Sequence Stratigraphy of the Palaeogene in the HGZ Area of Qaidam Basin *

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Abstract: Sequence stratigraphy can be used to predict the oil and gas reservoir bodies and to choose the oil targets. Fan delta and sublacustrine fan systems are developed in the HGZ Area, which is located in front of the Altun Mountain in the west of the Qaidam Basin. On the basis of seismic and well drilling data, the deposits in the area were studied by using sequence stratigraphy and reservoir prediction techniques. Various reservoir prediction techniques used under the constraint of high resolution sequence framework could help to improve the precision of reservoir prediction and to recognize the pinch out line of sand layers, the distribution of isolated sandstone bodies and the types of oil pools. The study of sequence stratigraphy makes reservoir prediction more effective by dividing different scales of sequences and distinguishing the system tracts and parasequence sets, and indicates the internal relationship between oil/gas and sedimentary bodies in different system tracts with evolution in time and space.

Key words: sequence stratigraphy, reservoir, systems tract, parasequence sets, exploration targets, Qaidam Basin

1. Introduction

Fan delta and sublacustrine fan systems are developed in the Honggouzi (HGZ) area, which is located in front of the Altun Mountain in the west of Qaidam Basin (Fig. 1). Well G5, one of a few exploration wells here, had a low production oil stream (Song, *et al.*, 2006). The distribution of sedimentary facies is not clearly known yet. Drilling data showed

that Well G4 Area belonged to the coarse fragment fan-delta facies, while Wells G5 and G6 belonged to the deep lake–semi deep lake subfacies. This indicates that there must be a transition area from fan-delta facies to deep lake–semi deep lake subfacies between Well G4 and Wells G5 and G6. Therefore, it is of significance to use sequence stratigraphy and reservoir prediction techniques to further study the sedimentary bodies.

Fig. 1 Location map of 3D Area in the HGZ Area

2. High-resolution sequence stratigraphy

The sandbodies in the sequence framework were recognized previously by the seismic facies recognition technique, which began to be used at the end of 1970s (Jia, *et al.*, 2002). The sandbody distribution maps in sequence unit made by this technique were qualitative

or semi quantitative. Although the seismic reservoir prediction technique has been widely used, it just reflects the distribution of multiple sandbodies without the constraining inversion of sequence stratigraphy, but not the distribution and contact relationship of single sandbodies (Vail, *et al.*, 1991; 1996). Therefore, sequence analysis without the use of reservoir inversion

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limits the precision of seismic reservoir prediction (Wu, *et al.*, 2003; 2005).

The precision of reservoir prediction can be improved by using various prediction techniques under the constraint of the high-resolution sequence framework (Van Wagoner, 1995; Van Wagoner, *et al.*, 1988; Vail, 1998). The high precision reservoir prediction technique could help to recognize sand layer pinchout lines, to understand the distribution of a single sandbody, and to predict the types and distributions of the reservoirs (Gu, 1995; Liu and Wu, 1999). On the basis of lake basin sedimentation and sequence stratigraphy, seismic prediction technique of reservoir was used in this study by integrating geology, well log and seismic data. The main research flow chart is shown in Fig. 2.

Based on the tracing closure of sequence boundaries, the application of various reservoir inversion techniques, the constant time slice technique, the classification technique of seismic waves and the 3D visualization

interpretation technique to sequence analysis sand thickness and sand percentage contours can be mapped at a more quantitative level (Zhu, 2000; Zhao, *et al.*, 2006).

Seismic inversion is the core technique of lateral prediction of reservoirs. In different phases of exploration and development of oil and gas, the method used should be specifically adaptable to different geological targets or to different data available (Emery and Myers, 1996; Vail, *et al.*, 1977; Cross, *et al.*, 1994). The precision of seismic inversion depends not only on the geological features of the study area, the number of wells drilled and the resolution and signal-to-noise ratios of the seismic data, but also on the appropriateness of the method used and the correctness of the processing parameters. There are many kinds of seismic inversion and different methods to be used, but no matter which seismic inversion method is chosen, we should pay attention to the following key steps in order to achieve good geological result.

Fig. 2 Flow chart of high resolution sequence stratigraphy study

1) Collect all original data for seismic inversion, including the geological data of the study area, seismic data, well logs, well test data and laboratory data. 2) Analyze the collected data to choose the proper inversion methods and processing flow diagram according to the geological data and work objective. 3) Calibrate the horizons by using VSP data, time-depth

relationship and composite traces, especially every event near the target layers. 4) Interpret the seismic horizons, which control the models. 5) Define the contact relationships between the layers according to the geological background of the study area. 6) Analyze the log curves, delete the useless data, and normalize the same curves. 7) Choose a proper processing flow

and inversion parameters to ensure the rationality and feasibility of the inversion.

3. Fine sequence strata in the HGZ Area

The research on sequence stratigraphy in the target block would help the analysis and prediction of reservoirs to improve its precision. In the HGZ Area, based on the research results of regional sequence stratigraphy, the parasequence sets were divided and correlated for favorable sequences, and then the sedimentary microfacies of reservoirs and the prediction of reservoirs were studied in the isochronal framework, and the favorable reservoir facies belt in front of the Altun Mountain were predicted. The (fan) delta front sandbody, sublacustrine fan channel sand and the other sand distribution areas were considered the favorable exploration areas, and the main target sequences were also selected, which were the basis of the subsequent study.

According to the division principles, method and standards of parasequence sets, the parasequence sets were divided in the main sequences of wells G4, G5, G6 and G7.

Based on the division of a single well parasequence

set, the results of the parasequence sets were demarcated on the seismic profile in order to determine the boundary of parasequence sets. After marking and testing, the parasequence sets were correlated in the study area. In the course of correlation, the association features of the faults should be paid attention to in order to avoid random error. In the HGZ Area, only Wells G4 and G6 met the SQ6 in the process of drilling but did not drill through. The SQ9 and SQ10 are not main target sequences.

The purpose of division and correlation of the parasequence sets is to trace and predict the reservoirs (Wu and Gu, 2002; Wu, *et al.*, 2005). For those parasequence sets with poor oil-bearing properties or poorly developed reservoirs, the tracing and prediction of reservoirs would be fruitless. Therefore, selecting the parasequence sets with good oil-bearing properties or well developed reservoirs is of significance. To determine the main parasequence sets, the lithology, thickness and percentage of sandstones and their sedimentary environment of the 16 parasequence sets were analyzed. The analysis results of Well G4 are shown in Table 1.

Table 1 Parasequence sets and statistics of sand of Well G4 in the HGZ Area

Stratum	Seq.	Lithology	Sedimentary environment	System tracts	Parasequence sets	Bottom depth m	Stratum thickness m	Sand thickness m	Sand percentage %		
N ₂ ²	SQ ₉						885				
N ₂ ¹	SQ ₈	Brown gray sand conglomerate interbedded with shallow mudstone	Fan Front	Delta	RST	PS ₈	1068	183	112.5	61	
						PS ₇	1229.5	161.5	102	63	
						PS ₆	1356.5	127	63.5	50	
						PS ₅	1555	198.5	88	49	
		Gray conglomerate, interlayer sandstone and mudstone	sand of Shallow Lake–Fan Delta Front	TST	PS ₄	1688	133	58	43		
					PS ₃	1811	123	57	46		
					PS ₂	1949.5	133.5	52.5	39		
					PS ₁	2104	159.5	80	50		
N ₁	SQ ₇	Yellow conglomerate, fine sandstone interbedded with mottle and mudstone	Fan Plain	Delta	RST	PS ₃	2300	196	112	57	
						PS ₂	2493.5	193.5	151	78	
		Brown conglomerate, sandstone and mudstone	red gray	Fan Front	Delta	TST	PS ₁	2815	321.5	193.5	60
	E ₃ ²	SQ ₆	Sand conglomerate and interlayer of gray mudstone siltstone	Fan Front	Delta	RST	PS ₅	2941	126	75.5	60
PS ₄							3062.5	121.5	68	56	
Gray mudstone interbedded with sand conglomerate			Shallow Lake–Fan Delta Front	TST	PS ₃	3160.5	98	39	40		
					PS ₂	3264	103.5	50	48		
					PS ₁	3379.4	115.4	56.5	49		

4. Reservoir prediction

4.1 Sedimentary mode

According to the features of sedimentary development and the controlling factors, we found that alluvial fan facies, fan delta facies, sublacustrine fan facies and lake facies developed successively from mountain front to lake basin in the HGZ Area (Zhao, 1998; Xue, 2002). The facies belts of the fan delta and the coastal shallow lake subfacies were very narrow and overlapped regularly (Fig. 3).

Fig. 3 The mode of sedimentary evolution in HGZ Area

①Alluvial fan; ②Fan delta; ③Sublacustrine fan; ④Limestone

The grain size was small in the fan delta front sandbody with a high calcareous content and low permeability, while the sublacustrine fan sandbody was a good oil and gas reservoir (Wu and Xue, 1998; Qiu and Xue, 1997). The subfacies of sublacustrine fan included fan root, fan middle and fan front. The lithology of the fan root was sand conglomerate with poor grading, high shale content and massive bedding. The lithology of the fan middle was sand conglomerate interbedded with siltstone with relatively poor grading and low to relatively high shale content (Du, *et al.*, 2006; Zhao, *et al.*, 2004). It showed normal grading structure occasionally. The fan front included siltstone and muddy siltstone interbedded with thin sand conglomerate with good grading and relatively well-developed bedding structures. The sedimentary mode of the HGZ Area was considered as the basis of seismic reservoir prediction.

4.2 Reservoir prediction

To establish the seismic geological model in the study area, we used inter-well linear interpolation to get the models of acoustic logging, wave impedance, natural gamma, and self potential in each of the parasequence sets. On this basis, we can make various attributes inversions and predict the reservoirs further. The reservoir attributes of the 9 key parasequence sets

mentioned above were analyzed. This paper takes the SQ7 as an example.

Parasequence set SQ7-PS1:

PS1 is a low oil production layer in Well G5. Its lithology mainly includes gray mudstone, gray sandy mudstone, argillaceous siltstone and muddy limestone (Feng, *et al.*, 1994; Jin, *et al.*, 2003). The thickness and percentage of sandstone are 26m and 11% respectively, comparing with those of muddy limestone 29m and 12%. The sedimentary facies is semi deep lake–deep lake subfacies.

The lithology of PS1 in Well G6 is dark gray mudstone and dark gray calcareous mudstone. The sedimentary facies is semi deep lake–deep lake subfacies.

The lithology and sedimentary facies of PS1 in well G4 are shown in Table 1.

The three fan bodies developed earlier advanced to the lake basin further. The border line of the semi deep lake and deep lake subfacies was between the Well G4 and Well G7. At the same time some sublacustrine fans appeared along the axis of the HGZ structure, where Wells G7, HS1 and HS2 were located. Muddy limestone was developed in a small sedimentary scope, including the area of the Well G5 and to its south (Fig. 4).

Parasequence set SQ7-PS2:

PS2 in Well G5 is a low oil production layer. Its lithology mainly includes dark gray–gray mudstone, gray sandy mudstone, argillaceous siltstone and muddy limestone. The thickness and percentage of sand are 8m and 5.23% respectively, comparing with those of muddy limestone 16m and 10.46%. The sedimentary facies is semi deep lake–deep lake subfacies. PS2 in Well G6: The lithology is dark gray mudstone and dark gray calcareous mudstone. The thickness of muddy limestone is 3m, which accounts for 1.52% of the whole sandbody. Five percent pinhole bubbles were observed on dark gray mudstone surface and mud pit gain was 8.9m³. Ten percent zebra oil blooms were observed on dark gray fluorescent muddy limestone surface. Well log indicated an oil-bearing water layer. The sedimentary facies is semi deep lake–deep lake subfacies.

The lithology and sedimentary facies of PS2 in Well G4 are shown in Table 1.

The three fan bodies developed earlier advanced to the lake basin further. The border line of semi deep lake and deep lake subfacies was near Well G7. Wells G7, HS1 and HS2 were located on the sublacustrine fans. The sedimentary scope of muddy limestone was larger than in PS1. The scope included the area of the Wells

G5 and G6 and to the south (Fig. 4).

Parasequence set SQ7-PS3:

PS3: The general sedimentary feature is similar to those of PS2. Sandstone was not developed. Its lithology mainly included gray–deep gray mudstone, sandy mudstone, argillaceous siltstone and muddy limestone.

SQ7-PS₁

SQ7-PS₂

Fig. 4 Sedimentary facies of SQ7 key parasequence sets in the HGZ Area

In general, we concluded the sedimentary features in the HGZ Area as follows:

1) The source was from the northwest. The lithological features of each sequence in different phases showed that the grain size changed from thick to thin from west to east. The increasing content of muddy limestone from west to east indicates that the farther

away from the source, the more stable the water.

2) The sedimentary facies changed greatly and rapidly from west to east. From mountain front to lake basin, the sedimentary system is alluvial fan–fan delta–semi deep lake facies (Sun, 2005; Wu, *et al.*, 2004).

3) The mountain front has a large palaeoslope. The source conditions include seasonal alluvial, short transport distance and dry climate. The sediments had not any source channels in the long term. Therefore, the multiphase aggradational deposit mode was formed vertically.

4) In the different parts of the structure, the lithology changes differed. In the west (Well H6 Area) and the east (Well G5 Area), grain size became smaller; while in the middle part (Well G4 Area) grain size became bigger from old to new formations. The SQ6 was the coarse clastic conglomerate sediments with a high content of clastic rocks. In the SQ7, the content of coarse fragment rock increased rapidly. Over 30% of the content of conglomerate was far higher than that of the same formation in east and west or of the upper and lower formation in the same area (the source of SQ7 is probably to the north of Well G4). The content of rock fragments was also very high and the grain size became smaller from older to younger formations in the SQ8 and SQ9.

5) The sedimentary facies changed from fan delta facies on the basin boundary to semi deep lake facies. The color of rock was dark at the bottom and became yellow and red gradually in the upper parts. The sedimentary environment turned from reducing to oxidizing from bottom to top (Zhang, *et al.*, 2003a; Dang, *et al.*, 2004).

6) The sedimentary cycle of water was shallow–deep–shallow in the Palaeogene. The features were not clear in the secondary sedimentary cycles, which were not favorable to form large scale reservoir-caprock assemblage (Zhang, *et al.*, 2003b; Shanley and McCabe, 1993).

7) Various types of sandbodies were present in the Palaeogene. Alluvial and channel sandbodies were distributed in the SQ4.. In the SQ5, SQ6 and SQ7 there were fan delta, sublacustrine fan, coastal shallow lake beach and bar sandbodies. In the SQ8 there were fan delta, coastal shallow lake beach and bar sandbodies. In the SQ9 there were braided channel and fan delta sandbodies. With the evolution of the lake, these sandbodies extended continuously to the lake, and formed side contact with the hydrocarbon source rock. They formed favorable source-reservoir assemblage.

5. Optimized evaluation of targets

The exploration in front of the Altun Mountain

established that the potential area is located in the southwest of the area, especially in the facies belts of subwater distributary channels in the fan-delta, the channels in sublacustrine fan, and sheeted sands. According to the seismic facies and attributes analysis, we found that the shore belts are located to the east of Well G4. There are two sources from west to east that formed fan and fan-delta system and turbidite in semi deep and deep lake. In the southwest, the sublacustrine fan sandbodies form lithological pools readily, although located in the lower part of the structure. Therefore, we considered that the oil pool targets and the potential reservoir are developed in the southwest area (lithological pools) and the area of Well G5 (fracture pools) (Fig. 5).

1) Reservoirs with good accumulation properties developed in the fan-delta and sublacustrine fan in different system tracts

The reservoirs in the HGZ area are characterized by conglomerate, graveled sandstone and sandstone with poor-good sorting. The pores are mainly residual primary inter-granular pores, and secondly intragranular dissolution pores and intergranular dissolution pores in the micrite matrix. The reservoirs have relatively good physical properties with moderate porosity and low permeability (Table 2).

2) Source rock condition

The regional geological information shows that both deep and shallow oil pools in the HGZ area have

sources from the oil-generating depression of E32 and N1. The deep pools are primary ones while the shallow ones are secondary. Most of the kerogen types are mixed ones. The hydrocarbon kitchen in the area was in the matured stage and expelled hydrocarbon in a large scale. The fact that there are discovered oilfields in the major structure confirms the favorable source rock conditions in the area.

Fig. 5 Map of oil targets estimation of sequence SQ7-PS1 in HGZ structure

Table 2 Physical properties of SQ6 and SQ7 in Well G7 (the Ganchaigou Formation)

Sequence	Interval m	Lithology	Texture	Effective porosity %	Lateral permeability $\times 10^{-3} \mu\text{m}^2$	Physical property score
SQ7	2923.36 –2926.37	Sandy conglomerate and mid-sandstone	Poor–mid sorting, subround and point contact	$\frac{5.1-6.0}{5.8(3)}$	$\frac{0.1-11.8}{9.3(3)}$	Low porosity, low-extra low permeability
SQ6	3789.86 –3791.64	Mid-fine sandstone	Mid sorting, subangular and point contact	$\frac{2.3-5.4}{3.7(7)}$	$\frac{0.17-1.4}{0.36(7)}$	extra low porosity, extra low permeability

3) Formation of oil pools are controlled by the two factors of tectonics and lithology

The shallow secondary oil pools were located high in the structure, which were destroyed strongly by tectonic movements. The situations in the limb and lows of the structure are complicated. In general, the formation of oil pools was controlled by the two factors of tectonics and lithology. The pools in the structural high positions were mainly structurally controlled, while the oil pools in the structural low positions were mainly controlled by lithology.

4) Oil accumulated in shallow targets SQ8 and deep

targets SQ6 and SQ7

The shallow target SQ8 is at the depth of 2000–4000m. There were composite reservoirs with structural and lithological traps in which oil was easily to be accumulated. The deep targets SQ6 and SQ7 are at the depth of 3000–5000m. There were mainly lithological traps.

6. Conclusions

Sequence stratigraphy can be used to predict oil and gas reservoir bodies and to choose oil targets. The evolution of sequences, sedimentary process and

diagenesis all take effects on the reservoir properties. Sequence boundaries could control the formation of the lithostratigraphic reservoirs. The study on sequence stratigraphy makes the reservoir prediction more effective by dividing different scales of sequences and distinguishing the systems tract and parasequence sets, and indicates the internal relationship between oil/gas and sedimentary bodies in different system tracts with evolution in time and space.

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