Genetic Analysis of Abnormally High Ground Temperature From the Existence of Magmatic Rock Beneath Pingdingshan Coalfield

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Studies on the genetic mechanisms of abnormally high ground temperatures in coalfields are of great significance for the efficient mining of coal mines and the development and utilization of geothermal water. Therefore, we measured the temperature of 45 Cambrian limestone groundwater samples, thermal conductivity values of 11 Cambrian limestone samples, and the contents of uranium, thorium, and potassium-40 of 40 rock samples, aiming to ascertain the heat source of the abnormally high ground temperature in the Pingdingshan coalfield. The results show that the average geothermal gradient in the coalfield is about 3.32°C/100 m, and the calculated values of the average ground heat flow are about 104.28 mW/m², which demonstrate the abnormally high ground temperature in Pingdingshan coalfield. We also concluded that the whole radiogenic heat generation in sedimentary and magmatic rocks is 1.53 mW/m², whose contribution rate to the local geothermal flow is only 1.47%. Hence, we can infer that magmatic rocks exposed in or near the coalfield area may supply the heat source for the abnormally high ground temperature beneath Pingdingshan coalfield. A comprehensive analysis further shows that the latest intrusion time of the magmatic rock mass in the coalfield was 35 Ma; its lava temperature was 900°C, its cooling rate is 20.0 °C/Ma, and the calculated residual temperature is more than 200.0°C. These values support the idea that the magmatic rocks may be the primary cause of the abnormally high ground temperature in the Pingdingshan coalfield.

Keywords: terrestrial heat flux, radionuclide exothermic, magmatic heat generation, residual temperature, Pingdingshan mining area

1 INTRODUCTION

Monitoring data have shown that the average geothermal gradient of the Pingdingshan coalfield is 3.32°C/100 m. At a buried depth of 1,000 m, the temperature can reach as high as 49.57°C in the rocks or groundwater. Hence, it is an area with an abnormally high ground temperature compared to other zones in Henan Province. Affected by the higher surrounding rock temperature and roof-pouring (gushing) water, the ambient temperature and air humidity of the underground mining space are
very high so that it not only increases the cost of coal mining, but also affects the physical and mental health and labor efficiency of the workers. Therefore, in this study an analysis of the genetic mechanism responsible for the abnormally high coalfield ground temperature seems to be of great significance.

In recent years, many scholars have focused on researching the heat-source mechanism of different geothermal areas via studying the heat production of radioisotopes and magmatic rocks. Burns et al. (2015) studied the steep permeability drop and low heat flow anomaly of a middle plateau aquifer system on the Columbia Plateau, which contains a heat flow regime at depths of 600–900 m. Their research showed that the steep permeability drop is related to hydrothermal transformation and pore-refilling minerals in the volcanic area. Peng et al. (2015) studied the geothermal field in the Linhuan mining area of the Huaiabei coalfield and concluded that the high geothermal gradient mainly occurs in areas containing intensively developed anticlines and faults, and a high-temperature anomaly also occurs mainly in areas with intensively developed folds, uplifts, and faults (Jun et al., 2015). Ren et al. (2017) calculated the heat generation rate of coal-measure sedimentary rocks and magmatic rocks based on the natural gamma (GR) logging values of 6,208 coal-measure rocks taken from 36 boreholes in the Zhuji coalfield, Huainan, China. Generally speaking, the contribution of radiogenic heat generation of coal-measure rocks to terrestrial heat generation in the thick crust and local thermal anomalies. According to the research of Sun et al. (2020), the ground heat flow value in southeast Guanxi is between 80 and 100 mW/m², and the temperature gradient is higher than 30°C/km. They concluded that the higher radionuclide content in the Indosinian granite in the area is the basis of the stable heat source. Based on the radiogenic heat generation rate data of 98 rock samples collected from the Gonghe Basin, Zhang et al. (2020a) calculated the heat production of radioactive elements of granitoids in the Gonghe Basin and Qinghai Tibet Plateau, and found that the abnormal heat flow in the Gonghe Basin may be a result of the combined action of radioactive element radiation heat generation in the thick crust and local thermal anomalies. According to the research of Sun et al. (2020), the ground heat flow value in southeast Guanxi is between 80 and 100 mW/m², and the temperature gradient is higher than 30°C/km. They concluded that the higher radionuclide content in the Indosinian granite in the area is the basis of the stable heat source. Based on the radiogenic heat generation rate data of 98 rock samples collected from the Gonghe Basin, Zhang et al. (2020b) analyzed the distribution characteristics of the radiogenic heat generation rate of main lithologic rocks in the basin and established a genetic model of the HDR geothermal resources in the area. Luo et al. (2020) calculated 6,094 radiogenic heat generation rates in the sedimentary layers in the Tarim Basin, finding an average value of 1.17 ± 0.336 μW/m². Mudstone has the highest heat generation rate, followed by sandstone, dolomite, and limestone, and lithology is the major factor affecting the heat generation rate. It was estimated that the heat flow contribution from radiogenic heat generation is 9.36 mW/m², accounting for about 21% of the total surface heat flow. The radiogenic heat generation also has an impact on the geothermal field in the Tarim Basin. Ogunsanwo et al. (2021) calculated the radiogenic heat production rate for 30 rock samples from 10 quarries in Ogun State, Nigeria, which showed a range of values of 0.549–3.122 μW/m², in which uranium contributes the most and thorium contributes the least. Weinert et al. (2021) calculated the radionuclide heat production rate based on 30 Triassic, Silurian, Ordovician, and Devonian intrusive rocks extracted from a complex in the Gonghe Basin. Their study showed that the heat production rate of radioactive elements in this area is less than 1 μW/m² in biotite granite, and greater than 5 μW/m² in syenogranite. Ma et al. (2021) found that the deep heat source of a geothermal abnormity in the eastern Himalayan structural junction area mainly comes from the Yarlung Zangbo River junction zone and nearby deep faults, and the surface heat is mainly controlled by secondary tension and torsion faults on both sides of the junction zone (Xin et al., 2021).
Regarding the abnormally high ground temperature in Pingdingshan coalfield, Zhang et al. (2000) analyzed the influence of groundwater migration on the temperature field based on the silica temperature scale method and isotope method, and expounded the causes of the uneven temperature distribution in the geothermal field. Based on an analysis of the distribution characteristics of the geothermal field in the Pingdingshan coalfield, Cao et al. (2014) clarified that the abnormal high-temperature area has the characteristics of a dense development of faults and fractures and fold uplift. The geothermal distribution is affected by the regional geological structure, groundwater activities, rock properties, and caprock properties (Bingqi et al., 2014).

Overall, studies on the abnormality of the ground temperature and its influencing factors in the Pingdingshan coalfield have been extensive, but there has been less research regarding the genetic mechanism of the abnormally high ground temperature. Therefore, based on field-measured data and geological setting conditions, we further studied the heat source of the abnormally high ground temperature in the Pingdingshan coalfield. The conclusions in this study may provide support for preventing and controlling mine heat damage, and promoting the development and utilization of geothermal water in the future.

2 GEOLOGICAL AND GEOTHERMAL CHARACTERISTICS

The Pingdingshan coalfield is located on an uplift fault block surrounded by the Jiaxian Fault, Xiangjia Fault and Luogang Fault, with an east–west length of 40 km and a north–south width of 10–20 km, and the mining area is about 650 km² (Figure 1). At present, Pingdingshan coalfield mainly mines the II1 coal bed with a depth ranging from 680 to 1,000 m, which represents a deep mining state.

The strata of the Pingdingshan coalfield includes an Archean metamorphic rock series, Archaean, upper Proterozoic Sinian, lower Paleozoic Cambrian, upper Paleozoic Carboniferous and Permian, Mesozoic Triassic, Cenozoic Neogene and Quaternary (Figure 1). A histogram of the stratum lithology in Pingdingshan coalfield is shown in Figure 2. The geothermal reservoirs in the Pingdingshan abnormity area are thick limestone composed of an upper Cambrian Gushan Formation and middle Zhangxia Formation. For buried stratum depths less than 420 m, karst caves of different sizes and shapes are densely distributed and karst is relatively developed. For buried depths greater than 420 m, the distributions of karst layers are variable, and there are no karst caves. Generally, the karst is not as developed as in the upper part, but at the intersection of structural development zones and faults, karst pores, karst gaps, and fractures are relatively developed.

The main structure in the area is a wide and gentle compound Likou syncline with many secondary folds located to the south and north of the Likou syncline axis. There also exists some large and medium-sized faults in Pingdingshan coalfield, such as Guodishan Fault, and most of them are blocking faults. The simple geological setting of the Pingdingshan coalfield is shown in Figure 1.
3 DATA AND METHODS

In order to ascertain the heat source of Pingdingshan geothermal abnormal area, a total of 45 temperature values were measured at the outlets of geothermal wells and drains in the Pingdingshan coalfield, and the locations, measured temperatures, and corresponding geothermal gradients are shown in Table 1.

In the Pingdingshan coalfield and neighboring Ruzhou coalfield, 11 limestone samples were collected from the Cambrian strata, and the values of the thermal conductivity were determined by Chinese Academy of Geological Sciences using thermal conductivity scanning (TCS), with a determining range of 0.20–25 W/(mK). The uncertainty of measured results was about 3%, and the results are shown in Table 2.

To obtain the radionuclide contents (uranium, thorium, and potassium-40) in the stratum of the Pingdingshan coalfield, 40 rock samples were collected from surface rock belts and geological drilling holes. At Beijing Research Institute of Uranium Geology (BRIUG), the contents of uranium and thorium were both measured by inductively coupled plasma mass spectrometry (ICP-MS; PerkinElmer Elan DCR-e), and the uncertainties were lower than 10% with a determining range of $0.05 \times 10^{-6}$ to $1,000 \times 10^{-6}$ mg/kg. The content of potassium-40 was determined by atomic absorption spectroscopy (z-2000) with an uncertainty lower than 2%. The densities of the rock samples were measured with a densitometer (AKD-120A) with a measurement precision and uncertainty of 0.0001 g/cm$^3$ and 2%, respectively, in the laboratory of Henan Polytechnic University. All the measured values are shown in Table 3.
4 RESULTS AND DISCUSSION

4.1 Characteristics of the Geothermal Gradient

The temperature of the constant-temperature zone in Pingdingshan is 17.2°C, and the depth of the constant temperature zone is about 25 m. According to the measured temperatures of the 45 groundwater samples of Cambrian limestone, the geothermal gradient of the Pingdingshan coalfield was calculated, and the calculated results for the different mines are shown in Table 1 and Figure 3. It can be seen that the geothermal gradient is 1.12–5.56°C/100 m, with an average of 3.32°C/100 m, inferring that the Pingdingshan coalfield is an area with an abnormally high ground temperature. It is interesting that the areas between the No. 13 mine and Shoushan No.1 mine show a high geothermal gradient.

The cap rock geothermal gradients are controlled by the buried depth of the Cambrian limestone reservoir. The results are shown in Table 4. In general, the geothermal gradient at buried depths less than 550 m is relatively low, with an average of 2.01°C/100 m. The geothermal gradient at buried depths of 600–850 m is relatively high, with an average of 3.96°C/100 m. The geothermal gradient at buried depths of more than 900 m is also low, with an average of 2.93°C/100 m.

### Table 1 | Geothermal gradient of cap rock in different mines.

| Locations                                              | Depth (m) | Well head temperature (°C) | Geothermal gradient (°C/100 m) |
|--------------------------------------------------------|-----------|----------------------------|-------------------------------|
| Special return air roadway of No. 2 mine               | 508       | 27                         | 2.03                          |
| 31,010 air roadway of No. 2 mine                       | 790       | 41                         | 3.11                          |
| Lower concentration roadway of No. 2 mine              | 816.7     | 40                         | 2.87                          |
| Downhill drilling of geng-1 belt in No. 2 mine         | 916       | 41.5                       | 2.73                          |
| Cambrian hydrological hole of No. 3 mine               | 690       | 42                         | 3.73                          |
| Geng-1 Drainage hole of No. 4 mine                     | 627       | 40                         | 3.79                          |
| Downhill 18# hole of No.4 mine                         | 902.5     | 43.5                       | 3.00                          |
| G18 + 3 m drainage hole of No. 4 mine                  | 1,017     | 43                         | 2.60                          |
| Drainage hole in F19 of No. 4 mine                     | 1,055     | 48                         | 2.99                          |
| Shimen water inrush point of No. 5 mine                | 616       | 40                         | 3.86                          |
| 320 water inrush point of No. 5 mine                   | 622       | 45                         | 4.66                          |
| Ji-2 water bunker of No. 5 mine                        | 975       | 46                         | 3.03                          |
| The downhill in the geng-2 area of No. 7 mine          | 365       | 21.5                       | 1.30                          |
| 13,141 cut hole of No. 8 mine                          | 465       | 36                         | 4.27                          |
| Ji-3 return air roadway of No. 8 mine                  | 513       | 37                         | 4.06                          |
| 11,032 drain hole of No. 8 mine                        | 585       | 40.7                       | 4.20                          |
| 13,011 drain hole of No. 8 mine                        | 598       | 38                         | 3.68                          |
| 13,022 drain hole of No. 8 mine                        | 590       | 40.7                       | 4.10                          |
| West roadway 1# hole of No. 8 mine                     | 680       | 49                         | 4.85                          |
| West roadway 2# hole of No. 8 mine                     | 760       | 49                         | 4.33                          |
| West roadway 3# hole of No. 8 mine                     | 843       | 52                         | 4.25                          |
| West roadway 4# hole of No. 8 mine                     | 850       | 49                         | 3.85                          |
| West roadway 5# hole of No. 8 mine                     | 860       | 49                         | 3.81                          |
| West roadway 6# hole of No. 8 mine                     | 875       | 49                         | 3.74                          |
| West roadway 7# hole of No. 8 mine                     | 925       | 49                         | 3.53                          |
| Ji-2 lower extension sump of No. 8 mine                | 1,179     | 47                         | 2.58                          |
| -618 hydrological hole of No. 9 mine                   | 893       | 37.5                       | 2.34                          |
| Ji-4 water bunker of No. 10 mine                       | 1,106.8   | 51                         | 3.12                          |
| Hydrological hole of No. 11 mine                       | 543       | 23                         | 1.12                          |
| Hydrological hole 2 of No. 12 mine                     | 1,091     | 54                         | 3.45                          |
| 5# drain hole of No. 12 mine                           | 1,119     | 52                         | 3.18                          |
| 7# drain hole of No. 12 mine                           | 1,114     | 54                         | 3.38                          |
| Hydrological hole of No. 13 mine                       | 580       | 45                         | 5.01                          |
| Inrush point 1# of No. 13 mine                         | 584       | 38                         | 3.72                          |
| Inrush point 2# of No. 13 mine                         | 660       | 27                         | 1.54                          |
| Inrush point 3# of No. 13 mine                         | 590       | 27                         | 1.73                          |
| Inrush point 4# of No. 13 mine                         | 627       | 42                         | 4.12                          |
| Inrush point 5# of No. 13 mine                         | 823       | 53                         | 4.49                          |
| Ji-3 bunker mouth of No. 13 mine                       | 822       | 49                         | 3.99                          |
| Hydrological hole of Xiangshan mine                    | 293       | 22                         | 1.79                          |
| Hydrological hole of Wuzhai mine                       | 438       | 26                         | 2.13                          |
| 2# hole in transportation roadway of Wuzhai mine        | 457.2     | 26                         | 2.03                          |
| -7,604 hole of Shoushan No.1 mine                     | 653       | 51                         | 5.56                          |
| -769 sump of Shoushan No.1 mine                       | 891.7     | 50                         | 3.78                          |
| Civil well near to Jiaxian                             | 421       | 25                         | 1.97                          |
| Mean Value                                             |           |                            | 3.32                          |
4.2 Calculating the Terrestrial Heat Flow

The Earth heat flux can be estimated by the Fourier formula:

\[ q = 10 \times \lambda \times \theta \]

where \( q \) is the geothermal flow (\( \text{mw/m}^2 \)), \( \lambda \) is the thermal conductivity of the surrounding rock (\( \text{w/(mk)} \)), and \( \theta \) is the geothermal gradient (\( ^\circ\text{C}/100\text{m} \)).

Based on the measured thermal conductivity of the limestone in the Cambrian system (Table 2), the average thermal conductivity of the oolitic dolomite of the Cambrian Zhangxia Formation in the Pingdingshan coalfield is 3.837 W/mK (Table 3), and that of the dolomitic limestone in the Gushan Formation is 2.420 W/mK; the former is significantly higher than the latter. The average thermal conductivity of the Cambrian limestone throughout the whole coalfield is 2.987 W/mK.

Because the areas near the southwest of the Guodishan Fault and northwest of the No. 13 mine are recharge areas of the Cambrian limestone, we may infer that the relatively low geothermal gradient is due to the influence of groundwater flow; so these areas were not used to calculate the ground heat flow. The calculations of the average geothermal gradient in different mines are shown in Table 5, where the heat flow value of each mine was obtained from Eq. 1. The mean values of the ground heat flow in the Pingdingshan coalfield is an abnormally high heat flow of 104.28 mW/m², which is much higher than the value of 65.88 mW/m² in the No. 1 well of the Chaochuan mine in the Ruzhou coalfield, 58.49 mW/m² in the Kaifeng Depression, and 62.63 mW/m² in the Tongxu Uplift.

4.3 Radiogenic Heat Generation in the Strata

4.3.1 The Computational Formula

The rock radiogenic heat generation rate refers to the heat generated in the decay process of radionuclides contained in rock per unit volume (or unit weight) per unit time. Uranium
(238\textsubscript{U}), thorium (232\textsubscript{Th}), and potassium (40\textsubscript{K}) in crustal rocks are three radionuclides that play an important role in the ground temperature because of their high abundances and high heat generation rates. Their half-lives (4.47 × 10\textsuperscript{9}\text{year}, 1.40 × 10\textsuperscript{10}\text{year}, and 1.26 × 10\textsuperscript{8}\text{year}, respectively) are equivalent to the Earth’s age (4.55 × 10\textsuperscript{9}\text{year}).

Based on the content of the radionuclides uranium, thorium, and potassium, and rock densities of the tested rock samples, the heat generation rate of radionuclides and the corresponding heat release can be calculated by using the Rybach formulas as:

\[ Q_A = 0.01 \times \rho \times (9.52 \times N_U + 2.56 \times N_{Th} + 3.48 \times N_K) \]  

\[ Q = 0.001 \times Q_A \times M \]

where \( Q_A \) is the heat generation rate of radionuclides in the rocks (\(\mu\text{W/m}\text{ }^3\)), \( Q \) is the heat generation rate of radionuclides in the rock formation (\(\mu\text{W/m}\text{ }^3\)), \( N_U \) is the \(\text{U} \) content in the rock (µg/g), \( N_{Th} \) is \(\text{Th} \) content in the rock (µg/g), \( N_K \) is the \(\text{K} \) content in the rock (%), \( \rho \) is the rock density (g/cm\textsuperscript{3}), \( Q \) is the radiogenic heat generation in the rock formation (mW/m\textsuperscript{2}), and \( M \) is the stratum depth (m).

### 4.3.2 Content of Radionuclides

According to the measured values of uranium, thorium, and potassium in the 40 rock samples collected from the Pingdingshan coalfield, their contents calculated as a function of time are shown in Figures 4–6, respectively. Obviously, the largest content of uranium, thorium, and potassium-40 in the Pingdingshan coalfield are, respectively, in the mudstone of the Lower Shihezi Formation, the bauxite mudstone of the Carboniferous Taiyuan Formation, and the bauxite mudstone of the Carboniferous Permian Taiyuan Formation. The lowest contents are found in the sandstone of the Liujiagou Formation.
the limestone of the carboniferous Taiyuan Formation, and the limestone of carboniferous Triassic Taiyuan Formation, respectively. Figures 4–6 show that the content of radionuclides in the magmatic rocks is at a relatively low level.

4.3.3 Radiogenic Heat Generation
The heat generation rate of radionuclides of different lithologies in the Pingdingshan coalfield (Figure 7) can be obtained using Eq. 2. The highest heat generation rate was found for the bauxite mudstone of the carboniferous Taiyuan Formation, followed by the mudstone of the Permian Lower Shihezi Formation, and the lowest heat generation rates were measured in 52 coal samples obtained from the Permian upper Shihezi Formation and 15 coal samples taken from the carboniferous Taiyuan Formation. The order of heat generation rate of the various lithology is mudstone > clay > thick limestone > sandstone > marl > andesite > thin limestone > coal seam; that is, the higher the argillaceous composition, the greater the heat generation rate.

The average radiogenic heat generation rate of the late Cambrian strata in the Pingdingshan coalfield is 1.05 μW/m³, the thickness of which is about 800 m. The average heat generation rate of radionuclides in the Cambrian strata is
1.12 μW/m³, whose thickness is about 300 m. The heat generation rate of radionuclides in the magmatic rock is 0.69 μW/m³, for a thickness of 500 m. The radiogenic heat generation rates in the late Cambrian strata, Cambrian strata, and magmatic rocks in the coalfield are 0.84, 0.34, and 0.35 mW/m², respectively, where the sum of the three is 1.53 mW/m².

Overall, the contribution rate of the radiogenic heat generation in the sedimentary rocks and magmatic rocks in the Pingdingshan coalfield is only 1.47% of the local large geothermal flow value of 104.28 mW/m², which is at a very low level. Therefore, we may infer that the abnormally high ground temperature in the Pingdingshan coalfield is not caused by the radiogenic heat generation in the sedimentary strata or magmatic rocks.

### 4.4 Heat Release of Magmatic Rocks

#### 4.4.1 Distribution of Magmatic Rocks

A magmatic rock intrusion was found during coal seam mining of the No. 13 coal mine in the Pingdingshan coalfield. The main lithology is neutral diorite porphyrite and basic diabase. The rock mass strikes northeast, with a length of 860 m and a maximum width of 60 m. A dyke intruded into the coal bearing strata, resulting in the existence of natural coke in the second group of coal seams.
Magmatic rocks are exposed in the Dongshan area of the Dazhuang mine, Shilong District, Pingdingshan City, with an area of about 2 km² and a maximum thickness of 337.9 m, showing in Figure 1. The lithology mainly includes neutral andesite and andesite porphyry. The magmatic rock mass in the coal-bearing strata is mainly shallow intrusive bedrock, dyke, and stock. From the perspective of the magma intrusion into different coal bearing sections and Neogene strata, the latest activity age should be the Neogene. Judging from the fact that the dyke was cut by the Yanshanian Liuzhuang Fault, the magmatism already formed in the Yanshanian Period.

In addition, a large area of magmatic rocks is exposed in the mountainous area of Lushan County, Pingdingshan City (Figure 1). The lithology is mainly late Yanshanian alkaline aegirine syenite, while acid granite porphyry and granite are also exposed locally. Shangtang, Zhongtang, Xiatang, and Jianchang hot springs are distributed along the Checu Fault that cuts through the magmatic rocks from top to bottom, and the temperatures of the springs are 71°C, 63°C, 64°C, and 35°C, respectively, indicating that there is also an abundant heat source in this zone.

4.4.2 Heat Generation of the Magmatic Rocks

The latest active age of the magmatic rocks exposed in the Dazhuang mine was during the Neogene, and its age is estimated to be about 35 Ma. In Mogou, southeast of Song County, Henan Province, which has the same age and lithology as Lushan’s magmatic rocks, Mao et al. (2010) extracted intrusive alkaline rock samples of late Yanshanian aegirine gabbro syenite and Indosinian syenite, and determined their ages to be 108 Ma and 194 Ma, respectively, using shrimp zircon. At the same site, Ren et al. (2001) and Lu et al. (2013) measured the ages of Indosinian syenites to be 208.5 ± 6.2 Ma and 245.5 ± 8.0 Ma, respectively (Fugren et al., 2001; Ren et al., 2013). In addition, Hou et al. (2007) measured the age of Late Mesozoic magmatic rocks from 40Ar and 39Ar isotopes in Dabie Mountain, finding 125–190 Ma (Hou et al., 2007). In conclusion, the activity of the intrusive neutral diorite porphyrite and basic diabase in the Pingdingshan coalfield began in the late Yanshanian Cretaceous and ended in the Himalayan Neogene, and has an age of 35–108 Ma.

The temperature of modern volcanic eruption lava measured directly on site shows that the magma composition is from acidic to basic, and the temperature of eruption lava was 735°C–1,225°C (Table 6) (Xu and Qiu, 2012). The intrusive magmatic rocks in the Pingdingshan coalfield are neutral diorite porphyrite and basic diabase. It is speculated that the lava temperature was more than 900°C.

At present, there have been a few literature studies on the cooling rate of neutral diorite porphyrite and basic diabase. Therefore, this paper compares the cooling rates of magmatic rocks in the Pingdingshan coalfield with the cooling rates of magmatic rocks with the same or similar lithology. Hourgian et al. (2004) found that the cooling rate of neutral syenite is 20°C/Ma in Kamchatka, Russia. For the basic cave granite in the late Yanshanian period in Zhangzhou, Fujian Province, studies by Shen et al. (2000) have shown, according to the isotope dating results and the closed temperature data in the different isotope systems, that igneous rocks always have changing cooling rates during the various geologic periods, such as, 103.0–97.1 Ma, 97.1–63.1 Ma, 63.1–57.5 Ma, 57.5–54.7 Ma corresponding to 16.9°C/Ma, 7.3°C/Ma, 8.9°C/Ma, and 53.6°C/Ma, respectively, with an average of 11.3°C/Ma. Therefore, it is estimated that the cooling rate of neutral diorite porphyrite and basic diabase in the Pingdingshan coalfield ranges from 11.3 to 20°C/Ma (Shen et al., 2000).

The latest intrusion time of the magmatic rock mass in the Pingdingshan coalfield is 35 Ma; with a lava temperature of 900°C. Therefore, assuming the cooling rate was 20°C/Ma, it is estimated that the residual temperature of the magmatic rock mass is more than 200°C. The higher residual temperature of the magmatic rock may cause its heat to be continuously transmitted upward through the rock strata or upward through faults, which provided a foundation for the high geothermal flow in the Pingdingshan coalfield. The conceptual model of abnormally high ground temperature caused by magmatic rocks is shown in Figure 8. Of course, the distribution of the ground temperature in the Pingdingshan coalfield seems to be uneven, which may be mainly controlled by the distributions of the different geological structures, intrusive rock mass distribution, Cambrian limestone groundwater migration, rock stratum structure, overburden performance, and other factors; however, further investigation of the effects of these structures and formations on the ground temperature distribution in the Pingdingshan coalfield is beyond the scope of the current study.

4.5 Discussion

In this study, we measured the outlet temperature values of 45 geothermal wells and water drains, and the thermal conductivity of 11 rock samples in the Cambrian layer. The measuring and sampling locations in the Cambrian layers with different burial depths are well-distributed, so the calculated geothermal gradient and

### Table 6 | Temperature of the ejected lava in the different volcanic areas (°C).

| Types | Compositions | T     | Locations | Source           |
|-------|--------------|-------|-----------|------------------|
| Acidic | Rhyolite (lava, fused tuff, pumice flow) | 735–780 | Taupo, New Zealand | Ewart et al. (1971) |
|       | Pyroxene rhyolite (pumice flow) | 860–890 | Taupo, New Zealand | Ewart et al. (1971) |
|       | Rhyolitic dacite pumice | 880 | New Britain in the Western Pacific | Herming and Carmichael (1973) |
|       | Rhyolitic dacite Obsidian | 900–925 | Iceland | Carmichael (1967) |
| Neutral | Dacite lava and pumice | 925 | New Britain in the Western Pacific | Herming and Carmichael (1973) |
|        | Andesite pumice | 940–990 | New Britain in the Western Pacific | Herming and Carmichael (1973) |
| Basic | Leucite basalt | 1,095 | Muragira, Congo | Verhoogen (1948) |
|       | Basaltic andesite | 1,020–1,110 | Parkinton, Mexico | Zies (1948) |
|       | Tholeiitic basalt | 1,150–1,225 | Kilauea, Hawaii | Wright et al. (1968) |
Geothermal heat flow values can represent the true conditions in the abnormal Pingdingshan geothermal area. Based on the contents of the main radionuclides, the amounts of radiogenic heat production and their contributions for terrestrial heat flow were calculated quantificationally, and radiogenic heat production only has a 1.47% proportion of the whole terrestrial heat flow in the Pingdingshan area, which allows us to conclude that the influence of radiogenic heat generation on the abnormally high geothermal temperature in the Pingdingshan coal field can be excluded. In view of the intrusion of magmatic rocks in the 13 mines of the Pingdingshan coalfield and the neighboring area (Dazhuang Mine), it is can be inferred that the abnormally high ground temperature may likely be caused by the continuous heat release of magmatic rocks, and the conclusion that the residual temperature of the magmatic rock body is more than 200°C seems to be credible, agreeing with relevant research at similar conditions.

In the future, gravity prospecting and 3D seismic method can be further used to explore the characteristics of deep rock structure and fault distribution. A geothermal, geologic, hydrogeologic, and mathematical model will be constructed to ascertain the heat production and locate the high temperature target areas and layers in Pingdingshan. The geothermal wells (boreholes) will be constructed in the remained spaces after excavating coal, and the mathematical models can also be calibrated to predict the reservoir temperatures at different locations and depths accurately, providing technical support for the protecting the reservoirs in Pingdingshan coalfield and exploiting the deep geothermal energy.

5 CONCLUSION

Based on the discussions above, we can obtain the following conclusions:

1) The geothermal gradients of the Pingdingshan coalfield range from 1.12 to 5.56°C/100 m, with an average value of 3.32°C/100 m. The calculated values of heat flow in this coalfield is 62.13–139.49 mW/m², with an average value of 104.28 mW/m². Therefore, we can conclude that the Pingdingshan coalfield belongs to an abnormal geothermal area.

2) The radiogenic heat generation rates of the late Cambrian strata, Cambrian strata, and magmatic rocks in the coalfield are 0.84 mW/m², 0.34 mW/m², and 0.35 mW/m², respectively, with a sum of 1.53 mW/m². The contribution rate of the radiogenic heat generation to the local large geothermal flow value is only 1.47%, which is at a very low level.

3) Neutral diorite porphyrite and a basic diabase intrusion were found during mining in the No. 13 coal mine, while neutral andesite and andesite porphyrite were exposed in the Dazhuang coal mine near the Pingdingshan coalfield. The heat release of magmatic rock may be the primary heat source causing the abnormally high ground temperature in Pingdingshan.

4) In the Pingdingshan area, the intrusion time of the magmatic rock mass is about 35 Ma and the lava temperature is about 900°C. Assuming the cooling rate is 20°C/Ma, we can obtain the residual temperature of the magmatic rock mass, which is more than 200°C. The relatively high residual temperature of the magmatic rock may be the main heat source of the abnormally high ground temperature in this coalfield.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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