Seismic stratigraphy analysis of main controlling factors of Lower Wuerhe Formation reservoir in Manan area

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Abstract. Fan delta sedimentary reservoirs developed in the Lower Wuerhe Formation of the Manan Slope in the Mahu Sag of the Jungger Basin have good prospects for oil and gas exploration and development. In order to clarify the high-quality reservoir system and the distribution range of the reservoir plane, a seismic stratigraphic interpretation of the Lower Wuerhe Formation is carried out in combination with geology, logging and 3D seismic data. The Lower Wuerhe Formation is divided into three stratigraphic series, a total of 8 four-level sequences, and 8 water body lifting cycles. Through seismic wave group and sedimentary evolution analysis, combined with pseudo-acoustic impedance amplitude and production test analysis, the high-quality oil-bearing reservoirs of the Lower Wuerhe Formation are mainly the third member of the Lower Wuerhe Formation. Oil-bearing reservoirs are mainly controlled by sedimentary facies belts caused by the ups and downs of water bodies. The well-developed oil-bearing reservoirs are developed in the fan delta plain-fan delta front-shore shallow lake sedimentary system.

1. Introduction
The Mahu sag is one of the most promising hydrocarbon-generating sags in the Zhungeer Basin. There are many sets of favorable oil-bearing reservoirs developed in the Cretaceous, Jurassic, Permian, and Carboniferous [1]. The Permian strata is the most important hydrocarbon source rock and reservoir system. Among them, the Permian Lower Wuerhe Formation is mainly alluvial fan and fan delta near-lacustrine sedimentary strata. As of 2019, many wells in the Mahu 1 well area have encountered the Wuerhe Formation under the target layer, and all have shown good oil and gas displays, which have good prospects for exploration and development.

Seismic stratigraphy is a sub-discipline of stratigraphy based on seismic data for stratigraphic division and comparison, sedimentary environment analysis, and lithofacies lithology prediction [2]. The core theory of seismic stratigraphy believes that the seismic reflection event axis is not a reflection of a single lithological interface, but a sedimentary isochronous surface. The application of seismic stratigraphy theory to the continental clastic rock strata can not only reduce the uncertainty of cross-well correlation, but also reveal positive significance for the spatial interpretation and lateral distribution of sedimentary isochrones [3]. Based on the basic theory of seismic stratigraphy and the seismic and logging data, a seismic stratigraphic interpretation of the lower Wuerhe formation in the southern slope of the Mahu area is carried out. The cycle law and the distribution of sedimentary facies have led to the
discovery of the spatial distribution law of high-quality reservoirs. This study aims to improve the accuracy of facies-controlled reservoir division and provide strong support for oil and gas development.

2. Materials and Methods

2.1. Sedimentary background
The Manan slope area is located in the transition zone between the edge of the basin and the center. It not only has a large amount of marginal coarse clastic deposition, but also a large amount of lacustrine mudstone deposition [4]. After water ingress and retreat, abundant reservoir sand bodies are formed in the slope area, including glutenite and sandstone, thus forming a variety types of reservoir-caprock combination, laying the foundation for hydrocarbon accumulation.

2.2. Research methods

2.2.1. Sequence identification and division. Obvious top truncation can be seen at the top of the Lower Wuerhe Formation, which is in angular unconformity contact with the overlying Upper Wuerhe Formation. At the bottom of Xiajijie, there is an obvious overshoot phenomenon, and the formation shows the trend of thinning from south to north. The entire Lower Wuerhe Formation overlaps the Xiajijie Formation at the bottom. Due to the severe uplift and denudation of the top, the identification marks of the parasequence group are difficult to identify. But it can be clearly divided into three parasequence groups, and the interface can be identified on the seismic section (Figure 1).

The bottom boundary of the Lower Wuerhe Formation (P2w1) is in integrated contact with the Xiajijie Formation. It appears as a strong wave crest reflection on the seismic profile. It has good stability throughout the Ma 1 well area and can be continuously identified and tracked. The deep part of the slope gradually rises westward and finally intersects at the top interface. The formation above the overlying strata presents angular unconformity contact and advances toward the slope. The bottom of the second member of the Lower Wuerhe Member (P2w2) is shown in the seismic profile as a medium-strong trough reflection, which has good continuity throughout the Ma 1 well area and can be tracked continuously in the area. This section of stratum is in integral contact with the underlying section of stratum, and the overlying stratum is above this layer. The bottom of the third section of Lower Wuerhe Member (P2w3) is a strong valley reflection. The top of the Lower Wuerhe Formation is characterized by strong wave crest reflections in the entire Manan slope. As it is gradually approaching the edge of the lake basin, the Lower Wuerhe Formation was severely eroded during the uplift and victory, which made the Lower Wuer of the Ma 1 well area unconformity contacts with the Upper Wuerhe Formation, and the unconformity runs through the entire Ma 1 area.

Classical sequence stratigraphy believes that in the process of marine sedimentation, the phenomenon of uplift indicates that these terrestrial seismic reflection layers are the basis for the continental sedimentation [5]. In a continental lake basin environment, it can also be indicated as a low-slope lake basin sediment super-sedimentary process. The up-pass end point is determined by the slope toward the continental margin. In a low-slope lake basin, the terrestrial deposition end point may be higher than the average lake level. The three groups of identified above super-formal unconformities above the seismic reflection wave group above the Xiajijie Formation constitute three seismic sequences. The same continuous event axis reflection represents the time strata under the same lake level condition [6]. The integrated contact of different seismic event axis combinations between the three sets of seismic sequences represents the continuous sedimentary relationship of the strata at different lake depth periods.
2.2.2. Division of single well cycles. The entire Manan slope can be divided into single well sequence according to Well Mahu 1. (1) Section 1 of Lower Wuerhe Formation. The bottom of the Lower Wuerhe Formation is brown-gray argillaceous fine sandstone with a natural gamma of 54 API, and gradually increases slightly upwards. Logging data shows that the bottom is brown-gray sandy conglomerate, and the upper lithological grain size gradually becomes smaller, mainly the gray-brown sandy mudstone, forming a positive grain sequence with coarser up and finer bottom, indicating that this period is a positive cycle of water ingress. The natural gamma value of the middle and lower strata of the Lower Wuerhe Formation is less than 56 API but increases to 64 API. The core interpretation results show that the brown-gray pebbly argillaceous fine sandstone in this section transforms upward into brown-gray argillaceous fine sandstone. The grey-brown sandy mudstone is manifested as a positive cycle of water body changing from shallow to deep. The upper part of Member 1 of the Lower Wuerhe Formation gradually increases in gamma value from top to bottom. The log shows the lower gray fluorescent sandy conglomerate and brown gray fluorescent pebbly argillaceous fine sandstone, and the upper brown gray fluorescent pebbly argillaceous fine sandstone. The top layer of brown-gray sandy mudstone is a positive cycle of fine upper and coarse lower, reflecting the gradual rise of water into the system tract. The first member of the Lower Wuerhe Formation divides three four-level sequences, all of which are positive cycles, indicating that the entire first member of the Lower Wuerhe Formation is a sedimentary cycle where the water body gradually deepens.

(2) Section 2 of the Lower Wuerhe Formation. The second member of the Lower Wuerhe Formation is divided into four fourth-order sequences with thick formations. The natural gamma value at the bottom is 55 API, and it gradually increases upward to 66 API. The bottom of the logging lithology is brown-gray medium-fine sandstone with large grain size, which transitions upward to brown-gray sandy mudstone, forming the first positive cycle. Afterwards, the brown-gray sandy mudstone changed upward to brown-gray argillaceous fine sandstone and gray fluorescent sandy conglomerate, forming an inverse grain sequence of coarse upper and fine lower, constituting the second inverse cycle. Then there is a small section of gray fluorescent sandy conglomerate, on which is a long section of gray-brown sandy mudstone and brown-gray argillaceous fine sandstone. The top layer is gray-brown conglomerate mudstone and brown-gray fluorescent sandy conglomerate. The sedimentary grain size from bottom to top changes from coarse to fine and then from fine to coarse, indicating that the water body changes from shallow to deep and then from deep to shallow, forming a complete Sedimentary cycle. (3) Section 3 of Lower Wuerhe Formation. The natural gamma value at the bottom of the third member of the Lower Wuerhe Formation is 44API, which gradually increases upward, and the gamma value at the top of the Lower Wuerhe Formation is 75API. Conglomerate, as a whole, presents the characteristics of fine top and thick bottom. The whole section is divided into a single positive cycle, which represents a complete water-ingress process.

2.2.3. The establishment of time stratigraphic framework. Based on the horizontal up-and-down cycles divided by a single well and a single-well synthetic seismic record, a single-well seismic profile or a combined well seismic profile is then used to calibrate and interpret the seismic sequence. The bottom
of Member 1 of the Lower Wuerhe Formation is a medium-strong wave crest, upwards are troughs, strong wave crests, and finally to the end of the strong wave crest cycle at the top of a section, which corresponds to three fourth-order sequences, reflecting the result of continuous water advance during this period. The top and bottom wave crests to the weak wave crests in the middle part of the Lower Wuerhe Formation indicate the end of the first completed cycle, during which, the first trough corresponds to the end of the first forward cycle and the beginning of the reverse cycle. The weak wave crest in the middle part to the strong wave crest in the upper part indicates the end of the second complete cycle, which is the same as the first complete cycle. The reflection of the crest in the middle corresponds to the forward and reverse cycles. The third member of the Lower Wuerhe Formation is divided into a four-level sequence. Although it corresponds to the undivided weak wave crests, considering the severe top denudation and the difference in the degree of regional denudation, the lithology in this section is roughly show the trend of thickening from top to bottom, which be divided into a positive cycle as a whole (Figure 2).

According to the results of the single-well sequence division, we pick up the reflection wave groups of the fourth-order sequence in each period on the 3D seismic data to interpret and track the entire Manan slope. Although the marginal area is severely denuded, it cannot be accurately extended in the denuded area to each overshoot point, but the overall trend can establish the time-stratigraphic framework of the entire study area (Figure 3).

Figure 2. Synthetic seismic record of Well Mahu 1.

Figure 3. Seismic interpretation section of the joint well.
2.2.4. Sedimentary facies analysis. The lower Wuerhe Formation on the Manan slope is in a stage of descending deposition. The three stratigraphic interfaces belong to medium-strong amplitude reflections, which are parallel or approximately parallel in space. Applying the traditional marine sedimentary seismic reflection law to the continental sedimentary system, the whole Lower Wuerhe belongs to the shallow water super series, indicating the Lower Wuerhe of the entire Manan slope is in a stable fan delta-lacustrine sedimentary system. Many parallel seismic reflection wave groups are all pinched to the west, so the west is the landward direction during this period.

In the initial stage of the Lower Wuerhe Phase I, only the lower part of the sediment formed, and then the water body expands to form the entire water inflow system, which gradually allows the whole area to deposit, forming the fan delta plain-fan delta front deposit of the first member of the Lower Wuerhe Formation. The lakes in the second stage of Lower Wuerhe expands rapidly, and the relative water level declines slightly in the later period, forming the sedimentary evolution system of fan delta front of the second member of Lower Wuerhe. The relative water level of the Lower Wuerhe third member has been rising in an orderly manner and then decreases in the later period, forming the fan delta plain-fan delta front-shore shallow lake-fan delta front sedimentary system of the lower Wuerhe third member.

3. Results & Discussion
The Manan slope area is located in the transition zone between the edge of the basin and the center. It not only has a large amount of marginal coarse clastic deposits, but also a large amount of lacustrine mudstone deposits. After several water ingress and retreats, abundant reservoir sands are formed in the slope area, thus forming various types of reservoir-caprock combinations. In a large stratigraphic framework, high-quality reservoirs can be evaluated through seismic attribute slices. High-quality reservoirs are first reflected in the huge wave impedance difference and speed difference between the overburden and the gravel reservoir.

When the action of water bodies in the near-land direction is strong, the deposited sand bodies are well sorted, with low shale content and good physical properties. When such sand bodies are covered with muddy caprocks, the large wave impedance difference will be affected on the seismic profile as a strong reflection crest.

The use of pseudo-acoustic impedance root mean square amplitude attributes in this study can effectively identify high-quality reservoirs (Figure 4). In the figure, it can be seen that the strong amplitude (red) of the Lower Wuerhe Formation is mainly distributed in the third member of the Lower Wuerhe Formation (P2w3), slightly distributed in the second member of the Lower Wuerhe Formation (P2w2), and almost none in the first member of the Lower Wuerhe Formation (P2w1). The third member of the Lower Wuerhe Formation is a standard positive rotation deposit. The sedimentary microfacies such as braided channels in the fan delta plain, and underwater distributary channels in the fan delta front provide high-quality sand and gravel reservoirs. Dams and lake mud form a good storage and cap system. There are similar sedimentary assemblages in the SQ2-SQ3 cycles of the second member of Lower Wuerhe Formation. Due to the lack of shore-shallow lake subfacies in the Lower Wuerhe Member, a good reservoir system has not formed. Based on the production test results and seismic profile analysis, the dominant oil-producing layers are concentrated in the third member of the Lower Wuerhe Formation. The profile mainly corresponds to high-yield oil layers with strong wave crests, and the sequence mainly corresponds to the termination stage of the last four-order cycle changes.
By comparing the sedimentary facies profile of the third member of the Lower Wuerhe Formation Guoke 202-Mahu 16-Mahu 012-Mahu 11-Mahu 22 and the oil test results, the high-yield oil layers are concentrated in the sand bodies of the fan delta front. For example, the thickness of the near provenance sedimentary sand body in the delta front of Well Mahu 22 is the largest, and the oil production is as high as 11.5t/d. On the plane, high-yield wells are basically concentrated on the inner front edge of the fan delta, which is close to the land direction and are spread out with the branch channel as the skeleton (Figure 5).

4. Conclusions
The high-quality oil-bearing reservoirs in the Manan slope are mainly controlled by sedimentary facies belts caused by the rise and fall of water bodies. The main oil layers of the Lower Wuerhe Formation in this area are developed in the third member of Lower Wuerhe. Through the seismic stratigraphic interpretation of the Permian Lower Wuerhe Formation on the Manan Slope, it is clear that high-quality oil-bearing reservoirs are concentrated in the fan delta plain-fan delta front-shore shallow lake sedimentary system. The strong reflected energy and continuous strong amplitude characteristics can provide ideas for the study of similar reservoir systems in this area.
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