

Article

3-D Inversion of Gravity Data of the Central and Eastern Gonghe Basin for Geothermal Exploration

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Abstract: The Gonghe Basin is one of the most important regions for the exploration and development of hot dry rock geothermal resources in China. However, there is still some controversy about the main heat source of hot dry rock geothermal resources in the Gonghe Basin. Combined with previous research results including three-dimensional magnetotelluric imaging and linear inversion of Rayleigh wave group and phase velocity result, we obtained a high-resolution underground spatial density distribution model of the Gonghe Basin based on satellite gravity data by using 3-D gravity focusing inversion method. According to the results, there are widely distributed low density anomalies relative to surrounding rock in the middle crust of the study area. The low-density layer is speculated to be a low-velocity, high-conductivity partial melting layer in the crust of the Gonghe Basin. The inversion result confirms for the first time the existence of a partial melt layer from the gravity point of view, and this high temperature melt layer may be the main heat source of the hot dry rock geothermal resources in the Gonghe Basin. It can provide a new basis for further research on the genesis of the hot dry rock geothermal system in the Gonghe Basin.

Keywords: Gonghe Basin; hot dry rock; 3-D inversion; satellite gravity data



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1. Introduction

With the continuous growth of population and economic scale in the world, human consumption of resources is at a high level. With the depletion of fossil fuels such as oil and coal, the climatic issues have become increasingly prominent, so it is urgent to improve the energy structure and make full use of clean and renewable energy [1]. Geothermal resources are one of the most important clean energy sources and play an important role in replacing traditional oil and gas resources [2]. As an important geothermal resource, hot dry rock geothermal resources are usually buried at a depth of about 3 km underground, and the reservoir temperature is over 150 °C. With huge potential for power generation, the enhanced geothermal system (EGS) developed on the basis of hot dry rock utilizes the hot dry rock to generate electricity through hydrofracture. It has extremely high application value and it is one of the important ways for the effective development and utilization of hot dry rock geothermal resources in the future to resolve the energy crisis [3,4].

Gravity anomalies mainly reflect the density difference of underground rocks. The lithology, mineral composition, burial depth, porosity, etc. are the factors that determine the density of rocks. The 3-D gravity inversion method can provide quantitative information such as the geometric position, shape, and physical size of anomalous bodies [5]. Gravity exploration has broad application prospects in the field of geothermal exploration. It can explore and find hot dry rock resources by studying the spatial distribution of magmatic rock intrusions, searching for large fracture structures, etc. [6]. In the Cooper Basin of Australia in 2003, people successfully discovered geothermal resources of dry hot rock with a temperature of up to 270 °C at a depth of 4500 m below the basin by using 3-D gravity

inversion methods [7]. Helga Wall et al. (2019) used gravity gradient data to calculate the likely depth of the granite intrusion that caused the geothermal heat in the Franco Basin in northeastern Bavaria [8]. Justus Maithya et al. (2020) used gravity exploration to delineate the geological structure that controls the geothermal system in the Eburru area and estimate the extent of geothermal reservoir [9]. In 2021, Jiang used satellite gravity and magnetic data of Changbai Mountain region for three-dimensional inversion, obtaining three-dimensional underground density and magnetic structure, which provides theoretical support for the exploitation of geothermal resources in the region [10].

Satellite gravity observation technology has the characteristics of high coverage and high precision, which greatly compensates for the lack of ground gravity measurement. Therefore, the use of satellite gravity data combined with 3-D inversion technology of potential field has certain advantages in solving actual geological problems. The Gonghe Basin is located in the northeastern part of the Tibet Plateau. It is an important hot dry rock exploration and development target area in China. In 2017, the temperature of the hot dry rock geothermal resources drilled at 3705 m below the well GR1 was as high as 236 °C [11]. It is the first discovered target area for hot dry rock geothermal resources with a temperature above 200 °C in China, which proves that the hot dry rock geothermal resources in the Gonghe Basin have further exploration potential [12]. However, there are still some controversies about the genetic mechanism and main heat source of the hot dry rock geothermal system in the Gonghe Basin. Regarding the above issue, scholars have formed three main views as follows. (1) The heat source mainly comes from the deep mantle and is recharged by the large fault structure as a heat channel [13]. (2) The regional thermal anomalies caused by radioactive heat generation in granite [14]. (3) The heat source comes from the high temperature part of the deep crustal melt layer and is conducted to the shallow part of the basin through the flower-like fractures developed in the basin [15,16]. Reference [13] only considered the influence of radioactive heat generation and did not consider the contribution of possible heat sources from the deep and reference [14] only considered the heat transfer effect of deep and large faults but did not consider the heat transfer effect of active faults. Both mantle and crustal heat sources are considered in reference [15] and it is the mainstream explanation for the genetic mechanism of hot dry rock in the Gonghe Basin.

The underground structure and mechanism of geothermal systems were delineated in the previous study via MT and Rayleigh wave analysis, however, the density structure of the Gonghe Basin is not yet clear. In this paper, we first briefly introduce the geological background of the Gonghe Basin and 3-D inversion method of gravity data. Then, based on the high-precision satellite gravity data, a 3-D inversion study was carried out on the Gonghe Basin, and a high-resolution underground density distribution model was obtained. Combining the results of 3-D inversion of gravity and previous research results, we provide new evidence for the heat source of the hot dry rock geothermal system in the Gonghe Basin from the perspective of gravity. The research results of this paper will help scholars to further understand the genesis of the genetic mechanism of the hot dry rock geothermal system in the Gonghe Basin.

2. Geological Setting

The Mediterranean–Himalaya tectonic belt across the Eurasian continent is one of the most famous geothermal abnormal zones in the world [17]. As the eastern part of the Tethyan belt, the Himalaya–Tibetan Plateau is one of the most concentrated regions for geothermal activities with great geothermal anomalies and higher heat flow values of 90–300 mW/m² [18]. The Gonghe Basin is located in the northeast margin of the Qinghai–Tibet Plateau, it is a Cenozoic intracontinental basin controlled by the common sinistral strike-slip faults of Kunlun fault, Altun fault and South Qilian fault [19]. The Gonghe Basin, which is located in the northeast of Tibet Plateau in Qinghai Province, has characteristics of strong tectonic activity, relatively complex stress state and uneven crustal structure and has become the third largest basin in Qinghai Province and the Gonghe Basin is about 280 km in length, 95 km in width, 2.1×10^4 km² in area and distributed in a diamond shape [20].

The Gonghe Basin is surrounded by several faults (Figure 1). To the north of the basin, Wahong Mountain-Hot Spring Fault (WHF) is in NW 20° direction. To the north of the basin, south slope fault zone of Qinghai South Mountain (QSF). Transtensional Waligong Mountain tectonomagmatic belt (WMB) is in NNW direction to the east of the basin [21,22].

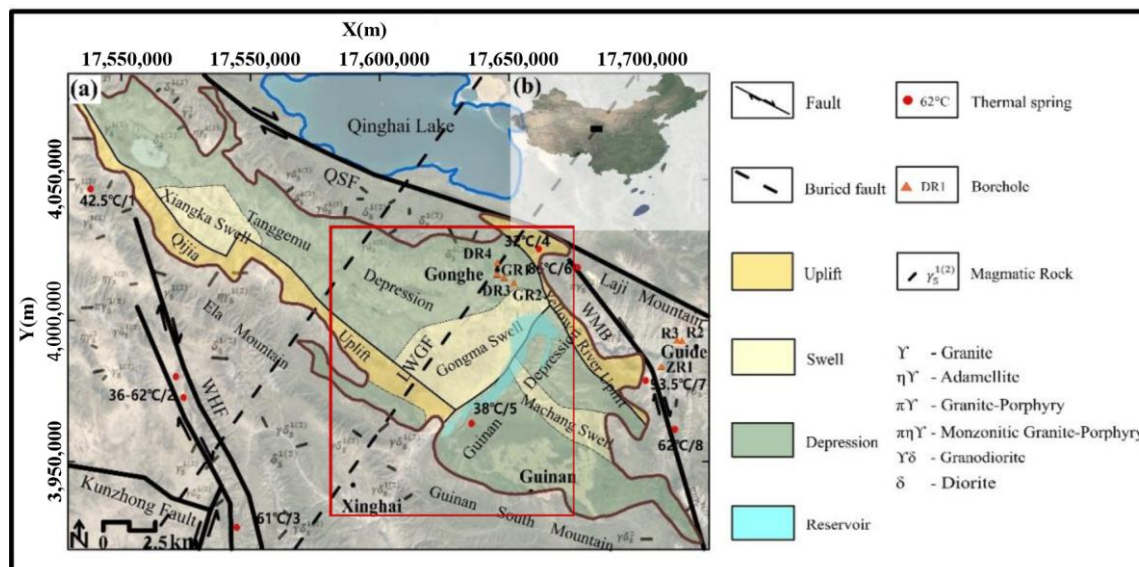


Figure 1. (a) Distribution of faults, wells and hot springs in the Gonghe Basin and surrounding areas, the red boxes represent the study and inversion region (revised from Wang et al., 2021 [6]); (b) location of the research area.

The upper base of the Gonghe Basin is mainly composed of the Early-Middle Triassic Longwuhe Formation, Middle Triassic Gulangdi Formation and Middle-Late Triassic granites. The middle and lower basement is presumed to be Paleozoic-Proterozoic metamorphic rock series [23]. The sediments above the basement are mainly Neogene and Quaternary, and the surface layer is Quaternary. As indicated in regional geological results, there have been no magmatic activities around the Gonghe Basin since the Cenozoic era [24]. The igneous and metamorphic rock sequences of the East Kunlun and West Qinling Orogen developed around the basin are composed of the middle and late Triassic metamorphic sedimentary rocks and Indosinian granites and granodiorites [25]. Figure 2a shows the stratum column of Gonghe area. The Cenozoic deposits in the basin generally show a trend of thin in the east and thick in the west. The thickness of Cenozoic deposits is generally about 500 m to 1500 m in the eastern part of Guide area, about 1500 m in the central and eastern parts of Qiabuqia area and can reach 6000 m in the west. The thickness of Cenozoic strata in Gonghe area is about 2500 m, among which the thickness of overlying Quaternary sedimentary strata is about 1500 m. The Gonghe Basin base is Indosinian granite. The GR1 hot dry rock exploration borehole in the Gonghe Basin has a final borehole depth of 3705 m and a hole bottom temperature of 236 °C. The core catalog of the GR1 borehole (Figure 2b) shows that the upper part of 0–500 m is a relatively thin mid-late Pleistocene fluvial sand-gravel pebble (Q2-3al) layer, with coarse grains and downward thinning (Figure 3). The main body in the middle and lower part is the Gonghe formation of the Early-Middle Pleistocene. The depth of 500–1350 m is the Pliocene Linxia Formation and Miocene Xianshuihe formation, the lithology is gray-black, blue-gray and blue-gray medium-thick mudstone interbedded with brown-red thin mudstone and gray-yellow, blue-gray and variegated medium-thick siltstone. The integrity of the mudstone is good, and the sandstone particles are finer. The 1350 m shallow borehole is the Cenozoic sedimentary caprock, 1350–3705 m is the middle and late Triassic granite, and the main lithology is granodiorite, granite, monzogranite and porphyry monzonite Granite, etc., constitute the thermal storage of hot dry rock geothermal resources [26].

erathem	system	stratigraphic	lithologic symbol	thickness /m	lithologic characteristics
Cenozoic era	Quaternary	Middle Pleistocene (Q_{3-4})		<300	Alluvial sand and gravel, alluvial sand and gravel; aeolian loess and aeolian sand, etc., moraine-ice water accumulation mud and gravel, etc.
		Gonghe group (Q_{1-2}^{al-lg})		<1500	Conglomerate, glutenite, sandstone, mudstone and conglomerate lens
	Neogene	Linxia group ($N_{2,l}$)		>185	Natural yellow, orange mudstone mixed with sandstone and conglomerate, the bottom is often conglomerate
		Xianshihe group ($N_{1,x}$)		>468	Purple, orange, variegated sandstone, mudstone, conglomerate, glutenite and gravel-bearing coarse sandstone
	Paleogene	Xining group ($EN_{1,x}$)		>100	Brick red claystone, siltstone and sandstone with fine sandstone
Mesozoic	Triassic	Gulangdi group ($T_{2,g}$)		>5978	Sandstone, sandstone, limestone with a small amount of siltstone, mudstone, rhyolite, etc.
		Longwuhe group ($T_{1-2,l}$)		>1672	Sand slate, sandstone sandwiched glutenite, bottom conglomerate
(a) Indosinian intrusive rocks					granite, granodiorite

stratigraphic age	the depth of the bottom layer/m	thickness/m	stratigraphic structure	lithologic characteristics
Gonghe group (Q_{1-2}^{al-lg})	505	505		Subsand soil, pebble gravel, sand pebble gravel; sub-sand soil, silt sand, medium and coarse sand interbed
Linxia group ($N_{2,l}$) and Xianshihe group ($N_{1,x}$)	1350	840		Brick red sandy mudstone, interbedded mudstone and sandstone, local glutenite
(b) Indosinian intrusive rocks	1450	100		Light-flesh red medium-grained monzogranite, gray medium-coarse-grained porphyritic monzogranite
	1650	200		Gray-white medium-coarse-grained biotite granite
	1750	100		Off-white medium-coarse-grained
	2300	550		Gray-white medium-coarse-grained biotite granite
	2600	300		Gray-white medium-coarse-grained porphyritic monzogranite
	2800	200		Blue-gray medium-coarse-grained altered granite
	2950	150		
	3100	150		Medium-coarse-grained altered biotite granite, medium-coarse-grained altered monzonite granite, medium-coarse-grained altered biotite granite, medium-coarse-grained porphyritic monzogranite
	3200	100		
	3326	126		
	3400	74		
	3705	305		Medium-coarse-grained porphyritic biotite monzogranite

Figure 2. (a) Strata in Gonghe area, (b) Strata of GR1.

There are many hot springs exposed in the Gonghe Basin with a relatively obvious concentrated distribution along the fault zone [27]. In addition to hydrothermal geothermal resources, the Gonghe Basin is also one of the most powerful areas for exploration and development of hot dry rock geothermal resources in China. The research shows that the average geothermal gradient in the Gonghe Basin is twice as big as the normal geothermal gradient [28]. According to the report of China Geological Survey and Department of Natural Resources of Qinghai Province in August 2017, the bottom hole temperature of five wells with depths between 3000 m and 3705 m in basin is between 180 °C and 236 °C [29].

3. 3-D Inversion of Gravity Data

3.1. Details of the Gravity Data

Satellite gravity observation technology has the characteristics of high coverage and high precision, which greatly compensates for the lack of ground gravity measurement. Topographic data and satellite gravity data can be obtained from open-source data access websites such as the International Center for Global Earth Models, the European Space Agency, and the Geoscience Research Center in Potsdam, Germany. Three professional gravity satellites CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity Field and Steady-state Ocean Circulation Explorer) are all polar low-orbit satellites with high observation accuracy, and their observation range basically covers the world, and play an important role in the detection of the earth's gravity field (the website for obtaining the data in this paper: <http://icgem.gfz-potsdam.de/home> (accessed on 25 May 2022)). Based on the massive satellite gravity data and in situ gravity data collected, major research institutions have established numerous earth gravity field models. Among them, the EIGEN-6C4 gravity field model was released in 2014, the accuracy of gravity anomaly is up to 2.73 mGal, it has a high accuracy in each ultrahigh order gravity field model. Therefore, in this article we use the Bouguer gravity data provided by the EIGEN-6C4 gravity field model with a resolution of 1 arc minute. The Bouguer gravity anomaly is defined by the classical gravity anomaly minus the attraction of the Bouguer plate [30]. Here it will be calculated by the spherical approximation of the classical gravity anomaly minus $2\pi G\rho H$. The topographic heights H are calculated from the spherical harmonic model of topography (ETOPO1) used up to the same maximum degree as the gravity field model, the Bouguer gravity anomaly is calculated by the following formula:

$$\Delta g_B = \Delta g_{cl} - 2\pi G\rho H \quad (1)$$

where Δg_B stands for the bouguer gravity anomaly and Δg_{cl} stands for the classical gravity anomaly.

The range of data obtained by satellite gravity is 99°36' E–100°48' E longitude and 35°36' N–36°36' N latitude [31]. In order to facilitate the data processing, the Gauss-Kruger projection method is used to transform the satellite gravity data. Then the data after the coordinate conversion is gridded by Kriging interpolation, and the grid spacing is set to 1.5 km [32]. The gridded data is used as the research object and the interpolated satellite gravity Bouguer anomaly map in the research area is shown in Figure 3.

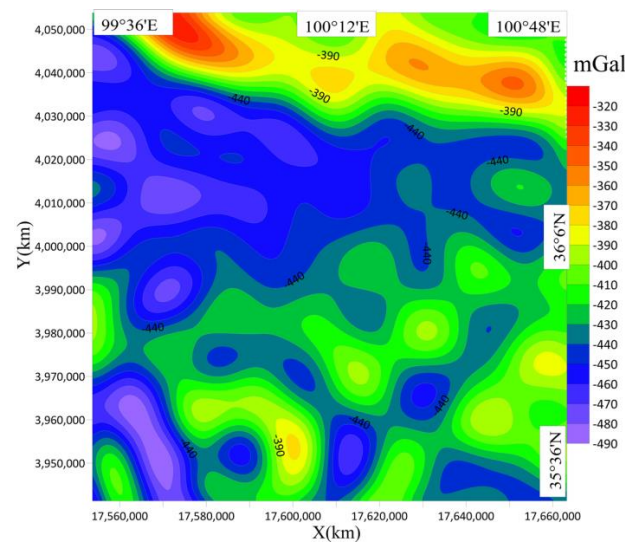


Figure 3. Satellite Bouguer gravity anomaly map in the study area.

3.2. 3-D Gravity Focusing Inversion Method

The 3-D gravity inversion is to calculate the density or geometric parameters of the underground structure or anomaly based on the anomalous data on the observation surface. For linear inversion problems, the underground space needs to be discretized.

A typical method is to divide the earth region of interest into cells with constant density and fixed interfaces. With N observations and M rectangular prisms, the discrete forward modeling operator for the potential field problem can be written in matrix form

$$d = Am \quad (2)$$

where d represents ground observation data with length N , m is the vector of the model parameters with length M . In 3-D gravity inversion, m represents the density of underground sources. A is the sensitivity matrix, which is a rectangular matrix of size $N \times M$. Usually, A is not a square matrix and the measured data is often much less than the parameters to be solved. In order to solve the serious multiplicity of solution and non-uniqueness problems in the solution process, the Tikhonov regularization method is usually used [33]. This problem is solved by minimizing the objective function. The objective function is composed of data fitting function, model constraints and regularization parameters, and its form is as follows:

$$\phi = \phi_d + \alpha \phi_m \quad (3)$$

where ϕ is the objective function to be solved, ϕ_d is the data fitting function, ϕ_m is the model fitting term and α is regularization parameters, the calculation formula of the objective function is as follows:

$$\phi = \phi_d + \alpha \phi_m = \|Am - d\|_2^2 + \alpha \|m\|_2^2 \quad (4)$$

In order to suppress the versatility and instability of the inversion as much as possible, it is necessary to add a model fitting term to the objective function. Model weighting matrix (W_m) and data weighting matrix (W_d) need to be introduced, the data weighting matrix has less influence on the inversion result, while the model weighting matrix has a greater influence on the inversion result. Since the sensitivity matrix decays with depth, gravity data faces a serious skin effect problem. As a result, the inversion results will be concentrated on the surface. The depth weighting function proposed by Li and Oldenburg [34,35] solves the serious skin effect problem of inversion, and its form is as follows

$$w(z) = \frac{1}{(z+z_0)^{\beta/2}} \quad (5)$$

where z is the depth of the center point of the underground space geological body, z_0 depends on the shape of the underground division unit and the observation altitude. In the inversion process, β takes a value of 2–3. Due to the low vertical resolution of the potential field, the inversion results often have serious tailing at the bottom. The improved depth weighting function proposed by Gao et al. [36] was utilized to ensure a higher vertical resolution for the inversion results. The form of the depth weighting function is as follows:

$$w(z) = \frac{1}{(z+z_0)^{\beta/2}} \frac{1}{(H-z-z_0)^{\beta/2}} \quad (6)$$

where H is the total vertical range of the inversion space.

Different norms can be used for model constraints. The model constraint term using the L_2 norm constraint can produce a smooth solution, its suitable for the situations where the geological boundary is not obvious. However, the objective function using the focus constraint function can often better indicate the boundary of the ore body. In this paper we adopt the idea based on the minimum anomalous volume introduced by Last et al. (1983) [37], and introduces the minimum support function into the objective function expression. Its form is as follows

$$W_e(m) = \frac{m^2}{m^2 + e^2} \quad (7)$$

where the parameter e represents a small value which approaches 0.

In summary, the objective function form used in the inversion is as follows

$$\phi = \phi_d + \phi_m = \|W_d(d - Am)\|_2^2 + \alpha \|W_m W_e m\|_2^2 \quad (8)$$

The model constraint term W_m adopts the improved depth weighting function form, and uses the conjugate gradient algorithm to solve the above objective function. Various methods, such as quasi-Newton method, Gauss-Newton method (GN method) and conjugate gradient method (CG method), have been proposed to solve inverse problems. The CG method is widely-used in geophysics and is adopted in this paper because it has advantages of low dependence on the initial model, less memory, rapid convergence and can avoid matrix decomposition and matrix inversion. The calculation process is that the partial derivative form is set to g_k . The first iteration direction p_k of the conjugate gradient algorithm is the negative direction of g_k , and the direction of each iteration thereafter is determined by the previous iteration direction and the new derivative function. The factor k represents the number of iterations. The basic flow of the algorithm is as follows (Algorithm 1).

Algorithm 1: CG method

```

1: Set  $k = 0$ ;  $m_0 = 0$ ; Set  $N_{max}$  to the maximum number of iterations.
2: while  $g_k \neq 0$ ;
3:    $k = k + 1$ 
4:   if  $k = 1$ 
5:      $p_1 = -g_1$ 
6:   else
7:      $\beta_k = \frac{g_{k-1}^T g_{k-1}}{g_{k-2}^T g_{k-2}}$ 
8:      $p_k = -g_{k-1} + \beta_k p_{k-1}$ 
9:   end
10:   $q_k = A p_k$ 
11:   $\alpha_k = \frac{g_{k-1}^T g_{k-1}}{q_k^T q_k}$ 
12:   $m_k = m_{k-1} + \alpha_k p_k$ 
13: end
14:   $m = m_k$ 

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3.3. 3-D Gravity Inversion Results

The gravity anomaly value is a comprehensive superposition result of anomalies generated by different depths and different density contrast sources underground. It is generally composed of two parts, the residual field and the regional field. We separated the regional fields by upward extension and obtained the residual field data of the study area as shown in Figure 4.

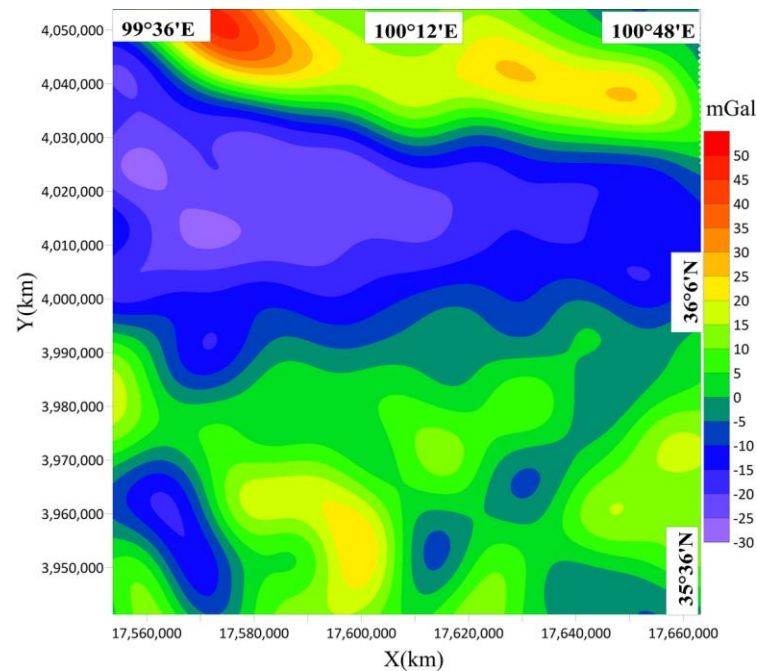


Figure 4. The residual Bouguer anomaly map.

The residual Bouguer gravity anomaly shows that there is a wide range of low gravity anomalies in the middle of the study area, which may be related to the low-density rock masses existing underground. The regional Bouguer anomaly in the central region is significantly lower than that in other regions. The 3-D physical property inversion for the residual gravity anomaly is performed in a Cartesian coordinate system, and the entire spatial range of the inversion is $111 \text{ km} \times 114 \text{ km} \times 40 \text{ km}$. The underground grid is divided into $74 \times 76 \times 40$ points, and the grid unit size is $1.5 \text{ km} \times 1.5 \text{ km} \times 1 \text{ km}$. Selecting appropriate regularization coefficients, initial model background density set to 0, after 20 iterations of inversion the RMS value drops to 0.002 mGal or less (Figure 5), a more credible underground density distribution model is obtained.

Figure 6 shows the horizontal slice of the three-dimensional gravity inversion results in the study area at 2 km, 5 km, 8 km, 10 km, 15 km, 20 km, 25 km and 30 km depth slices, respectively. There are widely distributed low-density anomaly areas below 2 km underground of the study area, which has a good corresponding relationship with Quaternary and Neogene sediments [38]. Obvious low-density banded anomalies appear on 5 km and 8 km sections. Combined with geological data, these banded low-density anomalies are interpreted as three proven concealed faults in the area, which are recorded as F1, F2 and F3, respectively. With the increase of horizontal slice depth, there is an obvious low density anomaly area in the study area within 15–25 km. The low-density anomaly area is consistent with the distribution position and strike of the three known faults [39]. According to the horizontal slice of the inversion results, the buried depth of the low-density abnormal body may be between 15 km and 30 km. Through the known hidden faults, there is a certain connection relationship between the low-density body and the surface.

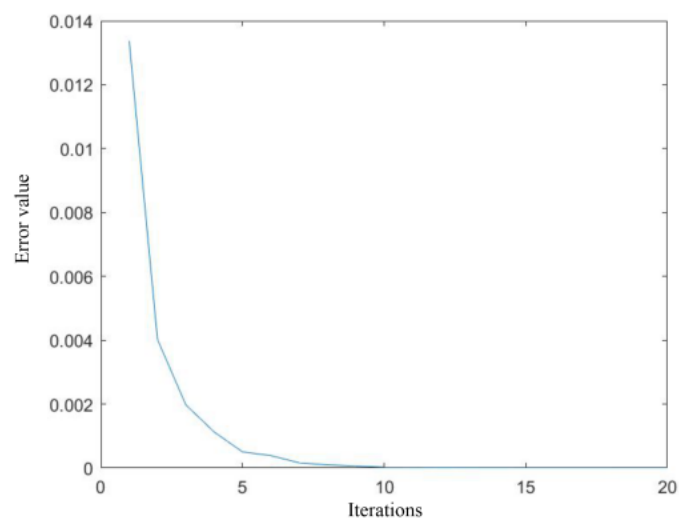


Figure 5. Iterative error curve of inversion.

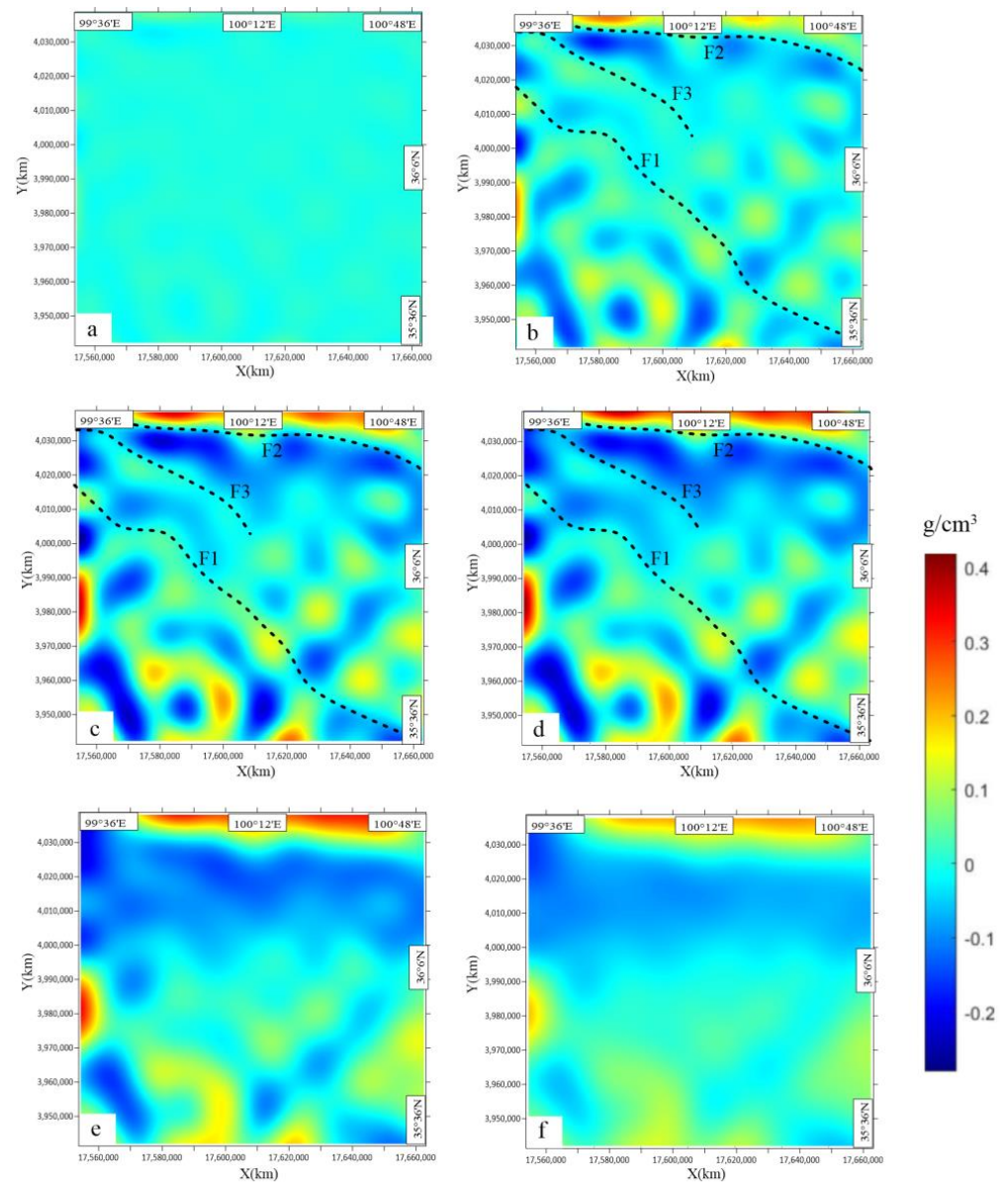


Figure 6. Cont.

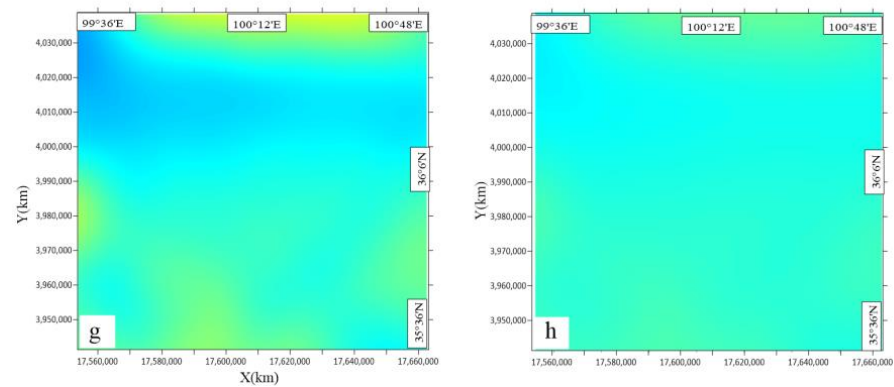


Figure 6. Schematic diagram of different depth horizontal slices of 3-D gravity inversion results (a) 2 km; (b) 5 km; (c) 8 km; (d) 10 km; (e) 15 km; (f) 20 km; (g) 25 km; (h) 30 km.

We have selected four sections along the north-south direction (Figure 7b–e), which clearly display the widespread low-density anomalies that exist underground. The depth range is about 15–30 km, and the trend of hidden faults in the inversion results can be clearly seen above the low-density body. These faults can serve as channels for underground heat sources (probably the partially molten layer) of hot dry rock geothermal resources in the Gonghe Basin.

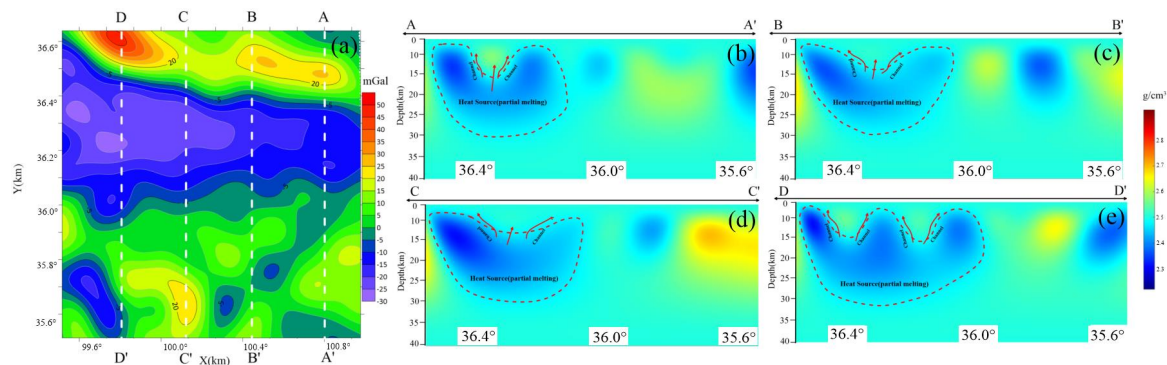


Figure 7. Cross sections of 3-D density model (b–e) along profiles indicated on (a).

4. Discussion

Combined with the above inversion results and analysis, this section will further discuss the hot dry rock geothermal resources, especially the heat sources of hot dry rock geothermal systems in the Gonghe Basin.

The Gonghe Basin is a high-temperature geothermal anomaly in China. Since the Cenozoic era there has been no magmatic activity in the Gonghe Basin and the surrounding orogenic belt [40]. The heat generation rate of rocks is $0.96\sim 4.11 \mu\text{W}/\text{m}^3$, which is slightly higher than that of the global Mesozoic and Cenozoic granites [41]. The average radioactive heat generation rate is $3.09 \mu\text{W}/\text{m}^3$ [42], but the radioactive heat generation rate is much lower than the $7\sim 10 \mu\text{W}/\text{m}^3$ of the granite in the Cooper Basin in Australia [43]. Therefore, the residual heat of the granite magma and the heat generated by the decay of radioactive elements are probably not the heat source of the hot dry rock in the Gonghe Basin. The partial melting layer in the middle-lower crust is the partial melting layer caused by the geothermal temperature close to or reaching the solidus of the rock within a certain depth of the crust. The low-velocity layer in the crust formed by the partial melting is called the partial melting low-velocity layer in the crust [44]. Since the 1980s, researchers have discovered that low-velocity and high-conduction zones generally develop in the crust of the Tibet Plateau and its surrounding areas [45]. Various studies have shown that the formation of the low-velocity and high-conductivity area in the crust is probably related to the partial melting of the granite-like material in the crust. The resistivity of rock is related

to lithology, rock and ore substance composition, temperature and pressure. When the rock is partially molten, its resistivity will decrease significantly. Generally, the resistivity range of 1–10 $\Omega\cdot\text{m}$ is used as the basis for delineating the partially molten layer in the crust [46,47]. When the rock is partially melted, its volume changes and the density decreases, which shows low gravity anomaly [48]. From the satellite Bouguer gravity map, it can be clearly seen that there are widely developed low gravity anomalies in the middle of the study area (Figure 4). Excluding the influence of other geological factors, the low gravity anomaly in this area may be related to the low-density sources, and it is likely to be a low-density high-temperature melt distributed within a certain range [49]. There are still some controversies about the formation of the partially molten layer in the crust. It is generally believed that the frictional heat generated by various strong underground tectonic movements is likely to be the main cause of the partially molten mass in the crust [50–52].

The 3-D gravity inversion results show that there are obvious low-density anomalies in the depth range of 15–30 km under the study area. The result can support the existence of partially molten layer in the crust of the Gonghe Basin. Due to the low depth resolution of gravity exploration methods and missing information of the anomalies of the shallow part in satellite gravity data, the inversion result does not clearly show the high-temperature rock mass existing above the low-density body. The Gonghe Basin was formed in the Mesozoic era and its near surface covered by quaternary sedimentary lake-related strata. The overlying Cenozoic sedimentary strata ranges from a few hundred meters to 2 km, which can serve as the caprock for the geothermal system in the Gonghe Basin. In addition, from the horizontal slices (Figure 5) of the inversion results, it can be seen that there are many hidden faults such as F1, F2, and F3. Since the Neogene, the Gonghe Basin has experienced strong tectonic activities, and the basement has been broken and uplifted and formed numerous compression faults [53]. The existence of these faults can serve as a thermal channel for the low-density molten mass in the crust to transport heat to the shallow caprock mass. The heat passes through the thermal channel and is transported to the hot dry rock, and the low thermal conductivity deposits covered by the caprock can effectively prevent the heat loss from the reservoir. According to the accumulation model proposed by Tang et al. (2020) [54], the middle-late Triassic granite with high thermal conductivity and low water content is also an important heat conductor for the partially molten layer in the crust to transport heat to the reservoir.

According to the magnetotelluric imaging results of Gao et al. (2018) (Figure 8) [55], there is an obvious low resistivity anomaly in the Gonghe Basin 15–35 km underground labeled as A, which may be caused by the partial melting layer of the crust. Heat is supplied to hot dry rock reservoirs through some hidden faults, and sedimentary strata near the surface can be the rock cap for geothermal system. The low-resistivity anomalies in the middle and upper crust regions, which have a good correspondence with the three-dimensional inversion results of gravity data. The high conductivity area is interpreted as partially molten layer of the lower crust in the Gonghe Basin. The inversion results further confirmed the possibility of the existence of melt in the mid-crust of the Gonghe Basin. At the same time, according to the 3-D magnetotelluric imaging results, the heat of the high-temperature and high-conductivity melt can be transferred to the reservoir through the hidden fault. It can also be transported to the reservoir through the instantaneous heat conduction of high-resistance metamorphic rocks and igneous rocks between the high-conductor and the surface. According to the linear inversion of Rayleigh wave group and phase velocity maps (Figure 9), the east-west and north-south vs. profiles under the Gonghe-Guide Basin show obvious low-velocity anomalies. This low-velocity anomaly covers the study area in this paper, further confirming that there may be a partially molten layer in the crust under the basin.

A useful geothermal system mainly consists of three components, a heat source, a heat reservoir, and a caprock. Based on the 3-D inversion results of gravity data, the 3-D magnetotelluric imaging results and the linear inversion of Rayleigh wave group and phase velocity maps, it is speculated that the heat source of the hot dry rock geothermal

resources in the Gonghe Basin is likely to be the low velocity and high conductivity in the lower crust of the Gonghe Basin. It is related to the low-density partially molten mass. The heat of the high-temperature partially molten mass may be transferred to the thermal reservoir through the instantaneous heat conduction process of the partially molten mass. In addition, through hidden faults caused by strong tectonic activities since the Neogene can serve as the channels for transporting the heat from heat sources to the reservoirs. The Quaternary sediments covering the surface of the Gonghe Basin can serve as the caprock for the geothermal system. It is estimated that the total amount of hot dry rock resources in the hot dry rock prospect area of the Gonghe Basin is conservatively estimated to be about 8974.74×10^{18} J, which translates to 3066.199×10^8 t of standard coal. The overall exploration results are at the same level as the Milford EGS site in the Salt City Lake area of Utah, USA, and the hot dry rock geothermal resources in the Gonghe Basin still have further exploration potential [56].

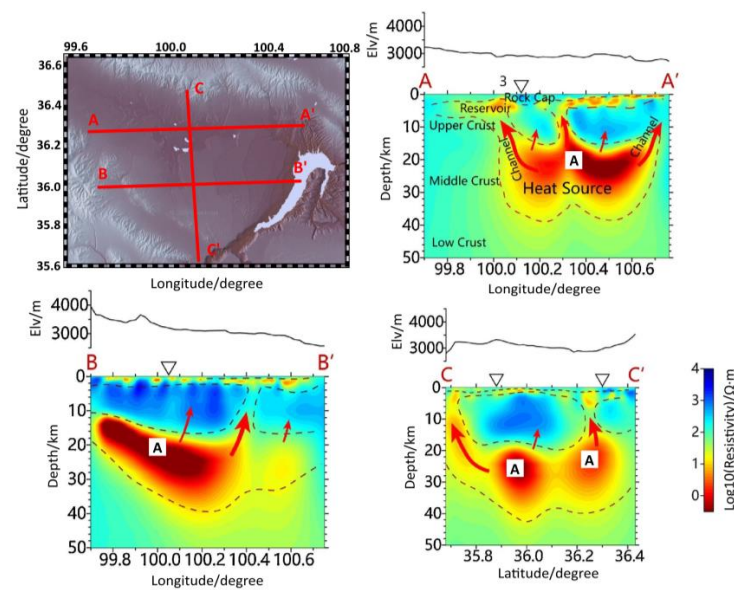


Figure 8. 3-D magnetotelluric imaging results (modified from Gao et al., 2018 [55]).

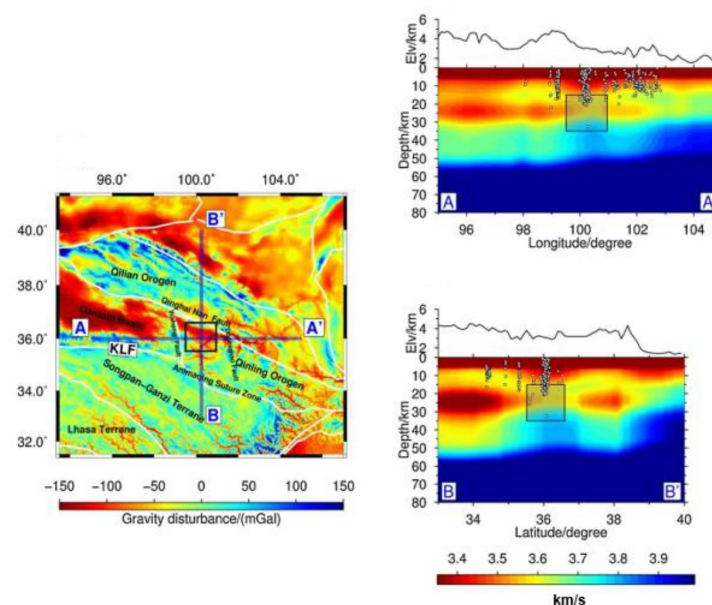


Figure 9. Linear inversion of Rayleigh wave group and phase velocity maps (Gao et al., 2018 [55]).

5. Conclusions

For further study of the genetic mechanism of hot dry rock resources in the Gonghe Basin, especially the heat source, we use the satellite gravity data in this area to conduct 3-D gravity inversion. By the results of gravity inversion, we presented a high-resolution underground density distribution model of the Central and Eastern Gonghe Basin. The inversion results show there are widely distributed low density anomalies in the crust of the Gonghe Basin, which have a good correspondence with the previous results of three-dimensional magnetotelluric inversion. Combined with the linear inversion of Rayleigh wave group and phase velocity, we speculate that this low-density anomaly area may be caused by partial melting of the crust. The crustal high temperature partial molten mass is likely to be the main heat source for the hot dry rock geothermal resources in the Gonghe Basin. This result confirms for the first time the existence of a partial melt layer in the crust from the gravity point of view and provides a new basis for further research on the genesis of the hot dry rock geothermal system in the Gonghe Basin.

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Nomenclature

Symbol	Quantity	Units
G	Universal gravitational constant	$\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$
ρ	Density	kg/m^3
H	Height	m
Δg_B	Bouguer gravity anomaly	mGal
Δg_{cl}	Classical gravity anomaly	mGal
d	Ground observation data	mGal
m	Density of underground sources	g/cm^3
A	Sensitivity matrix	$10^{-3} \text{cm}^4/\text{s}^2 \text{g}$
ϕ	The objective function of the inversion	-
ϕ_d	Data fitting function	-
ϕ_m	Model fitting function	-
α	Regularization parameters	-
$w(z)$	Depth weighting function	-
z	Depth of the center point of the underground space geological body	m
z_0	Depth parameter	m
β	Constant	-
W_m	Model weighting matrix	-
$W_e(m)$	Minimum support function	-
W_d	Data weighting matrix	-

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