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RESEARCH ARTICLE

Study on the Distribution Characteristics of Formation Water in Tight Sandstone Gas Reservoirs of the Shan 2^3 Member in the Zizhou Gas Field of Ordos Basin

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Abstract: To effectively formulate a scheme for the development of gas reservoirs, the distribution of formation water in the Shan 2^3 member of the Zizhou gas field of the Ordos basin in China was studied in depth, making full use of data covering formation water, logging and production. The study concluded that the types of formation water of the Shan 2^3 member in the Zizhou gas field are edge (bottom) water, lenticular water and formation water residue. The edge (bottom) water in the Shan 2^3 member is mainly distributed in three regions with low structures in the west, south and southeast of the area, respectively, to the well areas of Y47-Y29-Y43, Y64-Y40 and Y69. This layer is generally interpreted as a water layer by well logging and produces a large amount of water discharge in the processes of gas testing and production. The lenticular water in the Shan 2^3 member is mainly scattered in the middle and southern parts of the area and is generally interpreted as a water layer by well logging, mainly in small water bodies. The typical production characteristics of gas wells that produce formation water residue in a gas reservoir are as follows: With less water production, the gas saturation is high, and there is no obvious information about the water layer in the logging curves. However, during production, there is trace formation water, and as production continues, this part of the water is taken out. The edge (bottom) water is distributed in the lower structure of the area and is mainly distributed in the southwest part of the area. It is clearly controlled by the structure, especially the low-amplitude structure; thus, structure is more important for the control of edge (bottom) water. Structural characteristics have some influence on the lenticular water and the formation water residue in gas reservoirs. The position of the lower structure is the main area that enriches water. In a relatively independent region containing gas, the position of the lower micro structure is also a common distribution area of water. In addition, a larger water body often forms at the pinchout and the bend of a sand body.

Keywords: Zizhou gas field, Shan 2^3 member, gas reservoir, formation water, distribution characteristics.

1. INTRODUCTION

Oil and gas reservoirs in tight sandstone are widely distributed in foreign countries, accounting for a large amount of resources and reserves of oil and gas (Cumella *et al*., 2008). There are a large number of gas reservoirs in tight sandstone such as that in the Alberta basin in Canada and the Green river basin in America (Masters, 1979; Spencer, 1985). The Zizhou gas field in the Ordos basin is the giant gas accumulating area of unconventional and continuous tight sandstone in China (Hao *et al*., 2010).

Previous studies have shown that the size and the storage mode of formation water are the most important factors affecting the recovery ratio, and the distribution of gas and water is key in the process of gas exploration and development (Shanley *et al*., 2004). Formation water is one of the key factors affecting the development of gas field. Once water appears in the gas well, the permeability of the gas phase of the reservoir will be reduced, and the gas production will drop rapidly, even threatening the production of gas wells (Wang *et al*., 2013; Heidari Sureshjani *et al*.,

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2016). Early thought on the subject holds that the macro distribution of gas-water in the upper Paleozoic of Ordos basin has the trend of the margin of the basin containing water and the middle of the basin containing gas, with water being sporadic produced within the scope of the gas-containing area (Dou *et al*., 2010; Dai *et al*., 2012). However, with the increasing degree of exploration within the Zizhou gas field, many wells for testing gas have produced water. There is no uniform interface between gas and water in the gas reservoir, and the distribution of gas and water is very complex. Although the predecessors have to some extent conducted research on the formation water in the Zizhou region, there is still a lack of systematic research on the distribution characteristics of formation water.

In the industry, sampling and analysis of formation water and analysis of well logging data are commonly used to research the distribution characteristics of formation water (Hou *et al*., 2010; Fan *et al*., 2015). However, no study has identified logging response characteristics obtained from the analysis of formation water, and distinguished the distribution characteristics of formation water. Accordingly, on the basis of the existing research results, and combined with data on geology, logging, production dynamics, *etc*., this paper uncover the distribution characteristics of the formation water in study area.

2. REGIONAL GELOGICAL BACKGROUND

The Zizhou gas field in the study area is located in the eastern part of the Yishaan slope in Ordos basin; the Shan 2^3 member of the target layer is a single oblique structure, with inclines in the direction of the northeast to the southwest. The whole structure is gentle, and the general gradient is 6~14m/km. In addition, there is the multi row nose structure. The above reflects that the structure and the sedimentation in the sedimentary period of the Shan 2^3 member are stable (see Fig. **1**).

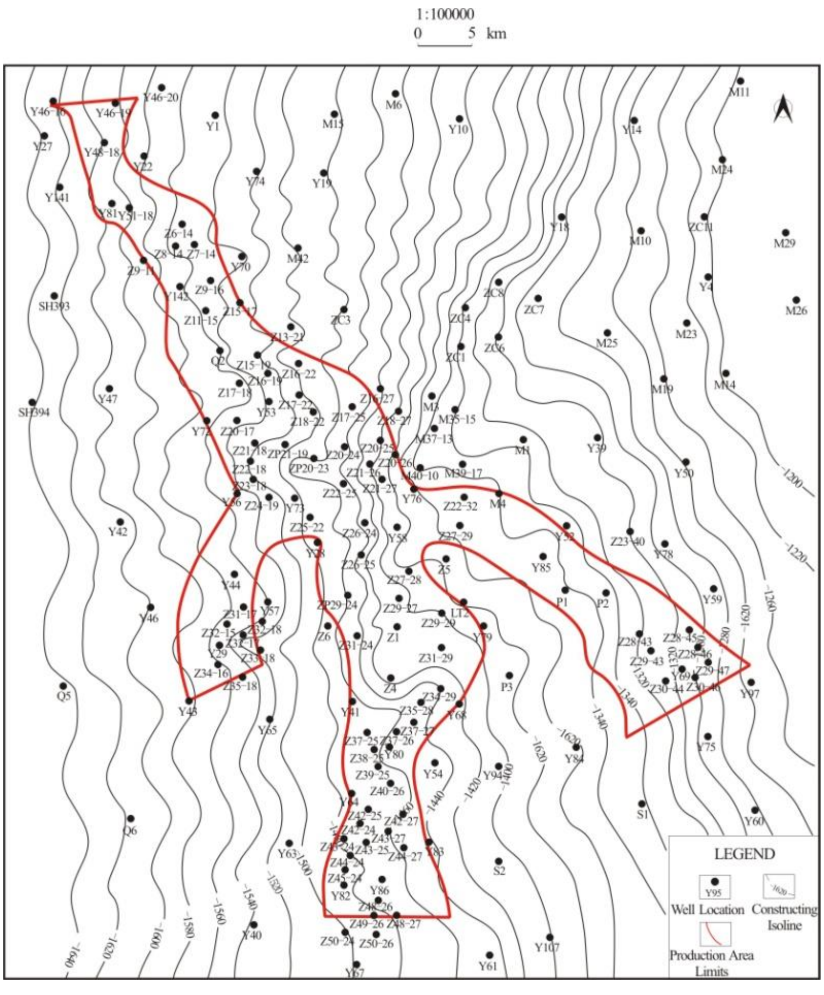

Fig. (1). Well location map of the Zizhou gas field.

The bottom boundary of the Shan 2^3 member is a large scour surface with a regional distribution at the bottom of the sandstone in North Chagou. It has an abrupt change in lithology, lithofacies and depositional environment with the underlying Taiyuan formation, and cuts into the Taiyuan formation. That makes the sandstone in North Chagou come into contact with different layers at the top of the Taiyuan formation. The top boundary of the section of Shan 2^3 is carbon mudstone and coal seams with large thickness and a regional distribution (see Fig. **2**).

The lithology of the Shan 2^3 member is pebbly coarse sandstone and the sandstone. The medium-grained and fine-grained sandstone are french grey and gray white. The silty sandstone, mudstone and carbonaceous mudstone and coal seam are dark gray and black. These constitute a sequence with upward fining. Large trough cross bedding is developed, with large tabular cross bedding and parallel bedding in sandstone, and ripple bedding and horizotal bedding are developed in silty sandstone and silty mudstone. There is a scour structure everywhere. In the reservoir of the Shan 2^3 member, the lithology is mainly quartz sandstone, which has good physical properties and is the main gas producing formation.

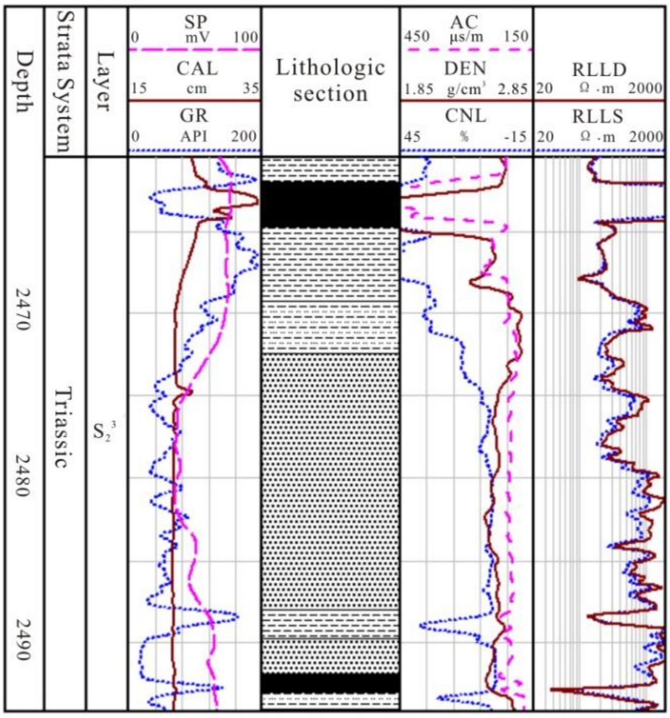

Fig. (2). Lithological column of the Shan 2^3 member in the well of Z29-27.

At present, 191 wells in the Zizhou gas field have been put into production. 58 of those wells produce water, of which 35 test gas and produce water, and 23 produce oil and produce water. The wells produce water in the entire region of the gas field on the plane and account for 30% of the total number of the decreasing wells. The vertical distribution is concentrated in the section of sandstone of the North Chagou in the bottom of the Shan 2^3 member. In the Shan 2^3 member, 15 wells in the Qingjian area were interpreted as a water layer/gas-water layer. This has seriously affected the development process of rolling expansion of the Zizhou gas field. The distribution between gas and water in the Zizhou gas field is very complex, and the relation between gas and water has become the largest obstacle to exploration and development in the Zizhou gas field. To a large extent, the situation restricts exploration and development in mining areas. Therefore, it is very necessary to research the distribution of formation water in the study area.

3. CAUSE OF WATER PRODECTION AND LOGGING RESPONSE CHARACTERISTICS OF FORMATION WATER

3.1. Edge (Bottom) Water

There is free water in the reservoir. Because of the difference of the production pressure, the liquid water in the formation flows from the reservoir into the wellbore and then outputs from the ground. This type of water that leaves the ground is called edge (bottom) water (Hao *et al*., 2010). The gas testing of this kind of well shows that the capacity of daily water production is large, and the capacity of daily gas production is generally not attained to the standards of industrial gas flow. This kind of well has obvious characteristics of water layer on the well logging curves, and is generally located in an area rich in water or an edge. The water saturation of the production layer and the water yield during production process are large.

The edge (bottom) water is commonly found in structural gas reservoirs, which are a conventional aquifer and locate in the lower part of a sand body with contiguous development (Dou *et al*., 2010). It is generally distributed in the low structure part of the reservoir, and comes into contacting with the high part of the gas layers in relationship to edge (bottom) water. The sand body has a unified interface between gas and water. The edge (bottom) water shows low natural gamma values, a high acoustic time difference, low resistivity and obvious differences with the gas layer. The interpretation shows that the porosity and thickness of permeable sand layers are large; thus, the water energy is strong. Its water yield is large during the gas testing, belonging to formation water with high salinity.

The Y44 well shows low natural gamma values (the average value is 26.5API) and low resistivity (the average value is 82.3Ω·m) in the section of 2663.00m~2667m, which was comprehensively judged as the aquifer (see Fig. **3**). There are low natural gamma values (the average value is 26API) and higher resistivity (the average value is 207.5Ω·m) in the upper part of the aquifer of the section of 2657~2663m. The results of gas testing indicate that the production of gas is 3.58×10^4 m^3/d, the production of water is 46.6 m^3/d. Integrating the above judgment, the upper part generally is a gas layer; the lower part is generally a water layer. Combined with the overall recognition of this area, there is a gas-water layer in the Shan 2^3 member of the Y44 well which constitutes a contact relationship with edge (bottom) water.

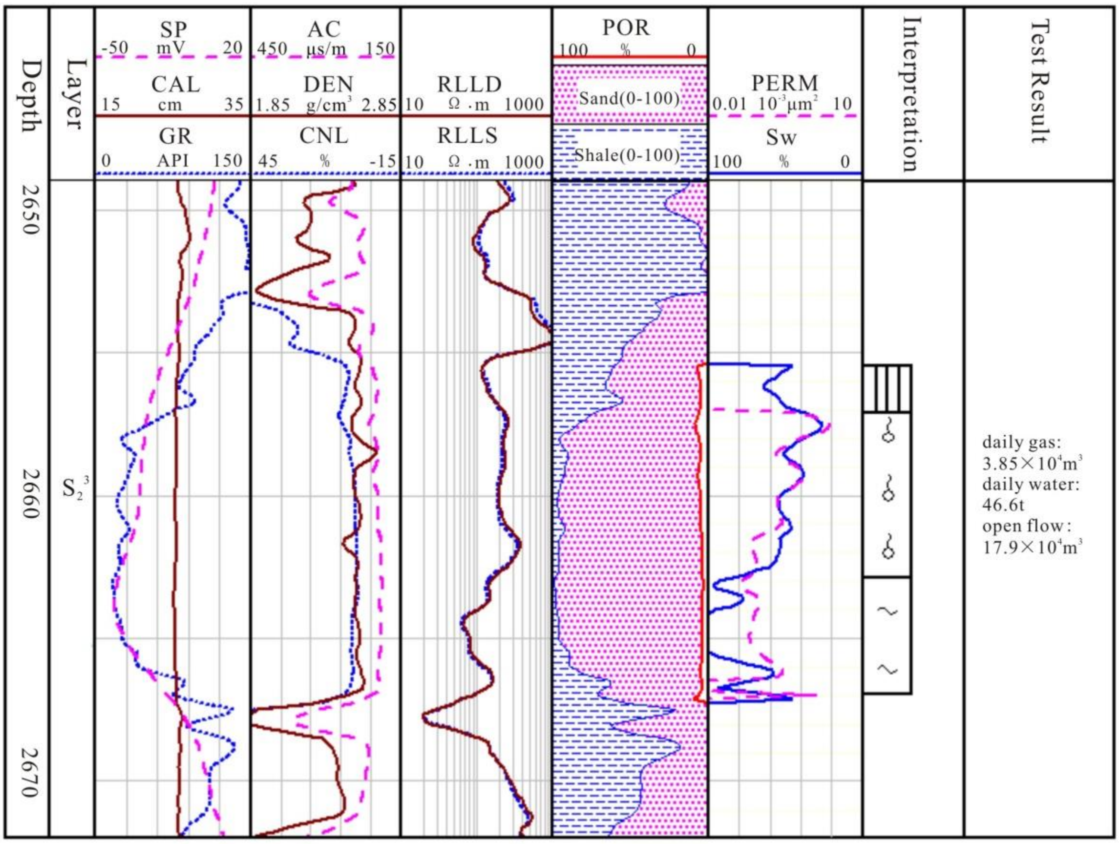

Fig. (3). Results of the comprehensive interpretation for the Y44 well.

3.2. Lenticular Water

Affected by heterogeneity, some isolated sand bodies containing water are interrupted or wrapped by non-permeable layers (Dai *et al*., 2012). Thus, natural gas cannot displace this part of the original water and the isolated water body with high water saturation forms. The sand body around the water layer pinches out. And it is not developed in adjacent wells in horizontal directions, and no gas layers are connected to it in the vertical direction. Therefore, it is a sand body with high water content and isolated development. Because of the limited volume of the isolated lenticular water, the producing characteristics of the drilling well are that the daily water yield is large in the early stage but drops rapidly.

Against the background of low porosity, low permeability and strong heterogeneity of the gas reservoir, the dense sand bodies are distributed in the lenticular sand body. In the early stage of sedimentation, the sand bodies in the reservoir are saturated by formation water. When the source rocks are in the peak period of hydrocarbon generation, due to the effect of hydrocarbon-generating pressurization, the natural gas is desolate to form free gas and migrate to the sand bodies of reservoirs. Then the water is discharged into a low position. First, the gas passes through the reservoirs with a relatively large channel and good connectivity, but for sand bodies with poor physical properties, the gas cannot displace the formation water in fine pore-throat or low-quality reservoir beds, which forms 'tight lenticular water' because of the insufficient filling energy of gas. The physical properties of this kind of aquifer are poor, and the logging characteristics are similar to that of a dry layer. The production capacity of the gas well is small.

A typical well that has the lenticular water layer is Y39 (see Fig. **4**). In the section of 2365.9~2380.6m of the Shan 2^3 member of this well, the average value of natural gamma is 40.4API, the average value of deep lateral resistivity is 20Ω·m, and the deep and shallow laterologs have basic coincidence or show a small positive amplitude difference (3Ω·m). The average value of the density logging is 2.5g/m^3, and the average values of acoustic logging and neutron logging are 225.1µs/m and 10.1%, respectively. The interpretation of this layer shows that the average porosity is 7.5%, the average permeability is 0.32 mD, and the average water saturation is 72%, which is comprehensively judged as an aquifer based on the log interpretation. The interpretation of the Shan 2^3 member of the west direction of the M1 well and the northeast direction of the M19 well shows no sand body (see Fig. **5**). The sand body around the water layer pinches out. In addition, the sand body is not developed in adjacent wells in horizontal directions, and no gas layers connect to it in the vertical direction. Therefore, it is a sand body with high water content and isolated development. The comprehensive judgment is that the Shan 2^3 member in the Y39 well belongs to the isolated lenticular water layer.

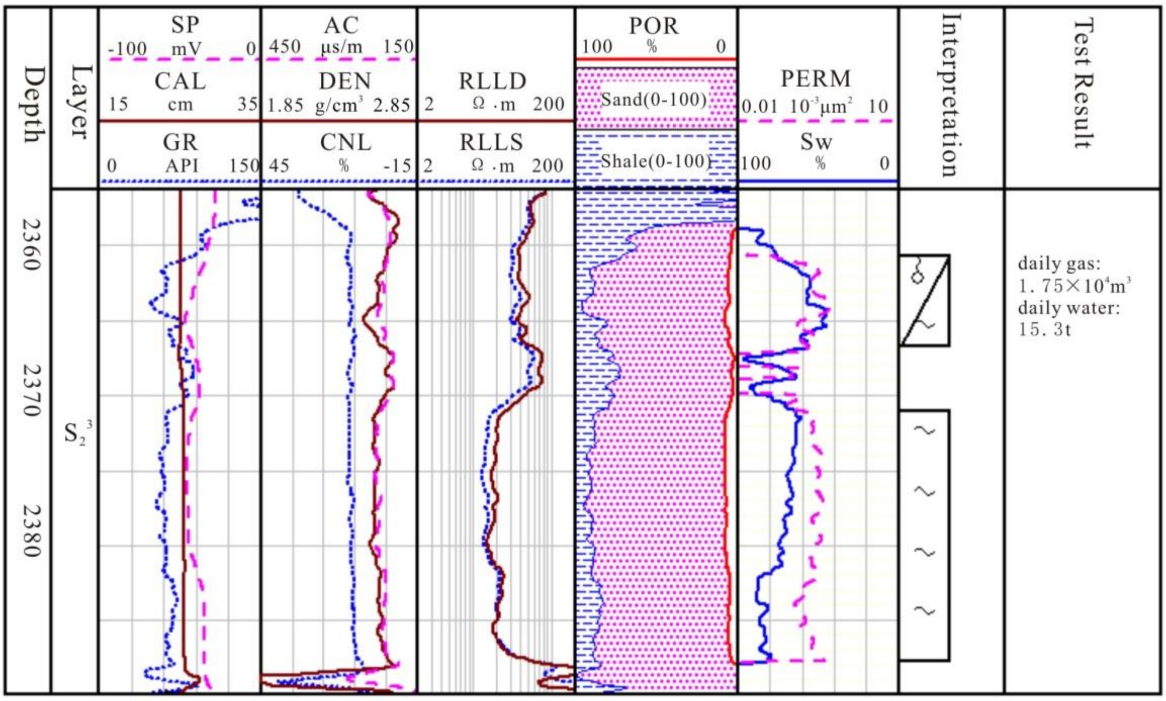

Fig. (4). Results of the comprehensive interpretation for the Y39 well.

3.3. Formation Water Residue in the Gas Reservoir

During the process of gas accumulation in gas wells that produce formation water residue in the gas reservoir, when gas migrates into a reservoir, the saturation of the formation water remaining in the gas reservoir is slightly higher than that of critical water due to the strength of the natural gas discharge not being sufficient (Hou *et al*., 2010). Its typical characteristics are that the gas saturation is higher, and the information about the water layer is not obvious in the well logging curves. However, during production, there is a small quantity of formation water, and following the production, this part of the water is produced. The logging characteristics of the formation water residue in the gas reservoir are as that of the gas layer in the well logging curves, and there is no obvious water layer information.

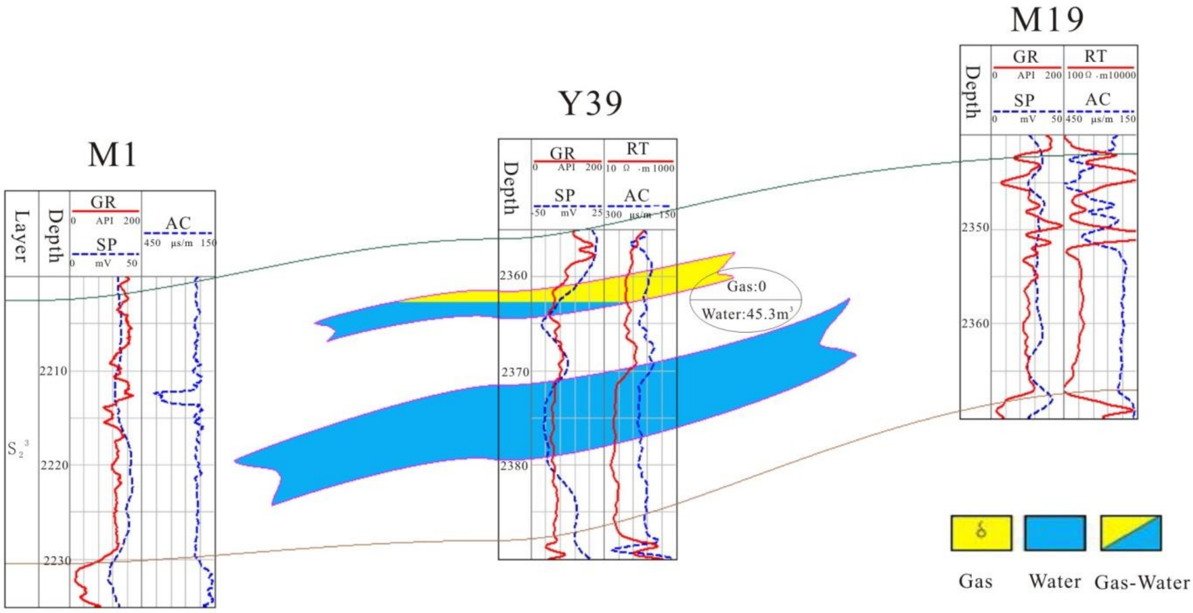

Fig. (5). Typical profile of the lenticular water.

This water type is relatively common in lithologic gas reservoirs but rare in structural gas reservoirs (Wood, 2012). The logging response characteristics are low natural gamma, high resistivity and low water saturation, which are comprehensively judged as a gas layer by log interpretation. During the process of gas testing and production testing, the water yield of the gas well is small and slightly higher than theoretical condensate water volume. Due to the influence of condensate water, the salinity of the produced water is small, belonging to desalinated formation water. In the process of production, the water yield decreases.

A typical well that produces 'the formation water residue in gas reservoir' is Z16-19 (see Fig. **6**). The produced layer of this well is the Shan 2^3 segment, and the log interpretation shows that it is a gas layer. The perforation interval is the section of 2709.5 m~2715.5 m, and the results of gas testing show that the gas production is 2.0342×10^4 m^3/d, with no water production. The well was put into production in August 29, 2007, the volume of daily water production was up to 1 m^3 in September 2007, but dropped rapidly, which was judged to be the result of fracturing fluid in the early stage. From December 2007 to April 22, 2008, the gas production was maintained at approximately 1×10^4 m^3/d, the water production was approximately 0.4 m^3/d, and the maximum volume of condensate water was calculated to be 0.157 m^3. It was judged that formation water was produced. Compared with the logging curves of this well, the average porosity and permeability of sandstone are 5.8% and 0.167 mD in the perforation layer. The output water was judged to be a mixture of condensate water and formation water residue in the gas reservoir. The proration increased from 1×10^4 m^3 to 2×10^4 m^3 after April 22, 2008, but daily water production decreased from 0.4 m^3 to 0.1 m^3. The degree of mineralization of the produced water was analyzed to be 3664.08mg/L, which is obviously condensate water.

3.4. Similarities and Differences Among Different Types of Formation Water

The similarities between the 'formation water residue in gas reservoir' and 'the lenticular water in tight reservoir' are that they belong to the retention water in the formation and have limited energy in the water body. In the process of testing or the production of gas wells, with a small amount of formation water, the degree of mineralization of the water sample in the separator of gas well decreased after the mixture of the formation water and condensate water, which demonstrates the characteristics of desalted formation water.

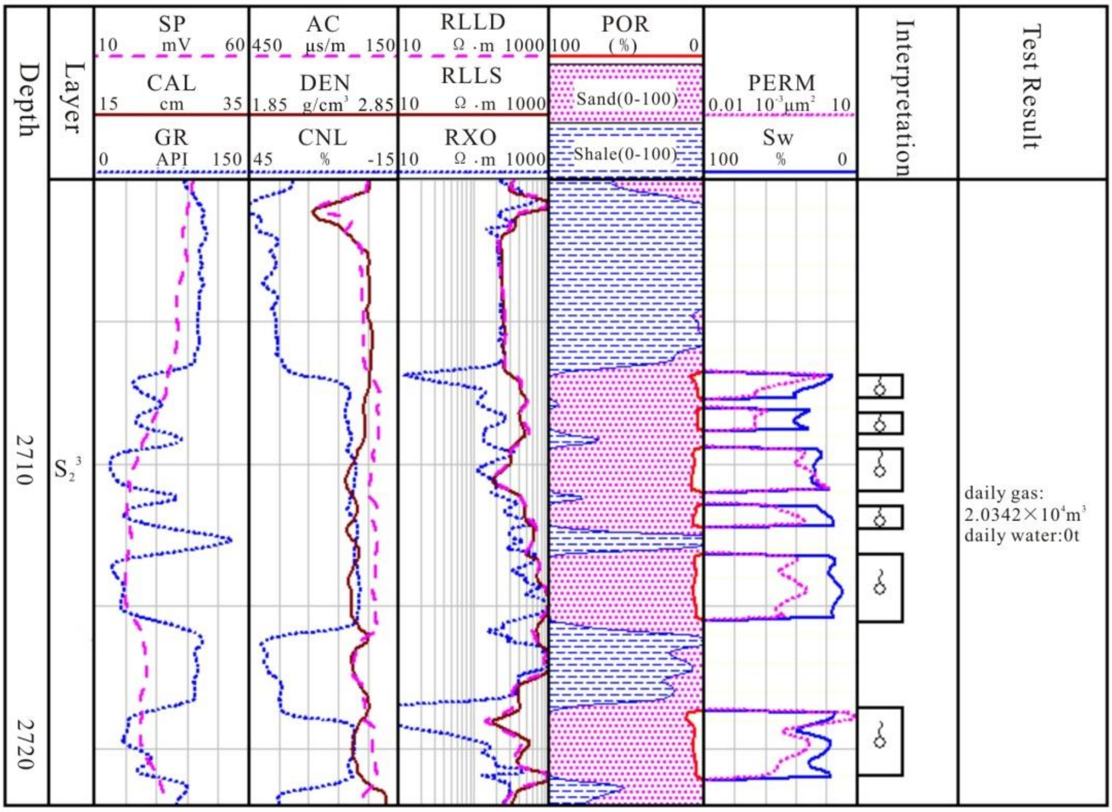

Fig. (6). Results of the comprehensive interpretation for wells 16-19.

The differences between both of them are that the porosity logging curves of the section of 'lenticular water in tight reservoir' shows poor physical properties and the gamma curve is higher, which is similar to the logging response characteristics of the dry layer, but the formation water residue in the gas reservoir is shown as a gas reservoir in the well logging curves.

The similarities between the isolated lenticular water and edge (bottom) water are that their logging characteristics are similar, and the logging curves shows good physical properties with a low gamma curve and deep lateral resistivity, which shows the characteristics of water layer. In the process of layer testing, the water yield is larger, which shows the characteristics of high-salinity.

The differences between them are that the edge (bottom) water is located in the lower part of the sand layer, the high position of the same connected sand layer has developed a gas layer, and both of them have a uniform interface between gas and water, which belongs to the same pressure system. In contrast, the sand body around the isolated lenticular water pinches out. The sand body is not developed in adjacent wells in horizontal directions, and no gas layers are connected to it in a vertical direction. Therefore, it is the isolated sand body with the high water content.

4. DISTRIBUTION CHARACTERISTICS OF FORMATION WATER

According to the logging interpretation results of a single well, and with the data of the dynamic production of gas testing and hydrochemical analysis, the distribution characteristics of formation water in the study area are systematically analyzed. Then, the distribution characteristics of formation water on the plane are researched.

4.1. Distribution Characteristics of the Profile of Formation Water in the Shan 2^3 Member

4.1.1. The Edge (Bottom) Water in the Shan 2^3 Member

The connecting-well profile of gas and water of the Y43—Z35-18—Z32-18 wells is located on the edge of the edge (bottom) water, near the direction of north-east. The gas testing of the Y43 well shows a water layer, and the water production is 39.8 m^3/d. The Z35-18 and Z32-18 wells are a gas layer, and the gas production of the Shan 2^3 member in Z32-18 well is 1.23×10^4 m^3/d. The sand bodies in the Shan 2^3 member have good connectivity, and there are two independent systems of gas and water in the Shan 2^3 member. The interface between gas and water is located at the section of 1585~1596m (see Fig. **7**).

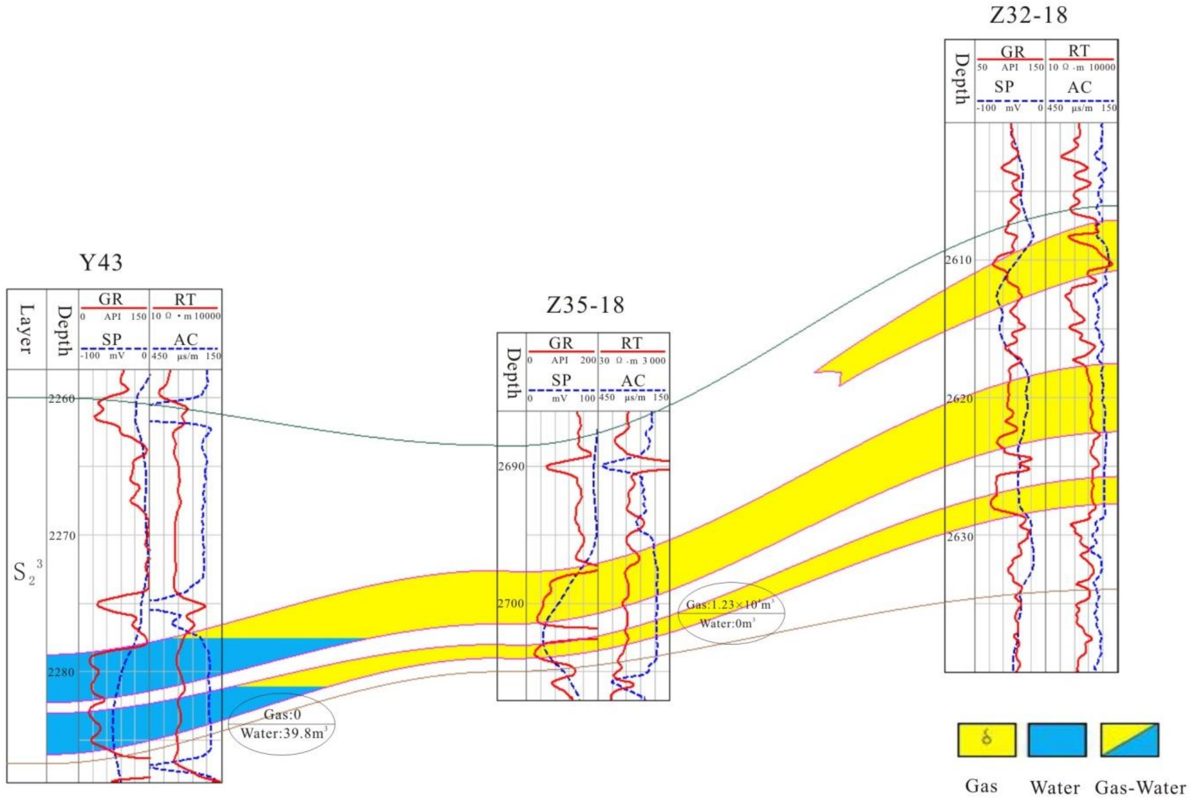

Fig. (7). Connecting-well profile of gas and water for the Y43—Z35-18—Z32-18 wells.

From Fig. (**7**), we can see that the distribution trend of formation water is controlled by the structure. With decreasing structural amplitude, the gas yield of this kind of reservoir decreases and the water yield increases. In addition, this kind of reservoir is gradually changed from producing gas to producing water. The phenomenon of differentiation between gas and water is more obvious, with a generally unified interface between gas and water. The structure of the Zizhou gas field is the large west dip monocline. In the process of differentiation between gas and water, gas goes upwards, and water flows downwards; thus, the water-rich area of Zizhou gas field is located in the western, southern and southwestern parts of the lower part of the structure.

4.1.2. Lenticular Water in the Shan 2^3 Member

The connecting-well profile of the gas and water of the S2—Y83—Z43-27 wells is located in the southern part of the work area, near the east-west direction, and the logging interpretation of the Y83 well shows that it is a water layer. In the connecting-well profile, the sand bodies in the Shan 2^3 segment of the Y83 well have poor connectivity and the sand bodies on both sides pinch out. The water layers cannot connect to surrounding wells in the Shan 2^3 member, and the formation water of the Y83 well are distributed in the lenticular sand body (see Fig. **8**). The sand body around the water layer pinches out, and no gas layers connect to it in the vertical direction. Therefore, it is the isolated sand body with high water content. The distribution of formation water is clearly influenced by the distribution of sand bodies and the physical properties of reservoir. Because of the limited volume of the lenticular water, the producing characteristics of the drilling well are that the daily water yield is large in the early stage but drops rapidly during production.

4.1.3. The Formation Water Residue in the Gas Reservoir of the Shan 2^3 Member

The typical production characteristics of gas wells that produce ‘formation water residue in the gas reservoir’ are the small water yield and the small impact on production. During the process of gas accumulation, when gas migrates into the reservoir, the saturation of the formation water remaining in the gas reservoir is slightly higher than that of critical water due to the strength of the discharge of natural gas not being sufficient.

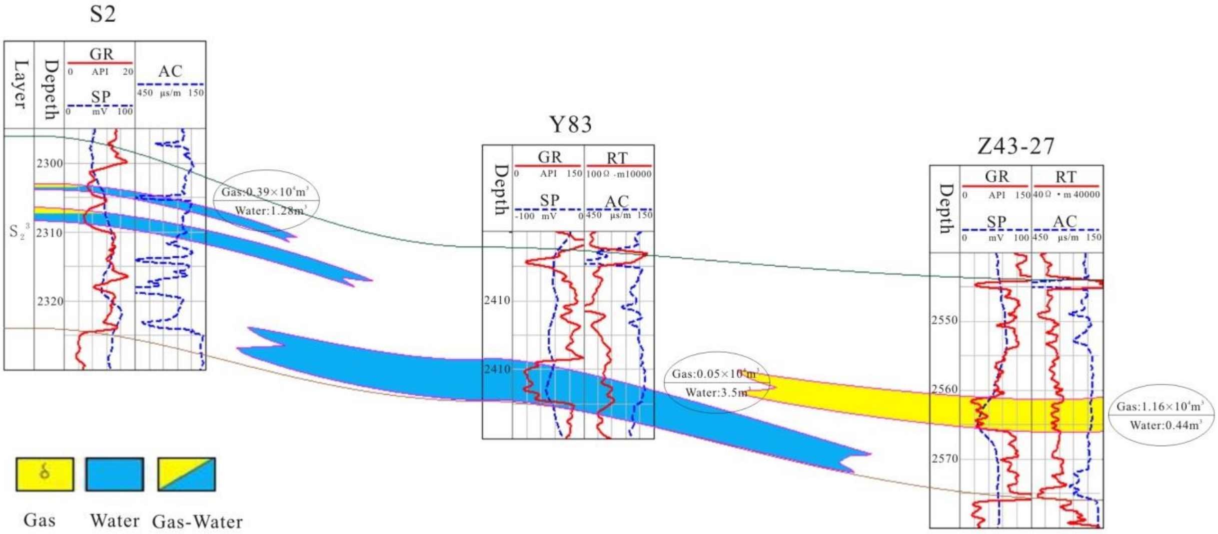

Fig. (8). Connecting-well profile of gas and water for the S2—Y83—Z43-27 wells.

Its typical characteristics are that the gas saturation is higher, the degree of differentiation between gas and water is lower, and information about the water layer is not obvious from the well logging curves (see Fig. **6**). However, during the production, a small quantity of formation water is produced.

4.2. Distribution Characteristics of Formation Water on the Plane in the Shan 2^3 Member

Study show that the types of formation water of the section of the Shan 2^3 in the Zizhou gas field are mainly edge (bottom) water and lenticular water. Based on the various types of formation water recognized by the well logging response characteristics, combined with predecessors' research results on the distribution characteristics of sand bodies and structures, a superimposed plan of the water bodies, sand bodies and superface structures of the Shan 2^3 member in the study area is drawn (see Fig. **9**). From this figure, we can see that the sand bodies of the Shan 2^3 segment are more developed, and the physical properties are relatively good. The gas layers and water layers are mainly distributed in the Shan 2^3 segment. In the study area, the gas and water in the same sand body follow the principle of the upper part being gas, and the lower part being water. Because of that, the reservoirs are influenced by the lithology, the physical properties and the structural height, and local edge (bottom) water and lenticular water are developed in this area.

The distribution of gas and water in the Zizhou area is controlled by the structure, and the water is mainly distributed in the Y47-Y29-Y43 well area, Y64-Y40 well area and Y69 well area with low structures in the west, south and southwest. This is determined to be edge (bottom) water after differentiation during the process of migration and accumulation of gas and oil. During this process, water migrates to nearby lower parts of the edge based on gas and oil, namely, the west and southwest of low part of structure. Then, relatively water-rich areas form in the west. In addition water-rich points of smaller area form in the east. For instance, the Y47-Y42-Y44-Y43 well area is a large-scale water-rich area, whereas the Y54-Y64 well area and the Z28-43—Z30-44 well areas in the east form relatively small water-rich areas. In the lower part of the sand body in the southwest, controlled by the relative height of the reservoir, the water bodies with a larger extended range appear. The water bodies are independent of each other, and there is no uniform interface between gas and water. In the relatively low structure part of the northeast, water-rich areas with relatively small extended ranges appear due to the shielding effect of the pinchout zone and the bend zone of the sand body. More lenticular water exists in the central and southern parts of the study area, and the water yield is small (less than $4m^3/d$). The scale of water body is very limited, mainly controlled by the change in reservoir conditions (reservoir heterogeneity), and there is no uniform interface between gas and water. In addition, due to the influence of reservoir characteristics, such as poor physical properties of the local area, there are a few residual areas of formation water in the well area, such as the Z16-19 well area.

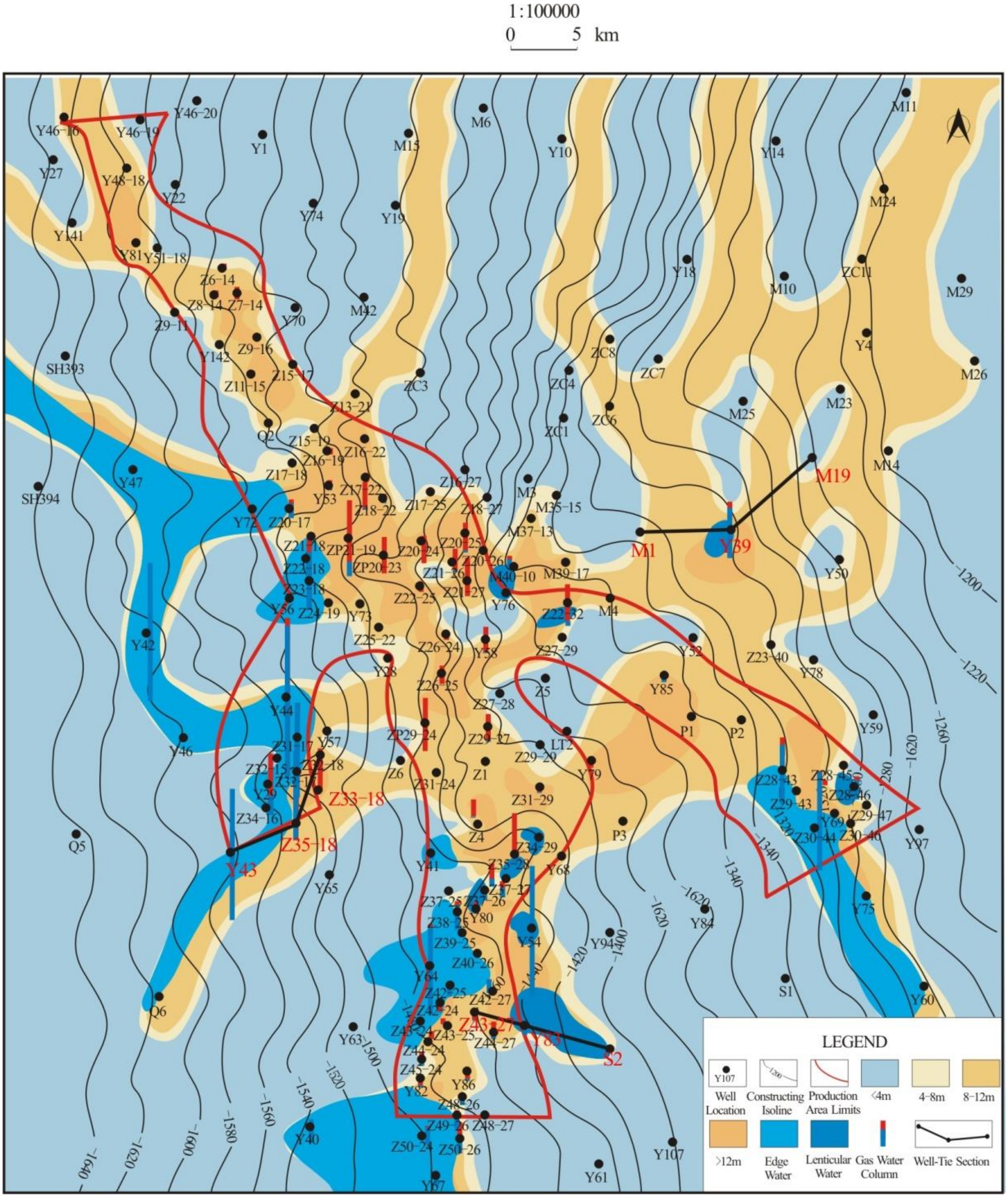

Fig. (9). Superimposed plan of water bodies and sand bodies and the superface structures of the Shan 2^3 member in the Zizhou gas field.

Based on the fine logging interpretation of 191 wells in the study area, and combined with the analysis of dynamic production, a statistical table of the types of water-producing wells in the Shan 2^3 member of the study area is shown in Table **1**. This table shows that the Shan 2^3 member in the study area mainly produce edge (bottom) water, followed by lenticular water. The formation water residue in gas reservoirs is relatively small.

Fig. (**9**) and Table **1** clearly describe the well areas with the distribution of formation water in study area. Based on these research findings, the gas reservoir development and the well placement can be easily developed.

The above research shows that the edge (bottom) water is clearly controlled by the structure, especially the low-amplitude structure; thus, the structure is more important for the control of edge (bottom) water. Structural characteristics also have a certain impact on lenticular water and the formation water residue in gas reservoirs. The lower part of the structure is the distribution area of the main water-rich area. In the relatively independent area with gas, the relatively low position of the micro structure is also a common distribution area of water bodies. In addition, the distribution of sand bodies also determines the distribution of formation water, and the physical properties of reservoir affect the size and the connectivity of formation water bodies.

Table 1. Statistical table of types of water-producing wells in the Shan 2^3 member of study area.

Types of formation water	Well area
Edge (bottom) water	Y47, Y72, Y42, Z21-18, Y46, Y44, Z31-17, Z22-18, Z32-15, Z32-17, Y29, Z23-18, Z34-16, Y43, Y41, Y56, Z38-25, Z39-25, Y64, Z30-46, Z42-25, Z42-27, Z42-24, Y75, Z43-24, Y40, Z50-24, Y60, Z50-26, Z49-26, Y67, Z30-44, Z28-43, Z29-43
Lenticular water	M40-10, Y76, Z22-32, Y39, Z37-26, Z34-29, Z35-28, Z28-45, Y83, Y80, Y54, S2, Z28-46
Formation water residue in gas reservoir	Z16-19, Y86, Z43-25, Z20-24, Y82, Z21-26, Z20-26

CONCLUSION

1. The three main types of formation water in the gas reservoirs of the Shan 2^3 member in the Zizhou gas field are local edge (bottom) water, lenticular water and formation water residue. The edge (bottom) water is commonly found in the structural gas reservoir and located in the lower part of sand body with contiguous development. It comes into contact with the high part of the gas layers, and the sand body has the unified interface between gas and water. The sand body around the water layer of lenticular water pinches out. It is not developed in adjacent wells in the horizontal direction, and no gas layers connect to it in the vertical direction. Therefore, it is the isolated sand body with high water content. The gas saturation of gas layers that produce formation water residue is higher, and the information about the water layer is not obvious based on the well logging curves; however, during the production, a little formation water is produced.
2. The edge (bottom) water in the Shan 2^3 member is mainly distributed in three regions with the low structure in the west, south and southeast of the area, corresponding respectively to the well areas of the Y47-Y29-Y43, the Y64-Y40 and the Y69. This water generally interpreted as the water layer by well logging, and produces a large amount of water discharge during the process of gas testing and production.
3. The lenticular water in the Shan 2^3 member is mainly distribute in the middle and southern parts of the study area and is generally interpreted as the water layer by well logging. It is mainly in small water bodies. This kind of well generally does not have gas testing data and is scattered in the middle and southern parts of the well area.
4. The edge (bottom) water is distributed in the lower structure of the study area and mainly distributed in the southwest. It is clearly controlled by the structure, especially the low-amplitude structure, which is more important for the control of the edge (bottom) water. A larger water body often forms at the pinchout and the bend of sand body. The heterogeneity of reservoir is the key factor to form the lenticular water in tight sandstone.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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