

# Study on the Basic Characteristics of the Geothermal Temperature Field in the Middle and Deep Layers of the Liaohe Depression

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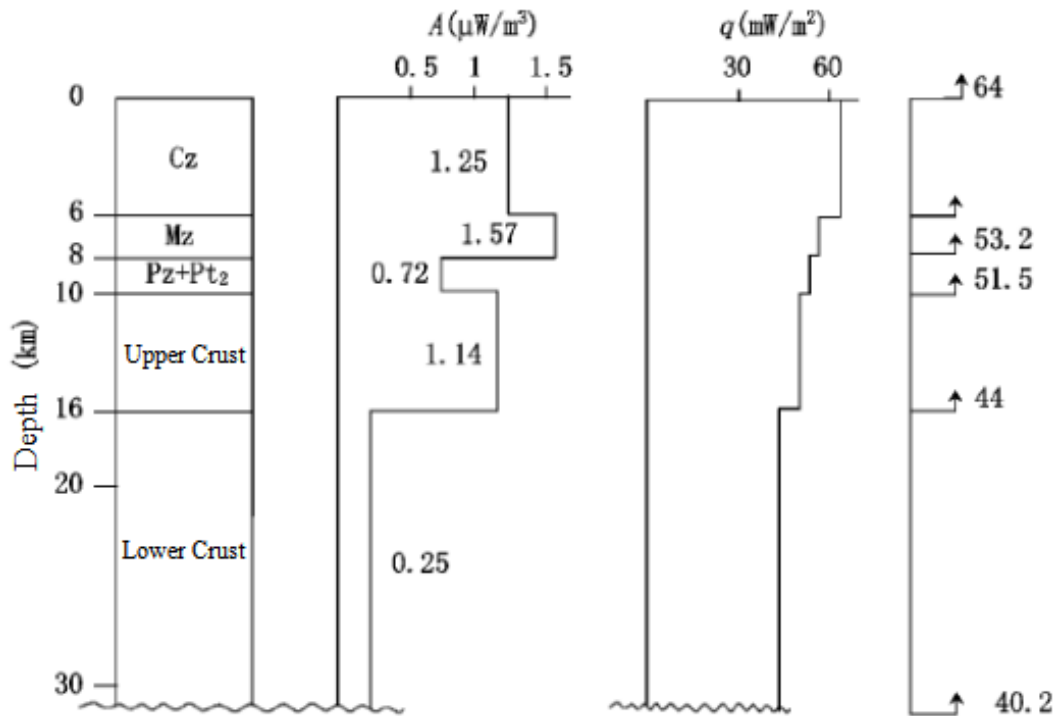
**Abstract.** The Liaohe Depression is a large "thermal field" with a Moho depth of 33 kilometers. It is located in a regional mantle uplift zone, where the crust is relatively thin, providing favorable conditions for the upward transfer of mantle heat. The characteristics of the geothermal temperature field in the middle and deep layers of the Liaohe Depression are not only controlled by the basic regional geological and geothermal features but are also influenced by several key factors. These include the burial depth of the bedrock, the lithology and structure of the bedrock and overlying unconsolidated layers, groundwater activity, magmatic activity, fault activity, and local variations in the content of radioactive elements. These factors, to varying degrees, affect the distribution of the temperature field. The regional fault structures are well-developed, and the bedrock shows significant fluctuations. This unique geological structure makes bedrock burial a regionally significant factor in controlling the geothermal temperature. According to the basic principles of heat conduction, the heat from deep sources is distributed among the geological bodies, forming the current basic characteristics of the temperature field in the Liaohe Depression. Through the study of these factors and the temperature field patterns, more accurate geothermal predictions can be made, laying a solid foundation for the development of geothermal exploitation plans.

**Keywords:** Geothermal; mid deep; temperature field; geothermal flow.

## 1. Analysis of the Main Controlling Factors of Temperature Field Anomalies

### 1.1. Crust-Mantle Structure

The thermal state of the Earth's interior is a crucial parameter in geothermal studies. The crust-mantle structure is the fundamental heat-controlling factor. The heat flow from the crust, generated by the decay of radioactive elements in the shallow crust, along with the heat flow from the deep crust and upper mantle, constitutes the surface heat flow. This crust-mantle heat flow directly affects the temperature conditions in the deep layers [1]. As shown in Figure 1, due to tectonic activity, the mantle heat flow in the rift basins of eastern China is relatively high, gradually decreasing towards the west. The Moho depth in the Liaohe Depression is approximately 33 kilometers, indicating a relatively thin crust situated in a regional mantle uplift zone. The variation in Moho depth across the region is minimal, suggesting that the heat source mechanism of the geothermal system is constrained by the differences in heat distribution between the crust and mantle. By establishing a crustal structure model of the Liaohe region, it is shown that this area has a unique thin crust structure, providing favorable conditions for the upward transfer of mantle heat, thus offering a solid geological foundation for the development and utilization of geothermal resources [2]. The mantle heat flow in the Liaohe Depression is  $40.2\text{mW/m}^2$ , accounting for 61% of the basin's surface heat flow [3-4].



**Figure 1.** Crustal Structure Model and Thermal Structure of the Liaohe Region

## 1.2. Analysis of Radioactive Heat Sources

In addition to the heat provided by the mantle, the decay of radioactive elements in the crust is also a major source of surface heat flow. The radioactive elements that contribute to the heat in the crust mainly include isotopes such as  $U^{238}$ ,  $U^{235}$ ,  $Th^{232}$  and  $K^{40}$ , whose half-lives are comparable to the age of the Earth. This section focuses on analyzing the composition of heat generated by radioactive elements in the Cenozoic era and its role in controlling the geothermal conditions. The calculated heat generated by radioactive elements in a 3km thick Cenozoic layer in the Liaohe Depression is approximately 893,380 HGU, which is about 1/17 of  $62.79\text{mW/m}^2$ . Therefore, the shallow geothermal characteristics in the Liaohe region are not significantly influenced by the enrichment or depletion of radioactive elements in the shallow layers.

## 1.3. The Impact of Fault Activity

Faults influence fluid flow within reservoirs, promote permeability, and contribute to aquifer development, playing a crucial role in the formation of geothermal fields [5-6]. The composition, characteristics, and intensity of activity of the fault structures within the basin provide favorable channels for water and heat transfer, also affecting the natural convection within the geothermal field [7]. In fault activity zones, intense hot water flows upward along fault zones, reaching the surface and creating geothermal manifestations. The shallow layers near faults exhibit high heat flow anomalies, forming a deep geological background of high geothermal anomalies [8]. Different tectonic settings determine the heat accumulation modes, water migration channels, and storage spaces within geothermal systems. Additionally, mechanical friction along faults generates heat, making the geothermal gradient and terrestrial heat flow relatively high along fault zones, thus acting as the main controlling factor of the heat source.

## 1.4. The Impact of Magmatic Intrusion and Basement Fluctuations

Magmatic intrusion is a significant geological process in geothermal formation. When molten magma rises from deep within the crust towards the surface, pressure decreases and temperature increases, releasing heat into the surrounding strata as an additional heat source, known as magmatic heat. This heat is then released towards the surface along faults and fractures in the crust, which serve as

channels for the heat release. Additionally, magmatic intrusion alters the properties of surrounding rocks, forming heat reservoirs and conductive channels, further promoting the formation of geothermal resources [9-10]. During the Mesozoic and Cenozoic eras, volcanic activity in the Liaohe Depression was frequent. High-temperature magma from the mantle erupted and overlaid sedimentary deposits, providing heat from top to bottom. The magmatic rocks formed by these eruptions and intrusions act as a bottom-up heat source. Furthermore, the high heat production rates of Archean granites and the high thermal conductivity of Mesozoic volcanic and clastic rocks also provide good heat sources. Therefore, the magmatic heat source is not the main factor influencing the distribution of geothermal temperatures.

Basement fluctuations in the Liaohe Depression, resulting in uplift and subsidence patterns, affect the distribution of regional geothermal fields and surface heat flow. These fluctuations cause the heat flow from deep sources to be redistributed, concentrating in areas with high thermal conductivity in the uplifted basement regions. The structure of the uplifted and subsided areas within the Liaohe Depression leads to differences in horizontal thermal conductivity, causing changes in the temperature field. This is reflected by low geothermal temperatures in the subsided zones and high geothermal temperatures in the uplifted zones.

### **1.5. The Impact of Groundwater Activity**

The highly developed permeable rock formations of the Cenozoic era in the Liaohe Basin are almost entirely controlled by groundwater activity. The Upper Tertiary Guantao Formation, an artesian aquifer, is in regional unconformable contact with the underlying Lower Tertiary. The Dawa aquifer is stable both vertically and horizontally, with uniform water content and good water quality, making it the main water supply layer in the oilfield region. The water content is abundant, with 90% of the water supply currently coming from the Guantao Formation. The low temperature and low geothermal gradient in the shallow layers are mainly due to the interference of the Guantao Formation groundwater with the geothermal conditions. The elongated basin topography provides favorable conditions for the intense movement of cold water along the aquifer. The Dongying Formation is affected to varying degrees by the shallow Guantao Formation groundwater, but with increasing depth, the runoff conditions weaken, and the geothermal temperature gradually returns to normal. Within the Cenozoic layers, the geothermal gradient increases from top to bottom. Data show that in shallower areas, around 1000 meters deep, the strong interference from groundwater results in relatively low-temperature anomalies. Moreover, at approximately 1500 meters, most of the western depression has passed through the Guantao Formation aquifer, and the influence of formation water gradually diminishes, while the impact of the burial depth of the bedrock becomes more pronounced. At a depth of around 2000 meters, the influence of groundwater activity essentially disappears, and the fluctuations in bedrock burial depth become the main controlling factor affecting underground temperatures.

## **2. Basic Characteristics of the Geothermal Temperature Field in the Middle and Deep Layers of the Liaohe Depression**

Based on the analysis of actual data from over 3,000 exploratory wells in the region, the depth of completed wells is generally around 30 meters, where the temperature is approximately 10.5°C, unaffected by atmospheric temperature. This paper consolidates the temperature data from the completed exploratory wells in the study area, particularly focusing on those wells that underwent oil testing and production. The regional thermal conductivity statistics indicate that the thermal conductivity of the Proterozoic strata is typically more than three times that of the loose cover layers, the Paleozoic strata are 2 to 2.5 times higher, and the Mesozoic strata are about the same level as the loose cover layers. The varying amounts of heat concentrated by these different thermal conductors in the deep heat flow lead to differences in the geothermal temperatures and geothermal gradients in the overlying loose layers. Additionally, the lithology and burial depth of the bedrock play a

controlling role in the upper geothermal temperatures. The topography and scale of the bedrock, along with other influencing factors, result in variations in the concentrated heat.

Generally speaking, the geothermal characteristics of the Cenozoic era show that the deeper you go, due to the compaction effect, the thermal conductivity increases, and the geothermal gradient decreases. However, in this region, the Quaternary period typically exhibits a geothermal gradient of about 3°C/100m, while in the Guantao Formation, it is only 2 to 2.5°C/100m. In the Dongying and Shahejie Formations, it generally increases to 3.5 to 4°C/100m, and in some areas of the third and fourth sections of the Shahejie Formation, the geothermal gradient exceeds 4°C/100m. Analysis suggests that this is mainly related to the low thermal conductivity of the Tertiary strata's clay content. Additionally, differences in the thickness of various Cenozoic strata, local lithological variations, varying temperature measurement depths, and the basic controlling factor of bedrock burial depth contribute to the fact that some temperature measurement wells do not exhibit this pattern.

Comprehensive analysis reveals the basic characteristics of the geothermal temperature field in the middle and deep layers of the Liaohe Depression as follows:

(1) At depths of 1,500 to 1,700 meters, the geothermal field is mainly controlled by the burial depth of the bedrock. In bedrock uplift areas, such as the central uplift, the western slope zone, and other high points of the bedrock, the temperature difference between the highest points, such as Gaoshen, Panshan, Shuangtaizi, and the deepest depressions, can generally reach 10 to 15 degrees. This is due to the more efficient heat flow concentration towards the elevated areas of the bedrock, resulting in relatively high temperatures in these regions. The characteristics of the temperature field are manifested in alternating structural highs and lows, corresponding to alternating high and low geothermal temperatures.

(2) At depths of 2,000 meters, the aforementioned relationship becomes significantly less pronounced. In the bedrock uplift areas, as the temperature gradient decreases and temperature increase slows down due to the entry into the lower thermal resistance bedrock, the temperature in the shallowest parts of the bedrock becomes lower than in the depressions. Within the depressions, relatively shallow bedrock areas have higher temperature values.

(3) At depths below 2,500 meters, the reverse temperature characteristics become more evident. The bedrock uplift areas all form low-temperature zones, with high temperatures occurring in areas where the bedrock is buried at depths of 2,500 to 3,500 meters. The temperature difference between deep depressions and relatively shallow depressions exists but tends to gradually decrease.

(4) The temperature and geothermal gradient in the Qianshan area, particularly in the Precambrian Qianshan surface and the overlying strata, show significantly higher values, exhibiting the characteristic of bedrock uplift controlling the geothermal temperature. In the eastern part of the Huanxiling Oilfield, the temperature above the Minghuazhen Formation is relatively higher than in other depression areas, which is mainly attributed to significant lithological differences. The geothermal gradient advantage in the Tertiary strata of the eastern depression shows a slight weakening trend.

### **3. Conclusion**

(1) The factors influencing the formation of the regional geothermal field are diverse, and the extent and intensity of their impact on the strata are multifaceted. Groundwater activity, fault structures, and the undulating shape of the basement are the primary influencing factors. Surface runoff and shallow groundwater activities carry away some heat, affecting the formation of shallow heat flow, leading to a decrease in the heat flow of the studied strata and ultimately resulting in lower shallow geothermal temperatures. A noticeable increase in geothermal gradients can be observed on both sides of the faults. Simultaneously, the amplitude, shape, and scale of bedrock undulations determine the redistribution of heat transmitted from deeper layers, with the undulating topography influencing the

geothermal temperatures. These factors are the main controls over the geothermal distribution in the Dawa Oilfield.

(2) The low-temperature field characteristics of the Liaohe Depression are generally normal, with no abnormal high-temperature features. Compared with other hydrocarbon-bearing basins in the Bohai Bay area, such as the Huabei Oilfield, where the geothermal gradient is generally around 2.8 to 3.5°C/100m, and the Shengli Oilfield, where the geothermal gradient is slightly higher, the geothermal gradient in the Liaohe Depression is generally less than 3°C/100m above 1,500 meters. The highest recorded geothermal gradient is 3.8°C/100m in well Shuang 91, with higher geothermal temperatures in bedrock uplift areas, similar to other oilfields.

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