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Study on the Characteristics of Neogene Sandstone Geothermal Reservoir in Xi 'an Sag

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ABSTRACT

The study on distribution characteristics and fine evaluation of stratified thermal reservoir can provide important basis for large-scale development of geothermal resources in sandstone geothermal reservoirs. The widely developed Neogene sandstone strata is the most important geothermal reservoir in Xi 'an Sag, Guanzhong Basin. This paper systematically discusses the reservoir characteristics of Neogene sandstone geothermal reservoirs in Xi 'an Sag, based on the core and logging data, and also discusses the relationship between reservoir characteristics and water-yielding capacity. The Neogene sandstone geothermal reservoirs, including Gaoling Group, Lantian-Bahe Formation and Zhangjiapo Formation, is composed of fluvial-delta-lacustrine interactive sand and mudstone deposition with positive rhythm characteristics. The reservoir rock is mainly feldspar lithic sandstone and lithic sandstone, and the reservoir space is dominated by dissolution pores and primary pores, with good porosity and permeability. Lantian-Bahe Formation has a large distribution area of high-quality sand bodies, with a large thickness of 150~400m and rich water storage, and it is currently the most developed sandstone geothermal reservoir. The water-yielding capacity of geothermal wells is affected by reservoir characteristics. The water production of a single sand body is mainly affected by the permeability and shale content. If it has a higher permeability, and a lower shale content, the water production always tends to be higher.

1. INTRODUCTION

Sandstone geothermal reservoir is a very important type of geothermal resources, where major part of the hot water is stored in the pores between the grains of rock. In the large areas of sedimentary basins in China, medium and low temperature geothermal resources stored in Cenozoic sandstone geothermal reservoir is a key object of geothermal energy utilization. A major part of the hot water is abstracted from these formations, such as in Hebei, Shandong and Shaanxi provinces, which shows a very high potential for space heating, replacing coal.

The research project focus on the Cenozoic sandstone geothermal reservoir in Xi'an Sag, Guanzhong Basin, where lays the main development area in Shaanxi Province. Geothermal resource exploration in Guanzhong Basin can dates back to the 1980s. Many geothermal geological studies have been carried out in the study area, including geological characteristics, earth heat flow background, hydrogeological conditions and so on. Wang (1997) analyzed the surface heat display, geothermal field variation, deep structure and heat source mechanism of the basin. More information of geothermal resource conditions, distribution characteristics, genetic model of geothermal system and other relevant information is available according to Sun (2015), Ren (2019), Zeng et.al(2019) and Ren et.al (2020).

Generally, the key areas of geothermal resource ultilization in Guanzhong Basin, including Xianyang, Xi 'an, Xingping, Wugong and Zhouzhi, are all distributed in Xi 'an Sag. The Neogene sandstone geothermal reservoirs are well exploited, including Gaoling Group, Lantian-Bahe Formation and Zhangjiapo Formation. The well depth is mainly 2000~3800m, the thickness of production section is generally more than 900m, and the water temperature is mainly 65~100 ℃, with the maximum to 118℃. The water volume exceeds 80m^3/d, and the maximum is more than 180 m^3/d.

However, due to the fact that most geothermal wells use mixed multilayer zone of large-section, although abundant reservoir characteristic datas are available, the reservoir description is still relatively sketchy, lacking of detailed research on the reservoir characteristics and the influence of reservoir characteristics on the productivity of geothermal wells. It sometimes limits the fine development of sandstone geothermal reservoir.

Based on the test results of core cuttings, geological and logging data of 15 geothermal wells, the research studies the reservoir characteristics of Neogene geothermal reservoirs in Xi 'an Sag from both micro and macro scale, and analyzes the influence of reservoir characteristics on productivity. It is expected to contribute to the scientific and efficient exploitation of geothermal resources.

2. REGIONAL GEOTHERMAL GEOLOGY CHARACTERISTIC OF XI'AN SAG

Heat sources, reservoirs, channels and cap rocks are important factors in the formation of geothermal systems. They can be analyzed through regional geological conditions. This chapter briefly describes the structure, stratigraphy, and sedimentary facies of Neogene strata in Xi'an Sag. The distribution of the geothermal field results from the comprehensive action of various elements, which can show the favorable areas of geothermal anomalies, and the characteristics are also introduced here.

2.1 Structural setting

Guanzhong Basin is located in the southwest margin of North China Plate, sandwiched between Qinling orogenic belt and Ordos block. It is a Cenozoic graben basin as a part of the Fen-Wei graben system. After multiple periods of complex tectonic evolution, several large faults were developed mainly striking nearly alone EW, NE-SW and NW-SE. Guanzhong Basin is divided into six units by these faults. Xi 'an Sag, lying in the southern part, is one of the two main sedimentary areas in the basin.

Tectonic activity is relatively strong in this area. Some of the main faults are still active today. Xi'an Sag is bounded by the Qinling mountain front fault (F1) in the south, and adjacent to the Xianli High by Weihe fault (F3) in the north. The eastern and western boundaries are Lintong-Chang 'an fault (F8) and Yabai fault (F6) respectively. These faults all play very important role in controlling the stratigraphic deposition and geothermal resource distribution. Figure 1a shows the tectonic units, main faults in Guanzhong Basin and the location of the study area.

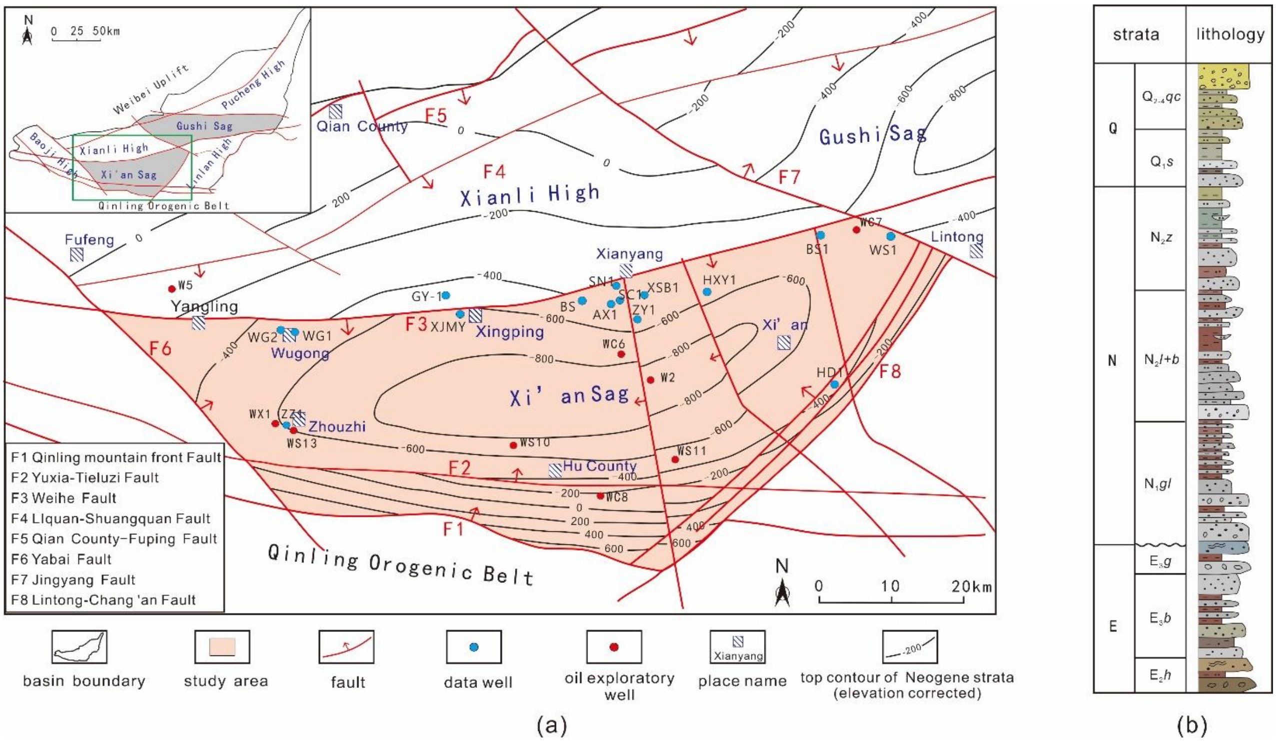

Figure 1: (a) Structure outline map of Xi 'an Sag and structure counter of top Neogene strata. The study area is colored. (b) Diagrammatic lithology profile of Cenozoic strata in Xi 'an Sag (according to Liu, 2004).

2.2 Stratum feature

The stratigraphic system of Guanzhong Basin has dual structure. In Xi 'an sag, the sedimentary basement of pre-Cenozoic strata was mainly formed by Proterozoic shallow metamorphic schists mixed with Yanshanian granite, and is widely exposed in Qinling orogenic belt (Liu, 2004; Li, 2018). The basin began receiving deposition since the Paleozoic, filling with thick sedimentary cover. The Cenozoic strata is well developed except for the absence of bottom of Paleogene (Fig. 1b). The total thickness can reach about 7000m near Hu County, in Xi 'an Sag.

There are still some differences in the division and naming of Cenozoic strata in Guanzhong basin. In this paper, the Neogene strata are divided into Gaolin Group (N_1gl), Lantian-Bahe Formation (N_2l+b) and Zhangjiapo Formation (N_2z) from bottom to top by using the division scheme of petroleum system.

Neogene strata distributes throughout whole area in Xi 'an Sag, which is the most important porous sandstone reservoir. The top Gaoling group buries generally from 1500m to 3200m underground, with the stratum thickness of 200 to 1500 meters. The top Lantian-Bahe Formation buries generally from 1200m to 2300m underground, and the strata thickness is 400 to 1400 meters. The top Zhangjiapo Formation buries generally from is 600m to 1300m underground, and the thickness of the strata is 400 to 1200 meters.

2.3 Sedimentary environment

The sedimentary environment and the distribution of different facies of Cenozoic strata in Guanzhong Basin are controlled by the evolution stages and structural faults, and the facies belts evolve gradually along the margin faults to the interior area. It shows characteristics of small water area, fast facies change and narrow facies belts (Li et.al,2015). There are 4 main types of sedimentary facies in Xi'an Sag, including alluvial fan facies, fluvial facies, delta facies and lacustrine facies.

When Gaoling group was deposited, the sedimentary range was limited to the central part of the basin. Facies transitioned rapidly from alluvial fan and fluvial facies to lacustrine facies from south to north in Xi'an sag. In the warm and humid climate during the late Gaoling, the water body deepened and extended rapidly with the strengthening of rifting. By the Lantian-Bahe period, the sedimentary range reached its maximum, forming alluvial fans, rivers and deltas. At the same time, affected by the Xianli High and Lishan High, two lacustrine sedimentary zones were formed, including Xi'an Sag and Gushi Sag. Up to the Zhangjiapo period, the sedimentary pattern was quite similar and the lake is further expanded. The middle-south of Xi'an Sag is dominated by fluvial and deltaic deposits, while the northern part is dominated by lacustrine deposits (Li 2017).

2.4 Geothermal field distribution

The terrestrial heat flow value generally ranges from 55.44 mW/m^2 to 93.31 mW/m^2, and the representative value is 68.33 mW/m^2, which is higher than the average value in China (Jiang et.al, 2016; Ren, 2019). The relatively high-value area is located in the Lintong-Xi'an-Xianyang-Wugong area, which is greater than 70mW/m^2. This is considered to be related to the deep lithosphere structure and structural faults.

The current geothermal gradient in the basin is mainly distributed in the range of 2.34~5.85°C/100m, with an average of 3.5°C/100m (Rao et.al, 2016; Zhou et.al, 2017). The geothermal gradient in Xi'an Sag is relatively high, which is overall greater than 3°C/100m, except for the western margin. The geothermal gradients in Xianyang-Xi'an can exceed 4.0°C/100m. Figure 2 shows the distribution of geothermal gradient in the study area.

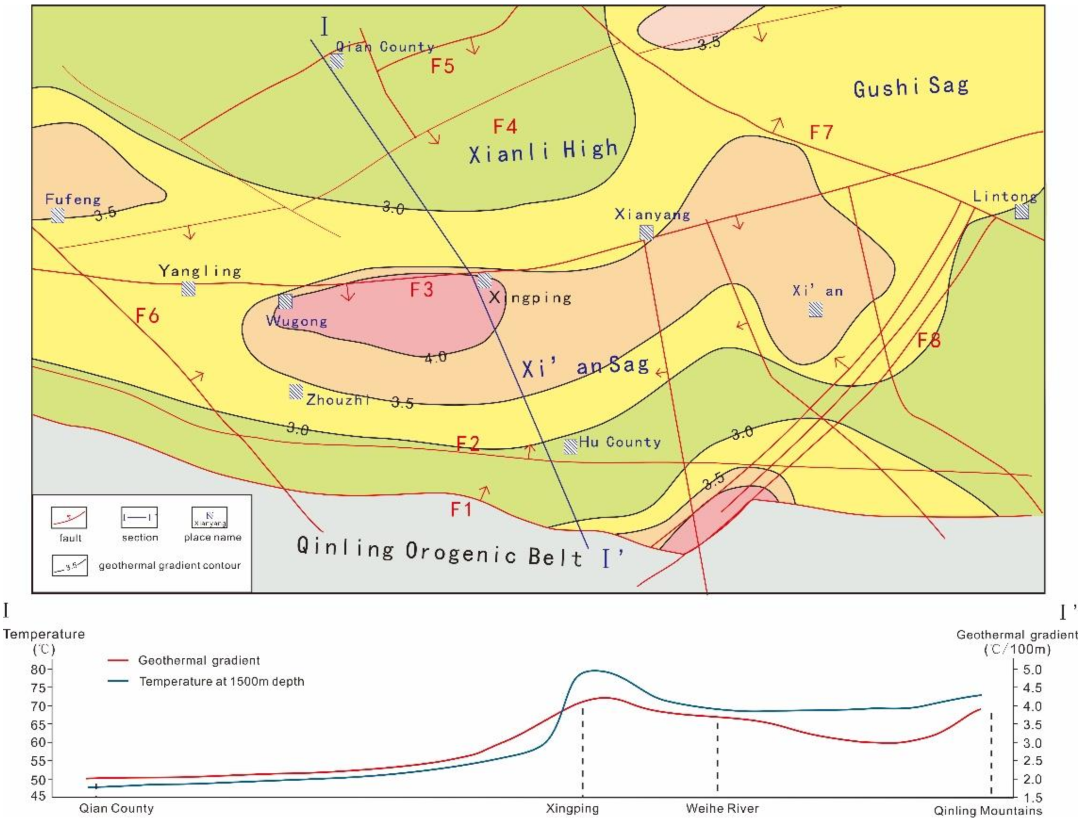

Figure 2: Distribution of geothermal gradient of Xi 'an Sag and surrounding areas. In section I-I', the blue line presents reservoir temperature at 1500 depth.

3. CHARACTERISTICS OF NEOGENE SANDSTONE GEOTHERMAL RESERVOIR IN XI 'AN SAG

3.1 Lithology

The lithology of the Gaoling Group is mainly mudstone, silty mudstone interbedded with fine-siltstone, with coarse to fine grain from bottom to top, and relatively compact structure. In Lantian-Bahe Formation, mudstone is interbedded with coarse-siltstone of varying thickness, also with the grain size coarser at the bottom. The lower part of the Zhangjiapo Formation is composed of interbedded mudstone and thin coarse-siltstone of varying thickness, and the upper part is dominated by mudstone interspersed with coarse-siltstone. The diagenesis of Zhangjiapo Formation is relatively poor. The typical lithologic profile is shown in Figure 1b.

3.2 Petrological features

According to Folk's sandstone classification scheme, samples from 5 wells were studied, and the result shows that: the rock types of Neogene sandstone geothermal reservoirs are dominated by feldspathic lithic sandstone, followed by lithic sandstone. In terrigenous clastic contents, the volume fraction of quartz components is 28%~66%; the volume fraction of feldspar is 11%~31%; the volume fraction of debris is 12%~58%. The rock debris are mainly metamorphic and igneous debris, reflecting a main provenance from the Qinling Mountains in the south.

The compositional maturity index [Q/(F+R)] ranges from 0.39 to 1.94. According to rock structure, the grinding condition is generally spiny-subcircular, and the particle sorting is moderate to poor. It shows that the Neogene sandstone geothermal reservoirs in Xi'an Sag have the characteristics of low compositional maturity and low structural maturity, which is related to the proximity to provenance and short transport distance.

3.3 Storage space characteristics

According to the casting sections of geothermal reservoir in the study area, the reservoir space types are mainly dissolved pores, primary pores and some micro-cracks (Fig. 3). Secondary dissolution pores, mainly appears in feldspar, debris particle edge and particle interior, accounted for about 60%. While primary pores accounted for about 35%. The proportion of dissolved pores in the Lantian-Bahe Formation and Gaoling Group reservoirs is higher than in Zhangjiapo Formation.

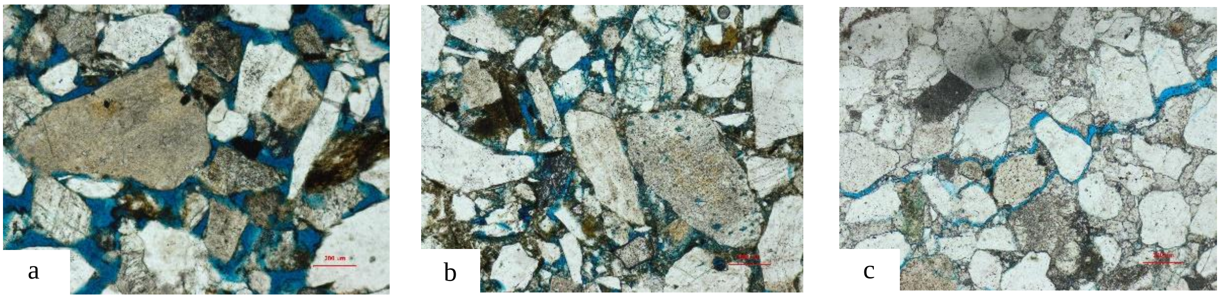

Figure 3: Reservoir space characteristics of Neogene sandstone in Xi 'an Sag. (a) Well ZZ1, 2374.86m, Lantian-Bahe Formation, primary pores (-); (b) Well WS1, 1392.75m, Lantian-Bahe Formation, dissolved pores (-); (c) Well HD1, 1412.81m, Lantian-Bahe Formation, particle edge micro-cracks (-).

3.4 Physical properties

The Neogene sandstone geothermal reservoirs in Xi'an Sag have well-developed pores and fissures, high effective porosity and permeability, which provide a good storage and migration space for geothermal water. Statistics were made on the logging physical property data of 15 typical geothermal wells in the Xi'an Sag, and the results are shown in Table 1.

Vertically, as the burial depth increases, the compaction enhances and the porosity decreases. While the dissolution in the reservoir below 1600m improves the porosity. Reservoir permeability also decreases with the increase of depth and has a good correlation with porosity. Figure 4 shows the variation of reservoir physical properties with depth.

Table1： Physical property parameters of Neogene sandstone reservoir in Xi’an Sag

strata	porosity		permeability（mD）	
	main range	averange	main range	averange
Zhangjiapo	22% ~ 42%	30.02%	180 ~ 1500	451.82
Lantian-Bahe	15% ~ 33%	20.43%	30 ~ 500	140.7
Gaoling	9% ~ 26%	17.28%	9 ~ 500	109.5

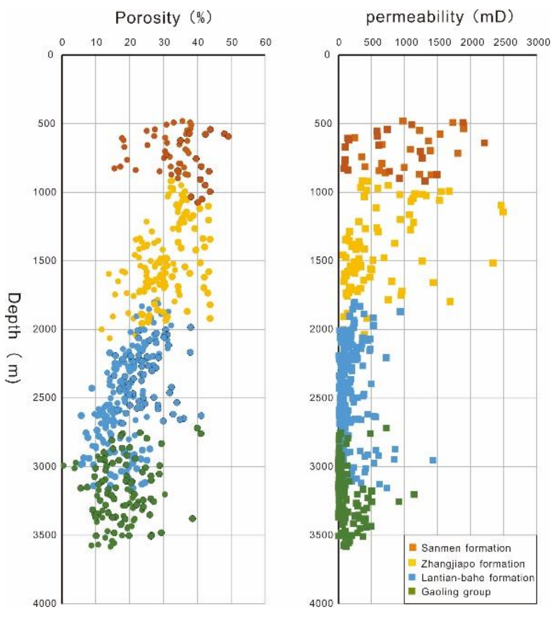

Figure 4: The variation of reservoir physical properties with depth of typical geothermal Wells in Xi 'an Sag

3.5 Thermal Reservoir Temperature

According to the logging data of geothermal wells, the temperature in Neogene sandstone reservoir increases linearly with depth (Fig. 5), showing the characteristics of conductive geothermal resources. The temperature in Xi'an sag is mainly distributed at 40~60°C at 1000m depth, at 70~90°C at 2000m depth, and at 80~130°C 3000m depth. Combined with actual drilling conditions, the top surface temperature of Gaoling Group, Lantian-Bahe Formation and Zhangjiapo Formation are respectively 65~110°C, 60~100°C and 40~70℃. The high value area mainly locates in Xi'an- Xianyang-Xingping-Wugong region. The temperature distribution of reservoir has a good consistency with depth and is also related to the distribution of the main heat source. Figure 6 shows distribution of the top surface temperature of Lantian-Bahe Formation.

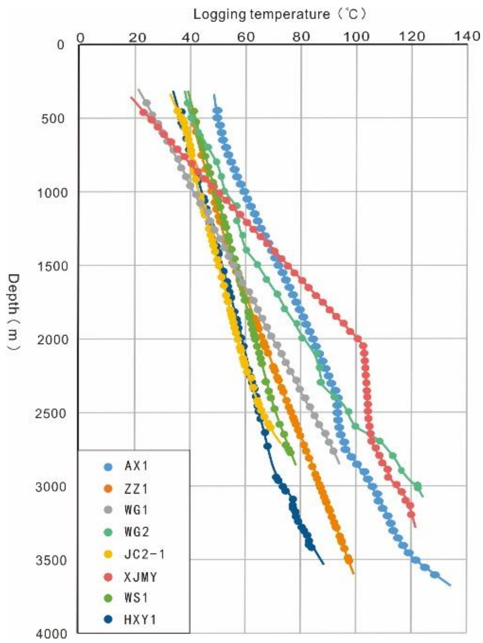

Figure 5: The temperature-depth curves of typical geothermal wells in Xi 'an Sag (logging data).

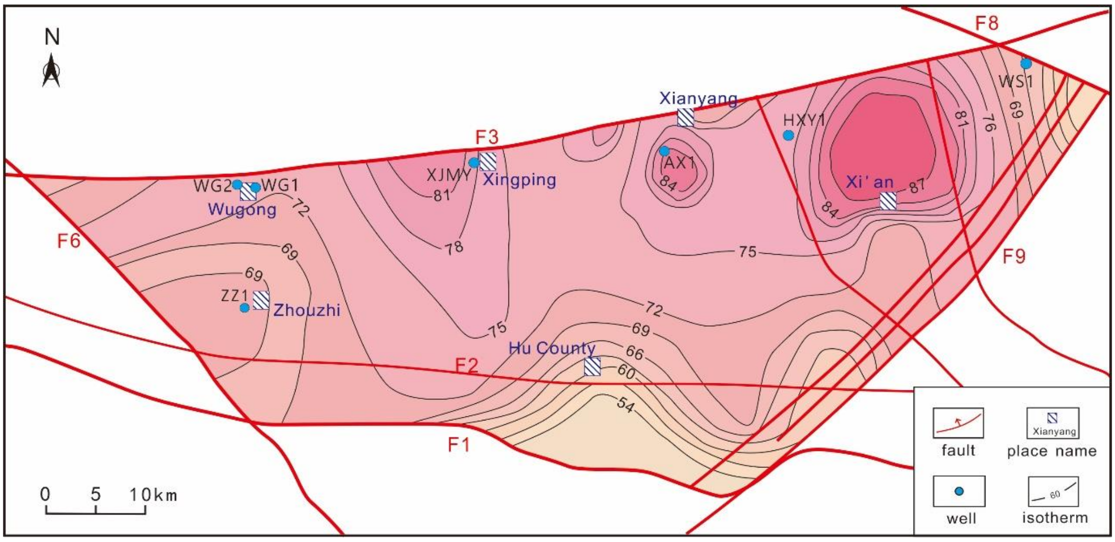

Figure 6: Distribution of the top surface temperature of Lantian-Bahe Formation in Xi'an Sag.

3.6 Favorable sand body distribution

In general, the reservoir sand bodies in the Xi'an Sag gradually advance from the southern and eastern margins to the interior, showing the advantages of wide distribution and large thickness (Hong et.al,2019).

Lantian-Bahe Formation has a large distribution area of high-quality sand bodies, with large thickness and rich water storage. The sand bodies have a total thickness of 150~400m, and a sand ratio of 15%~60%. It is currently the most developed sandstone geothermal reservoir, showing great resource potential during practical production. Figure 7 shows the distribution of high-quality sand bodies in Lantian-Bahe Formation.

The total sand bodies thickness of Gaoling Group is 130~350m, and the sand ratio is 15%~60%. The total sand bodies thickness of Zhangjiapo Formation is 50~300m, and the sand ratio is mainly 10%~25%, expect for the southern margin of about 45%~50%.

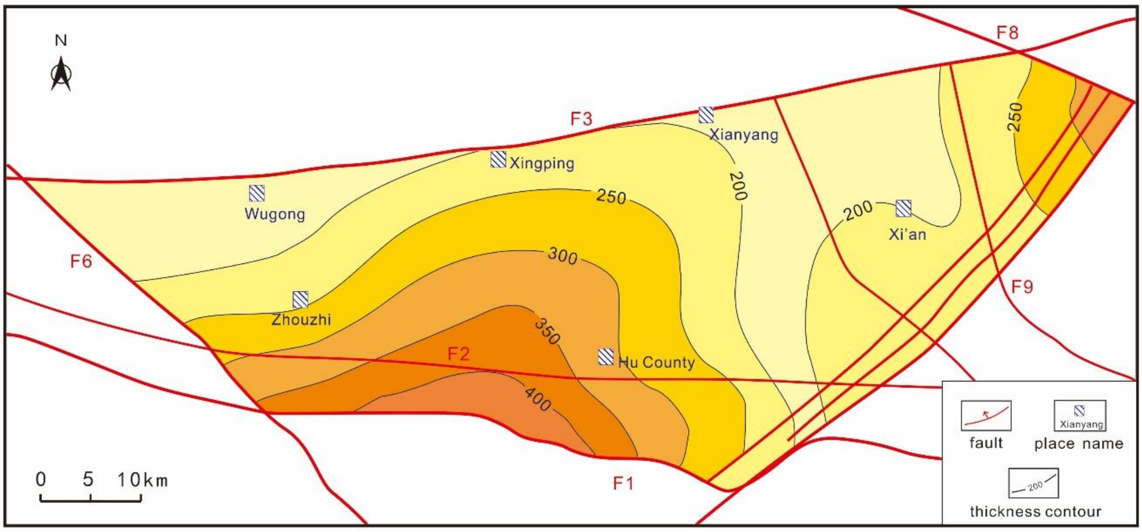

Figure 7: Thickness distribution of geothermal reservoir sand body in Lantian-Bahe Formation, Xi'an Dag

4. RELATIONSHIP BETWEEN RESERVOIR CHARACTERISTICS AND GEOTHERMAL WELL PRODUCTIVITY

The oxygen activated logging was adapted in Well BS in Xianyang. This method measures the upward fluid flow in the well, getting a fluid production profile to accurately give the stratified water production of each layer. The relationship between reservoir characteristics and water-yielding capacity was analyzed, using logging interpretation and fluid production data of Well BS.

According to logging results, 34 aquifers were interpreted, and the total water production during the test was 94.2 m^3/h. Physical property is a very important factor of water-yielding capacity. The physical properties of aquifers are significantly better than those of non-aqueous layers. Table 1 shows the minimum, average, and maximum values of porosity and permeability statistical. The porosity of the non-aqueous layers is generally less than 25%, while the permeability is generally lower than 80mD. However, the shale content has no obvious difference whether it is an aquifer or not, and mainly distributes between 8% and 30%.

For a single aquifer, the permeability has the most significant impact on the water production, followed by the influence of shale content. If the single sand body has a higher permeability, and a lower shale content, the water production always tends to be higher. Porosity and sand body thickness have relatively little effect on water production.

Table2： Physical property data of geothermal reservoir of Well BX

classification	Number of layers	porosity（%）			permeability（mD）		
		min	max	mean	min	max	mean
Aquifer	34	21.52	42.79	29.75	30.37	1653.77	249.43
non-aqueous layer	50	4.7	31.43	20.89	0.48	212	47.17

5. CONCLUSION

Neogene sandstone geothermal reservoirs are widely distributed in Xi'an Sag, Guanzhong Basin. The strata mainly composed by fluvial-delta-lacustrine deposition, sandstone and mudstone deposited interactively with a positive rhythm characteristic. The rock types are dominated by feldspathic lithic sandstone, followed by lithic sandstone, with relatively low compositional and structural maturity.

The reservoir space is mainly dissolved pores, primary pores and a small amount of micro-cracks. Zhangjiapo Formation has an average porosity of 30.02%, and an average permeability of 451.82mD. Lantian-Bahe Formation has an average porosity of 20.43%, and an average permeability of 140.7mD. Gaoling Group has an average porosity of 17.28%, and an average permeability of 109.5mD.

Sand body of the Neogene geothermal reservoir has large thickness, advancing from the south and east edge to the interior of the sag. Lantian-Bahe Formation has a large distribution area of high-quality sand bodies, with a total thickness of 150~400m and a sand ratio of 15%~60%. It has rich water storage and is currently the most developed sandstone geothermal reservoir.

The water-yielding capacity of geothermal wells is affected by reservoir characteristics, especially the physical properties of sand bodies. The water production of a single sand body is mainly affected by the permeability and shale content. If it has a higher permeability, and a lower shale content, the water production always tends to be higher. Porosity and sand body thickness have relatively little effect on water production. With the improvement of sandstone reservoir development precision, high-quality sand bodies with high porosity, permeability and low shale content can be selected for segmental exploitation according to well logging interpretation.

REFERENCES

Wang Xing: Geothermal field characteristics and geothermal system in Weihe Basin, *Shaanxi Coal*, 02, (1997), 43-50.

Sun Hongli: A Bearing features and genetic model for geothermal resources in Guanzhong basin, China University of Geosciences, 2015.

Ren Wenbo: Characteristics and development of geothermal resources in the middle and deep layers of the Weihe Basin, Northwest University, 2019.

Zeng Honglin, Zhang Yinlong, and Zhouyang: Research on the modes of occurrence and application of geothermal resources in the middle and deep layers of the piedmont area in southern Guanzhong Basin, *Geology of China*, 46(05), (2019): 1224-1235.

Ren Zhanli, Liu Runchuan, Ren Wenbo, Qi Kai, Yang Guilin, Cui Junping, Yang Peng, and Zhang Yuanyuan: Distribution of geothermal field and its controlling factors in the Weihe basin, *Acta Geology Scinica*, 94(07), (2020): 1938-1949.

Liu Hujun: Formation and Evolution of the Weihr River Basin and Uplift of the Eastern Qinling Mountains, Northwest University, 2004.

Li Yuhong, Zhang Wen, Yuan Bingqiang, Han Wei, Chen Gaochao, and Zhang Lin: Basement composition for Weihe Cenozoic Basin and its petroleum geological significance, *Journal of Xi'an University of Science and Technology*, 38(06), (2018): 966-974.

Li Zhichao, Li Wenhou, Li Yongxiang, Li Yuhong, Han Wei, Wen Jinhua, Chen Meng, and Qin Zhi: Sedimentary facies of the Cenozoic in Weihe Basin, *Journal of Palaeogeography*, 17(04), (2015): 529-540.

Li Zhichao: The Lithofacies Paleogeography and Paleoenvironmental evolution of the Cenozoic in the Weihe Basin, China. Northwest University, 2017.

Jiang Guangzheng, Gao Peng, Rao Song, Zhang Linyou, Tang Xiaoyin, Huang Fang, Zhao Ping, Pang Zhonghe, He Lijuan, Hu Shengbiao, and Wang Jiyang: Compilation of heat flow data in the continental area of China, *Chinese Journal of Geophysics*, 59(08), (2016): 2892-2910.

Zhou Yang, Mu Genxu, Zhang Hui, Wang Ke, Liu Jianqiang, and Zhang Yage: Geothermal field division and its geological influencing factors in Guanzhong basin, *Geology of China*, 44(05), (2017): 1017-1026.

Rao Song, Jiang Guangzheng, Gao Yajie, Hu Shengbiao and Wang Jiyang: The thermal structure of the lithosphere and heat source mechanism of geothermal field in Weihe Basin, *Chinese Journal of Geophysics*, 59(6), (2016): 2176-2190.