Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Mechanism of Heat Transfer and Accumulation in Geothermal Anomaly Belts of Sedimentary Basin-A Case Study of Bohai Bay Basin

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Keywords: geothermal anomaly, numerical simulation, heat transfer and accumulation mechanism, geothermal field type, Bohai Bay basin

ABSTRACT

The heat transfer and accumulation mechanisms of geothermal anomalies in sedimentary basins remain under explored. Using 2D finite element numerical simulation technology, this study investigates the relationship between geothermal anomaly size and factors, such as basement uplift morphology, basement thermal conductivity, and cap layer thickness, based on the diverse geothermal geological model of the Bohai Bay Basin. A geological profile in the middle of the Bohai Bay Basin is used to explore the formation mechanisms, controlling factors, and geothermal prospecting of geothermal anomaly belts. The formation of geothermal anomalies in sedimentary basins is driven by the rapid transmission of uniform deep heat flow in high thermal conductivity uplifts of the basement that accumulate in low thermal conductivity cap layers at shallow depths, leading to a "thermal flow deficit" in the deep basement and a "thermal flow enriching" in the shallow cap layers. Basement uplift amplitude and thermal conductivity are the main factors influencing geothermal anomaly size, and sufficient cap layer thickness guarantees the formation of these anomalies. The theoretical models predict temperature increases of up to 31.3℃ and positive anomaly amplitudes of up to 41.8% in the top layer of the basement geothermal reservoir (2 km depth). Based on differences in their geothermal anomalies caused by varying uplift amplitudes of the bedrocks, According to the difference of the bedrock bulge amplitude and its resulting geothermal anomalies, the Bohai Bay Basin is divided into seven types of geothermal fields, namely, high convex type, convex type, low convex type, concave type, gentle slope type, basin edge faulting-uplift type and shallow buried type, decreasing in turn the geothermal gradient of their cap rocks from > 5.0℃/l00m to < 2.0℃/l00m. Among them, the high-convex and the convex types are favorable targets for exploring shallow basement geothermal-reserves, and the low-convex and the concave types are the main targets for exploring deep high-temperature geothermal reserves of bed rocks (>150℃).

1. INTRODUCTION

The study of heat transfer law refers to inferring the relationship between the heat transferred per unit time and the corresponding temperature difference from the different heat transfer processes. According to different heat transfer media, heat transfer can be divided into three types: heat conduction, heat convection and heat radiation. For a sedimentary basin whose main body is composed of solid rocks, heat conduction is the most important way of heat transfer. Therefore, the thermal conductivity is the main factor that restricts the difference of heat conduction among different tectonic zones in the basin when the heat flow of the basin basement is determined. The predecessors first concluded by statistical method that the surface heat flow and the shallow geothermal gradient in the uplift area of the basin are higher than those in the depression area, and the amplitude can reach 30%~40% of the average value, thus forming a local geothermal anomaly area (Xiong Liangping and Gao Wei 'an, 1982; Ma Gang et al., 1983; Yan Dunshi and Yu Yingtai, 2000); This phenomenon is attributed to the heat flow disturbance caused by the high conductivity bedrock bulge, that is, thermal refraction and heat flow redistribution occur in the heat flow conduction process (Xiong Liangping and Zhang Juming, 1984; Chen Moxiang and Deng Xiao, 1990). In fact, the formation of shallow geothermal anomaly is not only related to the necessary condition of bedrock bulge with high thermal conductivity, but also related to the thermal sealing ability of caprock, the amplitude of

bedrock bulge and the heat conductivity ratio between bedrock and caprock. In order to further quantitatively describe that relationship between shallow geothermal anomaly and its influencing factor, many scholars have made fruitful explorations by means of numerical simulation. For instance, Xiong Liangping et al. (1984; 1988) used the two-layer structure model to preliminarily discuss the relative thickness of the cover layer and bedrock in the uplift zone, and the influence of heat conductivity on the surface heat flow and geothermal field; Chen Moxiang et al. (1990) simulated the geothermal field of Guangrao uplift-Chengdong bulge in the east of Bohai Bay Basin, and obtained semi-quantitatively that the geothermal field in the uplift area was 10~20℃ higher than that in the depression area on the depth line of 1500m. Mao Xiaoping et al. (2018) and Wang et al.(2020) put forward an "asymmetric mirror" distribution model of geothermal field according to the distribution law of formation temperature in the vertical section of the uplift belt; Wang Xinwei et al. (2021) took the geothermal field in Xianxian county, Hebei Province as an example, and compared and analyzed that the formation temperature at the top of Jxw Formation in Xianxian bulge was at least ~20℃ higher than that at the same depth in Raoyang sag, and the depth of heat conduction equilibrium line between them was ~3500m. On the whole, however, there are still some problems, such as too single geological model, insufficient comparative analysis of shallow geothermal anomaly and deep geothermal anomaly, etc. There is still a big gap from recognizing the heat transfer and heat accumulation mechanism of geothermal anomaly zone in the basin.

Bohai Bay Basin, as the largest Mesozoic-Cenozoic faulted basin in China, covers an area of about $12\times10^4 km^2$. It contains abundant petroleum resources and huge geothermal resources. It is the main area for geothermal heating and utilization in China, and the geothermal heating and utilization area has reached $1.2\times10^8 m^2$. The temperature measurement data of more than 20,000 oil and gas wells and more than 3,000 geothermal wells have laid a solid foundation for quantitative analysis of geothermal anomalies (Figure 1), and the concave-convex structural pattern and complicated deformation styles have provided rich materials for the establishment of geological models (Figure 2). In this paper, the geological model of three-layer structure is adopted, and the two-dimensional finite element numerical simulation technology is used to quantitatively discuss the relationship between the size of geothermal anomaly and the influencing factors such as the shape of bedrock bulge, the thermal conductivity of bedrock, and the thickness of caprock, etc. Then, combined with an example of a geothermal geological profile in the middle of Bohai Bay Basin, the formation mechanism, main control factors of geothermal anomaly zone and its guiding significance for geothermal exploration are discussed.

2. GEOTHERMAL GEOLOGICAL BACKGROUND

Bohai Bay Basin is a Mesozoic-Cenozoic faulted basin, which developed on the fold basement of Indosinian and Yanshanian movements after platform-type deposition from Middle-Late Proterozoic to Paleozoic (Hou Guiting, 2001). The main structural line is NE-direction, and the filled sediments are mainly extremely thick fluvial-lacustrine clastic rocks developed in the Paleogene strong rifting period and Neogene-Quaternary depression period, with the maximum stratum thickness exceeding 8 000 m. Influenced by the differential rise and fall of bedrock fault blocks during Paleogene rifting, the basin structure has the characteristics of east-west zoning and north-south segmentation (Yang Minghui, 2009). According to the difference of buried depth of bedrock, it can be divided into nine secondary structural units, such as Jizhong Depression, Jiyang Depression, Huanghua Depression, Linqing Depression, Dongpu Depression and Cangxian Uplift, Xingheng Uplift, Neihuang Uplift, Chengling Uplift (Figure 1). In each secondary structural unit, there are different scales of horst-graben, (tilted) half horst-half graben, single-fault shovel normal fault and other structural deformation styles on the plane. Vertically, it can be summed up as a three-layer geothermal structure consisting of bedrock geothermal reservoir (pre-Cenozoic), surrounding rock (Paleogene) and caprock (Neogene-Quaternary), thus forming a colorful geothermal geological model (Figure 2).

Figure 1: Plane distribution of geothermal gradient of cap rock in Bohai Bay Basin

The geothermal anomaly in the shallow part of Bohai Bay Basin has a good positive correlation with the bedrock uplift zone in plane distribution (Figure 1). According to the average geothermal gradient of 3.0 ℃/l00m in North China and 3.2 ℃ /l00m in Bohai Bay Basin, the geothermal gradient of the caprock in the study area is divided into three grades. (1) High geothermal gradient zone: the geothermal gradient is 3.5~6℃ /l00m, mainly distributed in the bedrock uplift zone such as Cangxian uplift zone and the central bulge zone of Jizhong depression, and the local buried hills such as Xiongxian and Jinghai are higher than 7℃/l00m. (2) The moderate geothermal gradient zone, with a geothermal gradient of 2.5 ~ 3.5℃ /100m, is mainly distributed in the depression zone and the transition zone between depression and uplift, such as Linqing depression and Huanghua depression, etc., and its average geothermal gradient is close to the average geothermal gradient of 3.0℃/100m in North China (i.e. the background value, the same below). (3) Low geothermal gradient zone: the geothermal gradient is 1.5~2.5℃/l00m, mainly distributed in the subsidence center of the depression and the edge of the basin, and lower in some piedmont zones.

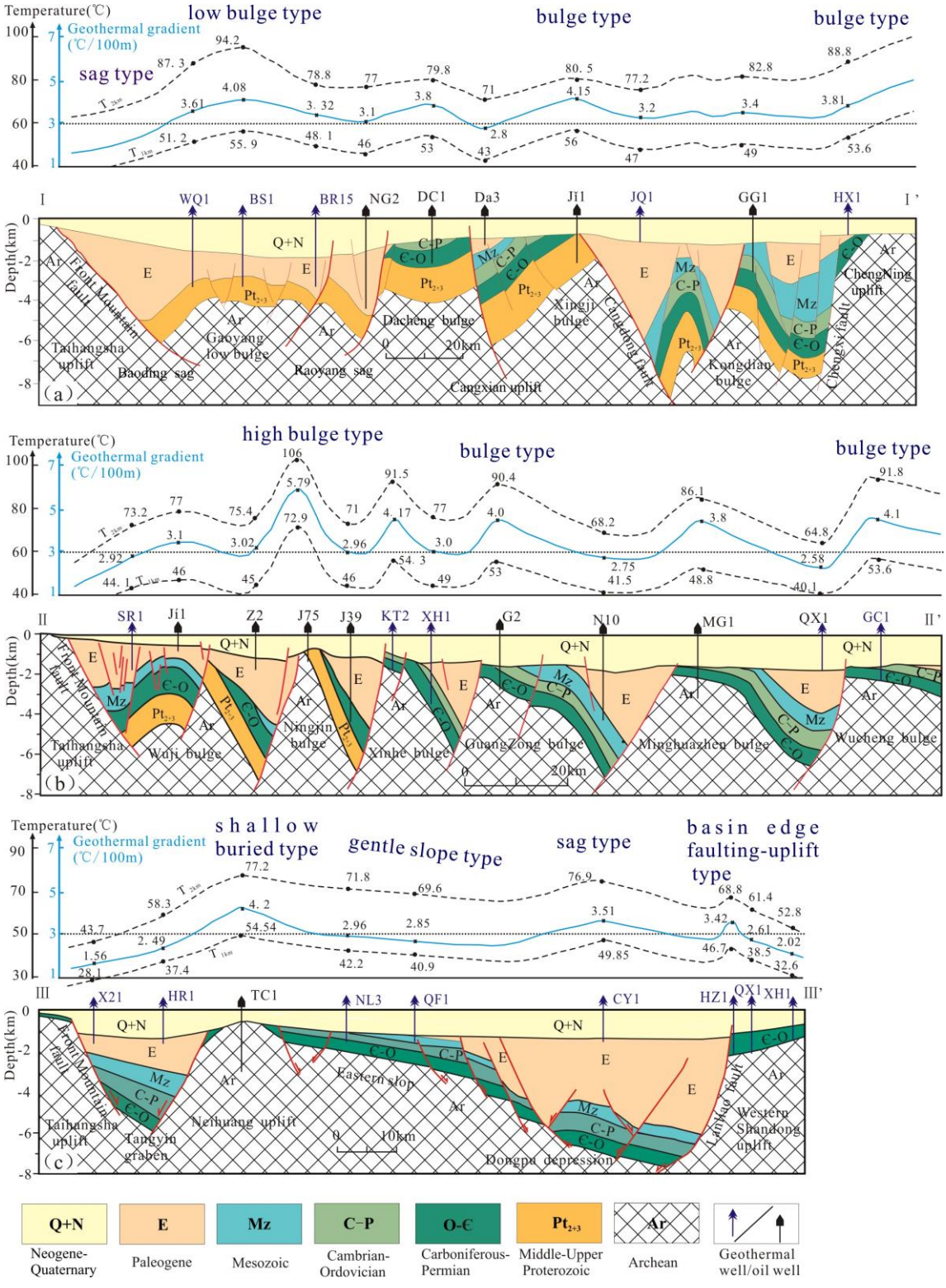


Figure 2: Series geothermal geological profiles of Bohai Bay Basin

The geothermal geological profile of Bohai Bay basin more clearly reveals the corresponding relationship between the geothermal anomaly of 10 km in the shallow part of the basin and the structural style of deep bedrock (Figure 2). The higher the amplitude of bedrock bulge caused by tilting fault block, the faster the temperature rise rate of its cover; The deeper the subsidence of the depression, the lower the heating rate of its cover. The difference of formation temperature at the depth of

2.0 km between the uplift area and the depression area is more than 30℃. However, from the analysis of the whole Bohai Bay basin with a wide scale of several hundred kilometers, the average heat flow is 64±8 mW/m^2 (Liu et al., 2016), which is slightly higher than the average of 60 mW/m^2 in Chinese mainland (Jiang Guangzheng et al., 2016) and is basically consistent with the global continental average of 65 mW/m^2 (Davies, 2013). The comparison of these heat flow data shows that the heat transfer in Bohai Bay Basin is mainly due to the heat conduction of crust-mantle heat flow, without the contribution of other additional heat sources such as magma pockets. The change of geothermal anomaly between the concave and convex zones of the basin is the result of the differential aggregation of uniform heat flow from the basin basement during its transmission to the shallow part of the basin (Xiong Liangping et al., 1988; Wang Xinwei et al., 2021). These understandings provide data support for us to further characterize the mechanism of heat transfer and heat accumulation through numerical simulation.

3. MODEL AND EXPERIMENT

3.1 theoretical model research

(1) Geologic model

According to the structural style of geothermal geological profile, this paper selects 14 simple geological models (Table 1) which can reflect the geometric shape, overburden thickness, bulge amplitude (that is, the thickness of surrounding rock) and the change of thermal conductivity of bedrock, and uses the finite element numerical simulation software (SGRE SEG 2.0) to carry out digital simulation experiments in turn to investigate their influence amplitude, scope and mode on geothermal anomaly. The series of theoretical models designed are two-dimensional profiles with a length of 20 km and a depth of 10 km, which are vertically divided into three layers of geological structures with different thermal conductivities (Table 1, Figure 3). Among them, k_3 represents the bedrock uplift zone with high thermal conductivity, k_2 represents the surrounding rock with medium thermal conductivity-Paleogene rifting deposit (E), and K_1 represents the low thermal cover-Neogene depression deposition (N + Q).

(2) Numerical model

Digital processing of geological model by numerical model is mainly divided into two steps (Figure 3). Firstly, a 2D geological section with a length of 20 km and a depth of 10 km is gridded with 200m×200m squares (steps), and a total of 5,151 grid nodes (steps of 101×51) can be obtained. Secondly, the thermal conductivity of the three-layer structure is assigned. According to their lithological characteristics, the thermal conductivities of the thermal cover, the surrounding rock and the bedrock bulge are set as k_1= 1.6W/(m℃), k_2= 2.4W/(m℃) and k_3= 3.6, 4.8 and 6.0W respectively. The three data of k_3 refer to the thermophysical parameters of Mesozoic sandstone, Lower Paleozoic limestone and Middle-Late Proterozoic dolomite in the bedrock uplift zone (Liu Lijun et al., 2010; Liu Qiongying et al., 2019).

(3) Boundary condition

The top boundary of the conditional 2D model is the temperature boundary, taking the average surface temperature T_0=15 ℃ (Figure 3); The bottom boundary of the model is the heat flow boundary, and the uniform heat flow value of the basement is taken as the average Q = 64 mW/m^2 in Bohai Bay Basin; The vertical initial geothermal gradient of the profile is set at 3.0 ℃/100m; There is no lateral heat exchange between the left and right boundaries, and the initial horizontal geothermal gradient is 0℃; The time length of forward simulation is t=500 ka.

Table 1: Geometric parameters and description of geological model used in heat conduction simulation

No.	Convex shape parameter	Thickness of caprock a(km)	Thickness of surrounding rock b(km)	Top width c(km)	Bottom width d (km)	Heat conductivity of bedrock K_3(W/(M K))	remarks

1	2	3	2	2	3.6	
2	2	4	2	2	3.6	The model 1~9 show the symmetrical horst with steep faults; Models 10 and 11 show symmetrical horst with fault dip.
3	2	5	2	2	3.6	
4	2	5	2	2	4.8	
5	2	5	2	2	6.0	
6	2	5	4	4	6.0	
7	2	5	8	8	6.0	
8	1.5	5	8	8	6.0	
9	1.0	5	8	8	6.0	
10	2	5	4	12	6.0	
11	2	5	8	16	6.0	
12	2	3	2	8	6.0	
13	2	4	2	8	6.0	Models 12, 13, and 14 show tilting half-horst.
14	2	5	2	8	6.0	

(4) Model experiment

According to the above-mentioned different numerical models and boundary conditions, the finite element numerical analysis method is adopted to solve the two-dimensional steady-state heat conduction equation without internal heat source shown in the following formula (1), and the formation temperature distribution map of each model can be obtained by forward modeling (Qiu Nansheng, et al.,2004).

$$K \cdot \nabla^2 T = 0, \text{ where } K \text{ is diffusivity and } \nabla^2 \text{ is Laplacian} \quad (1)$$

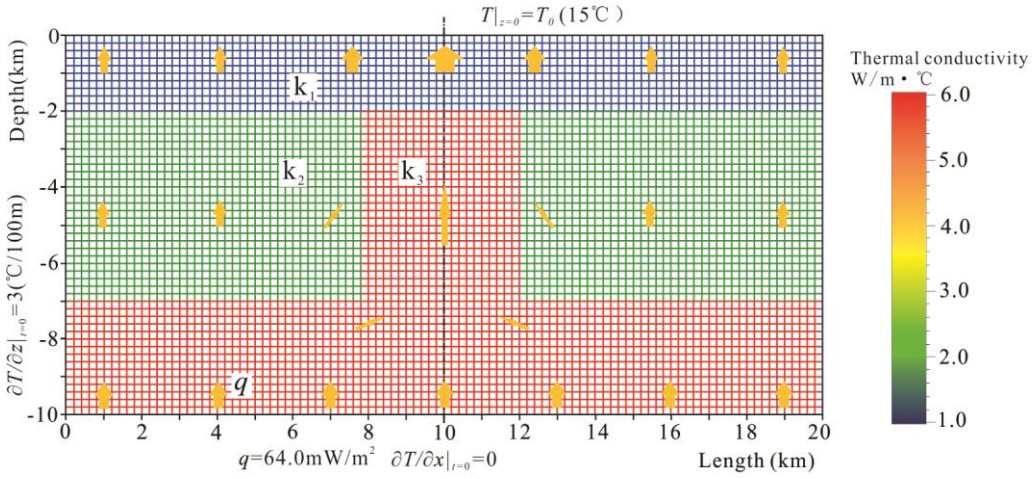


Figure 3: Digital schematic diagram of geometric model of bedrock bulge. Arrow shows the heat flow direction, and the volume represents the heat flow density size. Note: K_1, K_2 and K_3 respectively represent the thermal conductivity of the cap rock, surrounding rock and bedrock, and t represents the simulation time; k_1=1.6 W/(m·℃), k_2=2.4 W/(m·℃), k_3=3.6, 4.8, 6.0 W/(m·℃), and the basal heat flow is q=64.0mW/m^2, the ground temperature is T0=15℃, and the initial vertical gradient is $\partial T/\partial z|t=0$=3.0℃/100m, initial transverse gradient $\partial T/\partial x|t=0$=0℃/100m.

3.2 Measured geothermal geological profile model

The two-dimensional geological profile model selected in this paper is a comprehensive geological profile that crosses Gaoyan low bulge in Jizhong depression and Xianxian bulge in Cangxian uplift. This section is mainly based on the seismic section of Jizhong Depression (He Dengfa et al., 2018) and the comprehensive geological section of Cangxian Uplift (Chen Daxian,1989; Gao Zhanwu, et al.,2000; Shan Shuaiqiang, et al.,2019), with a total length of about 176 km, which passes through seven structural sub-units from west to east, including Baoding sag, Gaoyang low bulge, Raoyang sag, Xianxian bulge, Fucheng sag, Botou bulge and Nanpi sag (Figure 4). The thermoproperty parameters of each stratum are assigned the

actual measured value. Using numerical simulation, the differences of geothermal field anomalies under different basement heat flow backgrounds and different bulge amplitudes are investigated.

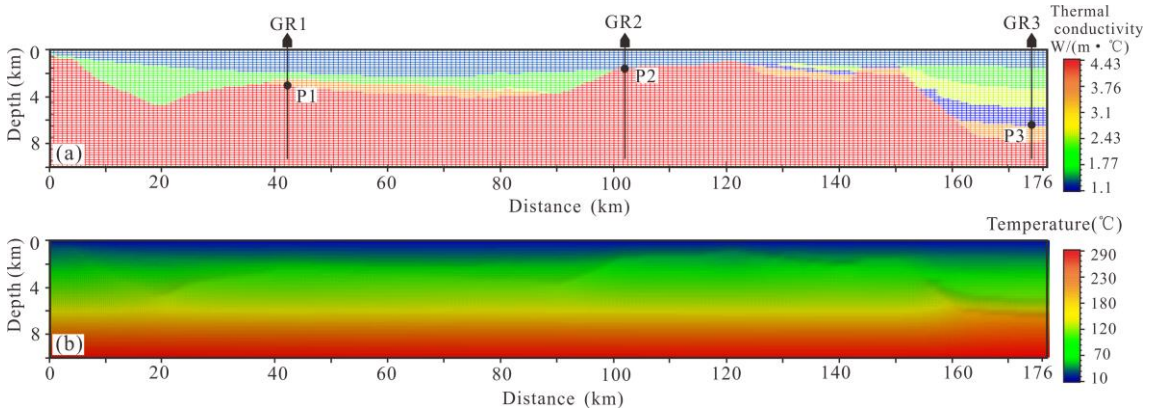


Figure 4: Numerical model (a) and simulation results of strata temperature distribution (b) for Gaoyang-Xianxian geological profile

4. OUTPUT AND ANALYSIS OF RESULTS

The forward simulation of formation temperature field is carried out by the heat conduction module in SGRE 2.0. The advantage of this software is that it can output geothermal information at any depth in a given time period, and it can be used to semi-quantitatively and quantitatively analyze the change law of formation temperature in the uplift zone. According to the needs of geothermal exploration and development of bedrock geothermal reservoir, for the theoretical model, the output of the results are mainly selected as follows: ① The temperature curve of the top surface depth of bedrock bulge, and the positive anomaly size of the geothermal reservoir temperature at the top of bedrock bulge and the formation temperature in the depression area at the same depth are to be quantitatively analyzed; ②The temperature curve of the bottom depth of the bedrock bulge zone is used to quantitatively analyze the influence of the bulge zone on the deep geothermal negative anomaly. For the measured model, the output of the results is also examined by the temperature difference of the interface depth line between the geothermal reservoir and the caprock.

4.1 Influence mode of bedrock bulge on strata temperature

As mentioned earlier, a certain height of bedrock bulge is a necessary condition for the formation of its shallow geothermal anomaly. Models 1~3 reveal the influence of the amplitude of bedrock bulge (i.e. the thickness of surrounding rock) on the geothermal anomaly of bedrock geothermal reservoir under the condition that the difference of cover thickness and thermal properties is constant (Figure 5). On the premise that the thickness of cap rock is 2 km, and the thermal conductivities of cap rock, surrounding rock and bedrock are 1.6, 2.4 and 3.6 w/(m℃) respectively, when the height of bedrock bulge is 3 km, 4 km and 5 km, the maximum positive anomalies of geothermal temperature of bedrock geothermal reservoir at the top of bulge zone are 7.4℃, 8.2℃ and 8.6℃ respectively, while the maximum negative anomalies of geothermal temperature of bedrock geothermal reservoir at the bottom of bulge zone are respectively. The comparative analysis of these data shows that when the amplitude of bedrock bulge increases by 1/3 and 2/3, the geothermal anomaly at the top of the bulge zone gradually increases, but the variation amplitude is small (~10%) compared with the background value of 75℃. The reason for this low geothermal anomaly is related to the fact that the heat conductivity of bedrock is only 0.5 times higher than that of surrounding rock. At the same time, the negative geothermal anomaly at the bottom of the bulge zone increases correspondingly with the increase of bedrock bulge amplitude, and the positive and negative anomaly amplitudes tend to compensate each other. According to this phenomenon, the influence mode of bedrock bulge on stratum temperature can be further abstracted: ① Under the heat conduction system without additional heat source, the heat enrichment (i.e., the positive anomaly of stratum temperature) at the top of bedrock bulge is caused by the heat loss (i.e., the negative anomaly of

stratum temperature) at the bottom of bedrock bulge, and the fundamental reason is the result of rapid heat flow transfer generated by the high thermal conductivity bedrock bulge. ② The temperature variation curves of the top depth line and the bottom depth line of the bulge belt are nearly mirror symmetrical (Figure 5), but the variation ranges of the top heat enrichment and the bottom heat loss are not completely one-to-one, reflecting that the heat enrichment degree at the top of the bedrock raised belt is also related to the heat sealing performance of the upper covering layer.

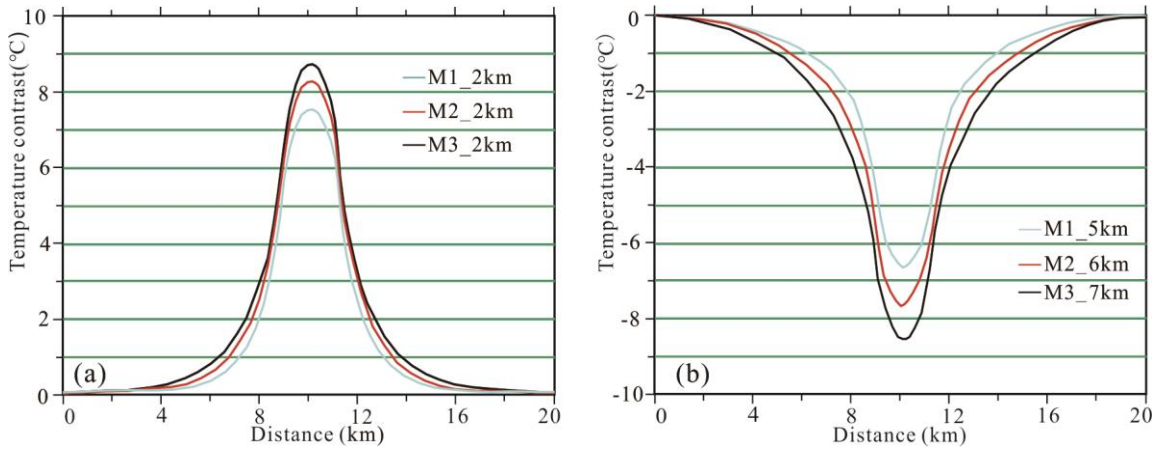


Figure 5: Temperature variation curves of top depth (a) and bottom depth (b) of bedrock bulge under different amplitude of bedrock bulge

4.2 Influence of heat conductivity and area of bedrock bulge zone on geothermal anomaly

In order to investigate the influence of thermal conductivity of bedrock on geothermal anomaly, three geothermal models, Model 3~5, are set up. Under the same conditions of other related parameters such as the thickness of cap rock and the amplitude of bedrock bulge, the thermal conductivities of bedrock of these three models are respectively set at 3.6, 4.8 and 6.0 W/(m℃) (Table 1), which are 1.5, 2 and 2.5 times of the thermal conductivities of surrounding rocks. The simulation results show that, with the increase of thermal conductivity of the bedrock bulge zone, the positive geothermal anomaly at the top of the bulge zone and the negative geothermal anomaly at the bottom of the bulge zone of the three models increase correspondingly, which are 8.6 ℃→15.4 ℃→21.1℃ and -8.3 ℃→-13.0 ℃→-15.8℃ respectively (Figure 6). According to the data, when the thermal conductivity of bedrock increases by 1/3 and 2/3, the increase of the top temperature anomaly is 0.8 times and 1.5 times. Compared with the stratum temperature background value of 75℃, the maximum temperature anomaly amplitude reaches 28.13%. Therefore, the change of thermal conductivity of bedrock bulge zone plays a decisive role in geothermal anomaly.

The simulation results of models 5~7 can reveal the influence of the area of bedrock bulge (when the height of bedrock bulge is a fixed value, it can be simplified to rectangular width) on geothermal anomaly (Figure 6). When the rectangular width of bedrock bulge is 2km, 4km and 8km respectively, the maximum positive geothermal anomalies at the top of the bulge are 21.1℃, 25.9℃ and 28.2℃ respectively, while the maximum negative geothermal anomalies at the bottom of the bulge are -15.8℃, -20.7℃ and -24.0℃ respectively. The comparative analysis of the data shows that when the area of the bedrock bulge zone expands to 2 times and 4 times, the increase of the maximum positive geothermal anomaly at the top is only 23% and 34%, while the increase of the maximum negative geothermal anomaly at the bottom is 31% and 52% respectively. According to the variation range of positive and negative anomalies of these three models, it can be inferred that the area of bedrock bulge belt (when it is extended to three dimensions, it is the volume) contributes positively to the formation of geothermal anomaly, and it seems that it promotes the negative geothermal anomaly at the bottom of uplift belt more obviously. It can be understood that the larger the area (or volume) of uplift belt, the wider the channel for rapid heat

conduction, which is more conducive to the acceleration of deep heat flow to the shallow part, thus causing more "deficit" of deep heat flow.

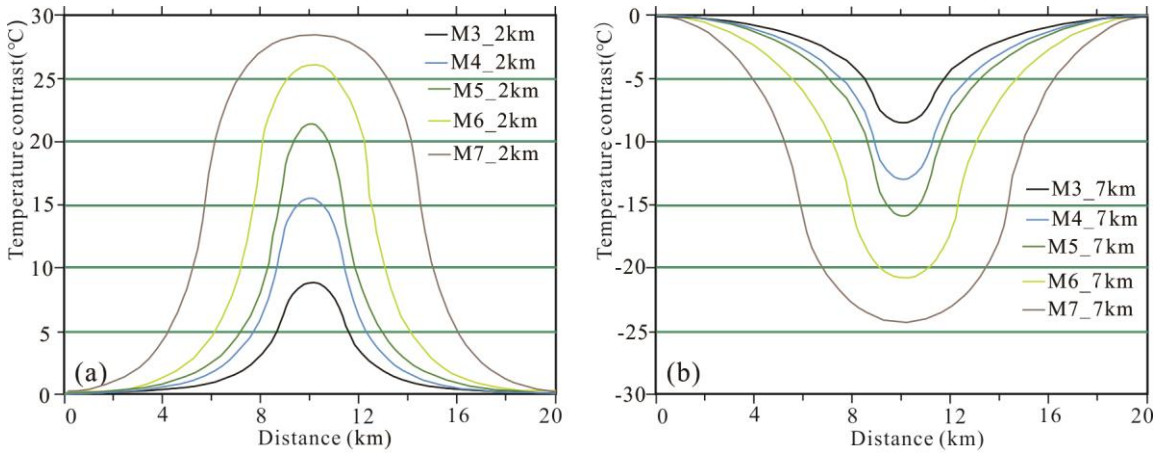


Figure 6: Temperature variation curves of top depth (a) and bottom depth (b) of bedrock bulge under different thermal conductivity and area conditions

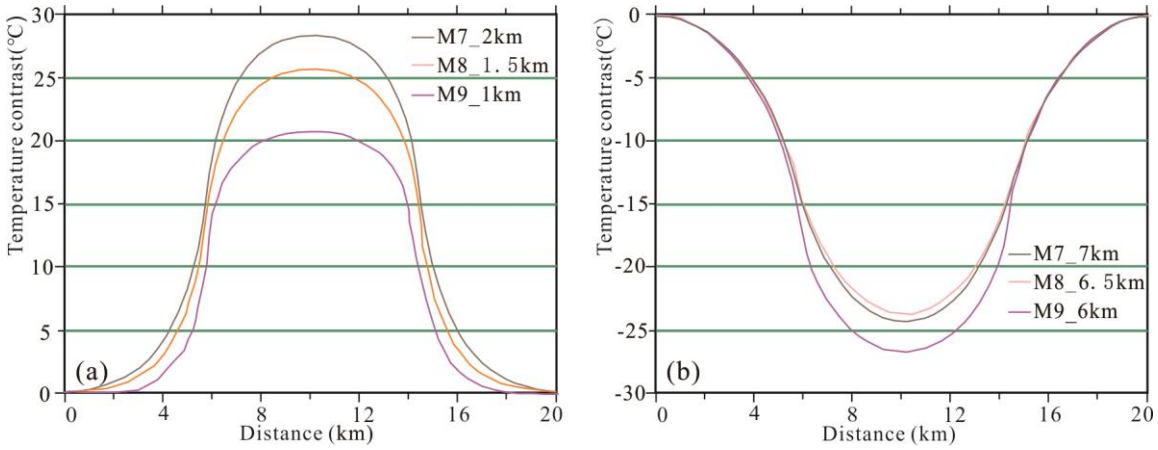


Figure 7: Temperature variation curves of top depth (a) and bottom depth (b) of bedrock bulge under different cover thickness conditions

4.3 The role of heat sealing performance of caprock

When the thermal conductivity of capping layer is given, the thermal sealing performance of caprock mainly depends on the thickness of caprock. The simulation parameters and simulation results of models 7~9 reveal the influence degree of cap thickness change on geothermal anomaly (Table 1 and Figure 7). When the cover thickness is 2.0 km, 1.5 km and 1.0 km respectively, the maximum positive geothermal anomalies at the top of the bulge belt are 28.2℃, 25.3℃ and 20.9℃ respectively, while the maximum negative geothermal anomalies at the bottom of the bulge belt are -24.0℃, -23.3℃ and -26.5℃ respectively. The simulation results show that, with the thickness of the caprock r decreasing by 25% and 50%, the maximum positive anomaly amplitude of the earth temperature on the top surface of the bulge belt decreases by 10.28% and 25.89% respectively. However, the maximum negative geothermal anomaly at the bottom of the uplift belt slightly increased by 10.42%, and the negative geothermal anomaly at the deep part of the bulge belt of Model 9 exceeded the positive geothermal anomaly at the shallow part by 26.8%. It can be reflected that the reduction of cap thickness is not conducive to the preservation of "enriched" heat flow in the shallow part, but more conducive to the transfer of deep heat flow to the shallow part. Therefore, the thermal sealing performance of the caprock is the guarantee condition for the formation of the shallow geothermal anomaly.

4.4 The influence range and scope of thermal refraction

"Thermal refraction" refers to the phenomenon that the transmission direction of heat flow changes when it passes through the inclined interface of rock thermal properties during its transmission to the shallow crust. Analogy to the refraction phenomenon that occurs when light propagates in different media (Liu Shaowen et al., 2017). In this paper, two symmetrical inclined strata models with different widths (or areas) are designed, namely model 10 and model 11 (Table 1), and compared with model 7 of non-inclined strata, to analyze the influence range and influence range of thermal refraction on geothermal anomaly (Figure 8). The simulation results show that the maximum positive geothermal anomalies at the top of the bulge belt of Model 7, Model 10 and Model 11 are 28.2℃, 31.3℃ and 28.3℃ respectively, while the maximum negative geothermal anomalies at the bottom of the bulge belt are -24.0℃, -20.0℃ and -18.5℃ respectively. ① Compared with Model 7, under the condition of keeping the height and area of bedrock bulge unchanged, the top width of Model 10 becomes smaller and the bottom width becomes larger, and the thermal refraction produced by the inclined rock stratum increases the maximum positive amplitude of geothermal anomaly at the top of the bulge by 11.0%; ② Compared with Model 7, under the condition of keeping the height and top width of bedrock bulge unchanged, the bottom width of bulge zone is enlarged and its area is enlarged by 0.5 times. The thermal refraction does not increase the amplitude of the maximum geothermal anomaly at the top of bulge, but increases the width (area) of the positive anomaly, but the range is only within 1/2 of the width of inclined strata. ③ The geothermal negative anomaly curves at the bottom of the bulge belt of the three models show the coupling change characteristics that the vertical negative anomaly amplitude gradually decreases and the lateral negative anomaly width correspondingly increases, which reflects that the thermal refraction of the inclined stratum is conducive to the "heat diversion" of the deep heat flow around the bulge belt to the top of the bulge belt. From the above analysis, it can be seen that the thermal anomaly at the top of the bulge belt mainly comes from the rapid transfer of heat flow at the bottom of the bedrock in bulge belt with high thermal conductivity and the gradual accumulation under the cover of the toprock. Thermal refraction has played a positive role in promoting the "thermal enrichment" at the top of the bulge belt, but its influence range is limited, ranging ~11% of size and ~1/2 of plane width.

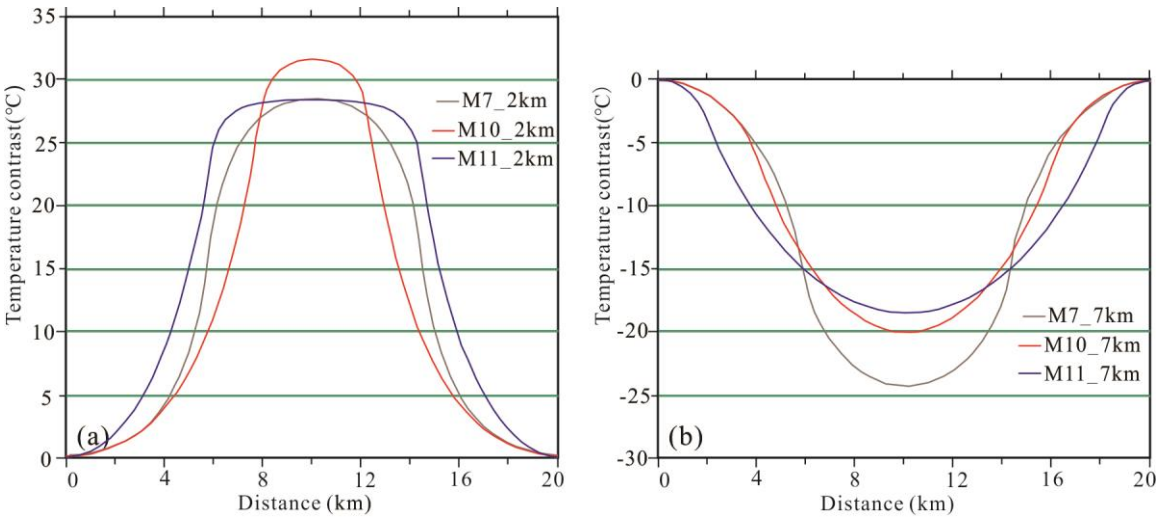


Figure 8: Temperature variation curve of top depth (A) and bottom depth (B) of bedrock bulge under the condition of inclined section

4.5 Influence of tilted fault block on geothermal anomaly

Tilting block is one of the most common deformation patterns in faulted basins, and it is the result of simple shearing action in the extensional background. Geometrically, it is characterized by a combination of half-horst and half-graben with one side faulted and the other overlapping, and the half-horst shows a sharp prismatic bedrock bulge with unequal slopes. This

geological model can be used to explore the thermal refraction effect of the two inclined rock strata in the heat conduction analysis. The simulation results of models 12~14 show (Figure 9): when the depth of fault depression (i.e. the thickness of surrounding rock B, Table 1) is 3 km, 4 km and 5 km respectively, the maximum positive geothermal anomalies at the apex of the bulge belt are 23.1℃, 25.0℃ and 25.8℃ respectively, while the maximum negative geothermal anomalies at the bottom of the bulge belt are -10.9℃, -13.6℃ and -16.8℃ respectively. Compared with the simulation results, it can be seen that: ① When the amplitude of bedrock bulge increases by 1/3 and 2/3, the maximum positive anomaly of stratum temperature with sharp points in the bulge increases by 8.2% and 11.2%; ② Compared with the positive geothermal anomaly curve at the top of the bulge belt, the negative geothermal anomaly curve at the bottom of the bulge belt obviously shows the characteristics of small vertical negative anomaly amplitude and large lateral negative anomaly width, which once again reflects that the thermal refraction of the inclined rock stratum is more conducive to the lateral "heat diversion" of the deep heat flow around the bulge belt. ③ Comparing the simulation results of Model 14 with the aforementioned Model 6, we can also get the same understanding, that is, under the condition that the height and area of the raised belt are the same (Table 1), the positive stratum temperature anomaly at the top of the bulge belt is basically the same, but the vertical negative anomaly amplitude at the bottom decreases and the lateral negative anomaly width increases (Figure 9).

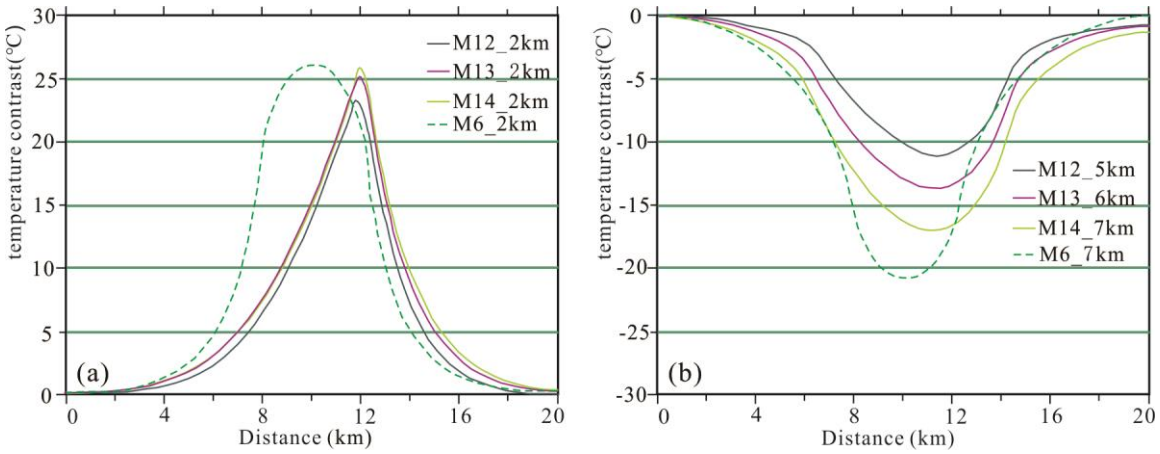


Figure 9: Temperature variation curve of the top surface depth (a) and bottom surface depth (b) of the bedrock bulge with the tilted block

4.6 Differences of geothermal anomalies in different tectonic zones in the basin

Gaoyang-Xianxian section involves three representative tectonic belts. ① Gaoyang low bulge: the bedrock structure is a large wide and gentle anticline, with the buried depth of the high point at the top of the anticline of 3500m, and the cover of the bedrock geothermal reservoir is E+N+Q, the surrounding rock is E. ② Xianxian bulge: Cangxian Uplift is a large compound buried hill-drape structure, and Xianxian bulge is located on its west side, with the buried depth of the bedrock top surface of 1500m, the thermal reservoir cap rock of (N+Q), and the surrounding rock of E. ③ Nanpi sag: it is a continuous subsidence zone with complete strata development, and the top surface of bedrock reservoir is buried at a depth of 6000m (Figure 4). On the numerical model diagram, three artificial wells with abscissa x=43km, 102km and 174km are selected respectively, which represent the geothermal variation characteristics of three structural zones, namely, Gaoyang low bulge, Xianxian bulge and Nanpi sag, so as to compare the differences of geothermal anomalies of geothermal reservoir under different burial depths (Figure 10).

The simulation results show that: ① On the 1500m depth line, the strata temperatures of Gaoyang low bulge, Xianxian bulge and Nanpi sag are 85.3℃, 96.3℃ and 71.1℃ respectively, which are 60℃ higher than the background value of the strata temperature (calculated according to the average gradient of 3.0℃/100m and the surface temperature of 15℃, the same below), and the largest geothermal anomaly occurred in the Xianxian bulge, with the ground temperature difference reaching

36.3℃ and the positive anomaly range reaching 60.5%t. This is very consistent with the actual situation of Xianxian bulge geothermal well YR1 with a well depth of 1600m and a wellhead water temperature of 97℃. ② On the depth line of 3500m, the biggest anomaly occurred in Gaoyang low bulge, and the stratum temperature of bedrock geothermal reservoir was 148.4℃, which was 28.4℃ higher than the background value of 120℃. This simulation data is basically consistent with the actual temperature of well BS1 in Boye country, with a well depth of 3758m and a maximum stratum temperature of 165.7℃. At the same time, the lowest point of stratum temperature is located in Nanpi sag, and its value has dropped to the background value of 121.7℃. ③ On the 6000m depth line, the structural belt with the highest stratum temperature is Nanpi sag (208.1℃), which is 13.1℃ higher than the background value (195℃); However, the stratum temperature of Gaoyang low bulge and Xianxian bulge is lower than the background value, and the negative geothermal anomaly of Xianxian bulge is lower, reaching -12.2℃. Therefore, the positive and negative geothermal anomalies of shallow and deep bedrock geothermal reservoir in the basin are mutually transformed in different structural zones, which are mainly controlled by the buried depth of bedrock in structural zones.

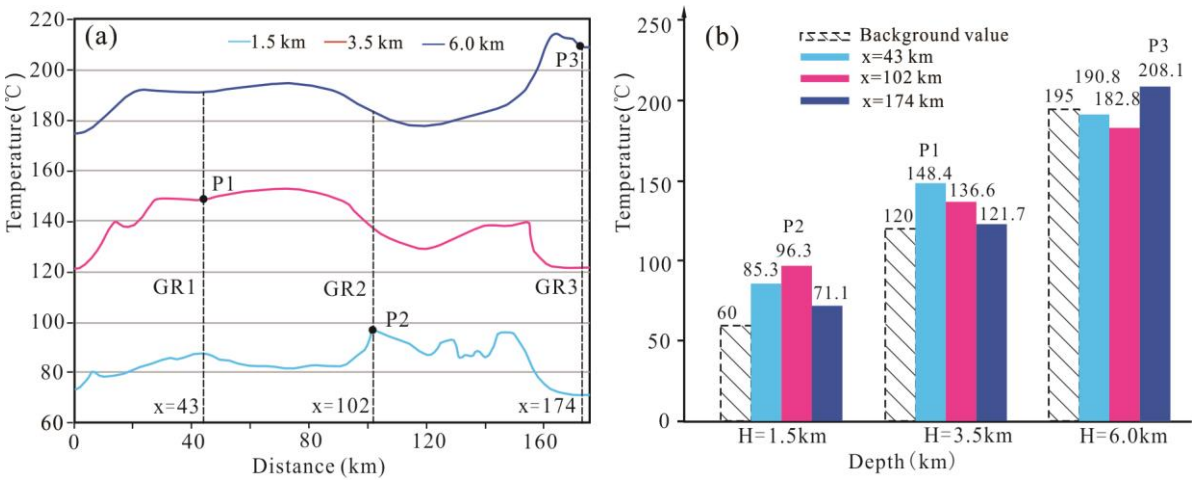


Figure 10: Comparison of strata temperature curves of Gaoyang - Xianxian geothermal profile at different depths (a) and strata temperatures of different structural zones (b)

5. DISCUSSION

5.1 Change law of heat transfer and heat accumulation

The analysis results of 14 theoretical models in this paper once again verify the research results of relevant scholars on heat conduction in recent years (Mao Xiaoping et al., 2018; Wang et al.,2020; Wang Xinwei et al., 2022), that is, the geothermal anomaly in the uplift belt of sedimentary basin is the result of the simultaneous action of "heat flow deficit" caused by the rapid heat transfer in the deep bedrock bulge section with high thermal conductivity and "heat flow enrichment" caused by the gradual accumulation of heat in the shallow thermal cap section with low thermal conductivity. Both of them have a nearly symmetrical coupling change law. Because of the complex geological structure and various influencing factors involved in this paper, this understanding is more comprehensive and reasonable. It is embodied in the following three aspects: ① One-dimensional vertical temperature change. The amplitudes of positive and negative anomalies show the characteristics of synchronous increase and decrease, that is, the more "deficit" of heat flow in deep geothermal reservoir (the ground temperature is lower than the background value), the more "enrichment" of heat flow in shallow geothermal reservoir (the stratum temperature is higher than the background value). However, in comparison, the amplitude of positive geothermal anomaly at the top of bedrock bulge is slightly larger than that of negative geothermal anomaly at the bottom (except Model 9) (Figure 7). ② Temperature change on two-dimensional cross section. The positive abnormal change curve of stratum temperature at the top of bedrock bulge is basically similar to the structural form of bedrock bulge, while the negative abnormal change curve of stratum temperature at the bottom of bedrock bulge has the characteristics of "asymmetric mirror

distribution" (Wang et.al., 2022). The maximum values of positive and negative stratum temperature anomalies are located on the middle vertical line of symmetric bulge (horst) (model 1~11) or the vertical line at the top of asymmetric bulge (half graben) (model 12~14); The positive and negative anomalies decrease rapidly in the transition zone from bulge to sag, until they disappear. The distribution characteristics of geothermal anomaly curve show that the vertical rapid transfer of deep heat flow is the main factor for the "enrichment" of top heat flow, and the heat flow diversion from the deep peripheral sag to the bulge is less. This is quite different from the previous view that "the main reason is the redistribution of heat flow from sag area to bulge area" (Xiong Liang Ping and Zhang Juming, 1988). ③ The heat transfer and heat accumulation in the shallow structural belt of the basin are controlled by its structural shape. The positive geothermal anomaly at the top of the bulge belt is the result of the joint action of the "heat accumulation" of the vertical rock section and the "thermal refraction" of the inclined rock section, but the contribution of the "thermal refraction" is relatively small. For example, the stratum temperature at the top of the bulge of Model 10 is 31.3℃, higher than the background value, with an amplitude of 41.8%, which is the highest value among all models, but the contribution of "thermal refraction" of the inclined rock is only 11% (Figure 8).

5.2 Main control factors of shallow geothermal anomaly

The formation of geothermal anomaly in the shallow part of the uplift belt involves the generation and preservation of "enriched heat flow". As mentioned earlier, the generation of "enriched heat flow" is caused by the differential heat conduction of the uniform heat flow of the substrate in the bulge zone and the sag zone. According to the single-layer flat-wall steady-state heat conduction model (Liu Shaowen,etal.,2017) and the parameter settings of the three-layer geological model constructed in this paper (Table 1 and Figure 3), the calculation formula for temperature difference between the bulge zone and the sag zone (ΔT) is:

$$\Delta T = qb(1/k_2 - 1/k_3) = qb(1 - k_2/k_3)/k_2 \quad (2)$$

According to the formula (2), under the assumption that the uniform heat flow (Q) of the basement and the thermal conductivity (k2) of the surrounding rock are constant, the most important factors for the formation of the geothermal anomaly in the uplift zone are the height of bedrock bulge (i.e. thickness of surrounding rock (B)) and thermal conductivity of bedrock (k3) (more specifically, the ratio of thermal conductivity of surrounding rock to thermal conductivity of bedrock (k2/k3)). According to the simulation results of 14 geological models in this paper, it seems that the change of thermal conductivity of bedrock has the greatest influence on geothermal anomaly. For example, in models 3~5, when the thermal conductivity increases by 2/3, the positive anomaly of the top temperature increases by 1.5 times. At the same time, it should be added that the area and structural form of bedrock bulge have a positive role in promoting the formation of geothermal anomaly. This promotion is reflected in that the expansion of the bedrock bulge area and the thermal refraction of the inclined rock stratum are more conducive to the lateral diversion of heat flow at the bottom of the bulge zone, but have a little contribution to the "thermal enrichment" of heat flow at the top (Figures 6 and 9). For example, in models 5~7, when the area of the convex belt is expanded to 4 times, the increase of the maximum positive geothermal anomaly at the top is only 34%; In Model 11, however, the "thermal refraction" effect of the inclined strata does not affect the middle part, and the influence range is only within half of the inclined width.

Another key factor of "heat flow enrichment" in the shallow part of the bulge is "heat preservation"-that is, the heat sealing performance of the cap rock. The thermal conductivity and thickness of the cap layer are the two main parameters to measure

its advantages and disadvantages. Wang Xinwei et al. (2022) classified the caprocks into (completely) effective caprocks, partially effective caprocks and ineffective caprocks according to the preservation of the heat accumulated in the underlying geothermal reservoir by the overlying caprocks, and tentatively put forward that "the minimum thickness of effective caprocks is not only directly related to its thermal conductivity, but also closely related to the heat enrichment degree of the required caprocks (that is, the geothermal anomaly size of the reservoir)". That is, the greater the geothermal anomaly of the reservoir, the greater the effective thickness of the required caprock. The simulation results of a series of theoretical models in this paper well prove this understanding, and it is also found that the effective thickness of the caprock is closely related to the preservation time of geothermal anomalies. The required preservation time here refers to the time limit of the last thermal event. That is, the closer the last thermal event occurs, the thinner the required effective thickness of the cap rock. Take the strata temperature-time curve of the bedrock geothermal reservoir at the top of the bulge belt of a series of theoretical models as an example (Figure 11): ① Models M4~7 have the same thermal conductivity and thickness of the cap rock, but model M7 has a relatively high geothermal anomaly, so its thermal preservation is relatively weak. At the end of the simulation time (T=500ka), the temperature of the bedrock geothermal reservoir drops by 1.6℃ from its highest value, while the temperature of the bedrock geothermal reservoir of model M4~6 has basically not decreased or has just reached the maximum value (Figure 11a). ② At the same time, the model M7~9 has the same "thermal enrichment" generating conditions. With the gradual decrease of the cover thickness, the time for the temperature of bedrock geothermal reservoir to reach the highest value is also gradually shortened, which is 300ka, 250ka and 220ka respectively (Figure 11b); In other words, if the time of the last thermal event occurred at 300ka, 250ka and 220ka respectively, the effective cover thickness required to preserve the positive anomaly temperature of 28.2℃ for geothermal reservoir is 2000m, 1500m and 1000m respectively.

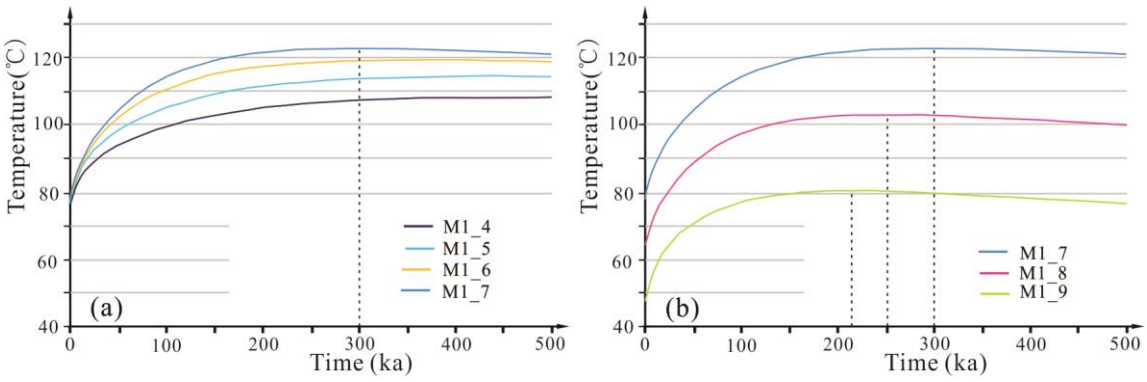


Figure 11: Comparison of temperature-time curves of bedrock geothermal reservoir at the top of uplift belt

(a) Models 4~7; (b) Models 7~9

To sum up, the heat transfer, heat accumulation and heat preservation in bedrock bulge zone is a dynamic equilibrium process. During the initial 100 ka of the thermal disturbance of the last thermal event, it is a rapid heat transfer and accumulation stage, followed by a slow heat preservation or heat dissipation stage. Under the condition of ensuring the thermal sealing performance of the cap rock, the higher the bedrock bulge, the greater the thermal conductivity and the thinner the cap rock thickness, the greater the geothermal anomaly formed by the bedrock geothermal reservoir at the top of the bulge. For the same sedimentary basin, when the thermal conductivity of bedrock, surrounding rock and caprock, and the basement heat flow are basically the same, the thickness of caprock and the amplitude of bedrock bulge (i. e., the structural form) are the main factors that affect the geothermal anomaly in the shallow part of the sedimentary basin in the 10km category.

5.3 Geothermal gradient of caprock and classification of geothermal field types

The average geothermal gradient in the caprock is the comprehensive embodiment of heat transfer, accumulation and heat sealing performance of the caprock. The average geothermal gradient of the caprock in Xianxian bulge is 5.42℃/100m

(Figure 11a), which is 80.7% higher than the average geothermal gradient of 3.0℃/100m, which is closely related to the rapid heat flow transfer in the bedrock section and the effective heat flow accumulation in the cover section caused by the thermal conduction of its structural form (including the bedrock uplift amplitude of ~4000m and the cover thickness of 1500m). The bedrock uplift amplitude of the Gaoyang low bulge is ~2500m, the cap rock thickness is 3500m, and the average geothermal gradient of the cap rock is 3.80℃/100m (Figure 11b), which indicates that with the decrease of bedrock bulge and the increase of cap rock thickness, the thermal enrichment degree in the cap rock gradually decreases. However, the average geothermal gradient of the cover layer in Nanpi sag is 3.22℃/100m (Figure 11c), which shows that the geothermal gradient of the cover layer gradually returns to the average background value of 3.0℃/100m in the non-thermal disturbance area without bedrock bulge.

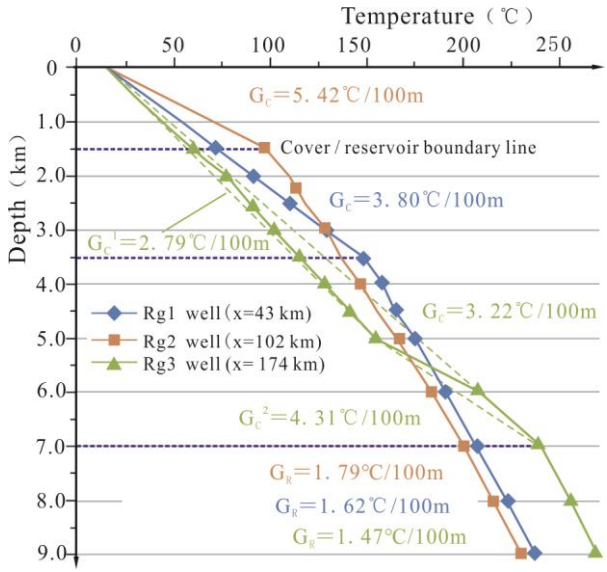


Figure 12: Strata temperature-depth curve of artificial well in Xiongxian-Xianxian section

GC, cover temperature gradient; GR, reservoir temperature gradient

From the above analysis, it can be seen that the amplitude of bedrock bulge caused by structural deformation in the faulted basin (i.e. the fault distance of the main normal fault in the rifting period) and the thickness of the overlying strata (i.e. the size of the overlying sediments in the depressed period) are the main factors that affect the geothermal anomaly in different structural zones (within the 10km level) in the shallow part of the sedimentary basin. For Bohai Bay Basin with a wide area and complex deformation patterns, this semi-quantitative analysis method of "the difference of structural deformation determines the shallow geothermal anomaly" is applied to geothermal research. According to the thickness of the upper overburden, the normal fault offset and the geothermal gradient of the caprock, the geothermal fields of bedrock geothermal reservoir in the basin are divided into seven types, namely, high bulge type, bulge type, low bulge type, sag type, gentle slope type, basin edge faulting-uplift type and shallow buried type. (1) The high bulge geothermal field mainly refers to the tertiary structural belt of the basin where the buried depth of the top surface of bedrock is 800~1500m, and the fault distance of the main control fault is more than 4000m. Because of the strong heat transfer in the bedrock bulge and the heat accumulation in the cover, the geothermal gradient of the cover in the bulge area is generally above 5℃/l00m, which is higher in some areas. (2) The bulge geothermal fields are mainly distributed in the tertiary structural belt of the basin, where the buried depth of the top surface of bedrock is 1500~2500m, and the fault distance of the main control extensional fault is 3000~4000. The heat transfer of bedrock section and the heat accumulation of caprock section are relatively strong, and the geothermal gradient of caprock is generally 4.0~4.9℃/l00m. (3) Low-bulge geothermal field refers to the low-amplitude uplift area of the basin where the buried depth of the top surface of bedrock is 2,500 ~ 4,000 m and the fault distance of the main control extension

fault is 2000~3000 m, and the geothermal gradient in the caprock is generally 3.5 ~ 4.0℃/l00 m. (4) The sag geothermal field means that the bedrock geothermal reservoir is buried under Cenozoic clastic rock with a thickness of more than 4000~7000m sedimenting in grabens or half-grabens. Although there is no thermal disturbance caused by bedrock bulge, the geothermal gradient of the caprock is 3.0~3.5℃/l00m, slightly larger than the average background value, due to the high heat flow in the tectonic active zone. (5) The gentle slope geothermal field refers to the relatively stable area with weak tectonic deformation in the faulted basin, and the slope areas on both sides of the bedrock uplift are developed, mainly with inherited subsidence, and the thickness of the cover layer is 1000~1500m. Because of the weak tectonic activity and the lower heat flow of the basement than the average value of the basin, the geothermal gradient of the cover layer is slightly lower than the average value, which is 2.5~3.0℃/l00m. (6) Basin-edge faulting uplift type refers to the basin-mountain transition area developed on the rising plate of the basin-edge deep fault (Cenozoic fault distance can reach more than 4,000 m), and the thickness of the cover layer is mostly 1,000 ~ 1,500 m. This geothermal field type has certain thermal sealing performance, but it is mainly affected by the low temperature of the cold water in the source area supplied by geothermal water, and the geothermal gradient of the cover layer is low, 2.0 ~ 2.5℃/l00 m. (7) The shallow buried geothermal field developed in the high-rise area of basin, whose thickness of Cenozoic caprock is less than 500m. The geothermal gradient of caprock is less than 2.0℃/l00m because of its thin caprock and poor thermal sealing performance.

The purpose of geothermal exploration and development is to obtain the maximum reservoir temperature at the shallowest horizon. The geothermal field classification method based on structural deformation difference can semi-quantitatively predict the drilling depth and geothermal reservoir temperature of different structural zones, which has important guiding significance for the exploration and development of bedrock geothermal reservoir in the basin (Table 2). High bulge type and bulge type of geothermal fields are the primary targets for shallow geothermal exploration and development because of their relatively shallow buried depth and relatively high temperature, such as well YR1 in Xianxian county with a well depth of 1,600 m and a wellhead water temperature of 97℃, and well KT2 in Xinhe county with a well depth of 1,569 m and a wellhead water temperature of 78℃. Low- bulge geothermal fields and sag geothermal fields are the main targets for searching deep high-temperature geothermal reservoirs (> 150℃). For example, well BS1 in Boye county has a well depth of 3,758 m and the highest formation temperature is 165.7℃. The gentle slope geothermal field and the basin edge fault uplift geothermal field have a low temperature (~55℃) even though the bedrock geothermal reservoir is shallow (< 2000m), so they have a resource base for large-scale exploration and development on the premise of good ground conditions. However, the shallow geothermal field has high economic risk because of its low geothermal reservoir temperature.

6. CONCLUSION

Based on the theoretical models of 14 geological structures and the two-dimensional numerical simulation analysis of geothermal geological profile in Gaoyang-Xianxian, Bohai Bay Basin, this paper obtains the following knowledge.

(1) The heat transfer and heat accumulation mechanism in the bedrock bulge belt of sedimentary basin is essentially the result of the simultaneous occurrence of "heat flow deficit" caused by the rapid heat transfer in the deep bedrock geothermal reservoir and "heat flow enrichment" caused by the gradual accumulation of heat flow in the shallow top cover, both of which have a nearly symmetrical coupling change law. The simulated strata temperature at the top of the bedrock geothermal reservoir can increase by 31.3℃ at the highest, with a positive anomaly amplitude of 41.8%. The simulation results are basically consistent with the existing exploration results, and there is no influence of high temperature additional heat source.

(2) The positive anomaly of stratum temperature at the top of bedrock geothermal reservoir in the bulge zone is the result of the combined action of "heat concentration" and "heat refraction". The main influencing factors are the amplitude (height), area (width) of bedrock bulge, lateral inclination of rock stratum (fault dip angle), heat conductivity of bedrock and thickness of overlying strata, etc. Among them, the heat sealing performance with a certain cap thickness (~1 km) is the fundamental guarantee for the formation of shallow heat accumulation, the height of bedrock bulge is the necessary condition for the

formation of shallow geothermal anomaly, the thermal conductivity of bedrock is the most obvious controlling factor, and the "thermal refraction" of inclined rock also contributes to some extent (~11%).

Table 2: Classification of geothermal field types in Bohai Bay Basin

type	Thickness of caprock /m	Normal fault offset /m	Geothermal gradient of caprock /℃/l00m	Tertiary structural belt	Example of drilling
High bulge type	800~1500	>4000	>5.0	Niutuozhen bulge, Xianxian bulge and Ningjin bulge.	Xianxian YR1 well has a depth of 1600m and a temperature of 97℃.
Bulge type	1500~2500	3000~4000	4.0~4.9	Xinhe bulge, Wucheng bulge	Xinhe KT2 well has a depth of 1569 m and a temperature of 78℃.
Low bulge type	2500~4000	2000~3000	3.5~4.0	Gaoyang low bulge, Renqiu buried hill and Wuji low bulge.	Well BS1 in Boye has a depth of 3758m and a temperature of 165.7℃
Sag type	4000~7000	Local fault depression center	3.0~3.5	Raoyang sag and Bazhou sag	Well NG2 in Hejian has a depth of 4951m and a temperature of 166.1℃
Gentle slope type	1000~1500	Inherited subsidence	2.5~3.0	Neihuang bulge east slope	Qingfeng 1 well has a depth of 1404m and a temperature of 56℃
Basin-edge faulting uplift type	1000~1500	>4000	2.0~2.5	Heze bulge, Qihe bulge	Well QX1 in Heze has a depth of 1707m and a temperature of 56.8℃
Shallow buried type	<800m	Inherited uplift	<2.0	Daxing bulge and Central part of Neihuang uplift	Well XR2 in Daxing has a depth of 2233m, and a temperature of 49.5℃.

(3) The average geothermal gradient in the caprock is the comprehensive embodiment of heat transfer, accumulation and preservation. According to the difference of structural deformation patterns in faulted basins and its decisive effect on the geothermal gradient of caprock, the geothermal fields of bedrock reservoir in Bohai Bay Basin are divided into seven types, namely, high-bulge, bulge, low-bulge, sag, gentle-slope, basin-edge fault-uplift and shallow-buried, showing the change characteristics that the geothermal gradient of caprock gradually decreases (from > 5.0℃/l00m to < 2.0℃/l00m). Therefore,

high- bulge and bulge geothermal fields are favorable targets for shallow bedrock geothermal reservoir exploration, while low-convex and sag geothermal fields are the main targets for searching deep high-temperature geothermal reservoirs (>150 ℃).

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