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

Geogenetic Analysis of Karst Thermal Reservoir in Gaoyang Geothermal Field in Hebei Province

Sui shaoqiang and Liu huiying

National Geothermal Energy Center of China, Beijing, 100083

suishaoqiang.xxsy@sinopec.com

Keywords: Gaoyang, geothermal field, karst, thermal reservoir, physical properties.

ABSTRACT

The aim of exploring the genesis model of karst thermal reservoir in Gaoyang geothermal field is to develop the geothermal field reasonably and effectively. Starting from the analysis of basic geothermal geological data such as regional structure, strata and geothermal features in Gaoyang geothermal field, this paper analyzes the structural characteristics, thermal reservoir distribution, physical properties, heat source, migration channel, hydrochemistry and cap layer. The distribution characteristics of the faults around and inside the Gaoyang geothermal field, the distribution characteristics of the buried hill thermal reservoir, and the distribution relations of the influencing factors in the formation of geothermal field thermal reservoir are defined. The buried hill thermal reservoir is developed in the Proterozoic Wumishan Formation, the Cambrian and Ordovician thermal reservoir has local residual, and the karst thermal reservoir has the spreading point in the north east - south west. The regional terrestrial heat flow value is high, the heat source condition is good. Geothermal water flows from the northwest to the southeast, principally from the Taihang mountains. The hot water migration channels are deep faults and unconformities. The cap layers are composed of Tertiary argillaceous rocks and Quaternary strata.

1. INTRODUCTION

Geothermal energy is a green and environmentally friendly renewable energy, which has got more interest in China.

Hebei province is rich in geothermal resources, on the one hand, because the crust of the North China Basin is relatively thin compared with other regions, faults are relatively developed, the terrestrial heat flow value is high, and the source of heat is sufficient. On the other hand, there are several sets of thermal reservoirs in Hebei province. The bedrock thermal reservoirs are mainly carbonate rocks such as Jixian and Ordovician, while the sandstone heat reservoirs are Neogene Guantao Formation and Minghuazhen Formation. Among them, Jixian bedrock thermal reservoirs are the most widely distributed and have the highest utilization rate. For example, Niutuozhen and Rongcheng geothermal fields in Xiongan New Area and Xianxian geothermal fields located on the Cangxian uplift are all developed for the Proterozoic Wumishan Formation karst thermal reservoir. Compared with sandstone thermal storage, bedrock thermal reservoir has higher temperature and greater water volume. The development and utilization of these geothermal fields have provided a large amount of heat energy for the Economic circle around Beijing, reduced pollution emissions such as coal burning, and made an important contribution to winning the battle for blue skies.

The Gaoyang geothermal field is located on the Gaoyang bulge with a buried depth of about 3000m at the top (the previously developed geothermal field has a shallow buried depth of about 1000m). It is a replacement area for the next large-scale geothermal development and utilization, with high development value and great significance. In the early years, a number of oil drilling encountered the Jixian thermal reservoir system, and it was found that the thermal reservoir property was relatively good and the storage space was relatively large. In recent years, a geothermal well was drilled in Boye county in the same tectonic belt. The water temperature was 1,100C and the water quantity was more than 70 m^3/h. The high enthalpy value proved that the production capacity was guaranteed.

Based on the results of geological research, this paper analyzes the geological characteristics of regional geothermal such as stratum, structure and geothermal field, and clarifies the basic conditions for the formation of thermal reservoir. By analyzing the distribution, thickness, physical property, migration channel, hydrochemistry and other factors of thermal reservoir, the genetic model is concluded and the genetic mechanism is clarified, which lays a good foundation for better exploitation and utilization of Gaoyang geothermal field heat resources in the future.

2. ANALYSIS OF REGIONAL GEOTHERMAL FEATURES

Gaoyang bulge belongs to the Chinese-Korean quasi–platform. It is a Quaternary structural unit in The Jizhong depression (III) of the North China Basin (II) in the North China Basin and is located in the south-central part of The Jizhong Depression. The main body of Gaoyang geothermal field is located on the Lixian county slopes and Gaoyang bulge, Baoding sag is to the west, Raoyang sag is to the east, Niutuozhen bulge and Bazhou sag are to the north and northeast, respectively, and Wuji-Gaocheng bulge and Jinxian sag are to the southwest (Fig. 1). The roof of the buried mountain is deeply buried, the main body is 2800~4000m, and the area is about 70 km^2. The karst thermal reservoir, dominated by the marine carbonate rocks of the Wumishan Formation, is thick and widely distributed.

The Yanshan movement is the most important tectonic movement in this area, which transformed from stable period to active area and developed a series of NE, NWW and EW-trending extensional faults. The Taihang mountains in the west and Yanshan mountainsin the northwest, and the Jizhong Depression subsided as a whole. However, the interior of the Jizhong Depression was uneven and on the whole, it is spreading in the northeast and the southwest, and distributed in the general direction, accompanied

by a large number of secondary faults and folds. At the end of the Cretaceous period, the whole region was compressed and uplifted, and only part of the region accepted deposition.

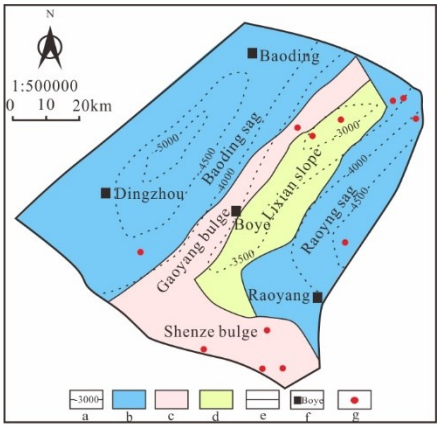

Figure 1:Schematic diagram of buried hill and surrounding tectonic units in Gaoyang geothermal field: (a) buried depth, (b) sag, (c) bulge, (d) slope, (e) study area boundary, (f) location, and (g) well location.

2.1 Formation characteristics

The regional strata of the Gaoyang geothermal field from the oldest to the most recent include the Archaean, the Changcheng and Jixian systems of the Middle and Lower Proterozoic, the Cambrian and Ordovician systems of the Lower Paleozoic, the Upper Paleozoic Carboniferous - Permian, the Jurassic - Cretaceous of the Mesozoic, as well as the Paleogene, Neogene and Quaternary systems of the Cenozoic. Under the influence of Jixian movement, the whole upper Proterozoic was missing. Under the influence of Caledonian movement, the Silurian and Devonian systems in the Lower Paleozoic are absent. Due to Hercynian motion, the Triassic system of Mesozoic is missing.

The basement strata from the bottom to the top mainly develop the metamorphic rocks of the Archean, the dolomite of the Wumishan Formation of the Jixian System in the Proterozoic, the Cambrian and Ordovician limestone, as well as the Carboniferous and Permian sea-land interaction strata. Carbonate buried hill stratum mainly consists of Proterozoic Wumishan Formation and some Cambrian and Ordovician strata. Among them, the dolomite of the Wumishan Formation is developed in the entire region of the geothermal field, the limestone of the Cambrian and Ordovician systems is developed in the southern region of the geothermal field, the Carboniferous - Permian strata remain only in the south, and the Mesozoic strata are basically distributed in the sag (Fig. 2 and Fig. 3).

The bedrock thermal reservoir caps are generally sandstone and mudstone interbedded in the Neocene-Paleogene and Neocene and Quaternary strata. The Guantao Formation of the Neogene and its Upper Cenozoic strata in the sag stage of the basin are distributed all over the region, with a thickness of about 2000m and unconformable contact with the Paleogene. During the Paleogene period, the basin was in the fault-depression stage, and the strata included Dongying Formation, Shahejie Formation and Kongdian Formation, etc., which were in the stage of filling and replenishment. The sedimentary range covered the whole study area, with a thickness of about 2000m, and the thickest area could reach 3000m. The Paleogene strata are in angular unconformable contact with the Ji Xian, Cambrian and Ordovician strata.

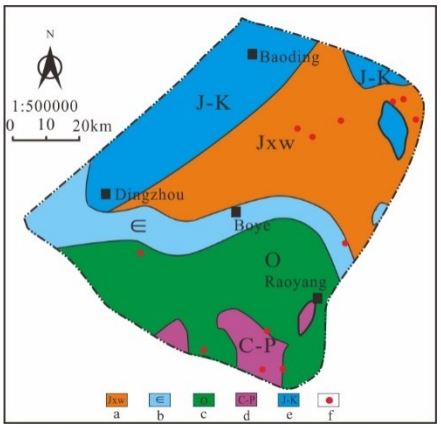

Figure 2: Distribution diagram of pre-Paleogene strata in Gaoyang geothermal field:(a) Proterozoic Wumishan Formation, (b) Cambrian, (c) Ordovician, (d) Carboniferous-Permian, (e) Jurassic- Cretaceous, and (f) well location.

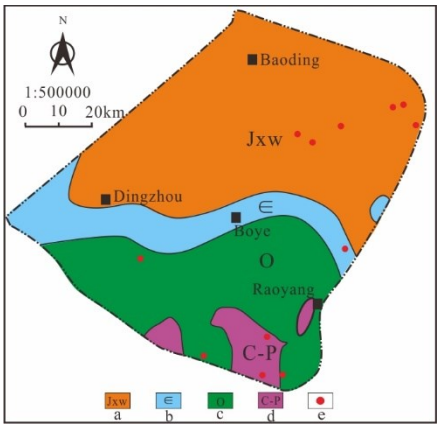

Figure 3: Distribution diagram of the Pre-mesozoic strata in Gaoyang geothermal field:(a) Proterozoic Wumishan Formation, (b) Cambrian, (c) Ordovician, (d) Carboniferous-Permian, and (e) well location.

2.2 Structural features

The main part of Gaoyang geothermal field is mainly developed near NE Gaoyang fault, Anguo fault and some other small faults. Gaoyang fault is a group of counter sloping normal faults whose strike is NE. It is the boundary between Gaoyang bulge and Lixian slope. Gaoyang fault and Anguo fault are nearly parallel and of NW direction. The Gaoyang fault extends to the Changcheng system and the upper fault to the Neogene strata, while the Anguo fault is relatively shallow and the lower fault only reaches the Paleogene strata (Fig. 4).

In the region, the Gaoyang geothermal field located in the NE direction has developed the Hengshui fault near NWW in the south, the Chuan fault near NWW in the north and the Baichi fault. The Hengshui fault is NE, intersects with the Anguo fault, and ends at the Xushui-Baoding-Shijiazhuang fault in the northwest. The Baichi and the Chuan faults have SW strike, and the Baichi fault reaches the Wumishan Formation (Fig. 10). The Paleogene strata and the Jixian strata are angular unconformities (Fig. 2 and Fig. 4). Those deep faults and unconformities constitute fluid migration channels.

According to the plane and profile distribution characteristics of the strata in Fig. 1, Fig. 2, Fig. 3 and Fig. 4, the Gaoyang geothermal field is mainly the karst reservoir of the Wumishan dolomite, and the capping layer is the sand and mudstone interbedding and Quaternary strata of the Neocene-Paleogene and the Neogene. From the distribution features of the depth of the top of the Wumishan Formation shown in Fig. 1, it can be seen that under the current economic and technological conditions (generally buried at a depth of over 3500 m), the main interest zone of this reservoir is generally located at the high portions of Gaoyang bulge and Lixian slopes.

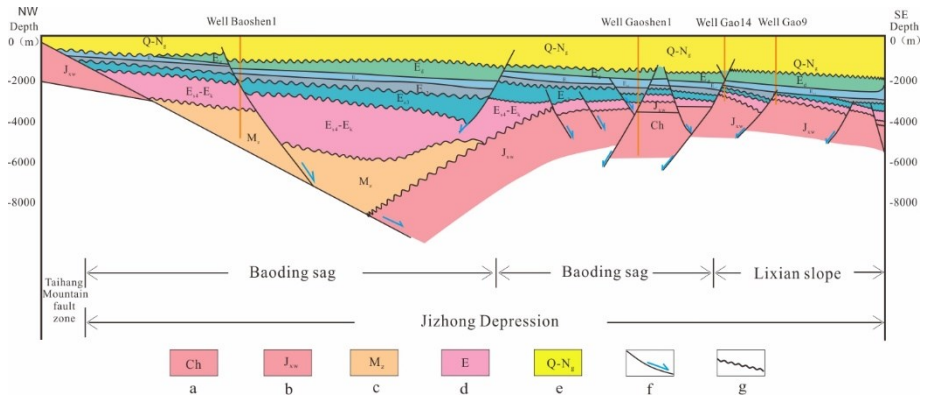

Figure 4: Profile of Gaoyang bulge structure: (a) Changcheng System, (b) Proterozoic Wumishan Formation, (c) Mesozoic, (d) Eogene, (e) Neocene-Quaternary, (f) fault, and (g) unconformity.

2.3 Geothermal field characteristics

The Cenozoic cap layer of Gaoyang geothermal field is relatively thick, and the buried depth of bedrock roof reaches about 3000m.However, the geothermal gradients of the cap layer are all greater than 3.5℃/100m, which fully indicates that the bedrock thermal reservoir temperature of Gaoyang geothermal field is relatively high.

As can be seen from the thermal reservoir temperature isoline map of buried hill of Gaoyang geothermal field (Fig. 5), there are two geothermal high temperature blocks, which are located in the north of Gaoyang bulge and the south of Raoyang sag, respectively. The maximum temperature is greater than 120℃, and the temperature isoline density is similar. The temperature isoline is in the NE-SW direction than the NW-SE direction, indicating that the temperature changes rapidly in the NW-SE direction. Therefore, it can be inferred that the water supply came from the Taihang Mountains in the northwest.

The geothermal gradient isolines in the northern block extend uniformly, but in the southern block, the geothermal gradient isolines in the northeast direction are obviously sparse compared with other directions, so it is speculated that the northeast is the hot water diffusion zone, which is consistent with the distribution of temperature isolines.

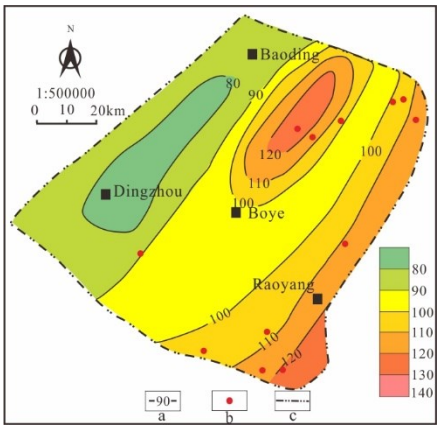

Figure 5: Isotherm of buried hill in Gaoyang geothermal field: (a) isotherm, (b) well location, and (c) study area boundary.

3. GENETIC ANALYSIS OF KARST THERMAL RESERVOIR

3.1 Characteristics of thermal reservoir and distribution

Marine carbonate buried hill thermal reservoir is widely developed in Gaoyang geothermal field. Among them, the most important thermal reservoir is the JixianWumishan Formation, with cambrian and ordovician limestone thermal reservoirs locally developed. The main thermal reservoir, Wumishan Formation, is characterized by dolomite lithology and a little cloud-limestone. The thermal reservoir facies is mainly subfacies from the upper part of the subtidal zone to the intertidal zone, which mainly develops algal reef beach and algal mat. The lithology of cambrian and ordovician strata in lower paleozoic is mainly limestone. Thermal reservoir is mainly developed in the tidal-flat subfacies, especially in the limestone -flat subfacies, followed by the dolomite -flat subfacies and the dolomite - limestone -flat subfacies.

The Gaoyang bulge in the middle has a small buried depth and the highest point is above 3000m. The buried hill stratum is successively composed of dolomite of the Wumishan Formation and limestone of cambrian and ordovician from north to south. The two sags in the western and eastern regions are low-lying and buried below 5000m (Fig. 3 and Fig.4).

The thermal reservoir thickness of buried mountain in the Gaoyang geothermal field reaches the maximum in the middle, up to more than 700m. The thermal reservoir thickness in the north and south decreases to less than 200m (Fig. 6).

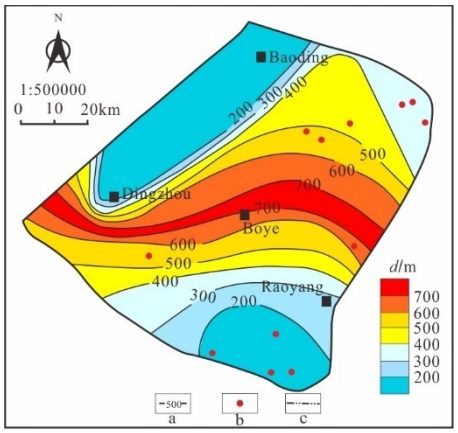

Figure 6: Distribution diagram of average thermal reservoir thickness of buried hill in Gaoyang geothermal field: (a) isopach, (b) well location, and (c) study area boundary.

3.2Thermal reservoir physical characteristics

The dolomite of the Wumishan Formation experienced tectonic evolution, denudation, weathering and leaching during the long geological history, resulting in the formation of reservoir spaces such as structural fractures, structural dissolution fractures, intergranular dissolution pores, intercrystalline dissolution pores, algal shelf pores, dissolution pores and dissolution caves. Rock porosity is mainly distributed within 6.0%, permeability is widely distributed between 0.01~100 mD, accounting for 87.8%, and the average permeability is 35~40 mD. The thermal reservoir pores of the buried hill in the Wumishan Formation have good permeability and are of high porosity and high permeability. This has something to do with the fact that the buried mountain thermal reservoir is located in the seepage zone and the undercurrent zone, which is conducive to the development of large karst caves.

The lower paleozoic cambrian and ordovician strata are mainly composed of limestone and a little dolomite -limestone is also developed. After a long geological history of denudation, weathering and leaching, tectonic fractures, tectonic dissolution fractures, intergranular dissolution pores, intergranular dissolution pores, algal shelf pores, dissolution pores and dissolution caves are well developed. Rock porosity is low, a small amount reaches 5%, permeability variation range is large, from 0.01~1000mD, mainly distributed in 0.01~100mD, the average permeability is 35~45mD.Therefore, Cambrian and Ordovician karst fissure type thermal reservoir has good permeability and is high porosity and high permeability. This is closely related to the development of large karst caves and dissolution pores in the seepage zone and the undercurrent zone, while the thermal reservoir in the slow-flow zone usually does not develop.

Gaoyang geothermal field buried hill karst thermal reservoir, porosity, permeability and other physical properties are the largest in the central Boye area, porosity of more than 5%, permeability of more than 30 mD, but in northwest, southwest, northeast direction decreases. In Baoding and Dingzhou, porosity is less than 2% and permeability is less than 5mD; in Raoyang, porosity is less than 3% and permeability is less than 10mD (Fig. 7 and Fig.8).

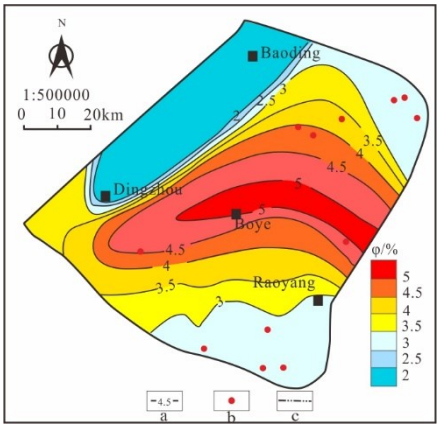

Figure 7: Distribution diagram of average porosity of karst thermal reservoir in Gaoyang geothermal field: (a) porosity, (b) well location, and (c) study area boundary.

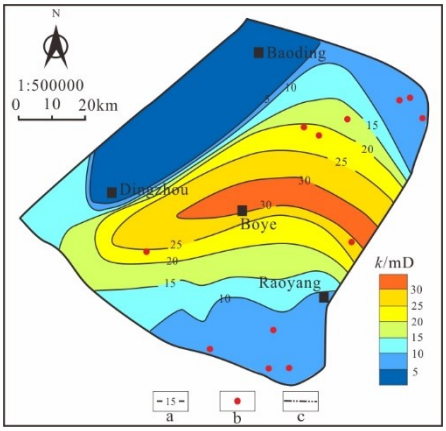

Figure 8: Average permeability distribution of karst thermal reservoir in Gaoyang geothermal field: (a) permeability, (b) well location, and (c) study area boundary.

3.3 Migration channel analysis

Hengshui fault, Chuan fault and Baichi fault are developed in the periphery of Gaoyang geothermal field, and Anguo fault and Gaoyang fault are developed in the geothermal field. All of these are important channels for geothermal water migration. At the same time, the Xushui-Baoding-Shijiazhuang fault at the foot of The Taihang Mountain also plays an important role, because the water of the geothermal field comes from the Taihang Mountain range. The Cenozoic strata of the Gaoyang geothermal field are directly overlaid on the bedrock such as the Wumishan Formation, forming widely distributed unconformities and providing an advantageous channel for the flow of geothermal water.

In a word, Gaoyang geothermal field hot water is mainly transported through faults, unconformity and other channels.

3.4 Hydrochemical characteristics analysis

According to previous studies on hydrogen and oxygen isotopes and 14C dating, Gaoyang geothermal field hot water originates from the Yanshan Mountains in the north and the Taihang Mountains in the west. Karst fissure water in buried mountain of Gaoyang geothermal field is rich in Cl- and Na+. According to the mineralization isoline map of buried hills in Gaoyang geothermal field (Fig. 9), it can be seen that the overall mineralization degree of Wumishan group is 5~6g/L, low in the northwest

and below 3g/L, high in the southeast, up to 12g/L. The distribution of salinity is consistent with the migration direction of geothermal water.

Chemical analysis of water in a geothermal well drilled in this area in recent years shows that the PH value is 7.85; total hardness: 236.35mg/L; total alkalinity: 549.91mg/L; total acidity: 155.00mg/L; the content of Na+ and Cl- in the hot water was 1,565.00 mg/L and 2,251.57 mg/L respectively. The hydrogeochemical type was Cl-Na water. The content index of lithium, meta-boric acid and meta-silicic acid in geothermal water reached the concentration of medical value.

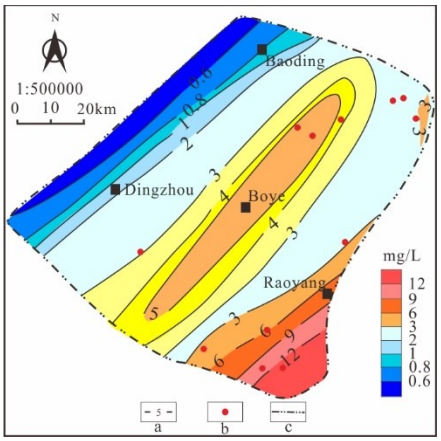

Figure 9: Salinity contour map of buried hill thermal reservoir in Gaoyang geothermal field: (a) salinity, (b) well location, and (c) study area boundary.

3.5Genetic model of karst thermal reservoir

The thermal reservoirs of carbonate buried hills in Gaoyang geothermal field are located in Gaoyang bulge and Lixian slope. In these areas, the buried mountain is relatively shallow and belongs to the tectonic highland. During the Yanshan Period, the buried hills of the Wumishan Formation were located in karst highlands and karst slopes, and there were less exposed karst basins, which were easy to be weathered and leached to form high-quality thermal reservoir.

According to previous studies, geothermal water is derived from atmospheric precipitation. TheXushui-Baoding-Shijiazhuang deep fault in front of Taihang Mountain has communicated with surface water and thermal reservoir, and the atmospheric precipitation migrated to Gaoyang bulge, Lixian slope, Shenze bulge and so on through Hengshui fault, Anguo fault, Baichi fault, Chuan fault and unconsolidated surface, etc., and accumulated into a reservoir in this trap. In the process of fluid migration, it continuously absorbs heat from surrounding rocks, turning cold water into hot water. In addition, hot and cold convection is formed in deep and large faults. Under the effect of density difference, hot water is continuously transported upward along the channels such as fault and unconformity.

A conceptual model of karst thermal reservoir in Gaoyang geothermal field was established by analyzing the factors of source-pass-reservoir-cap (Fig. 10).

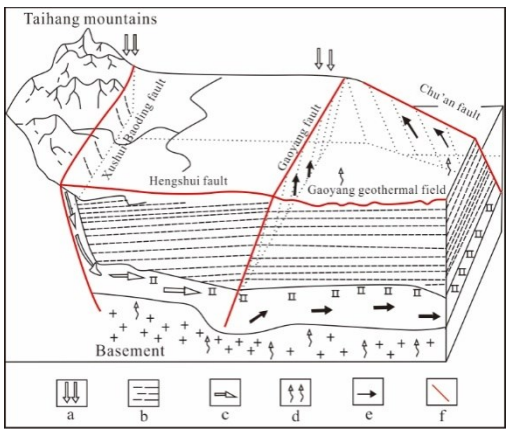

Figure 10: Genetic model of Gaoyang geothermal field: (a) atmospheric precipitation, (b) regional impermeable layer, (c) karst water flow direction, (d) geothermal heat flow, (e) geothermal water flow direction and (f) fault.

4. CONCLUSION

The karst thermal reservoir of The Gaoyang geothermal field is mainly dolomite of the Wuishan Formation, and is partly composed of lower paleozoiccambrian and ordovician limestone. The sedimentary facies belt mainly belongs to the upper algal reef beach complex of the intertidal subtidal zone, which is relatively favorable and has the dominant material basis for forming karst thermal reservoir. For a long time, the Karst thermal reservoir such as the Wumishan Formation was located in the favorable places such as

karst highlands and karst slopes, which were easy to be weathered and leached to form high-quality thermal reservoir. The roof temperature of the buried mountain is about 90~130℃, the terrestrial heat flow value is high, the heat source condition is good. The upper overburden is mainly tertiary argillaceous rock with large thickness and good thermal insulation, which lays a good foundation for thermal energy accumulation and preservation.

Geothermal water is mainly migrated to Gaoyang bulge and Lixian slope through mountain front deep fault, unconsolidated surface, Gaoyang fault and Hengshui fault, and has been heated by terrestrial heat flow to form geothermal water with high temperature. Geothermal water from north west to south east direction, by the Taihang Mountains of water supply, geothermal water salinity has increasing trend from north west to south east direction.

REFERENCES

Yan D S,and Yu Y T: Evaluation and utilization of geothermal resources in Beijing-Tianjin-Hebei oil region, *Chinese Geology University Publish House*, (2000), 8-95.

Chen M X, Wang J Y, and Deng X. Formation characteristics and potential assessment of geothermal resources in China, *Science Press*, (1994), 90-122.

Chen M X. North China geothermal, *Science Press*, (1998), 40-50, 89-117.

Wang J Y. Geothermics and its applications, *Science Press*, (2015), 1-15, 257-372.

Ye L J. North China platform sedimentary formation, *Science Press*, (1983).

Gao C H, Zhang X Z, Zha M, et al. Reservoir characteristics of buried hill in Jizhong depression, *Lithologic Reservoirs*,6, (2011),6-12.

Lu S K, Li J Y, Wu K Y, et al. Tectonic evolution and petroleum geological significance of buried hill in Jizhong depression, *Journal of Oil and Gas Technology*, 11, (2011),35-40.

Xiong L P, Zhang J M. Relationship between geothermal gradient and basement tectonic morphology in North China Plain,*Chinese Journal of Geophysics*, 2,(1988),146-155.