Sample analysis and validation; LY: Graphical collation and software; JY: Experimentation.

Acknowledgments

Thank you to the reviewers HC and WD for their constructive comments on this paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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