Research Article

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Utilizing Integrated Prediction Error Filter Analysis (INPEFA) to divide base-level cycle of fan-deltas: A case study of the Triassic Baikouquan Formation in Mabei Slope Area, Mahu Depression, Junggar Basin, China

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Abstract: The Mahu Depression is an important hydrocarbon-bearing foreland sag located at the north-western margin of the Junggar Basin, China. On the northern slope of the depression, large coarse-grained proximal fan-delta depositional systems developed in the Lower Triassic Baikouquan Formation (T_1b). Some lithologic hydrocarbon reservoirs have been found in the conglomerates of the formation since recent years. However, the rapid vertical and horizontal lithology variations make it is difficult to divide the base-level cycle of the formation using the conventional methods. Spectral analysis technologies, such as Integrated Prediction Error Filter Analysis (INPEFA), provide another effective way to overcome this difficulty. In this paper, processed by INPEFA, conventional resistivity logs are utilized to study the base-level cycle of the fan-delta depositional systems. The negative trend of the INPEFA curve indicates the base-level fall semi-cycles, adversely, positive trend suggests the rise

semi-cycles. Base-level cycles of Baikouquan Formation are divided in single and correlation wells. One long-term base-level rise semi-cycle, including three medium-term base-level cycles, is identified overall the Baikouquan Formation. The medium-term base-level cycles are characterized as rise semi-cycles mainly in the fan-delta plain, symmetric cycles in the fan-delta front and fall semi-cycles mainly in the pro-fan-delta. The short-term base-level rise semi-cycles most developed in the braided channels, subaqueous distributary channels and sheet sands. While, the interdistributary bays and pro-fan-delta mud indicate short-term base-level fall semi-cycles. Finally, based on the method of INPEFA, sequence filling model of Baikouquan formation is established.

Keywords: Mahu Depression; Baikouquan Formation; fan-delta; Integrated Prediction Error Filter Analysis; base-level cycle

1 Introduction

Over the past few decades, Sequence Stratigraphy has been highlighted in geological research in petroleum industry [1]. Cross brought the “base-level” concept [2], which was put forward by Wheeler [3], into the theory of Sequence Stratigraphy, forming High-Resolution Sequence Stratigraphy. However, the base-level is a dynamic surface controlled by many factors, which is difficult to characterize its rise or fall. Researchers usually combine analyses with well logs, seismic data, cores and experience in sequence stratigraphy subdivision. Inevitably, the results would be puzzled by the human factors and uncertainty. Large coarse-grained proximal fan-delta depositional systems developed in the Lower Triassic Baikouquan Formation (T_1b) on the slope area of Mahu Depres-

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sion, the northwestern Junggar Basin, China [4–6]. Due to the complicated lithological and depositional environments, traditional research methods have difficulties in the base-level cycle analysis of these fan-deltas.

Well logs contain comprehensive geological information with well continuity and high resolution, and they are regarded as useful and significant materials in subdividing the base-level cycle. Spectral analysis of signal processing technologies, such as Fourier Transform (FT) [7, 8], Wavelet Transform (WT) [9–13] and Maximum Entropy Spectral Analysis (MESA) [9, 10, 14, 15], have been applied in sedimentary cycles and sequences surfaces during recent decades. On the basis of MESA [16], Integrated Prediction Error Filter Analysis (INPEFA) has been introduced and successfully applied to divide the base-level cycle in several petroleum basins in China [9, 10, 17, 18]. In this paper, INPEFA is conducted on resistivity logs to study the base-level cycle in the single and correlation wells of the Baikouquan Formation in the Mabei Slope Area. One long-term base-level cycle and three medium-term base-level cycles are identified, and the sequence filling model is established for the fan-delta depositional systems.

2 Geological background

As the target geological formation, the Lower Triassic Baikouquan Formation (T_1b) of Mahu Depression, northeastern Junggar Basin, China, is subdivided into three members: the Bai-1 Member (T_1b_1), the Bai-2 Member (T_1b_2) and the Bai-3 Member (T_1b_3). The T_1b_1 is 30–50 m thick, which is mainly composed of grey and red-dark brown conglomerates with grey and light brown pebbly mudstone interbeds. The main reservoir member T_1b_2 is 60–100 m thick. It is composed mainly by dark brown and grey-green conglomerates with light brown-grey and dark brown mudstone interbeds. The T_1b_3 is 40–90 m thick with fine-grained sediments, which is composed of interbeds of grey sandstones, grey and red-dark brown mudstones, and some grey granules (Figure 1a). These coarse-grained sediments were provided by the northwest Zaire and Hala'alat Mountain in the Early Triassic, which formed large coarse-grained fan-delta aprons depositional systems on the gentle slope area, such as the Xiazijie Fan-delta in the Mabei Area and Huangyangquan Fan-delta in the Maxi Area (Figure 1b) [4–6]. In order to divide base-level cycle of fan-deltas, the Xiazijie Fan-delta in Mabei Slope Area is the primary considering object and data sources for this paper.

3 Database and methodologies

3.1 Database

There are more than 60 exploitation wells in the study area. Almost all the wells are measured by conventional logging suites. In general, coarse-grained sediments are less radioactive, while fine-grained sediments are more radioactive. Therefore, gamma ray (GR, API) logs are sensitive to the lithological variation, which is the reason that GR is widely used in the study of High-Resolution Sequence Stratigraphy. According to the 480.39 m cores in 14 wells and conventional logging of cored intervals, however, the above-mentioned understanding is not available in the Baikouquan Formation of Mahu Depression. With the decrease of grain size, the value of GR first decrease and then increase (Figure 2). According to mineral component identification, there are lots of intermediate-acid igneous rocks, such as volcanic tuff, andesite, felsite and granite mixed in the conglomeratic intervals. These igneous rocks are highly radioactive, which results in abnormal high GR values. On the other hand, because of the short transportation distance of the mudstones, the clay particle surface cannot adsorb abundant radioactive materials, resulting in low GR values [19].

Fortunately, with the decrease of grain size, the resistivity (RT , $\Omega \cdot m$) value decrease progressively (Figure 2). It means that conglomerate is less conductive and clay is more conductive in the Baikouquan Formation. Taken Well FN15 for example (Figure 3), determining from the sample logging, there are conglomerates in 2714–2726 m and 2742–2770 m with GR 80 API and RT $32 \Omega \cdot m$. There is an interval of argillaceous rocks in 2726–2742 m with GR 60 API and RT $6 \Omega \cdot m$. The RT value is response to the lithology more effective than GR. To guarantee the accuracy, RT , not GR, is selected to be processed to provide as basic data for this study.

3.2 Basic theory of INPEFA

In information theory, entropy is defined as a measure of signal uncertainty. Proposed by Burg [20], MESA, a method of spectral attribute analysis, can predict the unknown signal according to the known information with given constraints. Within the criterion of maximum information entropy, MESA has an advantage of high spectral resolution and is not limited by unanalyzed object length. What's more, it is equivalent with the autoregressive model [21]. In the given window with N logging records, the prediction

Figure 1: Synthesis columnar section and sedimentary facies map of the Baikouquan Formation in Mahu Depression. (a) Conventional and sample logging of the Baikouquan Formation in Well M134. (b) Sedimentary facies map, fan-delta aprons developed on the slope areas, Xiazijie Fan-delta in Mabei Slope Area is the primary data sources for this paper.

Figure 2: The change relationship between of GR and RT with the grain size in Baikouquan Formation. With the decrease of grain size, the GR first decrease and then increase, and the RT decrease progressively. RT is response to the lithology more effective. The cores are from 480.39 m cored intervals in 14 wells.

error of logging record could be regarded as

$$e_i = x_i - \hat{x}_i = x_i - \sum_{k=1}^m \alpha_k x_{i-k}, \quad i = m+1, \dots, N.$$

x_i ($i=1, 2, \dots, N$) is the true logging value, $\hat{x}_i$ is the prediction value of autoregressive model. If taken 1, $\alpha_1 \dots - \alpha_N$ as filtering factors and e_i as the output of the digital filter, a filter is designed, which is called Prediction Error Filter Analysis (PEFA). It shows the spectral change attribute

Figure 3: Synthetic graph of GR and RT log data and cutting composition in Well FN15. Conglomerates has high GR and RT values, and argillaceous rocks are in low GR and RT values. Intermediate-acid igneous rocks, such as volcanic tuff, andesite, felsite and granite, are the major mineral content, which may result in this unnormal relationship between GR and grain size. The content data is from mineral component identification experimental analysis.

of signals. A further integration of PEFA is called INPEFA, showing the spectral trend attribute of signals.

3.3 Application method of INPEFA

Radically, well logs are the superposition results of various signals. They are the indicators of comprehensive geological information in borehole. Effective information can be obtained from well logs by using the spectral analysis signal processing technique, such as INPEFA. According to the key attributes from well log curves processed by INPEFA, the sedimentary cycles can be subdivided easily. For instance, Figure 4 shows an ideal stratigraphic model including three geological units, with conglomerates at bottom and mudstones at top. LOG means a type of well log curve, on which high values correspond to conglomerates and low values correspond to mudstones. The spectral change attribute of LOG, PEFA is acquired by MESA. The maximum and minimum points of PEFA correspond to lithologic interfaces, which indicates important stratigraphic breaks. The spectral trend attribute of LOG, INPEFA derives trends in the spectral properties of the log. Variations of these trends are related to changes of the depositional environment. The trends and the turning points of the INPEFA curves are crucial and significant in sedimentary cycle research.

An interval with one trend is separated from other intervals with an opposite trend by turning points. If the values increase upward, the INPEFA curve has a positive trend. Or else, the values decrease upward, the INPEFA curve has a negative trend. A point where a negative trend changes to a positive trend is a positive turning point; a point where a positive trend changes to a negative trend is a negative turning point. Mathematically, a positive trend marks an interval through which the prediction error filter persistently under-estimates log values in the moving window, while a negative trend marks an interval through which the prediction error filter persistently over-estimates the log values. Geologically, a positive trend represents an interval in which the log values reveals more shaley components than predictions, which can be interpreted as a transgression with gradual base-level rise semi-cycle. A negative trend represents an interval in which the log values indicate more sandy components than predictions; which can be interpreted as a regression with gradual base-level fall semi-cycle [17, 18].

Figure 4: An ideal stratigraphic model for the application of INPEFA. The positive INPEFA trend may indicate base-level rise semi-cycle, and the negative INPEFA trend may suggest base-level fall semi-cycle.

4 Results

4.1 Base-level cycle in single wells

INPEFA is easy and quick for dividing the base-level cycle, which has been finished in single wells. Figure 5 shows the sedimentary microfacies and base-level cycle subdivision of the Baikouquan Formation in Well M17. The INPEFA curve of RT curve is marked as RT_INPEFA.

According to the trend of the RT_INPEFA curve in the Baikouquan Formation, three orders of trend could be identified. From bottom to top, the whole Baikouquan Formation has a positive trend, as first-order trend, which indicates transgression during fan-delta deposition. In three members of the formation, the RT_INPEFA has a second-order trend, symmetric positive-negative, representing medium-term base-level symmetric cycle (MSC1, MSC2 and MSC3). Furthermore, the more detailed third-order trend, indicating the short-term base-level cycles, is easily identifiable in the inner of the medium-term base-level cycle. Three symmetric third-order trends are identified in MSC1, which represent the variation of three short-term base-level symmetric cycles. In the same way, three base-level symmetric cycles and one base-level fall semi-cycle are observed in MSC2, and two base-level symmetric

Figure 5: Base-level cycle subdivision of Baikouquan Formation in M17 well. One long-term base-level rise semi-cycle, three medium-term base-level symmetric cycles and ten short-term base-level cycles are identified.

cycles and one base-level fall semi-cycle are recognized in MSC3. Therefore, using INPEFA, one long-term base-level rise semi-cycle, three medium-term base-level symmetric cycles [22, 23] and ten short-term base-level cycles are identified in the Baikouquan Formation.

The base-level characteristics may be compared with sedimentary facies in Well M17. The thickness of the pro-fan-delta gradually increases upward in the whole Baikouquan Formation, revealing the gradual retrogradation of the fan-delta, which corresponds to the long-term base-level rise semi-cycle. The main sedimentary sub-facies of the T_1b_1 , T_1b_2 and T_1b_3 are fan-delta front, with the medium-term base-level symmetric cycle. The distributary channels of the fan-delta front, the main part of the fan-delta, deposited in the short-term base-level rise semi-cycles. The interdistributary bays and the pro-fan-delta mud mainly developed in the short-term base-level fall semi-cycles.

4.2 Base-level cycle in correlation wells

The Mabei Slope Area of the Mahu Depression is a gently-dipping monoclinical slope whose tilts towards southeast with abundant coarse-grained sediments supply. Due to the thin Lower Triassic Baikouquan Formation and the low resolution seismic data, the division of base-level cycle is difficulty in the correlation wells. Base-level cycle of series correlation wells is studied using INPEFA in this study as well. Taken Well X74 to M16 for example, the result is shown in Figure 6. The linear distance between Well X74 and Well M16 is about 25 km.

In the fan-delta plain, the RT_INPEFA curve has a positive second-order trend mainly (Well X74 in MSC1, MSC2 and MSC3; and Well X92 in MSC2, *i.e.*), suggesting the medium-term base-level is rise semi-cycle mainly. The third-order positive trend in the braided channels sedimentation indicates a thick short-term base-level rise semi-cycles. The sedimentation or erosion of the interchannels reflects a thin short-term base-level fall semi-cycles. In the fan-delta front, the RT_INPEFA curve shows a symmetric positive-negative second-order trend (Well X92 in MSC3; MSC1, Well X7202 in MSC2 and MSC3; Well X15 in MSC1 and MSC2; and Well M16 in MSC1, *i.e.*), the medium-term base-level is a symmetric cycle, which characterizes a more complete sedimentary record. The third-order positive trend formed by the underwater distributary channels and the sheet sands reflects a short-term base-level rise semi-cycles. The third-order negative trend in interdistributary bays reflects the short-term base-level fall semi-cycles. In the pro-fan-delta, the RT_INPEFA curve has a negative second-order trend mainly (Well AK1 in MSC1, MSC2 and MSC3; and Well M16 in MSC3), which indicates medium-term base-level fall semi-cycles mainly. A small amount of coarse-grained sediments occurs and forms thin sheet sands, reflecting the short-term base-level cycle rise semi-cycles. As the sediments are far away from the provenance, the silt and mud gradually deposit to form thick fine-grained strata, which indicates that the short-term base-level fall semi-cycles. Therefore, the thick sedimentary microfacies including braided channels, underwater distributary channels and sheet sands sediments reflect the short-term base-level rise semi-cycles. On the contrary, the mud-containing sedimentary microfacies such as the interchannels, interdistributary bays and pro-fan-delta mud reflect the short-term base-level fall semi-cycles.

Figure 6: Base-level cycle subdivision in correlation wells of Mabei Slope Area (The position is shown in Figure 1). The INPEFA second-order trend has changed from positive trend mainly in provenance zone to positive-negative in land-water zone and negative trend mainly in lake basin.

Table 1: Characteristics of base-level cycle in different sub-facies of Baikouquan Formation, Mabei Slope Area.

Location	Sub-facies	INPEFA trend	Base-level cycle
Basin edge	Fan-delta plain	Positive mainly	Rise semi-cycle mainly
Land-water transition zone	Fan-delta front	Symmetric	Symmetric
Depression center	Pro-fan-delta	Negative mainly	Fall semi-cycle mainly

5 Discussions

The sequence stratigraphic evolution of an area is controlled by four main factors: tectonic movements, climate, eustasy and sediment supply. The Mahu Depression is located at the front of a foreland basin at the northwestern margin of the Junggar Basin, which is a result of collision and subduction between the Junggar-Turpan and the Kazakhstan Plates during the Late Paleozoic [24–26]. From Permian to Early Triassic, the climate gradually changed from arid-semiarid to warm and moist [4–6]. In the Early Triassic, the lake level rise gradually; the northwestern Junggar Basin was denuded and supplied sufficient sediments for the Mahu Depression and developed fan-deltas [4–6]. Based on the dipositional background and the sequence stratigraphic subdivision from the INPEFA curves, the sequence filling model of the Lower Triassic Baikouquan Formation in the Mabei Slope Area is established in Figure 7.

In the fan-delta plain, the RT_INPEFA curve of MSC1, MSC2 and MSC3 has a positive trend mainly, indicat-

ing a medium-short base-level rise semi-cycles. With the gradual increase of the base-level, sediments accumulate at the edge of basin and develop a retrogradation stacking pattern. In the fan-delta front, the RT_INPEFA curve has both positive-negative trend, which means a medium-short base-level symmetric cycle. In the pro-fan-delta, where sediment accumulation is far away from the provenance, the formation is in hiatus and developed in medium-short base-level fall semi-cycles mainly. Therefore, from the provenance to the center of the Mahu Depression, the sedimentary sub-facies of the fan-delta system gradually transform from fan-delta plain to fan-delta front and pro-fan-delta. Accordingly, in each medium-term base-level cycle, the trend of the RT_INPEFA curve transforms from positive mainly to the symmetric and negative mainly. And the medium-short base-cycle turns from rise semi-cycle mainly to symmetric cycle and fall semi-cycle mainly (Table 1).

Figure 7: Sequence filling model of Baikouquan Formation in Mabei Slope Area. The base-level of medium-term base-level cycles has changed from rise in fan-delta plain to rise-fall in fan-delta front and fall in pro-fan-delta mainly.

6 Conclusions

1. The study emphasizes on the base-level cycle division of the Baikouquan Formation in the Mabei Slope Area based on the method of INPEFA. The positive trend of the INPEFA curve represents base-level rise, while the negative trend represents base-level fall. One long-term base-level rise semi-cycle, including three medium-term base-level cycles, is identified overall the Baikouquan Formation.
2. From the provenance to the lake center, the sedimentary sub-facies gradually transform from fan-delta plain to the fan-delta front and pro-fan-delta. The medium-term base-level cycles gradually changes from the rise semi-cycles to rise-fall symmetric cycle and fall semi-cycles. For the short-term base-level cycles, braided channels, underwater distributary channels and sheet sands sedimentary se-

quence signifies that the base-level rise semi-cycles, while interchannel, interdistributary bays and pro-fan-delta mud reflects that the base-level fall semi-cycles.

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