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Evaluation of the Storage Characteristics and Circulation Model of the Low- and Middle-Temperature Geothermal Reservoir in Guanzhong Basin by Using the Data of Hydrogen-oxygen Stable Isotopes

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Keywords: Guanzhong Basin; hydrogen-oxygen isotopes; storage characteristics; circulation model

ABSTRACT

Guanzhong Basin is the typical geopressured-type low and middle-temperature geothermal field in the west of China. The hydrogen and oxygen isotope characteristics have some implications for the storage characteristics and circulation model of geothermal resources in this basin. This paper divides the study area into six tectonic units and conducts the systematic analysis of 121 sets of hydrogen-oxygen isotope data. The hydrogen-oxygen isotopes throughout Guanzhong Basin show a trend of gradual increase from the basin's peripheral areas to the basin center. For the recharge of groundwater, with Weihe Fault as a border, the area to the south is the piedmont geothermal system of Qinling Mountains, and the area to the north is the piedmont geothermal system of North Mountains. When the geothermal water is recharged through atmospheric precipitation, the atmospheric temperature is about 0.2-1.8℃. The main factors that affect the geothermal water $\delta^{18}O$ drifting in Guanzhong Basin include depth of geothermal reservoir and temperature at well heads, and also lithological characteristics, water-rock interaction, geothermal reservoir environment, and residence time. The $\delta^{18}O$-δD relation shows that the main source of geothermal water in the basin is the atmospheric precipitation, together with some sedimentary water, but there was no deep primary magmatic water and mantle water. If the distribution principle of hydrogen-oxygen isotopes is examined, the groundwater circulation model of this basin can be divided into open circulation type, semi-open type, closed type and sedimentary type, which offers some insights for the rational exploitation of geothermal resources.

1. INTRODUCTION

China's geothermal resources feature wide distribution and huge potentials, and mainly take the form of low- and mid-temperature geothermal resources. Specifically, 85% of hydrothermal resources are found in 15 large and medium-sized sedimentary basins, including North China Basin, Songliao Basin and Guanzhong Basin[1-2]. Geochemistry is an important way to study the geothermal sources, paths, covering and reservoir and the circulation and renewal of underground hot water in the sedimentary basin. The hydrogen-oxygen stable isotopes are widely used in the study of geothermal system. Hydrogen and oxygen are the most widely distributed elements. In nature, hydrogen has three isotopes including H, D and T (in rare existence)and the isotopic abundance ratio is 99.9844% and 0.0156% separately.

The isotopic data are often used to study the source of geothermal water and describe the hydrogeochemical process in the liquid movement [3-7]. Majumdar et al.(2005) analyzed the seasonal changes of ^{2}H and ^{18}O in geothermal water and surface water of Bakreswar and Tantloi geothermal fields, and discussed the recharge source of local geothermal water[5]. Pinti et al. (2013) used inert gas isotope, hydrogen-oxygen stable isotopes and carbon and strontium isotopes as tracers to study the evolution of Los Azufres geothermal field and the heat source of salt in geothermal water[7]. The researches during the recent years focus on evaluating the geothermal resources through the comprehensive use of different environment isotope techniques[8-10].

Craig(1961，1966)identified the linear relation between δD and$\delta^{18}O$ of atmospheric precipitation for the first time, namely global atmospheric precipitation line, pointed out that geothermal water in hydrothermal system mainly comes from atmospheric precipitation, and discovered that the noticeable phenomenon of "oxygen drifting" happens in the high-temperature hydrothermal system[11, 33]. Afterwards, Clayton (1975) used hydrogen-oxygen stable isotopes to study the water-rock interaction in geothermal system and hydrothermal mineralization process[12]. The isotope data in recent years are mainly used to study the source of geothermal water and describe the hydrogeochemical process in the liquid movement[5,7]. Chandrajith et al. (2013) concluded that the source of geothermal water in Sri Lanka is the atmospheric precipitation[13]. Giggenbach (1992) studied the characteristics of hydrogen-oxygen isotopes on the convergent boundary of plates, and concluded that the geothermal water is the result of mixture between local atmospheric precipitation and magmatic water[3]. Yosar used the hydrogen-oxygen isotope technique to examine the large karst geothermal reservoir available for exploitation in the shallow part of Teboursouk Basin, and studied the groundwater recharge and circulation characteristics by comparing the local and global atmospheric precipitation lines.

The use of the hydrogen-oxygen isotopes in China's geothermal study is focused on the convective geothermal system of uplifted mountains, mainly in Zhangzhou, Tibet, Jiangxi Province and other regions[14-19]. The isotope study of geothermal water in Guanzhong area lasted from the end of the 1980's to the beginning of the 21th century. When the changes of hydrogen-oxygen stable isotopes in atmospheric precipitation of Shaanxi Province were analyzed, Zhang Shengchun (1989) conducted a research into the factors that affect the change of δ value, including precipitation, temperature and evaporation, and proposed the correlation of hydrogen-oxygen isotopes between precipitation recharge and groundwater[20]. Qin Dajun et al. (2005) examined the hydrochemical composition and isotopic composition of geothermal water in the geothermal water well at the depth of 300m to 3000m in Xi'an, mentioned that the recharge area for geothermal water in Xi'an is located in Qinling Mountains and estimated the average velocity of groundwater according to the 14C age difference between geothermal wells[21]. Ma Zhiyuan et al. (2006) analyzed the composition of hydrogen-oxygen isotopes of geothermal water in the south of Guanzhong area, and found that the water at normal temperature accounts for more than 50% of the mixed body with geothermal water, there is a gap of about 16℃ in average temperature between recharge source and modern precipitation of net hot water in the study area, and the recharge source is the glacial water above the altitude of 1800m in Qinling Mountains during the last glacial period of Quaternary Period[22]. Moreover, they explored the hydraulic connection among all the major aquifers in this area, and found that the deep fractured zone on the basin edge is the key factor to enable the hydraulic connection among all the aquifers in the south of Guanzhong Basin. The research on δ18O and δD in geothermal water indicated that the geothermal water in Xi'an and Xianyang belongs to different geothermal systems with different recharge sources[23]. Li Xiucheng used the isotope-based hydrogeochemical method to find that the highest temperature of deep geothermal reservoir in Dongda Geothermal Field of Guanzhong Basin is 110℃, and the largest circulation depth of geothermal water is 3120m[24]. Generally speaking, due to the restrictions from sampling conditions and workload, the existing isotope-based geochemical researches in Guanzhong Basin are based on the single geological structure unit, but fail to generate the geochemical insights capable of covering the whole basin. Therefore, these researches are unable to examine the groundwater circulation model of the whole basin. This paper conducts an analysis and study of hydrogen-oxygen stable isotopes in six geological structure units of Guanzhong Basin as a whole, proposes the geothermal water circulation and generation model of Guanzhong Basin in the hope of offering some insights for the future planning and development of geothermal water resources in Guanzhong Basin.

2. TECTONIC BACKGROUND

Guanzhong Basin is China's typical low- and mid-temperature geothermal system. Without the special additional heat source as one of its generation conditions, Guanzhong Basin has sufficient water and a given circulation depth. The underground runoff can "collect" heat and useful elements that are scattered in the rocks. So it took a long time to form and build these geothermal systems. In addition, these geothermal systems are mostly found in the fault-fracture zone or the intersection part of two sets of fault zones on different directions[27], and the temperature of geothermal reservoir is usually lower than 140℃ and the runoff depth is less than 4.0km [28].

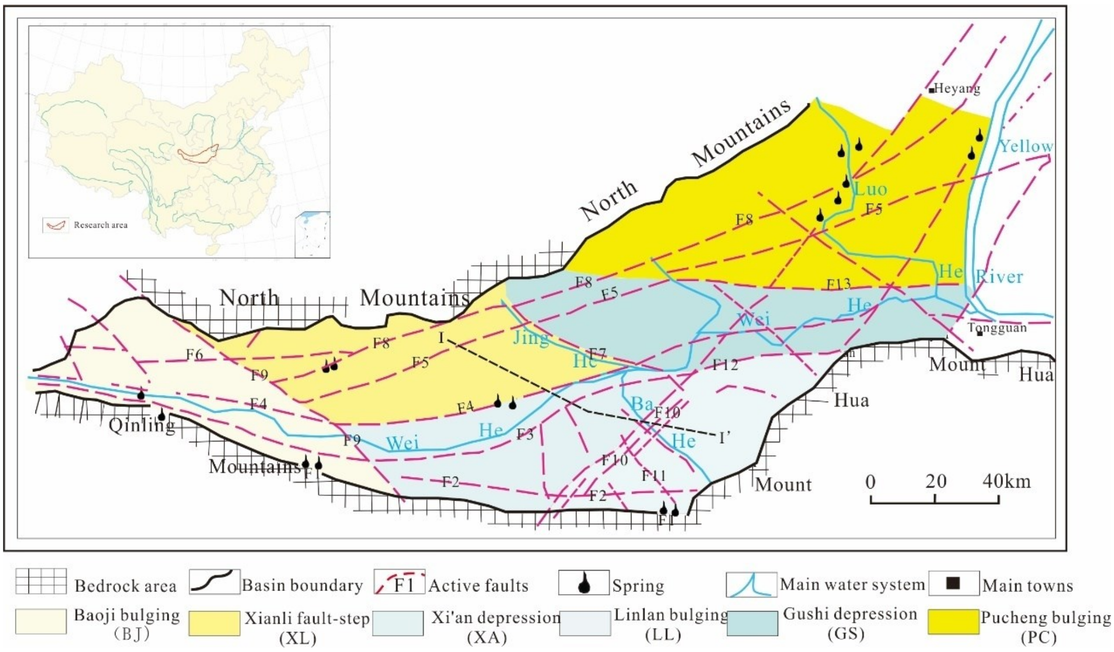

Fig.1 Main fracture distributions and tectonic zoning of Guanzhong Basin

3. ANALYSIS OF HYDROGEN-OXYGEN ISOTOPE

3.1 Analysis of geothermal water recharge

(1) Recharge resources

Based on the data of hydrogen-oxygen stable isotopes of atmospheric precipitation as obtained from IAEA/WMO Xi'an Station, the linear regression method is used to build the equation of Xi'an precipitation line as $\delta D=7.49\delta^{18}O+6.12$. Because the study area is located in China's landlocked arid and semi-arid area, there is limited precipitation and strong evaporation. The atmospheric precipitation is affected by evaporation, so when compared to the equations of global atmospheric precipitation line and China's atmospheric precipitation line, the equation of atmospheric precipitation line in Guanzhong area have a smaller intercept and gradient. The relation between δD and $\delta^{18}O$ in the study area is indicated in Fig.2.

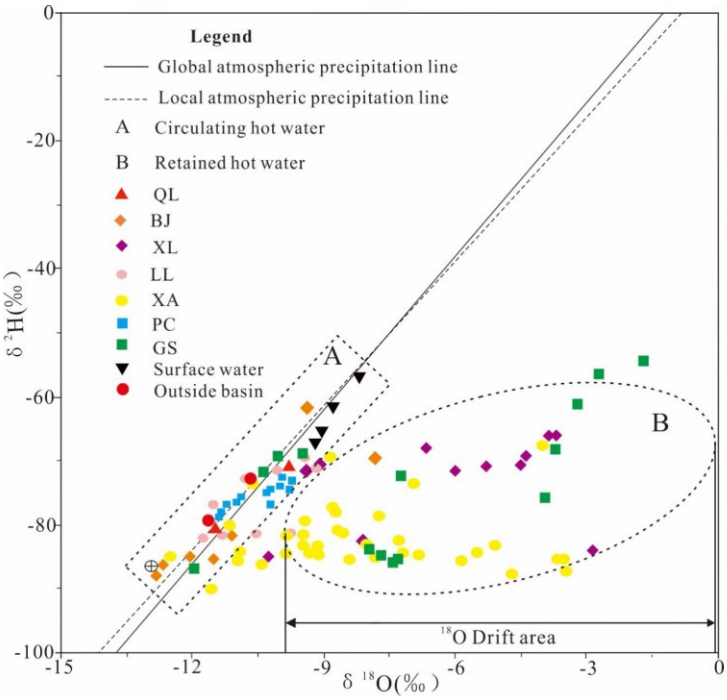

Fig.2 The relation between δD and δ^{18}O of geothermal water in Guanzhong Basin

The water in Qinling Mountains and the river water in study area both fall under the atmospheric precipitation line, and most geothermal water in Baoji bulging, Linlan bulging and Pucheng bulging are distributed near the rainwater line, showing there is the frequent renewal between geothermal water and surface water in the bulging area, and the modern atmospheric precipitation and river seepage are the main form of recharge. Some piedmont geothermal water of Qinling Mountains in Xi'an and the geothermal water along the North Mountains of Xianli and Gushi are distributed along the rainwater line. Moreover, the geothermal water in Xi'an and Xianyang has the similar δD value to the piedmont geothermal water of Qinling Mountains, and the geothermal water in Gushi has the similar δD value to the piedmont geothermal water of the North Mountains, showing that they are located in different hydrogeological unit. With Weihe Fault as a border, the area to the south is Qinling piedmont geothermal water system, which is mainly recharged by atmospheric precipitation and surface water of Qinling Mountains, and the area to the north is piedmont geothermal water system of North Mountains, which is mainly recharged by atmospheric precipitation and surface water of North Mountains.

The considerable δ^{18}O drifting quantity also reveals that there is the strong water-rock interaction between geothermal water and wall rocks of Huayin Section in Gushi depression. Because of the enclosed geological environment, the geothermal water is recharged at a low temperature. The drifting of ^{2}H and ^{18}O happens to a few sampling points of geothermal water at the same time. The maximum drifting quantity of ^{2}H is 17.4‰ in Weinan-Huayin section of Gushi depression, showing that the geothermal water in this area may be found in the reduction-type enclosed geological environment. In addition, δD-δ^{18}O points of geothermal water in Xi'an, Xianyang and Gushi depression areas have the overlapping or intersection phenomenon, showing that the mutual mixture or recharge may exist among geothermal water of different regions.

(2) Recharge temperature

The temperature difference when geothermal water is recharged through atmospheric precipitation is also a contributor to the drifting of δ^{18}O. The relational expression between the oxygen isotope of atmospheric precipitation and the annual average temperature in Xi'an Meteorological Station is δ^{18}O=0.47T-12.24, and the correlation coefficient r=0.976[29]. This relational expression shows that, if the annual average temperature falls by 1℃,the annual average value δ^{18}O of atmospheric precipitation will drop by 0.47‰. According to the existing data about Guanzhong Basin, the average value of atmospheric precipitation δ^{18}O in the study area is -7.38‰. The major drifting characteristics of δ^{18}O are found in Xianyang-Xi'an section and Weinna-Huayin section within the study area. The calculation results reveal that Xianyang-Xi'an section and Weinna-Huayin section are the trap center of δ^{18}O value. When the geothermal water is recharged, the atmospheric temperature is 10.8℃ and 12.7℃ lower than modern temperature, and averages 11.8℃. If the modern temperature averages 12-13.6°C annually in Shaanxi Province, the atmospheric temperature is about 0.2-1.8℃ in the study area when the geothermal water is recharged through atmospheric precipitation. The gap between the atmospheric temperature at the moment of recharge and the modern atmospheric temperature is consistent with the ground temperature change since the last glacial period when the record of sporo-pollen research is made in the north of China [30](Yao Tandong et al., 2001), showing that the geothermal water in the areas with the major drifting of δ^{18}O in Xianyang-Xi'an section and Weinna-Huayin section within the study area is recharged through atmospheric precipitation at the last glacial period.

3.2 Analysis of influencing factors of ^{18}O drifting

As stated above, there are quite a few contributors to δ^{18}O drifting of geothermal water. After the atmospheric water from different periods and at different recharge latitudes make their ways into the geothermal reservoir through various seepage paths. δ^{18}O drifting will be related to such factors as geothermal water's storage environment, runoff retardance coefficient, lithological characteristics, and the water-rock interaction between geothermal water and wall rocks. Specifically, because the rich contents of ^{18}O in rock minerals, ^{18}O is often used to measure the strength of water-rock interaction. This paper discusses about the possible factors of $\delta^{18}O$ drifting in Guanzhong Basin.

(1) Depth of geothermal reservoir

As indicated in Fig. 3a, the $\delta^{18}O$ value of geothermal water in Guanzhong Basin is in positive correlation to the depth of geothermal reservoir. The correlation coefficient is described as: r^2=0.53. The positive correlation is most obvious in the deep geothermal wells, and the $\delta^{18}O$ value of geothermal water which is less than 1000m deep is near the precipitation line, showing that the interaction and renewal of shallow geothermal water and atmospheric precipitation get frequent, ^{18}O has the low interaction degree and the water-rock interaction is less strong. On the contrary, the closed condition of deep geothermal water is stronger than that of shallow geothermal water. In other words, ^{18}O tends to happen in the deep closed environment. But in the active faults with good start-up conditions or satisfactory connection with ground surface, ^{18}O value remains immune to the change in depth, such as the geothermal point near the big fault zone of Qinling Mountains to the south of Xi'an depression.

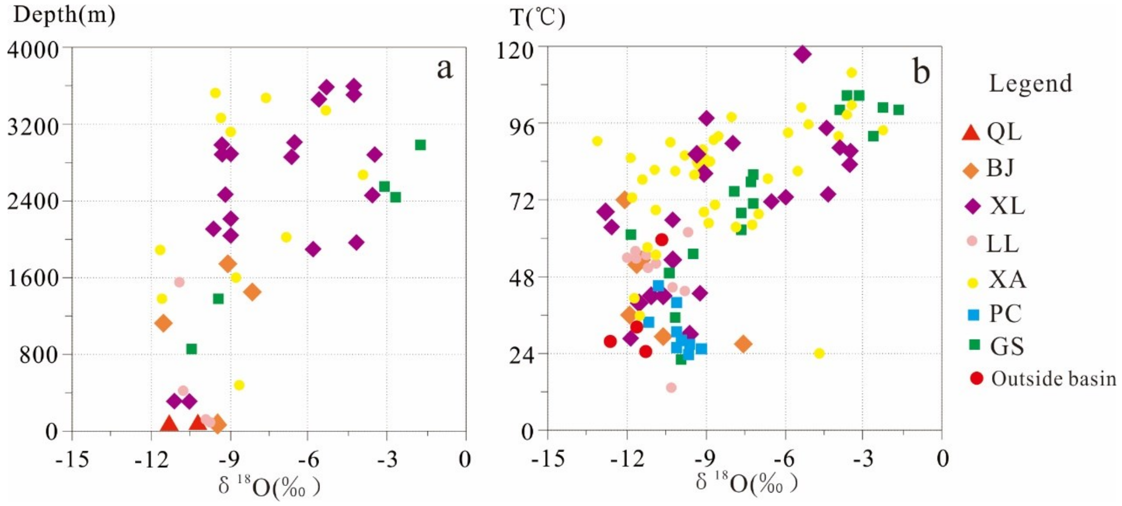

Fig 3: Relation between $\delta^{18}O$ value and depth (a) and temperature of geothermal water in Guanzhong Basin

(2) Temperature at well heads

As the sampling temperature of geothermal water increases, $\delta^{18}O$ drifting quantity gradually grows (Fig. 3b). The positive correlation coefficient is described as: r^2=0.68. Correlation rises with the increasing temperature at well heads, showing that high temperature is more conducive to the positive drifting of ^{18}O. Under the same condition, the water-rock interaction is very likely to happen in the high-temperature groundwater. Besides, the temperature of geothermal water depends on such factors as the proportion of cold surface water involved, or depth of geothermal water and availability of favorable geological condition. The factors should be taken into conditions.

(3) Water-rock interaction

Water-rock interaction is an important factor that affects ^{18}O. Fig. 4a indicates the relation between TDS and $\delta^{18}O$, showing that the concentration of $\delta^{18}O$ value happens along with the increasing TDS in geothermal water system. Without the foreign TDS source, TDS can usually reflect the strength of water-rock interaction. So the larger TDS, the more frequent exchange of ^{18}O and the larger drifting scope. As indicated in Fig. 4b, the concentration of $\delta^{18}O$ value happens along with the increasing Sr contents in geothermal water system. The positive correlation coefficient is described as: r^2=0.48, showing that ^{18}O drifting quantity of geothermal water is related to the water-rock interaction. The stronger water-rock reaction is, the larger ^{18}O drifting quantity is. The strong water-rock reaction is an important factor that affects ^{18}O drifting quantity.

Rock type is also a key factor that causes the ^{18}O drifting of groundwater. Fig. 7 c-e shows the relation between anions from different types of mineral rocks and the $\delta^{18}O$ value of geothermal water. As indicated in Fig 4c, the concentration of $\delta^{18}O$ value in geothermal water system happens along with the increase in $HCO3^-$ contents. They are in the weak positive correlation (coefficient: r^2=0.32). This reveals that there are the mineral rocks with carbonate lithotype in geothermal reservoir, such as calcite and dolomite. When the regional tectonic analysis is made, the water-rock interactions with carbonate involved are frequent near the fault zone and the fault transitional zone. Fig 4d reveals that ^{18}O drifting quantity of geothermal water will increase along with the rise in SO_4^{2-} contents. The positive correlation coefficient r^2=0.38. The exchange between the minerals with carbonate such as plaster, and the geothermal water, makes SO_4^{2-} contents increase and ^{18}O drifting quantity considerable. As shown in Fig 4c and 4d, the strong carbonate lithotype water-rock interaction also happens in the water sampling points of strong carbonate water-rock interaction, but the ratio of different water-rock reactions at different points is a bit different. According to Fig 4e, when SiO_2 contents in geothermal water is rather high, $\delta^{18}O$ drifting quantity is considerable. This means that the water-rock interaction between carbonate minerals in wall rocks of geothermal reservoir and the geothermal water is another factor that causes the ^{18}O drifting of geothermal water in study area.

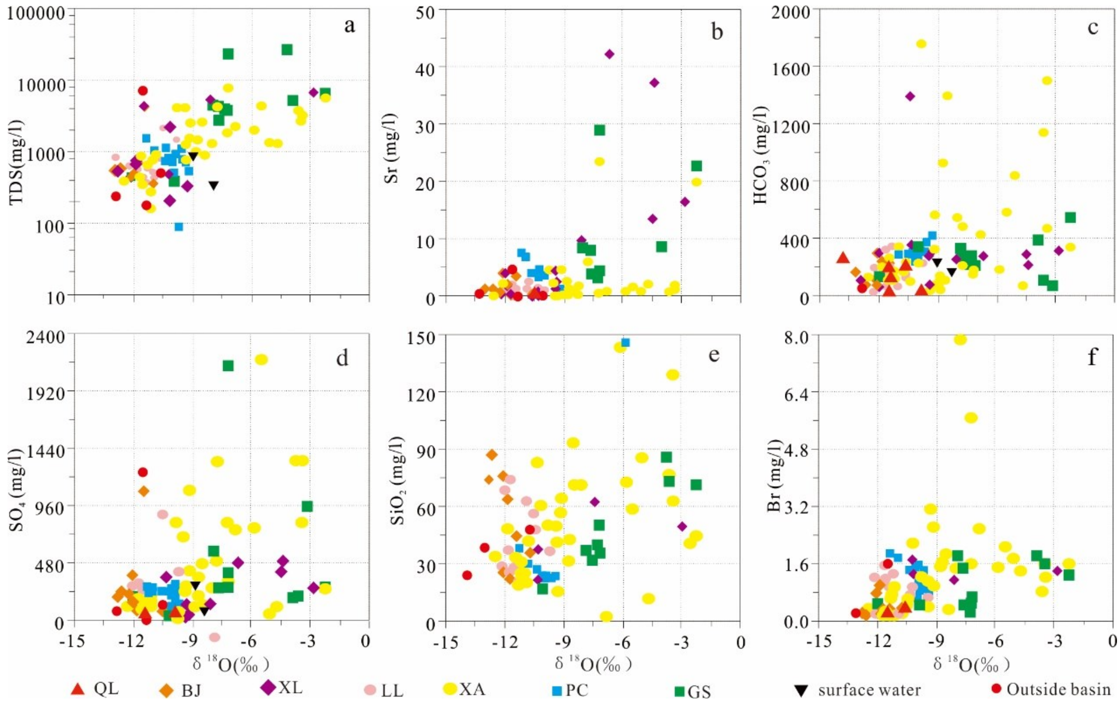

Fig 4 : Relation between δ^{18}O value of geothermal water in Guanzhong Basin and TDS, Sr, HCO_3^-, SO_4^{2-}, SiO_2 and Br

4. FORMATION MECHANISM AND CIRCULATION MODEL OF GEOTHERMAL WATER

4. 1 Formation mechanism

The geothermal water of Guanzhong Basin is likely to have ancient water of sedimentation genesis. According to Fig. 5 that shows the δ^{18}O-δD relation of different genesis types, the geothermal water in the study area is almost unlikely to have deep primary magnatic water and mantle water as its source. The metamorphic water at the temperature of 300-600℃ can't recharge the geothermal water in this study area. The δ^{18}O-δD value in the geothermal water within the parts of Gushi depression, Xianli fault-step and Xi'an depression falls within sedimentation water. This means that some of the geothermal water within the parts of Gushi depression, Xianli fault-step and Xi'an depression may get recharged by ancient surface water, namely sedimentation water. The distribution scope of sedimentation water mainly falls near Weihe fault of Gushi depression, Xianli fault-step and Xi'an depression. This is consistent with the conclusion drawn from the fact that ρ（Cl-）/ρ（Br-）ratio is larger than 293. Thus, this further reveals the genetic characteristics of sedimentary geothermal water in Gushi depression and the features of residual sedimentation water near Weihe fault of Xi'an fault and Xianli fault-step.

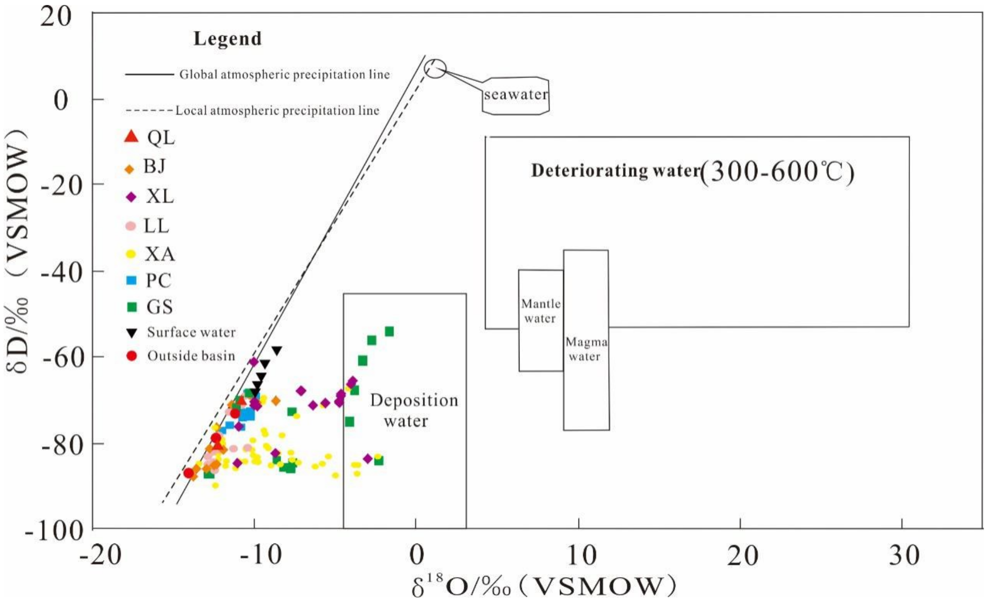

Fig 5: Hydrogen-oxygen isotope relation of geothermal water of different genetic types

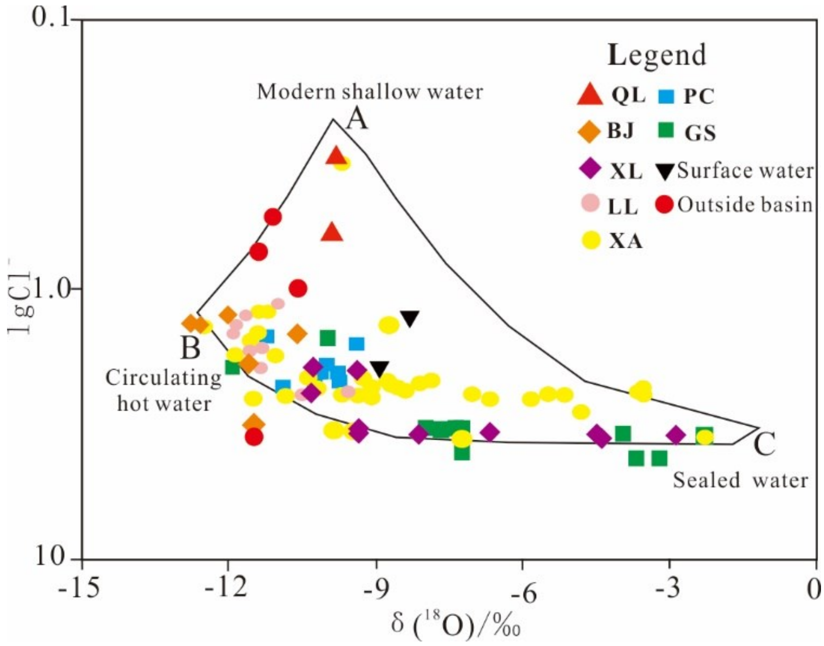

Fig 6: Triangular chart of geothermal water in Guanzhong Basin

According to the relation between $\delta^{18}O$ value and Cl^- contents of geothermal water, the geothermal water in the basin can be classified as follows. As indicated in Fig. 6, Point A represents the source value of modern circular geothermal water that is quite open and active in the shallow surface or ground surface of the basin, and Point B represents the source value of circular geothermal water on the basin edge. The typical zones are geothermal wells of bulging area and geothermal wells along Qinling Mountains in Xi'an depression. Point C represents the source value of closed geothermal water in the basin hinterland. The typical zones are geothermal wells in Gushi depression, Xi'an depression and the part of Xianli fault-step. The $\delta^{18}O$ value and Cl- value of geothermal water, which changes from the shallow surface of basin edge, through the basin's peripheral areas, to the basin center, experiences an evolution from Source A to Source B, and finally to Source C. To be specific, during the evolution from Source A to Source B, the proportion of modern atmospheric precipitation decreases, the geothermal water gets older and shows a less strong circulation and renewal ability; during the evolution from Source B to Source C, the geothermal water sees a growing $\delta^{18}O$ value, stronger water-rock interaction, weak circulation and renewal ability, and less frequency of hydraulic connections, and more closed geothermal reservoir. Also according to this figure, the geothermal water in Gushi depression performs very poor in renewal ability and hydraulic exchange ability, the most closed geothermal reservoir, and then comes the geothermal water in Xianli fault-steps and Xi'an depression.

4. 2 Circulation model

According to the discussion results, the storage environment of geothermal water in Guanzhong Basin can be divided into four types, including open circulation, half-open, closed and sedimentary[32]. The classification type is indicated in Fig 7.

(1)Open circulation type: This type of geothermal water refers to the geothermal water within bulging areas and the shallow geothermal water along the southern foot of North Mountains and the piedmont of northern foot of Qinling Mountains within the depression area.

(2)Semi-half and semi-closed type: This type of geothermal water refers to the geothermal water in depression, including some of deep geothermal water that moves toward the basin hinterland within Xianli fault-step, Gushi depression and Xi'an depression.

(3) Closed type: This type of geothermal water mainly refers to the deep geothermal water that is distributed in the hinterland of Guanzhong Basin and Xianli fault-step, and on the two sides of Weihe fault in Xi'an depression.

(4) Sedimentary closed type: This type of geothermal water refers to the geothermal water that is distributed in Gushi depression and Huxia-Huayin area. The typical features are the extremely high contents of main ions and TDS contents in geothermal water, mainly taking the form of highly mineralized Na-Cl saline geothermal water, and δD-$\delta^{18}O$ value is distributed extremely away from the atmospheric precipitation line.

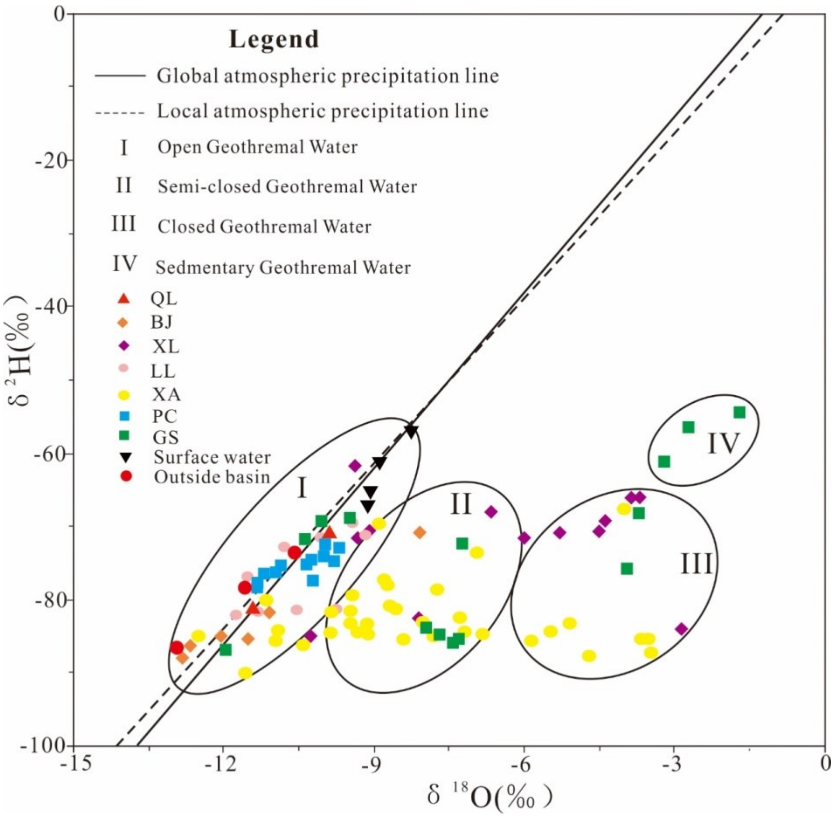

Fig 7: Classification of geothermal water storage environments in Guanzhong Basin

5. CONCLUSION

(1)The Guanzhong Basin is a giant fault zone formed during the Himalaya period in western China.This paper systematically analyzes the hydrogen and oxygen isotope characteristics of various tectonic areas in Guanzhong Basin from the perspective of geothermal research, which is of great significance for studying basin-scale hydrothermal activities.The isotope technique is an effective way to study the heat circulation and storage of geopressued-type low and mid temperature geothermal system. The environmental isotope materials of geothermal water in Guanzhong Basin can provide the direct evidence for the source, mixture, circulation and water-rock interaction of geothermal water in the basis, and lays a theoretical basis for the scientific exploitation, use and management of local groundwater resources.

(2)Most of the geothermal research in Guanzhong Basin concentrated on the history of thermal structure and thermal evolution of the basin. The research carried out from the perspective of geochemistry based on the entire basin instead of individual geothermal points.The systematic analysis and study of stable isotopes in the whole basin is conducted. The -$\delta^{18}O$ result shows that the geothermal water in the basin is mainly recharged by atmospheric precipitation. Most of the geothermal water points on the basin edge and in the bulging areas are distributed along the precipitation lines. This shows that the geothermal water and surface water in bulging areas have frequent exchange and renewal, and the geothermal water gets mainly recharged by modern atmospheric precipitation and river seepage. In contrast, the geothermal water in Xianyang, Xi'an and Huayin in the basin hinterland are discharged by the atmospheric precipitation at the last glacial period. The change of δD value indicates that, with Weihe Fault as a border, the area to the north is North Mountains groundwater system, which is mainly recharged by piedmont surface water of North Mountains, and the area to the south is Qinling groundwater system, which is mainly recharged by atmospheric precipitation and surface water of Qinling Mountains.

(3)The factors that affect $\delta^{18}O$ drifting in Guanzhong Basin include depth of geothermal reservoir, temperature at well heads, water-rock interaction, geothermal reservoir environment, lithological characteristics and residence time. The d-excess influencing factors are almost the same as the factors that affect ^{18}O drifting. The distribution characteristics of d value show that the runoff of geothermal water in Guanzhong Basin trends from the basin edge to the basin center.

(4)The flow state of water is a key factor in heat transfer. Most of the geothermal resources in the basin are based on static resources and qualitative evaluation of resource quality. Analysis of the geothermal occurrence characteristics of the basin from the perspective of groundwater flow systems is of great significance for resource evaluation.The circulation and genetic models of geothermal water in the basin are built. Based on the hydrogen-oxygen isotope characteristics of Guanzhong Basin, the storage environment of geothermal water in the basin can be divided into four types, including open circulation type, half-open and half-closed type, closed type and sedimentary closed type. The open circulation type refers to the geothermal water within bulging areas and the shallow geothermal water along the southern foot of North Mountains and the piedmont of northern foot of Qinling Mountains within the depression area. The half-open and half-closed type refers to the geothermal water in depression, including some of deep geothermal water that moves toward the basin hinterland within Xianli fault-step, Gushi depression and Xi'an depression. The closed type refers to the deep geothermal water that is distributed in the hinterland of Guanzhong Basin and Xianli fault-step, and on the two sides of Weihe fault in Xi'an depression. The sedimentary closed type refers to the geothermal water that is distributed in Gushi depression and Huxia-Huayin area.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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