ISSN Print: 2707-2398 Online: 2707-2401
Environment and Resource − 2025, 7(2)
https://doi.org/10.35534/er.0702029

Well Logging Prediction of Total Organic Carbon Content in Shale Gas Reservoirs of the Long 11 Submember in Southern Sichuan

—Taking the Z205 Well Area as an Example

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Abstract: Total organic carbon (TOC) is not only an important indicator for evaluating the hydrocarbon generation capacity of shale gas reservoirs, but also a crucial parameter for the evaluation of shale gas reservoirs and the selection of platinum target areas. The existing TOC content prediction methods either have low prediction accuracy or require a large number of samples. This article takes the Long 1_1 submember in the Z205 well area of southern Sichuan as the research object. Based on the measured TOC data from the core samples, it was clearly determined that the logging responses of the four microlayers in the Long 1_1 submember in the well area were all different. By combining the "layered fine prediction" and "stepwise regression" methods, a TOC prediction model for each of the four microlayers in the Long 1_1 submember of the well area was established. In the past, the study area always regarded the Long 1_1 submember as a single entity. The TOC was predicted using the "input method" in the "multiple regression method", without considering the actual logging response characteristics of each layer. This led to numerous "false fitting" occurrences. This study selects the optimal logging parameters for different layers. By using the "stepwise regression method", the occurrence of "false fitting" is avoided, thereby improving the interpretation accuracy. The study reveals that the TOC development occurs in the Long 1_1 submember of the Z205 well area, and the variation patterns of TOC in different layers are quite distinct.

Key words: Long 1_1 submember; Shale gas; Well logging prediction; TOC; Stepwise regression method

1 Introduction

Shale gas is natural gas that is freely or adsorbed in the pores of shale and can only be obtained as industrial gas

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Article Citation: Gong, X., Li, J., Luo, A., He, J., Liu, X., Cao, W., Su, H. Z., Ren, X. H., Yang, Z. N. (2025). Well Logging Prediction of Total Organic Carbon Content in Shale Gas Reservoirs of the Long 11 Submember in Southern Sichuan — Taking the Z205 Well Area as an Example. *Environment and Resource, 7*(2), 339-348.

after artificial modification(ZHANG Ye et al., 2015). It is an important unconventional oil and gas resource worldwide. Shale gas has the characteristic of self-generation and self-storage. TOC (Total Organic Carbon), as a representative parameter reflecting the amount of organic matter in rocks, is not only an effective indicator for judging the hydrocarbon generation capacity of shale, but also a core parameter for revealing the reservoir capacity of shale for hydrocarbon gases(Wang Pengwei et al., 2019). The TOC of shale gas reservoirs is mainly obtained through experimental analysis of core samples, etc. However, core analysis has the following drawbacks: on the one hand, it involves complex procedures, takes a long time, has poor timeliness, and cannot keep up with the progress of exploration and development; on the other hand, it is costly and has a negative impact on the concept of cost reduction and efficiency improvement of oilfield companies.

The TOC prediction of shale gas reservoirs is generally based on logging data(MEYER B L et al., 1984). Currently, the commonly used TOC prediction methods in China are: ΔlogR method(Meyer B L et al., 1984; Dembicki H, 2017; Passey Q R et al., 1990; Zhu G Y et al., 2003; Wang L et al., 2021), multiple linear regression method(Miao H et al., 2022. Tang B Q et al., 2021), neural network(Yang Z W et al., 2022; Wang H J et al., 2020), etc. The ΔlogR method is the most convenient and widely used approach, which is mainly calculated by superimposing the acoustic wave time difference and the resistivity curve. The multivariate linear regression method involves using well logging parameters and measured TOC for multivariate fitting to establish a multivariate regression model. Neural networks are a new prediction method that emerged after the rise of artificial intelligence. They use deep learning techniques to predict TOC.

The Z205 well area in southern Sichuan is located within the Ziliujing Structure group of the Zigong block. The sedimentary environment is characterized by a typical shallow marine shelf facies and deep water shelf subfacies. The black organic-rich shale formed in the Long1_1 submember is a high-quality reservoir for shale gas, and the shale gas resources are mainly concentrated in the Long 1_1^1 - Long 1_1^3. The Long 1_1 submember in the well area has a relatively large burial depth (burial depth ≥ 3500m), and it belongs to a typical deep shale gas reservoir. The research and analysis of this reservoir are much more difficult than those of shallow ones, and the TOC distribution prediction is not detailed due to the large scale of the previous exploration. In order to further clarify the vertical and planar distribution characteristics of TOC in the Z205 well area, and considering the limited availability of core samples in this area, this paper uses the multiple regression method to establish a TOC logging prediction model for the shale gas reservoir of the Long 1_1 submember in the Z205 well area. By using the “layered fine prediction” method and the “stepwise regression method”, four TOC prediction models corresponding to each of the four microlayers of the Long 1_1 submember were established. The results achieved good performance, and the predicted values were almost consistent with the actual experimental analysis data.

2 Regional Geological Background

The structural position of the Z205 well area is located within the northeastern part of the low-lying fold belt in southwestern Sichuan Province, where the Ziliujing structure group is situated. The overall structure is oriented in a north-eastern direction. From west to east, it mainly consists of structures such as Huangjiachang, Longshizhen, Shengdengshan, and Yundingchang. The area is mainly characterized by the Xindian, Huilongchang, Gaoshikan and Panlongchang synclines. The structure is simple, and the strata are gentle. The tectonic structure within the Z205 well area is oriented in a north-northeast direction and is distributed in a strip-like pattern. The Huangjiachang structure in the north, the Longshizhen structure in the east, and the Shengdengshan structure are relatively steep, while the structures in the southwest are relatively gentle, mainly consisting of synclines and the terminal parts of the structures (Figure 1).

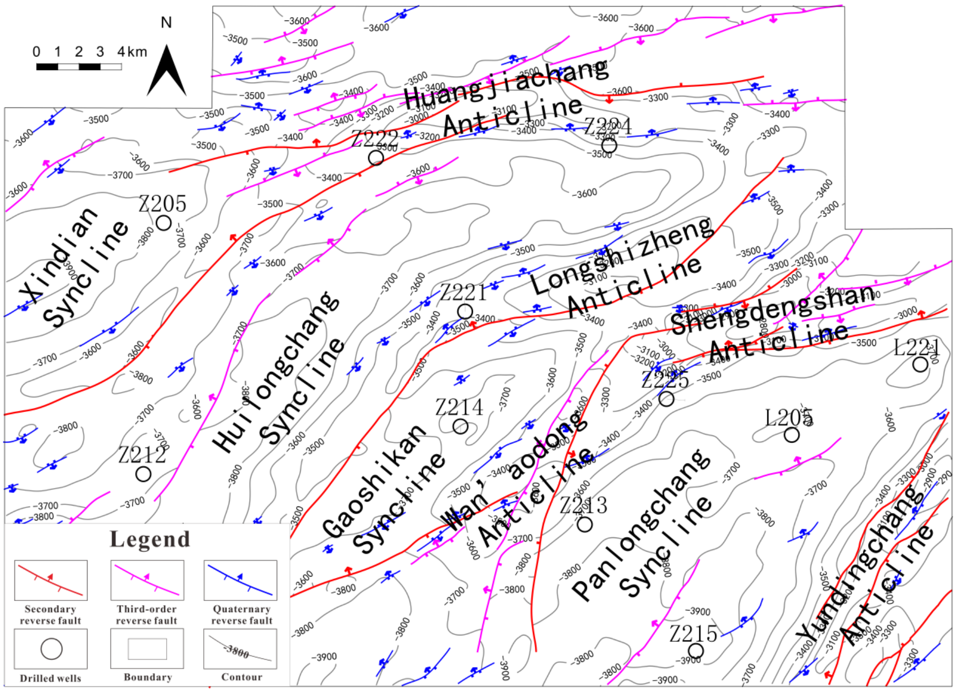


Figure 1 The seismic reflection structure map of the bottom boundary of the Wufeng Formation of the Upper Ordovician in the Z205 well area

The 3D seismic data show that the burial depth of the Longmaxi Formation in the well area varies significantly, ranging from 3200 to 4200m. The burial depth at the syncline is all greater than 3500m. Based on electrical and lithological characteristics, the Long 1_1 submember can be subdivided into Long 1_1^1, Long 1_1^2, Long 1_1^3 and Long 1_1^4 in the Z205 well area.

3 Establishment of TOC Prediction Model

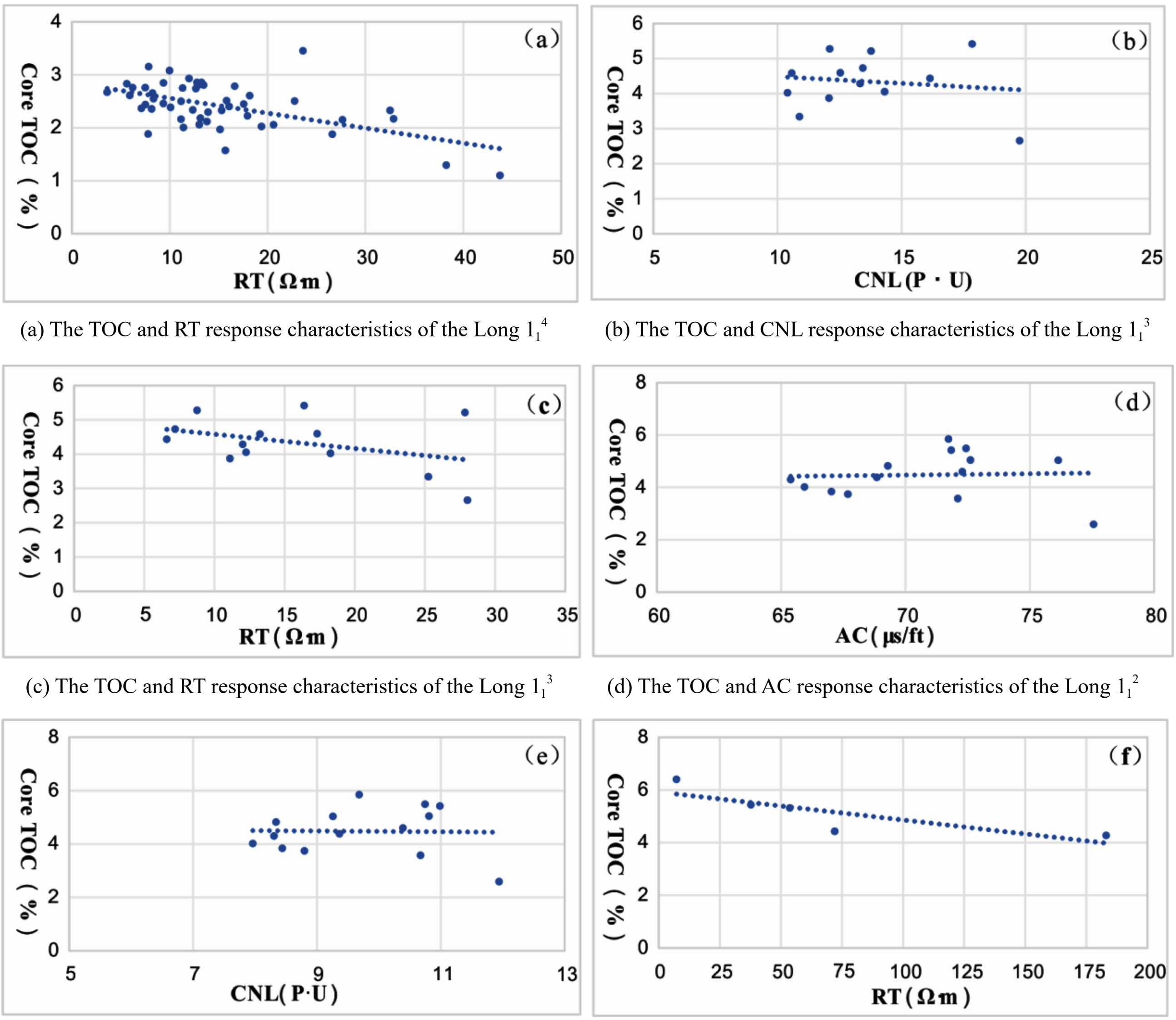
3.1 TOC Well Logging Response Characteristics

Compared with the rock skeleton, source rocks are rich in organic matter. The physical properties of organic matter-bearing rocks are significantly different from those of the rock skeleton, and this difference is the fundamental basis for identifying and evaluating source rocks using well logging curves(SONG Zhan-dong et al., 2009. ZHOU Yan et al., 2022). Organic matter typically exhibits the characteristics of "four highs and one low", namely high natural gamma ray(GR), high sonic transit time(AC), high neutron(CNL), high resistivity(RT), but low density(DEN). Consequently, TOC shows a positive correlation with natural gamma ray, sonic transit time, neutron, and high resistivity, while it shows a negative correlation with density, resulting in the "four positive and one negative" pattern(GUO P et al., 2019).

However, in the actual research process, the response relationship between TOC and logging parameters is not only controlled by the organic matter present in the rock, but is also influenced by geological fluids, rock properties, pressure, and other factors(Liang Haoran et al., 2023). For example, in the mixed sedimentary rock reservoir of the Luchaogou Formation in the Santanghu Basin, the TOC is negatively correlated with resistivity, sonic transit time, neutron, natural gamma ray, and density(Chen Liangyu et al., 2025). In the Lianggaoshan Formation of the northwestern part of the Sichuan Basin, the TOC shows a positive correlation with natural gamma ray, sonic transit time, and neutron, while it shows a negative correlation with natural gamma ray and density(Ren G et al., 2025). At the same time, overpressure formations, hydrocarbon fluids, and changes in rock properties can all cause abnormal variations in the logging curves(Xu Z Y et al., 2019; Qu Y S et al., 2011; Du W F et al., 2016).

Therefore, the traditional TOC well logging response characteristics, namely “four highs and one low”, do not have universal applicability. Factors other than organic matter will, to some extent, interfere with and blur the identification and response function of logging parameters for TOC.

The sedimentary environment of the Long 1_1 submember in the Zigong area is complex. The shale formed under different environments shows significant differences in reservoir properties, such as organic matter content. The organic matter shale exhibits strong heterogeneity both horizontally and vertically(Luo A et al., 2025), resulting in a relatively complex response between TOC and logging parameters.



(a) The TOC and RT response characteristics of the Long 1_1^4

(b) The TOC and CNL response characteristics of the Long 1_1^3

(c) The TOC and RT response characteristics of the Long 1_1^3

(d) The TOC and AC response characteristics of the Long 1_1^2

(e) The TOC and CNL response characteristics of the Long 1_1^2

(f) The TOC and RT response characteristics of the Long 1_1^1

Figure 2 The logging response characteristics of the TOC of the Long 1_1^1-Long 1_1^4 from the Z205 well area in some drilling wells

The TOC logging response characteristics of the Long 1_1 submember in the part of wells in the Z205 well area are shown in Figures 2a-2f. Long 114 and Long 111 TOC showed a certain negative correlation with RT (Figures 2a,f). Long 1_1^2 TOC has no significant correlation with AC and CNL (2d,e). The TOC of Long 1_1^3 has a strong negative correlation with CNL and RT (2b,c).

The above study indicates that there are significant differences in the TOC logging response characteristics of different layers in the well area. This suggests that the sensitivity of the four microlayers of the Long 1_1 submember in the well area to logging parameters is not fixed. Therefore, it is necessary to establish specific TOC logging prediction models for each of the four microlayers of the Long 1_1 submember, based on their distinct logging response characteristics.

3.2 Method Optimization

Among the current TOC prediction methods, the △LogR method is the most convenient and widely used one. This method is simple to operate and mainly utilizes the sonic transit time and resistivity to predict TOC. However, this method only utilizes the sonic transit time and resistivity. In actual geological formations, the sonic transit time and resistivity do not always provide a good response to TOC. Moreover, in the LogR method, no actual measured TOC is required for the calculation, which makes the prediction process unable to be effectively constrained. As a result, the accuracy of the prediction results is difficult to guarantee. In recent years, new prediction methods such as neural networks and support vector machines have emerged. The key feature of these methods is their extremely high prediction accuracy. The establishment of the prediction model requires a large amount of measured TOC data from core samples as learning samples to meet the requirements of high-precision modeling. This undoubtedly increases the exploration and development costs of oilfield companies.

Compared with the previous methods, the multiple regression analysis has a wider range of applicability. Compared with the △LogR method, multiple regression analysis is equally simple to operate and can incorporate various logging parameters such as natural gamma ray, resistivity, sonic transit time, neutron, and density. This enables the prediction model to carry more geological information and is more geologically significant. Moreover, a highly accurate TOC prediction model can be established without the need for a large amount of core measured TOC data. Taking various factors into consideration, it is concluded that multiple regression analysis is more suitable for the establishment of the TOC model in the study area.

In the past, when using multiple regression for TOC model prediction, people often directly employed “input regression”. “Input regression” is a simple and crude regression method. Without considering whether the independent variables have statistical significance, it forcibly integrates all dependent variables into the model. Such results are highly likely to cause problems such as “multicollinearity” or “false fitting” in the model. “Multicollinearity” will lead to inaccurate calculation of regression coefficients, thereby causing distorted or inaccurate model predictions. “False fitting”, on the other hand, will make the model perform well in predicting known value data but poorly in predicting unknown values.

Compared to “input regression”, “stepwise regression” has obvious advantages. “Stepwise regression” gradually incorporates each independent variable from one to all of them, and at each step, it analyzes whether the model has improved to explore the independent variables with significant contributions. “Stepwise regression” has a more reasonable mechanism for selecting independent variables, which not only avoids the impact on the regression equation caused by independent variables without statistical significance, but also effectively prevents the “false fitting” problem in the model and significantly reduces the influence of “multicollinearity” on the model.

3.3 Establishment of the TOC Prediction Model

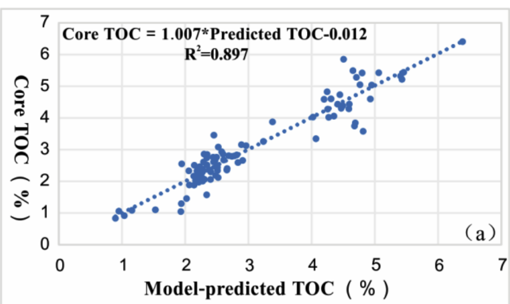
In previous studies, the Long 1_1 submember was generally regarded as a single entity. "Input regression" was used to establish a TOC prediction model for the entire Long 1_1 submember. However, as mentioned earlier, the TOC logging response characteristics of the four microlayers in the Long 1_1 submember are all different, and "input regression" also has many more issues compared to "stepwise regression". Therefore, in this study, the "hierarchical precise prediction" method was adopted, and a TOC prediction model for the study area was established using the "stepwise regression" in multiple regression analysis.

Table 1 shows that the TOC prediction model for the four microlayers of the Long 1_1 submember in the well area, established using "stepwise regression", has an R^2 value ranging from 0.765 to 0.907, and the values obtained from the Durbin-Watson test range from 1.412 to 1.824. The model residuals show no significant autocorrelation, which meets the basic assumptions of the linear regression model. The model has a good fitting effect, and the prediction results can effectively reveal the variation characteristics of TOC in the study area. In contrast, the traditional model that predicts the TOC of the Long 1_1 submember as a whole using "input regression" has an R^2 value of 0.674 and a Durbin-Watson test value of 1.097. It is pointed out that the previous models failed to adequately explain the variation pattern of TOC in the shale gas reservoirs of the study area, and were unable to effectively reveal the distribution characteristics of TOC in the vertical direction.

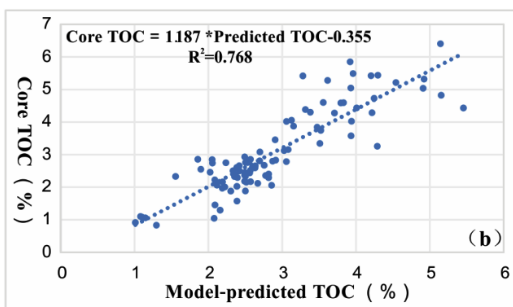
Table 1 Comparison of TOC prediction models for shale gas reservoirs in the long 1_1 submember in the Z205 well area

Operational method	Microlayer	Models	R^2	Durbin-Watson
Stepwise Regression	Long1_1^4	TOC=12.163+0.012*GR-4.442*DEN	0.774	1.412
	Long1_1^3	TOC=-10.384+0.241*AC-0.226*CNL	0.808	1.638
	Long1_1^2	TOC=35.437-12.368*DEN	0.765	1.745
	Long1_1^1	TOC=-9.342+0.229*AC-0.077*CNL-0.010*RT	0.907	1.595
Input Regression	Long 1_1 submember	TOC=26.508+0.017*GR+0.001*AC-0.067*CNL-9.856*DEN-0.001*RT	0.674	1.097

By comparing the mathematical relationships between the two TOC prediction values and the corresponding core TOC measured values (Figure3a,b), the correlation coefficient between the "stepwise regression" stratified model prediction values and the core TOC measured values reached 0.897 (Figure3a), which was higher than the 0.768 (Figure3b) correlation coefficient between the overall model prediction values of the traditional "input regression" and the core TOC measured values. This further proved that the prediction values of the "stepwise regression" stratified model were more consistent with the measured values and had a better fitting effect. Based on the above comprehensive analysis results, it is concluded that the "stepwise regression stratified model" has relatively high TOC prediction accuracy overall, and the TOC prediction results can truly and effectively reflect the vertical variation patterns of TOC.



(a) The predicted values of the "stepwise regression" model



(b) The predicted values of the "input regression" model

Figure 3 The predicted values of the model and the core TOC intersection graph

4 Distribution characteristics of TOC in the reservoir layer

Using the "stepwise regression stratified model" of TOC established for the aforementioned well area, the TOC of the Z205 well area was predicted. As shown in the comprehensive column chart of the Z205 well area (Figure 4), the predicted TOC distribution in the Long 114 of the well area is between 2.3% and 3.2%, with an average of 2.5%. The predicted TOC distribution in the Long 113 of the well area is between 3.2% and 5.0%, with an average of 4.6%. The predicted TOC distribution in the Long 112 of the well area is between 3.7% and 4.9%, with an average of 4.5%. The predicted TOC distribution in the Long 111 of the well area is between 4.0% and 7.3%, with an average of 5.4%.

Vertically, the TOC content in the Long 1_1 submember of the well area increases as one goes deeper, with the Long 1_1^1 having the highest TOC. The TOCs of Long 1_1^2 and Long 1_1^3 are basically the same. The TOC of the Long 1_1^1 - Long 1_1^3 is higher than that of the Long 1_1^4. It is basically consistent with the previous understanding of the well area.

On the plane, the TOC of Long 1_1^4 is lower in the east and higher in the west, showing a gradually increasing trend from east to west (Figure5a); the TOC content of Long 1_1^3 is lower in the north and higher in the south, increasing from north to south (Figure5b); the TOC content of Long 1_1^2 is the highest in the Z224-Z221-Z214 wells and gradually decreases towards the east and west (Figure5c); The Long 1_1^1 show a decreasing trend from north-west to south-east (Figure 5d). The above evidence indicates that the variation patterns of TOC in each microlayers of the Long 1_1 submember in the Z205 well area are significantly different, and there are considerable differences in the patterns among different microlayers.

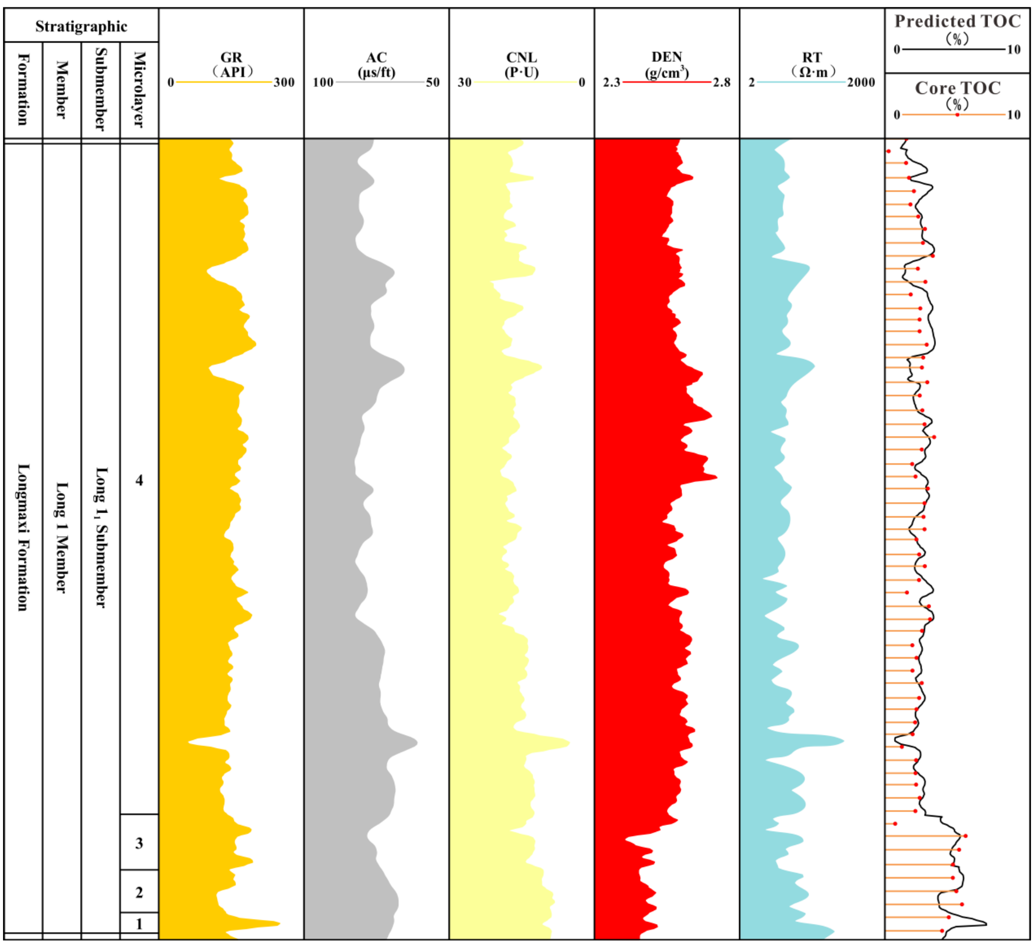
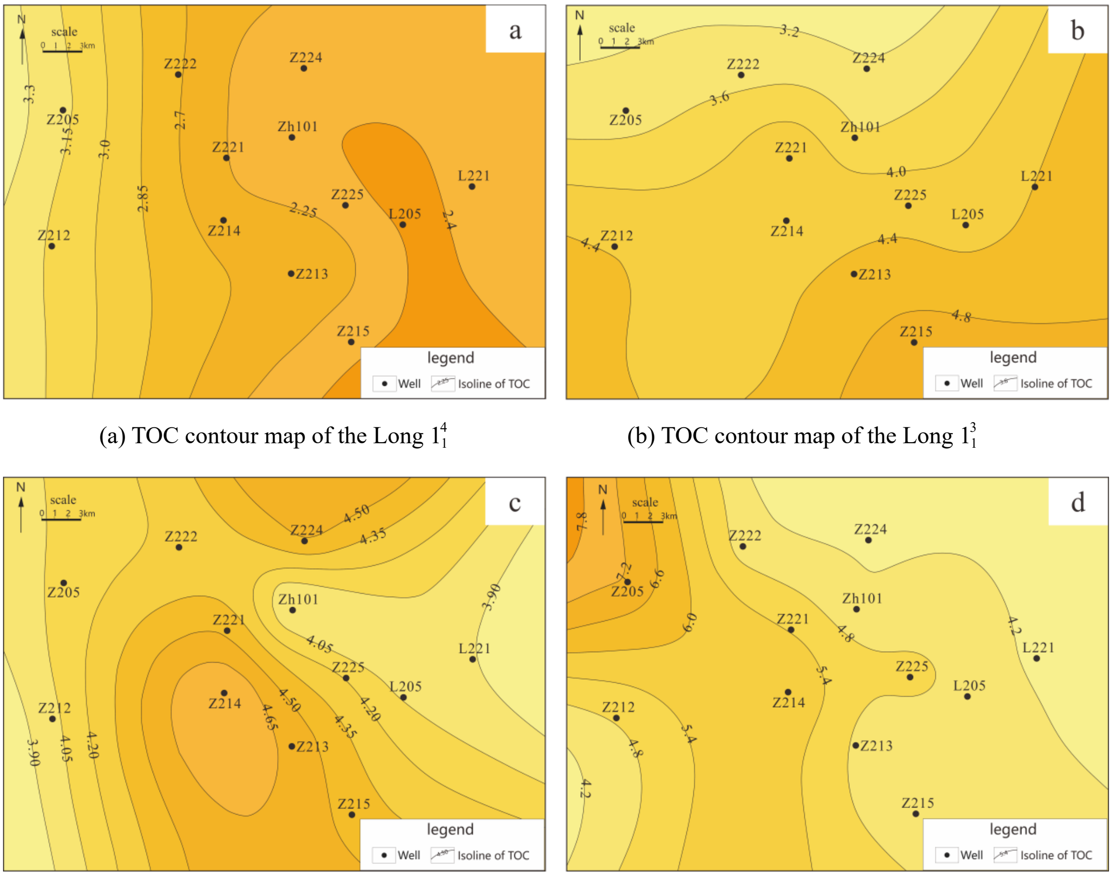


Figure 4 The TOC column chart for the prediction of the Long 11 submember in the Z205 well area



(a) TOC contour map of the Long 1_1^4 (b) TOC contour map of the Long 1_1^3

(c) TOC contour map of the Long 1_1^2 (d) TOC contour map of the Long 1_1^1

Figure 5 TOC contour maps of the Long 111 to Long 114 in the Z205 well area

5 Conclusion

This paper takes the Z205 well area as the research object and conducts a study on the prediction model of TOC in this well area. The following conclusions have been obtained.

Based on the measured TOC data from the core samples of the well area, the specific TOC logging response characteristics of each of the four microlayers of the Long 1_1 submember in the study area were identified.

By combining the "layered precise prediction" method with the "stepwise regression method", four TOC prediction models for each of the four microlayers of the Long 1_1 submember in the study area were established. The R^2 values of the models ranged from 0.765 to 0.907, and the values obtained from the Durbin-Watson test were within the range of 1.412 to 1.824. The correlation coefficient between the predicted values and the measured TOC values from the cores reached 0.897.

The variation patterns of TOC in the four microlayers of the Long 1_1 submember in the Z205 well area show significant differences, and there are considerable variations in the regional patterns among different microlayers. On the plane, the TOC of Long $1_1{}^4$ is lower in the east and higher in the west, while that of Long $1_1{}^3$ is lower in the north and higher in the south. The TOC of Long $1_1{}^2$ is the highest at the Z224-Z221-Z214 wells. The TOC of Long $1_1{}^1$ gradually decreases from the north-west direction to the south-east direction.

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