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Genetic Mechanism of Geothermal System in Shulu Sag, Jizhong Depression, Bohai Bay Basin

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ABSTRACT

The analysis of the characteristics of geological factors in the geothermal system is the basis to establish its genetic model, and is also the basis for later exploration and development. Combined with previous research and regional geothermal well data, we analysis the main geological factors include "source, reservoir, migration, cap" of the geothermal system in the Shulu Sag, Jizhong Depression, establish the genetic model of the geothermal system. The Shulu Sag is a typical Cenozoic half graben, which may be supplied heat by a low-resistance body about 20 km in the deep crust structure. The Guantao Formation sandstone thermal reservoir and Ordovician karst thermal reservoir make up two sets of geothermal systems respectively. The sandstone thermal reservoir in Guantao Formation is stably distributed in the whole study area, which buried depth of the bottom boundary is between 1100~2000 m. The thickness of the reservoir is about 200~320 m, with 15-35% porosity, and the permeability can reach up to 1200mD. The temperature of the thermal reservoir bottom boundary is mostly 57~78ºC; The Ordovician carbonate reservoir distribution is controlled by the half-graben and shows a monoclinal dip, which buried depth of the top boundary is from 1800 to 6000 m. The thickness of the carbonate reservoir is about 100 to 550 m, the porosity is mostly 2 to 18%, the permeability is mostly 0.5 to 50 mD. The wellhead temperature of the thermal reservoir is about 75~92ºC. These two geothermal systems are replenished by atmospheric precipitation from the Taihang Mountains in the west of study area. The water migrated along the unconformity of the layers and the faults, and warmed by deep heat conduction and local heat convection, finally enriched in the reservoirs. The overlying loose Quaternary sediments and Minghuazhen Formations fluvial sediments are 300~1400 m thick, and the thermal conductivity is 0.9~1.8 W/(m·K), can be a good cap layer.

1 INTRUDUCTION

Geothermal energy has received increasing attention in recent years due to its abundant resources, renewability and environmental protection (Muffler et al, 1978; Chen et al, 1994; Chen, 1998; Wang et al, 1993; Moeck, 2014; Zhou, 2015; Wang et al, 2017). The understanding of the concept of geothermal systems has evolved with the development of geothermal research. In the early years, geothermal systems were defined as those with sufficient geothermal enrichment to constitute energy resources (Rybach et al., 1985), followed by Wang (2015), who emphasizes that "a geothermal system is a relatively independent geological unit in terms of heat and fluid circulation in which geothermal energy is aggregated to an exploitable degree." In recent years, in order to highlight the internal relationship and effective matching between various geological factors of geothermal system, many scholars have introduced the research methods of petroliferous basin analysis into geothermal field research (He et al., 2017; Zhang et al., 2017), defining the geothermal system as a relatively independent geological unit containing " source, reservoir, migration, cap " and a series of geological processes such as heat transmission, storage, preservation and dissipation. A geothermal system can span multiple tectonic units (geothermal fields) in plan, while a tectonic unit (geothermal field) can contain multiple geothermal systems in vertical direction. Most of the previous studies have tended to investigate the Genetic Mechanism of just one set of geothermal systems in a geothermal field, while less research has been conducted on the genesis linkage of two geothermal systems within the same tectonic unit, and the similarities and differences between them need to be systematic compared and analysed by dissecting typical geothermal fields.

The Shulu Sag is located at the southern of Jizhong Depression in the Bohai Bay Basin, and is a typical east-break half graben (Fig. 1) containing two sets of geothermal systems: the shallow Guantao Formation sandstone thermal reservoir and the deeper Ordovician carbonate thermal reservoir. Xinji City, located in the northern part of the Shulu Sag, is an area where geothermal resources were explored and developed earlier, and both sets of thermal reservoirs have been exploited (Table 1). In recent years, with concentrated exploration and development of the area, more than 40 geothermal wells have been completed and a heating area of about 2.5×10^6 m^2 has been realized.Geological studies in the Shuanglu Depression currently focus mostly on oil and gas exploration and development, including buried hill oil and gas reservoir types and groundwater chemical analysis (Huang et al. 2018; Wu and Chen 2018; Zhu et al. 2019; Cai et al. 2020), while less research has been conducted in geothermal geology (Li et al., 2017; Liu, 2017), especially in terms of the genesis mechanism of its geothermal system has not been carried out in a comprehensive analysis. On the basis of previous achievements, combined with the latest geothermal drilling data and hydrochemical analysis data, this study analyzed the four geological elements of "source", "reservoir", "migration" and "cap", identified their heat transfer and heat accumulation mechanism, established and compared the genetic models of the upper and lower geothermal systems in Shulu Sag. So it can provide a theoretical basis for the later geothermal exploration and development in the region.

2 GEOLOGICAL SETTING

The Shulu Sag is a Tertiary tectonic unit within the Jizhong Depression of the Bohai Bay Basin (Fig. 1), which has been strongly modified by the Indo-Chinese, Yanshan, and Himalayan movements. It is controlled by the Xinhe Fault to the east and the

Hengshui Fault to the north, with the Ningjin Uplift in the west, the Xinhe Uplift in the east, the Shenxian Sag in the north, and the Xiaoliucun Uplift in the south (Kong, 2005; Guo et al., 2018).

The stratigraphic sequence of the Shulu Sag shows that four sets of tectonic layers developed above the Archean crystalline basement (Fig. 1), from the old to the new, are in the order of (i) middle-upper Proterozoic, which mainly developed the Changcheng System and Jixian System, and the lithology is composed of carbonate rocks and a few clastic rocks; (ii) The Lower Paleozoic Cambrian-Ordovician system is mainly composed of limestone, dolomite and mud shale; (iii) Mudstone, carbonaceous mudstone and coal seam are mainly developed in the Upper Paleozoic Carboniferous Permian, and their distribution ranges are limited due to regional uplift and denudation; (iv) The Cenozoic is mainly composed of clastic rock deposits.

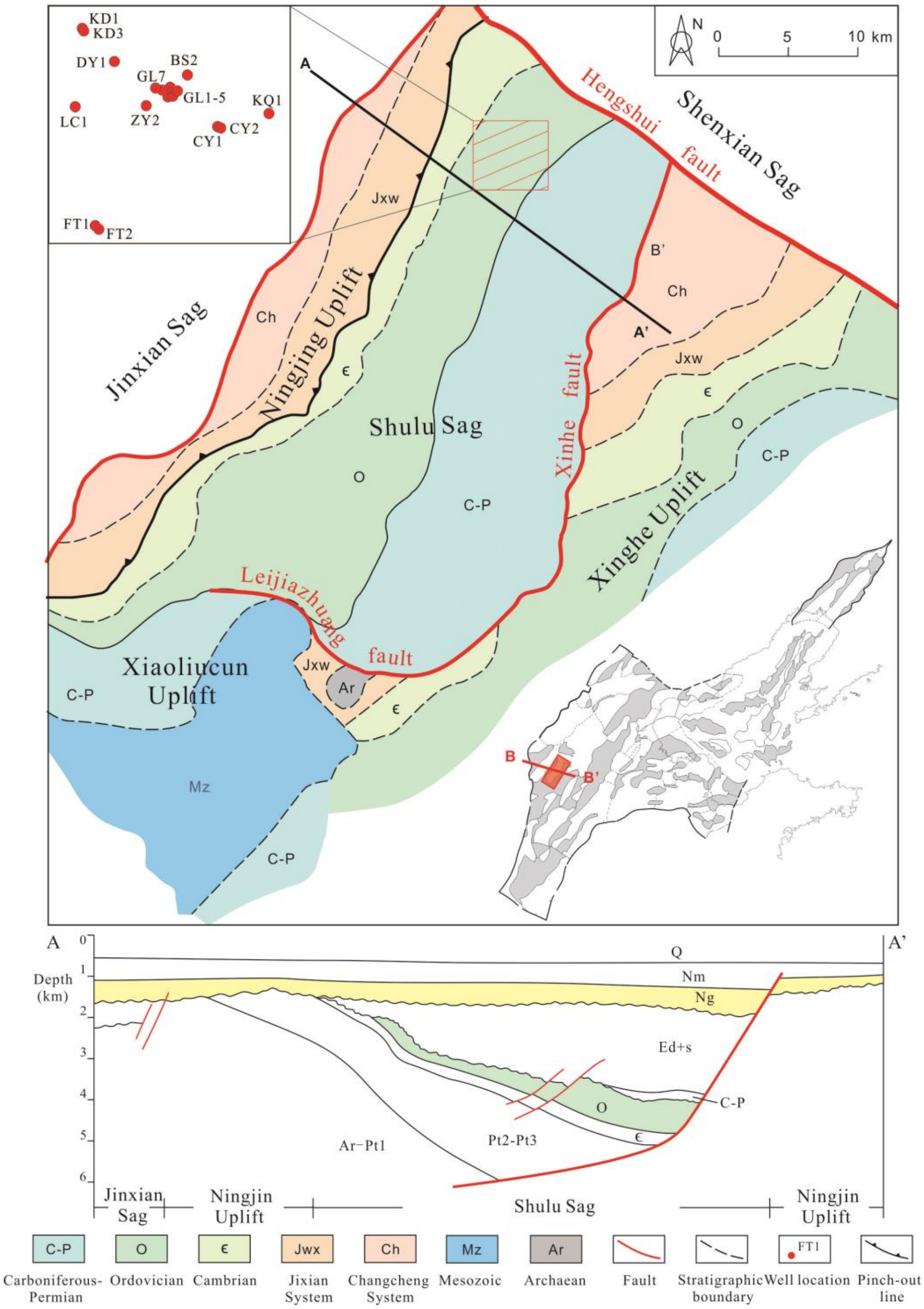

Fig.1 Structual units and lithology distribution in Shulu Sag and its adjacent area (Modified from Wu, 2018)

Two types of geothermal reservoirs are mainly developed in the Shulu Sag and adjacent areas (Fig. 1), namely, Cenozoic geothermal reservoir dominated by continental clastic deposits and Paleozoic and Meso-Neoproterozoic carbonate karst type geothermal reservoir dominated by Marine sediments. Geothermalt reservoirs are restricted by sedimentability and tectonic evolution. Among them, the sandstone geothermal reservoirs are mainly the Neogene Minghuazhen Formation and the Guantao Formation, which are distributed throughout the study area; the karst thermal reservoirs are mainly the Paleozoic Ordovician and Jixian System Wumishan Formation thermal reservoirs, which are distributed in the Shulu Sag, and are uplifted and denuded on the

Ningjin Uplift and the Xinhe Uplift. The main objects of this study are the Neogene Guantao Formation and the Palaeozoic Ordovician thermal reservoirs, which constitute upper sandstones geothermal systems of and lower carbonate geothermal systems respectively.

Table 1 Typical geothermal boreholes data in Shulu Sag

Number	Well	Structure	Abstraction section （m-m）	Reservior	Wellhead temperature (ºC)	water yield(m^3/h)
1	LC1	Shulu Sag	1305-1773	Ng	62	80.2
2	DY1	Shulu Sag	1286-1764	Ng	62	85
3	KQ1	Shulu Sag	1410-1802	Ng	60	101.9
4	CY1	Shulu Sag	1379-2124	Ng	62	105.5
5	CY2	Shulu Sag	1367-2092	Ng	61	81.4
6	GL1	Shulu Sag	1288-1831,	Ng	60	80.36
7	GL2	Shulu Sag	1386-2187	Ng	59	80.36
8	GL3	Shulu Sag	1367-1890	Ng	61	90
9	GL4	Shulu Sag	1273-1914	Ng	61	88
10	GL5	Shulu Sag	1438-2125	Ng	62	89
11	GL7	Shulu Sag	1346-1799	Ng	46	—
12	ZY2	Shulu Sag	2519-2926	O	82	43.9
13	BS2	Shulu Sag	2483-3048	O	86	86.8
14	FT1	Shulu Sag	2472-2890	O	83	100
15	FT2	Shulu Sag	2434-2900	O	80	100
16	KD1	Shulu Sag	2150-2546	O	81	101
17	KD3	Shulu Sag	2156-2628	O	81	101

3 GEOLOGICAL FACTORS OF GEOTHERMAL SYSTEM

The geological factors of geothermal systems mainly include mechanism of heat source, characteristics of geothermal reservoir, groundwater migration, and cap conditions, etc. Clarifying the characteristics of each geological factor and interpreting the heat transfer and heat accumulation mechanisms between those factors are the basis for establishing the genesis model of geothermal systems, and also the basis for further evaluation of geothermal resources (Zhu, 2011; Lang, 2016; Wang et al.)

3.1 Mechanism of heat source

3.1.1 Deep earth crustal structure

The buried depth of the Moho surface in the Shulu depression is about 34~36km. According to the deep electrical structure of magnetotelluric data (Zhan et al., 2011), the Jinxian fault (F4) and Xinhe fault (F5) with a depth of more than 10km show an obvious electrical difference zone, which is characterized by low resistance body (LRB) of the fault hanging wall and high resistance body (HRB) of the fault footwall, which is consistent with the location of the surface geological delineation (Fig. 2). The Jinxian fault (F4) extends about 10km to the west, with a depth of about 7km, and gently merges over the Taihang piedmont fault (F1). The Xinhe fault extends westward to a depth of about 5km. At a depth of 10km, there exists a large deep hidden electrical difference zone (EDZ) in the electrical structure of the Shulu depression and its adjacent areas, which extends down about 30km and intersects with the Xinhe fault upwards. It is inferred that this hidden difference zone, Xinhe fault and Jinxian fault form a favorable channel for the upward transport of deep heat flow (Fig. 2).

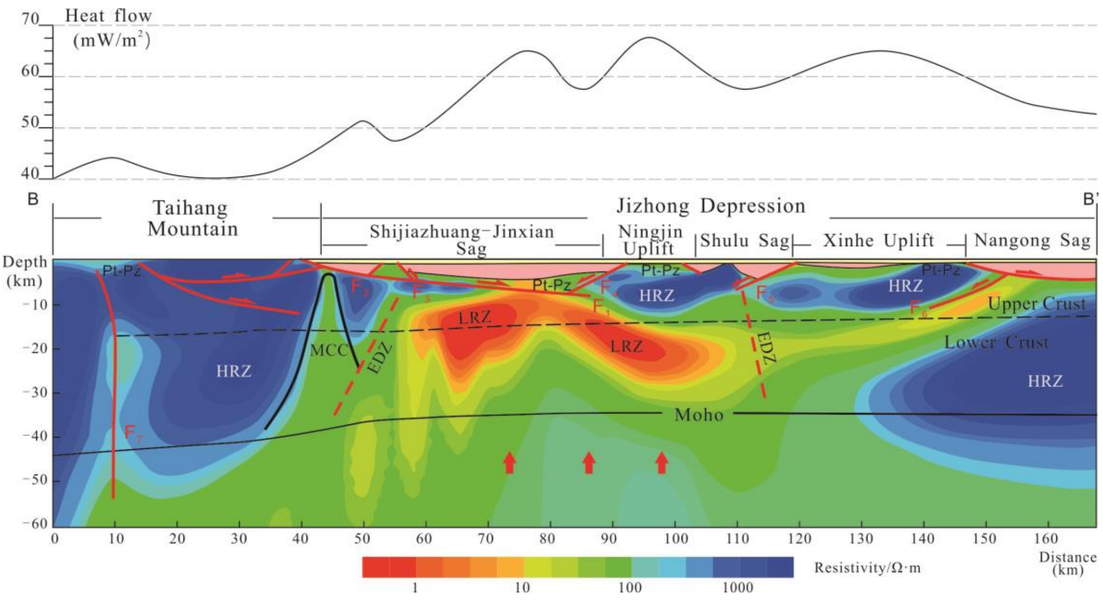

Fig.2 2-D geo-electrical structure model obtained by the NLCG along the profile of south Jizhong Depression (modified from Zhan et al., 2011) and Variation of Heat flow values in south Jizhong Depression (modified from Wang et. al., 2019)； F1:Piedmont fault of Taihang Mountains; F2 Beixi fault; F3 Luancheng fault; F4 Jinxian fault; F5 Xinhe fault; F6 Minghuazhen fault; F7 Jing-huo fault; MCC Metamorphic core complex;

The geothermal flow is a visual representation of the deep thermal state of the crust or lithosphere at the surface. From the comparison between the deep electrical structure of the electromagnetic profile and geothermal flow values in the southern Jizhong Depression (Fig. 2), it can be found that the geothermal flow values corresponding to the electromagnetic profile have a certain correspondence with their deep structure, showing that the Moho surface burial depth gradually becomes shallower from west to east, and the corresponding geothermal flow values gradually become larger from west to east. The high resistance body within the crust corresponds to relatively low geothermal heat flow values, while the low resistance body within the crust corresponds to relatively high geothermal heat flow values. In Shijiang-Jinxian Sag, Ningjin Uplift and Shulu Sag, the crust with low resistivity and high conductivity is about 10km deep and 20km thick, which may be due to the partial melting of felsic minerals, which is related to the rise of hot materials in the upper mantle (Yang et al., 2016).The heat flow value of the Shulu Sag and its adjacent areas can be as high as 68mW/m^2, suggesting that the low resistance body provides a certain amount of heat energy for the area.

3.1.2 Heat transfer mode

By analyzing the relationship between the temperature depth of the upper cap and the reservoir in wells (Fig. 3), it can be found that the temperature curve of the geothermal wells in the Shulu Sag shows that the temperature increases with the increase of the depth, which is generally in a segmentation form, that is, the geothermal gradient of the Quaternary sediments is obviously high (up to 8.13ºC/100m), while that of the lower reservoirs is relatively low (mostly between 1 and 2ºC /100m). It reflects that there is a great difference in heat conduction velocity between reservoir and cap bed due to different thermal conductivity.

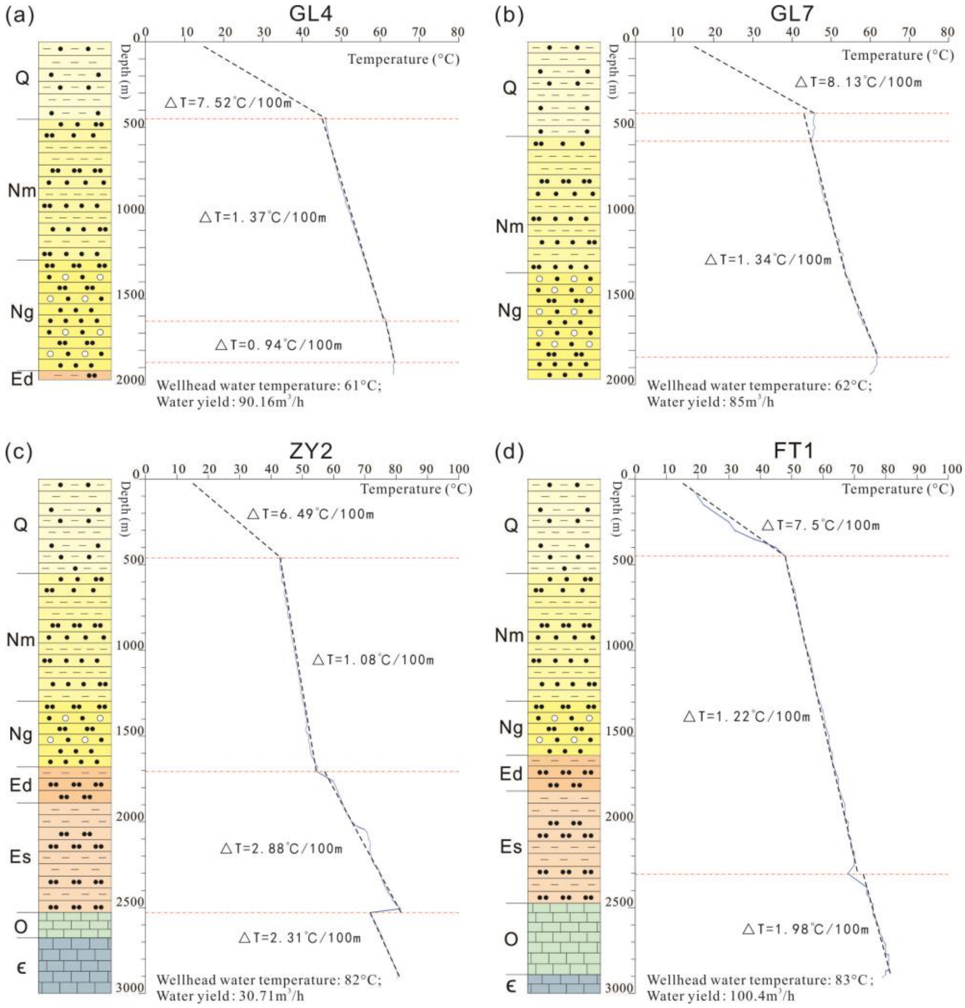

Fig.3 Relationship between formation temperature and depth of geothermal wells in Shulu Sag

The temperature-depth curve of the sandstone geothermal reservior in the sandstone of the Guantao Formation is two-stage (Fig. 3), with a reservoir geothermal gradient of 1-1.5ºC /100 m. As can be seen on well GL7 (Fig. 3b), a section of the temperature-depth relationship exists in the upper part of the Minghuazhen Formation, which shows that the formation temperature is greater than its reservoir geothermal gradient fitting temperature, reflecting the possible injection of high-temperature fluids laterally (Fig. 3b), indicating that heat transfer in the sandstone geothermal reservior is dominated by heat conduction, with localised thermal convection.

The temperature-depth curve of the Ordovician karst-type thermal reservoir is four-stage (Fig. 3c) and three-stage (Fig. 3d), with the reservoir geothermal gradient ranging from 1.5 to 2.5ºC /100m, slightly higher than that of the sandstone thermal reservoir, and heat transfer is mainly by heat conduction. The ground temperature gradient of the Dongying-Shahejie Formation in the upper ZY2 well (2.88°C/100m) is slightly higher than that of the lower Ordovician-Cambrian (2.31ºC /100m) and significantly higher than that of the upper Minghuazhen-Guantao Formation (1.08ºC /100m), indicating that the Dongying-Shahejie Formation is a fine set of water barrier and heat barrier for the underlying Ordovician karst thermal reservoir.

3.1.3 Characteristics of shallow geothermal field

In general, for the basal uplift area, there is a higher geothermal gradient, while in the basal depression area there is a lower geothermal gradient (Mao, 2018; Wang et al, 2019). In this study, based on the measured geothermal gradient and thermal physical parameters, the planar distribution of the mean Cenozoic geothermal gradient in the Shulu Sag and adjacent areas was mapped (Fig. 4a) in combination with previous research results, from which the characteristics of the shallow geothermal field were analysed. The geothermal gradients show significant lateral variations in the planar distribution, with low geothermal gradients in the depressions and high geothermal gradients in the raised areas. In the southwestern part of the depression, the geothermal gradient is higher, reaching 3.75°C/100m; in the western part of the Ningjin Uplift, the geothermal gradient is mostly between 3 and 3.75°C/100m; in the eastern part of the Xinhe Uplift, the geothermal gradient is mostly between 3 and 4°C/100m; and in the southern part of the Xiaolucun Uplift, the geothermal gradient is up to 4.5°C/100m. Combined with the bedrock geological map of the study area (Fig. 1), the analysis shows that the older the exposed strata in the raised area, corresponding with the higher geothermal gradient, and the greater the thickness of the sedimentary strata in the depressed area, corresponding with the lower geothermal gradient.

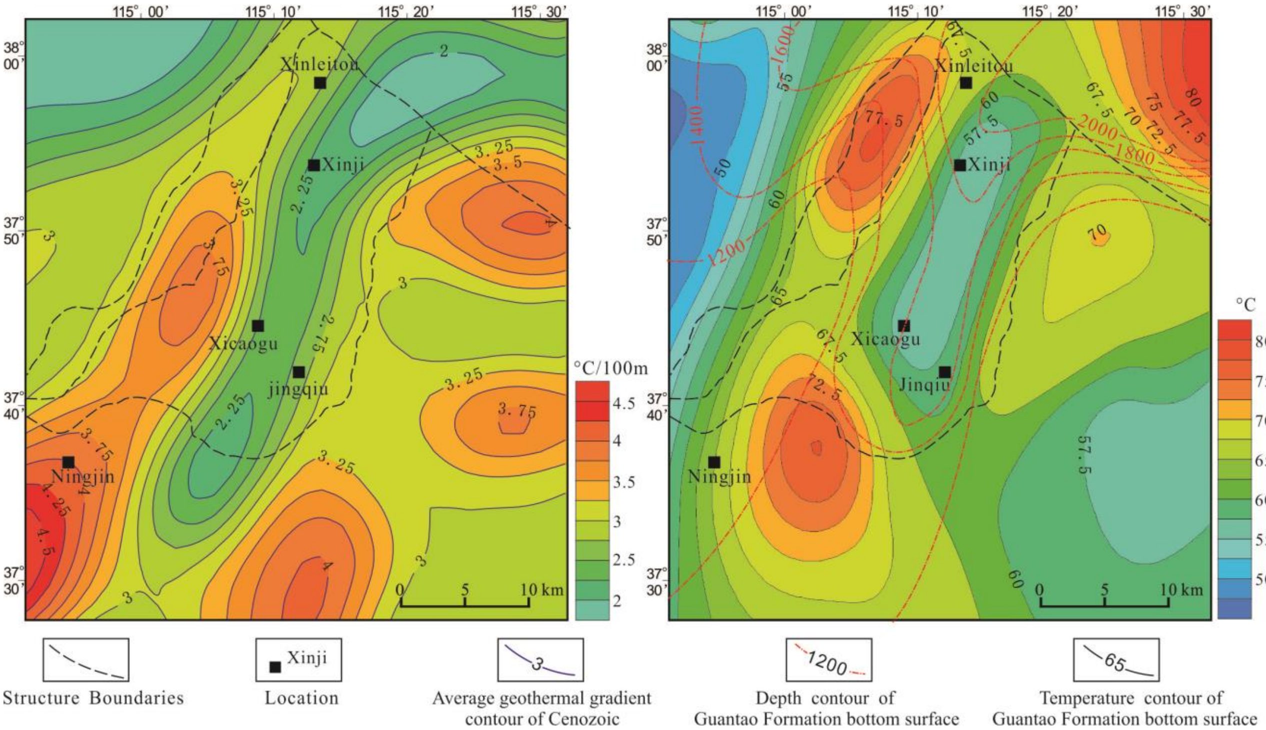

Fig.4 Distribution of Cenozoic strata geothermal gradients in Shulu Sag and its adjacent area (a); Distribution of temperature and depth of bottom Guantao Formation (b)

3.2 Characteristics of geothermal reservior

3.2.1 Porous sandstone geothermal reservior

The porous sandstone thermal reservoir currently being exploited is mainly Guantao Formation, and its plane distribution and longitudinal stratification characteristics are as follows:

(i) Depth of the top and bottom surface: The sandstone geothermal reservior in the Shulu Sag and adjacent areas of the Guantao Formation is mainly limited by tectonic units, with the burial depth of the top surface ranging from 300 to 1600 m and the burial depth of the bottom surface ranging from 1100 to 2000 m. Overall, the burial depth of the bottom surface of the geothermal reservior increases from south to north and from west to east (Fig. 4b).

(ii) Bottom surface temperature: The temperature of the bottom interface of the Tatau Formation is influenced by differences in heat transfer, and its planar distribution characteristics correspond to the concave-convex pattern. The temperature is lower in the depressions and higher on the surrounding bumps. In the Shulu Sag, the bottom interface temperature of the Guantao Formation is mostly between 57 and 67°C, with a maximum of 75°C in the southwest of the depression; on the Ningjin Uplift in the west and the Xiaolucun Uplift in the south, the temperatures are relatively high, 65-78°C and 65-75°C, respectively; on the Xinhe Uplift in the east, the temperatures are mostly 57-70°C.

(iii) Physical property of the reservoir: The thermal reservoir of the Guantao Formation is mainly composed of grey-white gravelly fine sandstone, with grey medium sandstone at the bottom, with an overall high sand-mud ratio. Combined with the information from existing wells in the study area, can reach 55-70%, with a reservoir thickness of about 200-320 m. Generally, it shows a large porosity of about 15-35% and a high permeability of up to 1200 mD. Multiple sets of gravel-bearing sandstone and mudstone interbedded, showing the characteristics of multiple sets of aquifer and water barrier superposition.

(iv) Vertical stratification: Taking Well GL7 in the study area as an example (Fig. 5a), 21 aquifer layers were interpreted in the depth range of 1487-1971 m, with a cumulative effective thickness of 291m and a converted sand-thickness ratio of 60.1%, with the maximum thickness of a single layer reaching 42 m and the minimum 2.6 m. The mud content was generally low, with an average value of 13.7%. The porosity is relatively homogeneous, ranging from 17.9 to 33.8%, with an average value of 25.2%; the permeability is highly variable, ranging from 14.4 to 1180.1 mD.

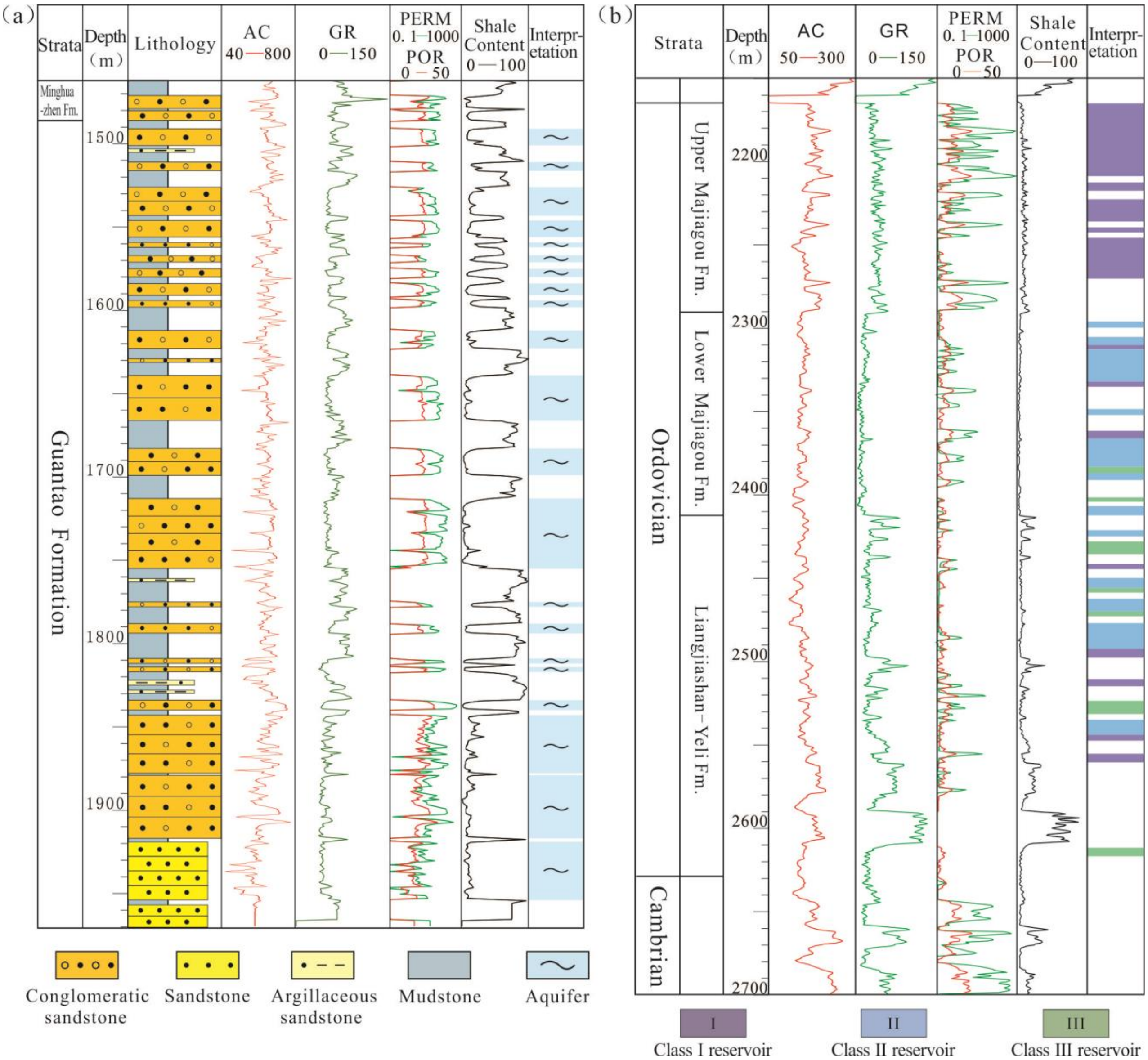

Fig.5 Typical single well characteristics of different types of thermal reservoir in Shulu Sag: porous sandstone geothermal reservoir in Guantao Formation (a); Ordovician karst geothermal reservoir (b)

<u>3.2.2 Carbonate thermal reservoir</u>

The Ordovician is the main layer of carbonate karst geothermal reservoir development and utilization, and its spatial distribution is mainly controlled by the monoclinic tectonic pattern. The top surface burial depth varying greatly between 1800~6000 m, and pinch out upwards on the western slope of the Shulu Sag. According to the existing geothermal drilling data, the wellhead temperature of the Ordovician karst thermal reservoir is concentrated at 78~91ºC at a well depth of 2100~3500m. The drilling rock fragments reveal that the lithology of the Upper Ordovician is mainly limestone, and the lithology of the Lower Ordovician is mainly dolomitic limestone and calcareous dolomite. The thickness of the layer is about 550~1100m (Li, 2013), with an overall reservoir thickness ratio of 20-50% and a reservoir thickness of about 100-550 m. The karst thermal reservoir is highly heterogeneous, with porosity ranging from 2-18% (Li, 2018); permeability ranges from 0.5 ~50 mD.

The Ordovician thermal reservoir is also characterised by stratification in the vertical direction. Taking Well KD3 as an example (Fig. 5b), a total of 34 layers of Class I, II and III thermal reservoirs were identified in the depth range of 2165-2628 m, with a total effective reservoir thickness of 267.9 m. Among them, 13 layers of Class I thermal reservoirs were developed, with a total thickness of 121.8 m, an average porosity of 4.1% and an average permeability of 0.7-3.0 mD. The pore-permeability parameters of the well are generally lower than the average values in the study area.

3.3 Groundwater migration

3.3.1 Hydrochemical characteristics

The geothermal water in the study area has the characteristics of relatively concentrated hydrochemical types and high mineralization, in which Na+ is absolutely dominant among cations, followed by Ca^{2+} and the lowest content of Mg^{+}; Cl^{-} is absolutely dominant among anions, followed by HCO_3^- and the low content of SO_4^{2-}. The hydrochemical types are classified according to C.A Shukarev as two types of Cl-Na and Cl-HCO_3-Na (Fig. 6).

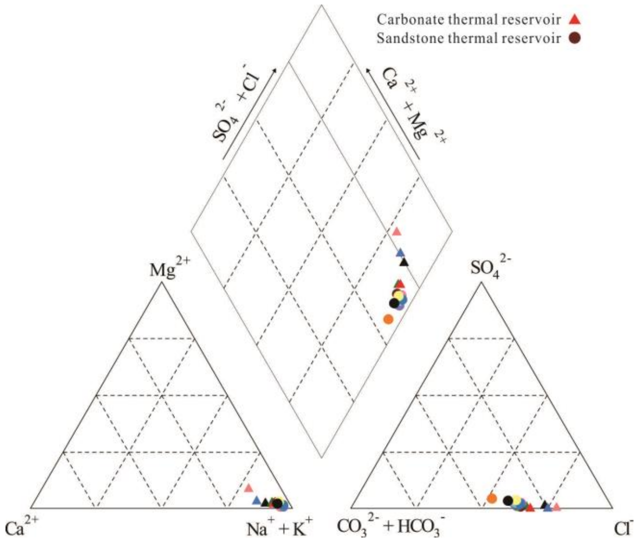

Fig.6 Piper triangular diagram of the major ions in underground water from Shulu Sag

Table 2 Chemical composition and information of groundwater samples in Shulu Sag

Well	Abstraction section (m-m)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	TDS	γNa/γCl	Hydrochemical characteristics
		mg/L									
LC1	Ng	28.06	9.72	641.2	27.85	634.61	691.28	9.61	1782.6	0.93	Cl·HCO_3-Na
DY1	Ng	14.03	1.22	364.7	5.67	451.55	311.96	33.62	996.67	1.17	Cl·HCO_3-Na
KQ1	Ng	21.92	5.4	604.1	10.83	565.5	574.1	13.03	1958	1.05	Cl·HCO_3-Na
CY1	Ng	22.04	3.64	606.7	3.58	573.39	638.1	28.82	1646.6	0.95	Cl·HCO_3-Na
CY2	Ng	15.44	2.01	546	7.4	555.5	541.08	25.47	1458.15	1.01	Cl·HCO_3-Na
GL2	Ng	18.85	5.71	574.3	14.06	592.5	592.4	31.93	1897	0.97	Cl·HCO_3-Na
GL3	Ng	15.42	4.56	624.6	9.64	590.9	642.3	24.46	1977	0.97	Cl·HCO_3-Na
GL4	Ng	26.05	13.37	820	26	811.57	833.08	67.24	2214.14	0.98	Cl·HCO_3-Na
GL5	Ng	30.06	7.29	710	23.5	732.24	680.64	52.83	1905.69	1.04	Cl·HCO_3-Na
GL1	Ng	9.93	3.35	405	4.9	482.25	310.08	81.97	1098	1.31	Cl·HCO_3-Na
ZY2	O	86.75	12.41	921.6	49.66	723.1	1223	26.64	3174	0.75	Cl-Na
BS2	O	121.1	51.24	860.3	53.68	635.9	1372	4.5	3222	0.63	Cl-Na
FT2	O	121.1	19.48	947.4	56.05	723.1	1278	2.21	3258	0.74	Cl·Na
KD1	O	48.38	11.06	743.7	44.54	744.7	886.4	12.11	2583	0.84	Cl·HCO_3-Na
KD3	O	53.04	10.42	881.5	51.89	805.4	1019	2.78	2926	0.86	Cl·HCO_3-Na

Note: Hydrochemical data obtained from analysis and testing by Sinopec Key Laboratory of Geothermal Resources Development and Utilization

The hydrochemical type of the sandstone thermal reservoir of the Guantao Formation is all Cl-HCO_3-Na type. The Cl^- in the groundwater of the Guantao Formation is mostly in the range of 450-700 mg/L, and the TDS is relatively low, mostly below 2000 mg/L. The metamorphic coefficients γNa/γCl of the geothermal water of the Guantao Formation range from 0.93 to 1.31, all of which are higher than 0.85, indicating an open hydrodynamic environment.

The geothermal water of Ordovician karst reservoir is Cl-Na type and Cl·HCO_3-Na type.The TDS is higher than that of the Guantao Formation, generally above 2500 mg/L. Ca^{2+} is significantly enriched in the karst geothermal water of the Ordovician, up to 121.1 mg/L, and Cl^- basically exceeds 1000 mg/L, which is significantly higher than that of the Guantao Formation (Table 2). The metamorphic coefficients γNa/γCl of the Ordovician geothermal water range from 0.75 to 0.86, indicate a closed hydrodynamic environment. Compared with the Guantao Formation sandstone, the cation in the interaction between water and rock in the Ordovician karst water are dominated by the dissolution of Ca^{2+} containing minerals. The interaction between water and rock is higher, the migration time is longer, the storage environment is relatively closed, and the maturity of water is higher.

3.3.2 Recharge elevation

The hydrogen and oxygen isotopes in atmospheric precipitation have an elevation effect. In hydrogeochemistry, if atmospheric precipitation has been identified as the source of groundwater recharge, the elevation effect of hydrogen and oxygen isotopes can be used to determine the recharge area and recharge elevation (Sanchez et al., 2004). The groundwater recharge source for sedimentary basin-type geothermal resources is usually atmospheric precipitation, and the groundwater recharge elevation can be calculated from the $\delta^{18}O$ values in geothermal water in the study area, using the following equation.

$$H=\frac{\delta G-\delta P}{K}+h \qquad (1)$$

Where H is the elevation of the recharge area, m; h is the elevation of the sampling site, m; δG is the value of $\delta^{18}O$ in groundwater, ‰; δP is the value of $\delta^{18}O$ in precipitation at the sampling site, taken as -7.6‰; K is the $\delta^{18}O$ isotope height gradient, taken as -0.11‰/100 m. The calculation results are shown in Table 3:

Table 3 Parameter and supply elevation calculation results

Well	Abstraction section (m-m)	δG：$\delta^{18}O$（‰）	h：Sampling point elevation（m）	H：Recharge elevation（m）
108	Ng	-9.4	42	1678
109	Ng	-10	40	2222
FT1	O	-9.07	37	1373
KD3	O	-9.11	41	1414

Note: The isotope data of Wells 108 and 109 were cited from Fang et al. (2015). FT1 and KD3 isotope data are Beta Analytic laboratory tests in the United States

The calculation results show that the geothermal water recharge area in the Shulu Sag is between 1300 and 2300m above sea level. Combined with the local geomorphology, it is believed that the groundwater recharge mainly comes from atmospheric precipitation in the exposed mountainous areas of the southern section of the Taihang Mountains to the west, and is transported from west to east in the study area.

3.4 Cap conditions

For conductive geothermal, the cover with relatively low thermal conductivity has a particularly important influence on the distribution of geothermal field (Gong Yuling, 2011). There is a negative correlation between thermal conductivity and geothermal gradient, and the higher the geothermal gradient of the cover, the better the sealing performance. The thickness of the Quaternary Pingyuan Formation and Neogene Minghuazhen Formation in the study area is about 300~1400m, in which the Pingyuan Formation is mainly deposited with loose argillaceous silt and fine sandstone, which is a good water-proof layer. At the same time, for the two sets of underlying thermal reservoirs are also high quality thermal insulation cover, whose thermal conductivity is about 0.9~1.8 W/(m·K), and the geothermal gradient can reach 6.5~8.5 ºC /100 m. When the heat flow from deep underground passes through this layer, the ground temperature decreases rapidly. The thickness of the Palaeocene and Carboniferous-Permian is about 300-800 m. The main lithology is mudstone intercalated with siltstone and fine sandstone, and black mud shale is locally developed, which has a good blocking effect on the vertical transport of geothermal fluids. The thermal conductivity of this section is mostly around 1.7 W/(m-K), and the ground temperature gradient is 1.2-3.5 ºC/100 m, which is slightly higher than that of the underlying thermal reservoir, and together with Quaternary Pingyuan Formation and Neogene Minghuazhen Formation, it forms a high-quality cover for the lower Ordovician carbonate thermal reservoir.

4 CONCEPTUAL MODEL OF GEOTHERMAL SYSTEM

Based on the above analysis of the four geological factors of the geothermal system in the Shulu Sag, namely”source, storage, migration and cap”, allows us to establish a model for the genesis of the two geothermal systems in the study area. The source of the geothermal system in the Shulu Sag is probably the low resistance body in the lower part of the depression at a depth of 20 km, and the hidden difference zone in the east of the low resistivity body and the Xinhe and Jinxian faults in the upper part constitute a favorable channel for the upward transport of heat flow from the deep part. The Guantao Formation sandstone and Ordovician carbonate rocks are two sets of layered thermal reservoirs in the study area, both of which are supplied by atmospheric precipitation from the western Taihang Mountain uplift, separated by thick sand and mudstone deposited in the Paleogene and carboniferous and Permian coal deposits, forming two sets of independent geothermal systems. The atmospheric precipitation takes the stratigraphic unconformity and fault as the migration channel, through deep circulation, heating of surrounding rock, and water-rock reaction with surrounding rock, minerals and trace elements dissolve to form geothermal water, which is enriched and filled in the thermal reservoir. The fine sedimentary strata of the upper Quaternary system and Minghuazhen Formation formed a good cap bed, and the ground temperature decreased rapidly when heat flow was conducted in the strata. .Both geothermal systems are dominated by heat conduction, with local heat convection acting together to transfer heat flow (Fig. 7).

The depth of the Guantao Formation bottom surface is between 1100~2000 m, the thickness of the reservoir is about 200~320 m, the temperature of the reservoir bottom surface is mostly 57~78 ºC, the hydrochemical type of the geothermal water is Cl·HCO_3-Na, the hydrodynamic environment is open, and the overlying plain Formation and Minghuazhen Formation constitute the sealing cap. The buried depth of the top surface of the Ordovician karst geothermal system is between 1800~6000m, the thickness of the reservoir is about 100~550 m, and the wellhead temperature is between 75~92 ºC. The hydrochemical type of the geothermal water is mainly Cl-Na type, and the hydrodynamic environment is relatively closed. Pingyuan Formation, Minghuazhen Formation, overlying Paleogene and Carboniferous - Permian formed the sealing cap.

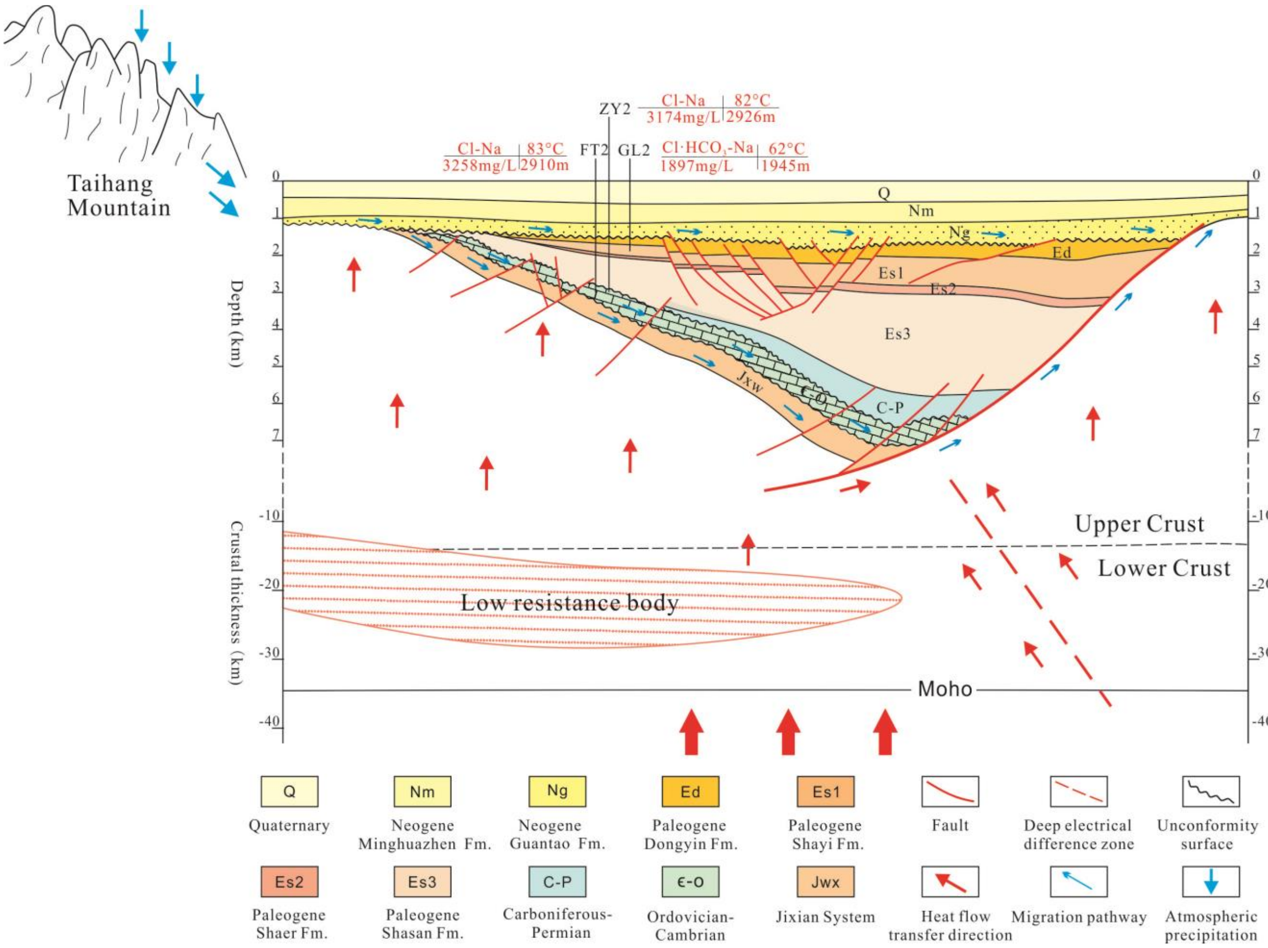

Fig.7 Conceptual model of geothermal system in Shulu Sag

5 DISCUSSION

The two geothermal systems in the Shulu Sag have the same water source, both accepted atmospheric precipitation from the exposed mountains in the southern section of the Taihang Mountains, but there are differences in the transport path, timing and hydrochemical characteristics of the formation: (i) Migration pathway: the shallow Guantao Formation sandstone thermal reservoir stratum is uniform and gentle as a whole, with a burial depth of 1600-2000m, and geothermal water in the sandstone thermal reservoir is transported more smoothly from west to east. The deep Ordovician carbonate thermal reservoir is affected by the rotation and differential rise and fall of the Paleozoic fault block, and the stratum is characterized by multiple juxtaposed irregular monoclinic or fold-like features, and the burial depth of the top plate varies greatly, about 1800-6000m, with complex transport paths and large geothermal water circulation depth; (ii) Migtation time: according to the 14C age of the Ordovician hot water obtained from this test is more than 40,000 years, and the collected hot water of the Guantao Group 14C age is 32,900±0.16 million years (Fang Lianyu et al., 2015), indicating that it originates from atmospheric precipitation in the same area and has been transported within the Ordovician reservoir in the study area for a relatively longer period of time; (iii) Hydrochemical characteristics: there are obvious differences in the hydrochemical characteristics of geothermal water in the two geothermal systems, with the mineralization of geothermal water in the sandstone thermal reservoir ranging from 900 to 2300 mg/L and the hydrochemical type mainly being Cl-HCO_3 -The hydrochemical characteristics are closely related to the differences in transport path and time. However, comparing the mineralization of geothermal water between the two geothermal systems and the Palaeocene and Carboniferous-Permian systems (Fig. 8), it can be seen that the mineralization of the fluid system of the Shahejie Formation is the highest, ranging from 0 to 150,000 mg/L. It is dominated by brine and brine, and the storage environment is closed, which plays a role in separating the upper and lower geothermal systems in the vertical direction, so that the two sets of geothermal reservior form independent geothermal systems. The low mineralisation of the geothermal water of the Neoproterozoic Guantao Formation and Ordovician suggests that the geothermal water storage environment is relatively open and suitable for later exploitation.

In addition, from a regional perspective, the distribution characteristics of the upper and lower geothermal systems are universal in the southern end of Jizhong Depression, for example, the Shijiazhuang Sag in its western part also contains the Neoproterozoic Guantao Group sandstone geothermal system and the bedrock karst fissure geothermal system, which receives recharge from atmospheric precipitation (Hu and Guo, 2008). The sandstone geothermal system of the Guantao Formation has a burial depth of 943-1825.5m and a thickness of 200-656m, with a Hydrochemical of Cl-HCO_3-Na type, a mineralisation of 1000-3000 mg/L and a wellhead temperature of 50-59°C. The carbonate geothermal system has a burial depth of 1300-2000m and a thickness of 25-350m on the top surface of the thermal reservoir, with a hydrochemical of Cl-HCO_3-Na and HCO_3-Na types, with TDS ranging from

2080 to 3130 mg/L and wellhead temperatures of 50-83°C, displaying characteristics largely similar to those of the Shulu Sag geothermal system.

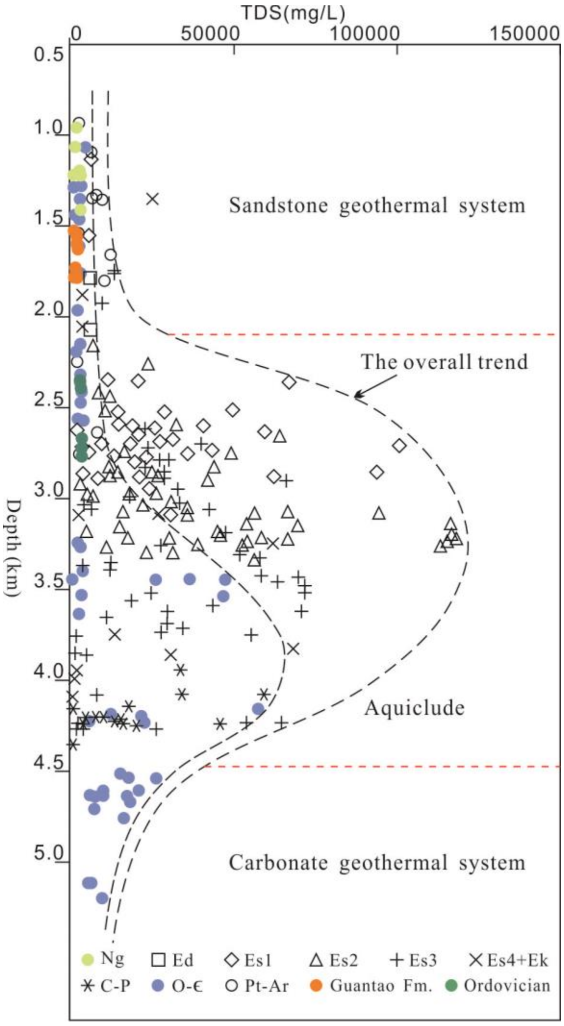

Fig 8 Relationship between TDS and depth of wells in Shulu Sag（modified from Cai et al., 2020）

6 RESULTS

(1) The Shulu Sag may receive heat from low-velocity high conductors in the deep crustal structure 20 km below it, and the hidden electrical difference zone to its right connects the upper Xinhe Fault and the Jinxian Fault to form a favourable channel for upward transport of deep heat flow. The shallow geothermal field in the Shulu Sag and adjacent areas is characterised by relatively low values of geothermal gradients in the depressions, mostly between 2-3°C/100m, and relatively high values of geothermal gradients in the raised areas, mostly between 3-4°C/100m. Heat transfer is mainly by thermal conduction, with localised thermal convection conduction.

(2) The burial depth of the bottom surface of the Guantao Formation sandstone geothermal reservoir in the Shulu Sag and adjacent areas ranges from 1100 to 2000 m, with a reservoir thickness of about 200 to 320 m, porosity of about 15-35%, permeability of up to 1200 mD and reservoir bottom surface temperature of 57-78°C. The burial depth of the Ordovician karst geothermal reservoir top surface varies greatly, ranging from 1800 to 6000 m, with a reservoir thickness of about 100 to 550 m, porosity mostly in the range of 2~18%, permeability mostly in the range of 0.5~50 mD, and geothermal water wellhead temperature in the range of 75~92ºC.

(3) In the Shulu Sag, the hydrochemical type of geothermal water in the Guantao Formation is mainly $Cl·HCO_3$-Na type, and the geothermal water in the Ordovician thermal reservoir is $Cl·HCO_3$-Na and Cl-Na type, both of which are supplied by atmospheric precipitation from the western Taihang Mountain uplift. By taking the stratigraphic unconformity and fault as the migration channel, through deep circulation, heating of surrounding rock, enriched in the thermal reservoir.

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