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Estimation on organic carbon content of source rocks by logging evaluation method as exemplified by those of the 4^{th} and 3^{rd} members of the Shahejie Formation in western sag of the Liaohe Oilfield

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Abstract One of the most important tasks of evaluating natural resources of petroliferous basins is to determine the organic matter abundance of source rocks in the basin. The usual method for assessing the organic carbon content of source rocks is based on laboratory analyses. There is a deviation in calculating organic carbon content due to the heterogeneous distribution of organic matter and the artificial factors when sampling. According to the continuous characteristics of information logging, the conventional logging curves (mainly acoustics and resistivity, etc.) were calibrated with the organic carbon experimental data of cores, cuttings or sidewall cores. The organic carbon content of source rocks of the 4^{th} (Es_4) and 3^{rd} (Es_3) members of the Shahejie Formation in western sag in the Liaohe depression was estimated directly by a great amount of continuous data including resistivity and acoustic logging, etc. Comparison between the results from computer processing and lab analysis of logging data shows that the organic carbon contents derived from the computer processing of logging data have the same reliability and accuracy as the lab analysis results. The present data show that this method is suitable to evaluate the source rocks of western sag in the Liaohe depression and has great potential in evaluating natural resources of sedimentary basins in the future. On the basis of logging data of source rocks, experimental data and existing geochemical analyses of the Liaohe Oilfield, the corresponding total organic carbon (TOC) isograms of source rocks were plotted. The source rocks of Es_4 and Es_3 of the Shahejie Formation are thought to be beneficial to hydrocarbon accumulation due to the high TOC.

Key words TOC (total organic compound); source rock; logging data; western sag

1 Introduction

Total organic carbon (TOC) is an important parameter for hydrocarbon generation of a petroliferous basin. The measured TOC in lab can determine the hydrocarbon-generating potential of the basin, as well as the thickness and volume of the source rocks, providing evidence for resources evaluation of the petroliferous basin. Due to the limit of sample amount, the continuous TOC of the entire source rocks cannot be obtained, which will make the source rocks evaluation rely barely on the geometric average of interval TOC. Also, the work is affected by the long period of analysis, high experimental costs and limited rock samples from only a few wells in one basin. Fortunately, logging information has the characteristics of high vertical resolution. According to $\Delta \log R$ technique, the quantitative relation model between logging information and organic carbon of the source rocks has been established (Xu Xiaohong et al., 1998; Zhang Zhiwei and Zhang Longhai, 2000; Yun Huayun et al., 2000; Wang Guiwen et al., 2002), which shows undoubtedly the correct deviations of laboratory samples analyses. This work, hopefully, will offer some help to the future study on basin resources evaluation.

In recent decades, foreign scholars' attention has been attracted to logging data obtained in the study of source rocks (Passey et al., 1990). For example, Schmoker estimated TOC in terms of density logging data and pointed out the correlation between high natural gamma and source rocks (Schmoker, 1981; Schmoker and Hester, 1983; Hester et al., 1990). Herron et al. (1988) proposed the use of C/O neutron logging data to calculate TOC. Meyer and Nederlof (1984) identified source rocks by the combination of resistivity logging, density logging and acoustic logging. Mann and Müller (1988) evaluated source rocks by the combination of natural gamma ray spectrometry logging, volume density logging, acoustic logging and resistivity logging, and then they found out some empirical relations between the logging response parameters mentioned above, TOC or maturity of source rocks (Mc Tavish, 1998). At present, both logging evaluation method on organic carbon proposed by IFP in the late 1980s (Carpentier et al., 1991) and $\Delta\log R$ method put forward by Exxon Company are more practical and mature methods (Herron et al., 1988). Based on the logging curve response characteristics of TOC in source rocks, the above two methods established the interpretation model of using conventional acoustic logging and resistivity logging to calculate the organic carbon content. At the same time, we can adjust the interpretation model appropriately by the geochemistry parameters which can reflect the maturity of oil source rocks with different maturities. This paper applies the logging evaluation method on organic carbon to analyzing the Liaohe western sag.

The western sag of the Liaohe Oilfield, located in the southwest of the Liaohe depression in the northeast of the Bohai Bay Basin, is the largest of the three sags in the depression (Fig. 1), being 135 km long, 15−30 km wide and covering an area of 2560 km^2. Up to now, the western sag has been the foremost oil production base in the Liaohe Oilfield, and the hydrocarbon generation quantities of its main source rocks (Es_3 and Es_4) are 209.51×10^8 and 60.62×10^8 t, respectively. The hydrocarbon expulsion quantity of these two members is also large. Comprehensive analysis demonstrates that the western sag possesses large geological resources and remaining geological resources as well. Therefore, it can be clearly seen that there is relatively large oil and gas exploration potential in the study region and research on the organic matter abundance of the source rocks is bound to play an important role in the further exploration.

2 Research methods

2.1 Logging response characteristics of source rocks

Source rocks rich in organic carbon are of low density and strong absorption (Wang Fangxiong et al., 2002; Zhang Lipeng et al., 2001; Fertl and Chillnger, 1988; Mallick and Raju, 1995). It is assumed that the source rocks rich in organic carbon are composed of rock skeleton, solid organic matter and fluid in pore, while the non-source rocks only consist of rock skeleton and fluid in pore. The pore spaces of immature source rock are only filled by formation water and those of mature source rocks are formation water and liquid hydrocarbons because that part of the organic matter in mature source rocks has been converted to liquid hydrocarbons and these hydrocarbons entered into the pores. The responses of logging curves on organic carbon content and the differences among the physical properties of the fluids in pores are the foundations for identifying and evaluating source rocks (Tan Tingdong, 1988; Zhu Zhenyu et al., 2003).

Under normal conditions, the organic carbon content of rocks can be calculated by the log outlier. The higher the organic carbon content is, the more abnormal the well log curve will be. The logging curve responses on source rocks are mainly presented as follows: (1) abundant radioactive elements of the source rocks lead to the high anomalies on natural gamma curve and spectral log; (2) the density of source rocks is lower than that of other rocks, so there appear anomalies of low density and high interval transit time; (3) the mature source rocks show high anomaly on the resistivity curve, because there are non-conductive liquid hydrocarbons existing in its pore fluid. From these responses, whether the source rocks are mature can be identified (Zhu Guangyou et al., 2003).

2.2 Model for estimating organic carbon content by logging evaluation methods

There are about 1600 wells drilled in recent 40 years in western sag of the Liaohe Oilfield. Because different logging instruments were used in each period, there are multiple logging suites in different exploratory wells. The results obtained by different logging instruments must involve systematic errors for the logging projects are not in the same time period. The early exploratory wells in the research area (before 1990) mainly received logging of the standard procedure, so there are few exploratory wells with density logging and gamma ray logging. After adequate survey of the logging data of western sag, the acoustic and resistivity curves are used to calculate the organic carbon content of source rocks.

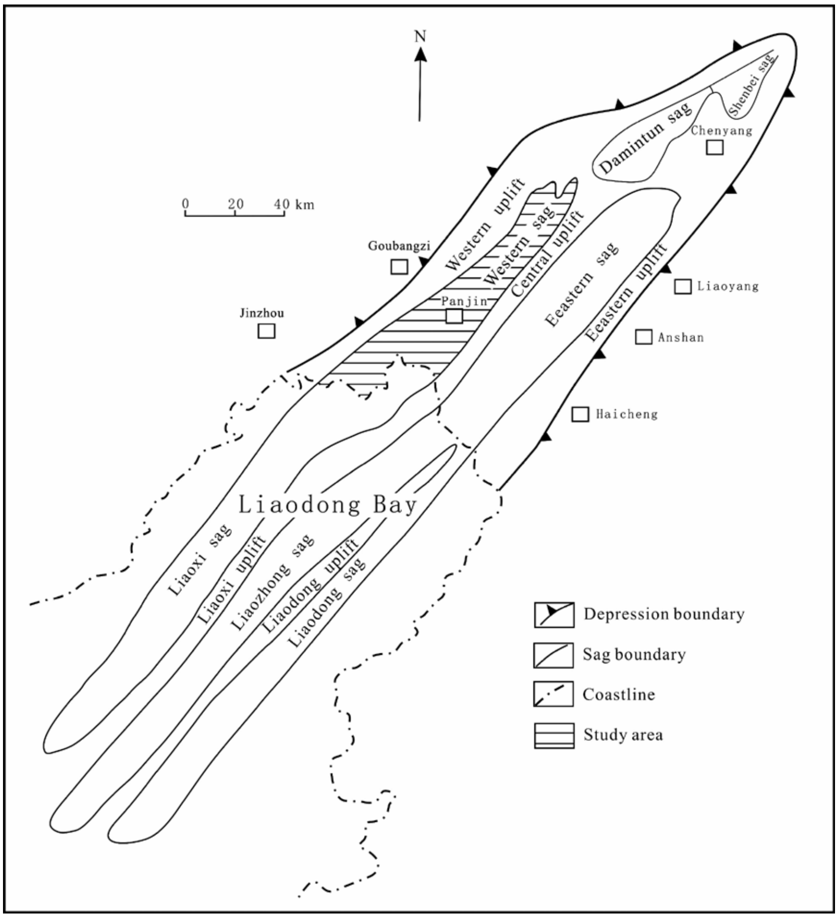

Fig. 1. Sketch map showing the location of the western sag of the Liaohe depression.

The $\Delta\log R$ method applied to carbonate and clastic rocks was developed by Exxon Company and Esso Company in 1979, which was utilized to evaluate the quality of source rocks in our research areas. This method uses logging data to identify and calculate T of the rocks containing organic matter. The $\Delta\log R$ method superimposes a porosity curve with a special scale (interval transit time curve) on a resistivity curve (the curve measured by prospecting instrument). If there is no suitable interval transit time curve, the density curve or neutron curve can be used. In a word, it is more precise to use the combination of acoustic-resistivity than density-resistivity or neutron-resistivity due to their adverse effects on density and neutron logging made by wellbore. The relative scale means that the circle of each two logging resistivity is 100 μs/ft (328 μs/m), namely the ratio compared to a resistance unit is 50 μs/ft (164 μs/m). For example, 200 Δt (200-150-100-50-0 μs/ft; 656-492-328-164-0 μs/m) corresponds to 4 logging logarithmic coordinates units of RT (0.01-0.1-1.0-10-100 Ω·m). The superimpose interval transits time curve with resistivity curve, and then takes the fine-grained non-source rocks as the baseline. The identical trajectory tracking of transit time curve or resistivity curve or overlapping at a significant depth is the existent condition for the baseline. The difference of the two curves is defined as $\Delta\log R$, which is determined by each incremental depth. The variables of overlapping curves are as follows:

$$RT_1=\log(R/R_{\text{baseline}})$$
$$DT_2=0.02(\Delta t-\Delta t_{\text{baseline}})$$
$$\Delta\log R=\log(R/R_{\text{baseline}})+0.02(\Delta t-\Delta t_{\text{baseline}}) \quad (1)$$

where R represents the rock resistivity (Ω·m), Δt represents the actual measured interval transit time (μs/m), R_{baseline} is the resistivity corresponding to R baseline (Ω·m), $\Delta t_{\text{baseline}}$ is the interval transit time corresponding to Δt baseline (μs/m), and the coefficient of 0.02 based on interval transit time of each 50 μs/ft (164 μs/m) is equal to the logging logarithmic coordinates units of resistivity R.

After superimposing the two curves together and determining the baseline, the rocks rich in organic matter can be identified by the difference of the two curves. RT_1 and DT_2 of non-oil source bed are equal or close to zero; and as to oil source bed, RT_1 is greater than or equal to zero, while DT_2 is less than zero (Fig. 2, Table 1). In addition, RT_1 of the hydrocarbon-generating source rocks is much greater than that of the non-hydrocarbon-generating ones, but the case is opposite for DT_2.

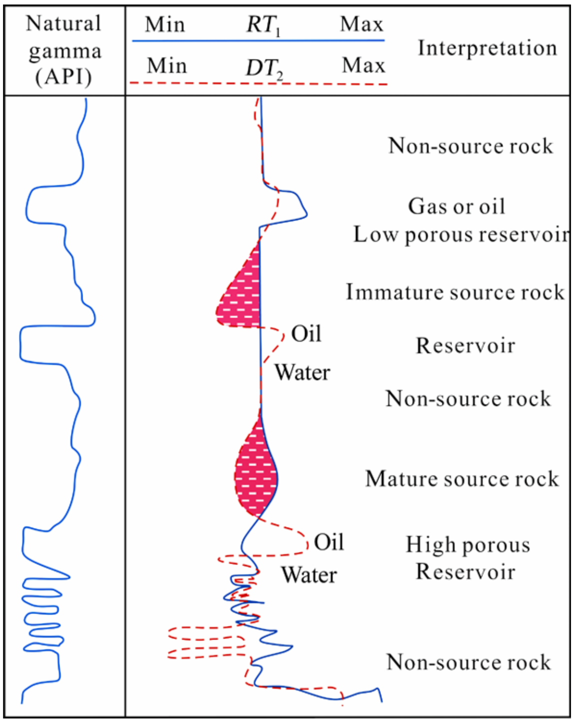

Fig. 2. Diagram to explain the various features on the composite map of Δlog*R*.

Table 1 Source rock identification according to RT_1 and DT_2

	Non-source rock	Source rock
Resistivity difference (RT_1)	Equal or close to zero	Greater than or equal to zero
Acoustic time difference (DT_2)		Less than zero

There is a linear relationship between Δlog*R* and TOC, and the Δlog*R* is a function of maturity. If the maturity can be determined or estimated, Δlog*R* can be converted to TOC. The empirical formula to calculate TOC can be obtained by statistical analysis, i.e.,

$$TOC=\Delta\log R\times 10^{\alpha}$$

Passey et al. (1990) proposed the empirical formula:

$$a=2.297-0.1688R_0$$

So

$$TOC=\Delta\log R\times 10^{(2.297-0.1688R_0)} \quad (2)$$

In the formula, TOC represents total organic carbon content (%); R_0 (%) represents vitrinite reflectance. Due to the lack of maturity parameters (R_0) among the collected data, we must amend the formula (2) as the following in order to establish a suitable calculation model for the western sag:

$$TOC=k\times\Delta\log R \quad (3)$$

The following formula can be gained after substituting formula (1) into equation (3),

$$TOC=k\times[\log(R/R_{baseline})+0.02(\Delta t-\Delta t_{baseline})] \quad (4)$$

As a result, equation (4) can be converted to the following formula, because *TOC* is mainly affected by $(R/R_{baseline})$ and $(\Delta t-\Delta t_{baseline})$

$$TOC= a\times\log(R/R_{baseline})+b\times(\Delta t-\Delta t_{baseline}) \quad (5)$$

The coefficients *a* and *b* in equation (5) are calculated by applying the least squares fitting. According to equation (5), the abundance of source rocks can be evaluated.

3 Results and discussion

3.1 Rock types of source rocks

From south to north, there are six sub-sags in western sag of the Liaohe Oilfield, namely Yuanyanggou, Qingshui, Panshan, Chenjia, Tai'an and Niuxintuo, which are of great hydrocarbon generation potential (Fig. 3). The main lithology of the six sub-sags is lacustrine dark mudstone, with several source rocks including the 4th, 3rd, 1st and 2nd members of the Shahejie Formation. These source rocks are widely distributed horizontally and deposited with a large thickness. The Es_4 and Es_3 source rocks are considered as the chief source rocks. The strata division is listed in Table 2.

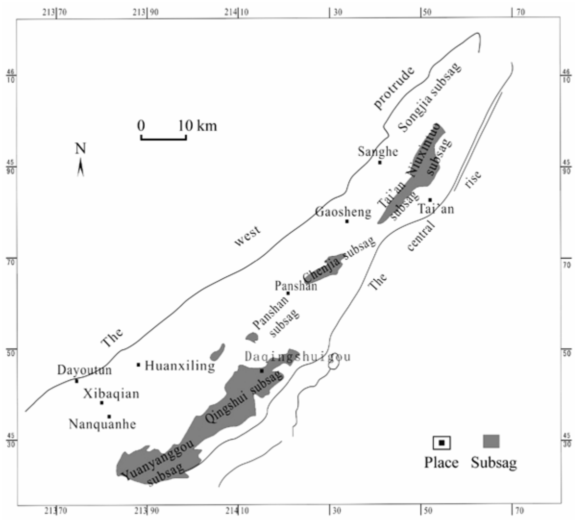

Fig. 3. Distribution of hydrocarbon generation sub-sags in western sag of the Liaohe Oilfield.

From the study on the lithologic characteristics, the abundance of organic matter and the sedimentary facies zone of Es_4 and Es_3 source rocks, the source rocks are divided into 5 types (Table 3). The source rocks of Types A and B are of high abundance with a good type of organic matter, which have maximal hydrocarbon generation potential. For the Type C source rocks, the abundance and type of organic matter are next to those of Types A and B, so their hydrocarbon generation potential is next to that of Types A and B. The source rocks of Type D have an intermediate abundance and type of organic matter, so they also possess the potential to generate hydrocarbons. However, the source rocks of Type E are of low abundance and inferior type of organic matter, so the hydrocarbon generation potential of the Type E source rocks is low.

3.2 Application examples and effect analysis of organic carbon estimation by logging evaluation method

SG1 well is a new exploratory well in the Qingshui sub-sag drilled in the Liaohe Oilfield in late 2005. The logging data of this well are complete and accurate, and the cutting logging data are rich, which lay down a solid foundation for the evaluation on source rocks by logging data. The lithology of target beds in exploration wells is mainly sandstone with only a small amount of mudstone. In addition, the cores are deficient in western sag of the Liaohe Oilfield. We have to utilize cuttings to replace mudstone cores for source rock study. This will impact the precision of source rocks evaluation by logging data. In this study, the Es_3 mudstones in Well SG1 were densely sampled, and organic carbon analysis was carried out on theses samples.

The measured values of resistivity logging and acoustic logging are prone to errors because of some objective conditions. For example, a certain error is involved in the value of resistivity logging due to the influence of well diameter and mud resistivity. In order to get more accurate results, necessary correction for relevant logging data should be carried out. On the basis of logging data correction, the least square method is used to fit TOC of 281 samples from SG1 with its corresponding depth interval transit time and logarithm of resistivity according to formula (5). Then, the coefficients a and b are calculated, and the relative coefficient reaches 0.7012 and the reliability is high. Finally, the evaluation formula for source rocks by logging data in western sag of the Liaohe exploration area is obtained.

$$\mathrm{TOC}=0.9828\times\log(R/R_{\mathrm{baseline}})+0.0514\times(\Delta t-\Delta t_{\mathrm{baseline}}) \quad (6)$$

In formula (6), the unit of interval transit time is μs/ft. If the unit is μs/m, which must be alternated, 1m is equal to 3.2808 ft.

Because there are some system errors in each logging series, we must calibrate each exploratory well to gain the corresponding lithologic baseline. By these means, the difference can be reduced significantly and the TOC content of the formation can be reflected factually.

The results calculated by the above method may contain the TOC values from petroliferous reservoir beds, which will be reduced to get the TOC of source rocks. In this study, the reservoirs from mudstone and shale are divided by the differences of density and natural gamma logging, etc., and relatively true TOC after the corresponding treatment on the TOC of the reservoirs is gained. By comparing the TOC calculated by logging data with those measured in lab, the researchers found out that they are in fair agreement (Fig. 4), so it is believed that the evaluation method for source rocks by logging data is quite reasonable.

Table 2 Sequence division of the Shahejie Formation in western sag of the Liaohe Oilfield (after Zhu Xiaomin, 2008)

Strata				Oil layer	Strata age	Second-order sequence	Third-order sequence	Contact relationship between the overlying and underlying strata of sequence bottom boundary	Tectonic evolution
System	Formation	Member	Sub-member						
Paleogene	Shahejie	3rd	Upper	Rehetai	43 Ma	II	SQ_5	Local unconformity (local apparent truncation below the surface, local onlap above the surface)	Deep-depression stage
			Middle	Dalinghe			SQ_4	Local unconformity (local apparent truncation below the surface, local onlap above the surface)	
			Lower	Lianhua			SQ_3	Reginal smally angular-angular unconformity (local truncation below the surface, widespread onlap above the surface)	
		4th	Upper	Dujiatai	45.4 Ma	I	SQ_2	Large-range angular unconformity (truncation below the surface, onlap above the surface)	Rifting stage
				Gaosheng			SQ_1	Regional angular unconformity (intensely truncated strata below the surface)	
				Niuxintuo					

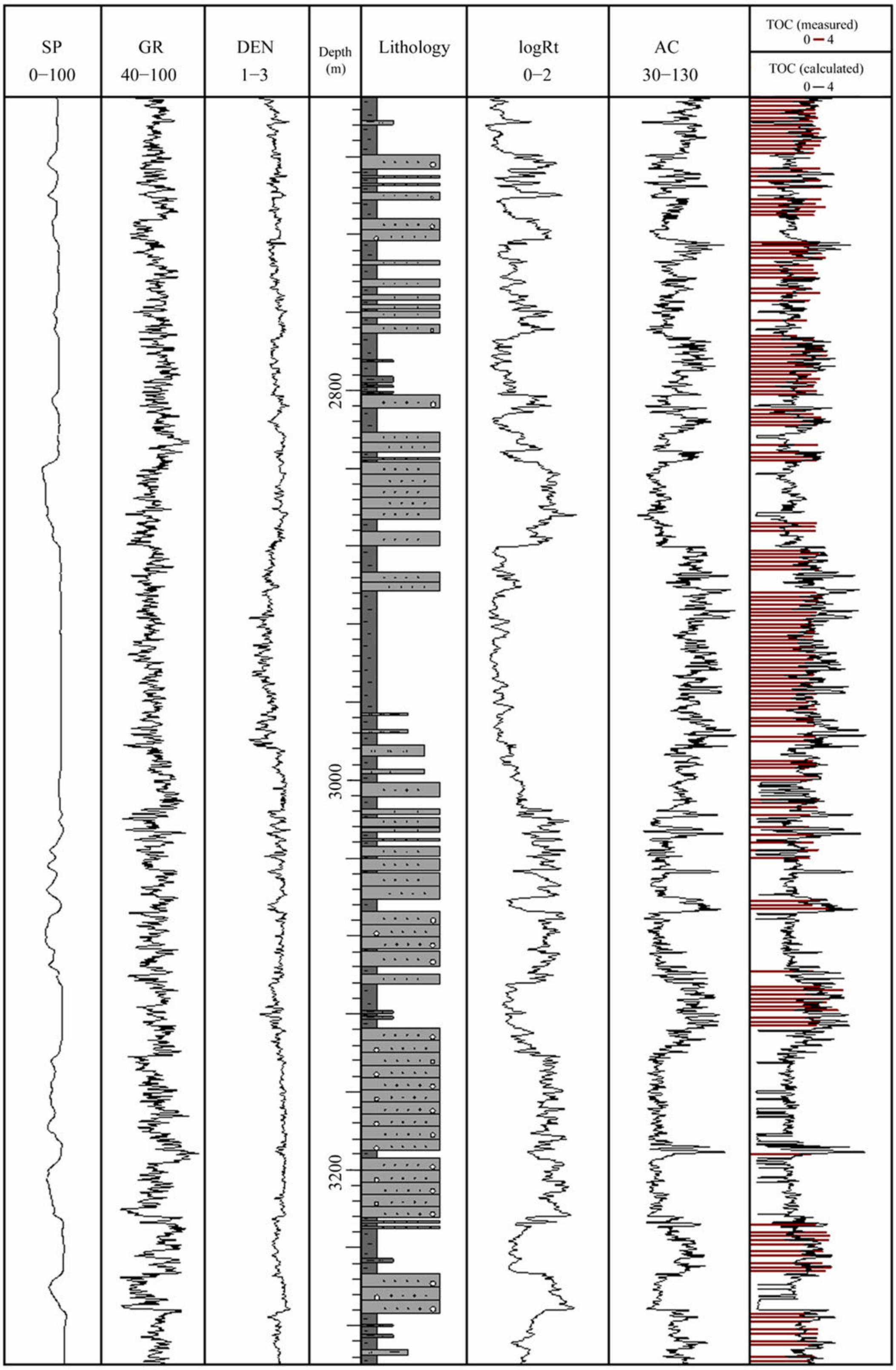

Fig. 4. Comparison between measured TOC and calculated TOC by logging data of the 3rd member of the Shahejie Formation, Well SG1, western sag, Liaohe Oilfield.

Table 3 Division of source rocks types in western sag of the Liaohe Oilfield

Type	Lithology of source rock	Organic carbon content (%)	Organic matter type	Sedimentary environment	Development layer
A	Oil shale	>3.0	Ⅰ	Shallow lake—semi-deep lake	Es_3, Es_4
B	Grey calcareous mudstone	2.0–6.0	Ⅰ—$Ⅱ_1$	Shallow lake— semi-deep lake	Es_3, Es_4
C	Black grey—charcoal grey mudstone	1.5–4.0	$Ⅱ_1$—$Ⅱ_2$	Deep lake—semi-deep lake	Es_3, Es_4
D	Grey—light grey mudstone	1.0–2.0	$Ⅱ_2$—Ⅲ	Semi-deep lake—shallow lake	Es_3, Es_4
E	Grey green—dark brown mudstone	0.2–1.0	Ⅲ	Shallow lake-lakeshore	Es_3, Es_4

3.3 Testing on the model of source rocks evaluation by logging data

In order to test the validity of the evaluation method on source rocks by logging data, another exploratory well (Q233) with dense sampling was used to verify the formula which was obtained by the fitting of Well SG1 and logging data. TOC was calculated by the above formula (6) for Es_4 logging data of Q233 and compared with the measured TOC. The results showed that they match very well (Fig. 5). It is indicated that this evaluation method on source rocks by logging data is a better approach to evaluate the organic matter abundance of source rocks, which can be used to evaluate the TOC of source rocks in western sag of the Liaohe Oilfield.

3.4 Organic carbon characteristics of the 4th and 3rd members of the Shahejie Formation in western sag of the Liaohe Oilfield

The quality of source rocks is mainly controlled by the organic matter abundance, which is characterized by TOC. Therefore, it is significant to evaluate source rocks through the horizontal distribution of organic matter abundance.

The measured TOC contour maps of Type A+B+C source rocks of Es_4 and Es_3 (Table. 3) in western sag of the Liaohe Oilfield were drawn based on the measured TOC data (383 samples of Es_4 source rocks and 757 samples of Es_3 source rocks). In Fig. 6, the TOC of Es_4 source rock is generally higher than 2.0%, and the quality of the source rocks is thought to be good. The highest TOC of Types A+B+C of Es_4 source rocks exists in the central south of West Slope, which is over 5.0%. And the next one is the Niuxintuo sub-sag in the north, whose TOC is up to 4.5%. The TOC of the Tai'an sub-sag and Shuangtaizi sub-sag in the south of West Slope is also up to 3%. On the whole, the quality of Es_4 source rocks in the central south is better than that in the north. From the measured TOC contour maps of Type A+B+C Es_3 source rocks (Fig. 7), the TOC of Es_3 source rocks is generally higher than 1.0%. Three high TOC-value areas of Es_3 A+B+C source rocks are distributed in the south, the central West Slope and the Chenjia sub-sag, respectively, with the highest one over 3.0%. In general, the quality of Es_3 source rocks in the south is better than that in the north.

Considering that the collected TOC values by experimental analysis in the Liaohe Oilfield may not reflect the overall situation of source rocks, in this study, continuous TOC of source rocks was obtained by logging data evaluation from other 237 wells. Finally, the TOC contour maps of Es_4 and Es_3 source rocks in western sag of the Liaohe Oilfield were plotted on the basis of logging data of these 237 wells and experimental data of 149 wells from the analysis of this project. In the TOC contour maps, the average TOC values are shown, so it is able to represent the overall characteristics of organic matter abundance.

The highest TOC of Types A+B+C of Es_4 source rocks exists in the central south of West Slope in western sag, which is over 5.0% (Fig. 8). The TOC of the Niuxintuo sub-sag is also high, up to 4.5% in the north of western sag. There are two TOC high-value areas in the Tai'an and Shuangtaizi sub-sags in the south of West Slope, both of which reach 3.5%. From the entire horizontal distribution of TOC, it can be seen that the TOC of the Es_4 A+B+C source rocks, which is higher than 2.0%, is distributed widely and covers nearly all the West Slope of the whole depression. But on the whole, the TOC in the central south part (with wider distribution) is higher than that in the north. This conclusion is generally consistent to the measured TOC data of the A+B+C source rocks, showing that the interpretation results are comparatively accurate. But there are also differences in the Chenjia sub-sag, where several low TOC values appear while logging interpretation results are highly reliable. That is because of the lack of measured data after analysis.

The highest TOC of Es_3 A+B+C source rocks occurs in the Qingshui sub-sag in the south of western sag, which is up to 4.0%. There are also three high TOC-value areas in the south and central of West Slope and the Tai'an sub-sag in the north of western sag with the highest TOC over 3.0% (Fig. 9). From the horizontal distribution of TOC, it can be seen that the TOC which is higher than 1.5% is almost distributed throughout the whole sag. The maximum TOC in the south is higher than that in the north, and there is a significantly large maximum TOC area in the south, thus the contribution of source rocks in the south is greater than that in the north. Through the contrast of the measured TOC contour map and the calculated TOC contour map, the overall trend is consistent. Because there are only a few measured data and very slight difference that the high TOC-value areas in the Qingshui sub-sag can not be reflected in the measured TOC contour maps. Therefore, the overall perspective of source rocks cannot be reflected by the TOC of source rocks measured in laboratory, while the use of logging data to predict TOC makes up the above disadvantage and has a comparatively high accuracy, so as to establish the theoretical basis for the next step exploration.

From the horizontal (Figs. 8 and 9) and vertical (Figs. 5 and 6) distributions of TOC, the Types A+B+C of the Es_4 and Es_3 source rocks are considered as the chief source rocks for hydrocarbon accumulation in western sag of the Liaohe Oilfield, because their TOC contents are generally higher than 1.5%. And there are wide distributions of multiple high TOC-value areas.

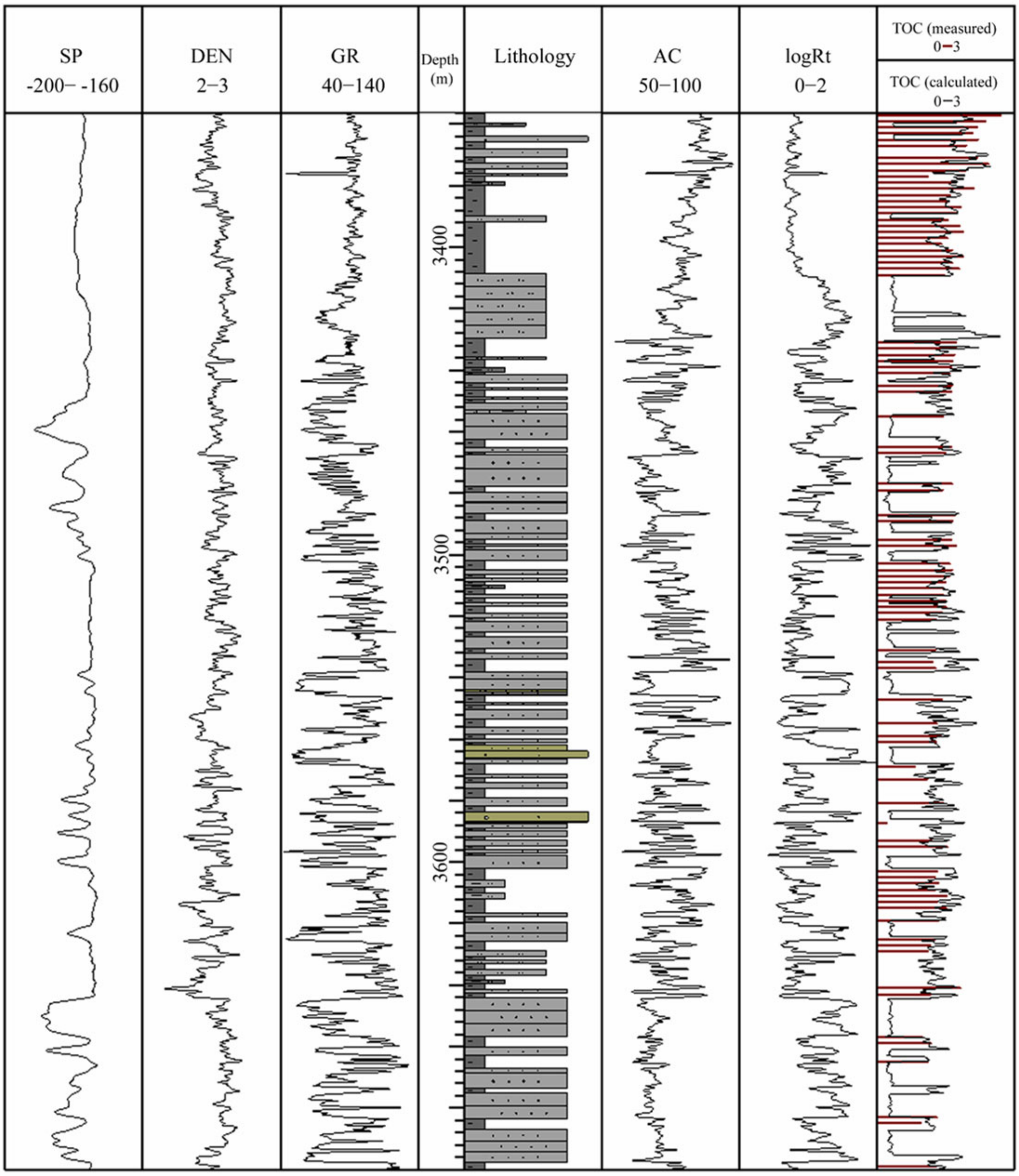

Fig. 5. Comparison between measured TOC and calculated TOC by logging data of the 4th member of the Shahejie Formation, Well Q233, western sag, Liaohe Oilfeild.

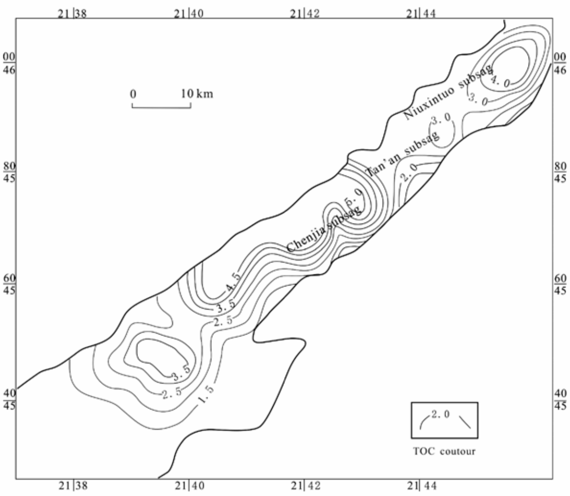

Fig. 6. Measured TOC contour map of Type A+B+C Es_4 source rocks in western sag of the Liaohe Oilfield.

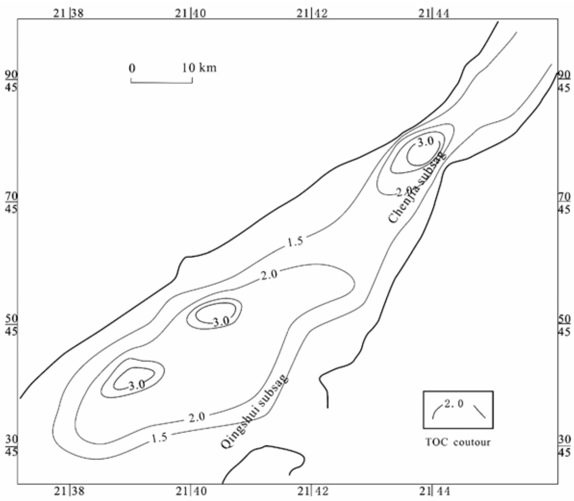

Fig. 7. Measured TOC contour map of Type A+B+C Es_3 source rocks in western sag of the Liaohe Oilfield.

4 Conclusions

(1) The use of logging data to evaluate source rocks is rapid and economic, which can provide more accurate organic carbon content for resources evaluation. Compared with the traditional methods, this method has its obvious superiority in the calculation of organic carbon content of Es_4 and Es_3 source rocks by logging data. This estimation method of organic carbon is able to get vertically continuous TOC and lay the foundation for the heterogeneity study and identification of source rocks.

(2) From the study on the geological and geochemical characteristics of source rocks of the 4th and 3rd *M*embers of the Shahejie Formation in western sag of the Liaohe Oilfield, the source rocks are divided into 5 types: Type A is brown oil shale, Type B is grey calcareous mudstone, Type C is black grey—charcoal grey mudstone, Type D is grey—light grey mudstone and Type E is grey green—dark brown mudstone. The source rocks of Types A and B have high abundance and good types of organic matter, with a maximal hydrocarbon generation potential. For Type C source rocks, the abundance and types of organic matter are next to those of Types A and B, so the Type C source rocks also have a great hydrocarbon generation potential. The source rocks of Type D have general abundance and types of organic matter, so it is also of medium hydrocarbon generation potential. However, the source rocks of Type E are low in abundance of organic matter, and the type of organic matter is inferior, so the hydrocarbon generation potential of Type E source rocks is low.

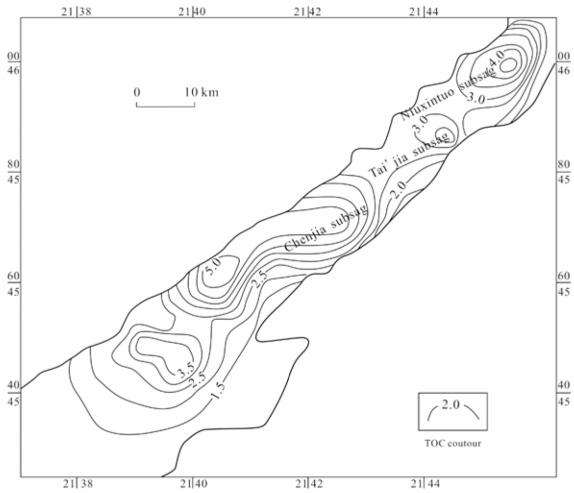

Fig. 8. Calculated TOC contour map of Type A+B+C Es_4 source rocks in western sag of the Liaohe Oilfield.

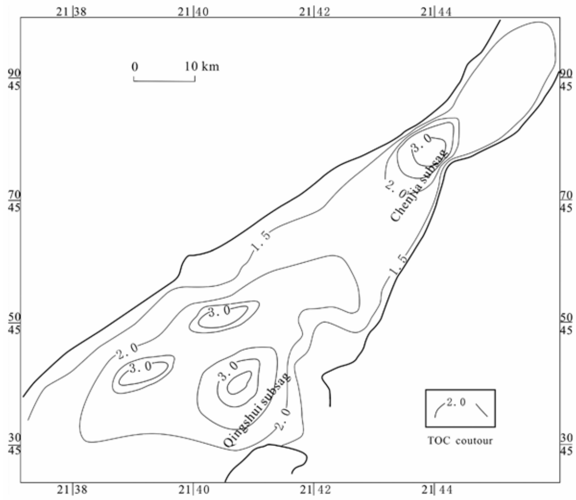

Fig. 9. Calculated TOC contour map of Type A+B+C Es_3 source rocks in western sag of the Liaohe Oilfield.

(3) From the horizontal distribution of TOC, we can see that the TOC content of Type A+B+C Es_4 and

Es_3 source rocks are generally higher than 1.5%, with a wide distribution and multiple high TOC value areas. Therefore, the Type A+B+C Es_4 and Es_3 source rocks are the chief source rocks for hydrocarbon accumulation in the western sag of the Liaohe Oilfield.

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