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 are still some controversies about the genetic mechanism of the hot dry rock geothermal system in the Gonghe Basin. Geophysical exploration methods are important means of geothermal resource exploration. Gravity exploration is a kind of geophysical exploration method based on the density difference of natural rock ore bodies. It has the advantages of low cost, high resolution, wide coverage, and large detection depth. It plays an important role in identifying faulted structures and delineating concealed rock ore bodies. 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 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. According to the previous research results, the low density layer is speculated to be a low-velocity, high-conductivity partial melting layer in the crust of the Gonghe Basin. The results of this study for the first time confirm the existence of partial melting layer based on gravity data inversion, and quantitatively explain the underground structure of the Gonghe Basin and the mechanism of geothermal system. This high-temperature melting layer may be the main heat source of the hot dry rock geothermal resources in the Gonghe Basin. Then the heat energy transfer from the hidden faults to the shallow reservoir rocks. The overlying cenozoic sedimentary strata can serve as the caprock for the geothermal system in the Gonghe basin.

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 has become increasingly prominent, so it is urgent to improve the energy structure and make full use of clean and renewable energy (Apergis et al., 2011). Geothermal resources are one of the most important clean energy sources and play an important role in replacing traditional oil and gas resources (Kana et al., 2015). 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 ℃. With huge potential for power generation, the enhanced geothermal system (EGS) developed on the basis of hot dry rock utilizes the hot dry rock reservoir to generate electricity through hydrofracture. It has extremely high application value and it is one of the important way for the effective development and utilization of hot dry rock geothermal resources in the future to resolve the energy crisis (Teke et al., 2018; White et al., 2018).

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. 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. (Gao et al., 2019). In the Cooper Basin of Australia in 2003, people successfully discovered geothermal resources of dry hot rock with a temperature of up to 270℃ at a depth of 4,500 meters below the basin by using 3-D gravity inversion methods (Xu et al., 2012). Satellite gravity observation technology has the characteristics of high coverage, high precision and high resolution, 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 Qinghai-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 3705m below the well GR1 was as high as 236℃. It is the first discovered target area for hot dry rock geothermal resources with a temperature above 200 ℃ in China, which proves that the hot dry rock geothermal resources in the Gonghe Basin have further exploration potential(Yan et al., 2015; Zhang et al., 2018). However, there are still some controversies about the genetic mechanism of the hot dry rock geothermal system in the Gonghe Basin, and the following opinions have mainly formed. The heat source mainly comes from the deep mantle and is recharged by the large fault structure as a heat channel (Zhang et al., 2018), and the regional thermal anomalies caused by radioactive heat generation in granite (Zhang et al., 2018), and the heat source mainly comes from both the deep mantle and Magma sac heat conduction Feng et al., 2018 .

The underground structure of the Gonghe Basin and the mechanism of geothermal are not yet clear. In this paper, we first briefly introduces 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. The inversion results show that there are widely distributed low-density anomalies relative to surrounding rock in the middle crust of the study area, which is speculated to be a low-velocity, high-conductivity partial melting layer in the crust of the Gonghe Basin, and it might be the main heat source of the hot dry rock geothermal resources in the Gonghe Basin. The result will provide some reference for the hot dry rock exploration and development in the Gonghe Basin.

Geological Setting

The Gonghe Basin, which is located in the northeast of Qinghai-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 (Zhang et al., 2018). The Gonghe basin is surrounded by several faults(Fig. 1). As a typical Cenozoic faulted basin bounded by Ela Mountain and Yellow River valley in the south and Qinghai Nan Mountain in the north, it is tectonically controlled by Kunlun Orogen in the south and Qilian Orogen in the north (Fang et al., 2005). Surrounded by Qinghainan fault in the north, Duohemao Fault in the east and East Kunlun Fault in the southwest, Gonghe Basin is about 280km in length, 95km in width, 2.1×10^4 km^2 in area and distributed in a diamond shape (Zhang et al., 2006).

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(Feng et al., 2003). The sediments above the basement are mainly Neogene and Quaternary, and the surface layer is Quaternary. As indicated in regional geological results, these has been no magmatic activities around Gonghe Basin since Cenozoic (Zhang et al., 2007;Zhang et al., 2020). The igneous and metamorphic rock sequences of the East Kunlun and West Qinling Orogen developed around the basin is composed of the middle and late Triassic metamorphic sedimentary rocks and Indosinian granites and granodiorites (Yan et al., 2015). The Cenozoic deposits in the basin generally show a trend of thin in the east and thick in the west. And the thickness of Cenozoic deposits is generally about 500m to 1500m in the eastern part of Guide area, about 1500m in the central and eastern parts of Qiabuqia area and can reach 6000m in the west (Tang et al., 2020).

There are many hot springs exposed in Gonghe Basin with a relatively obvious concentrated distribution along the fault zone (Feng et al., 2018). In addition to hydrothermal geothermal resources, 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 Gonghe Basin is twice as big as the normal geothermal gradient (Liu., 2017). 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 3000m and 3705m in basin is between 180℃ and 236℃(Wang and Kang, 2017).

3-d Inversion Of Gravity Data

Details of the gravity data

Satellite gravity observation technology has the characteristics of high coverage, high precision and high resolution, 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. 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, with a spatial resolution of 9km and the accuracy of gravity anomaly is up to 2.73mGal, it has a high accuracy in each ultrahigh order gravity field model. Therefore, in this article we use the gravity data provided by the EIGEN-6C4 gravity field model with a resolution of 1 arc minute, and the range of data obtained by satellite gravity is 99°36'E- 100°48'E longitude and 35°36'N- 36°36'N latitude (Ince et al., 2019). 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 1.5km. The gridded data is used as the research object and the interpolated satellite gravity Bouguer anomaly map in the research area is shown in Fig. 2.

3-D gravity focusing inversion method

In this section, we will introduce the 3-D gravity inversion method briefly and the method was proposed by Gao et al. (2019). The inversion method is realized by matlab language. 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

$$d = Am \ 1$$

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 uderground medium. 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 (Tikhonov and Arsenin, 1977). This problem is solved by minimizing the objective function. The objective function is composed of data fitting items, model constraints and regularization parameters, and its form is as follows:

$$\varphi\left(m\right) = \varphi_d\left(m\right) + \alpha\varphi_m\left(m\right) \ \ 2$$

Where $\varphi\left(m\right)$ is the objective function to be solved, $\varphi_d\left(m\right)$ is the fitting items, φ_m is the model constraints and α is regularization parameters, The calculation formula of the objective function is as follows

$$\varphi = \varphi_d + \varphi_m = \|Am - d\|_2 + \alpha\|m\|_2 \ 3$$

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 Oldengburg(1996,199,)solves the serious skin effect problem of inversion, and its form is as follows

$$w\left(z\right)=\frac{1}{{\left(z+{z}_{0}\right)}^{\beta /2}}\ 4$$

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. By using the improved depth weighting function proposed by Gao et al. (2019) makes the inversion result more concentrated,ma, es the vertical resolution of the inversion result higher. Its form is as follows

$$w\left(z\right)=\frac{1}{{\left(z+{z}_{0}\right)}^{\beta /2}}\frac{1}{{\left(H-z-{z}_{0}\right)}^{\beta /2}}\ 5$$

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), and introduces the minimum support function into the objective function expression. Its form is as follows

$$W_e\left(m\right)=\frac{m^2}{m^2+e^2}\ 6$$

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

$$\varphi ={\varphi }_{d}+{\varphi }_{m}={‖{W}_{d}\left(d-Am\right)‖}_{2}+\alpha {‖{W}_{m}{W}_{e}m‖}_{2}\ 7$$

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. In the first iteration process, the iteration direction is the negative direction of the partial derivative of the objective function, the search step size satisfies $t_0\frac{p_k^T g_k}{p_k^T p_k}$, and the model parameter $m=m_{k-1}+t_{k-1}d_{k-1}$. When the inversion objective function is less than the cut-off error or the number of iterations is less than the preset value of the number of iterations, the next iteration process is entered until the cut-off error value or the preset maximum number of iterations is met. And the factor k represents the number of iterations.

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 local field and the regional field. The regional field is caused by deeply buried and widely distributed rock masses, and the frequency of anomalies is low, and the amplitude of anomalies is large. The local field is caused by the rock mass with relatively shallow depth and small distribution, and its anomaly amplitude is small and the frequency is high. Anomaly separation is an important part of the work of gravity anomaly interpretation. In this paper, the most commonly used upward continuation method will be used to process the satellite gravity data in the study area, and then the local anomaly field in the study area will be obtained. The original gravity anomaly field is separated by the result of 30km upward continuation, and the local anomaly field obtained is shown in Fig. 3.

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 Bouguer gravity 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 111km×114km×40km. The underground grid is divided into 74×76×40 points, and the grid unit size is 1.5km×1.5km×1km. Selecting appropriate regularization coefficients, after 20 iterations of inversion, a more credible underground density distribution model is obtained.

Figure 4 shows the horizontal slice of the three-dimensional gravity inversion results in the study area at 2km, 5km, 8km 10km, 15km, 20km, 25km and 30km depth slices, respectively. There are widely distributed low-density anomaly areas below 2km underground of the study area, which has a good corresponding relationship with Quaternary and Neogene sediments. Obvious low-density banded anomalies appear on 5km and 8km 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 15km-25km. The low-density anomaly area is consistent with the distribution position and strike of the three known faults. According to the horizontal slice of the inversion results, the buried depth of the low-density abnormal body may be between 15km and 30km. Through the known hidden faults, there is a certain connection relationship between the low-density body and the surface.

We have selected four sections along the north-south direction (Fig. 5b-e), which can clearly see the widespread low-density anomalies that exist underground. The depth range is about 15km-30km, 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 of hot dry rock geothermal resources in the Gonghe Basin.

Discussion

At present, the Gonghe Basin is one of the most favorable areas for the exploration and development of hot dry rock geothermal resources in China. Drilling GR1 in the Gonghe Basin at a depth of 3705 m reaching the temperature of 236℃. It is now drilled hot dry rock geothermal resource in China with the highest temperature (Zhang et al., 2018). This section will further discuss the hot dry rock geothermal resources in the Gonghe Basin based on the results of 3-D gravity inversion and previous research results.

The Gonghe Basin is a high-temperature geothermal anomaly basin (Zhang et al., 2018). According to the results of regional geological survey, since the Cenozoic there has been no magmatic activity in the Gonghe Basin and the surrounding orogenic belt (Zhang et al., 2020). The heat generation rate of rocks is 0.96 4.11μW/m^3, which is slightly higher than that of the global Mesozoic and Cenozoic granites (Zhang et al., 2020). The average radioactive heat generation rate is 3.09μW/m^3 (Artemieva et al., 2017), but the radioactive heat generation rate is much lower than the 7–10μW/m^3 of the granite in the Cooper Basin in Australia (Beardsmore., 2004). 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 in the middle-lower crust is the partial melting 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 (Yang et al., 1998). Since the 1980s, the researchers have discovered that low-velocity and high-conduction zones generally develop in the crust of the Qinghai-Tibet Plateau and its surrounding areas (Nelson, 1996; Zhang et al., 2020). 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 Ω·m is used as the basis for delineating the partially molten layer in the crust (Li et al., 2003; He et al., 2016; Zhang et al., 2020). When the rock is partially melted, its volume changes and the density decreases, which shows low gravity anomaly (Gu et al., 1980). 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 (Fig. 5). 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 (Zhang et al., 2020). 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 (Fleitout and Froidevaux, 1980; Yuan et al., 1985; Qi et al., 2003).

The 3-D gravity inversion results show that there are obvious low-density anomalies in the depth range of 15km-30km 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, 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 (Gao et al., 2018). In addition, from the horizontal slices (Fig. 4) and vertical slices (Fig. 5) of the inversion results, it can be seen that there are many hidden faults (F1, F2, and F3) on the low-density body. Since the Neogene, the Gonghe Basin has experienced strong tectonic activities, and the basement has been broken and uplifted and formed numerous compression faults (Hao et al., 2012). The existence of these faults can serve as a thermal channel for the low-density molten mas in the crust to transport heat to the shallow caprock mass. The heat passes through the thermal channel and is transported to the reservoir of 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), the middle-late Triassic granite with high thermal conductivity and low water content is also an important heat conductor for the partially molten mass in the crust to transport heat to the reservoir.

According to the magnetotelluric imaging results of Gao et al. (2018) (Fig. 6), there is an obvious high conductivity area at a depth of 15km-35km. There is a relatively strong low-resistivity anomaly in the mid-crust and upper-crust region, which has a good correspondence with the 3-D inversion results of gravity data. The high conductivity area is interpreted as partially molten mass of the lower crust in 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 (Fig. 7), 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 be 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 (Zhang et al., 2019). The overall exploration results are at the same level as the Milford EGS site in the Salt City Lake area of Utah, USA (Zhang et al., 2018), and the hot dry rock geothermal resources in the Gonghe Basin still have further exploration potential.

Conclusions

In this study, we carry out the research and application of the 3-D inversion method for the satellite gravity data in the Gonghe Basin for the first time. And a high-resolution underground density distribution model of the study area is obtained to analyze the underground structure of the Gonghe Basin, and the mechanism of geothermal system from the point of view of gravity inversion. Based on the inversion results, there are widely distributed low-density anomalies in the crust in the Gonghe Basin. 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. Combined with the horizontal slice of the geological data and the inversion results, there are many hidden faults in the study area. These faults can be used as heat channels for heat transfer from the heat source to the heat reservoir. The low thermal conductivity Cenozoic sedimentary strata covering the surface of the Gonghe Basin can be serve as the caprock for the geothermal system. Based on the 3D inversion result of gravity data, the internal heat source and heat transfer channel in Gonghe Basin are further interpreted and characterized quantitatively, which provides theoretical support for the further exploration of geothermal resources in the area.

Abbreviations

3-D: Three dimensional;

GN: Gauss-Newton;

CG:conjugate gradient.

Declarations

Acknowledges

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Authors’ contributions

ZS performed all the analysis and wrote the manuscript. ZZ analyzed the inversion results and supervised all the work. ZJ and ZS wrote the code for 3D inversion. ZJ, ZZ and ZS analyzed and interpreted the inverted model. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on any request.

Competing interests

The authors declare that they have no competing interests.

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abstract)

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Figures

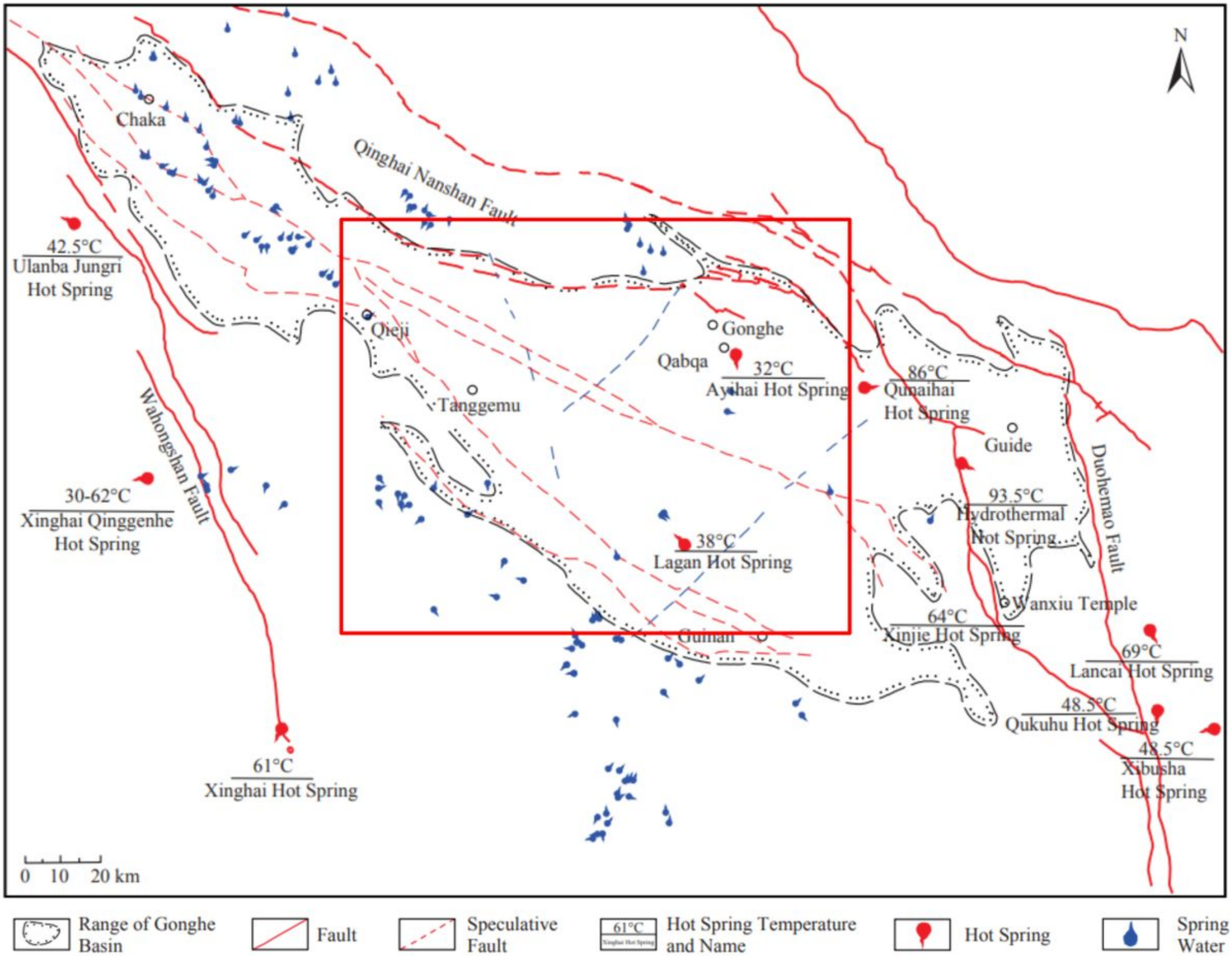

Figure 1

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 Feng et al., 2018)

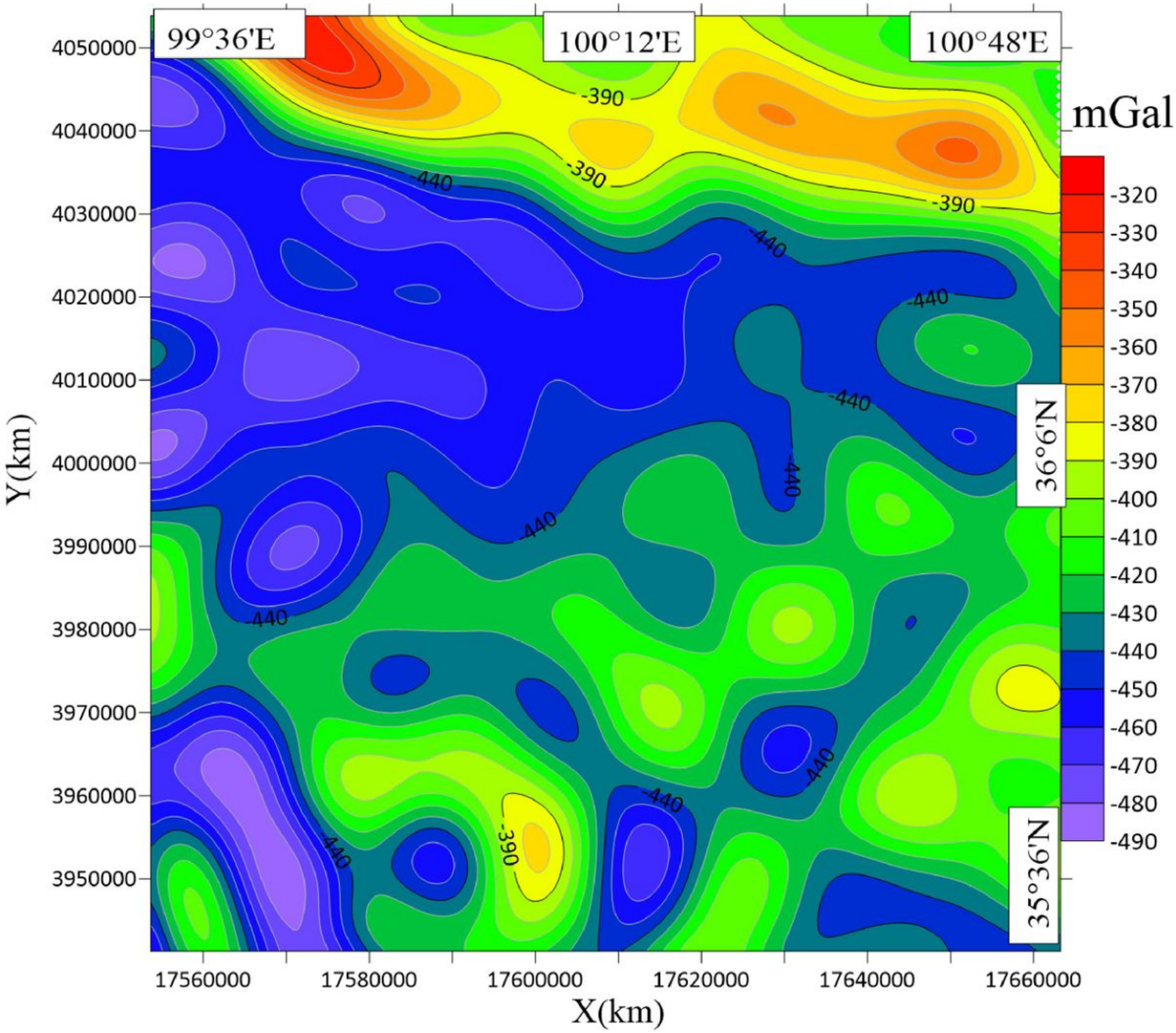

Figure 2

Satellite Bouguer gravity anomaly map in the study area

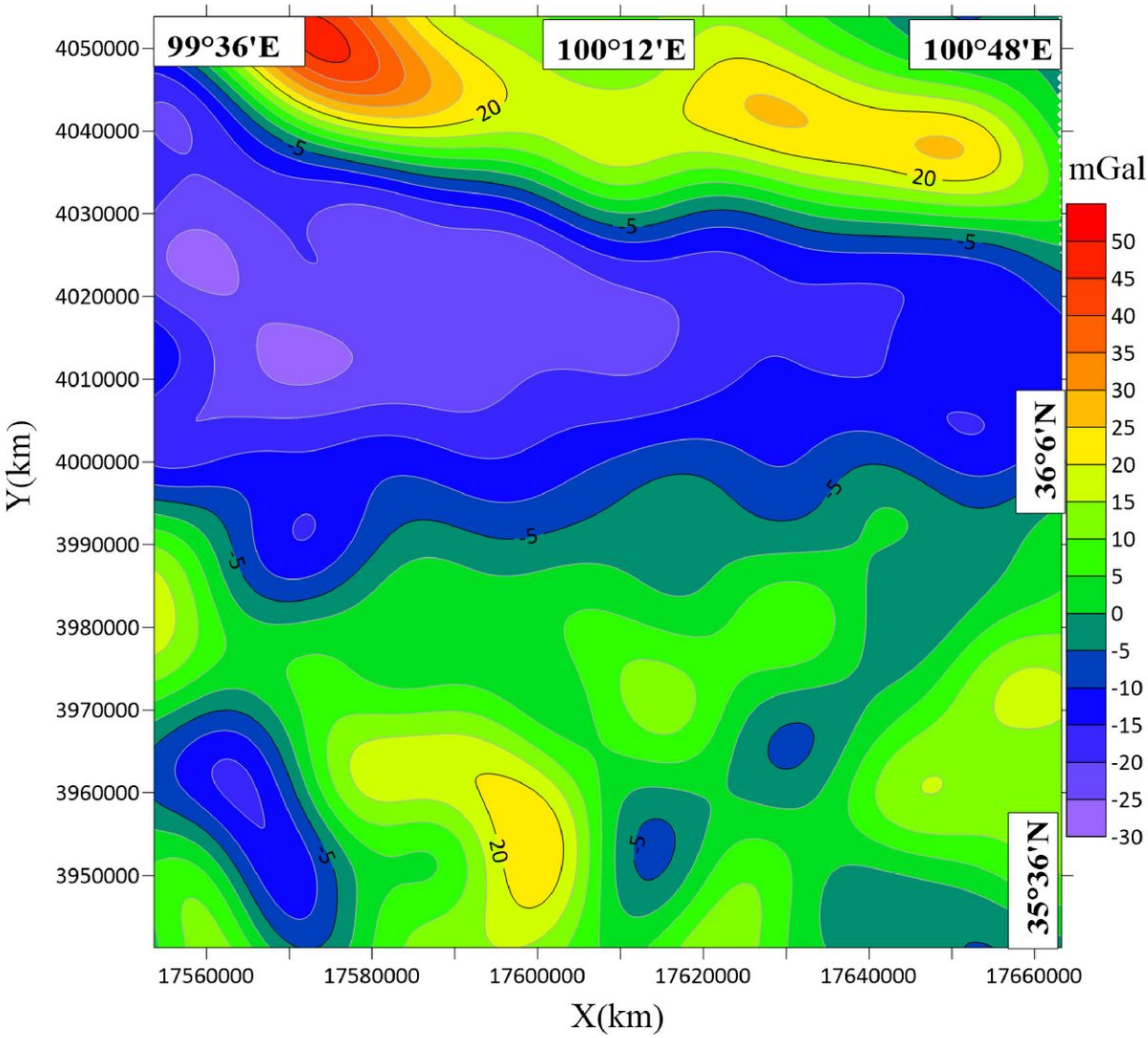

Figure 3

The residual Bouguer anomaly map

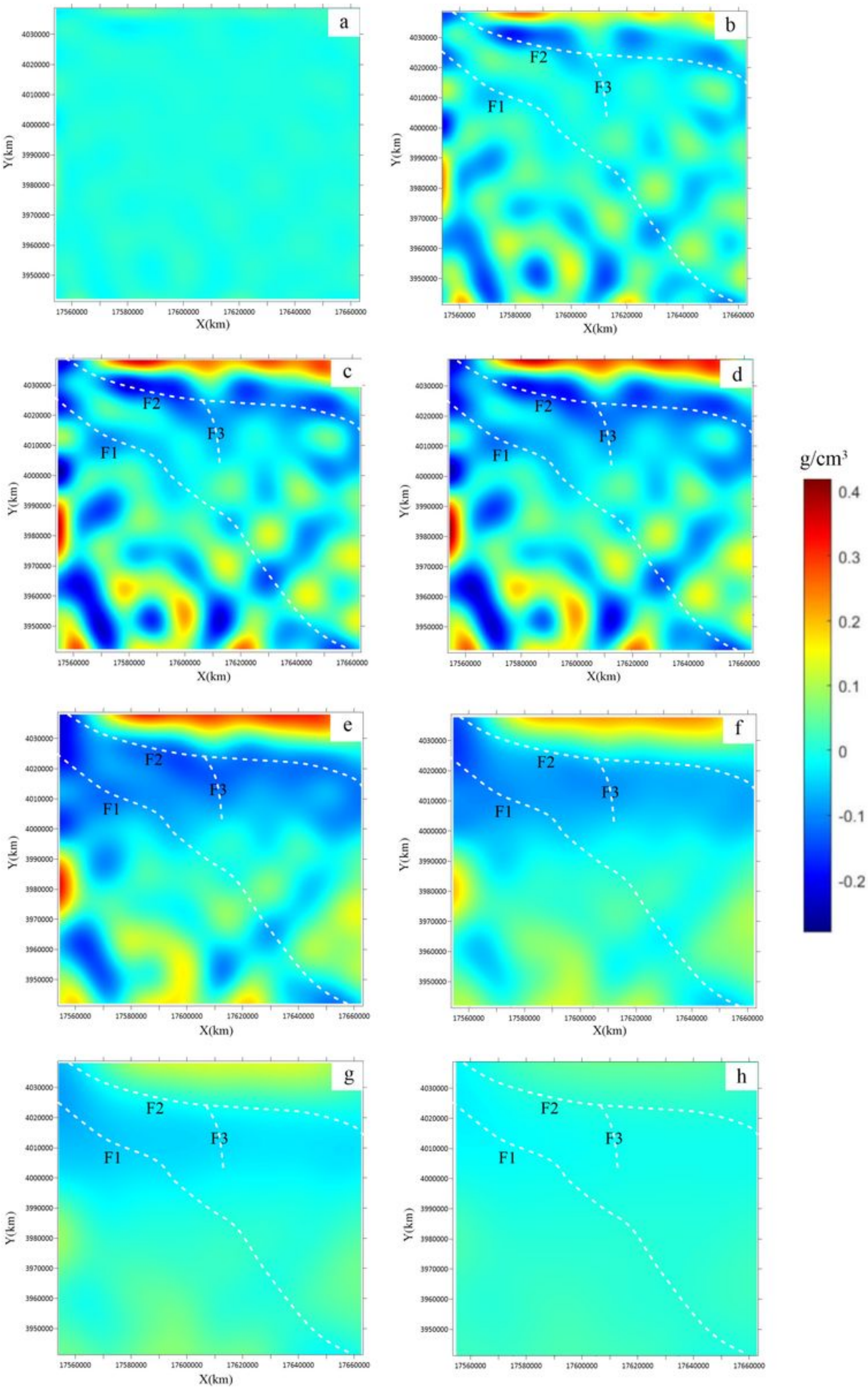

Figure 4

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

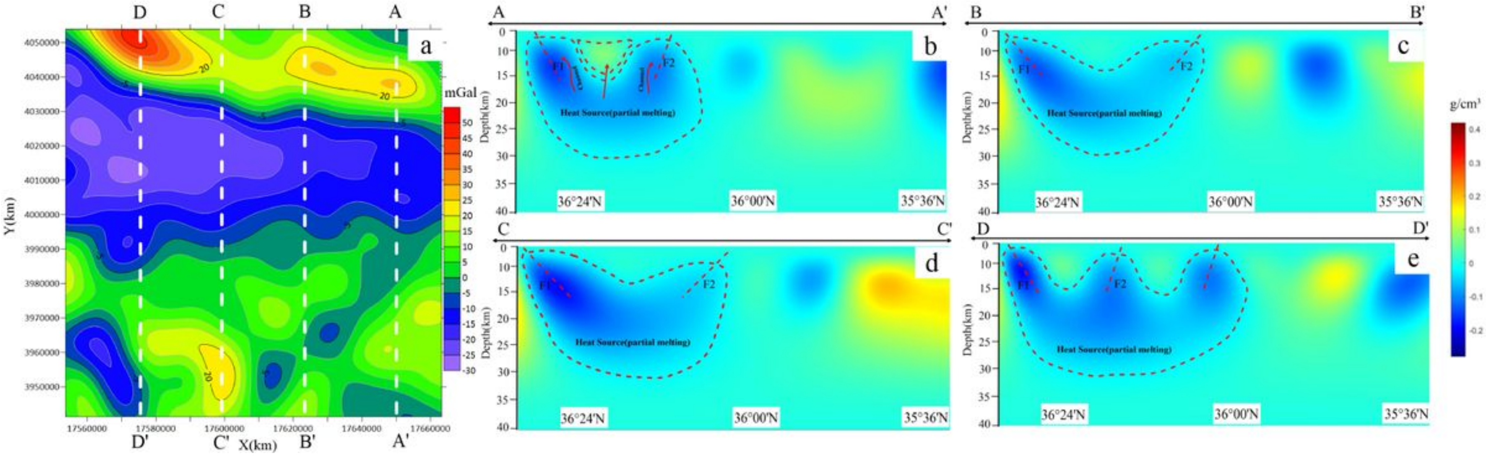

Figure 5

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

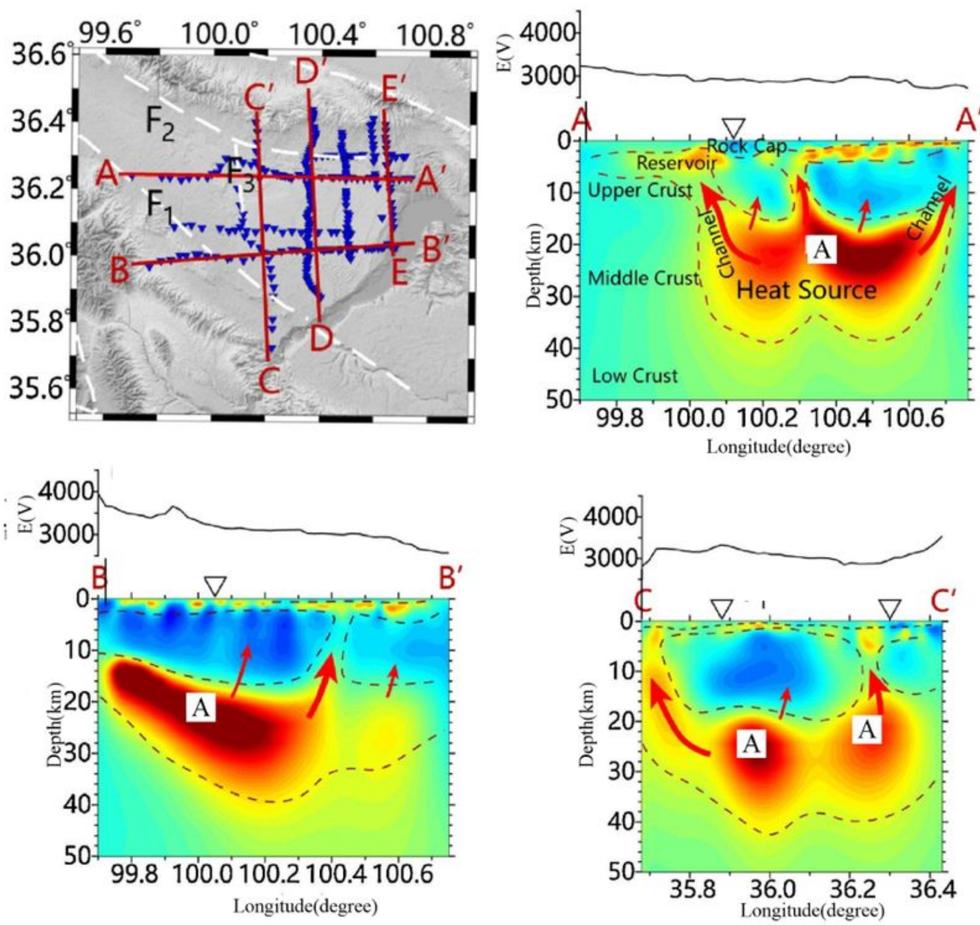

Figure 6

3-D magnetotelluric imaging results(Modified from Gao et al., 2018)

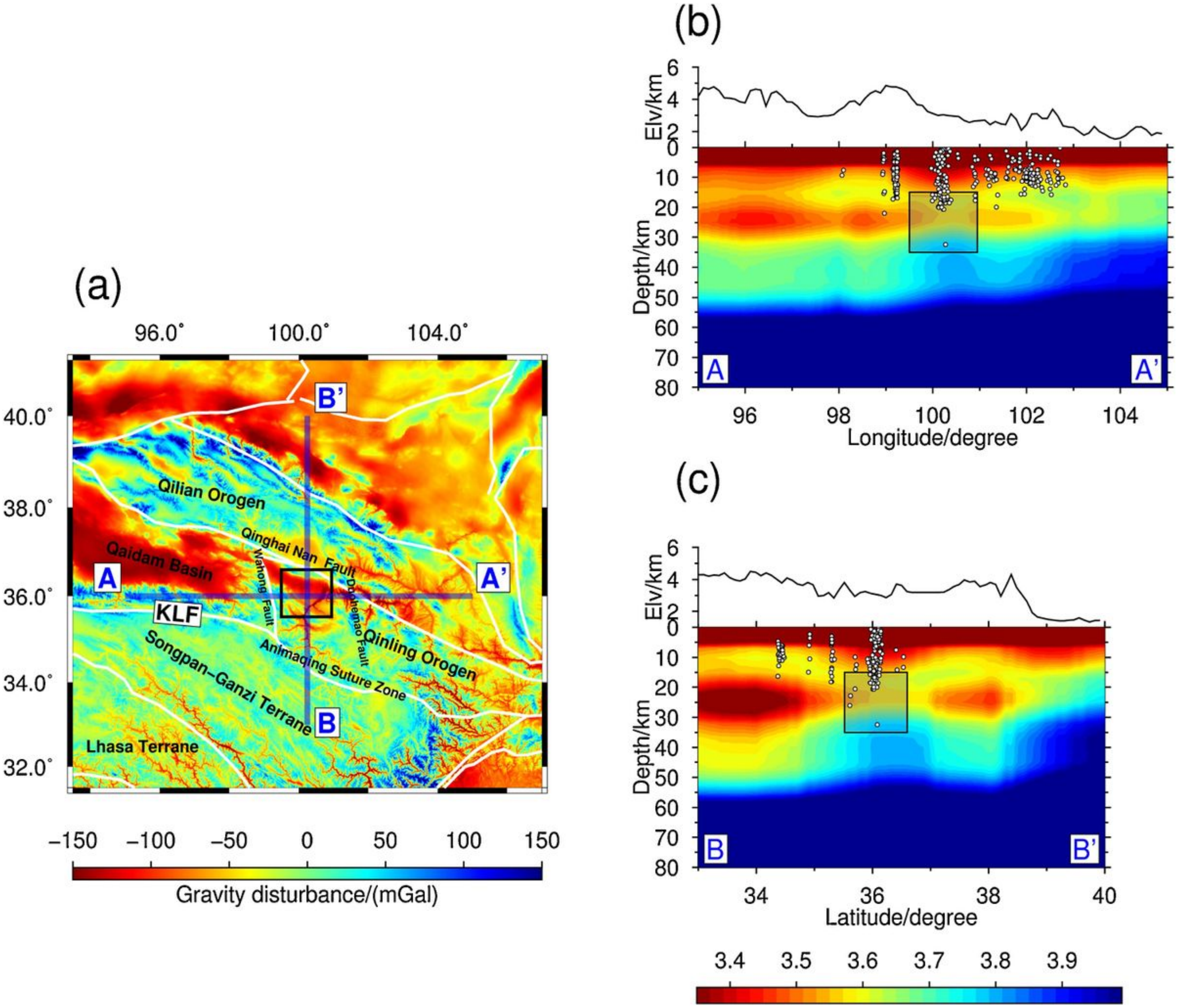

Figure 7

Linear inversion of Rayleigh wave group and phase velocity maps (Gao et al., 2018)