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Quick Evaluation of Present-Day Low-Total Organic Carbon Carbonate Source Rocks from Rock-Eval Data: Middle–Upper Ordovician in the Tabei Uplift, Tarim Basin

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Abstract: Previous studies have postulated the contribution of present-day low-total organic carbon (TOC) marine carbonate source rocks to oil accumulations in the Tabei Uplift, Tarim Basin, China. However, not all present-day low-TOC carbonates have generated and expelled hydrocarbons; therefore, to distinguish the source rocks that have already expelled sufficient hydrocarbons from those not expelled hydrocarbons, is crucial in source rock evaluation and resource assessment in the Tabei Uplift. Mass balance can be used to identify modern low-TOC carbonates resulting from hydrocarbon expulsion. However, the process is quite complicated, requiring many parameters and coefficients and thus also a massive data source. In this paper, we provide a quick and cost effective method for identifying carbonate source rock with present-day low TOC, using widely available Rock-Eval data. First, we identify present-day low-TOC carbonate source rocks in typical wells according to the mass balance approach. Second, we build an optimal model to evaluate source rocks from the analysis of the rocks' characteristics and their influencing factors, reported as positive or negative values of a dimensionless index of Rock-Eval data (I_R). Positive I_R corresponds to those samples which have expelled hydrocarbons. The optimal model optimizes complicated calculations and simulation processes; thus it could be widely applicable and competitive in the evaluation of present-day low TOC carbonates. By applying the model to the Rock-Eval dataset of the Tabei Uplift, we identify present-day low-TOC carbonate source rocks and primarily evaluate the contribution equivalent of 11.87×10^9 t oil.

Key words: present-day low-TOC, carbonate source rocks, quick evaluation model, Rock-Eval, Tabei Uplift

1 Introduction

The origin of the discovered oil in the Tabei Uplift, Tarim Basin, China, has long been an issue of open debate (Graham et al., 1990; Liang Digang et al., 2000; Zhang et al., 2000; Wang Zhaoming and Xiao Zhongyao, 2004; Sun et al., 2003; Zhang Shuichang et al., 2004; Li et al., 2015; Liu Wenhui et al., 2017; Pang Xiongqi et al., 2018). According to geochemical biomarkers and carbon-isotopic characteristics, the Middle–Upper Ordovician carbonate source rocks act as a major contributor to marine hydrocarbon sources (Hanson et al., 2000; Wang Zhaoming and Xiao Zhongyao, 2004; Zhang Shuichang et al., 2004; Zhang Jing et al., 2017). However, recent exploration data (from 246 wells, some of which are located in the slope close to the Manjiaer Depression, such as SB1 well of SINOPEC and GL2 well of PetroChina) suggest that the Middle–Upper Ordovician carbonates are commonly poor in organic matter (present-day total organic carbon (TOC)≤0.5%), compared to significant hydrocarbon accumulations in the carbonate platform successions in the basin (Fig. 1) (Chen et al., 2018a).

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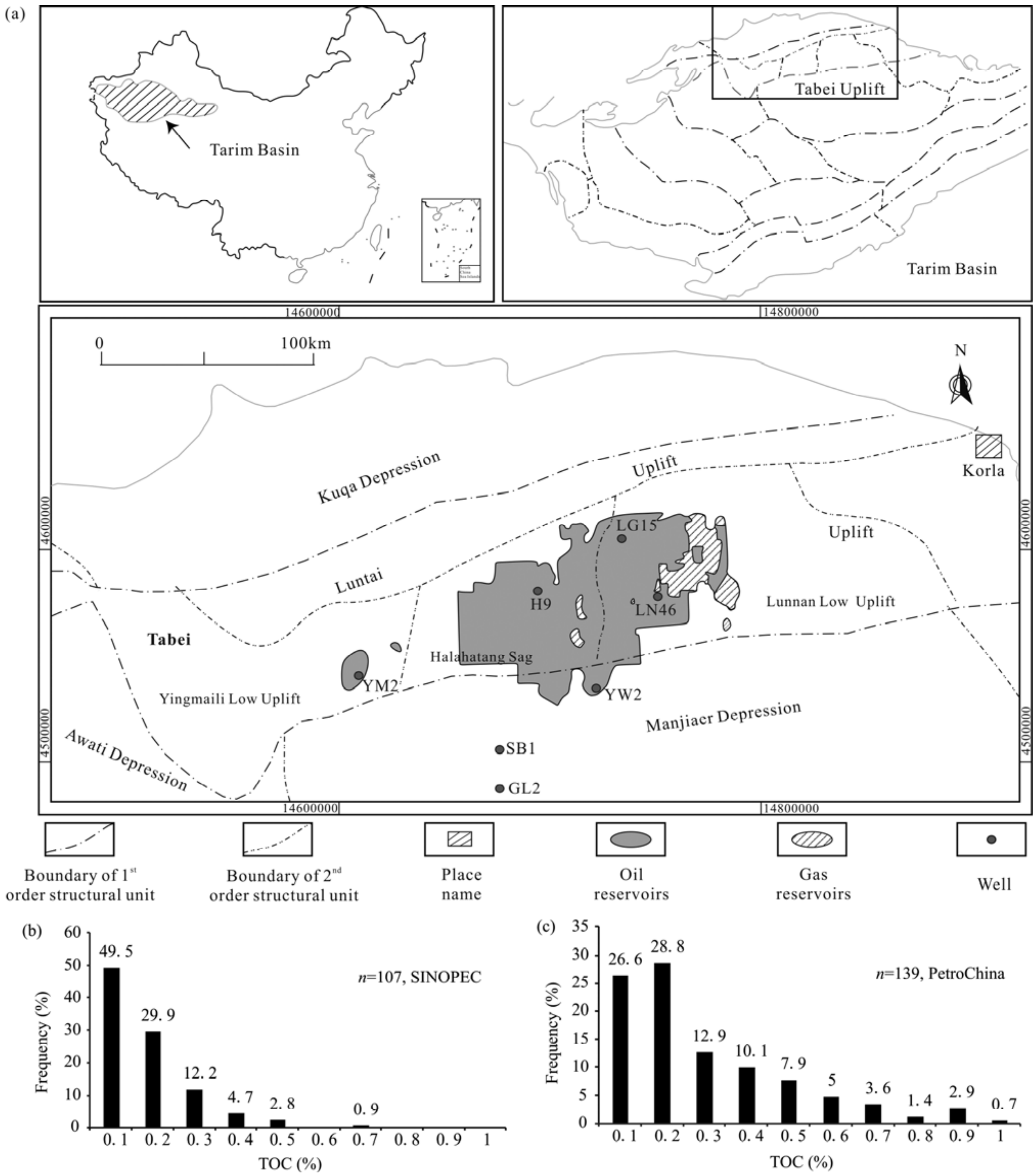

Fig. 1. (a), Map showing location, structure, and distribution of discovered hydrocarbon reservoirs in the Ordovician System in the Tabei Uplift (China basemap after China National Bureau of Surveying and Mapping Geographical Information); (b), TOC distribution of the Middle–Upper Ordovician source rocks from SINOPEC wells and (c), TOC distribution of the Middle–Upper Ordovician source rocks from PetroChina wells in the platform of the Tarim Basin. Figs.1b and 1c are after Chen et al., 2018a.

Thus, the high-quality Cambrian–Lower Ordovician source rocks (TOC>0.5%) are thought to be responsible for the widely distributed oil and gas resources in the carbonate platform (Li et al., 2015; Pang et al., 2016). However, from the third round of national resource assessment, the predicted in situ oil equivalent resources in the Tabei Uplift is 2.47×10^9 t, based on the contribution of source rocks abundant in organic matter. Meanwhile, the present 3P reserves of oil have been more than 3.0×10^9 t (Yang Haijun, 2012, personal communication), implying some contribution of Middle–Upper Ordovician carbonates with present-day low TOC. Based on this, Liu Wenhui et al. (2017) and Pang Xiongqi et al. (2018) appealed that the contribution to hydrocarbon accumulation from present-day low TOC carbonate source rocks with high maturity in the Tarim Basin cannot be ignored. Moreover, latest studies on hydrocarbon migration and accumulation using the method of changing concentrations and biomarker ratios in mixed oils show that marine oil accumulation of the Tabei Uplift is attributed to either lateral or vertical migration within short distances (Zhan et al., 2016; 2017), demonstrating that present-day low-TOC marine carbonate source rocks have generated and expelled hydrocarbons during their geological history and contributed to accumulations.

Early in 1978, Tissot and Welte found that the present-day organic matter content is only part of the original amount, and the original organic matter content may have been up to double the present amount. Daly and Edman (1985) suggested guidelines for the extent of the conversion of various kerogen types. They showed values of 80%, 50%, and 20% for the total amount of the initial TOC that could be converted for kerogen types I, II, and III, respectively. Therefore, these carbonates with present-day low-TOC (present-day TOC≤0.5%) may have been high TOC source rocks earlier in paleo-time. The initial TOC values of carbonate source rocks in the Tarim Basin with a calculated vitrinite reflectance of >1.2% can reach 3.2 (types I), 2.2 (types II) and 1.5 (types III) times of the present-day TOC (Pang Xiongqi et al., 2014). However, this is not true for all the present-day low-TOC carbonate rocks exhibiting hydrocarbon expulsions (Chen et al., 2018a; Pang Xiongqi et al., 2018). According to our continuously sampled experiments, there are two types of carbonate source rocks with present-day low TOC: those that have generated and expelled hydrocarbons and those that have not. The former rocks have high initial TOC; however, their present-day TOC is the residue after hydrocarbon expulsion which contributed to local hydrocarbon accumulation. The latter comprises a relatively poor type of kerogen or a reworked inactive carbon and contributed little or nothing to hydrocarbon expulsion. Thus, it cannot be counted as source rock. It is crucial to distinguish between the present-day low-TOC carbonates that have already expelled sufficient hydrocarbons and those that have not for source rock evaluation and resource assessment in the carbonate strata of the Tabei Uplift.

The present-day low-TOC carbonates resulting from hydrocarbon expulsion can be identified through a mass balance approach (Chen et al., 2018a; Pang Xiongqi et al., 2018). However, the analysis requires many parameters, such as vitrinite reflectance (R_o), porosity (φ), formation temperature (T), pressure (P) and water salinity (X_K), oil density, gas composition, and rock density, as well as some coefficients describing source absorption capability (Pang Xiongqi et al., 1993). The calculations are complex and require lots of time and data resources when deploying to a basin with maximal quantities of wells. The objective of this study is to discuss a quick and cost effective method for identifying carbonate source rock with present-day low TOC, using widely available Rock-Eval data. We selected the Middle–Upper Ordovician which developed two types of present-day low-TOC carbonates, as a case study in the Tabei Uplift, Tarim Basin, and conducted TOC and Rock-Eval measurements. According to the mass balance approach, we identify the present-day low-TOC carbonate source rock samples and analyze their characteristics and influencing factors. Then, we use multivariate linear stepwise regression to provide an optimal model based on Rock-Eval data. Through the application of the optimal model to the Rock-Eval dataset of the Tabei Uplift, we identify present-day low-TOC carbonate source rocks and evaluate their contribution to hydrocarbon accumulations.

2 Methodology

2.1 Mass balance model

According to the principle of mass balance, for the organic matter that can be converted into hydrocarbons in the source rock, if the material is not exchanged with the external environment in the process of evolution, the total amount of matter must be constant (Dickey, 1975; Barker, 1980; Jones, 1981; Cooles et al., 1986; Durand, 1988; Pang et al., 2005; Chen and Jiang, 2016). The hydrocarbon potential can be divided into the following three parts: (1) kerogens or residual organic matter that have not yet been transformed to hydrocarbons; (2) hydrocarbons that have been generated and remained in the source rock; and (3) hydrocarbons that may have been expelled from the source rock. Pang et al. (2005) proposed the concept of an expulsion threshold to reveal the mass balance and the critical conditions for the expulsion of hydrocarbon from source rocks. The expulsion threshold is defined as the critical balance point at which the source rocks have generated enough hydrocarbons to allow for their migartion against capillary sealing (i.e., secondary migration), expelling large quantities of movable hydrocarbons (Pang et al., 2005) (Fig. 2). Before the hydrocarbon expulsion threshold, the hydrocarbon generation curve is lower than residual curve. This means that because the fluids are not enough to be able to migrate against capillary sealing, all of the hydrocarbons are being

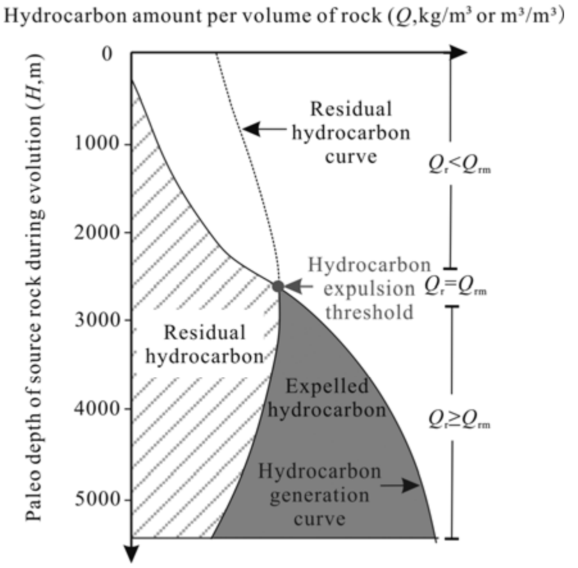

Fig. 2. Model showing mass balance of hydrocarbon generation, retention and expulsion of source rocks (modified from Pang et al., 2005).

retained in source rocks. These two curves overlap at the hydrocarbon expulsion threshold, indicating that fluids in the source rock are sufficiently abundant to trigger secondary migration. After the hydrocarbon expulsion threshold, the source rock expels movable hydrocarbons and the difference of the two curves is the expelled hydrocarbon amount (Fig. 2).

Thus, according to the approach of mass balance and the definition of the expulsion threshold (Pang et al., 2005), the residual hydrocarbon amount at the expulsion threshold can be calculated as the theoretical minimum amount of hydrocarbon generation necessary for a source rock to expel hydrocarbons (Formula 1) (Pepper, 1992; Sandvik et al., 1992; Pang Xiongqi et al., 1993). Conversely, the actual residual hydrocarbon amount of hydrocarbons can be obtained based on the measurement and the evaporative-losses calibration of chloroform bitumen "A" or free hydrocarbon amount S_1 from Rock-Eval measurement against indigenous oil (Formula 2) (Pang Xiongqi et al., 1993). Thus, these values can be used to identify the present-day low-TOC source rocks that have expelled hydrocarbons (Formula 3). Samples can be identified as non-hydrocarbon expelling when the actual residual amount does not reach the minimum generation amount needed to expel hydrocarbons (Q_d<0). Otherwise, source rocks can be identified as being originally effective since they have crossed the expulsion threshold, indicating they already expelled hydrocarbons previously in their history (Q_d≥0) (Fig. 2). The mathematical model to identify present-day low abundance carbonate source is follows:

$$Q_{rm} = f(TOC, Ro, \phi, T, P, So, X_K), \quad (1)$$

$$Q_d = f(S_1, Ro), \quad (2)$$

$$Q_d = Q_r - Q_{rm} \begin{cases} <0, \text{ no hydrocarbon expulsion} \\ \geq 0, \text{ hydrocarbon expulsion} \end{cases} \quad (3)$$

where, Q_{rm} is the minimal amount of hydrocarbon required to saturate the source rock's porosity at a certain depth in the source rock per unit volume, kg/m^3; Q_r is the amount of actual residual hydrocarbon at the same depth in the source rock per unit volume, kg/m^3; Q_d is the difference of Q_r and Q_{rm} at the same depth in the source rock per unit volume, kg/m^3; TOC refers to organic matter abundance, %; R_o is vitrinite reflectance, %; φ is porosity, %; T is the formation temperature, °C; P represents formation pressure, MPa; X_K is formation water salinity, g/l; S_1 is the free hydrocarbon amount acquired by pyrolysis measurement, mg/g.

2.2 Quick evaluation model

In basins with high level of exploration, wherein datasets are consummate and data are widely available, people can choose to use a mass balance approach to identify carbonate source rock directly. As mentioned previously, progressive analyses require many parameters, which require lots of time and data resources to deploy at the basin scale. A quick and reliable evaluation is essential to maintaining competitive advantages and success because hydrocarbon resource exploration and development are capital-intensive. In many cases, the requirements for information on the characteristics of source rock hydrocarbon expulsion are time-sensitive for business decisions. In this study, a quick quantitative evaluation model using Rock-Eval data to identify the present-day low-TOC carbonate source rock is described. Since Rock-Eval results are available for almost any source rock system from sedimentary basins, direct evaluation of the contributions of target source rocks using archived Rock-Eval data would allow companies to position themselves with a competitive advantage.

We propose I_R based on the identification process using the mass balance discussed in section 2.1 to characterize the critical condition necessary for source rocks to expel hydrocarbons, and to analyze the characteristics and influencing factors of present-day low-TOC carbonate source rocks. Then, we provide an optimal model to quickly identify present-day low-TOC carbonate rocks with hydrocarbon expulsion, which contribute to accumulation by checking for positive or negative I_R. I_R is designed to describe the difference of Q_r and Q_{rm} (Q_d); the maximum of I_R (i.e., largest Q_d) is set to 1; and the minimum of I_R is set to −1, (i.e., smallest Q_d). The value assignment model is shown as Formula 4 and in Fig. 3.

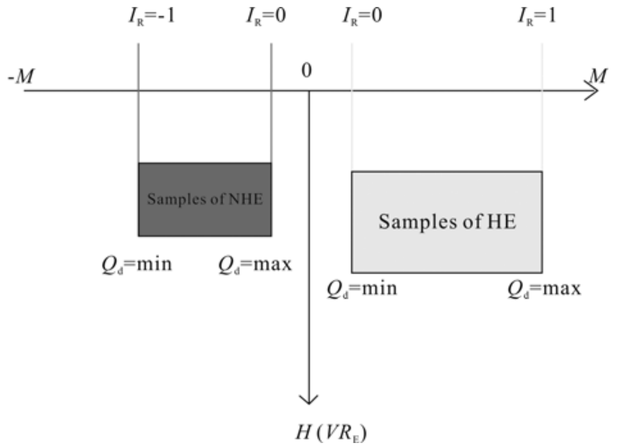

Fig. 3. Model showing the process of designing I_R values of each sample. HE means carbonates have hydrocarbon expulsion during their history and NHE means carbonates have no hydrocarbon expulsion.

$$\frac{I_R - I_R\min}{I_R\max - I_R\min} = \frac{Q_d - Q_d\min}{Q_d\max - Q_d\min} \quad . \tag{4}$$

To directly identify present-day low-TOC carbonates with hydrocarbon expulsion by checking positive of negative of I_R value, we set the I_R of samples without hydrocarbon expulsion from −1 to 0, and I_R of samples with hydrocarbon expulsion from 0 to 1. Then, we calculate I_R values of two types of samples, respectively (Fig. 3). Among present-day low-TOC samples without hydrocarbon expulsion, therefore, the I_R value is 0 corresponding to the maximum Q_d and −1 corresponding to the minimum Q_d. Therefore, Formula 4 can be expressed as Equation 5 and the I_R value can be set according to Formula 6. Similarly, I_R values among present-day low-TOC samples with hydrocarbon expulsion is 0, at the smallest Q_d and 1 at the largest Q_d. Then, Formula 4 can be transferred to Equation 7, and I_R values can be obtained according to Formula 8.

$$\frac{I_R - (-1)}{0 - (-1)} = \frac{Q_d - Q_d\min}{Q_d\max - Q_d\min} \quad , \tag{5}$$

$$I_R = \frac{Q_d - Q_d\max}{Q_d\max - Q_d\min} \quad , \tag{6}$$

$$\frac{I_R - 0}{1 - 0} = \frac{Q_d - Q_d\min}{Q_d\max - Q_d\min} \quad , \tag{7}$$

$$I_R = \frac{Q_d - Q_d\min}{Q_d\max - Q_d\min} \quad . \tag{8}$$

Furthermore, we analyze the characteristics and the influencing factors of present-day low-TOC carbonates with hydrocarbon expulsion to obtain the relationship of I_R and each factor (Equation 9). Consequently, n of I_R values and m of variables can form a matrix (Equations 10, 11, and 12). By the application of multivariate linear stepwise regression, we derive an optimal mathematical model of simulating I_R values by minimizing the sum of deviation squares (S) between the actual I_{Rn}^{0} and the calculated I_{Rn} (Equation 13):

$$I_R = f(x_1, x_2, x_3, x_4, x_5, \ldots x_m) \ , \tag{9}$$

$$I_{R1} = f(x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, \ldots x_{1m}) \ , \tag{10}$$

$$I_{R2} = f(x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, \ldots x_{2m}) \ , \tag{11}$$

$$I_{Rn} = f(x_{n1}, x_{n2}, x_{n3}, x_{n4}, x_{n5}, \ldots x_{nm}) \ , \tag{12}$$

$$S = \sum_{k=1}^{n} (\mathrm{I}_{\mathrm{Rk}}^{0} - \mathrm{I}_{\mathrm{Rk}})^2 \quad . \tag{13}$$

3 Applications

3.1 Geological setting

The Tabei Uplift is located in the north of the Tarim Basin in the west of China (Maqingyou et al., 2015; Liu Gecun et al., 2016; Fang Ronghui et al., 2017; Huang Chenjun et al., 2017; Wang Ke et al., 2017; Yang Xin et al., 2017), with an exploration area of approximately 54 $\times 10^3$ km^2 (Fig. 1a). The structural units of the Tabei Uplift mainly include the Yingmaili Low Uplift, Halahatang Sag and Lunnan Low Uplift from west to east (Fig. 1a). With the development of exploration theory and technology, a large amount of oil and gas has been discovered in Ordovician carbonate formations in the Tabei Uplifts, with a distribution featuring of oil in the west and gas in the east (Fig. 1a). The strata of the Ordovician System in the Tabei Uplift includes the Yingshan Formation from the Lower Ordovician, Yijianfang Formation from the Middle Ordovician, Tumuxiuke Formation, Lianglitage Formation and Sangtamu Formation from the Upper Ordovician (Fig. 4), with some formations of which wedge out in certain area.

Since the Yangwu 2 (YW2) well and the Lunnan 46 (LN46) wells are typically used to investigate Middle–Upper Ordovician source rocks, they were chosen as case studies. They were continuously sampled during corresponding intervals. The YW2 well is located in the west of the YW2 structure among the Manbei structural zones to the north of Manjiaer Depression, Tarim Basin (Fig. 1a). Currently, the target formations of YW2 capture the Upper, Middle and Lower Ordovician from top to bottom, with the Yingshan Formation of the Lower Ordovician left unpenetrated. The penetration in this well is the deepest among the wells in the area, and it contains the most varied lithology, including limestone, muddy limestone, lime mudstone and mudstone, and limestone. Limestones include micrite, siltite and sparite. The sampled Ordovician interval in the YW2 well is 86 m from a depth between 6,411 m to 6,496 m, covering the Middle–Upper Ordovician. 86 samples were taken, with

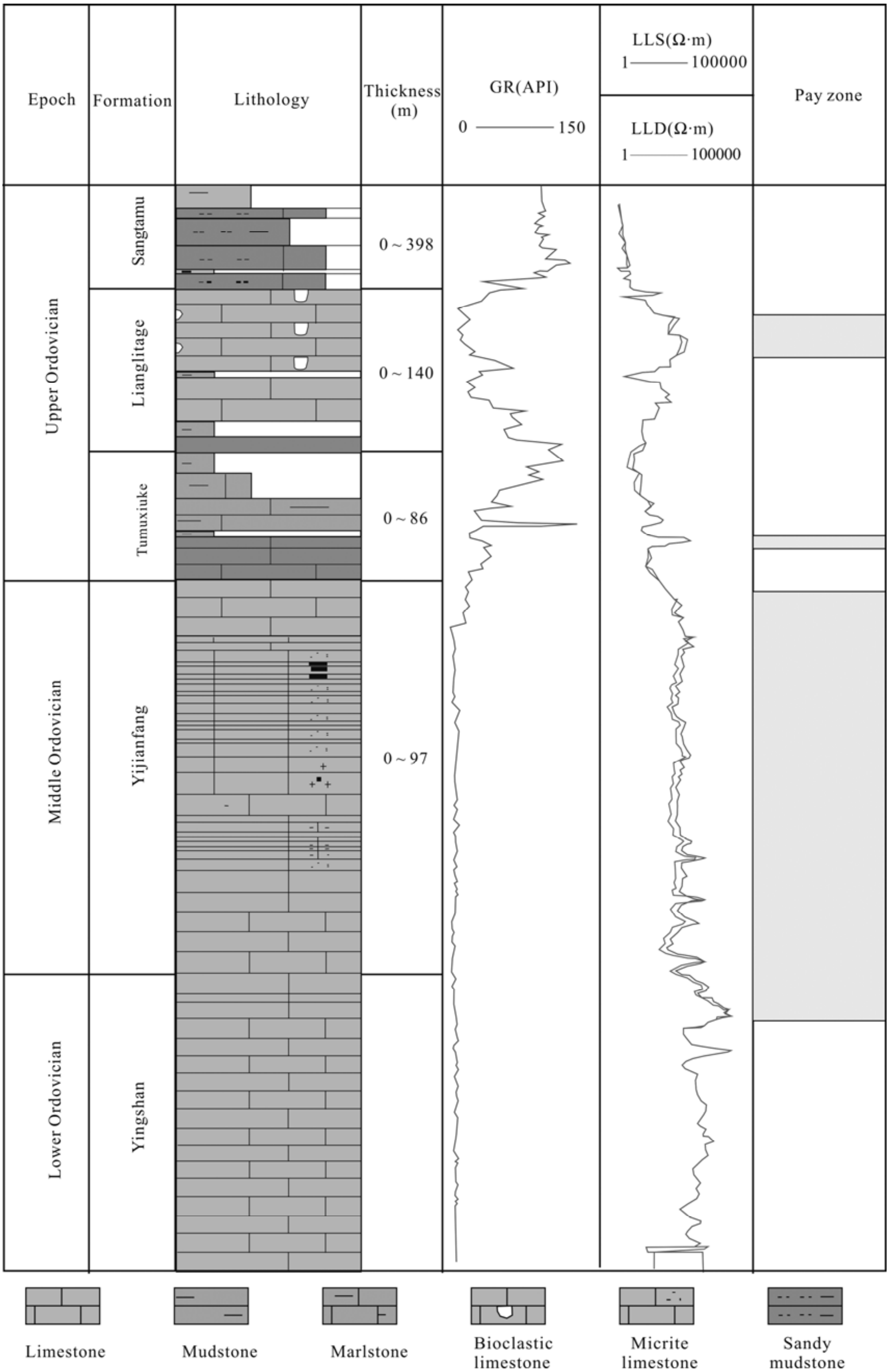

Fig. 4. Stratigraphic framework of the Ordovician System in the Tabei Uplift, Tarim Basin.

one cutting sample in each meter. The LN46 well is located in the high point of Sangtamu south slope of the Lunnan buried-hill-structure of the Tabei Uplift (Fig. 1). The penetration of the well is right up to the Middle Ordovician Yijianfang Formation (which is unpenetrated), with good hydrocarbon shows. The sampled Ordovician interval is 87 m from a depth between 6,122 m and 6,208 m. Samples points are not continuous due to the absence of cores and cuttings, with 1–4 samples of cores and one cutting samples in each meter. The total points counted are 25 core-samples and 25 cutting samples.

3.2 Rock-Eval and TOC analysis of samples

Prior to sample preparation, QA/QC omits samples that may be affected by weathering and potential contaminations. The samples were washed in distilled water to remove any additives from drilling mud. Then, these samples were crushed and milled to 80 mesh after drying for 5 h at 55 °C and were sealed in a glass bottle before the measurements were conducted.

The Rock-Eval-6 analyzer was used to generate all the Rock-Eval results on source rock samples. The initial temperature of pyrolysis was set at 300 °C and held for 5 min. Then, the temperature was programmed to increase to 650°C at a heating rate of 25 °C/min and then was allowed to decrease naturally. The amount of rock samples routinely loaded for the Rock-Eval analysis is 100 mg. In the TOC analysis, each sample was weighted to 300 mg, using the CS-230HC machine. Inorganic carbon was removed by dripping dilute hydrochloric acid onto the sample until no bubbles were formed, and the samples were then neutralized by rinsing several times in ultrapure water. Then, they were dried at a low temperature (approximately 40°C) and were finally incinerated with oxygen at a high temperature to convert the TOC content to CO_2. An infrared detector was used for the measurements.

The GBW (E)070037a with a 8.2±0.3 mg/g S_2 and 439±2 °C T_{max} has been used as a standard rock sample for the purpose of QA/QC of the Rock-Eval and TOC experiments. To ensure the consistency of the Rock-Eval and TOC data generated over time, the standard sample was analyzed at both the beginning and end of every batch of samples as well as between every 6 and 10 samples within the batch.

3.3 Results

QA/QC removes 5 and 12 abnormal data with extremely high or low T_{max} of the YW2 well and LN46 well samples, respectively. Among the 78 samples from the Middle–Upper Ordovician in well YW2, 71 have with low present-day TOC (accounting for 91 %), ranging from 0.09% to 0.45%; S_1 of present-day low-TOC carbonates ranges from 0.01 to 0.61 mg/g, and S_2 from 0.06 to 0.48 mg/g (Fig. 5). Among the 38 samples of Middle–Upper Ordovician in well LN46, 38 of them have low present-day TOC (accounting for 100 %) from 0.05% to 0.49%; S_1 from 0.03 to 3.38 mg/g and S_2 from 0.05 to 1.03 mg/g (Fig. 6).

3.3.1 Distinguishing by the mass balance approach

The results showed that the Q_{rm} of the YW2 well ranges from 0.40–0.42 kg/m^3, with an average of 0.41 kg/m^3, while Q_r lies between 0.03 and 2.95 kg/m^3. The $Q_d \geq 0$ interval of the YW2 well is distributed in the depth of 6452–6487 m in the Yijianfang Formation, showing that hydrocarbon expulsion occurred in the present-day low abundance carbonate source rock (Fig. 5). For the LN46 well, Q_{rm} ranges from 0.49–0.51 kg/m^3, with an average of 0.50 kg/m^3, and Q_r is between 0.07 and 11.39 kg/m^3. The present-day low abundance carbonate with hydrocarbon expulsion mainly distributed in the 6122–6144 m range in the Tumuxiuke Formation (based on 38 samples in the study) (Fig. 6).

3.3.2 Characteristics and factors

3.3.2.1 Depth

Due to the capillary sealing of the rock pore throat, the residual liquid hydrocarbons in the source rock cannot be expelled (Pepper, 1992; Sandvik et al., 1992; Pang Xiongqi et al., 1993). The size of rock pore throat and the change of porosity and permeability are primarily controlled by the compaction effect. Shallow-depth rocks are under relatively weak compaction with relatively large porosity and pore throat radius, leading to relatively small capillary sealing. Therefore, the saturation of the critical residual liquid hydrocarbon to expel is relatively small. The compaction effects on the rocks suffered grow with increasing depth; porosity and pore throat radius become small, and the resistance-forces increase. Thus, the expulsion of liquid hydrocarbons is difficult, and the critical residual-oil saturation for independent phase expulsion required is large. In contrast, with increasing depth, the maturity of source rock grows and the hydrocarbon generation amount increases.

According to the previously introduced principle of mass balance and the hydrocarbon expulsion model (Fig. 2), we statistically analyze the changes in residual amount (S_1/TOC), with the depth of carbonates in the Tabei Uplift and discuss the effect of depth on source rock expelling hydrocarbons (Fig. 7). The results show that the hydrocarbon residual amount of carbonates has an increasing trend first, followed by a decreasing trend with depth and around a depth of 4800 m (VR_E is about 1.0%;

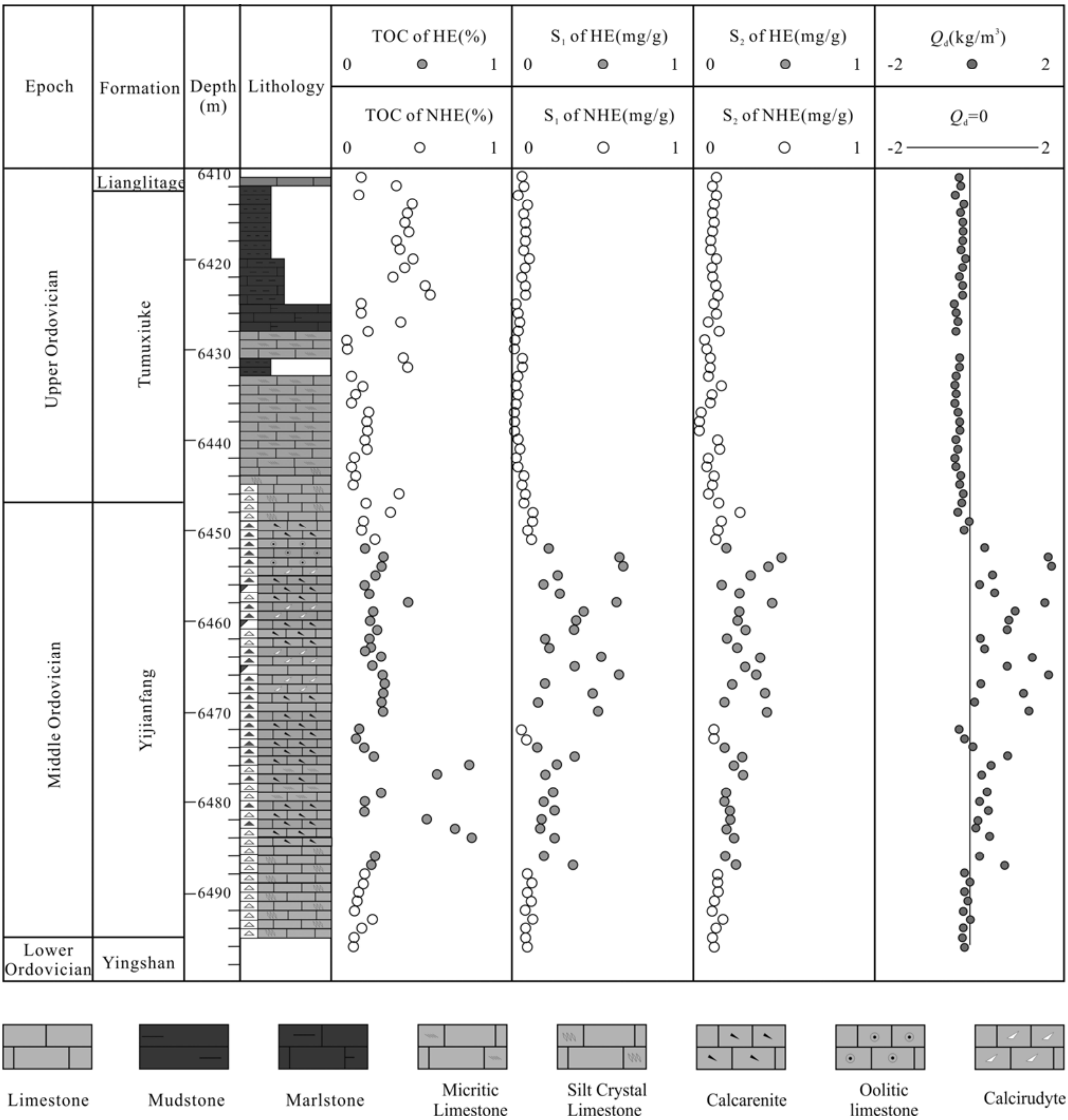

Fig. 5. Identification results and characteristics of the present-day low-TOC carbonate source rock in the Middle–Upper Ordovician in the YW2 well (location is shown in Fig. 1a). In the figure, HE means carbonates have hydrocarbon expulsion during their history and NHE means carbonates have no hydrocarbon expulsion.

before the oil cracking to gas stage, S_1/TOC decreasing due to oil cracking can be excluded). Thus, it is indicated that above 4800 m, the hydrocarbon generation amount is insufficient to push against the capillary sealing; therefore, expulsion cannot occur. The reason for decrease in the residual amount with increasing depth, after reaching the expulsion threshold, is because with the increase in depth, the formation temperature and the pressure increase gradually. The rising temperature reduces the viscosity of the hydrocarbon components, and enhances the molecular activity, which favor hydrocarbon migration. The increasing pressure can increase the solubility of crude oil in natural gas and provide the motive force for migration (Pang Xiongqi et al., 1993).

3.3.2.2 Pyrolysis parameters and their assemblage

We investigate the effect of pyrolysis parameters including S_1, S_2, T_{max} (VR_E), and TOC of the YW2 well and the LN46 well from the Rock-Eval measurements, and

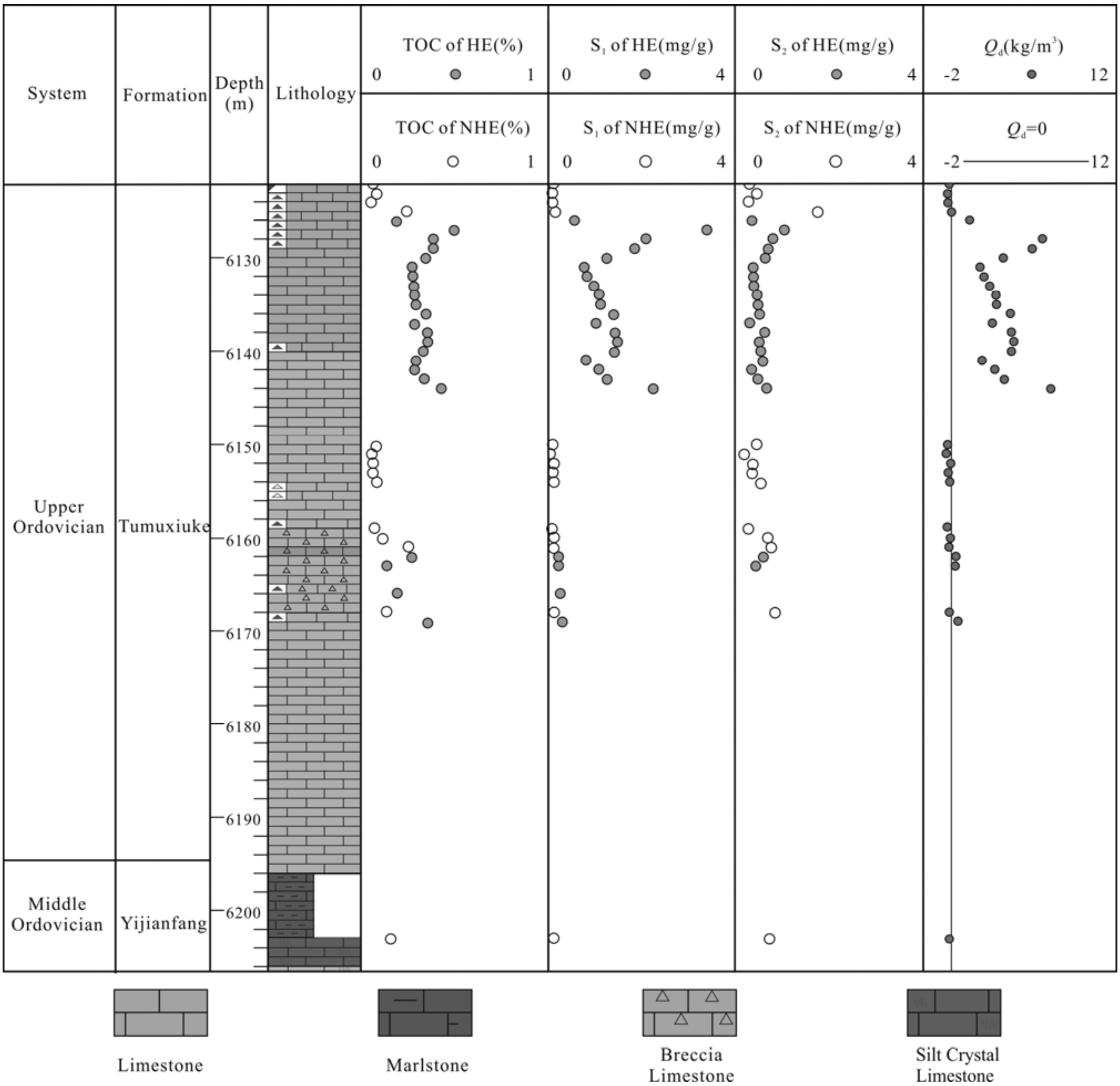

Fig. 6. Identification results and characteristics of the present-day low-TOC carbonate source rock in the Middle–Upper Ordovician in the LN46 well (location is shown in Fig. 1a). In the figure, HE means carbonates have hydrocarbon expulsion during their history and NHE means carbonates have no hydrocarbon expulsion.

their assemblages such as S_1/S_2, S_2/S_1, (S_1+S_2), $S_1/(S_1+S_2)$, S_1/TOC, S_2/TOC and $(S_1+S_2)/TOC$, which can reflect the hydrocarbon generation and retain capability (Fig. 8).

Each factor has a good relationship with Q_d, among which S_2/S_1 and T_{max} (VR_E) are negatively correlated with Q_d and other factors are positively correlated with Q_d (Fig. 8). S_1 and S_1/TOC are absolute and relative residual hydrocarbon amount (Jarvie, 2012). Large values of them relate to large possibility to exceed the minimal amount of hydrocarbon needed to saturate the source rock porosity, i.e., large Q_d (Figs. 8a and 8j). Large values of S_2 and S_2/TOC correspond to large hydrogen index, indicating a relatively good type of organic matter (Carroll and Bohacs, 2001) (Figs. 8b and 8k), and large values of (S_1+S_2) and $(S_1+S_2)/TOC$ indicate a relatively good hydrocarbon generation capability of source rocks (Tissot and Welte 1978; Pang et al., 2005), which benefit from the generation of enough hydrocarbons to expel from source rocks (Figs. 8h and 8l). When the generation potential is certain, commonly, a sample with hydrocarbon expulsion (positive large Q_d) has relatively larger S_1 and smaller S_2, making larger S_1/S_2 and $S_1/(S_1+S_2)$ and relevantly smaller S_2/S_1 (Figs. 8f, 8i and 8g). Since the residual amount decreases with increasing depth after reaching the

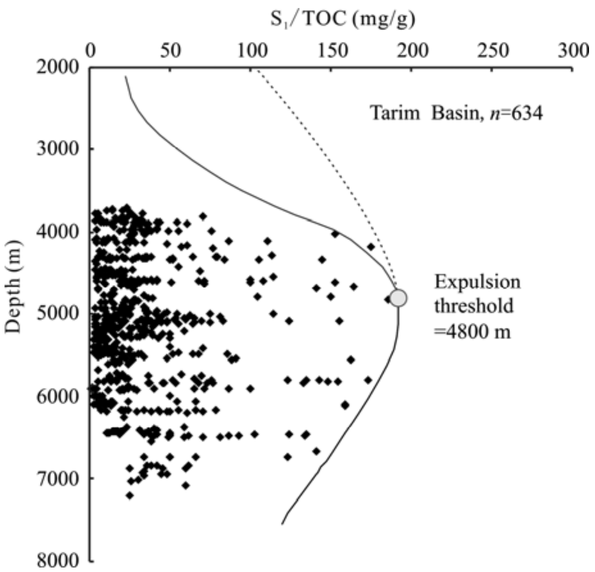

Fig. 7. Relationship between S_1/TOC and depth of carbonate source rock in the Tarim Basin.

expulsion threshold (Fig. 7), the relationships between Q_d and T_{max} (VR_E) is negatively correlated (Figs. 8d and 8e). It is likely the capability of retaining hydrocarbons in a source rock is controlled by both its permeability and the surface property of its pore systems, which may be closely related to its organic content and thermal maturity (Jiang et al., 2016; Chen et al., 2018b); therefore, at the certain maturity, the residual amount of the source rock is positively correlated with TOC (Fig. 8c).

3.3.3 Quick evaluation and validation

According to our quick evaluation model, we firstly obtain the I_R values of samples of the YW2 well and the LN46 well (Fig. 9). Then, we set the 12 input parameters as independent variables including the above mentioned factors, i.e., VR_E, pyrolysis parameters, and their assemblages, and 116 I_R values as dependent variable. Subsequently, we conduct the multivariate linear regression progress to obtain the optimal mathematical model for simulating I_R values with smallest sum of deviation squares between the actual I_{Rn}^{0} and the calculated I_{Rn}. Multivariate linear regression is generally based on two assumptions: first, all random variables are independent, and second, each variable is linearly related to the function. However, the two assumptions are not always suitable in many cases. We perform stepwise regression progress between I_R and all the variables to avoid these deficiencies and to select the reliable factors. Eventually, we obtain several models numerically simulating I_R values, of which, the optimal model with the smallest sum of deviation squares between the actual I_{Rn}^{0} and the calculated I_{Rn} can be expressed as Equation 14 with R=0.925, and R^2=0.856.

$$I_R=0.001\cdot(S_1+S_2)/TOC+0.787\cdot TOC-0.749\cdot VR_E-0.055\cdot S_2/S_1+0.593\cdot S_2+1.067 \quad (14)$$

To verify the reliability of the quantitative model, we compared the calculated values of I_R with those from the Rock-Eval pyrolysis measurements (i.e., measured I_R as shown in Fig. 9). The correlation coefficient (R^2) between the calculated I_R and the measured I_R is 0.829, revealing a good correlation (Fig. 10). Thus, it is feasible to use fitting equation to simulate the I_R values in the Middle–Upper Ordovician Formation of the YW2 well and LN46 well. In a further analytical study of calculated I_R value distribution among samples with and without hydrocarbon expulsion (Fig. 11), we find that the two distribution curves are crossed over the I_R range from −0.25 to 0 (with 50% of frequency of each samples); when $I_R \geq 0$, 92% of samples are with hydrocarbon expulsion; and when $I_R \geq 0.25$, 100% of samples are with hydrocarbon expulsion (Fig.11). Compared with the identified source rock from the mass balance approach, the identification results according to our quick evaluation model match well with a detection rate as high as 87% (101 correct in 116 samples) (Figs. 12 and 13). Therefore, we can identify the present-day low-TOC carbonates with hydrocarbon expulsion simply using the calculated $I_R \geq 0$. Moreover, I_R is positively correlated to (S_1+S_2)/TOC, TOC and S_2 (Equation 14). Thus, larger positive I_R values indicate better quality of the present-day low carbonate source rocks.

4 Discussions

Previous studies have confirmed that there are two sets of high organic matter abundance marine source rocks (present-day TOC > 0.5%) in the Tarim Basin, specially from the Cambrian–Lower Ordovician and the Middle–Upper Ordovician (Zhang Shuichang et al., 2004; Li et al., 2015). The crude oils generated by the two sets of source rocks have remarkable differences (Zhang et al., 2000; Sun et al., 2003; Pan et al., 2009; Cai et al., 2015; Li et al., 2015; Pang et al., 2016). Commonly, the regular steranes of the oil from the Cambrian–Lower Ordovician source rocks display "oblique type" or "reverse-L type" ($C_{27} \leq C_{28} < C_{29}$); conversely, oil from the Middle–Upper Ordovician source rocks typically exhibit different features with "V type" regular steranes ($C_{27} > C_{28} < C_{29}$) (Zhang et al., 2000; Li et al., 2015). An oil-source correlation study was conducted based on biomarker characteristics between the crude oil samples from discovered oil accumulations and present-day low carbonates with hydrocarbon expulsion in the YW2 well (Chen et al., 2018a). The result suggests that crude oils in the Yingmaili, the Halahatang and the Lungu oilfields in

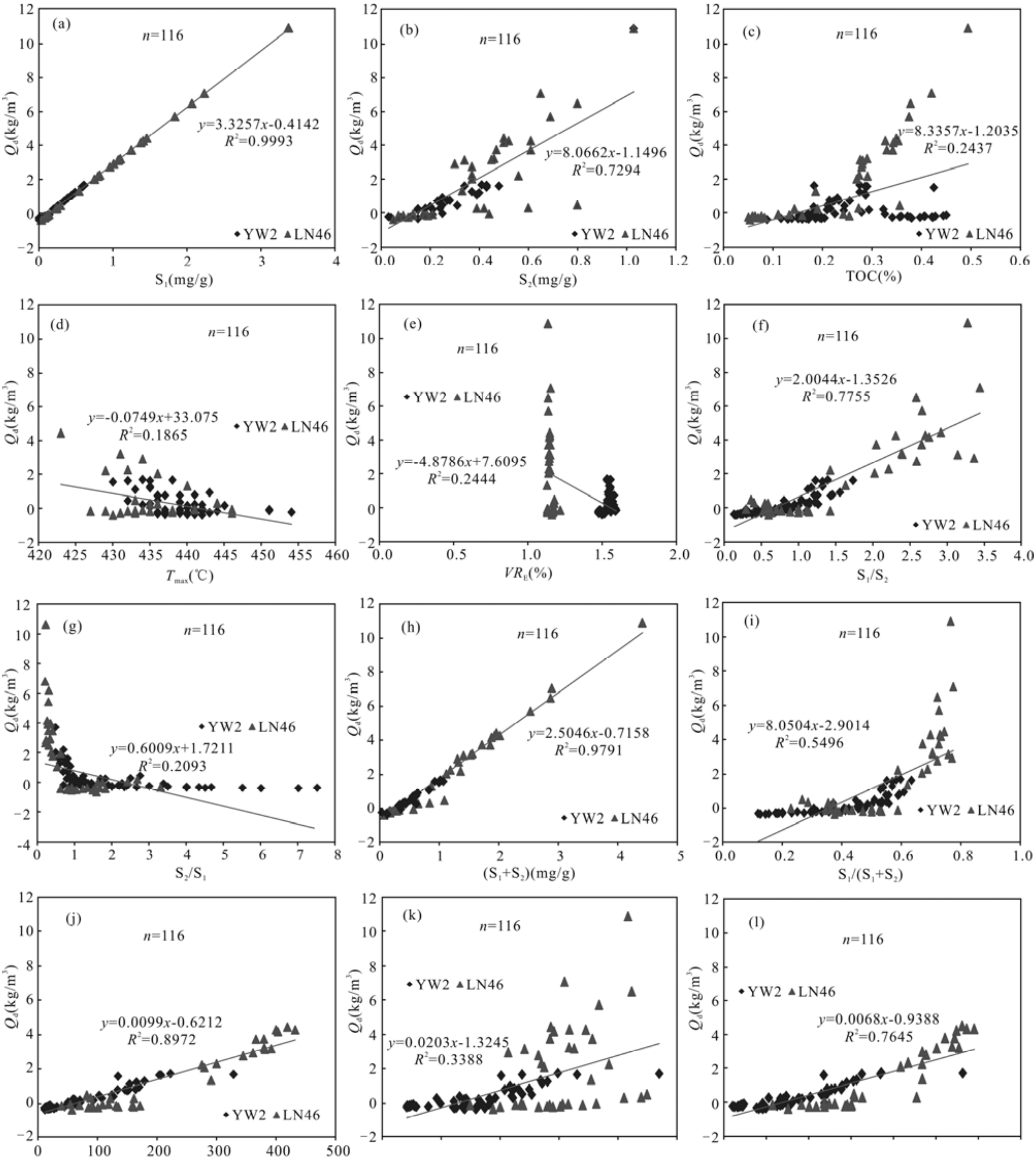

Fig. 8. Cross plots showing relationships of Q_d with pyrolysis parameters and their assemblages of the YW2 well and the LN46 well from Rock-Eval measurements.
(a), S_1; (b), S_2; (c), T_{max} ; (d), VR_E ; (e), TOC; (f), S_1/S_2; (g), S_2/S_1; (h), (S_1+S_2); (i), $S_1/(S_1+S_2)$; (j), S_1/TOC; (k), S_2/TOC; (l), (S_1+S_2)/TOC.

the Tabei Uplift have similar biomarker fingerprints compared with the oil extracts of present-day low-TOC carbonates in the YW2 well with respect to sterane distribution (C_{27}, C_{28} and C_{29} regular steranes), showing a "V" shaped trend (Chen et al., 2018a); this indicates that the crude oils accumulated in the Tabei Uplift may be contributed to by the expulsion of the present-day low-TOC carbonates from the Middle–Upper Ordovician in the Tarim Basin.

By the application of the quick evaluation model on Rock-Eval dataset of the 14 wells with the Middle–Upper Ordovician Formations penetrated in the Tabei Uplift, we

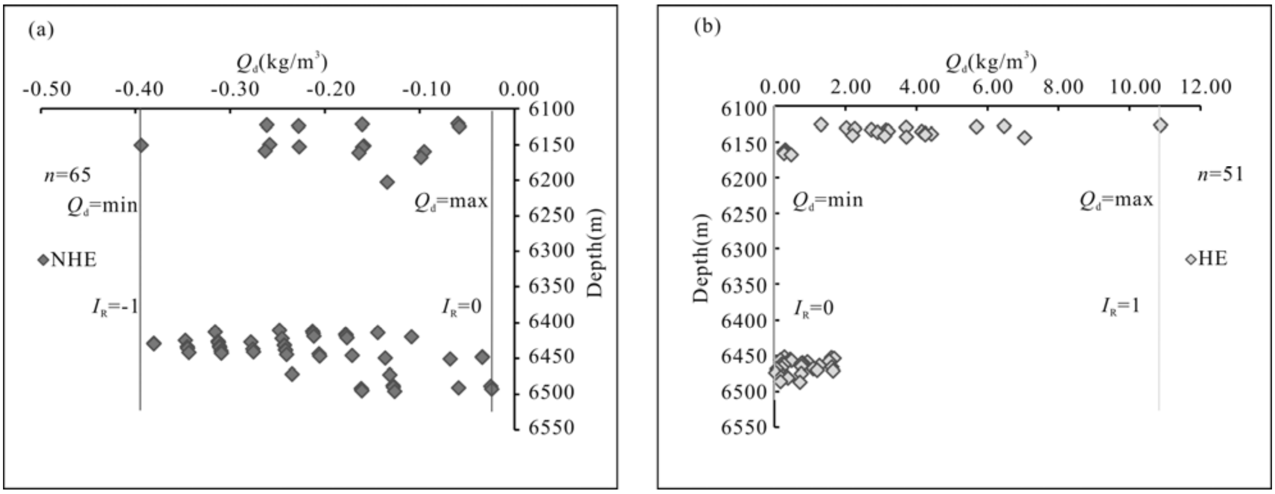

Fig. 9. Cross plots showing process of designing I_R values of samples of the YW2 well and LN46 well.

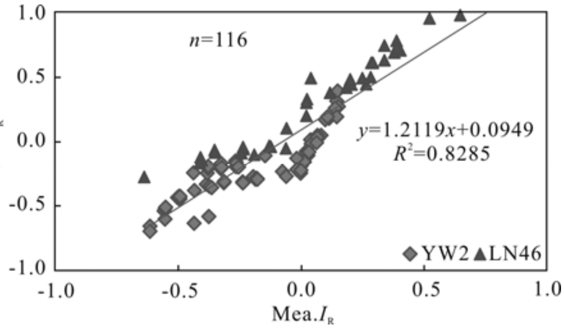

Fig. 10. Cross plots showing relationship of the calculated I_R based on proposed model and the measured I_R based on measurements of samples in the Middle–Upper Ordovician in the YW2 well and the LN46 well in the Tabei Uplift.

quickly identified the present-day low-TOC carbonates with hydrocarbon expulsion. We the obtain thickness distribution of present-day low TOC carbonates with the hydrocarbon expulsion, which contributed to oil accumulation (Fig. 14). Employing a widely applied method of evaluating hydrocarbon generation and expulsion amount based on expulsion threshold (Pang et al., 2005), we preliminarily estimated the quantities of the hydrocarbon expulsion amount from the Middle–Upper Ordovician present-day low TOC carbonate source rocks in the Tabei Uplift of 11.87 × 10^9 t oil equivalent. The amount we calculated represents the smallest possible value because Rock-Eval data are not continuous. If 10% of expelled hydrocarbons were trapped and combined with the resources from high TOC carbonate source rocks estimated in the third round of national resource assessment, the total resource potentials can explain the 3P oil reserves, which are higher than the total resource potential by considering the high TOC Cambrian source rocks (TOC>0.5%) alone. This provides insights into the long-standing controversy regarding the major source rocks contributing to the hydrocarbon resources in the carbonate platform in the basin among geologists and geochemists. In addition, this indicates that the contribution to the hydrocarbon accumulations from the present-day low-TOC source rocks in the Middle–Upper Ordovician succession can be significant in the basin.

In principle, checking the positive and the negative of the Q_d can identify the present-day low-TOC carbonate source rocks expelled hydrocarbons. However, the values of Q_d range from −0.39 to 12.88 kg/m^3 (the YW2 and the LN46 well); the contrasts of 0 to −0.39 and 12.88 to 0 are

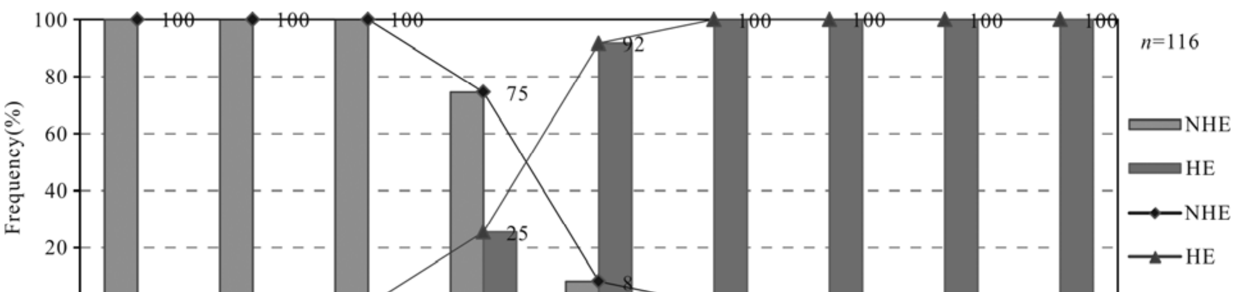

Fig. 11. Statistical analysis of the calculated I_R distribution of samples from the YW2 well and the LN46 well in the Tabei Uplift. NHE and HE represent samples without and with hydrocarbon expulsion, respectively.

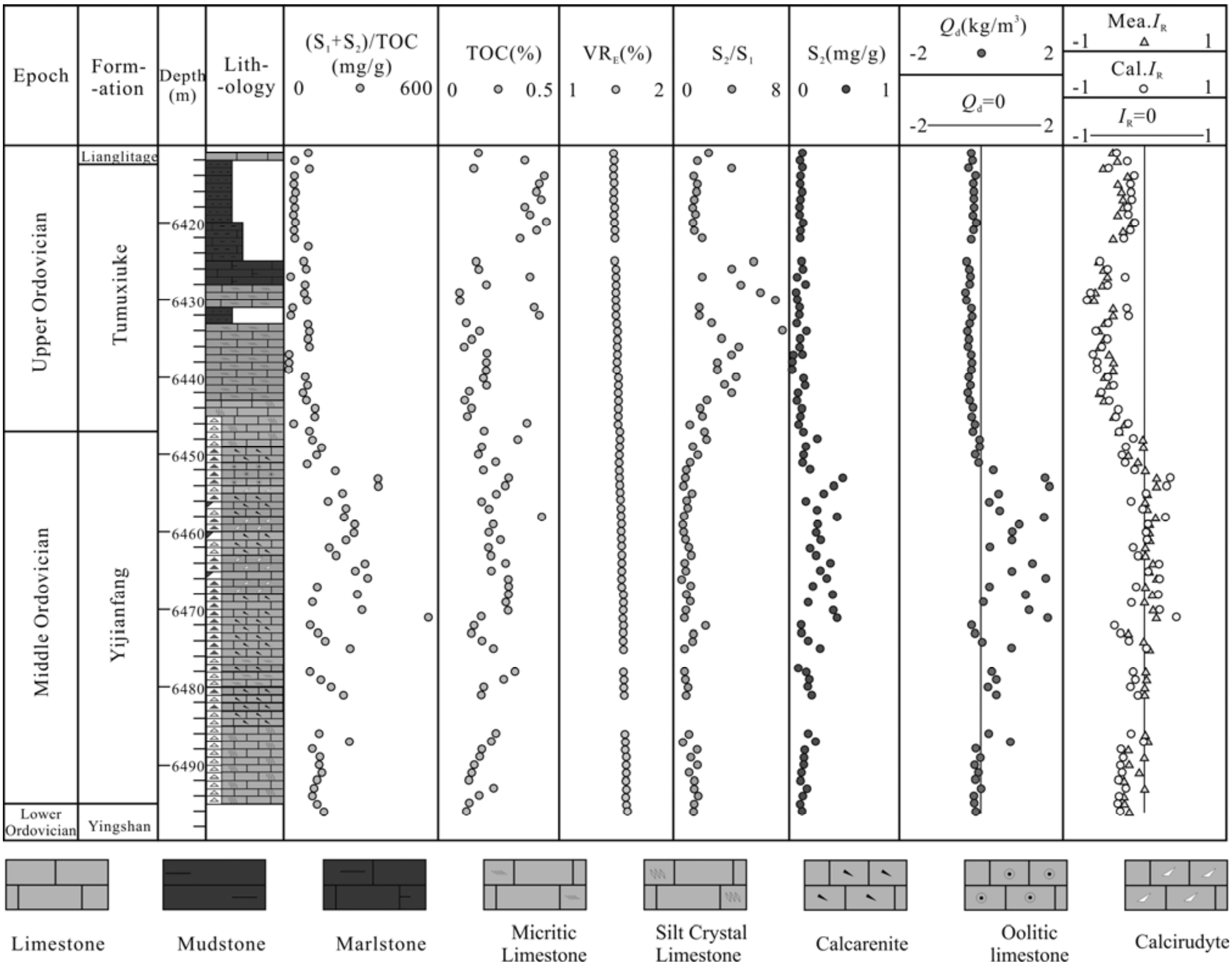

Fig. 12. Comparison of calculated I_R based on proposed model and measured I_R based on measurements of samples in the Middle–Upper Ordovician in the YW2 well in the Tabei Uplift.

greatly unbalanced. The sum of deviation squares of predicted and actual Q_d can be large. Therefore, identifying the HE and NHE in other dataset based on directly checking the positive and negative of predicted Q_d values remains high uncertainty. Renormalized I_R values were assigned from −1 to 1. The contrasts of 0 to −1 and 1 to 0 keep balanced. The identification by checking the positive and negative of I_R values can be relatively more accurate. In this study, we provide a quick and cost-effective model herein that can accurately evaluate present -day low-TOC marine carbonate source rock accurately. The advantages of the model include two aspects. The first advantage is the reduction of the multiple complicated geological variables to a few parameters, which can be obtained easily from the Rock-Eval pyrolysis data, making it more widely applicable in present-day low-TOC carbonate evaluation. The second advantage is the optimization of the complex calculations and simulation processes and, thus, is more competitive when people need to make time-sensitive business decisions. The disadvantage of the model is the evaluation of source rocks can only represent a smallest value since the Rock-Eval data are not continuous.

5 Conclusions

Carbonate source rocks with present-day low TOC are identified by the approach of mass balance. Hydrocarbon expulsion took place in the Yijianfang Formation of the YW2 well between 6,452 and 6,487 m and the Tumuxiuke Formation of the LN46 well between 6,122 and 6,144 m, where the actual free hydrocarbon retained in the source rock surpasses the threshold value.

A quick evaluation model is built to predict present-day low-TOC carbonate source rocks by checking the positive or the negative of the dimensionless I_R. Positive I_R corresponds to samples having expelled hydrocarbons and larger positive I_R values indicate better quality of the present-day low carbonate source rocks. I_R can be calculated using the parameters (S_1+S_2)/TOC, TOC, VR_E,

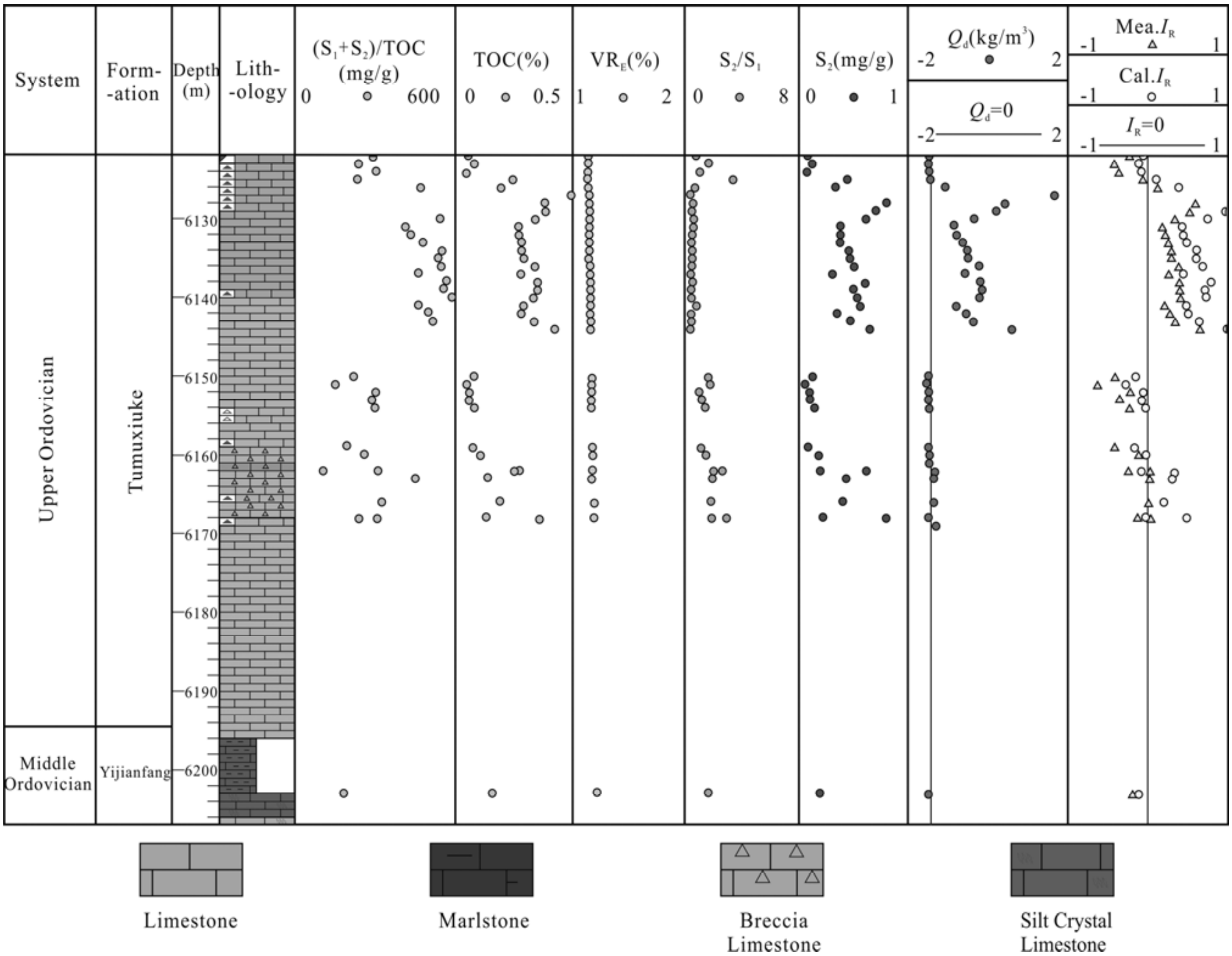

Fig. 13. Comparison of calculated I_R based on proposed model and measured I_R based on measurements of samples in the Middle–Upper Ordovician in the LN46 well in the Tabei Uplift.

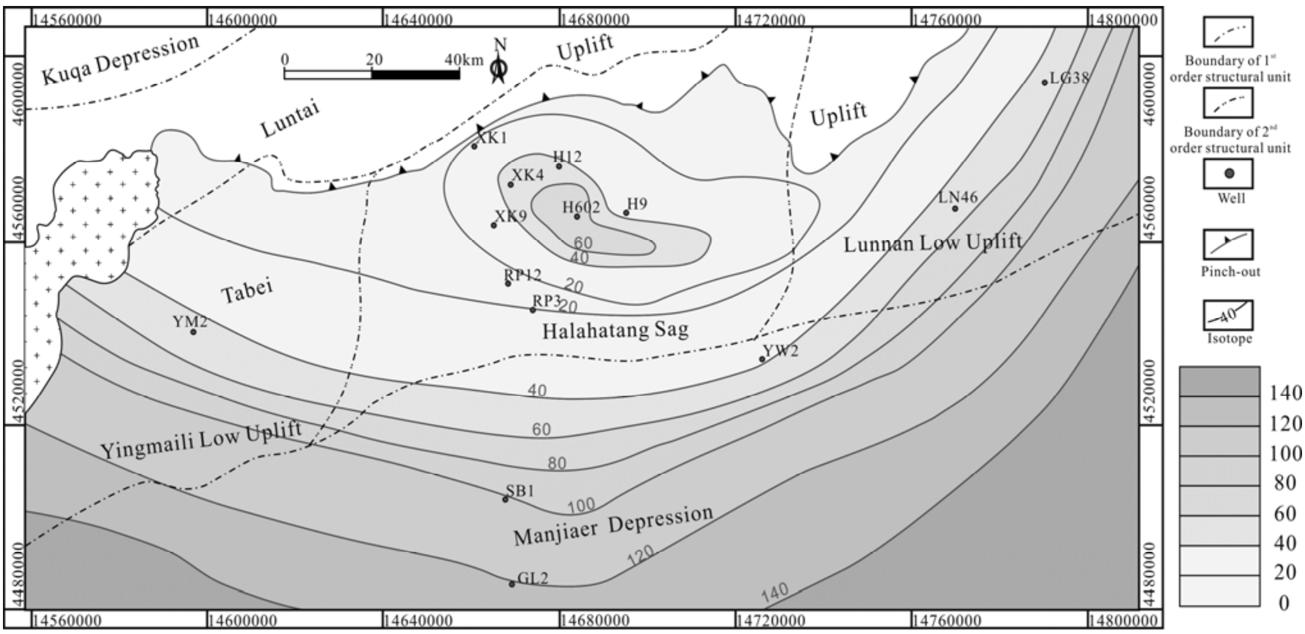

Fig. 14. Map showing the thickness distribution of present-day low-TOC carbonate source rock of the Middle–Upper Ordovician in the Tabei Uplift, Tarim Basin.

S_2, and S_2/S_1. The optimal model has two advantages. The first is the reduction of the multiple complicated geological variables to a few parameters, which can be obtained easily from Rock-Eval data. The second advantage is the optimization of the complex calculations and simulation processes and, thus, is more widely applicable in present-day low TOC carbonate evaluation and competitive regarding to making time-sensitive business decisions.

By applying the evaluation model to the Middle–Upper Ordovician Formation in the Tabei Uplift, the contribution of the present-day low-TOC carbonate source rocks to the hydrocarbon accumulation in the Tabei Uplift is primarily evaluated to be 11.87×10^9 t oil equivalent.

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