Oil Shale, 2012, Vol. 29, No. 2, pp. 128–150
doi: 10.3176/oil.2012.2.04
ISSN 0208-189X

QUANTITATIVE EVALUATION OF OIL SHALE BASED ON WELL LOG AND 3-D SEISMIC TECHNIQUE IN THE SONGLIAO BASIN, NORTHEAST CHINA

JIANLIANG JIA[(a,b)], ZHAOJUN LIU[(a)*], QINGTAO MENG[(a)], RONG LIU[(a)], PINGCHANG SUN[(a)], YONGCHENG CHEN[(c)]

[(a)] College of Earth Sciences
Jilin University
Changchun 130061, China
[(b)] Department of Applied Geosciences and Geophysics
Montanuniversität Leoben
A-8700 Leoben, Austria
[(c)] SINOPEC Northeast Petroleum Bureau
Changchun 130056, China

Abstract. *The quantitative evaluation of the Upper Cretaceous oil shale has been conducted by abundant testing, log and seismic data from the Songliao Basin in Northeast China. Based on the log-seismic characteristics of oil shale, the technique of log-seismic multi-attributes reconstruction to evaluate single-well oil shale has been adopted. By using the method of log-constrained seismic inversion, the inversion volume of wave impedance, total organic carbon (TOC), and oil yield have been obtained to carry out evaluation of oil shale. According to the evaluation results, the inversion of wave impedance can only be used for qualitative evaluation of the spatial distribution of oil shale. Meanwhile, the inversion of TOC and oil yield can be used not only to evaluate the spatial distribution of oil shale, but also for quantitative evaluation of the quality of oil shale. Hence, the evaluation technique of oil shale was developed combining single-well log evaluation and spatial seismic evaluation, which integrates the quantitative evaluation of oil shale with geophysical technique.*

Keywords: *Songliao Basin, the Upper Cretaceous, log technique; seismic technique, quantitative evaluation.*

1. Introduction

China has abundant oil shale resources. According to the data of "The National Oil Shale Resource Evaluation of China", oil shale resources in

* Corresponding authors: e-mail *liuzj@jlu.edu.cn; jljia82@yahoo.cn*

China were 719.9 billion tonnes in 2006, only second to that of the US. The Songliao Basin has resources of 323.7 billion tonnes, accounting for 45.0 wt% of the region's total [1]. The huge resource potential of oil shale in this basin has not been investigated profoundly.

Oil shale is an emerging type of strategic energy source and has attracted extensive attention in recent years [2–8]. The traditional evaluation of oil shale is based mainly on the determination of oil yield and TOC. Such an approach is constrained by the number and distribution of samples, as well as by testing costs. Because of the predictable defects of this method, log evaluation technique of oil shale was developed. He et al. [9] adopted the curve overlap and ΔlogR method for the assessment of oil shale.

Numerous studies have been carried out on the log evaluation of source rock. Beers, Swanson, Fertl and Rieke, Schmoker, Tan, Hertzog et al. [10–15] adopted the gamma-ray log method to identify source rock. Schmoker [16] and Hester [17] used the density log method to determine organic matter content in source rock. Autric [18], Hussain [19] adopted the acoustic and resistivity log prediction method for source rock. Meyer and Nederlof [20], Zhao [21] formulated a linear equation from the correlation diagram of well logs to distinguish source rocks and non-source rocks. Mendelson and Toksoz [22], Fertl and Chilingar [23], Kamel and Mabrouk [24], Xu and Zhu [25] formulated a multiple linear regression equation with multiple log parameters to quantitatively assess source rock. Passey et al. [26] adopted ΔlogR technology for the quantitative assessment of source rock. Xu et al. [27], Zhang and Zhang [28], Zhu et al.[29], Kamali and Mirshady [30] applied the ΔlogR technology. Huang et al.[31], Huang and Williamson [32], Kamali and Mirshady[30], Kadkhodaie-Ilkhci et al. [33] adopted the artificial neural network algorithm for identification of source rock, and solving the implicit relationship between logs and TOC. Patterson et al. [34] used doppler broadening to examine the relationship between TOC of core samples and a source rocks. The above-mentioned log assessment methods of source rocks use single to multiple parameters and qualitative to quantitative assessment, but the assessment result is limited only to a single well. It is difficult to assess source rocks in the entire basin. Even in the basin with high degree of exploration, high drilling density, and abundant log data, the assessment of source rocks between wells is a challenging task. The spatial assessment of source rocks has been conducted using the seismic method [35–36], in which qualitative prediction of high quality source rocks is performed by the seismic facies and velocity methods. This approach allows roughly estimating the thickness and the range of source rocks and does not allow the quantitative evaluation of source rocks.

2. Geological setting

Songliao Basin is located in the northeast of China with an area of 26×10^4 km^2. The basin can be divided into 6 first-order tectonic units and 32 second-order tectonic units [37] (Fig. 1). The distribution of oil shale is constrained mainly by the tectonic features, and oil shale is distributed mainly in the southeast uplift zone, northeast uplift zone and central depression zone. The Songliao rift basin has gone through three main tectonic evolutions during Mesozoic era: syn-rift subsidence stage (fault subsidence), post-rift thermal subsidence stage (depression), and rift-shrinking stage (fold) [38]. The oil shale developed during the depression stage.

Development of oil shale in the Songliao Basin is mainly concentrated in the Upper Cretaceous Qingshankou (K_2qn) and Nenjiang (K_2n) Formations (Fig. 2). The oil shale layers of the 3-D seismic study area (Fig. 1) are at the depth of 1100–1800 m with the monolayer thickness of about 6 m in the Qingshankou Formation deposition, and at the depth of 400–900 m with the monolayer thickness of about 8 m in the Nenjiang Formation deposition (Fig. 2). The Qingshankou Formation is divided into three members based on the lithology. The first member (K_2qn_1) incorporated a large lake area

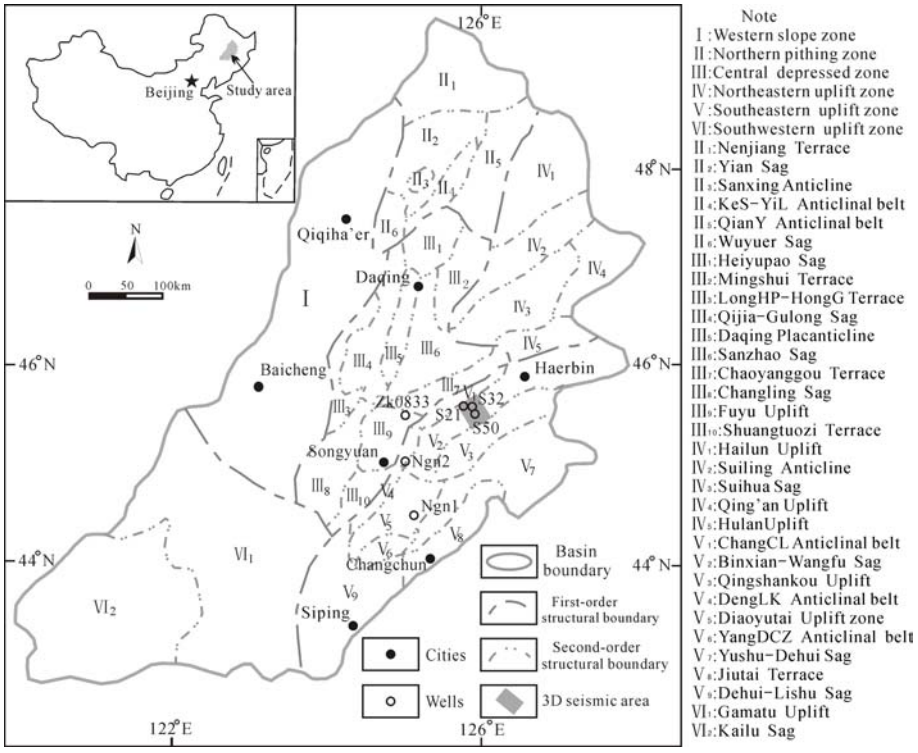
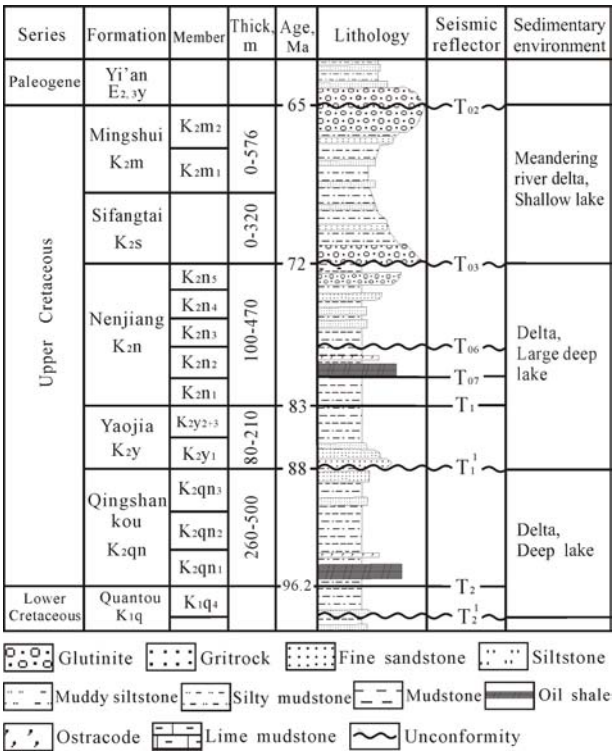


Fig. 1. Zoning map of structural unit of the Songliao basin (modified according to Feng et al., 2010).

during the sedimentary period and developed semi-deep to deep lake facies, with a lithology of mainly gray-black and dark gray mudstone-shale in combination with oil shale, which is mainly formed in semi-deep to deep lake facies. The Nenjiang Formation is divided into five members based on the lithology. A lacustrine transgression phase is reflected by sediments of shallow to semi-deep lake facies. These include grey-black and dark grey mudstones/shales in combination with grey-green siltstones and oil shale that was deposited during the formation period of the first (K_2n_1) and second (K_2n_2) member. The oil shale at the bottom of the second member (K_2n_2) corresponds to the largest lacustrine transgression, during which the Songliao Basin primarily developed and most densely distributed stable oil shale deposits were formed.



Note: The same legend of below lithology columns

Fig. 2. The Upper Cretaceous stratigraphy of Songliao Basin (modified according to Feng et al., 2010 [37].

3. Geophysical evaluation

This paper uses abundant core testing, logging, and 3-D seismic data as a basis. The measured data are from three fully cored wells (Ngn1, Ngn2, and

Zk0833), where each value represents 1 m of core. The 3-D seismic study area is located at the southeast uplift of Binxian-Wangfu Sag, and covers an area of 408 km^2. Good-quality seismic data serves as a favorable foundation for the exploration of oil shale with geophysical technique.

Based on above data and combined with geophysical methods used by the predecessors on source rock, the technique of log-seismic multi-attributes reconstruct inversion has been applied to carry out the quantitative evaluation of oil shale, to improve efficiency and save costs of the exploration. There are several key steps:

1) Geophysical characteristics of oil shale. This paper analyzes log and seismic response characteristics based on the petrologic characteristics of high organic matter of the oil shale. This constructs a theoretical base to estimate oil shale in the Songliao Basin.

2) Single-well evaluation of oil shale. This paper analyzes the ΔlogR technique based on the log response characteristics of oil shale, and constructs the ΔlogR-TOC relational model of the Nenjiang Formation. As ΔlogR method is unsuitable for use in the Songliao Basin, we mainly adopt the method of log-seismic multi-attributes reconstruction to predict the TOC of single wells.

3) Seismic quantitative evaluation of oil shale. In this paper 3-D seismic data is used. The inversion volume of wave impedance is obtained through the sequence-log constrained seismic inversion method and the inversion volume of TOC. The relationship between TOC and oil yield (measured by the BGMR Fischer Assay method of Royal Dutch Shell Plc) is used to obtain the inversion volume of oil yield and realize the quantitative evaluation of oil shale.

On the basis of above key steps, a technical flowchart for the quantitative evaluation of oil shale with geophysical technique is provided, as shown in Fig. 3.

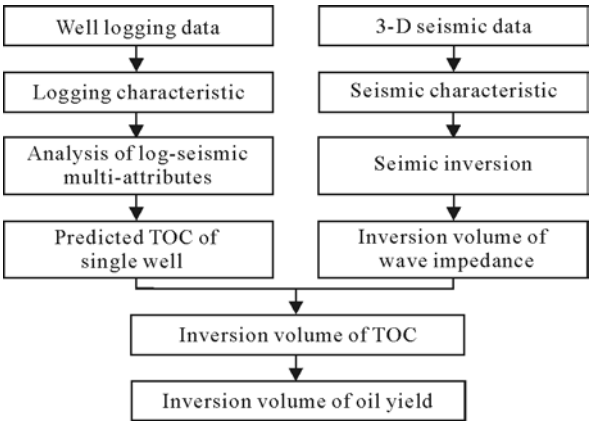


Fig. 3. Evaluation flowchart of geophysical technique of oil shale.

4. Geophysical characteristics of oil shale

The oil shale of the Songliao Basin is mainly composed of lacustrine shale or mudstone, mostly grey-brown, dark grey, and grey-black. It has an organic carbon content of 5.0–10.0 wt% up to 13.6 wt%, and an oil yield of 3.5–8.0 wt% up to 12.1 wt% (Fig. 4).

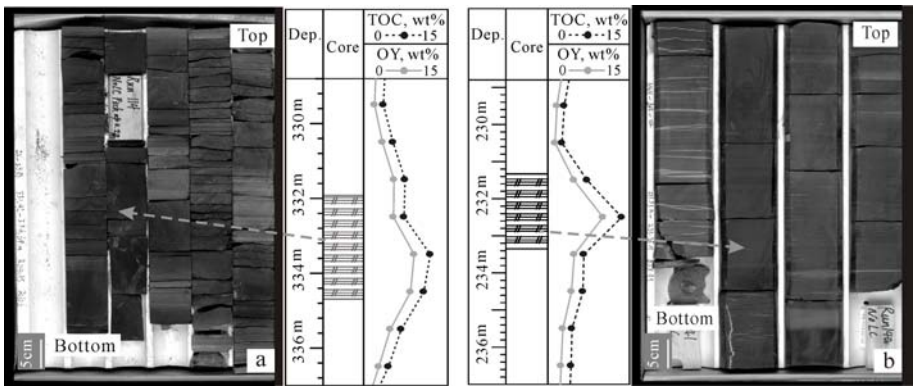


Fig. 4. Petrologic characteristics of oil shale in the Songliao Basin (a) Zk0833 well, K_2n_2, grey-brown oil shale; (b) Ngn2 well, K_2qn_1, deep grey oil shale.

4.1. Log characteristics of oil shale

The log response characteristics of oil shale depend mainly on the log response to organic matter and rock matrix. The oil shale with high organic matter content has the following characteristics: (1) organic matter has strong radioactivity, and its natural gamma value is higher than that of rock matrix; hence, the oil shale has a high gamma log value; (2) the organic matter is a non-conducting material and its occurrence worsens the conducting property of the rock. Its resistivity is greater than that of rock matrix; thus, the oil shale has a high resistivity log value; (3) the organic matter is the light-weight medium that is not conducive to acoustic wave transmission. The acoustic travel time is greater than that of rock matrix, endowing the oil shale with a log value of high acoustic travel time log value; (4) the organic matter has low density and its density is much lower than that of rock matrix, so the oil shale has a low-density log value; (5) the organic matter has low density, and its hydrocarbon content is considerably higher than that of rock matrix, presenting high-neutron porosity values. Therefore, the log response of oil shale exhibits the "four-high and one-low characteristics": high-natural gamma, high resistivity, high acoustic travel time, high-neutron porosity, and low density (Fig. 5).

The above-mentioned log response of oil shale can be influenced by the following factors: (1) the radioactive elements in rocks increase the natural

gamma value. For example, the silty thin layers of K_2qn_2 and K_2qn_3 have radioactive uranium, which increases the natural gamma value; (2) the ostracoda beds (Fig. 5, 1502.8 m), sandstone (Fig. 5, 1513 m), and oil shale have similar high resistivity response characteristics; (3) the mudstone layer developed fissures or have gases exhibiting low acoustic velocity, and the log response has a high acoustic travel time log value; (4) the mudstone layer is prone to wall collapse (Fig. 5, 1498 m and 1508 m), and the mud transgression drives the density log value of the undisturbed formation much lower than the normal mudstone. Hence, oil shale exhibits an integrated log response, and its identification is explained by several log methods.

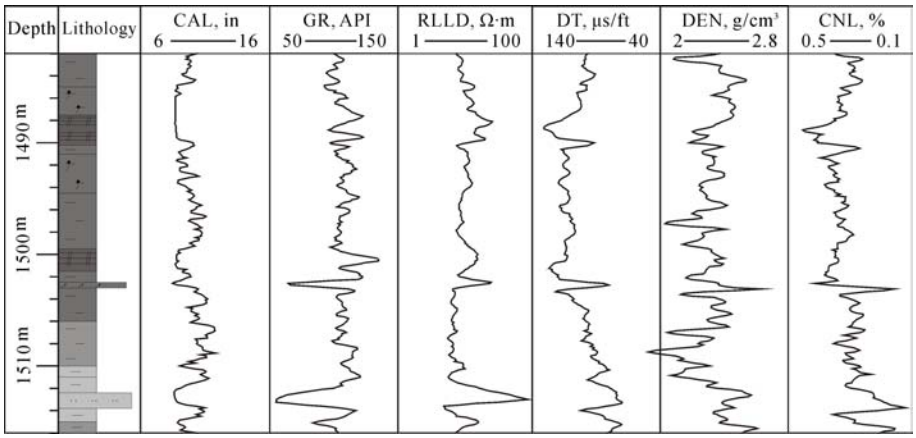


Fig. 5. Log response characteristics of oil shale of well S35 in the Songliao Basin.

4.2. Seismic characteristics of oil shale

The oil shale in the Songliao Basin has the following seismic sedimentary characteristics: (1) The oil shale presents the features of higher frequency, better continuity, and medium-strong amplitude; (2) the seismic reflection structure of oil shale is parallel to subparallel having mainly parallel sedimentation of lacustrine strata in deep water environments. Fig. 6 illustrates the seismic reflection profile across the wells S21-S32 in the Songliao Basin. The profile has four groups of strong reflectors: (1) the seismic event above T_2 shows low-frequency and high-amplitude seismic reflection features. Affected by tectonic fault, the seismic event has low continuity; (2) the seismic event about 1100 ms of well side shows low-frequency, good-continuity and high-amplitude seismic reflection features; (3) the seismic event above T_1 shows double-track seismic reflection features with low frequency, good continuity, and medium-high amplitude; (4) the seismic event above T_{07} corresponds to the maximum transgressive period of Nenjiang Formation, and shows seismic reflection features with high frequency, medium–high amplitude and good continuity. Thus, the Nenjiang Formation has the

seismic reflection features of high frequency and good continuity and the well calibration, which shows that Nenjiang Formation has thick single layer of oil shale. In view of this, we carry out the log and seismic evaluation mainly on the oil shale of Nenjiang Formation.

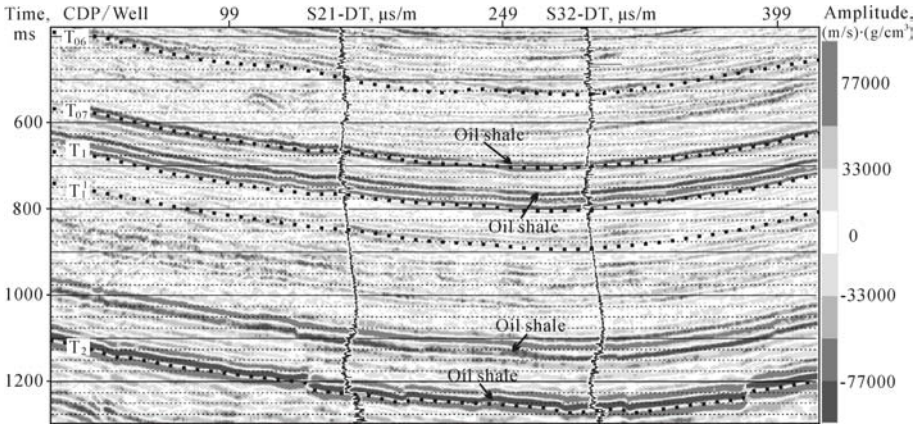


Fig. 6. Seismic response characteristics of oil shale in the Songliao Basin.

Because of seismic resolution constraints, the identification of oil shale on a regular seismic profile can be conducted based only on the drilling calibration result. The seismic reflection feature with strong amplitude is possibly the comprehensive response of the interbedding of mudstone and oil shale. Accurate calibration of the oil shale on the seismic profile is difficult; thus, it is identified by using other seismic methods.

5. Single-well evaluation of oil shale

5.1. Analysis of ΔlogR technique

During the logR analysis, three-porosity log curves (acoustic, density and neutron) generally overlay with the resistivity curve. In this study area, the natural gamma response and resistivity curve have good overlay and the oil shale layer has prominent characteristics. Thereby we take gamma/resistivity as the type of curve overlay for ΔlogR analysis and assign physical meaning to it. In ΔlogR analysis, the combination of log curves reflects the lithology of undisturbed formation correctly and the overlay of log and resistivity curves corresponds to the most prominent log response of oil shale. Only one type of curve cannot be applied blindly.

Figure 7 shows the gamma/resistivity overlay for ΔlogR analysis of oil shale in the Nenjiang Formation. The natural gamma response at this well has the most prominent response to oil shale. Although the density curve exhibits good log response at the oil shale layer, it is prone to wall collapse.

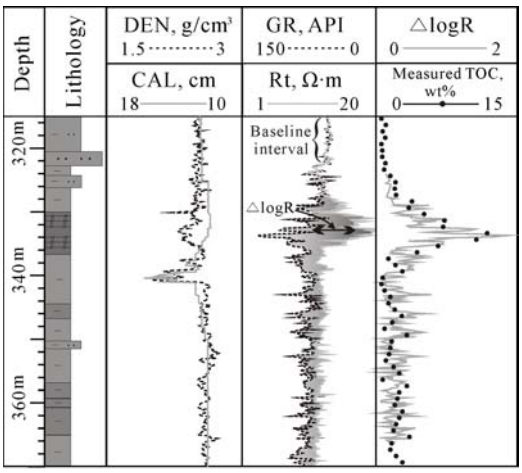


Fig. 7. Analysis of ΔlogR of well Zk0833 in the Songliao Basin.

Hence, ΔlogR analysis is carried out through gamma/resistivity overlay. Assume that the natural gamma response and resistivity overlay equation for the calculation of ΔlogR is:

$$\Delta \log R = \log_{10}(R / R_{\text{baseline}}) + 0.02 \times (GR - GR_{\text{baseline}}), \quad (1)$$

where ΔlogR is the curve separation measured in logarithmic resistivity cycles; R, $R_{baseline}$ present the resistivity log value and the baseline of the overlaid resistivity in Ω·m, respectively; GR, $GR_{baseline}$ denote the gamma log value and the baseline of the overlaid gamma response in API, respectively; 0.02 is based on the ratio of 50 API per one resistivity cycle mentioned above, an empirical parameter.

According to the baseline of curve overlay, $GR_{baseline}$ is 62.03 API and $R_{baseline}$ is 5.02 Ω·m. These are introduced into equation (1) to obtain ΔlogR curve, combined with the measured TOC for linear regression analysis (Fig. 8) and the relational model between the TOC and ΔlogR of the Nenjiang Formation from the Songliao Basin is constructed:

$$TOC = 7.3211 \times \Delta \log R + 0.2771, \quad (2)$$

where TOC is the total organic carbon content measured in wt%; ΔlogR is the curve separation measured in logarithmic resistivity cycles; 0.2771 is the baseline value of TOC. The "0.2771" is very important to compensate the background value of TOC, and it means that the TOC value is not zero when the ΔlogR is zero, which can be proved by measuring TOC from Fig. 8. The TOC and ΔlogR show an apparent positive correlation, with a correlation coefficient (R^2) of 0.913, indicating that TOC and ΔlogR have good correlation and TOC can be predicted by using this relational model.

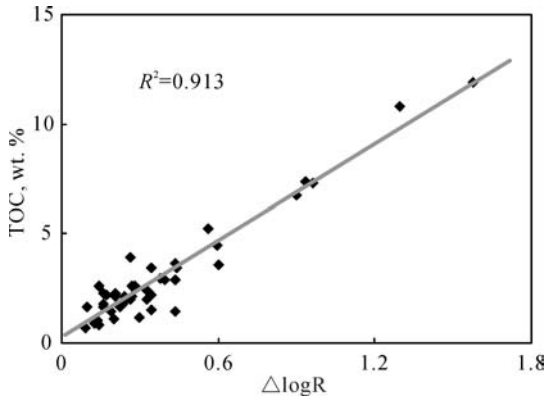


Fig. 8. Correlation diagram of ΔlogR vs. measured TOC in the Songliao Basin.

The following two aspects are being paid much attention to during the application of ΔlogR technique: (1) the log curve is always influenced by the well environment and cannot reflect the information on undisturbed formation accurately. The accuracy of the log response was monitored before application; (2) the baseline of the ΔlogR method represents non-source rocks, and the baseline TOC value is defined as zero value of TOC. However, the TOC of "non-source rock" is not zero, but just lower than the defined value of source rock. Hence, the background value of the TOC curve predicted by the ΔlogR method is lower. Generally, a fixed background value is directly added to compensate the baseline value of TOC (e.g. equation (2)). However, in practice the background value may be changed vertically depending on lithology of formation.

5.2. Analysis of log-seismic multi-attributes

Regarding to potential issues in the application of ΔlogR technique, log-seismic multi-attributes are used to predict TOC. By analyzing the oil shale log and seismic response features, a comprehensive geophysical response is obtained. In this study the TOC is predicted by choosing the prominent log-seismic attributes among the response multi-attributes of oil shale. Additional information regarding the undisturbed formation is incorporated to lay the foundation for improving the precision of TOC prediction. Using log-seismic multi-attributes, the TOC from ΔlogR technique is taken as the target curve and carefully chosen log-seismic multi-attributes are integrated to obtain the predicted TOC. This process is divided into two key steps:

(1) Preferred combination of log-seismic multi-attributes: log attributes that are not influenced by the well environment and have good log response are chosen by analyzing the log response characteristics of oil shale. The stepwise regression method is adopted, and the attributes among the log-seismic multi-attributes are chosen based on their degressive error (Table 1).

A preferred combination of log-seismic attributes that have significant influence on the target curve was chosen.

Table 1. The results of stepwise regression, applied to the TOC prediction problem

No.	Prediction	Final attributes	Error, %
1	TOC	$(GR)^2$	0.8077
2	TOC	log(Rt)	0.2319
3	TOC	1/DT	0.2297
4	TOC	Filter 25/30-35/40	0.2262
5	TOC	Cosine of the instantaneous phase	0.2211
6	TOC	Derivative instantaneous amplitude	0.2189

(2) Integrating log-seismic multi-attributes: the method of multiple step-wise regression analysis is adopted, and the chosen log-seismic attributes (based on their degressive error) are individually intregated into the regression equation. To eliminate the difference in the frequency of the log and seismic attributes, the convolution algorithm is adopted and the single sampling point on the log-seismic attributes is expanded to the adjacent multiple sampling points (Fig. 9), to correlate with the target curve. The weighed average of a group of sampling points on each attributes is taken to calculate a point on the predictive curve, which has almost the same resolution with target curve (well log). The regression equation after convolution is:

$$P = w_0 + w_1 * A_1 + w_2 * A_2 + \ldots + w_n * A_n \,, \tag{3}$$

where P is the predictive curve; * represents convolution; w_i are operators of a specified length; A_i are attributes [39–41].

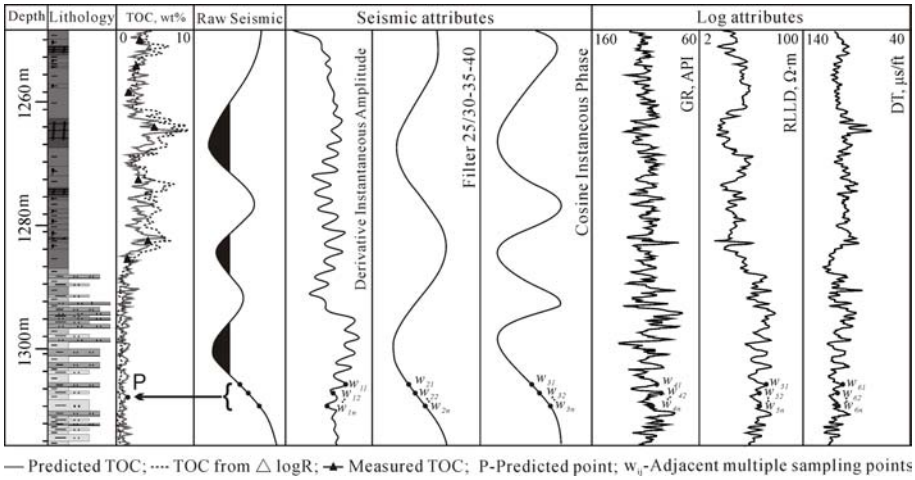


Fig. 9. Analysis of the log-seismic multi-attributes of well S50 in the Songliao Basin.

To simplify, it was considered to use only four sample values and four log-seismic attributes in equation (3) to predict the TOC. Equation (3) is rewritten as:

$$\begin{bmatrix} TOC_1 \\ TOC_2 \\ TOC_3 \\ TOC_4 \end{bmatrix} = w_0 + w_1 \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} + w_2 \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} + w_3 \begin{bmatrix} GR_1 \\ GR_2 \\ GR_3 \\ GR_4 \end{bmatrix} + w_4 \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \end{bmatrix}, \tag{4}$$

where TOC is the total organic carbon content measured in wt%; E_i are the energy attributes in (m/s)·(g/cm^3); A_i are the amplitude attributes in (m/s)·(g/cm^3); GR_i are the gamma attributes in API; ρ_i are the density attributes in g/cm^3.

Also, the case of a 3-point operator was taken into consideration, which could be written as follows:

$$w_i = \left[w_i(-1), w_i(0), w_i(+1) \right]. \tag{5}$$

Equation (5) was intregated into equation (4), and the matrix is expressed as follows:

$$\begin{aligned} \begin{bmatrix} TOC_1 \\ TOC_2 \\ TOC_3 \\ TOC_4 \end{bmatrix} = w_0 &+ \begin{bmatrix} w_1(0) & w_1(-1) & 0 & 0 \\ w_1(+1) & w_1(0) & w_1(-1) & 0 \\ 0 & w_1(+1) & w_1(0) & w_1(-1) \\ 0 & 0 & w_1(+1) & w_1(0) \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} \\ &+ \begin{bmatrix} w_2(0) & w_2(-1) & 0 & 0 \\ w_2(+1) & w_2(0) & w_2(-1) & 0 \\ 0 & w_2(+1) & w_2(0) & w_2(-1) \\ 0 & 0 & w_2(+1) & w_2(0) \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} \\ &+ \begin{bmatrix} w_3(0) & w_3(-1) & 0 & 0 \\ w_3(+1) & w_3(0) & w_3(-1) & 0 \\ 0 & w_3(+1) & w_3(0) & w_3(-1) \\ 0 & 0 & w_3(+1) & w_3(0) \end{bmatrix} \begin{bmatrix} GR_1 \\ GR_2 \\ GR_3 \\ GR_4 \end{bmatrix} \\ &+ \begin{bmatrix} w_4(0) & w_4(-1) & 0 & 0 \\ w_4(+1) & w_4(0) & w_4(-1) & 0 \\ 0 & w_4(+1) & w_4(0) & w_4(-1) \\ 0 & 0 & w_4(+1) & w_4(0) \end{bmatrix} \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \end{bmatrix} \end{aligned} \tag{6}$$

Items 2, 3, 4 and 5 were reset in equation (6) by turning and simplified as follows:

$$\begin{bmatrix} TOC_1 \\ TOC_2 \\ TOC_3 \\ TOC_4 \end{bmatrix} = w_0 + \begin{bmatrix} E_2 & E_1 & 0 \\ E_3 & E_2 & E_1 \\ E_4 & E_3 & E_2 \\ 0 & E_4 & E_3 \end{bmatrix} \begin{bmatrix} w_1(-1) \\ w_1(0) \\ w_1(+1) \end{bmatrix} + \begin{bmatrix} A_2 & A_1 & 0 \\ A_3 & A_2 & A_1 \\ A_4 & A_3 & A_2 \\ 0 & A_4 & A_3 \end{bmatrix} \begin{bmatrix} w_2(-1) \\ w_2(0) \\ w_2(+1) \end{bmatrix}$$
$$+ \begin{bmatrix} GR_2 & GR_1 & 0 \\ GR_3 & GR_2 & GR_1 \\ GR_4 & GR_3 & GR_2 \\ 0 & GR_4 & GR_3 \end{bmatrix} \begin{bmatrix} w_3(-1) \\ w_3(0) \\ w_3(+1) \end{bmatrix} + \begin{bmatrix} \rho_2 & \rho_1 & 0 \\ \rho_3 & \rho_2 & \rho_1 \\ \rho_4 & \rho_3 & \rho_2 \\ 0 & \rho_4 & \rho_3 \end{bmatrix} \begin{bmatrix} w_4(-1) \\ w_4(0) \\ w_4(+1) \end{bmatrix} \tag{7}$$

From the equations above, it can be deduced that if single sampling points with (n) attributes are used, there are (n+1) parameters related to the target curve; if multiple sampling points are used, there are (Nw_i×n+1) parameters related to the target curve, and Nw_i are the number of operators. With the same number of attributes (n), when the convolution factor algorithm is used, the number of parameters is increased by (Nw_i–1)×n, which is similar to the increase in attributes with lower error; this enables the usage of better attributes in predicting the target curve and thereby improving prediction accuracy.

A combination of 6 log-seismic attributes (GR, Rt, DT, Derivative instantaneous amplitude, Filter 25/30-35-40, and Cosine instantaneous phase) in well S50 is obtained by analyzing the applied stepwise regression, and using a nine-point convolutional operator. The results are shown in Table 1, where each row shows a multi-attribute transform with an increasing number of attributes. The first row shows that the single best attribute is $(GR)^2$ and a prediction error given by using this attribute is 0.8077%. The second line shows that the best pair of attributes is $(GR)^2$ and log(Rt), and a prediction error given by using this pair is 0.2319%. Table 1 shows combinations up to 6 attributes.

Figure 9 illustrates the analysis of log-seismic multi-attributes in well S50. The predictive TOC curve is obtained by using the convolution factor algorithm and is validated by the core data measured. The overlay of the predictive TOC, TOC from ΔlogR and measured TOC under the same dimension shows that the predictive TOC is much better than the TOC from ΔlogR to the measured TOC. The background value of the TOC vertically deviates from the zero line and the baseline changes reasonably, conforming to the vertical variation of organic matter in the undisturbed strata. The quantitative analysis (Fig. 10) shows that the error value of (ΔTOC_1 = predictive TOC–measured TOC) falls between (–0.541) wt% and 0.533 wt%, and the accumulated average error ($(\Sigma_{i=1}^{n}|\Delta TOC|)/n$) is 0.293 wt%. However, the error value of (ΔTOC_2 = TOC from ΔlogR–measured TOC) is between (–1.109) wt% and 2.082 wt%, and the accumulated average error is

0.995 wt%, which is far more than the ΔTOC_1, so the predictive TOC is rational in comparison to the TOC of ΔlogR.

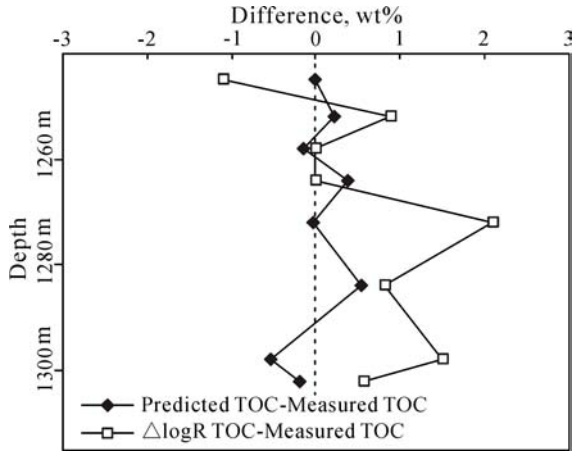


Fig. 10. Analysis of TOC difference of well S50 in the Songliao Basin.

The widespread application of the log-seismic multi-attributes method is limited by data constraints in the study area. However, this method still presents certain advantages: (1) the introduction of seismic attributes of the well site that are not influenced by the well environment to avoid the quality of the log curve to become influenced by the environmental factor of the well; and (2) the good usage of the log-seismic multi-attributes to determine that the shale has better geophysical response, and the adoption of convolution factor algorithm to predict TOC, so that the predictive result responds more accurately to the strata information and allows for a vertically compensated background value of TOC. This conforms to the vertical geological variations of strata in the TOC.

6. Seismic quantitative evaluation of oil shale

6.1. The log-constrained seismic inversion

Seismic inversion is a common and effective method for interpreting lithology. No report on the interpretation of oil shale using the inversion method has been published because the realization process is subject to numerous constraints, such as the seismic response and seismic resolution of oil shale. The oil shale in the Nenjiang Formation of the Songliao Basin has high-frequency, good-continuity, and medium-high amplitude seismic response characteristics. By drilling, it is determined that the oil shale has thick single layers, which makes identification through the inversion volume possible.

To improve inversion resolution, seismic prediction of oil shale using the seismic inversion method, based on the logging-constraint, was carried out. To make the log and seismic response comparable, the seismic geological horizon is marked during the inversion. This paper uses the seismic synthesis recording method for marking. The seismic synthesis record can be expressed as the convolution of the seismic wavelet and reflection coefficient. The seismic wavelet is obtained through the multi-trace seismic statistical method, and the reflection coefficient is obtained mainly through the acoustic log data. The synthesized seismic trace is compared with the actual seismic trace of well site. The main seismic reflective interface is marked and the synthesis recording of the accurate time-depth relationship is obtained through repeated proper tuning at the given position to realize the marking of the seismic geological horizon. The seismic synthesis recording in Fig. 11 shows that the artificially synthesized seismic trace corresponds very well to the seismic trace of well site. The correlation coefficient is as high as 0.71. Constructing the accurate time-depth relationship is the foundation for log-constrained seismic inversion.

The marking of seismic geological horizon is taken as the sequence constraint. The initial inversion model is constructed by interpolating and extrapolating the log data in the 3-D seismic volume. Setting up the rational inversion parameters and testing them repeatedly at the cross well profile, we evaluated the results within the permissible range. If it exceeds the error limit, the parameters are adjusted and recalculated so that the predicted result becomes reasonable after comparison with the log data. These are then applied to the entire 3-D study area to obtain the inversion volume of wave impedance. Fig. 12 shows one inversion profile crossing wells S21-S32 in the inversion volume. The profile has two apparent abnormal low-velocity belts (brown belts). Through comparison of the drilling lithology, the low-velocity belts are found to be the responses of oil shale in the K_2n_1 and K_2n_2.

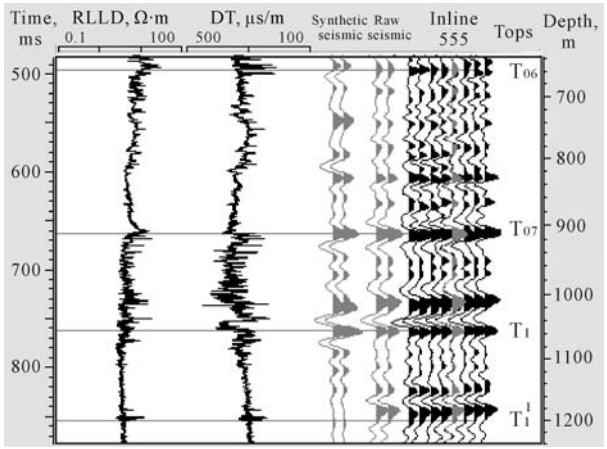


Fig. 11. Seismic synthetic recording of well S21 in the Songliao Basin.

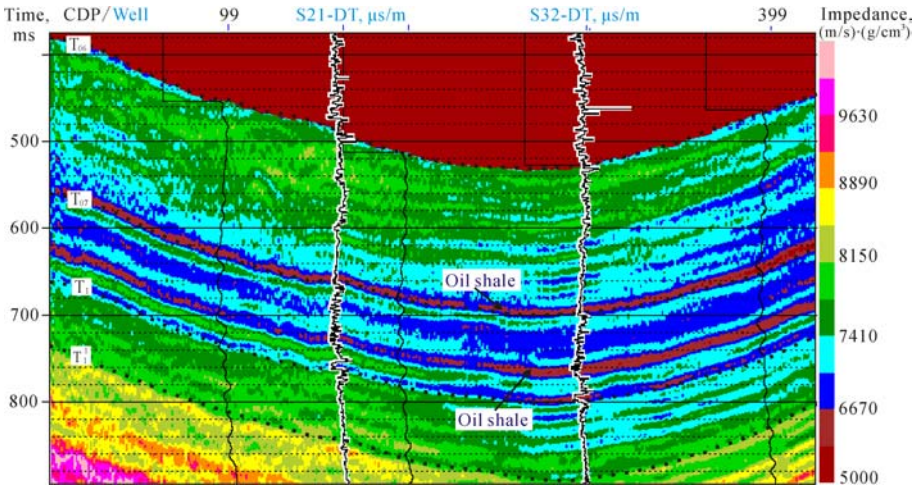


Fig. 12. Inversion profile of wave impedance along a cross section of wells S21-S32 in the Songliao Basin.

The low-velocity belt in the K_2n_2 has good horizontal continuity and stable distribution. The low- K_2n_2 belt in the K_2n_1 has poor continuity and large vertical change in thickness. Hence, the low-velocity belt in the inversion volume has prominent characteristics of spatial distribution, and the spatial distribution of oil shale can be qualitatively predicted by the inversion of low-velocity belt through the log calibration.

The inversion volume of wave impedance is used to predict the spatial distribution of oil shale by displaying relatively low velocity through the adjustment of color marks; this does not achieve the target of quantitative assessment of the spatial distribution of oil shale. To achieve the seismic quantitative evaluation of oil shale, the quantitative parameters like TOC and oil yield of oil shale must be predicted.

6.2. Prediction of the inversion volume of TOC

In combining the TOC curves of single-well obtained through log-seismic multi-attributes method and the inversion volume of seismic inversion, we calculate the relationship between the TOC of well site and seismic wave impedance from well side, and then use above relationship to extrapolate from the well to the entire 3-D study area. Finally we obtained the inversion volume of TOC to realize the seismic quantitative evaluation of oil shale.

Spatial quantitative evaluation based on the inversion volume of TOC allows to predict the spatial distribution of oil shale and also enables the quantitative evaluation of oil shale quality. Figure 13 shows the inversion profile of TOC crossing wells S21-S32 in the Songliao Basin. Different colors in the profile represent different TOC values. “Brown” represents the oil shale layers marked by a section with a TOC greater than 5.0 wt%. The

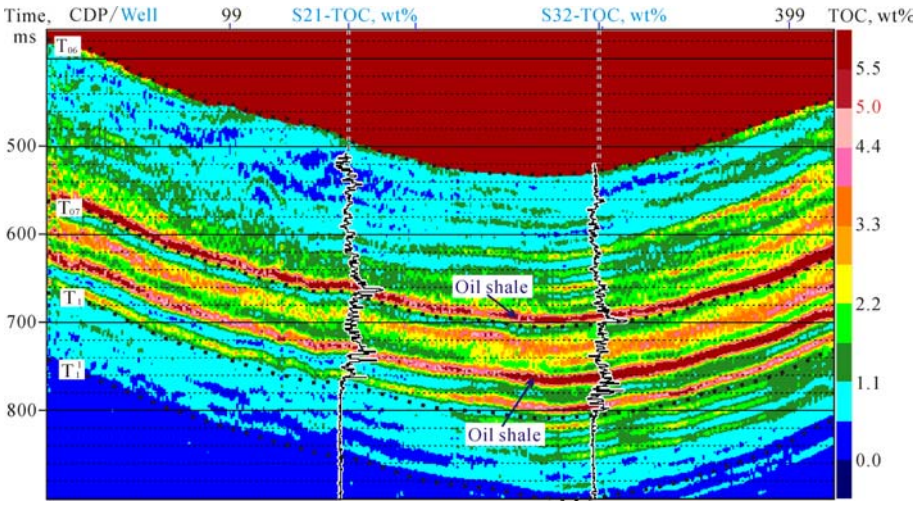


Fig. 13. Inversion profile of TOC along a cross section of wells S21-S32 in the Songliao Basin.

Nenjiang Formation has mainly developed in two oil shale layers. As for the transverse extension, the K_2n_2 has good continuity, whereas the K_2n_1 has poor continuity. The TOC inside the oil shale layer changes both transversely and vertically. In Fig. 16, the curves of well-points are the prediction TOC of single-well. Comparing the single-well TOC and inversion TOC of well site shows that the two have good correspondence, which indicates that the seismic method enables the rational prediction of TOC.

6.3. Prediction of the inversion volume of oil yield

Oil yield is a direct parameter for quantitative evaluation of the the oil shale and the inversion volume of oil yield must be obtained for the seismic quantitative evaluation of oil shale. By determining the relationship between the TOC and oil yield, the inversion volume of oil yield is obtained through the inversion volume of TOC. To obtain the reliable quantitative relationship between the TOC and oil yield, the data should satisfy the following conditions: (1) to avoid the influence of tectonic factors on oil shale formation, collecting data from wells at different positions of the study area is a more favorable approach; (2) to eliminate model instability resulting from incomplete rules in the section disclosed by the data, collecting data from the continuously cored well is a better technique. The relationship between TOC and oil yield is constructed by 327 measured data from three fully cored wells (Ngn1, Ngn2, and Zk0833) (Fig. 1), as shown below:

$$OY = 0.8015 \times TOC - 0.6645, \tag{8}$$

where OY is the oil yield measured in wt% and TOC is the total organic carbon measured in wt%.

Figure 14 shows a good linear relationship between the TOC and oil yield, and the correlation (R^2) is as high as 0.968. When the TOC is 5.0 wt%, the oil yield is about 3.5 wt%. Hence, OY>3.5 wt% and TOC >5.0 wt% are taken as the criteria for the quantitative evaluation of oil shale.

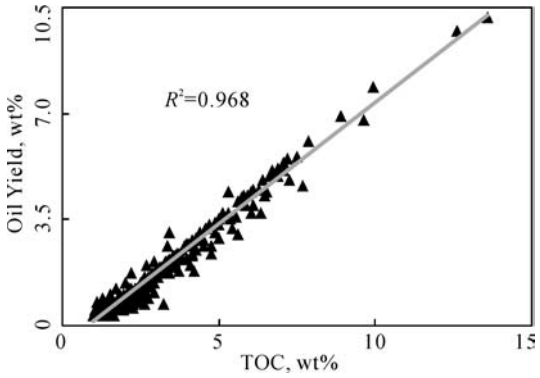


Fig. 14. Correlation diagram of TOC vs. oil yield in the Songliao Basin.

Figure 15 shows the inversion profile of oil yield crossing wells S21–S21 in the Songliao Basin. In the figure, the black layer is the section with an oil yield greater than 3.5 wt%. It can be directly and quantitatively assessed as oil shale. The spatial distribution of oil shale has features similar to the inversion result for the wave impedance and TOC. It is continuous in trans-

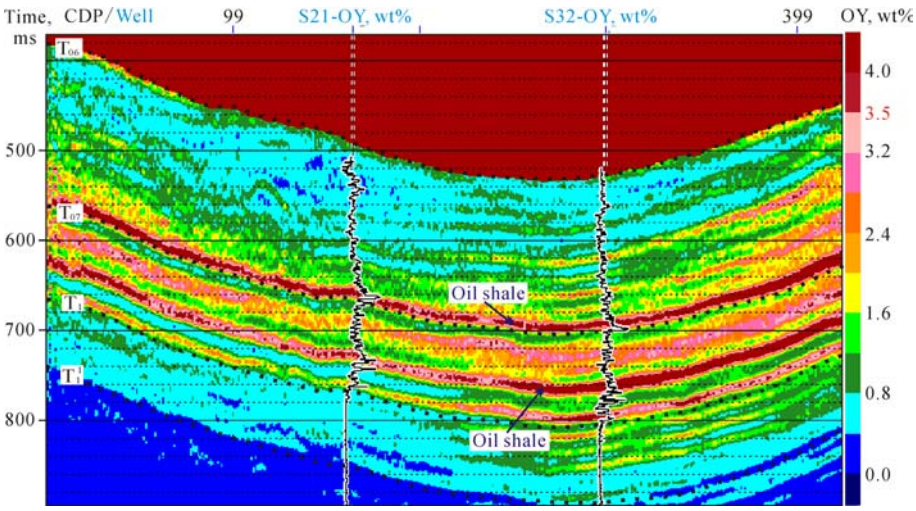


Fig. 15. Inversion profile of oil yield along a cross section of wells S21-S32 in the Songliao Basin.

verse extension and has the distribution features of multi-layers at the vertical direction. The inversion results of oil yield can provide more accurate evaluation. In Fig. 15, the oil yield curve of well and inversion oil yield of well site show better consistency; hence, the inversion result for oil yield is quite rational.

Figure 16 shows the 3-D diagram for the spatial quantitative evaluation of oil shale in the Songliao Basin. In the figure, the layer with oil yield greater than 3.5 wt% is marked as the oil shale. According to the evaluation result, the spatial distribution of oil shale has multi-layers and good continuity. However, the spatial distribution varies among different oil shale layers. The oil shale in the K_2n_2 has good continuity and relatively high oil yield. The fact that K_2n_1 has poor continuity and low oil yield, indicates that the K_2n_2 has better quality of oil shale compared to the K_2n_1. Meanwhile, the oil shale layer is thick at the bottom of the K_2n_2 and steadily developes in the entire study area, and the inversion of oil yield is either transversely or vertically unstable; the vertical upward inversion changes from low to high and then back to low, and the peak appears at the lower middle part of the oil shale layer. The higher value of oil yield in transverse upward inversion appears at the edges of basin with smaller variations and faults in the secondary tectonic unit. The variation of oil yield from the transverse to the vertical direction indicates that the oil shale represents heterogeneity in spatial

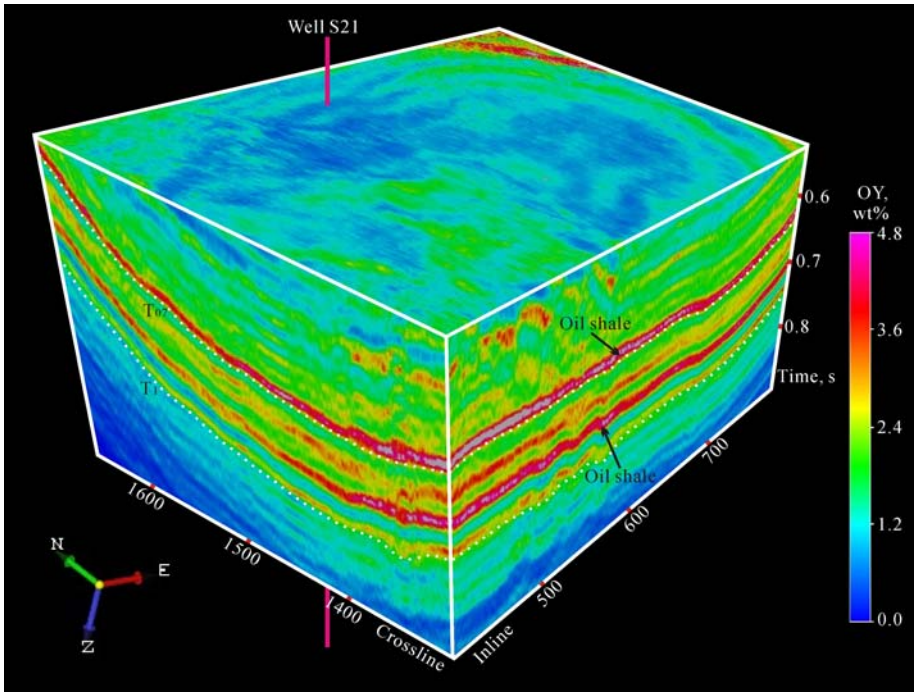


Fig. 16. 3-D diagram for spatial quantitative evaluation of oil shale in the Songliao Basin.

distribution. Hence, the inversion result for oil yield enables quantitative evaluation not only of the spatial distribution of oil shale, but also of the grade of oil shale.

7. Conclusion

In this paper, the seismic technique was incorporated into the evaluation system of oil shale, the single-well quantitative evaluation of oil shale with the technique of log-seismic multi-attributes construction was carried out, and the seismic quantitative evaluation of oil shale using the method of logging-constrained seismic inversion was performed. The following conclusions are drawn:

(1) The oil shale of the Songliao Basin exhibits the log response with high natural gamma, high resistivity, high acoustic travel time, high-neutron porosity and low density of the "four-high and one-low characteristics", and seismic response with higher frequency, better continuity, medium–high amplitude, and parallel to sub-parallel seismic reflection structure.

(2) The ΔlogR-TOC relational model for the Nenjiang Formation in the Songliao Basin was constructed and single-well TOC was predicted with log-seismic multi-attributes method. The convolution factor algorithm incorporates $(Nw_i-1)\times$n low-error attributes, and the accumulated average error of predictive TOC is 0.293 wt%, which is less than ΔlogR. Hence, this method improved the precision of TOC prediction and eliminated the issues caused by the incorrect background values for TOC prediction in the ΔlogR method.

(3) A method for the quantitative evaluation of oil shale was proposed using the seismic technique; TOC>5.0 wt% and OY>3.5 wt% was taken as the criteria for the quantitative evaluation of oil shale. According to the evaluation results, the inversion volume of wave impedance obtained through the method of logging-constrained seismic inversion enables the qualitative evaluation of the spatial distribution of oil shale; the inversion volume of TOC and oil yield enables not only the qualitative prediction of the spatial distribution of oil shale, but also the quantitative evaluation of the quality features of oil shale.

The seismic quantitative evaluation of oil shale is supported by abundant log and 3-D seismic data. The prediction accuracy is influenced by the thickness of oil shale and resolution of seismic data. Hence, the technique can be applied in other suitable study areas.

Acknowledgements

We thank Prof. Dr. R. F. Sachsenhofer and Dr. A. Bechtel for their helpful discussion and suggestions. We are grateful to Dr. S. F. Dai for his constructive and valuable comments. This paper benefited greatly from the

critical remarks by two anonymous reviewers of Journal Oil Shale. The research project was financially supported by the National Natural Science Foundation of China (No. 40972076), the National innovation project of production–study–research application of China (No. OSR-01-02), the National Technical Key Special Project of China (No. 2008ZX05018-001-004), the innovation team of Jilin University of China (No. 201004001) and the Graduate Innovation Fund of Jilin University of China (No. 20111043).

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Presented by J. Kann
Received July 25, 2011