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Analysis Method and Application of Multiple Antiquities Sources in the Shahejie Formation of the Paleogene in the Southern Bohai Sea

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Abstract

B Oilfield is the most representative mid to deep oil field in the Bohai Sea, with the main oil bearing intervals being the upper and middle Shahejie-3 sections of the Paleogene Shahejie Formation. Through the development of ancient landforms, characterization of material source channels, analysis of missing heavy mineral sources, and seismic reflection characteristics of multiple material source missing, the material sources of the middle and upper Shahejie-3 sections are analyzed. During the sedimentation period of the II oil formation in the middle section of the Shasan Formation, the study area was mainly dominated by the Kendong Uplift source rocks; During the sedimentation period of the I oil formation in the middle section of the Shasan Formation, there were three material sources in the study area, namely the Kendong Uplift, the Laibei Low Uplift, and the Weibei Uplift. The Kendong Uplift was the main material source, followed by the Laibei Low Uplift; During the sedimentation period of the Upper Shasan Formation, the study area still had three sources of material supply simultaneously. At this time, the Laibei Low Uplift was the main source area, while the Kendong Uplift and Weibei Uplift had a relatively small supply capacity for the study area. In the analysis of archaeological sources, the distribution characteristics of the sedimentary system in the third section of the Shahejie Formation have been clarified, providing a research basis for the later development and adjustment of the oilfield.

Keywords

Paleogeomorphology, Characterization of Source Channels, Tracing of Heavy Minerals, Seismic Reflection Characteristics, Sedimentary Systems

1. Introduction

The deep and complex oil and gas reservoirs in the Bohai Sea have enormous exploration and development potential, and are important intervals for increasing storage and production in the Bohai Oilfield [1] [2]. In response to the problems of large burial depth, complex sedimentary system types, fast spatiotemporal distribution of reservoirs, poor quality of deep seismic data, and complex geophysical response characteristics in the development process of mid to deep oil and gas reservoirs in Bohai Oilfield [3] [4], a detailed description study of mid to deep reservoirs is carried out to clarify the supply of materials, sedimentary system types, and sedimentary distribution in different sedimentary periods, as well as the characteristics of sedimentary microfacies and the development of high-quality reservoirs, guide the efficient development of complex oil and gas reservoirs in the middle and deep layers, and provide necessary sedimentary reservoir technical support for the sustained and stable production of 30 million tons in the Bohai Oilfield.

2. Geological Setting

The B oilfield in the research area is located in the northern steep slope zone and Beiwa of the Laizhou Bay depression, 35 km north of the Bozhong 34-1 oilfield and about 70 km east of Longkou [5]. The average water depth within the oilfield is 17.3 meters. The regional structure is located on the descending plate of the southern boundary fault (Laibei No. 1 Fault) of the Laibei Low Uplift, adjacent to the Laibei Low Uplift to the north by the Laibei No. 1 Fault, and adjacent to the northern depression of the Laizhou Bay Depression to the south. The overall structural form is a semi anticline structure complicated by the fault [6] [7] [8].

The Laizhou Bay Depression is based on the Mesozoic Era and consists of the Quaternary Plain Formation [9], the Neogene Minghuazhen Formation, and the Guantao Formation from top to bottom, as well as the Paleogene Dongying Formation and Shahejie Formation. The Shahejie Formation is further subdivided into Shahejie Member 1, Shahejie Member 2, Shahejie Member 3, and Shahejie Member 4. The oil bearing strata are mainly developed in the Shahejie Member 3 of the Paleogene Shahejie Formation, followed by the Minghuazhen Formation [10] [11].

3. Analysis of Antiquities Sources

The restoration methods of ancient landforms mainly include residual thickness compensation thickness restoration method, stripping and filling method, sedimentological analysis method, sequence stratigraphy method, and layer leveling method [12] [13]. This study mainly adopts layer leveling technology.

3.1. Development of Ancient Landforms and Characterization of Material Source Channels

Selecting the top interface layer of sequence SQs3M to flatten, the ancient landforms before sedimentation of sequence SQs3M were restored (**Figure 1**). The

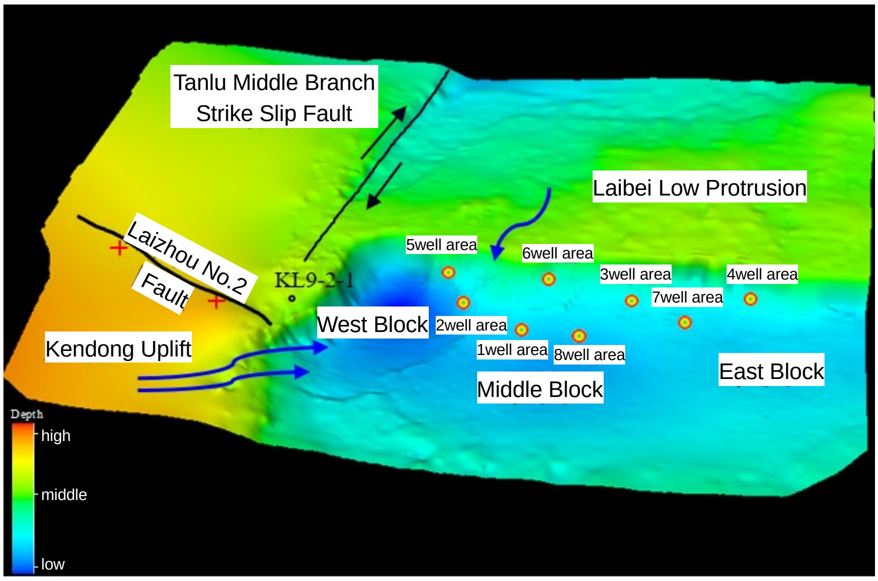

Figure 1. The paleogeomorphic pattern of SQs3M sedimentary period in B oilfield, Laizhou Bay depression.

geomorphological map shows that there are three subsidence centers developed in the northern depression of Laizhou Bay, and the sedimentary thickness of the western subsidence center is significantly greater than that of the northeast slope zone. According to the development characteristics of the subsidence center, the study area is divided into three sedimentary areas: the western block sedimentary area developed adjacent to the western part of Laibei No. 1 Fault. The northeast slope of the Laibei No. 1 Fault is divided into a middle block sedimentary area and an eastern block sedimentary area from west to east [14] [15].

During the sedimentation period of the Shasan Formation, the western part of the study area inherited the development of wide and gentle slopes and large gullies. The geomorphological map shows the obvious development of material source entrances in the western part of the study area, and the debris sediments generated by weathering and erosion in the Kendong Uplift pass through this large gully, continuously supplying sources to the sedimentary area. At this time, the Laibei low uplift is basically submerged underwater, making it difficult to provide detrital sediment to the sedimentary area. The Laibei low uplift slowly uplifted at the end of the SQs3M sequence and suffered erosion above the lake level. At the same time, the geomorphological map of this period shows that the B oilfield is located on one side of the steep slope zone of the Laibei low uplift fault, indicating that the debris sediment generated by weathering and erosion of the Laibei low uplift mainly supplies to the Huanghekou depression (slope zone), and the supply capacity to the B oilfield is limited.

Select the top interface layer of sequence SQs3U to flatten and restore the ancient landforms during the sedimentary period of sequence SQs3U (**Figure 2**). During this period, the geomorphic characteristics of the sedimentary area were inherited and developed, maintaining a pattern of three subsidence centers. At

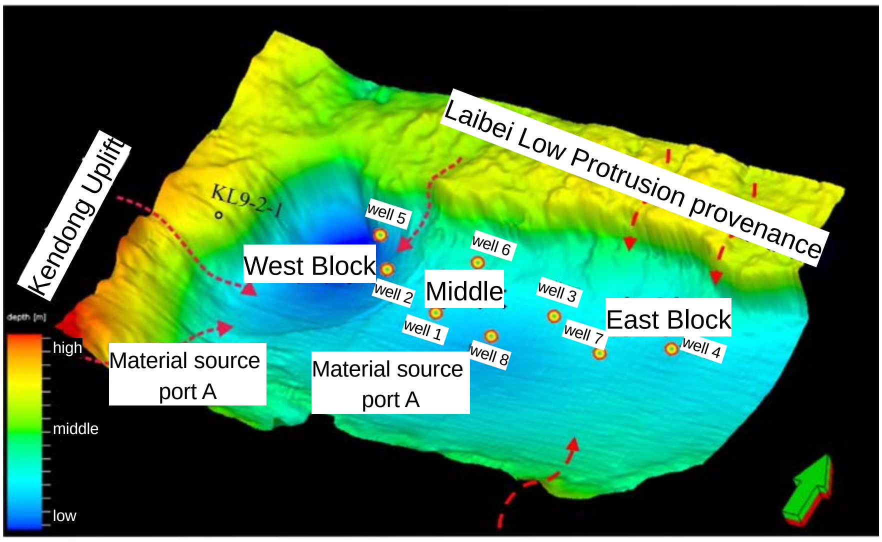

Figure 2. The paleogeomorphic pattern of SQs3U sedimentary period in B oilfield, Laizhou Bay depression.

this stage, the Laibei low uplift has significantly uplifted and suffered erosion above the lake level, serving as a regional point source to supply the surrounding sedimentary areas. The research area mainly receives material supply from the Laibei Low Uplift, and the Laibei Low Uplift near the sedimentary East Block 4 well area has a higher terrain and greater supply potential. At the same time, the western part of the research area is still supplied by the sedimentary area due to the inherited development of ancient valleys from the Kendong Uplift.

3.2. Traceability of Heavy Mineral Sources

Heavy minerals refer to transparent and non transparent minerals with a specific gravity greater than 2.86 g/cm^3 and low content that exist in terrestrial clastic rocks. They are mainly concentrated in fine sandstone and siltstone, and their content generally does not exceed 1%. There are many types of heavy minerals, which can be divided into two categories based on their resistance to weathering stability: stable heavy minerals and unstable heavy minerals. The former has strong weathering resistance and is widely distributed, with a relatively higher content in sedimentary rocks far from the parent rock area; The latter has weak weathering resistance and is not widely distributed. The further away it is from the parent rock, the lower its relative content. The heavy minerals in sandstone mainly include pyroxene, hornblende, epidote, crosshair, garnet, spinel, monazite, zircon, apatite, rutile, sphene, olivine, etc. (Table 1). Heavy minerals, due to their wear resistance, strong stability, and ability to retain the characteristics of their parent rocks, play an important role in source analysis.

A comprehensive analysis of the heavy mineral assemblage characteristics of multiple wells in the SQs3M high-level system domain of the Shasan Formation sequence in B oilfield, including KL10-1-1, KL10-1-2, KL10-1-3, KL10-1-4, KL10-1-5, KL10-1-6, and KL9-2-1, reveals that the heavy mineral types of well

Table 1. Common types of heavy minerals in clastic rocks.

Stable heavy minerals	pomegranate, zircon, corundum, tourmaline, cassiterite, rutile, perovskite, perovskite, magnetite, titanite, crossite, kyanite, monazite
Unstable heavy minerals	barite, apatite, epidote, zoisite, actinolite, andesite, andalusite, sillimanite, pyrite, tremolite, clinopyroxene, diopside, clinopyroxene, olivine, biotite

KL10-1-1 are: garnet zircon perovskite magnetite epidote; The heavy mineral combination of KL10-1-2 well is magnetite zircon epidote; The heavy mineral combination of KL10-1-3 well is: magnetite garnet zircon hematite perovskite chlorite; The heavy mineral combination of KL10-1-4 well is: hematite garnet magnetite zircon epidote; The heavy mineral combination of KL10-1-5 well is: hematite garnet zircon magnetite cassiterite epidote hornblende; The heavy mineral combination of KL10-1-6 well is: hematite garnet zircon magnetite cassiterite epidote hornblende; The KL9-2-1 heavy mineral combination in the direction of Kendong is: garnet magnetite zircon perovskite epidote chlorite.

The combination of heavy minerals in Kendong Uplift is: stable heavy minerals garnet zircon magnetite perovskite, while unstable heavy minerals are mainly epidote; The combination of heavy minerals from the Laibei low uplift is composed of stable heavy minerals such as hematite garnet zircon, while unstable heavy minerals mainly consist of amphibole and epidote.

The sedimentary period of the SQs3M II oil formation in the B oilfield sequence is mainly derived from the Kendong uplift (except for well areas 5 and 6); During the sedimentation period of the first oil formation, the Laibei Uplift began to provide a small amount of local sources (significant in the 3 well area). During the sedimentation period of the Shasan Middle I to Shasan Upper III oil formations, the mixing effect of various well areas in B oilfield was significant, and during the mixing sedimentation period of well areas 5 and 6, Laibei was the main source. During the sedimentary period of the IV oil formation in the SQs3U sequence, there is an increasing trend in the supply of resources to the north of Lai in well area 1. During the sedimentary period from the V oil formation to the IV oil formation in the Shasan upper part of well area 3, the supply of resources to the east of Kendong is stronger, while the supply of resources to the north of Lai is weaker; After the sedimentation period of the III oil group, the supply of oil to the north of Laibei in each well area significantly increased, while the supply of oil to the east of Kendong uplift weakened; During the sedimentary period of the Shasan Upper II and Upper I oil formations, the Laibei Low Uplift dominated the supply of energy.

3.3. Multiple Source Tracing of Seismic Reflection Characteristics

Based on the seismic reflection characteristics and their external reflection structures, the direction of the material source can be determined, which plays an important indicative role in the distribution of material source channels. Usually, seismic pre accumulation reflections in terrestrial lake basins can indicate the process of sediment advancing towards the basin direction, and are generally developed in the delta front, indicating the relative transport distance of sediment sources.

The east-west regional seismic profile of the study area shows that the SQs3M and SQs3U sequences of the Shasan Formation show a pre seismic reflection structure developed from west to east. The SQs3M sequence has a clear high angle "S"-shaped pre seismic reflection, with a large vertical and horizontal distribution scale; In the early sedimentary stage of sequence SQs3U, locally developed low angle stacked tile shaped progradations can be seen, with a relatively small development scale (**Figure 3**). It indicates that under the influence of the activity of the middle branch of the Tanlu Fault, the Kendong Uplift provided material sources to the B Oilfield during the early sedimentation of the SQs3M and SQs3U sequences, and its supply capacity gradually weakened.

In the NW-SW seismic profile A-A', two sets of oblique progradational seismic facies with medium frequency, weak amplitude, and moderate continuity can be seen from different directions. The main feature is that the progradational layers terminate at the top and bottom interfaces of the stratigraphic units in a top and bottom overtaking manner, respectively. Due to the limitation of vertical accumulation, the top layer is missing (**Figure 4**). The oblique front product advancing from NW to SE direction intersects with the oblique front product advancing from SE to NW direction in the central part of the study area. The pre accumulation reflection from the NW direction (Laibei low uplift) advances towards the center of the lake basin from the Laibei low uplift. The early advance distance of sequence SQs3U is far, and the delta shows a receding trend as a whole. By the end of sequence SQs3U, the advance distance towards the center of the lake basin decreases. On the contrary, the delta from the SE direction (Weibei low uplift) shows a trend of gradually advancing towards the center of the lake basin. In the early stage of sedimentation, a short distance of delta advancement can be seen in the study area, and then it continues to advance towards the center of the lake basin. This phenomenon indicates that a large area of delta from two sources is advancing towards the center of the lake basin, and this trend is increasing and decreasing.

4. Planar Distribution of Sedimentary Systems

During the sedimentary period of the SQs3M high-level system tract (Shasan Middle II Oil Formation), the study area mainly received material supply from the Kendong Uplift, and developed 5 periods of delta sedimentation. In the early stage, the well area of B oilfield was mainly dominated by lacustrine sedimentation, and the delta had not yet advanced to the well area. During this period, the lake level was in a descending stage, and the braided river delta formed was advancing from west to east. The study area was mainly composed of mudstone, with locally developed front edge collapse bodies; Subsequently, the lake level continued to decline, and the delta lobes continued to advance towards the well area, beginning to spread on a large scale within the well area. The delta front sand body gradually expanded from the southwest to the northeast of the study area, and the distribution range gradually expanded; With the continuous decline of lake level and the continuous supply of resources from the Kendong uplift, by the end of sedimentation, the delta covered the entire area, and sand bodies developed in all well areas.

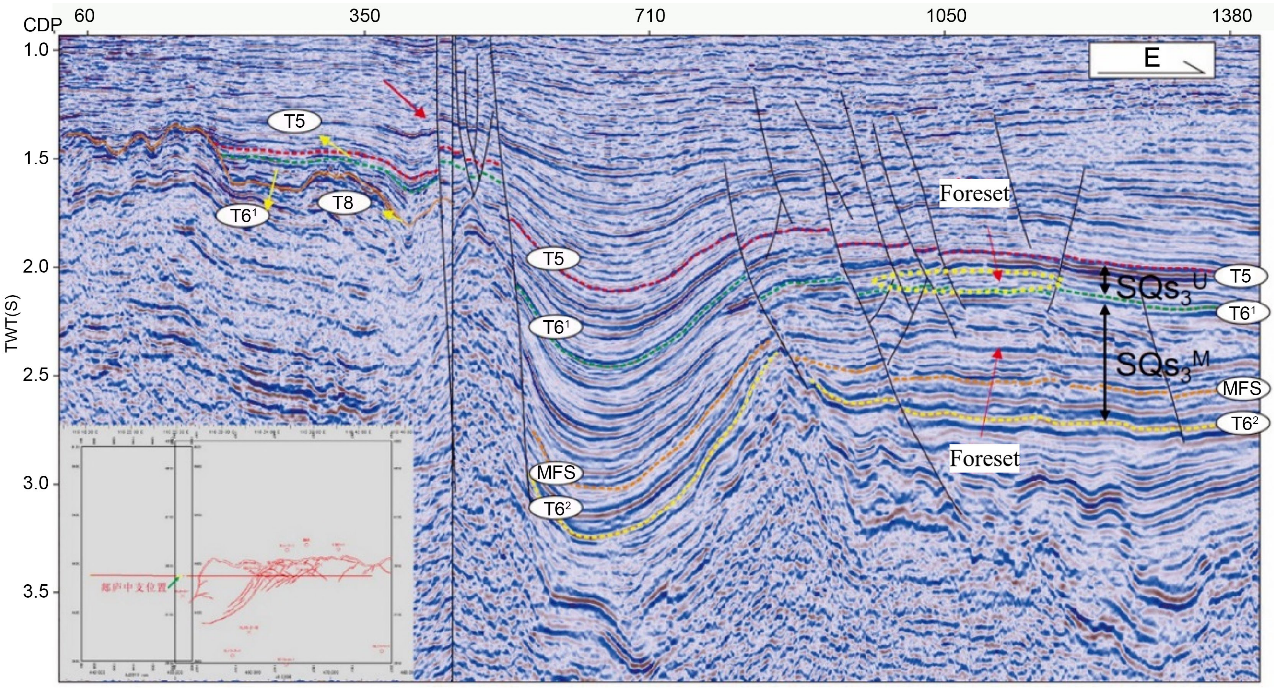

Figure 3. East west regional seismic profile of B oilfield in Laizhou Bay depression.

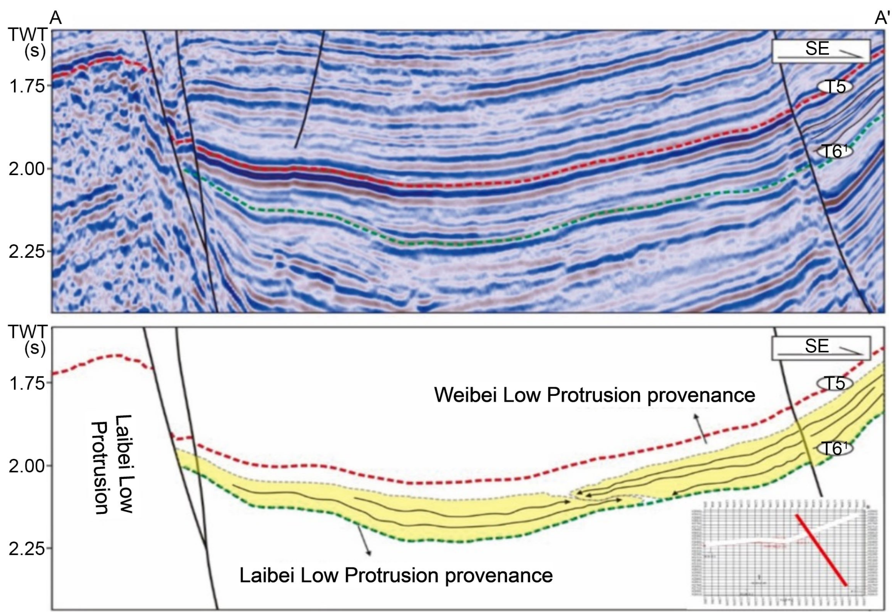

Figure 4. SQs3U sedimentary period NW-SE seismic profile of B oilfield in Laizhou Bay depression.

During the sedimentary period of the Shasan Middle I Oil Formation in the forced lacustrine retreat system tract of sequence SQs3M, the lake level continued to decrease. At this time, there were three source directions, namely the Kendong Uplift, the Laibei Low Uplift, and the southeastern Weibei Uplift. Compared with the II oil formation in Shasan Middle, the Laibei low uplift begins to supply sources, and the delta from the northern fault area is the main sedimentary facies type in the oilfield area. The supply of materials in the northern part is enhanced, and the delta advances forward; The supply capacity of the Kendong Uplift in the southwest has weakened, and the delta has retreated; The supply capacity of the southeastern region is gradually increasing, and due to the influence of transportation distance, only the delta front subfacies are developed in the study area.

The sequence SQs3U is characterized by the main development of low stand system tracts, and the lake level undergoes a process of first decreasing and then gradually rising. During the sedimentary period from the Upper Shasan V Oil Formation to the I Oil Formation, the Laibei Low Uplift continued to supply the source, and the northern delta advanced forward. The distribution range of the delta was large, showing cyclic changes. From the V Oil Formation to the I Oil Formation, the distribution range of the northern delta first decreased and then gradually increased, mainly consisting of delta plains and delta front sediments. At the same time, the supply capacity of the Kendong Uplift weakened, and only the delta front subfacies developed in the southwest; The source of materials in the southeast migrated to the south, developing a delta front subfacies, with the northern delta connecting to the southern delta front; At this time, beach and bar sedimentation is developed in the study area, with most of the beach and bar distributed in lake basins near the delta front.

5. Conclusions

1) Based on the analysis of ancient landforms, characterization of source channels, disappearance of heavy mineral sources, and disappearance of seismic reflection characteristics, the study area mainly focuses on the Kendong Uplift source during the sedimentation period of the Sha-3 Middle Member II oil formation in the B oilfield area; During the sedimentation period of the I oil formation in the middle section of the Shasan Formation, there were three material sources in the study area, namely the Kendong Uplift, the Laibei Low Uplift, and the Weibei Uplift. The Kendong Uplift was the main material source, followed by the Laibei Low Uplift; During the sedimentary period of the Upper Shasan Formation, the study area still had three sources of sediment simultaneously. At this time, the Laibei low uplift was the main source area, controlling the distribution of the sedimentary system in the study area.

2) Based on the analysis of material sources, the distribution of sedimentary systems in different oil formations in the study area was analyzed, and the main reservoir distribution characteristics of the oilfield were clarified, laying a solid foundation for the later development adjustment of the oilfield.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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