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Using TOUGH2 numerical simulation to analyse the geothermal formation in Guide basin, China

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Abstract: The Guide sedimentary basin is located in the northeastern part of Qinghai-Xizang Plateau, which is rich in geothermal resources. However, exploitation of the geothermal resources has so far been limited, because of limited understanding of the resources quantity and storage gained from scientific researches. In this study, using a typical cross section across the basin and taking into account its geothermal and geological conditions, a new water-heat coupled model was built and associated modelling was done by the software TOUGH2. During modelling process, the accuracy and applicability of the model was confirmed through the calibration of relevant parameters for modelling the heat and water transport and the formation of geothermal reservoir across the basin, with particular focus on the Neogene geothermal field. Results show that the groundwater that flows from the basin margins to the center is heated by the Neogene and Paleogene sedimentary rocks with high geothermal gradients. Since the east-west extending fault F1 is conductive, it acts as preferential flow paths which on one hand provide additional and rapid flows to the thermal reservoir; and on the other hand, cool down the thermal water to a certain extent due to the infiltration of shallower water sources in the vicinity of the fault. Furthermore, the estimated geothermal resources quantity is close to that of previous studies. In comparison with the Paleogene rock formations, the Neogene geothermal reservoir shows a better nature in terms of water content, aquifer permeability and resources exploitability, although the resource quantity of the Paleogene reservoir is considerable.

Keywords: Guide basin; TOUGH2; Two-dimensional modelling; Numerical simulation; Geothermal resource evaluation

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Introduction

The low temperature (as T, less than 140°C) geothermal fields are abundant in Guide sedimentary basin, particularly in the Zhacang geothermal field within the basin, which is currently the key area of geothermal investigation and research. The geothermal survey in the Guide basin was initiated in the late 1970s; and since then limited further investigation or relevant research has been done for the resources assessment and development. From 1977 to 1979, the Second Hydrogeological Team of the Geological Bureau, Qinghai Province conducted a survey to the geothermal field in the basin and evidenced the presence of the geothermal water, which marked the beginning of the geothermal research in this area. Among them, the remarkable one is FANG Bin *et al.* (2009), who used isotope methods to analyze the origin, circulation, and age related to the formation of geothermal water. Another important research was done by LIN Wu-le *et al.* (2017), who used

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gravity and electromagnetic methods to investigate the shallow geothermal fields in the basin and concluded that the geothermal water was originated under a sedimentary geo-environment. In general, the condition of low-temperature thermal reservoir and the evolution of associated stratigraphic units in the shallow portion of the basin have basically been grasped (LIAO Juan *et al.* 2013; SONG Chun-hui *et al.* 2001; WANG Gui-ling *et al*. 2018). However, studies of the deep geothermal distribution and the structural characteristics and formation of the thermal reservoir have yet not been done.

The water-heat coupled model is a method for numerical modelling, which combines water movement and temperature field analysis. With the development of computer technology, numerical simulation has gradually become an effective tool to study the thermal structure of a basin. There are several geothermal research has been discussed (Pruess *et al.* 1999; Michael *et al.* 2001). For example, Ben *et al.* (2008) established a two-dimensional thermal model of the lithosphere in the northeastern German basin, and calculated the thickness of the heat-producing rock layers and the temperature of the Moho surface. Alberto *et al.* (2012) calculated the radiogenic heat production in the Spanish Central System and the Tajo basin, and simulated the heat-controlling structure in the local lithosphere. Oliver *et al.* (2013) used FEFLOW to simulate the temperature of shallow thermal reservoirs in the metropolitan area of Perth, Western Australia; and their results showed that the convection flow influenced the temperature distribution in thermal reservoirs. In China, the research on water-heat coupled model has rapidly been developed in the past decades. XUE Yu-qun *et al.* (1980) established a three-dimensional mathematical model for water and heat flows, based on the thermomechanical dispersion with data derived from a pilot study on Shanghai energy reservoir, from which a corresponding finite element approach to the model was developed. WANG Gui-ling *et al.* (2002) established a water-heat coupling model, based on the study of the geothermal conditions in Xi'an geothermal field, to simulate artificial recharge of geothermal tailing water in this area. ZHANG Yuan-dong *et al.* (2006) applied numerical simulation technology to establish a three-dimensional water-heat coupling model. WANG Yang *et al.* (2011) discussed the advantages of TOUGH2 2D model in the simulation of enhanced geothermal system. Using the same model, LEI Hong-wu (2014) simulated the hydrothermal dynamic coupling process of the EGS development in Songliao basin; YUE Gao-fan *et al.* (2015) simulated the geothermal system in the Gonghe basin.

In this study, on the basis of previous researches and the thermal-physical parameters of the rock formations in the Guide basin, the TOUGH2 model is used to further verify the applicability of the method. After that the structure and distribution of the geothermal field will be examined through the modelling results, to provide a theoretical basis for the development and utilization of geothermal resources in the Guide basin.

1 Study area

Guide basin is located in the northeastern part of Qinghai-Xizang Plateau and belongs to the western part of the West Qinling Orogenic Belts (Li *et al.* 2013). The Guide basin is a faulted basin developed by the Indo-Chinese tectonic movement. The northern boundary of the basin is the Qinghai Lake-Nanshan fault and the eastern one is the Duohemao fault, while the western part is separated from the Gonghe basin by a magmatic rock uplift belt along the Waligongshan fault zone. As a result, a relatively independent structural area is defined (Fig. 1) (LI Le-le, 2016). There are a large number of hot springs emanating on the edge of the basin, and the temperature of the spring water is as high as 93.5°C, slightly higher than the local boiling point of 92°C (Chen, 2014). In the meantime, the geothermal wells in the basin have good heat-displaying characteristics. The local annual average temperature is only 8°C, while the temperature of 24 boreholes are above 20°C (Fig. 2) and most of them are less than 300 m deep (LANG Xu-juan, 2013). Geologically, the granite which intruded into the Middle and Lower Triassic strata formed a mixed basement of the basin, with its outcrops widely distributing in and around the basin. Above the basement, the sedimentary rocks mainly consist of the Neogene and Paleogene sandstones, which provide a good thermal reservoir host rock and hot water storage space for the formation and occurrence of underground hot water, due to their good permeability and large thickness (Table 1).

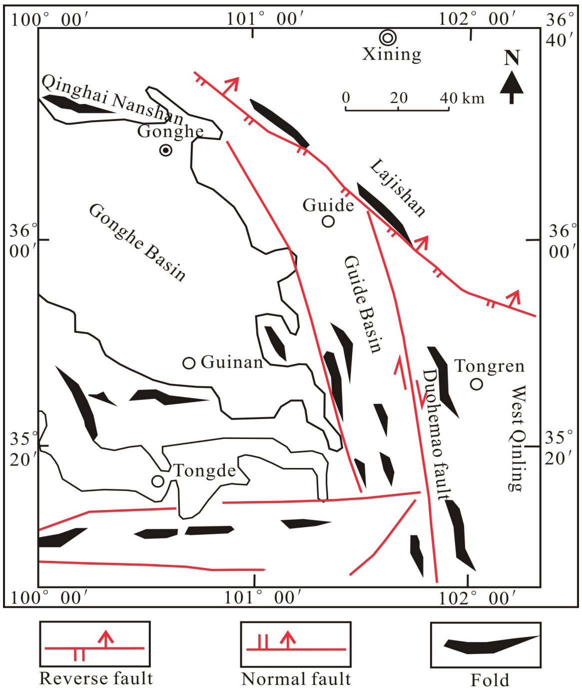
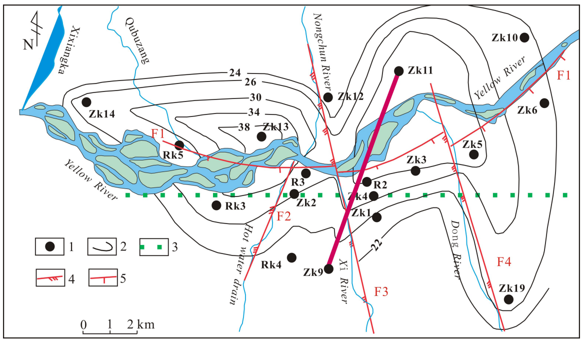


Fig. 1 Sketch map of tectonic of Guide basin



Legend explanation: 1. Boreholes with water temperature greater than 20°C; 2. 200 m temperature contour (°C); 3. MT measuring point; 4. Inferred compressive fracture; 5. Inferred tensile fractureone.

Fig. 2 Isotherm map of Guide basin at a depth of 200 m

According to geophysical survey results, there are four major faults in the study area. Among them, the fault F1 traverses the entire basin in a nearly east-west direction. As it cuts through the base of the basin, it is speculated that this fault is one of the deepest and the earliest faults in this area. The boreholes with water temperature above 20°C are basically observed along the fault, which indicates that this fault is one of the major faults controlling the geothermal condition of the basin (Fig. 2). The other three, F2, F3 and F4, are all compressional torsion faults, with their depth reaching the base of the basin. Due to the compression thrust, not all the fault zones can be water-bearing, but geothermal heat which migrates from the deeper portion along the fracture network can reach to the vicinity of the basin base. This is shown by the data derived from 200 m deep temperature logs which gradually decreases from the basin center to the margins. Therefore, it can be inferred that the temperature decrease is related to conduction heating of the sedimentary layers which are the thickest in the central part of the basin (Table 1).

In terms of groundwater flow field, most of the groundwater in the Guide basin is artesian, with the highest water heads in the middle. The groundwater mainly runs from the southern and northern mountainous areas to the middle of the basin. The 200 m temperature contour of the groundwater has the maximum increase degree in the runoff direction of the Nongchun and Xihe rivers from which it can be inferred that the central area of the basin is the main groundwater runoff zone. The shallow Neogene low-temperature heat reservoir exposed by boreholes R2 and R3 has the largest discharge of 1 288.22 m^3/d.

Based on the above geothermal and geological conditions and restrained by the limited information about the whole basin, the research selects the ZK9-ZK11 section as an example to conduct a 2D heat-water coupled simulation along the cross section. The ZK9-ZK11 section is located in the main geothermal field in the middle of the basin, and it also crosses the deepest borehole R2 (2 700 m) in the study area and the major heat-water controlling fault F1. This simulation attempts to present the interaction between the heat source and the water source in the Guide basin to the greatest extent, as well as to analyze the genetic mechanism of the basin's geothermal resources and the thermal water movement.

2 Model establishment

2.1 Simulation tools

Numerical simulation has been an important technical method for the development and evaluation of geothermal fluids and the study of the circulation of geothermal water system (GAO Liang *et al*. 2013). It is especially an effective tool

Table 1 Geothermal reservoir of Neogene in geothermal field

Borehole No.	Hole depth (m)	Elevation (m)	Lithology of heat reservoir	Hydraulic head (m)	Draw-down (m)	Flow (m^3/d)	Water temperature (°C)	Salinity (g/L)
ZK_2	266.88	2 222.96	Medium sand, coarse sand and gravel	+23.0	22.99	603.245	18.5	0.423
ZK_4	272.50	2 224.98	Medium sand, coarse sand and gravel	+20.33	18.13	554.342	21.5	0.568 7
ZK_{13}	293.38	2 212.93	Medium sand, coarse sand and sandy gravel	+24.75	18.90	1 074.211	25.5	0.413 3
ZK_3	385.63	2 231.15	Medium sand, coarse sand and gravel	+8.52	7.71	27.862	34.6	0.646
RK_2	404.41	2 212.12	Medium sand and coarse sand	+20.8	19.39	1 219.795	26.5	0.495 6
ZK_{15}	470.41	2 226.94	Medium sand, coarse sand and sandy gravel	+9.13	8.15	145.843	22.5	0.464 2
RK_1	603.95	2 207.48	Moderate coarse sandstone	+32.85	15.53	1 221.35	28.0	0.528 2
R_2	1 709.5	2 206.00	Medium sandstone and medium fine sandstone	+11.07	28.1	1 288.22	36.5	0.527
R_3	2 701.2	2 213.00	Medium sandstone and medium fine sand	+12.4	43.08	968.46	41.0	0.638

to study the multiphase and multi-field coupling water and heat transport, which has widely been used in the fields of hydrothermal simulation, the EGS thermal storage engineering (LEI Hong-wu, 2014), nuclear waste treatment (LIU Xue-yan, 2010), vadose zone hydrology (LI Zhao-hong, 2016) and carbon dioxide storage (ZHENG Yan, 2009). On the basis of geothermal data derived from various sources, in this study, the software TOUGH2.0 is used to establish a two-dimensional water-heat coupled model which is suitable for this study area and can evaluate and predict the thermal reservoir dynamically.

2.2 Conceptual model

2.2.1 Selection of simulation area

As shown in Fig. 2, the geothermal wells in the Guide basin mainly distribute along two directions, namely, the east-west extending the Yellow River valley and the north-south Nongchun River-Xihe River valleys. All these valleys are proved to be conductive geothermal fields; and their geothermal gradients fall in the range of 3.59~9.7°C/100 m, with the highest of 17.62°C/100 m in this area. The calculated heat flow value is mostly between 74 mW/m^2 and 79.5 mW/m^2 (LANG Xu-juan *et al.* 2016) with an average value of 76.5 mW/m^2, higher than the global continental average heat flow value of 65±1.6 mW/m^2 (Pollack *et al.* 1993). The Guide basin is apparently a high geothermal area where the geothermal water may occur in places. In the high geothermal environment, it is believed that, on one hand, the underground temperature increase is attributed to geothermal conduction in the sedimentary rocks. On the other hand, the convection of deep thermal energy along fault and fracture systems is also critical for the temperature increase and the formation of geothermal water.

On this basis, the 2D profile shown in Fig. 2 is selected for current modelling study, with the reasons as follows:

(1) In terms of geothermal conditions, the zone in relation to the selected profile is situated in the middle of the basin with the most suitable geothermal conditions. There are many geothermal wells located in the vicinity of the section line across the entire basin. In addition, the selected section well intersects with the fault F1, the major heat-controlling geo-structure in the Guide basin.

(2) In terms of aquifer conditions, the groundwater in the basin mainly flows in a north-south direction, that is, from both sides of the mountains to the Yellow River. This section is basically defined as the same as the groundwater flow direction in the center of the basin, which is convenient for groundwater flow simulation.

(3) Many previous in-depth researches have

been conducted in the area along this section, providing abundant data for current study. The previous researchers have drawn the Neogene stratigraphic profile of the basin, based on the measured stratigraphic data of wells ZK9, ZK11, RK1 and other wells installed along the cross section, which is also key zones for subsequent geophysical and geothermal surveys.

(4) The well R2 in the center of the basin is 2 700 m deep, which is the deepest geothermal well in the study area. The area around R2 has the best geothermal conditions in the Guide basin, where many geothermal wells have relatively high water temperature; and some of the wells are artesian wells. Thus, this area can best represent the heat generation mode and geothermal resource generation conditions in the Guide basin.

2.2.2 Model discretion and boundary conditions

So far, as the geothermal resources in the basin have not been well utilized, so the simulation as discussed latter did take the geothermal water exploitation into consideration, with the intention of simulating its steady flow in natural conditions. The size of the simulation area and the amount of calculation has been considered comprehensively. For model discretion, the simulation area was divided into 500 rows×1 column using regular rectangular grids; and each layer has a 16 m×1 m uniform division format. There are 25 500 effective cells (Fig. 3).

According to the present research, this study set the elevation of 2 297.54 m as the model top boundary and the elevation of -465.47 m as the bottom boundary. Both top and bottom boundaries of the model was considered as constant temperature boundaries. The temperature at the top of the model was set at 8°C, which is the earth temperature of this area (Chen, 2014). The average geothermal gradient of the sedimentary layers in Guide basin is 4.3°C/100 m (Liu *et al*. 2017). The bottom boundary temperature was calculated as 69~119°C, based on the geothermal gradient and bedrock depth fluctuations. The borders on the north and south sides were defined as water- and heat-insulating boundaries, respectively. As a result, the conceptual model and associated properties are shown in Fig. 3 and Table 2. All parameters are averaged based on the actual measured values of drilling core samples with the sampling quantity shown in Table 2. In the conceptual model, vertically, the Neogene and the Paleogene thermal reservoirs are generalized into two thin equivalent thermal reservoirs, respectively, according to their thickness and depth, while the other formations are treated as aquifuges. Horizontally, because the middle part of the model is affected by the faults which displace the rock formations involved, the permeability of the fault is relatively larger than its country rocks.

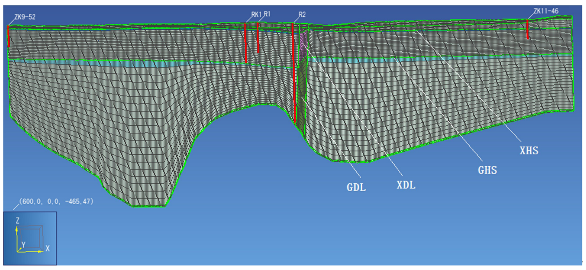


Fig. 3 Schematic diagram of model discretion and material distribution of the Guide basin on the selected profile

Table 2 Main parameter table

Material name	No. of samples	Density (kg/m^3)	Porosity	Permeability			Thermal conductivity (W/(m·c))	Specific heat capacity(J·kg·C)
				(X) (m^2)	(Y) (m^2)	(Z)(m^2)		
Aquifuge (GSC)	2	2 490.0	0.18	1.0E-16	1.0E-16	1.0E-16	1.85	1 112.45
Neogene aquifer (XHS)	5	2 380.0	0.131	2.26E-12	2.256E-12	2.256E-12	1.72	920.17
Paleogene aquifer (GHS)	3	2 463.0	0.127	7.0E-15	7.0E-15	7.0E-15	1.76	924.35
Neogene fault (XDL)	2	2 380.0	0.131	5.0E-12	1.0E-16	1.0E-16	1.72	920.17
Paleogene fault (GDL)	1	2 463.0	0.127	14.0E-15	14.0E-15	14.0E-15	1.76	924.35
Thermal insulation boundary (GRBJ)		2 490	0.108	1.0E-16	1.0E-16	1.0E-16	0	1 112.45

The lateral inflow of the model is expressed by the source-sink terms. Previous researchers calculated, on the basis of the section, the flow rates of the Neogene and Paleogene thermal reservoirs at both north and south edges of the basin by using the equation q=Q/L, where the length of the section was 13.5 km. Then, values were assigned to the two cells at the extreme edge of the layer. As a result, the source and sink terms of the Neogene thermal reservoir were 43.78 g/s on the south and 40.96 g/s on the north, respectively. In the meantime, the values for the Paleogene thermal reservoir were 0.14 g/s on the south and 0.13 g/s on the north, respectively. The temperature at the source and sink term was also calculated, based on the geothermal gradient.

Five geothermal wells ZK9-52, RK1, R1, R2, ZK11-46 (Fig. 2) were also included in the geothermal modelling process. There is basically no thermal water mining at present, so the pumping volume is not calculated in this simulation. As the model was built for thermal reservoirs with caprocks, the flows of unconfined aquifers and the Yellow River which might affect the unconfined groundwater were not considered in current study.

2.3 Model calibration

In order to identify and verify the model parameters, the method of estimation-correction was adopted in this study. During the model calibration, the parameters of rock permeability, porosity and other parameter were adjusted at a multiple stages, in order to compare the calculated values of temperature, water level with those measured in the field. The parameter adjustment would not be ceased until calculated values fit well with measured ones. The result of final correction showed that the permeabilities of each layer in three dimensions were the same. Among them, the permeability of the aquifuge is 1×10^{-16} m^2, while that of the Neogene aquifer is 2.256×10^{-12} m^2, the Neogene fault is 5.5×10^{-12} m^2 and the Paleogene fault is 1.45×10^{-15} m^2. The porosity of the aquifuge is 0.118, and other parameters remain unchanged.

On the basis of the location of monitoring boreholes and associated data of water levels monitored, both calculated and monitored water levels, as well as calculated 200 m temperatures and monitored ones were fitted and compared in the model domain for the Neogene aquifer (Fig. 4). In the meantime, the measured temperature of the well R2 borehole in the vertical direction (Fig. 5) was fitted by the ground temperature calculated through the modelling. After repeated adjustments, the fitting results are shown in Fig. 4 and Fig. 5, where the abscissa is the distance between the borehole and the starting point.

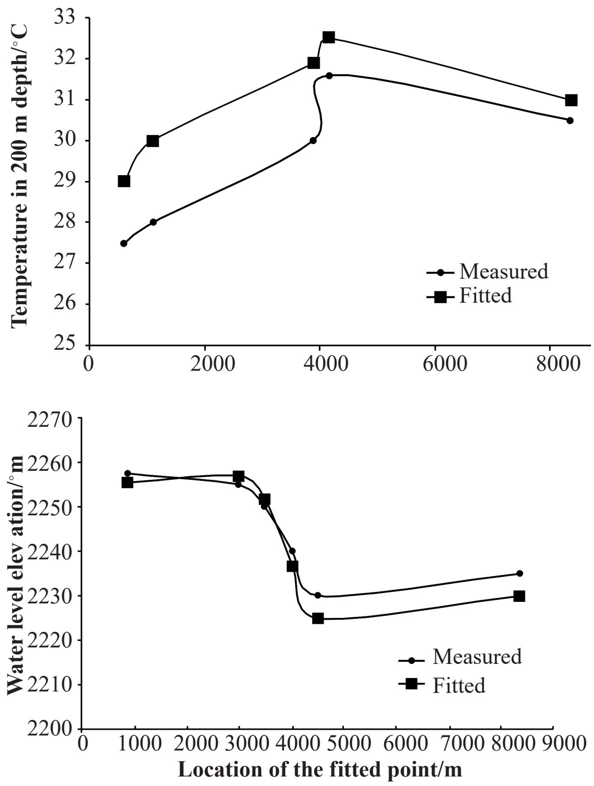


Fig. 4 Fitting curve of model Neogene thermal reservoir depth (left) and ground temperature at the 200 m depth (right)

Fig. 4 shows that the overall fitting of the water flow field in the Neogene thermal reservoir is good. The measured and fitting curves have the same trajectory, with the error rate between the two of less than 10%. Among them, the fitting effect on the south side is better than that of the north side, because there are more monitoring sites in the south than that of the north. The pattern of logged borehole water temperatures to a depth of 200 m is almost the same as that of the fitted curve, of which the error rate between the two does not exceed 10%. This phenomenon is quite normal, because the measured ground temperature of the Neogene thermal reservoir is represented by the water temperature at the corresponding position in the Neogene borehole. The mixture of shallow water with lower temperature may cause the Neogene thermal reservoir to have lower temperature than the actual ground temperature.

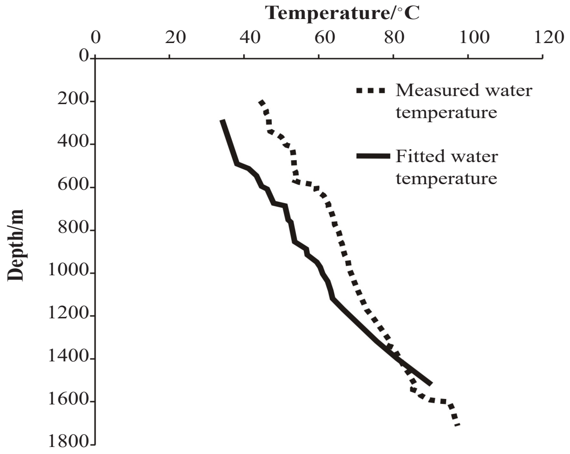


Fig. 5 Fitting curve of the relationship between depth and ground temperature in well R2

Fig. 5 shows that the temperature fitting effect in the deep part of well R2, while it indicates that the measured water temperature in the shallow part is larger than the ground temperature derived from the simulation. It is speculated that the shallow water temperature rises due to the deep Paleogene ground temperature. The error rate between the measured and fitted deep geothermal temperature is small, which suggests that the temperature fitting effect of the Paleogene thermal reservoir is suitable. At the same time, according to the simulation result, the water level of the well R2 is higher than the elevation of the wellhead, which is consistent with the current status of the artesian flow of the well.

The effect of each fitting curve shows that the simulation model basically meets the accuracy requirements and basically reflects the geothermal and geological conditions of the study area, and the basic characteristics of the geothermal water flow field and temperature field. The model can be used for prediction.

2.4 Model application

According to the modified parameters of the model and the obtained geothermal field, some formula can be used to estimate the amount of thermal storage resources. This essay adopts the thermal reservoir method with the formula as follows:

$$Q_{ri}=A_i\times H_i\times C_i\times (T_{ri}-\mathrm{T}_0)$$

Where:

Q_{ri}- heat stored in the ith layer of thermal storage (J);

A_i- area of heat reservoir (m^2);

H_i- thickness of thermal reservoir (m);

C_i- average volumetric specific heat capacity of thermal storage rock and geothermal fluid;

T_{ri}- thermal reservoir temperature (°C);

T_0- reference temperature (8°C);

Thermal reservoir cell area A_i: The total cell area of each individual thermal reservoir can be directly derived. As the rectangular grid was used for the model discretion, the size of each cell is the same, and the area A_i of each cell equals to the total area A divided by the number of the cells. According to previous study (Chen, 2014), both model length across the basin and the length of the section perpendicular to model section were known. Thus, it was able to calculate the area of each thermal reservoir.

In this study, the average thickness of the thermal reservoir H_i is the arithmetic mean value of the thickness of ith rectangular unit. In TOUGH2.0, the rock layer is no longer divided in the vertical direction, so the thickness of each cell is the layer thickness, namely $H_i=V/A$.

For the average temperature of thermal reservoir T_i, the final temperature of each cell can be output on a layer basis by the program. And the thermal reservoir reference temperature T_0, according to the average temperature of the Guide region, is 8°C.

There are many factors that have an impact on the average volume specific heat capacity C. However, in the case of a relatively homogeneous thermal reservoir where the lithology, rock density and rock specific heat capacity do not change much, and the average volume specific heat capacity can be used for the water-heat simulation. In this case, the average specific heat capacity of the Paleogene heat storage is 2.34×10^6 J/m^3·°C.

After determining the above formula, the geothermal resources of the Guide basin can be obtained by using a FORTRAN program to calculate the components of each layer as aforementioned. The total amount of geothermal resources in the Neogene is 1.1×10^{14} KJ, which is in line with the results of other researchers' studies (1.72×10^{14} KJ) (Chen, 2014). According to Geologic Exploration

Standard of Geothermal Resources (GBT11615-2010), the Neogene heat reservoir in Guide basin is a sandstone type, and the exploitable geothermal resources are 2.75×10^{13} KJ, accounting for 25% of the total. The results are similar to the study results of previous researchers. In this study, the total amount of geothermal resources in the Paleogene reservoir in the Guide basin is calculated to be 4.69×10^{14} KJ, with an exploitable geothermal resources of 1.17×10^{14} KJ.

In addition, the resource evaluation results show that the Paleogene thermal reservoir has more geothermal resource storage, around 4 times as much as that of the Neogene thermal reservoir. However, as the permeability of the Paleogene thermal reservoir is fairly low, it is not favorable to extract the resources from this reservoir. In terms of the geothermal resources development, how to maintain the balance between water and heat requires a comprehensive plan for sustainably use the resources.

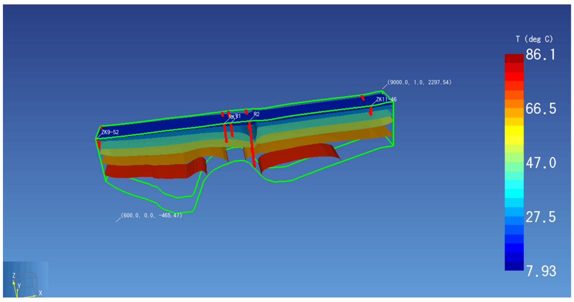


Fig. 6 The initial geothermal field of the simulated section

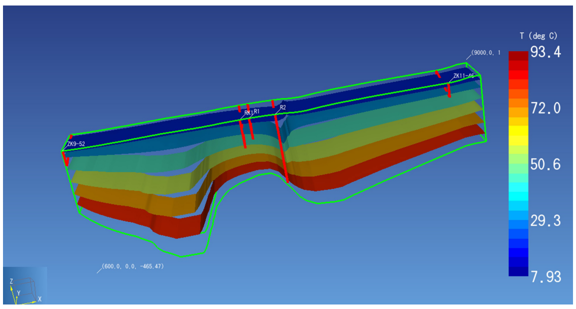


Fig. 7 Stable ground temperature field in simulated section

As shown in Fig. 6 and Fig. 7, the geothermal curve at the fault F1 is concave as a result from the stable geothermal field simulation, which indicates that the fault has a relatively low temperature. This is perhaps attributed to the infiltration of shallower groundwater of lower temperature through the fault zone, which in turn reduces the temperature at the deep portion. However, on a regional scale, the heat of geothermal field is largely dependent on natural geothermal gradient triggered by the involved rock formations. This finding is in line with the research results of the local lithospheric thermal structure and terrestrial heat flow (LANG Xu-juan, 2016; LIU Feng *et al*. 2017), and is consistent with the initial setting condition of the model that the deep part of the basin is mainly heated by the heat conduction between formations.

3 Conclusions

(1) According to the local geothermal conditions, a 2D water-heat coupled conceptual model was established in this study, with the intention of modelling the water-heat transport in the Guide basin. During the modelling process, the calibration of model parameters were carefully done by using monitoring data, resulting in good fitting effects.

(2) It can be seen from the modelling outputs that the ground temperature on the simulated domain is basically distributed on a layer basis, indicating that the ground temperature is mainly obtained through natural heating by the rock formations. However, the ground temperature anomalies in the vicinity of the fault F1 can be attributed the infiltration of groundwater with lower temperature of the shallower portion of the reservoir. This on one hand indicates that the fault F1 is highly conductive for the groundwater flow through the fault zones; and on the other hand it suggests that this fault is very important for the movement of geothermal water in the basin.

(3) The numerical modelling approach was firstly used to evaluate the resource quantity of both the Paleogene and the Neogene geothermal fields in the Guide basin. The estimated resources storage of the Paleogene is considerable, comparing with that of the Neogene thermal reservoir, whereas due to its low permeability the exploitability of the Paleogene reservoir becomes uncertain. In respect of the entire Guide basin, the estimated quantity of the geothermal resources is close to that of the previous studies, with the differences arose from the scope of study area taken into account for the resources calculation.

As regard to the formation mechanism of the Guide basin geothermal reservoir, it is believed that the groundwater that flows from the basin edges towards the center is heated by the Neogene sedimentary rocks with high thermal gradients; and as a result forms the Neogene thermal reservoir. Furthermore, faulting systems across the basin act as preferential groundwater flow paths which on one hand provide additional and rapid flows to the thermal reservoir, but on the other hand assist in cooling down the thermal water in the vicinity of the faults.

At the same time, the study of geothermal resources in Guide basin is still relatively insufficient. This study did not consider the changes in the physical properties of the reservoir during the fluid flow process and certain errors in the representativeness of the sectional two-dimensional flow model among the thermal state of the entire basin. In the future, further in-depth research should be conducted for the purpose of the sustainable development and utilization of local geothermal resources.

Acknowledgements

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References

Alberto J, Javier R, Carlos V, *et al*. 2012. The thermal state and strength of the lithosphere in the Spanish Central System and Tajo basin from crustal heat production and thermal isostasy. Journal of Geodynamics, 58: 29-37. Doi: 10.1016/j.jog.2012.01.005.

Ben N, Andrea F, Niels B. 2008. Heat flow and lithospheric thermal regime in the Northeast German basin. Tectonophysics, 460: 215-229. Doi: 10.1016/j.tecto.2008.08.022.

Chen HJ. 2014. Qinghai Province Guide basin characteristics of geothermal geology and geothermal resource evaluation. M.S thesis. Beijing: China University of Geosciences (Beijing).

FANG Bin, ZHOU Xun, LIANG Si-hai. 2009. Characteristics and utilization of the Zhacang hot springs in Guide County, Qinghai. Geoscience, 23(1): 57-63.

GAO Liang, LIANG Juan-e. 2013. Numerical simulation of thermal reservoir of Guantao Formation in Wuqing region based on TOUGH 2.0. China Water Transport, 13(11): 141-142, 145. Doi: CNKI:SUN:ZSUX.0.2013-11-060.

General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. 2011. Geologic exploration standard of geothermal resources (GBT11615-2010).

LANG Xu-juan, LIU Feng, LIU Zhi-ming, *et al*. 2013. Terrestrial heat flow in Guide basin, Qinghai. Geological Science and Technology Information, 3: 227-232. Doi: CNKI:SUN:DZKQ.0.2016-03-031.

LANG Xu-juan. 2016. The thermal structure and geothermal genesis mechanism in Guide basin. Ph.D thesis. Beijing: Chinese Academy of Geological Science.

LEI Hong-wu, JIN Guang-rong, LI Jia-qi, *et al*. 2014. Coupled thermal-hydrodynamic processes for geothermal energy exploitation in enhanced geothermal system at Songliao basin, China. Journal of Jilin Unviersity: Earth Science Edition, 44(5): 1633-1646. Doi: 10.13278/j.cnki. jjuese.201405207.

LIAO Juan, MA Teng, CHEN Liu-zhu, *et al*. 2013. Hydrochemistry of high-arsenic thermal groundwater of low-temperature in the Guide basin in Qinghai, China. Hydrogeology and Engineering Geology, 40(4):121-126. Doi: CNKI:SUN:SWDG.0.2013-04-024.

LI Le-le. 2016. Research on the preservative research on the preservative law and genetic model of geothermal resources in Guide basin, Qinghai Province. M.S. thesis. Nanchang: East China University of Technology.

Li XW, Mo XX, Yu XH, *et al*. 2013. Petrology and geochemistry of the early Mesozoic pyroxene andesites in the Maixiu Area, West Qinling. China: Products of subduction or syn-collision? Lithos, 172-173: 158-174. http://dx.doi.org/10.1016/j.lithos.2013.04.010.

LI Zhao-hong. 2016. LNAPLs leakage and migration feature assessment in one watersealed cavern based on water curtain and air tightness theory. M.S. thesis. Beijing: China University of Geosciences (Beijing).

LIN Wu-le, HU Xiang-yun, CHEN Yu-feng, *et al*. 2017. Geothermal research in Guide basin. Annual Meeting of Chinese Geoscience Union 2017.

LIU Feng, LANG Xu-juan, LU Chuan, *et al*. 2017. Thermophysical parameters and lithospheric thermal structure in Guide basin, northeast Qinghai–Tibet Plateau. Environmental Earth Sciences, 76: 199. DOI:10.1007/s 12665-017-6503-2.

LIU Xue-yan. 2010. Numerical analysis of coupling between heat transfer and seepage in fracture rock near field of nuclear waste repository. M.S. thesis. Beijing: Beijing Jiaotong University.

Liu YS, Gao S, Jin SY, *et al*. 2001. Geochemistry of lower crustal xenoliths from Neogene Hannuoba basalt, North China craton: Implications for petrogenesis and lower crustal composition. Geochimica et Cosmochimica Acta, 65(15): 2589-2604. DOI: 10.1016/S0016-7037(01)00609-3

Michael JOS, Karsten P, Marcelo JL. 2001. State of the art of geothermal reservoir simulation. Geothermics, 30(04): 395-429. Doi: 10.1016/S0375-6505(01)00005-0.

Oliver S, Heather A, Sheldon L, *et al*. 2013. Hydrothermal models of the Perth metropolitan area, Western Australia: Implications for geothermal energy. Hydrogeology Journal, 21:605-621. DOI: 10.1007/s10040-012-0945-0.

Pollack HN, Hurter SJ, Johnson JR. 1993. Heat flow from the earth’s interior: Analysis of the global data set. Reviews of Geophysics, 31:267-280. Doi: 10.1029/93RG01249.

Pruess K, Coldenburg, Gmoridis. 1999. TOUGH2 user’s guide. USA: Lawrence Berkeley National Laboratory: 1-210.

SONG Chun-hui, FANG Xiao-min, GAO Jun-ping, *et al*. 2001. Tectonic uplift and sedimentary evolution of the Guide basin in the northeast margin of Tibetan Plateau in Cenozoic Era. Acta Sedimentologica Sinica, 19(4):493-500. Doi: 10.3969/j.issn.1000-0550.2001.04.003.

WANG Gui-ling, ZHANG Wei, MA Feng, *et al*. 2018. Overview on hydrothermal and hot dry rock researches in China, China Geology, 1: 273-285. doi: 10.31035/cg2018021.

WANG Gui-ling, LIU Zhi-ming, LIU Qing-xuan, *et al*. 2002. Modeling of geothermal reinjection in Xi’an geothermal field, West China. Acta Geoscientica Sinica, 2: 183-188. DOI: 10.3321/j.issn:1006-3021.2002.02.016

WANG Yang, ZHANG Ke-ni. 2011. Fracture simulation method of enhanced geothermal system (EGS). Annual Meeting of Chinese Geoscience Union.

XUE Yu-qun, XIE Chun-hong. 1980. A review of numerical methods application in hydrogeology. Hydrogeology and Engineering Geology, 1: 40-45. DOI: CNKI: SUN: SWDG.0.1980-01-012.

YUE Gao-fan, DENG Xiao-fei, XING Lin-xiao, *et al*. 2015. Numerical simulation of hot dry rock exploitation using enhanced geothermal systems in Gonghe basin. Science & Technology Review, 33(19): 62-67. Doi: 10.3981/j.issn.1000-7857.2015.19.010.

ZHANG Yuan-dong, WEI Jia-hua, WANG Guang-qian. 2006. Impact of regional groundwater flow on geological temperature field with energy abstraction from the aquifer. Journal of Tsinghua University (Science and Technology), 9: 1518-1521. DOI: 10.3321/j.issn:1000-0054.2006.09.007.

ZHENG Yan. 2009. Numerical simulation study on geological storage of carbon dioxide in Jiangling Sag, Jianghan Basin. M.S. thesis. Wuhan: China University of Geosciences (Wuhan).