Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Study on the Heterogeneity of Carbonate Heat Reservoirs in the Southwest of the North China Platform

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Keywords: carbonate heat reservoir, heterogeneity, water-richness, fracture, connectivity.

ABSTRACT

Carbonate heat reservoirs are an important type of geothermal reservoirs, where the reservoir volume is composed of dissolved pores, holes, cracks, etc. The heterogeneity of carbonate heat reservoir refers to its distribution characteristics, and the development of dissolved pores, caves, cracks and the connectivity of cracks in the carbonate heat reservoir varies in space. This has an important impact on the water-richness in carbonate heat reservoirs. In this paper, the heterogeneity of carbonate heat reservoirs in the southwest of the North China Platform is studied in detail. The results show an abundance of pores and fractures. Furthermore, the reservoir connectivity is good in the carbonate exposed area where the groundwater is replenished, but in the deep carbonate areas the amount of carbonate pores and fractures is less than that of the exposed areas. Water pumping tests showed that the water-richness of carbonate is very low in the deep carbonate area. We think that the most important factor leading to the difference in water-richness between the deep carbonate area and exposed area is the strong heterogeneity of carbonate, with its poor fracture connectivity resulting in a slow recharge of groundwater. For the exploration and development of carbonate heat reservoirs, to judge the water-richness of carbonate reservoirs, it is necessary to study influential factors, especial heterogeneity. The heterogeneity of carbonate has a great impact on whether geothermal resources can be achieved for large-scale development. Therefore, the study on carbonate heterogeneity is an important link.

1. INTRODUCTION

Carbonate heat water is an important geothermal resource, and it is present in weathered carbonate rock. The physical properties of carbonate rocks represent key factors for exploration and development of hydrocarbons or geothermal resources, and the heterogeneity of the reservoirs plays a very important role in such applications.

Reservoir heterogeneity refers to the non-uniform spatial variation of reservoir properties, which is a result of sedimentation, diagenesis and tectonism during the formation process (Yu, 2009). According to reservoir characteristics (scale), it can be divided into interlayer heterogeneity, areal heterogeneity, intralayer heterogeneity, and pore heterogeneity. The complex reservoir heterogeneity is generally described hierarchically. That is, it can be described qualitatively and quantitatively in a descending order of size. The qualitative description mainly involves the geological characteristics affecting physical reservoir properties, such as faults, caves, fractures, interbeds, epigenetic changes, pore types and distribution. The qualitative analysis can be carried out using core, logging, thin section and outcrop data (Sun, 2016). The quantitative description is a kind of multi-prospective and multi-parameter analysis on the heterogeneity of a carbonate reservoir, which is strong due to sedimentation, tectonism, and subsequent strong weathering, denudation and leaching.

This paper will present the qualitative description of intralayer heterogeneity of the Lower Paleozoic carbonate reservoir in the Taikang Upheaval in the Southern North China Basin.

2. STRUCTURAL AND SEDIMENTARY CHARACTERISTICS

The Southern North China Basin, in the southwestern North China Platform, refers to the region to the north of the Qinling-Dabie orogenic belt, the west of the Tanlu Fault zone and the south of the Fengpei Upheaval. It includes six first-order tectonic units, i.e., the Yuxi Upheaval, Zhoukou Sag, Taikang Upheaval, Kaifeng Sag, Changshan Upheaval, Xinyang-Hefei Sag, and Huaibei Upheaval, with a total area of 15×10^4 km^2 (Figure 1) (Quan, 1989; Ma, 2011). Structurally, the Southern North China Basin stretches across the southern part and southern margin of the North China Platform, with a thrust fold orogenic belt at the southern edge, and it presents as a Mesozoic–Cenozoic superimposed basin inheriting from the North China Platform (Xie, 2007). The NWW-trending Taikang Upheaval in the northern part of the Southern North China Basin is a gentle complex anticline superimposed with NEE-trending short-axis folds, and cut by NWW-, NE- and NNE-trending faults. The study area is located in the west of the Taikang Upheaval.

The Taikang Upheaval has experienced two stages of basin development and uplift, including six evolution periods; namely, marine basin development in Cambrian–Ordovician, marine–continental transitional basin development in Carboniferous–Permian, continental basin development in Triassic, compression and uplifting in Late Triassic–Early Cretaceous, uplifting and disintegration in Late Cretaceous–Early Tertiary, and re-subsidence in Late Tertiary–Quaternary (Sun, 1996). Accordingly, the west of the Taikang Upheaval contains the Quaternary, Upper Tertiary, Triassic, Carboniferous–Permian and Cambrian–Ordovician strata, from top to bottom. According to the drilling and geophysical data, the Quaternary and Neogene are 350–1700 m thick in total, and composed of clayey alluvium and celadon sandy mudstone, respectively; the Triassic is 1000–3200 m thick, and composed of celadon and brown-red sandy mudstone; the Carboniferous–Permian is 600–1100 m thick and composed of gray mudstone, fine sandstone and limestone; the Cambrian–Ordovician is 400–1300 m thick and composed of marine carbonate rocks.

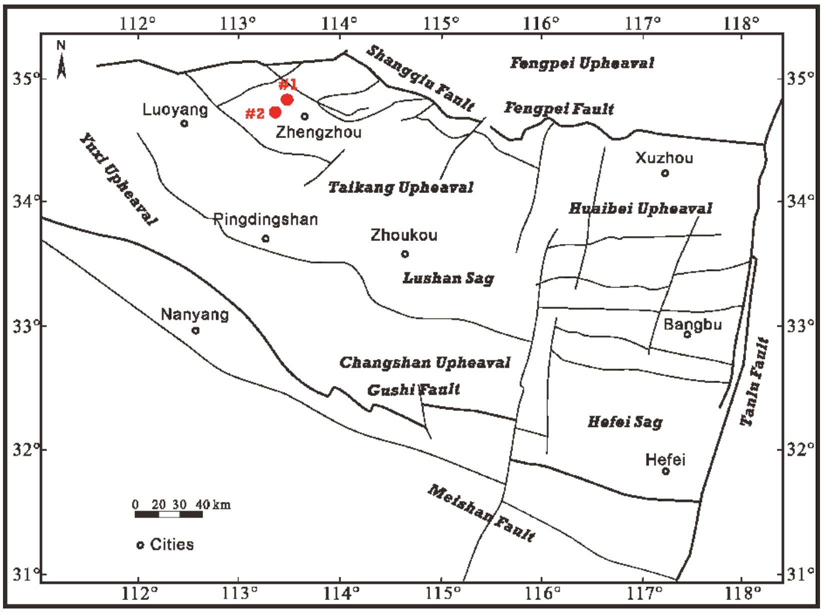

Figure 1: Tectonic units of the Southern North China Basin.

3. CARBONATE HEAT RESERVOIR

The heat reservoir in the study area is the Cambrian–Ordovician carbonate rock. The overlying Quaternary to Carboniferous sandy mudstone can serve as a caprock. The Carboniferous bauxite mudstone directly covers the Ordovician limestone, and this structurally tight rock with a strong seal capacity was formed by the mixture of weathered carbonate and terrigenous sediments (Zheng and Zhang, 1996). The vertical permeability of bauxite rocks in the study area is 2.06×10^{-7} to 20.7×10^{-7} μm^2.

According to the morphology, the carbonate reservoir space can be divided into: pores and fractures. The former refers to the space with the length-width ratio less than 10:1, and the latter refers to the space with the length-width ratio more than 10:1. Pores can be subdivided into pores (with diameter <2 mm) and vugs (with diameter >2 mm) (Zheng et al., 1996). The Ordovician thermal reservoir in the study area is the lower Majiagou limestone, and contains fractures and a small amount of karst vugs. The vugs are mostly isolated or in the form of phenocrysts, with poor connectivity. Many fractures are observed in the cores, including structural fractures, diagenetic fractures, dissolved fractures and pressolutional fractures, which are mostly filled and rarely semi-filled (Figure 2).

Figure 2: Limestone core filled with calcite.

The Upper Cambrian Fengshan Formation dolomitic limestone and Middle Cambrian Zhangxia Formation thick layered dark-gray oolitic limestone are also developed in the study area, and both are mainly composed of fractures and vugs. The former is dominated by fractures, with a porosity of 3–8%. The latter contains only a few fractures and vugs, indicative of a poor accumulation property, which may reflect that the Middle Cambrian Zhangxia Formation experienced strong diagenesis and weak weathering and leaching (Figure 3).

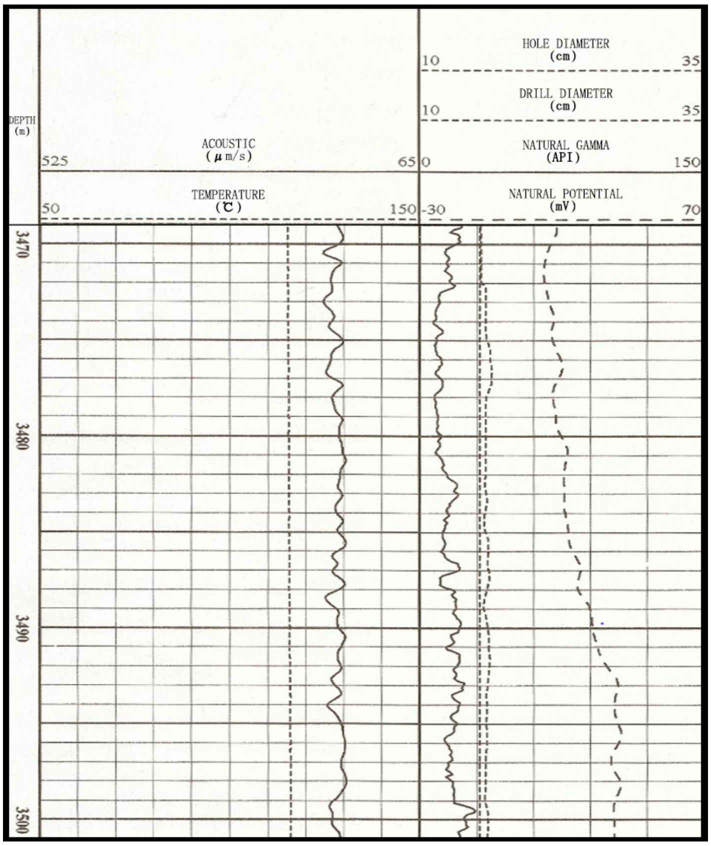

Figure 3: Electrical logging curve of the Middle Cambrian Zhangxia Formation in Well 1.

4. PUMPING TEST

The underground water in the study area is sourced from the mountains in the southwest, where limestone is exposed, pores and fractures are well developed, reservoir connectivity is good, and water supply is sufficient. However, the study area is located in the deep-buried carbonate rock area, with less carbonate rock pores and fractures than the outcrop area. Two geothermal wells (Well 1 and Well 2) in the study area are both located in the west of the Taikang Upheaval, with a distance of 3.5 km (Figure 1). Both wells were drilled into the Quaternary, Upper Tertiary, Triassic, Carboniferous–Permian and Cambrian–Ordovician strata, and completed at the Cambrian. The total depth is 3600 m for Well 1 and 3210 m for Well 2. In Well 1 and Well 2, the Ordovician is 2980 m and 2570 m deep at the top, and 3214 m and 2820 m at the bottom; the Cambrian thickness is 386 m and 390 m, respectively. The thermal reservoirs are Ordovician Lower Majiagou Formation limestone, Upper Cambrian Fengshan Formation dolomitic limestone and Middle Cambrian Zhangxia Formation oolitic limestone. According to the electrical logging results, the Ordovician Lower Majiagou Formation limestone is about 80 m thick, with a tight lithology and low porosity (Figure 4).

The Upper Cambrian Fengshan Formation dolomitic limestone encountered is 95 m and 98 m thick, respectively. According to the drilling data of Well 1, a leakage occurred at the depth of 3285 m, and the water flowed naturally after washing by gas lift, indicating that this interval contained water and had a certain formation pressure. After carrying out a fracturing and acidizing operation, the static water level dropped to 50 m, and the water was pumped out and quickly drained. After the pump stopped, the water level recovered very slowly. According to the electrical logging results, the reservoir space consists of carbonate rock pores, vugs and fractures, showing good physical properties (Figure 5). The analysis shows that the water content of the formation is insufficient, lacks recharge, and the connectivity of the reservoir is poor. After the same drilling process as Well 1, Well 2 needs intermittent pumping although the water amount is not large, and the water level recovers much faster than Well 1. The comparative analysis of the two wells shows that although the same reservoir, similar thickness and similar physical conditions, they have different burial depths. This is not the main reason for the large difference in water output between the two wells, while the heterogeneity of the reservoir is the fundamental factor. This layer has strong heterogeneity, which is mainly reflected in the difference of connectivity. The fracture connectivity is good in the study area and the water recharges well. Usually in deep buried areas of limestone, carbonate rock has low water abundance and poor fracture connectivity. As a result, remote water sources cannot be effectively recharged.

The two wells drilled into thick dark gray oolitic limestone in the Middle Cambrian Zhangxia Formation, with a thickness of about 100 m. According to the electrical logging data, the two wells have similar physical properties and tight lithology, and only a few squares were found during the water testing.

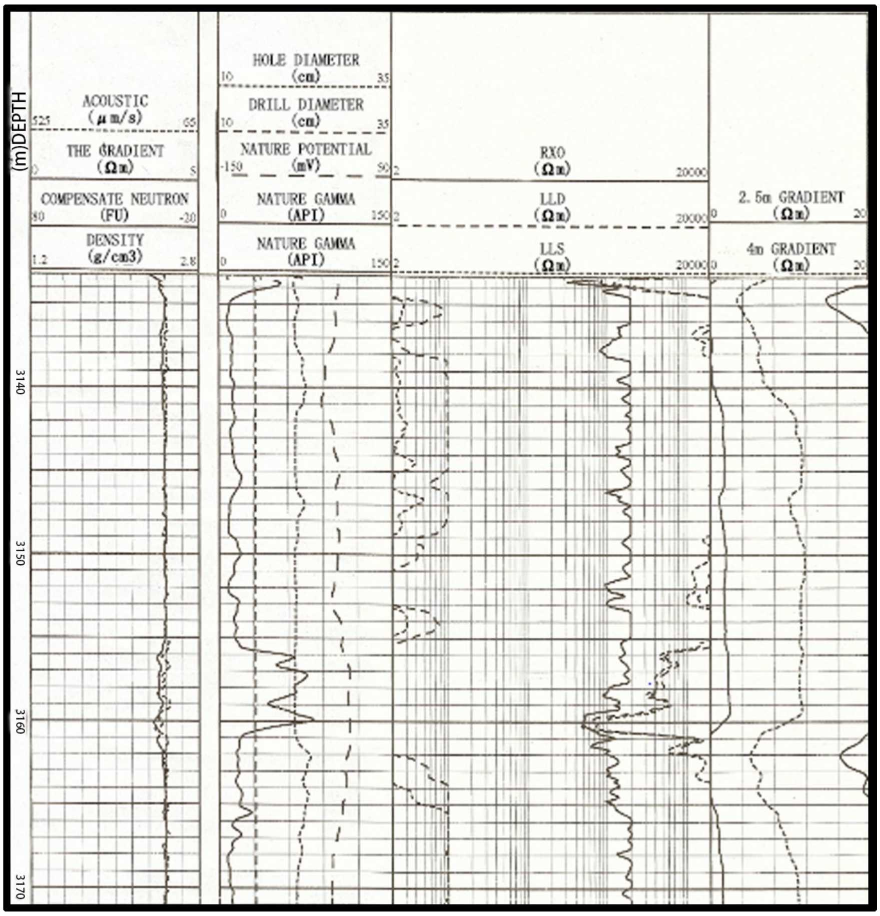

Figure 4: Electrical logging results of the Ordovician Lower Majiagou Formation in Well 1.

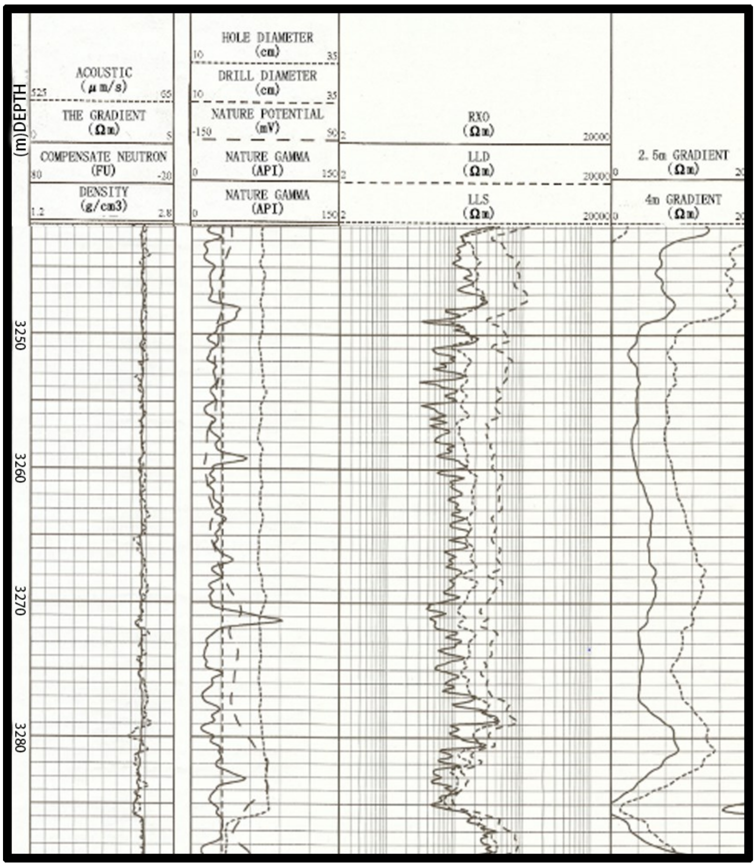

Figure 5: Electrical logging results of the Upper Cambrian Fengshan Formation in Well 1.

5. CONCLUSION

Based on the analysis of the water output from two geothermal wells in the west of the Taikang Upheaval in the Southern North China Basin, it is evident that the Upper Cambrian Fengshan Formation dolomitic limestone has strong heterogeneity, which is mainly reflected in the difference of connectivity. In the area with good fracture connectivity, the water can be sufficiently supplied. Generally, in the supply area with limestone outcrops, pores and fractures are developed, reservoir connectivity is good, and the underground water supply is sufficient. However, in the deep-buried carbonate rock area, pores and fractures are less developed, and fracture connectivity is poor, making the remote water fail to recharge effectively. Therefore, to explore and develop the carbonate rock reservoirs, identification of the geothermal resources and water richness is necessary for understanding the heterogeneity of the carbonate rock reservoirs.

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