Analysis on Log Response Characteristics of Oil Shale and In-situ Mining Geological Evaluation in Qingshankou Formation of South of Songliao Basin

Guihua Tan

Exploration and Development Research Institute of Daqing Oilfield Company Ltd., Daqing 163712, China

Abstract. In order to study the log response characteristics of oil shale in Qingshankou formation of the south of Songliao basin, the geology of in-situ mining of oil shale in this area is preliminarily evaluated, so as to provide scientific basis for in-situ mining of oil shale in this area. Based on the log response principle of oil shale, the Qingshankou formation oil shale in this area is identified qualitatively, and the in-situ geological parameters of oil shale are analyzed in combination with the characteristics of oil shale. The results show that the oil shale of Qingshankou formation in the south of Songliao basin is with the log response characteristics of high natural gamma, high resistivity, high acoustic time difference, and low density, and the organic carbon owns the best correlation with resistivity and density logs. Through analysis of the geological parameters affecting in-situ oil shale mining, the geological parameters affecting in-situ oil shale mining include oil content, thickness, burial depth, mineral type and its content, organic matter type and its maturity, water content, sulfur content, rock assemblage characteristics, ore body distribution characteristics, and dip distribution characteristics, etc.

Keywords: southern part of Songliao basin; Qingshankou formation; oil shale; log response characteristic; in-situ mining geological evaluation.

1. Introduction

The Songliao basin contains multiple layers of oil shale with industrial value, which are of favorable quality characteristics and huge reserves, among which the Qingshankou formation in the cretaceous period has good geological conditions for oil shale formation [1,2]. Oil shale is usually defined as a fine-grained sedimentary rock containing organic matter, which produces a large amount of oil and combustible gas during pyrolysis. Its oil content is over 3.5%, and its calorific value is generally 4.18kJ/g or more than that [3-5]. It is of petrological characteristics, physical properties, organic component characteristics, quality characteristics, and geochemical characteristics [6]. Logging evaluation of oil shale began in the 1940s, and its logging identification has gone through a development process from single parameter identification to multi-parameter identification, and from qualitative to quantitative identification [7]. At present, with the increasing pressure of environmental protection and the gradual...
development of in-situ oil shale mining technology in China, the oil shale of qingqing pass is of great development potential [8].

In summary, the oil shale formed in the Qingshankou formation area in the south of Songliao basin during the post-rift thermal sedimentation period is mainly studied in this study. The natural gamma-ray (GR) curve, resistivity (RT) curve, acoustic time difference (AC) curve, and density (DEN) curve are selected to carry out qualitative identification for Qingshankou formation oil shale, and the logging response characteristics are analyzed. Through the study of oil content, thickness, burial depth, mineral type and its content, organic matter type and its maturity, water content, sulfur content, rock assemblage characteristics, ore body distribution characteristics, and dip angle distribution characteristics of oil shale, the geological factors conducive to the implementation of in-situ mining technology are analyzed and the stratification is determined.

2. Methods

I: the oil shale’s log response characteristics are as follows. Based on the principle of log response of oil shale, influence factors such as shale natural gamma logging value, resistivity log, density log and sonic moveout log value are analyzed. The relationship between the four response values and the total organic carbon content (TOC) is determined through the correlation intersection figure, the oil shale is identified qualitatively by the density curve of response value.

II: the oil shale in-situ mining geological evaluation is as follows. Through the study of oil content, thickness, burial depth, mineral type and its content, organic matter type and its maturity, water content, sulfur content, rock assemblage characteristics, ore body distribution characteristics, and dip angle distribution characteristics of oil shale, the geological parameters affecting in-situ mining of oil shale are analyzed to determine the strata in favor of in-situ mining of Qingshankou formation.

3. Results and discussion

3.1. Log response of oil shale

I. Gamma ray logging.

Natural gamma ray logging responds to oil shale ore bodies by detecting the natural gamma intensity in oil shale [9]. The main factors affecting the natural gamma logging value of oil shale are the contents of organic matter and clay minerals. Because of the strong adsorption capacity of organic matter and clay minerals, radioactive elements can be centralized. As shown in figure 1, there is no correlation between natural gamma ray and organic carbon content, and the correlation coefficient $R^2=0.1657$. It shows that the logging response of oil shale in the study area is mainly related to clay minerals in oil shale. According to the investigation, the content of clay minerals in Qingshankou formation oil shale is very high.

![Figure 1](image-url)
II. Resistivity logging.

Resistivity logging responds to oil shale ore bodies by measuring the conductivity of oil shale. The main factors affecting oil shale resistivity logging value are the content of organic matter. Due to the poor conductivity of organic matter, the conductivity of rock becomes worse as the content of organic matter in rock gradually increases, and the resistivity of rock gradually increases [10]. As shown in figure 2, resistivity logging is of favorable positive correlation with organic carbon content, with correlation coefficient $R^2=0.8227$, that is, the resistivity increases with the increase of organic carbon content.

![Resistivity logging correlation](image)

**Figure 2.** Correlation chart of organic carbon and resistivity logging curve.

III. Sonic logging.

Acoustic velocity logging of oil shale is mainly responsive to the change of lithology. Under the condition that the time difference response of each component to the acoustic wave remains unchanged, the larger the organic carbon content and the clay mineral content are, the greater the acoustic time difference is. Therefore, sound velocity logging mainly responds to the content of organic matter and clay minerals. As shown in figure 3, the acoustic time difference is of favorable positive correlation with the organic carbon content. The correlation coefficient $R^2=0.4034$, that is, the acoustic time difference increases with the increase of the organic carbon content. However, the correlation between them is lower than that between resistivity and organic carbon, for the oil shale in the study area contains high content of clay minerals, and the acoustic logging response is the result of the interaction between clay minerals and organic matter.
IV. Density logging.

Density logging is to measure the volume density of oil shale formation to respond to the formation of oil shale. The main factors affecting oil shale density logging are the contents of organic matter and heavy minerals. Compared with terrigenous clastic minerals, clay minerals, et al, the density of organic matter is low, and heavy minerals are relatively denser than it. As shown in figure 4, density logging is of favorable negative correlation with organic carbon content, and the correlation coefficient $R^2=0.8022$, that is, the density decreases with the increase of organic carbon content.

3.2. Qualitative identification of oil shale

As shown in figure 5, oil shale is mudstone due to its rich organic matter and lithology. Therefore, the oil shale of Qingshankou formation is of the log response characteristics of high natural gamma, high resistivity, high acoustic time difference, and low density, that is, the logging curve is often characterized by “three high and one low” at the development layer of oil shale. According to this feature, the oil shale in the studied area can be well identified.
3.3. Geological evaluation of in-situ mining of oil shale

I. Oil content.

Oil content is the most important index to judge oil shale mineral. The oil content is also a crucial geological parameter for in-situ geological evaluation of oil shale mining, and only when the oil content reaches a certain standard can in-situ mining be valuable [11]. According to ICP and MIT in-situ mining technology, the oil content of oil shale suitable for in-situ mining should be 3.5%, and the higher the oil content is, the better the in-situ mining level of oil shale is. The oil content of QS3 in Qingshankou formation is up to 10.2%, the minimum oil content is 3.6%, and the average oil content is 5.8%. Therefore, it is conducive to in-situ mining of oil shale.

II. Thickness.

Under the condition of the same oil content, the larger the thickness is, the more favorable it is for in-situ mining of oil shale [12]. According to the MIT in-situ mining technology, the thickness of a single layer of oil shale suitable for in-situ mining should be 1m, and the thickness requirement increases as the oil content decreases. The maximum thickness of QS3 in Qingshankou formation is up to 13m, the minimum is 0.75m, and the average thickness is 4.2m. Therefore, it is conducive to in-situ mining of oil shale.

III. Burial depth.

The burial depth of oil shale is an important parameter to evaluate the oil shale resources and optimize the favorable mining area. From the economic point of view, the burial depth of oil shale determines the mining way of oil shale. From the geological perspective, the burial depth of oil shale affects the physical conditions of in-situ mining of oil shale. The deeper the burial depth is, the greater the formation pressure is, which is not conducive to improving the permeability of oil shale after dry distillation, thus is not conducive to the implementation of in-situ horizontal fracturing technology. The QS3 and QS4 oil shale ore beds in Qingshankou formation are mainly buried within 1000 meters, and the formation pressure is relatively low.

IV. Mineral type and its content.

The presence of minerals in oil shale affects the in-situ mining of oil shale. Generally speaking, the more brittle minerals are in oil shale ore beds, the more favorable it is for the implementation of in-situ fracturing technology. In this study, the brittleness of QS3 and QS4 ore beds in Qingshankou formation is evaluated. It can be seen that the brittleness index of QS3 ore bed is between 0.46~0.50, with an
average of 0.48. The brittleness index of QS4 ore bed is 0.47. According to the standard of fracturing shale gas reservoirs in North America (>0.4), the QS3 and QS4 oil shale ore beds are of favorable brittleness, which is conducive to fracturing.

V. Water content.

The water content of oil shale also affects in-situ mining. When the water content of oil shale is too high, it will consume a lot of energy in the heating in the early stage of in-situ mining and increase the cost of mining. And the higher the water content is, the lower the recovery rate of shale oil is. According to the research, the water content of oil shale in QS3 and QS4 ore bed is low, which is conducive to in-situ oil shale mining.

VI. Organic matter type and its maturity.

In in-situ mining, type I kerogen of organic matter is the best, followed by type II kerogen, finally the type III kerogen. When the types of organic matter are the same, the lower the maturity is, the more favorable it is for in-situ mining [13]. According to the characteristics of the oil shale pyrolysis results, the organic matter type of QS3 and QS4 ore beds are type I kerogen and type II kerogen, mainly type I kerogen. The oil shale of QS3 and QS4 ore beds are immature-low mature ($T_{\text{max}} \leq 445^\circ \text{C}$). Therefore, the oil shale of QS3 and QS4 ore beds are conducive for in-situ mining.

VII. Rock assemblage characteristics of roof and floor.

Rock characteristics of oil shale roof and floor are also important geological parameters for evaluating in-situ oil shale mining [14]. Through the investigation of in-situ mining technology, it can be known that the upper cover plate and lower bottom plate of the oil shale suitable for in-situ mining should be as complete as possible, and it is better to be water-resistant mudstone or shale, and the thickness should be greater than the thickness of the oil shale. According to the core observation and experimental test analysis, the lithology of the top and bottom plates of QS3 and QS4 in Qingshankou formation is mainly gray-green, gray and dark gray mudstone, the porosity and permeability of mudstone are small (porosity $<2.7\%$ and permeability $<0.001 \text{mD}$), and its thickness is large and it is continuous, which can be used as a good barrier layer.

VIII. Distribution characteristics.

The distribution characteristics of oil shale are also important geological parameters to evaluate in-situ oil shale mining. Generally speaking, when the thickness of oil shale remains unchanged, the better the horizontal continuity of oil shale is, the better it is for the implementation of in-situ mining technology of oil shale. According to the ore layer comparison and surface distribution characteristics of the study area, it can be seen that the QS3 and QS4 ore beds of Qingshankou formation have a particularly good continuity and are stable.

IX. Dip angle.

The dip angle of oil shale ore beds is also an important geological parameter to evaluate in-situ mining of oil shale. According to the investigation of in-situ mining technology, the dip angle of oil shale seam should be less than 15°. According to the distribution of dip angle in oil shale characteristics, the dip angle of QS3 and QS4 ore beds in Qingshankou formation is between 0° and 6°. The dip angle of QS3 and QS4 ore beds is the type of slow dip angle ($\leq 6^\circ$), which is suitable for in-situ mining.

X. Sulfur content.

Sulfur content is an important geological parameter to evaluate the environmental pollution of oil shale in-situ mining. Generally speaking, the lower the sulfur content is, the less environmental pollution is, it is suitable for in-situ mining [15]. According to the sulfur content characteristics of the oil shale, the sulfur content of the oil shale of QS3 and QS4 formations is lower than 1.0%, which is ultra-low-sulfur oil shale. It is of little potential pollution in in-situ mining and is conducive to it.

4. Conclusion

Through the analysis of the collected samples and logging data, the results show that the oil shale of Qingshankou formation is of the response characteristics of high natural gamma, high resistivity, high acoustic time difference, and low density. According to the features, the oil shale in the study area can be well identified. And the QS3 and QS4 ore beds of Qingshankou formation in the study area are
favorable in-situ mining of oil shale through in-situ geological evaluation. In this study, only the qualitative analysis of oil shale is carried out according to the logging curve, and there is a lack of exploration on quantitative identification. In the following research, the oil shale shall be quantitatively identified to obtain the continuous value of organic carbon. Furthermore, the oil shale shall be further identified quantitatively by delta $\Delta \log R$ technique and multiple regression analysis.

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