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Geothermal reservoir forming model and resource potential of North-South geothermal belt in southern Tibet

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ABSTRACT

Geothermal resource evaluation and development potential analysis are important basis for accurate development of geothermal resources in the zone. On the basis of synthesizing the previous research results and the latest field work results, the geothermal reservoir forming model in the key geothermal zones in southern Tibet is established by the analysis of the main factors such as geothermal geological conditions, main structural characteristics and geothermal water supply sources. The high-temperature geothermal resources in southern Tibet is under the background of high geothermal flow value in Tethys convergent plate edge geothermal domain, the high temperature geothermal fluid formed by atmospheric precipitation and snowmelt water as cold water supply source, infiltrating along the fault to the deep melt to heat. The hydrochemical types of geothermal water are mainly Cl-Na and Cl·HCO_3-Na. The fluid interacts with the surrounding rock, finally discharged through hot springs, geothermal wells and other forms. According to the density of hydrothermal display, the scale of active structure development, and the market demand for geothermal power generation and heating, The three nearly north-south graben tropics of Shenza-Dingjie, Naqu-Yangbajing-Yadong and Riduo-Cuona in southern Tibet are selected as geothermal resource development potential areas, the total geothermal reserves is 65.6×10^{14}kJ, which is equivalent to 22427×10^{4}t of standard coal, have a good prospect of geothermal market development.

1 INTRODUCTION

The formation model of geothermal units in China is based on different levels of tectonic units, combined with structural development, stratigraphic structure, geothermal display and distribution characteristics of geothermal resources. It is divided into five levels from large to small: geothermal domain, geothermal region, geothermal zone, geothermal system and geothermal reservoir (He Zhiliang et al., 2017). The southern part of the Qinghai-Tibet Plateau is located in the Tethyan plate margin geothermal domain (Zhang Ying et al., 2017). Under the tectonic background of the strong collision between the Indian plate and the Eurasian plate, a series of high-temperature hydrothermal systems are densely distributed along the Yarlung Zangbo suture zone, concentrated on the north-south fault depression zone in the Lhasa-Gangdise terrane (Xu Jiren, 2005). The specific table of such high-temperature hydrothermal system is as follows: after the continental collision, the rocks in the crust are remelted and the deep-circulated groundwater is heated (Tong Wei et al., 1990), which is transported to the shallow thermal reservoir or directly exposed to the surface through the cataclastic water transmission section in the geological structure (zone) along the fault zone, intrusive rock contact zone and volcanic eruption channel. Some scholars consider the geothermal system temperature is controlled by the thermal conduction of magma sac as "magma heat source type" geothermal system (Guo Qinghai, 2022). At present, the temperature of 131 geothermal fields are higher than 150°C in the Yarlung Zangbo suture zone and the modern active tectonic belt on both sides of southern Tibet, of which 8 geothermal fields have temperature higher than 200 ℃ (Duoji, 2003).

As one of the few regions in China that are suitable for large-scale development of geothermal power generation and cascade comprehensive utilization, the geothermal resources exploration in Tibet in the 1970s. From 1973 to 1976, during the first comprehensive scientific expedition to the Qinghai-Tibet Plateau, the geothermal resources in Tibet was preliminarily investigated and studied. The Geothermal Geology Brigade of the Geological and Mineral Exploration Bureau of the Tibet Autonomous Region carried out two rounds of regional geothermal resource zoning work in 1987-1990 and 2007-2009. The general survey of hydrothermal geothermal resources in Changdu, Shigatse and Shannan completed in 2015-2018, preliminarily grasped the distribution and relevant information of geothermal resources in the key regions of Tibet. In general, the exploration level of geothermal resources in Tibet is far from enough compared with other regions with rich geothermal resources. The different accumulation pattern types of geothermal resources determine their geothermal resource grade and utilization potential (Wang Xinwei, 2021). The hot water reservoir formation model in Tibet is controlled by tectonic movement. The hot water exchanges material and energy with the surrounding rock during the rise along the main thermal control fault. After reaching the shallow part, the temperature decreases due to the mixing effect of cold water (Zhang Meng, 2014). The conceptual model of typical geothermal field also has a certain research basis. For example, the deep heat source of Chazi geothermal field is Himalayan magmatism, and the strong tectonic activity provides a channel for the infiltration of groundwater. The groundwater and the heat source body are heated after contact, and rise to the surface along the fault structure to form a hot spring (Luo Shaoqiang, 2020). Based on the above research, this paper, starting from the regional tectonic-sedimentary evolution-geothermal anomaly in southern Tibet, dissects the south-north key geo-tropical reservoir-forming model in southern Tibet and analyzes the impact of tectonic movement on the geothermal reservoir-forming model in the region according to the analysis idea of "source, reservoir, migration and cover". This paper puts forward the development direction of different types of geothermal fields in the region, which provides certain theoretical and technical support for the next step of finding out the scale of geothermal resources in southern Tibet and making rational use of them as required.

2.Geothermal geological conditions

2.1 Regional tectonic background

The basic geological conditions decide the geothermal enrichment area in a broad sense, and the later tectonic movement is the main control factor of geothermal reservoir formation. On the formation process of the Qinghai-Tibet Plateau, predecessors have done a lot of basic research work, and their understanding of its overall pattern is basically the same, the Qinghai-Tibet Plateau is formed by the combination of multiple terrains after the land-continent collision (Liao Zhijie, 1999). The migration of the original, ancient and new Tethyan tectonic systems from north to south is a kind of relay collision (Pan Guitang, 2012). From south to north, several collision zones have been formed successively, such as the Yarlung Zangbo River, Shiquan River - Shenzha-Namco Lake, Bangong

Lake - Nu River, Chasang - Shuanghu Lake, Ulan Ula - North Lancang River, Hoh Xili - Jinsha River. Affected by the remote effect of the collision orogenic belt, the Tethys Himalaya block, Lhasa-Gangdise block, Qiangtang block, Songpan-Ganzi block and Qaidam block are developed with the suture zone as the boundary, and the tectonic activity gradually weakens to the north. In this paper, the southern region of Tibet, where geological activities are the most intense and a variety of tectonic associations are developed, is the main research area. The tectonic movement in the area is reflected by the several graben systems after nearly south-north compression to nearly east-west extension, which are roughly limited between the Himalayan piedmont thrust fault zone and the Bangong-Nujiang suture zone in the south. The large-scale grabens distributed from east to west are Riduo-Cuona, Yadong-Gulu, Shenzha-Dingjie and Nima-Dingri grabens (Fig. 1). These grabens basically pass through the Yarlung Zangbo River to the north, cut the Himalayan block and Lhasa block at the same time, and cut the southern Tibetan detachment system to reach the high Himalayas (Ding Lin et al., 2006), which is the current shallow seismic development area (He Rizheng, 2003) and the concentration area of late Cenozoic magmatic activity and recent hydrothermal activity, taking the complex geological structure as the background. A large number of medium-high temperature geothermal resources have been formed in the graben system in southern Tibet.

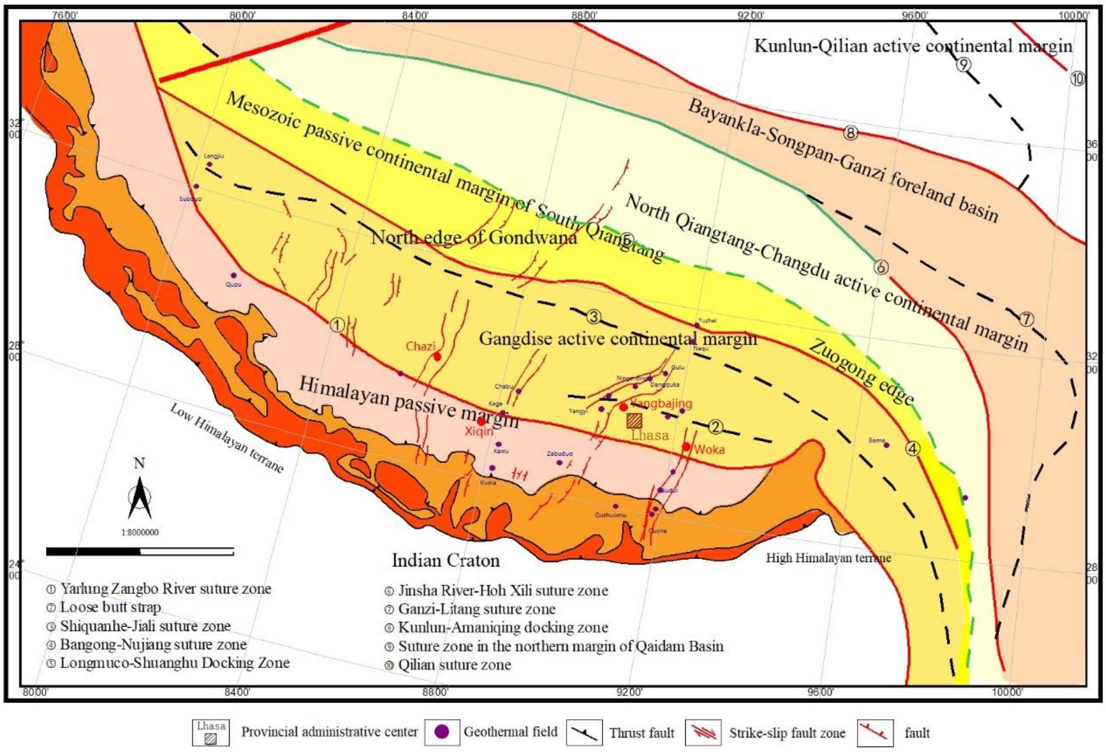

Fig. 1 Tectonic unit map of the Qinghai-Tibet Plateau and its periphery

2.2 Heat control by active structure

The geothermal resources in southern Tibet are concentrated in the intersection of regional faults on both sides of the Lhasa-Gangdise block and its southern Yajiang suture zone, characterized by high geothermal flow(>100mW/m^2), large variation (90~150W/m^2) and high water temperature (geothermal wellhead temperature 55~329℃). There are strong hydrothermal activities in the active zone. The display type is mainly hot springs. At the same time, there are many geysers, boiling fountains and large areas of hydrothermal alteration, including 84 hot spring areas, with an average temperature of 69℃ (Fig. 2). At present, the proven high-temperature hydrothermal areas are mostly distributed in the Quaternary small fault basin (such as the Yangbajing basin) in the active zone.

The active fault hot spring, as a manifestation of the movement of deep crustal hot water along the active fault, can further explain that the geothermal enrichment in southern Tibet is controlled by the active structure. The active structure not only provides a migration channel for hydrothermal activity, but also controls the distribution and activity of young magma in the deep crust. The surface display of geothermal energy is strongly correlated with SN structure, which proves that the Cenozoic tectonic activity has an obvious control effect on geothermal energy. The geotropics in southern Tibet are basically consistent with the corresponding active tectonic zone boundaries, with the largest scale of the Riduo - Cuona, Yadong - Gulu, Shenzha - Dingjie and Nima - Dingri geotropics. At the same time, there are differences in the distribution of several high-temperature geotropics, showing the characteristics of strong in the north and low in the south, strong in the east and weak in the west.

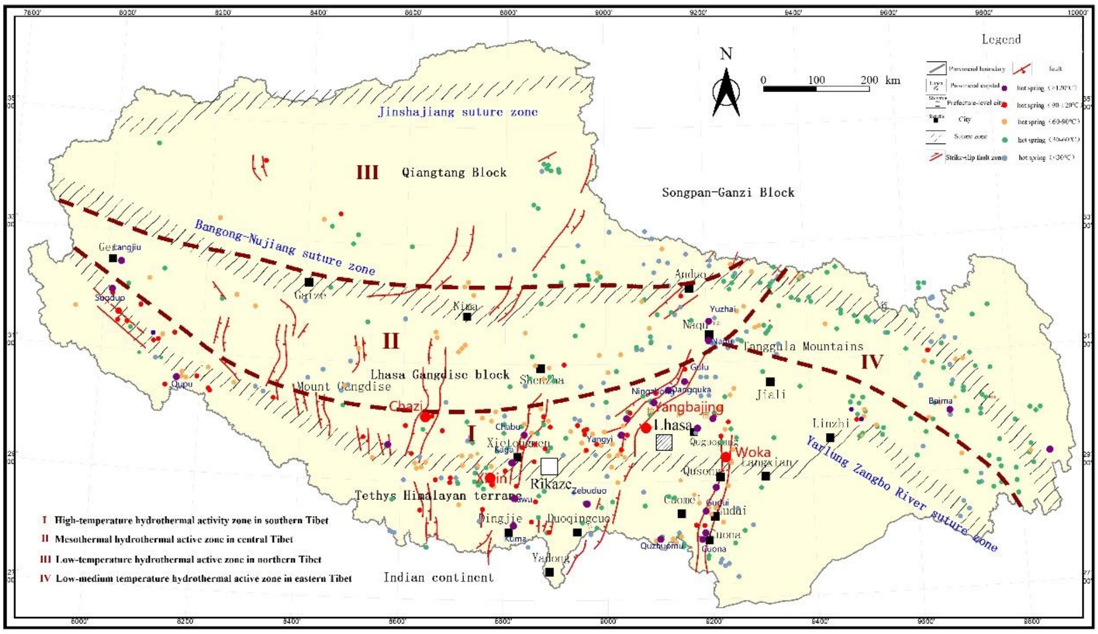

Fig. 2 Distribution of geothermal water activities in Tibet

2.3 Sedimentary evolution and reservoir control

The graben and fault basin in southern Tibet experienced the sedimentary evolution stages of the uplift of the Paleo-Tethys, Neo-Tethys and Neogene plateau. The lithology and physical properties of the strata changed under the influence of multiple tectonic movements, thus forming one or more sets of reservoir-cap assemblages at each sedimentary evolution stage. According to the field measured profile and the reservoir-seal assemblage of the developed geothermal fields such as Yangbajing, Yangyi and Gudui, the Paleozoic-Mesozoic sedimentary rocks deposited in the Tethyan rock series in the area, as well as the locally developed high-grade metamorphic rocks, and the intrusive rocks formed under the Cenozoic orogeny, such as the widely developed Linzizong Group volcanic rocks in the Lhasa block, and the Cenozoic sandstone strata in the fault basin. All above have loose porosity, high permeability and good thermal conductivity, form high-quality geothermal reservoir in this area.

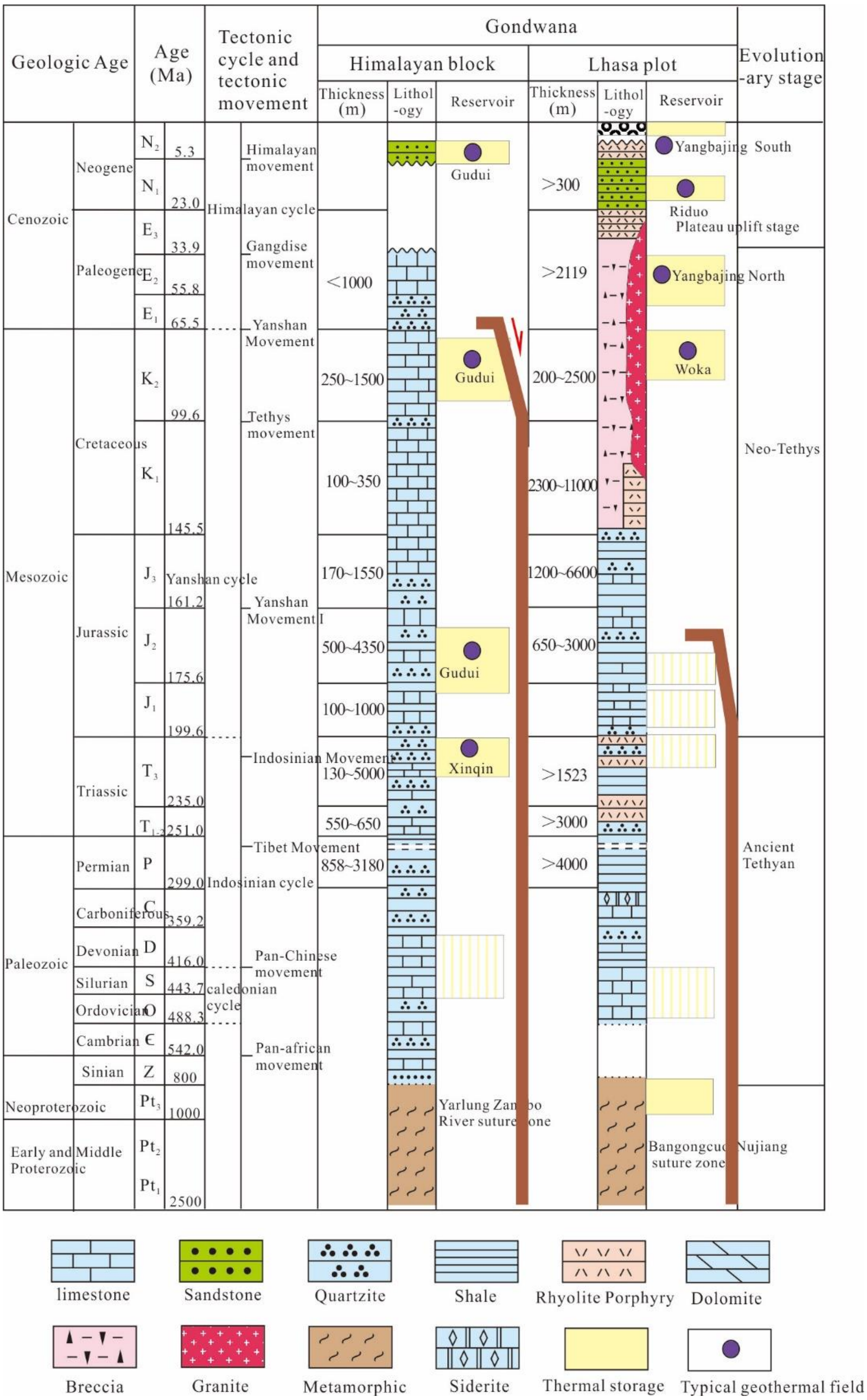

Fig. 3 Stratigraphic histogram comparison of typical structural belt in southern Tibet (revised from Wang Xinwei, 2022)

3 Geotropic genetic factors

3.1 Heat source analysis

Geothermal anomaly is an anomaly formed by the relatively concentrated heat flow in the deep crust in the process of upward movement at or near the surface, including geothermal anomaly, heat flow value anomaly, physical anomaly, chemical anomaly, seismic anomaly, magma and volcanic activity anomaly, etc. (Xu Shiguang, 2009).

Plane distribution characteristics

It can be seen from the distribution map of geothermal flow in Tibet (Fig.4), the crustal thermal structure in the Himalaya region is characterized by the horizontal development of the middle-deep regional thermal variation zone and the vertical extension of the local thermal anomaly zone, indicating that the deep heat mainly comes from the tectonic heat generation. The high value area of large geothermal flow in Tibet is basically consistent with the location of the suture zone, and gradually decreases from south to north, from 120 mw/m^2 to 55 mw/m^2 due to the influence of tectonic compression strength. The maximum earth heat flow value can reach 150mw/m^2, which is located near the Yarlung Zangbo River suture zone, Shiquanhe-Jiali suture zone, and Bangong-Nujiang suture zone. This area is also the area with the most obvious geothermal anomalies and has developed high-temperature geothermal fields such as Yangyi, Gudui, Gulu, and Xietongmen. In the confluence area of the fault, such as the confluence of the Tanggula piedmont fault zone and the Yarlung Zangbo River suture zone, have been developed the Yangbajing and Ningzhong high temperature geothermal fields with 120mw/m^2 earth heat flow value.

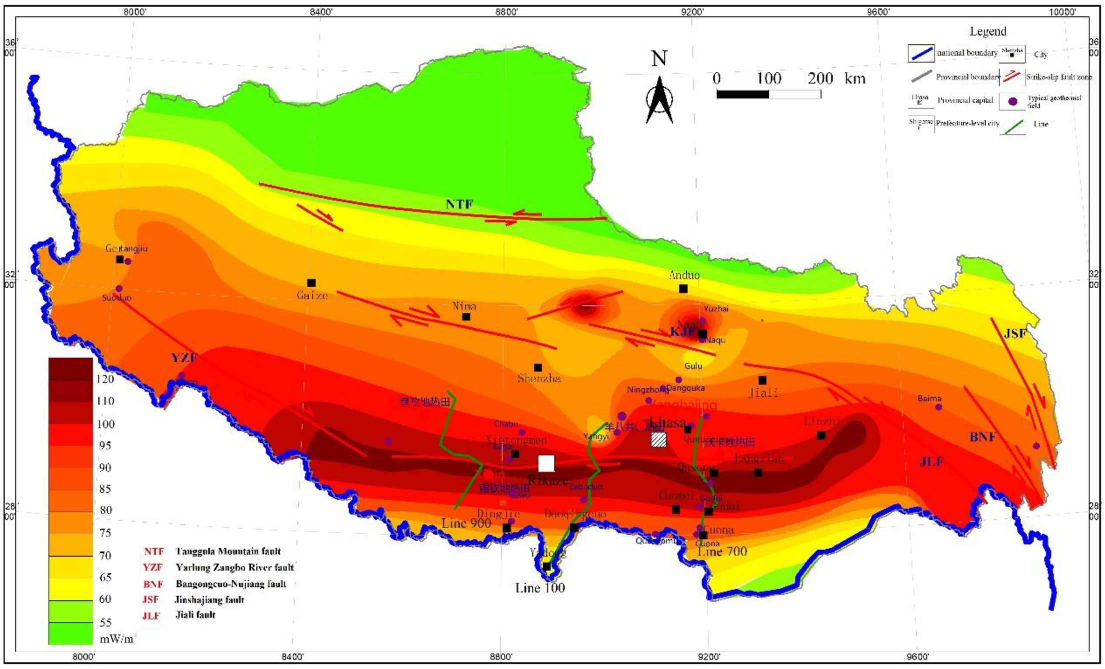

Fig.4 Distribution Map of Land Heat Flow in Tibet

Vertical distribution characteristics

The modern magnetotelluric sounding results in southern Tibet show that discontinuous and uneven partial melting bodies have developed at the bottom of the upper crust with a buried depth of 15~35km. The theory that partial melting bodies characterized by low velocity and high conductivity layers which provide heat source for the upper strata has been widely recognized (Figure 5). The relationship between the two-dimensional electrical structure profile and the earth heat flow value shows that there is a certain scale of crustal remelting type magma source area and some drop-shaped magma sacs caused by the late tectonic emplacement in the middle of the crust, which are shown as large-scale regional geothermal anomalies. Section 900 starts from the north slope of Mount Everest in the high Himalayan tectonic region in the south, passes through the north Himalayan tectonic region and the Yarlung Zangbo suture zone in the north, and enters into the Tsomei in the middle of the Lhasa-Gangdise block (Jinsheng, 2009). In the area south of the Yarlung Zangbo River, there are two small-scale and discontinuous low-velocity high conductors in the upper crust between points 921-933, with resistivity less than 10 Ω • m and corresponding earth heat flow value greater than 120 mw/m^2. Section 100 starts from Yadong in the south of the high Himalayan tectonic region in the south, passes through the high Himalaya, the north Himalayan tectonic region and the Yarlung Zangbo River suture zone in the north, and enters the Chegula in the south of the Lhasa-

Gangdise block. The high conductivity melt connected by the Xietongmen-Zhenjiu fault near the point 170 point, about 40km from the surface, provides heat source for the upper part, and the regional geothermal flow value can reach 150mw/m^2. The Himalayan fault and the Jilong-Gangba fault also develop a continuous small low resistivity anomaly zone within 20km of the shallow part. Section 700 starts from Channa in the south of the high Himalayan tectonic region, passes through the high Himalaya, the north Himalayan tectonic region and the Yarlung Zangbo suture zone in the north, and enters the Mozhugongka in the south of the Lhasa-Gangdise block. The point 720 and 760 correspond to the Cuona and Gudui high temperature geothermal field. The continuous low speed high conductor is developed in the lower crust as the heat source, and the fault is used as the channel to transfer heat to the surface. The earth heat flow value can also be as high as 105 mw/m^2. Obviously, southern Tibet is characterized by a wide thermal background superimposed with a large area of melting or partial melting layer, and its heat mainly comes from the hot asthenosphere uplift and magmatic melting layer. At the same time, the complex tectonic deformation movement of the middle and upper crust caused by the subduction of the Indian plate has induced a series of heat generation and heat transfer processes, forming a shallow thermal anomaly zone distributed along the tectonic junction. It is concluded that the heat source conditions in southern Tibet are formed under the complementary action of local melt, tectonic movement, hydrothermal activity and seismic activity.

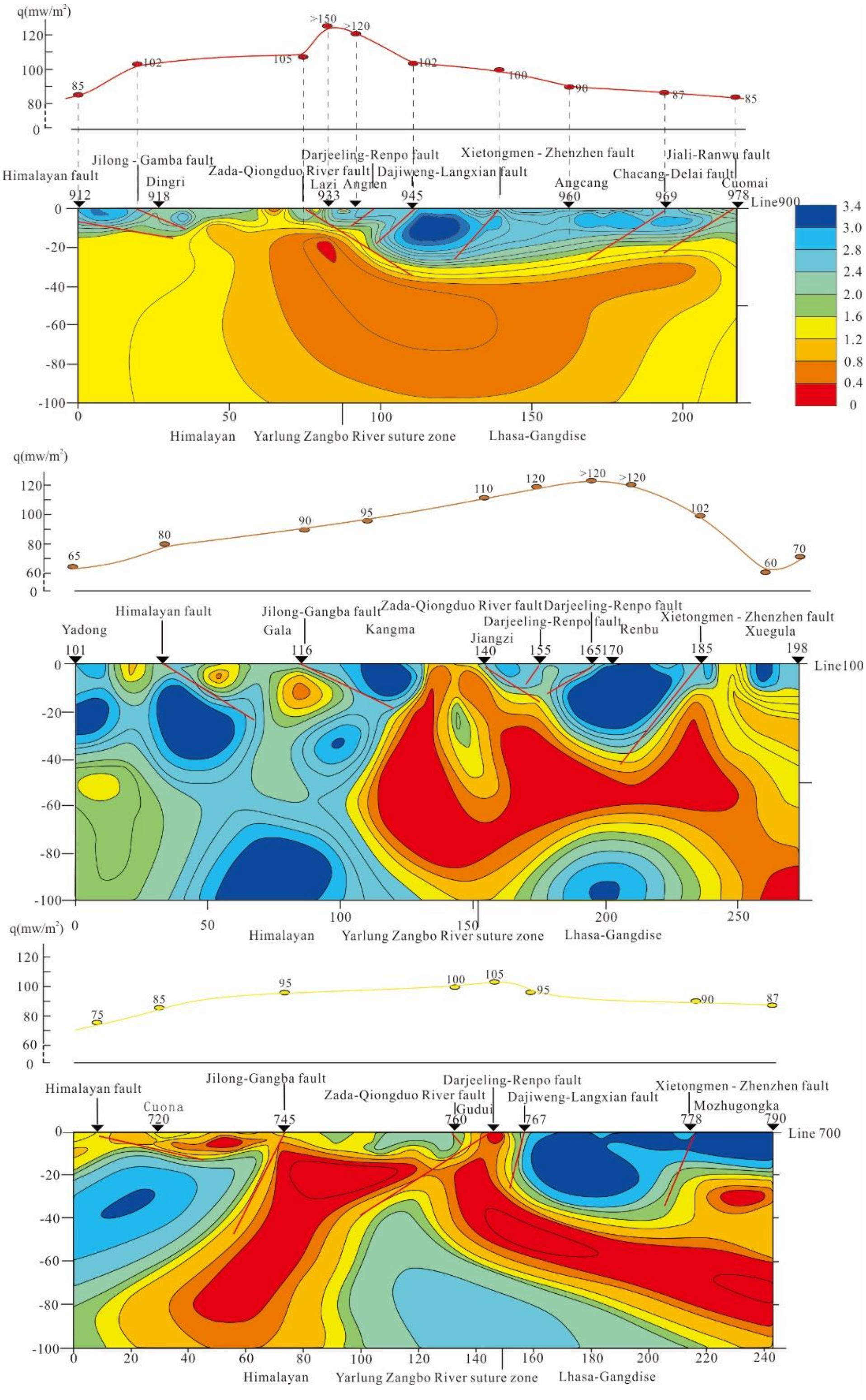

Fig.5 Relationship between two-dimensional electrical structure profile and terrestrial heat flow in southern Tibet

3.2 Heat transfer mode

The heat energy in the deep part of the earth is transmitted to the shallow part of the earth by convection and conduction, and the surface energy release mode is mainly ocean-continental process, basin-mountain process, magmatic activity, etc., forming the heat release tectonic system (Figure1) (Li Dewei et al., 2017). Affected by complex geological conditions, the heat transfer mode in southern Tibet is dominated by shallow conduction-deep convection superposition. Taking the geothermal well temperature-depth curve in Yangbajing area as an example, the shallow temperature-depth curve at 180m shows a linear increase trend, and the geothermal gradient is close to 11℃/100m, indicating that the heat transfer mode of the shallow caprock is mainly conductive. The temperature in the middle section of 280~450m decreases, which may be caused by the mixing of shallow surface cold water and underground hot water along the fault. There are two heat transfer modes: heat conduction and heat convection. When entering the 1000m deep stratum, the heat transfer is mainly conducted by convection, and the temperature of geothermal water is almost unchanged with the increase of depth.

3.3 Characteristics of reservoir-cap combination

The evolution stage of the geothermal development area in southern Tibet has gone through the Paleotethys, Neotethys and plateau uplift stages, and the rock strata of the Precambrian, Paleozoic, Mesozoic and Cenozoic geological periods have been developed, with remarkable inheritance and continuity. In the Himalayan block south of the Yarlung Zangbo suture zone, the Triassic - Jurassic bedrock fissure thermal reservoir and Neogene sandstone thermal reservoir belonging to the Tethyan rock series can be used as favorable reservoirs in the graben. The caprock is the clastic rock overlying the thermal reservoir that is not affected by the fault. The typical geothermal fields are Gudui and Chabu geothermal field. The favorable reservoirs of Lhasa block to the north of the Yarlung Zangbo suture zone are mainly the Cretaceous - Paleogene porous volcanic reservoirs and the Quaternary glutenite reservoirs distributed in small basins. The reservoir and cap assemblages of geothermal fields such as Yangbajing, Yangyi, Gulu and Woka are all of this type.

The caprock in the whole area is mainly Quaternary loose sedimentary caprock or spring bloom, with limited distribution. The temperature of the shallow conductive thermal reservoir is closely related to the sedimentary thickness of the cap rock, showing a linear warming trend. The temperature of deep thermal storage has little change due to convection heat transfer. Therefore, the focus of development in this area should be on the combination of shallow high-temperature thermal reservoir and deep convective thermal reservoir that initially enter the constant temperature section.

3.4 Chemical characteristics of geothermal water and its recharge, runoff and discharge mode

Geothermal hydrochemical types and characteristics are the result of water-rock interaction, and the main influencing factors in this process include reservoir lithology and its mineral composition, recharge area lithology and its mineral composition, reservoir temperature, interaction time (i.e. groundwater age), etc. The geothermal water samples in Tibet mainly include Gudui, Riduo, Ningzhong, Gulu, Yangbajing, Yangyi, Kaga and other typical geothermal fields. The TDS of geothermal water is mostly 1~3g/L, belonging to brackish water. The cations are mainly Na+, and the anions Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-} are distributed. The geothermal water of Gudui, Ningzhong, Gulu, and Yangbajing is mainly Cl-Na and Cl HCO_3-Na, with typical Na-Cl water characteristics. It shows that the components of hot spring water may be derived from deep hydrothermal fluid and have experienced a certain intensity of water-rock exchange in the later stage. The geothermal water is more mature than the geothermal field with a higher proportion of SO_4^{2-} in the anions such as Riduo, Yangyi and Kaga. According to previous research results, the recharge elevation of Yangbajing geothermal field is 4800~5000m (Wei Keqin et al., 1983), The accumulation of alpine ice and snow at an altitude of more than 5000 m in Tibet has brought a beneficial supplement to the recharge of underground hot water, and the gravity potential energy of recharge water formed by the huge topographic elevation difference has provided a driving force for the deep circulation of underground hot water (Wang Xinwei, 2022).

During this process, the surrounding rock material is continuously leached and added, and the underground hot water enters into the banded distribution fractures to form the bedrock fissure type thermal reservoir, which has a good thermal insulation of the thermal reservoir cover. The bedrock fissure in the semi-closed state is not only the channel for the underground hot water migration, but also the underground hot water storage site, and finally discharged through the form of hot springs, geothermal wells or jet holes.

4. Geotropical reservoir formation model and resource potential

4.1 Reservoir-forming mode

The north-south graben in southern Tibet provides four basic elements of "source, reservoir, migration and cap" for the development of high-quality geothermal fields. In the late Cenozoic, the Qinghai-Tibet Plateau was in the extensional strike-slip tectonic environment of the crust (Bai Jiaqi, 2006). At this time, the active faults in the Cenozoic basin were mainly tensional normal faults and tensional shear oblique slip faults, which were nearly equispaced north-south grabens and active tectonic belts in different directions. In the late Cenozoic, the Qinghai-Tibet Plateau was in the extensional strike-slip tectonic environment of the crust (Bai Jiaqi, 2006). At this time, the active faults in the Cenozoic fault basin were mainly tensional normal faults and tensional shear oblique slip faults, which were nearly equispaced north-south grabens and active tectonic belts in different directions. In particular, the Yarlung Zangbo River tectonic belt intersects with each other, and the tectonic fault system composed of crisscross active structures provides a channel for the upwelling of local molten bodies existing in the lower part of the geothermal field, controls the distribution and scale of surface hydrothermal activities, provides a storage space and migration channel for underground fluids, and ensures the continuous supply of heat and water sources. On the basis of ensuring the supply of heat source and water source, the capping effect of the cap also plays a role in keep the heat unlost. Quaternary sediments (clay layer or siliceous and calcareous spring) in the Cenozoic fault basin are high-quality thermal insulation cover. At the same time, the Quaternary glutenite, bedrock fissure granite and other lithologic strata with good porosity and permeability conditions distributed throughout the region can be used as high-quality thermal reservoirs. The south-north geotropics in southern Tibet with the above conditions for the formation of geothermal fields are mainly three high-temperature geotropics, namely, Naqu - Yangbajing - Yadong, Shenzha-Dingjie and Riduo – Cuona.

4.2 Resource potential

The geothermal resource potential in the study area is calibrated by using the thermal storage volume method to calculate the geothermal resource quantity. The area is dominated by the type of conductive and convective superimposed resources, the thermal storage volume is relatively assigned when the thermal storage volume method is used to calculate the geothermal resource quantity, and the geothermal resource development potential in different tropics is compared with the relative value. According to the physical parameters of the three main geothermal reservoirs (Table 1) and the thermal reservoir volume calculation formula (1), the geothermal resources of Naqu-Yangbajing-Yadong, Riduo-Channa and Shenzha-Dingjie are relatively 52.7×10^{14}kJ, 3.88×10^{14}kJ and 9.11×10^{14}kJ. Among them, the highest abundance of resources in Naqu-Yangbajing-East Asia is 25.9×10^{10}kJ/km^2 (Table 1). The resource quantity calculated is only relative to that proposed by the hydrothermal system. Because the resource quantity of the dry-hot rock in this area is much higher than that of the hydrothermal type, the actual geothermal resource quantity of the tropical zone should be greater than the current result.

$$Q=Q_r+Q_l=A\times d\times 2.25\times (t_r-5) \quad ...... \quad (1)$$

Q——Geothermal resources（J）;A——Thermal storage area（km^2）;d——Thickness of thermal storage（km）;tr——temperature（℃）;Thermal capacity value of unit mixed volume of rock and water——2.25 J/cm^3·℃;Reference temperature in southern Tibet——5℃;Hot storage volume according to temperature class（from high to low:>200℃、200℃ ~ 120℃、<120℃）, Area assignment 6 km^2、3 km^2、1.5 km^2;Thickness assignment 2km、1km、1km.

Table1： Development potential of typical geothermal resources in southern Tibet

Geotropics	Average heat storage temperature（℃）	Area（km^2）	Thermal storage area（km^2）	Thickness（km）	Resources（10^{14}kJ）	Equivalent to standard coal（10^4t）	Resource abundance（10^{10}kJ/km^2）
	200	20348.9	6	2	52.7	17988	25.9
	120	5836.7	1.5	1	3.88	1326	6.65

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	140	11106.3	3	1	9.11	3113	8.20
总计					65.6	22427	

(①Naqu - Yangbajing - Yadong High Temperature Geotropics;②Riduo - Tropics with high temperature;③Shenzha-Dingjie High Temperature Geotropics)

5.Conclusion

(1) The heat source conditions in southern Tibet are formed by the complementary effects of local melting bodies, tectonic movements, hydrothermal activities and seismic activities. Based on the density of the hydrothermal display area and the scale of active tectonic development, the boundary between the southern Tibet geotropics and the corresponding active tectonic zone is basically the same, with the largest scale of the Riduo-Channa, Yadong-Gulu, Shenzha-Dingjie and Nima-Dingri geotropics.

(2) The favorable reservoir-cap assemblages in southern Tibet are mainly distributed in the grabens in the north-south direction. The caprocks in the area are mainly Quaternary loose deposits or spring blooms. The shallow conductive thermal reservoir temperature is closely related to the sedimentary thickness of the caprocks, showing a linear warming trend. Due to the fact that the deep thermal reservoir is mainly convective heat transfer, the temperature of the thermal reservoir has little change. The geothermal development needs to focus on the shallow high-temperature thermal reservoir and the thermal reservoir of the deep convective thermal reservoir that initially enters the constant temperature section.

(3) The water source migration mode in southern Tibet is atmospheric precipitation and snowmelt water as the recharge source, and the cold water continues to seep down along the fault and the temperature continues to increase. With the continuous addition of gas components, the geothermal fluid begins to migrate upward. During this process, the surrounding rock material is continuously leached, and the underground hot water enters into the banded distribution of fractures to form the bedrock fracture type thermal reservoir, which has a good thermal reservoir cap layer water insulation. The bedrock fissure in the semi-closed state is not only the channel for the migration of underground hot water, but also the place for the storage of underground hot water, which is finally discharged in the form of hot springs, geothermal wells or jet holes.

(4) The total geothermal resources of the three major geotropics in Tibet are 65.6×10^{14}kJ, equivalent to 224.27 million tons of standard coal. According to the comprehensive geothermal geological conditions, resource abundance and market demand, the geothermal development conditions of Naqu - Yangbajing - Yadong high temperature geothermal zone are the best, among which the Ningzhong geothermal field has a certain geothermal development potential.

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