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Genetic mechanism and Exploration Target of the Gulu Geothermal Field in Tibet, China

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ABSTRACT

Gulu geothermal field locates in the north place of Naqu-Nimu geothermal belt, which is the most important geothermal belt in Tibet. There are lots geothermal fields in the belt, including the famous Yangbajing geothermal field. In order to evaluate the geothermal resources, geological, hydrogeological and geophysical works were carried out. There is a low resistivity anomaly zone, about 4-8 km below the surface. The low resistivity anomaly zone indicate that there is partial melt in the deep of the field, which constitutes the main heat source of the Gulu geothermal field. The S-N striking fracture F_{4-2} is considered to control the thermal activities due to the fact that most hot spring spots occur along this fracture. The hydrogeological work shows that the hydrochemical type is mainly $HCO_3 \cdot Cl$-Na, salinity is from 2.2 g/L to 2.8 g/L. The content of fluorine in the hot water is more than 10 mg/L, indicating that it experienced deep circulation. According to the SiO_2 geothermometer, the highest temperature of the geothermal reservoir in the deep is from 215 °C to 228 °C. There are two types of geothermal reservoirs in the field: banded geothermal reservoir and layered geothermal reservoir. The banded geothermal reservoir is controlled by the fracture F_{4-2}, and located in the fracture F_{4-2}, together with the joints of the hanging wall of F_{4-2}. The sinter and the Quaternary is the cap of the geothermal reservoir. In the exploration area, the fault zone of F_{4-2} is the target of exploration; but outside the exploration area, the fault on the east side of the Gulu basin should be the paid more attention.

1. INTRODUCTION

Gulu geothermal field is a high-temperature geothermal field in the Naqu - Nimu geothermal belt of Tibet, which is located about 90 km south of Naqu City. At present, the geothermal field is still in the exploration stage. The predecessors have carried out a lot of research work on the structural characteristics, hydrochemistry, sinter deposit characteristics and genetic models of the Gulu geothermal field (Zhao et al., 2010; Zhang et al., 2014; Hao et al., 2022). However, the above achievements mostly focus on the geophysics, hydrology and hydrochemistry, and lack of systematic understanding of the genesis of the Gulu geothermal field.

Based on the geological survey, hydrological and hydrochemical research, geophysical survey and borehole verification results carried out in the early stage, this paper expounds the basic geological characteristics, deep heat source, heat control structure, groundwater circulation process and cap rock characteristics of the Gulu hot field, and then the genetic mechanism of the geothermal field were analyzed, providing a basis for further exploration and development.

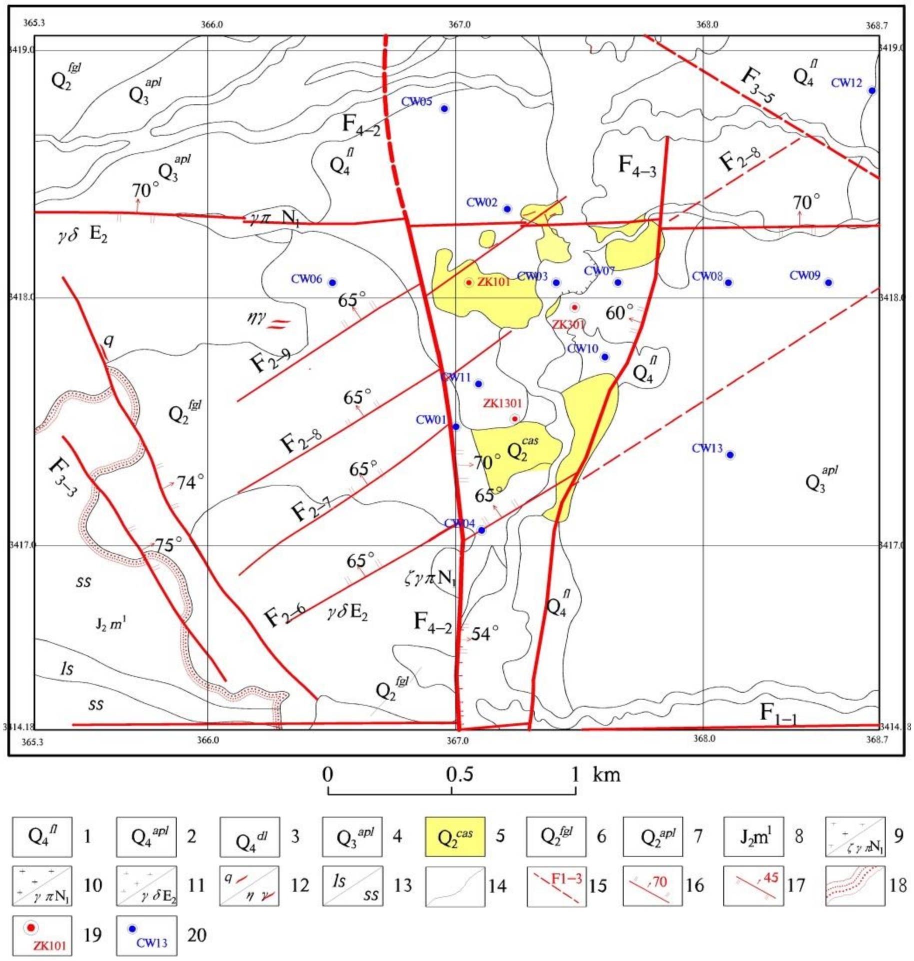
2. GEOLOGY

2.1 Rock types

Gulu geothermal field is located in the west of Gulu basin, and the exposed strata on the surface include Middle Jurassic Mali Formation and Quaternary. The Mali Formation is distributed in the southwest and southeast of the geothermal field, with an area of about 3.5 km^2 and a thickness of more than 500 m. The main lithology is quartz sandstone, limestone interbed with sandstone, carbonaceous shale, etc. Affected by intrusive rocks, thermal metamorphism occurred in Mali Formation. The geothermal field is largely covered by the Quaternary, about 25 km^2, including: Holocene alluvial-proluvial deposit (Q_4^{apl}), Holocene swamp deposit (Q_4^{fl}), Late Pleistocene alluvial-proluvial deposit (Q_3^{apl}), Middle Pleistocene alluvial-proluvial deposit (Q_2^{apl}), Middle Pleistocene ice-water deposit (Q_2^{fgl}), Middle Pleistocene sinter (Q_2^{cas}) (Fig. 1). Among them, the sinter is closely related to the formation of the geothermal field in this area, which is the direct product of geothermal activities.

2.2 Structures

The fault structures in Gulu geothermal field mainly include S-N, E-W, N-E and N-W groups. The fault of S-N includes F_{4-2} and F_{4-3}; EW fault structure includes F_{1-1} and F_{1-3} fractures; N-E fault structure includes F_{2-2}, F_{2-6}, F_{2-7}, F_{2-8}; NW fault structure includes F_{3-3}, F_{3-4} and F_{3-5}. Among the above faults, the F_{4-2} fault in SN direction is the most important fault in the thermal field. The fault is on the west edge of the Gulu basin, which runs through the west side of the whole hot field in the north-south direction. The fault dip is E, and the dip angle is between 60 ° and 70 °. The F_{4-2} fault extends northward through the EW-trending F_{1-3} fault, and then is covered by the Quaternary sediments. Compared with S-N fault, N-E fault is relatively small in scale. On the surface of sinter platform, a large number of NE-trending tensile fractures are developed. These fractures are channels of hot water near the surface, some are active, and some have been blocked. According to the statistics of these fractures, their strike changes in a wide range, ranging from 20 ° to 70 °.



1-Holocene swamp deposit; 2-Holocene alluvial-proluvial deposit; 3-Holocene swamp deposit; 4-Late Pleistocene alluvial-proluvial deposit; 5-Sinter; 6-Middle Pleistocene ice-water deposit; 7-Middle Pleistocene alluvial-proluvial deposit; 8-Mali Formation; 9-Syenogranite porphyry; 10-Granite porphyry; 11-Granodiorite; 12-Quartz vein and monzogranite vein; 13-Limestone and sandstone; 14-Geological boundary; 15-Inferred fault; 16-Measured normal fault; 17-Measured reverse fault; 18-Alteration belt; 19-Exploration well; 20-Temperature measuring hole.

Fig.1 Geological map of Gulu geothermal field

3. HEAT SOURCE

Previous researchers have studied the heat source of some geothermal fields in Tibet, and believe that the driving mechanism of hydrothermal activity in Tibet is the low-velocity and high-conductivity layer (partial melting layer) commonly existing in the crust. The depth of the melting layer is 5-6 km and 15-20 km. The partial melting layer not only provides heat source for shallow hot water activities, but also provides fluids and ore-forming materials (Zhao et al., 2001). Although many mathematicians agree that the heat source is the partial melting layer in the shell. There are still some disputes about the depth, scale and existing form of the molten layer in the crust (Shen et al., 1984; Zhao et al., 2002; Duo et al., 2003; Hou, et al., 2006).

In order to further identify the heat source of the Gulu thermal field, several MT profiles across the basin were carried out in the geothermal field. In the core area of the field, the section point spacing is 100 m. At the periphery of the field, the section point spacing is gradually widened to 500 m. The detection frequency is 0.01 HZ, which can effectively reflect the characteristics of resistivity anomalies at a depth of 10 km below the surface. Among them, on the MT 5 profile (Fig. 2) passing through the core area of the geothermal field in the valley, it can be found that there are low resistivity anomalies with resistivity values less than 40 $\Omega \cdot$ m within the depth range of 4-8 km below the surface. The low resistivity anomaly is located directly below the geothermal field, with a thickness and width of about 2 km, while this low resistivity anomaly does not exist on the MT 7 profile about 2 km north of the MT 5 profile. The MT 5 profile passes through the core area of the Gulu hot field. Therefore, it is speculated that the low resistivity anomaly may be the "melting body" of deep granitic magma.

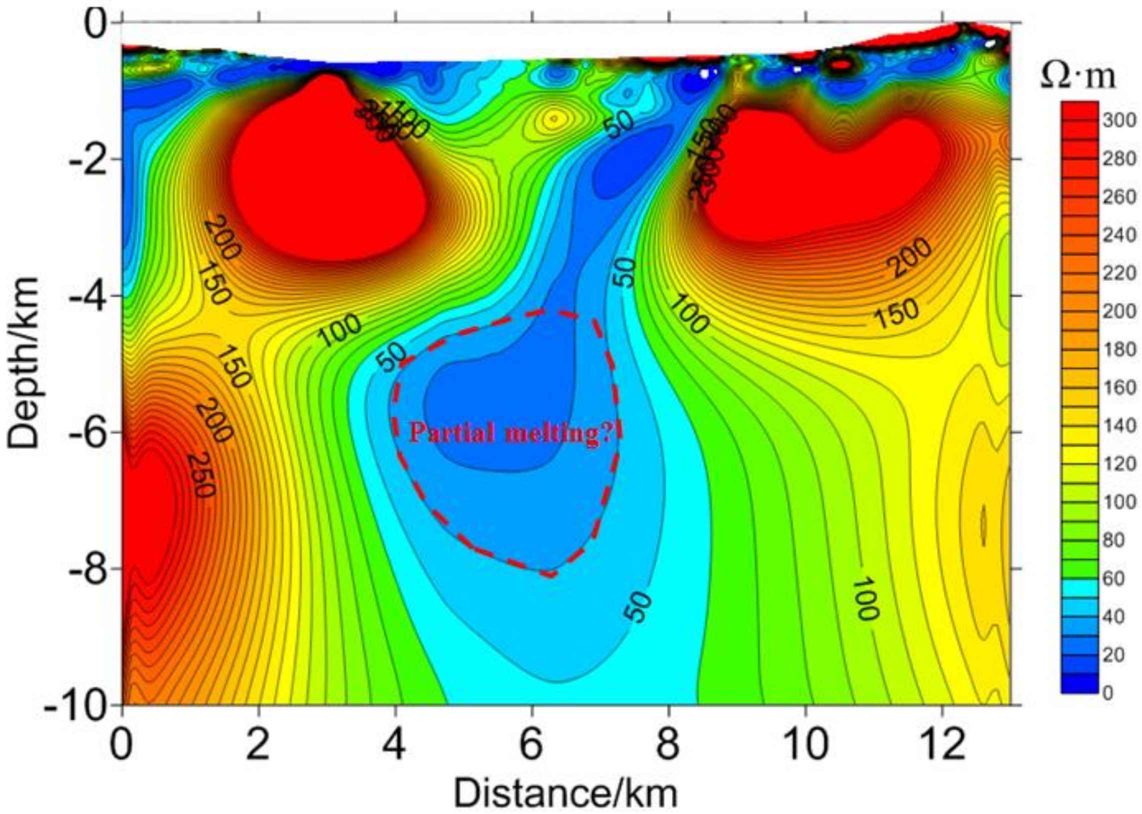


Fig. 2 Resistivity characteristics of MT 5 profile in the geothermal field

4. STRUCTURE AND CONTROLS ON RESERVOIR

4.1 Characteristics of structure

The fault on the west side of Gulu basin tends to the east, with an average dip angle of 66°, mostly between 51 ° and 78°; The fault on the east side of Gulu basin dips to the west, with the dip angle mostly between 60° and 87°, with an average of 74°. On the other hand, the MT geophysical section across the basin also reflects that the dip angles of faults on the east and west sides of the basin are steep in the west and gentle in the east. On the MT 5 profile of the basin, the dip angle of the fault on the west side of the basin is relatively gentle, mostly about 60 °, while the dip angle of the fault on the east side of the basin is relatively steep, mostly about 70 °.

Both the eastern and western faults of the basin are often characterized by multi-period activities. On the east side of the Gulu basin, there is a fracture zone, with a fracture width of about 0.5 m and an extension of more than 5 m. Tectonic breccia cemented by rock debris is developed in the fracture zone. At the same time, it is observed that the fault fracture zone is staggered by a normal fault in the same direction in the later stage, and the fault dip angle is 80°. It shows that the fault has at least two phases of activity (Fig. 3). It is also observed that two groups of scratches in different directions appear on the fault plane, which also indicates the multi-period activity characteristics of the fault.

The north-south faults on the east and west sides of the basin are mainly normal faults with strike-slip characteristics. Among them, NE-trending faults are mostly left-lateral strike-slip and NW-trending faults are mostly right-lateral strike-slip. This feature matches the stress field direction of the whole Qinghai-Tibet Plateau in the north-south compression. On the east side of the Gulu basin, a west-dipping normal fault can be seen. The dip direction of the fault is 255° and the dip angle is 86°, the dip direction of the scratch on the fault surface is 358°, and the dip angle is 65°, indicating that the fault is dominated by normal fault with weak dextral strike slip (Fig. 4).

No matter in the east or west of the basin, there is more than one basin-margin fault, often a group of parallel faults, which together form the basin-margin fault system. However, among these faults, the fault at the edge of the basin is often the largest and deepest fault, and the other faults tend to converge towards the main fault in the deep. These fault systems often form low resistivity anomaly zones with a width of 300 m - 1000 m, and the resistivity is generally lower than 100 Ω · m. It is speculated that these low resistivity anomaly zones are water-bearing fault fracture zones controlled by fault systems. In the fault system, low resistivity anomalies with resistivity lower than 30 Ω· m and even lower than 10 Ω· m often occur within 2 km below the surface. Some of these low resistivity anomalies are in the form of long strips and some are in the form of lumps. It is speculated that these low resistivity anomalies are caused by hot water (reservoir) in the tectonic fracture zone. Below 2 km of the surface, even in the fault zone, the resistivity also has a trend of increasing gradually, reflecting that with the increase of depth, the tensile fault zone is gradually closed, and the deeper the water content is relatively worse. Therefore, it is an important target in shallow geothermal exploration with low resistivity anomaly.

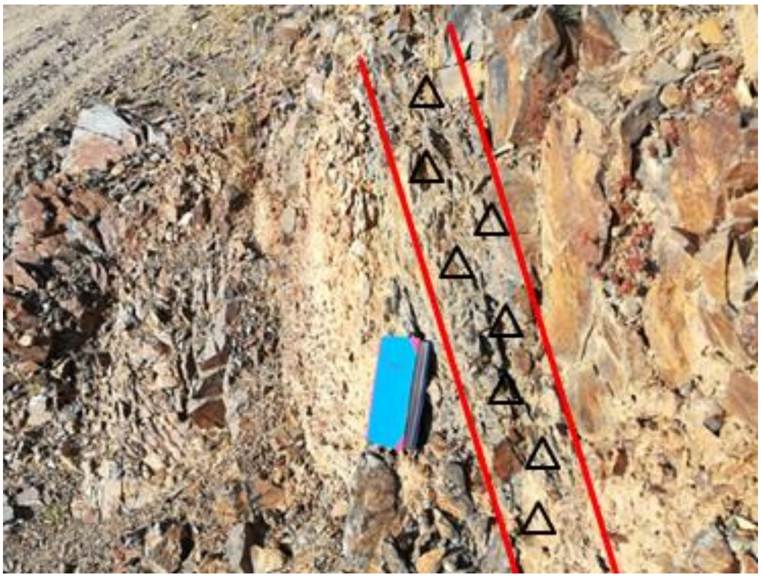


Fig. 3 Fault characteristics of two phases activity in the east of Gulu basin

Fig. 4 The scratch on the fault surface indicates that the normal fault has dextral strike-slip

5. HYDROGEOLOGICAL CHARACTERISTICS

The Sangqu River, which passes through the Gulu geothermal field, has a salinity of 52~159 mg/L and a hydrochemical type of HCO_3-Ca or $HCO_3 \cdot SO_4$-Ca. Because of the supply of high salinity hot water in the heat display area, the salinity of the downstream is higher than that of the upstream. In the Gulu hot field, the salinity of hot water is 2.2~2.8 g/L, and the hydrochemical type is $HCO_3 \cdot$ Cl-Na or Cl $\cdot$ HCO_3-Na. Among them, the hydrochemical type of Gulu boiling spring is Cl $\cdot$ HCO_3-Na type, with relatively high degree of mineralization and weak mixing of surface cold water. The fluorine content in the Gulu boiling spring water sample is 14.3 mg/L and 13.4 mg/L respectively, indicating that it has the characteristics of deep circulation.

According to the SiO_2 geothermometer, the reservoir temperature of Gulu geothermal field is 180~206 °C, the reservoir temperature calculated by the Na-K temperature scale is 215~228 °C, and the reservoir temperature calculated by the K-Mg temperature scale is 198~243 °C. According to the relationship between the chemical temperature scale of Yangbajing reservoir temperature and the measured value, the cation temperature scale in the high temperature system is closer to the measured value, so it is speculated that the thermal storage temperature of Gulu geothermal field is 215~228 °C.

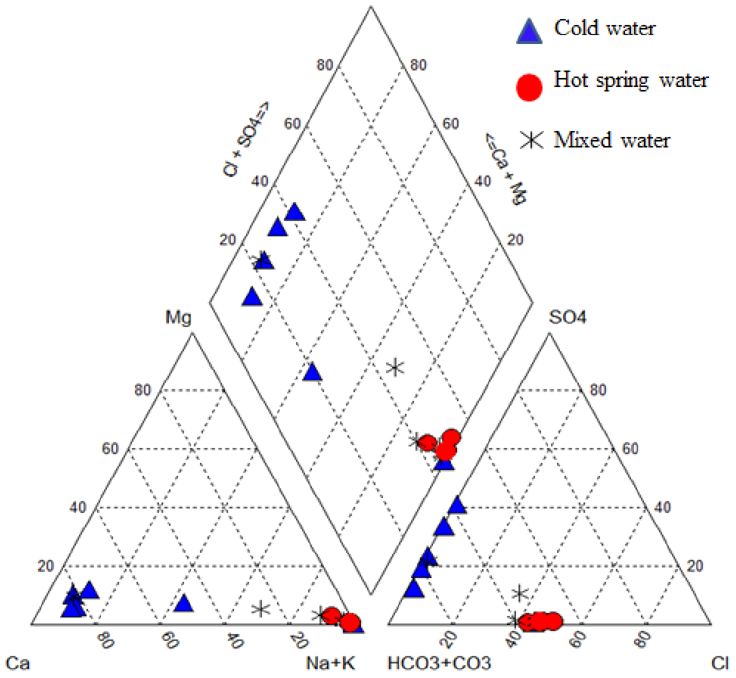


Fig. 5 Hydrochemical type map of Gulu geothermal field

6. CAP CHARACTERISTICS

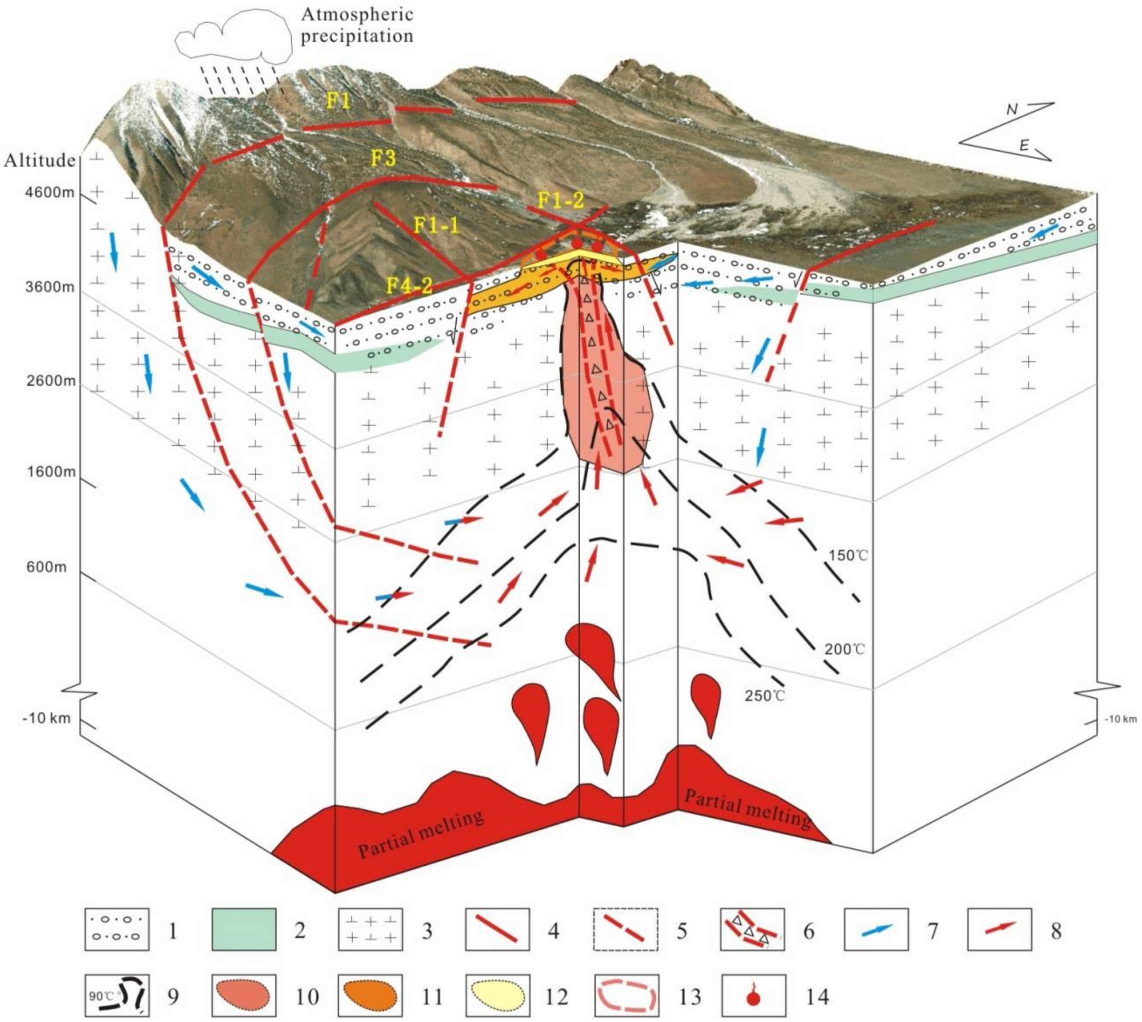
There are two types of caprocks in Gulu geothermal field, one is siliceous sinter, and the other is argillaceous sediment. The distribution area of siliceous sinter in Gulu geothermal field is relatively large, about 0.5 km^2. The drilling revealed that between 55 m and 80 m, there is a high temperature thermal reservoir with a temperature of about 150 °C. Although there are many groups of fractures in the surface sinter, the water volume on the surface is not large, which indicates that the sinter has played a good role in protecting the thermal reservoir under it. In addition, the argillaceous sediments in the Quaternary also play a good role in capping the Quaternary reservoir. Before the construction of CW08 temperature measuring hole, there was no surface temperature anomaly at surface. The temperature measurement curve of the hole shows that the temperature reaches 110.5 °C at 48 m below the ground surface, and a constant temperature zone with a thickness of about 16 m appears, indicating that there is a reservoir in the Quaternary. From the surface to the reservoir, the temperature gradient reaches 199 °C /100 m. It shows that the argillaceous sediment of the Quaternary plays a good role in capping the reservoir.

7. RESERVOIR CONCEPTUAL MODEL

Within the depth of 4-8 km below the surface of the Gulu hot field, there are low resistivity anomalies with resistivity values less than 40 Ω · m. The low resistivity anomaly may be a "melting body" formed by partial melting of deep granitic rocks, which may be the heat source of the hot field. Most of the underground hot water comes from the atmospheric precipitation, and a small amount of fluid from magma. During the circulation of underground water depth, the concentration of Cl in high-temperature geothermal water is relatively high due to the continuous water-rock interaction. The F_1 fault on the western edge of the basin, with its large scale, deep cutting and sufficient water sources nearby, is the main supply channel for the deep thermal fluid of the thermal field in the region. F_{4-2} fault is the main channel for geothermal fluid to rise. The NE-trending fault in the basin is the main channel for the lateral migration of geothermal fluid in the shallow part. After the geothermal fluid rises along the main channel and is blocked (sinter, altered rock), it will enter the faults in other directions and diffuse along these faults to other directions. Some of the thermal fluid enters the Quaternary gravel layer, forming a shallow Quaternary thermal reservoir. Sinter and Quaternary argillaceous sediments are the cover of the thermal field.

CONCLUSIONS

The partial melt at a depth of 4-8 km below the surface of the Gulu hot field provides heat source. F_1 on the west side of the basin is the main channel for fluid supply of the hot field; F_{4-2} fault is the main channel for the rise of thermal fluid. The hydrochemical type of geothermal water is HCO_3 · Cl-Na. The fluorine content in hot spring water is more than 10 mg/L, indicating that the groundwater has experienced deep circulation. Sinter and the argillaceous sediments in the Quaternary are the main caprocks of the geothermal field. There are two types of reservoirs in the geothermal field, namely, bedrock fissure thermal reservoir and Quaternary reservoir. F_{4-2} fault and its controlled thermal reservoir are the main exploration targets of future thermal fields.



1-Quaternary; 2-Mali Formation; 3-Granodiorite; 4-Fault; 5-Inferred fault; 6-Fracture zone; 7-Migration direction of cold water; 8-migration direction of hot fluid; 9-Isotherm; 10-Bedrock reservoir; 11- Reservoir in Quaternary; 12-Sinter; 13-Surface thermal anomaly; 14-Hot spring

Fig. 6 Reservoir conceptual model of Gulu geothermal field

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