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Preliminary Study on the Feasibility of Segmental Development of Thermal Reservoir in Jixian System Wumishan Formation

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ABSTRACT

In order to explore the occurrence of geothermal reservoirs in deep bedrock of the earth, and provide the basis for the exploration, development and utilization of geothermal resources, this paper makes full use of the existing exploration results and lots of first-hand data, based on the analysis of lithological characteristics of each member of Wumishan Formation, the test data and parameters of geothermal wells with the 3rd - 4th and the 1st - 2ad intake layers are analyzed and compared. The results show that the difference between the two intake layers is obvious, the parameters such as unit inflow and permeability coefficient of the former are larger than those of the latter; the water quality is also better than the latter. The "red strata" developed between the two intake layers can play a good role in water resistance, and can be used as the water barrier between the two, indicating that the Wumishan Formation can be developed by segmentation.

1. INTRODUCTION

Tianjin is rich in geothermal resources, and porous thermal reservoirs have poor reinjection effect, which limits their development [1]. Deep bedrock thermal reservoir of Wumishan Formation is highly praised for its stable development, high fluid temperature, large water yield, moderate burial depth, good reinjection effect and low development risk. It has become the main exploitation layer because of its large utilization scale. However, the prospected reserves are difficult to meet the growing market demand, and a water depression cone has been formed in the concentrated mining area[3], so the prospect is not optimistic.

Currently exploited thermal reservoirs of Wumishan Formation are mostly confined to the upper 3rd - 4th member (Jxw^{3-4}). Although the deeper buried geothermal wells of the 1st-2nd member (Jxw^{1-2}) have been exploited for exploratory, the thermal reservoir characteristics are still limited to the overall study from the general to the group [4-5], not refined to the segment, and systematic comparative analysis of the characteristics of segmented thermal reservoirs have not been carried out. Therefore, whether the "red strata" (i.e. brick red or purple red mudstone dolomite) between the3rd - 4th member and the 1st-2nd member have water-resisting and whether they can be developed by segment has become an urgent problem to be solved.

This paper will focus on this topic, and make use of the domestic and oversea research results of lithology sequence and paleontology of Wumishan Formation [6-9], especially the research of many experts and scholars (Shixing Zhu, Mingxiang Mei, etc.) on the world-famous "Jixian Section" of Mesoproterozoic and Neoproterozoic [10-13]. Combining with the analysis of the distribution and water-resisting of the "red strata" at the bottom of the 3rd member, we will compare the different lithology and thermal reservoir parameters of each member，and find out the development of water-resisting between the 3rd-4th member and 1st-2nd member of Wumishan Formation, and demonstrate the feasibility of development by stages, which provides a basis for resource management planning and development and utilization.

2. DISTRIBUTION AND CHARACTERISTICS OF WUMISHAN FORMATION

2.1 Distribution of Wumishan Formation

Tianjin is located in the northeastern part of North China Basin. The thermal reservoir of Wumishan Formation is widely distributed, the northern mountainous areas are abundantly exposed, and the southern plain areas are covered by Cenozoic. The thickness of Jixian sedimentary center is 3416m, which accounts for about 1/3 of the total thickness of Mesoproterozoic and Neoproterozoic. The sedimentary thickness is the largest. Its lithology, sequence, rock assemblage and stromatolithic facies are basically stable in horizontal and vertical distribution. Thickness gradually thinned from Jixian, the sedimentary center, to the southern plain area, and decreases to about 1000m in Southern Tianjin. The depth of burial is about 200 m in shallow bedrock area, more than 800 m [2] in deep bedrock area and more than 4000m in depression area. At present, most of the geothermal wells with this thermal reservoir as the target layer are located in Cangxian uplift area with relatively shallow bedrock buried in deep bedrock area(Fig 1).

2.2 Lithological characteristics of Wumishan Formation

Wumishan Formation is divided into four sections. Its lithology and sequence are stable. It belongs to multi-rhythmic deposits of littoral-shallow-littoral facies, and its type is epicontinental marine dolomite assemblage. Magnesium-rich carbonate rocks with a small amount of clastic rocks and clay rocks are the main types of carbonate rocks. The sedimentary rhythm is well developed[7]. High content and complex morphology of chert ,and rich in stromatolites and organic matter. The sedimentary rhythm of single-rock carbonate rock type is very prominent. In the longitudinal sequence, the similar regularity of rocks, paleontology and sedimentary structure with similar characteristics appears repeatedly. Generally, the lithology is composed of five rhythmic layers: clastic mudstone dolomite (I), chert-bearing block powder dolomite (II), algae-bearing conglomerate lime stromatolite dolomite (III), chert strip dolomite (IV) and siliceous rock (V). The five rhythmic layers appear irregularly and repeatedly. Aaccording to the regional survey data, Wumishan Formation is composed of at least 380 basic prosodic units[7]. However, the number, thickness and structure of each rhythmic layer are different.

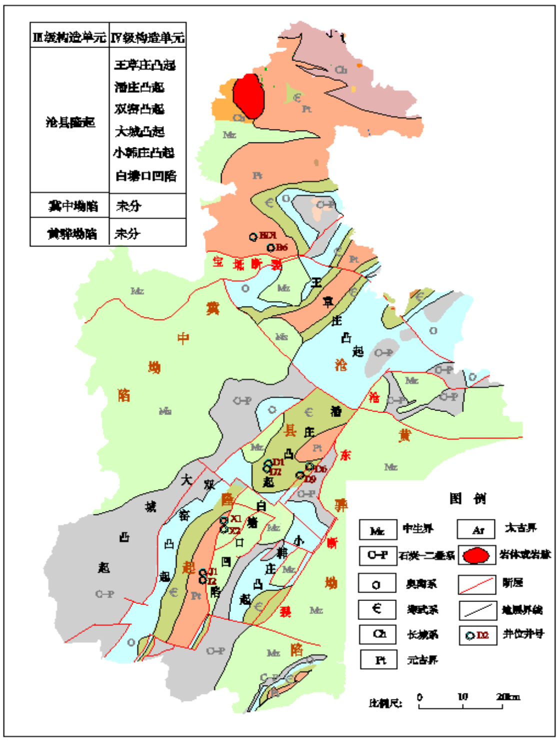

Figure 1: Geological map of bed rocks in Tianjin

Five rhythmic layers in the first section appear repeatedly and develop evenly; the first rhythmic layer in the second section decreases and the third to fifth rhythmic layer increases; the first rhythmic layer in the lower part of the third section increases, the fourth and fifth rhythmic layers increase and the single layer thickens; the sandstone develops in the bottom of the fourth section in a small range, while the first rhythmic layer is only visible at the top. The third and fourth rhythmic layers are well developed, and the thickness of single layer is increased. The highest limestone content is in the middle of the fourth member, which is rhythmic deposit composed of light-gray, light-brown medium-thick silty gravel-bearing microcrystalline dolomite and gray-greige medium-thick dolomitic limestone and limestone-bearing gravel-clastic dolomite. The highest CaO content is 49%. The rhythmic layer of mudstone dolomite (I) appears repeatedly in the middle and lower parts of the first and second sections, showing grayish-white shale shape. It is fragmented from the outcrop, thin in thickness and the number of layers decreases upwards, and rarely develops at the top of the second section. It occurs repeatedly at the bottom and middle of the third section, with 3-13 layers of mudstone dolomite at the bottom of the third section, they are mainly brick red and purple red with medium thickness and thick layers, with a small amount of thin-layer shale-like grey-white micrite dolomite; to the upper third and fourth members rarely developed, only the top of the fourth member has two layers of mudstone dolomite with small thickness, and only developed in local areas.

3. CHARACTERISTICS OF "THE RED STRATA" AT THE BOTTOM OF THE THIRD MEMBER OF WUMISHAN FORMATION

At the bottom of the third member of Wumishan Formation, there are several striking layers of brick red, purple red argillaceous dolomite and dolomitic mudstone (i.e. the first rhythmic layer mentioned above). They are usually called "red strata" (later collectively called red strata) because of their distinct red characteristics. In the process of geothermal drilling, the distinctive red beds are used as the boundary between the third and the second members of Wumishan Formation, and taking the bottom of the last red layer as the bottom of the third member of the Wumishan Formation, the second member of the Wumishan Formation enters under the red layer.

3.1 The characteristics of "red strata" in mountainous areas

There are some transverse differences in red strata. Four layers are commonly seen in the north of Jixian City. The bottom layer is thin and shale-like, only 3-4m thick. There are often sandwiches of gray-white and gray-green shale-like sand-clastic dolomite. Transversely, we can see the phenomenon of transformation from sandy debris dolomite to iron cemented quartz fine sandstone. The two layers in the middle are striking purple-red and brick-red, medium-thick layered. The thickness of the single layer is large, and the thickest is up to 35m. The fourth layer is light pink and fleshy red in color, and the bottom is rich in terrigenous and internal debris. The four layers have their own characteristics and are easy to compare. In the south of Jixian, the number of layers is obviously increased, the thickness of single layer is thinned, the number of layers varies from place to place, and it is not easy to compare between layers, the maximum number of layers is 13. The bottom layer contains a large number of red siliceous nodules, which are much less in the same horizon in the north of Jixian City. Secondly, it only occurs in the areas of the Flamboyant Mountains and Huangjiashan Mountains, the former is 3.5m thick, and the latter is 20m thick. The distribution is very unstable, lenticular, and rapidly pinches out laterally. It is replaced by dolomitic siliceous cemented clastic sandstone or dolomite with intrinsic clastic[7]. The exposed red strata have compact structure and no pore development.

Table 1 Characteristic of red strata exposed in BD-1 well

Number	**1**	**2**	**3**	**4**	**5**	**6**
Thickness（m）	8	24	40	10	18	6
Lithological characteristics	Purple mudstone dolomite	Brick red mudstone dolomite	Brick red mudstone dolomite and dolomitic mudstone	Brick red mudstone dolomite	Purple mudstone dolomite	Brick red mudstone dolomite
SP（mV）	20～22	18～21	12～22	12～20	64～76	70～88
R2.5(Ω•m)	705～1040	620～925	325～840	410～1025	125～300	125～620
Debris photo						

3.2 The characteristics of "red strata" in plain area

The thickness of red strata that have been exposed in drilling holes in plain areas varies from tens to hundreds meters. BD1 well in Baodi area, located in shallow bedrock buried area,is a well with obvious red strata characteristics and the thickness of the red strata is the largest in Tianjin at present. At the bottom of the third member of Wumishan Formation in this well, there are 6 layers of red strata from 1711m to 2038m. The thickness of the single layer is 6-40m. The interbeds are unequal to the light gray-white dolomite, and the interval between the red stratas is 7-164m[7]. In terms of electrical characteristics, the first to fourth red strata are similar, the SP curves are generally straight and fluctuate, ranging from 12 to 22mV, while the apparent resistivity (R2.5) fluctuates in a wide range, ranging from 325 to 1040Ω•m. The electrical characteristics of the fifth to sixth red strata are similar, the SP curves fluctuate wavelike, ranging from 68 to 88mV. The apparent resistivity (R2.5) ranges from 125 to 620Ω•m (Table 1) . The electrical characteristics of the red stratas from 1st to 4th are different from those of the 5th to 6th, which should be related to the variation of shale content in the beds, the latter being slightly higher.

In addition, 7 layers of red stratas are exposed in well D2 of Southeast Panzhuang bulge in the central part of Cangxian uplift. The lithology is brown red, brick red argillaceous dolomite and dolomitic mudstone. The thickness of the single layer is 4-14m. Logging shows that there are no fractures in the red stratas, indicating that the structure is compact. When the Wumishan Formation was exposed by J1 and J2 wells on Shuangyao bugle to the south, the third member of Wumishan Formation were drilled with 50m and 68m respectively. The main lithologies are siliceous dolomite and thick layer brown-red dolomitic mudstone (red strata). There is no mud leakage. Because the bedrock stratum of the well directly encountered the bottom of the third member, there is no complete red strata characteristic data.

4. COMPARISON OF THERMAL RESERVOIR CHARACTERISTICS BETWEEN THE 1ST-2ND MEMBER AND THE 3RD-4TH MEMBER OF WUMISHAN FORMATION

The Wumishan Formation is generally water-rich, and satisfactory water temperature and quantity can be obtained in both the 3rd-4th and the 1st-2nd member of the target thermal reservoir. Because there are many factors affect the temperature of geothermal fluid in the original data of well completion, we do not use it as a comparative factor. Quantitative comparison is made between hydrogeological parameters and hydrochemical characteristics, and the water barrier between them is analyzed.

4.1 Shallow buried area of bedrock

BD1 well and B6 well, located in the same tectonic unit, are selected for comparison in terms of hydrogeological parameters and fluid chemical characteristics. The target reservoir of the two wells are the 1st-2nd and the 3rd-4th member of Wumishan Formation, respectively.

4.1.1 Comparison of hydrogeological parameters

Table 2 Comparison of hydrogeological parameters between BD1 well and B6 borehole

Well number / Parameter	BD1	B6
Unit water inflow（$m^3/h·m$）	0.398	21.42
Permeability coefficient（m/d）	0.22	8.18
Fracture rate（%）	0.6～4.85	1.73～6.32
Permeability（μm^2）	0.1～1.14×10^{-3}	0.1～1.83×10^{-3}

The results of geophysical logging and pressure reduction tests show that the unit water inflow, permeability coefficient, fracture rate and permeability of BD1 well are significantly lower than those of B6 well(Table 2), indicating that the karst fracture development degree and water-rich capacity of the 3rd-4th member are better than those of the 1st-2nd member of Wumishan Formation.

4.1.2 Comparison of main chemical characteristics of geothermal fluids

BD1 Well has SO4-Na fluid chemical type, pH value of 8.33, salinity of 1268.8 mg/L, total hardness of 50.5 mg/L and total alkalinity of 220.2 mg/L. The chemical type of B6 well fluid is HCO3-Na, the pH value is 8.17, the salinity is 485.30 mg/L, the total hardness is 116.23 mg/L, and the total alkalinity is 204.7 mg/L[14]. There are great differences in fluid chemistry type, salinity and hardness between the two wells. Except for CO32-and total hardness, the concentration of other components in the 3rd-4th member is significantly lower than that in the 1st-2nd member, indicating that there is no hydraulic relationship between them.

4.2 Deep buried area of bedrock

4.2.1 Comparison of hydrogeological parameters

The 3rd-4th member of Wumishan Formation is the main thermal reservoir in this area, while the1st-2nd member wells are relatively few. The representative wells J1, J2, D2 and X2 of the 1st- 2nd member are compared with D1, X1, D6 and D9 of the 3rd-4th member (Table 3). X1 and X2, J1 and J2, D1 and D2 are geothermal pair wells.

Through comparison, it can be clearly seen that the water volume of the the 3rd-4th member of Wumishan Formation is more than 100 m^3/h, and the unit water inflow, permeability coefficient, fracture rate, hydraulic conductivity, permeability and porosity are higher than those of the 1st- 2nd member, while the shale content is opposite. Similar regularities are also generally shown in comparison with other boreholes of the 1st- 2nd member and the 3rd-4th member.Statistical analysis of mud leakage and logging results from various wells shows that the total thickness of leakage and development of type I and II fractures in the 3rd-4th member is obviously larger than that in the 1st- 2nd member, and the water-rich property of the 3rd-4th member is better. The development of karst fracture is obviously different between the two. It can be seen that the thermal storage characteristics of the 3rd-4th member and the 1st- 2nd member of Wumishan Formation are obviously different.

Table 3 Comparison of hydrogeological parameters between the 3rd - 4th member and the 1st - 2nd member in Wumishan formation

Well number	Location	Water volume (m^3/h)	Unit water inflow ($m^3/h·m$)	permeability coefficient（m/d）	fracture rate（%）	hydraulic conductivity	permeability（$10^{-3}μm^2$）
D9	The 3rd-4th member	100.4	4.48	3.96	2.81	148.1	0.13～0.87
D6		112	7.06	1.29	-	199.49	0.54～28.79
D1		112.78	2.55	1.55	-	86.12	0.11～1.92
X1		119.3	10.78	4.1	1.82～8.19		0.1～3.0
X2	The 1st-2nd member	119.3	3.72	1.77	0.75～7.45		0.1～1.86
D2		95.69	1.09	1.37	1.44～6.53	41.95	0.11～0.53
J1		100.4	3.94	1.01	2.38～9.11	116.05	0.12～6.50
J2		89.99	4.18	4.18	2.28～7.18	132.5	0.12～4.85

4.2.2 Comparison of main chemical characteristics of geothermal fluids

Over the years, the research results show that the geothermal fluid chemical composition concentration and mineralization of the 3rd-4th member of Wumishan Formation gradually increase along the runoff direction from south to North in the plane; in the vertical direction, the water quality is basically not affected by the depth because of the development of karst fracture, good hydraulic connectivity, strong vertical convection[15]. If the water quality between the 3rd-4th member and the 1st- 2nd member is compared vertically, and the law is obeyed, it shows that there is a hydraulic connection between the two members and there is no water barrier, otherwise there is water barrier.

Table 4 Main chemical components of geothermal fluids in X1 and X2 well

Analytical Projects	Concentration (mg/L)		Analytical Projects	Concentration (mg/L)		Analytical Projects	Concentration (mg/L)	
	X1	X2		X1	X2		X1	X2
K^+	69.2	76.9	SO_4^{2-}	371.9	407.2	Total alkalinity	280.3	290.3
Na^+	530.8	519	HCO_3^-	341.7	353.9	Total hardness	142.1	193.2
Ca^{2+}	38.7	55.5	CO_3^{2-}	0	0	Temporary hardness	142.1	193.2
Mg^{2+}	11.1	13.3	NO_3^-	0.0033	0.035	Negative hardness	138.2	97.1
Fe^{2+}	0.24	0.32	F^-	10	10	Salinity	1957.1	2052.8
Free CO_2	17.6	4.4	Cl^-	524.7	549.5	Solids	1786.2	1875.8
pH	7.63	8.08	PO_4^{3-}	0.06	0.02	SiO_2	69	77.5

X1 and X2 wells and D1 and D2 wells are production and irrigation wells, and the mining horizons are different, the wellhead is the closest, and the water quality is compared vertically, which has a certain representativeness. From Table 4, it can be seen that the geothermal fluid chemical types of the two wells are identical, and there are some differences in component concentration, salinity, hardness and pH value. The chemical type of geothermal fluids in the two wells is $Cl·SO_4·HCO_3$-Na, which is weak alkaline water. The concentration of Na^+, free CO_2, PO_4^{3-}, negative hardness and SiO_2 in the fluid of X1 well are higher than that of X2 well. In addition, other analysis items show that the concentration of X2 well is higher than that of X1 well. D1 and D2 have the same results after well comparison, which indicates that the hydraulic connection between the 3rd-4th member and the 1st- 2nd member is poor, and there are water barriers.

4.3 Water Insulation Analysis of "Red Strata"

From the lithology of Wumishan Formation, it is found that there is no mudstone dolomite developed between the third and fourth members of Wumishan Formation. The mudstone dolomite developed between the first and the second members is shale-like, schistose-like, with a thickness of less than 0.5m, and no effective water barrier has been formed. Only the thick layer red strata with poor permeability developed between the third and the second members of Wumishan Formation, with a thickness of 3-40m, have high shale content, compact rock structure and undeveloped fractrue, so they have poor permeability and good water resistance.

During drilling operation, there is no drilling fluid leakage when drilling in "red strata". According to the outcrop "red strata" and logging data, no fractures are found, and the fractures in dolomite intercalated in red strata are poorly developed. It also shows that the "red strata" have compact rock structure and high shale content, which has played an effective role of water insulation.

From the comparison of the thermal reservoirs mentioned above, it can be seen that there are obvious differences in hydrogeological parameters and fluid chemical characteristics between the thermal reservoirs in the 1st- 2nd member and the 3rd-4th member of Wumishan Formation. The latter is obviously superior to the former in all parameters, which indicates that the existence of "red strata" leads to the poor exchange of water-rock chemical reactants between the third and second member of Wumishan Formation. The hydrodynamic conditions between the two are relatively poor, and there is no obvious hydraulic connection, which proves that the "red strata" has obvious water-proof effect.

5. CONCLUSION

(1)There are obvious differences in lithological characteristics, unit water inflow, permeability coefficient, fracture rate, hydraulic conductivity, permeability and porosity between the 3rd - 4th member and the 1st-2nd member of Wumishan Formation. The former is superior to the latter.

(2) The red strata at the bottom of the third member have compact lithological structure, undeveloped fractures and poor permeability, which can be used as effective water barriers.

(3)The 3rd-4th member and the 1st-2nd member of Wumishan Formation can be used as two relatively independent thermal reservoirs to be developed and utilized separately.

In a word, the Wumishan Formation thermal reservoir can be developed by stages, and the third and fourth members have become the main thermal reservoirs in Tianjin, and the development prospects are self-evident; the first and the second thermal reservoirs will also play an immeasurable role in the future development process, and the well data show that the water output is moderate and the temperature is high, which indicates that they have the conditions for separate development. Although some wells have slightly worse water output, stimulation measures such as acidizing and fracturing are also of great mining value. As a new bedrock thermal reservoir, it will provide a basis for alleviating resource shortage, resource management, exploration planning and mineral rights setting in the next step.

At present, most of the geothermal wells in Wumishan Formation are completed in the 3rd and 4th members, while the 1st and 2nd members are less, some data acquisition is not complete, and some are near the fault zone or exist mixed mining and so on, which makes some available data imperfect. It is suggested that with the increase of thermal reservoir development in the 1st and 2nd member of Wumishan Formation, strict approval of water intake horizons can be carried out, mixed production can be reduced, and accurate acquisition of basic data of new wells can be strengthened. In addition, the study on sedimentary tectonic sequence [16] and its spatial karst fracture development, thermophysical parameters and isotopic age of geothermal fluids in Wumishan Formation should be strengthened. In order to improve the systematic comparative analysis of thermal reservoir characteristics in space and deepen the research, it will provide a more reliable quantitative basis for the research of supplementary drainage of geothermal fluids and the expansion of rational development and utilization of thermal reservoirs in the 1st and 2nd member of Wumishan Formation.

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