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Genesis Analysis of Geothermal Systems in Guanzhong Basin of China with Implications on Sustainable Geothermal Resources Development

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ABSTRACT

Based on results of comprehensive oil and gas exploration, together with data of the exploited Xian an Xianyang geothermal fields, we propose a new model of genesis for the geothermal systems in Guanzhong Basin in Northwest China. The model emphasizes the role of up-lifting and faulting activities that can be related to the movement of the Tibetan plateau towards northeastern direction. The model is different from most geothermal systems commonly found in other sedimentary basins in China that are controlled by heat flow redistribution as a consequence of basement fluctuation. Using geochemical modeling and isotopic analysis, we study the water-rock interaction processes in the main geothermal reservoirs and discuss the anticipated challenges in used water re-injection. Chemical stimulation is suggested, aiming at improving the injectivity of the geothermal reservoir.

1. INTRODUCTION

The Guangzhong Basin, with an area of 20,000 km^2, is located in Shaanxi Province, Northwest China (Fig.1). It sits between the Qinling Mountains on the south, the North Mountains on the north, and the Yellow River on the east. The terrain in the basin is flat and tilts to the southeast, the elevation descends from 600m to 340m from the west to the east, the elevation of the surrounding mountains falls in the range of 1200-3300m. Wei River constitutes the main river system, and drains into the Yellow River. The mean annual temperature is 13℃, annual precipitation is 600 mm, concentrated in July to October.

The static geothermal reserves of the Guanzhong Basin is about 133.7 billion m^3 and the exploitable part is 2 billion m^3. The total heat is up to 2.67×10^{18} kcal and the exploitable heat within 4000m depth accounts for 68%. Xi'an and Xianyang, found in the middle of the basin are the main geothermal fields. Since 1970s, geothermal resources in the basin have been commercially exploited on a large scale near Xian, in Xianyang moer rcently. By 2007, there were 346 geothermal wells and the geothermal space heating reached 3.5 million m^2.

In spite of the proven economic and social benefits, geothermal utilization is faced with many challenges. The principal problem is how to utilize the geothermal resources in a sustainable way. In order to achieve this goal, it is important to study the genetic origin of the geothermal systems. It is also necessary to understand geochemical processes in the geothermal reservoir so as to optimize the mode of exploitation.

Recent exploration activities for oil and gas resources in the Guanzhong Basin offered uniques opportunity to better understand the geology of the basin as related to geothermal resources, Based on the information, together with hydrogeology and geochemistry, we attempt to develop a genetic model on the mechanism of geothermal systems and discuss the implications on sustainable development.

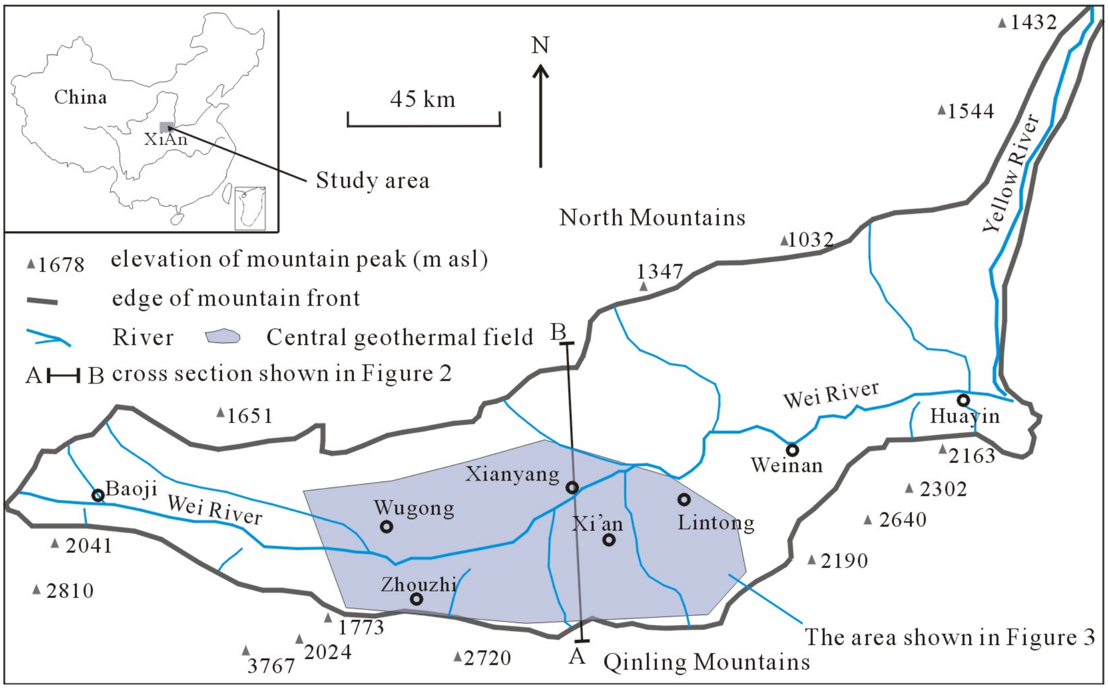

Fig.1: Location study area in Guanzhong Basin, China

2. TECTONIC STRUCTURE AND GEOTHERMAL FIELDS

2.1 Basin Evolution and Geothermal Background

The Guanzhong Basin is a Cenozoic rift basin (Fig.2). It develops along with the uplift of the Tibet Plateau, undergoing a process of strike slip succeeded by rise and fall. By now the subsidence process is still going, and the main faults are still active, thus the basin is still in the formation stage. The upper mantle upwelling associated with the rift structure have resulted in a high heat flow background that is the main heat source of geothermal system.

The Cenozoic basement is pieced together by several tilting micro fault blocks. Structural feature shows asymmetric step-type trough bend. The basement to the north of the Wei River fault consists of Palaeozoic limestone; while to the south consists of Proterozoic schist and Cenozoic granites. The basin is mainly filled with Tertiary fluvial and Aeolian sediments, and Quaternary loess. The basement rock consists of Proterozoic schist and Cenozoic granites. The Xi'an geothermal field covers an area of about 1300 km^2, including the cities of Xi'an, Lintong, Chang'an and Zhouzhi. Geothermal anomalies are found between the Wei River and the southern margin of the Guanzhong Basin. A 40-60m thick aeolian sediment package, consisting of loess interlayered with paleosoils, covers most of the second terrace of the Wei River. Alluvial strata (silty clays interbedded with sands and gravels), about 17-80m thick, are distributed over all river terraces. Other alluvial deposits (i.e., interbedded yellow silty clays, sands and gravels) between 15 and 60m thick are found below the loess and river terrace sediments. The Quaternary aquifers consist of porous, aeolian and alluvial sediments, overlain by an aquitard of sandy and silty clays. Four geothermal reservoirs have been identified and are being exploited from 400 to 3000m depth in Xi'an geothermal field. The shallowest is in Quaternary sediments, in the 400-800m depth interval, with a porosity of 18%-19%. The other three are in Tertiary sediments at depth intervals of 800-1250m, 1500-2500m, and 1900-3000m, with a porosity of 15%-28%, 9%-24%and 17.7%, respectively. Thick clay layers act as aquitards between the geothermal reservoirs. The third geothermal reservoir is the most productive.

2.2 Distribution of Fault Systems and Geothermal Localities

Faults are widely found in Guanzhong Basin (Fig.3). According to their magnitude and function, these faults can be divided into three categories.

1) Faults developed along the basin margin, controlling the development of the basin and the boundaries to the adjacent tectonic units. These include Qinling Mt. front fault (F1) and North Mountain front fault (F2).

2) East-westwardly developed faults, controlling the development of the basin, the distribution of the sediment and their facial types, acting as the boundaries between the structural units in the basin. These include Yuxia fault (F3) and Wei River fault, Zhouzhi fault (F4), etc.

3) North-eastward and north-westwardly developed faults, constituting the boundary between the structural subunits in the basin and controlling the distribution of the sediments. These include Chang'an-Lintong fault (F5), etc.

The main faults occur east-westwardly or nearly east-westwardly. The north-eastward and north- westward ones are usually secondary. All the faults are high angle normal faults, with dip angles ranging between 50°and 75°. At cross-sectional view, they are Y shaped fracture system of step angles, showing the dominant effect of extensional stress field. The fault throw are larger than 1km. These faults not only control the formation and development of the basin, structure zoning and Cenozoic deposition, but also control the distribution of geothermal abnormal areas and serve as the main pathways among different geothermal reservoirs. For example, the Qinling Mountain front faults connects the surface water, Quaternary aquifer, Tertiary aquifer and bedrock geothermal water（Ma, et al., 2006）.The connectivity among the aquifers depends on the degree of opening of the active faults. Based on the heat source and structure, geothermal abnormal areas in the basin can be divided into three zones: geothermal zone along the north marginal faults, geothermal zone along the south marginal faults, and the central geothermal zone（ Xianyang and Xi'an geothermal fields).

3. ENVIRONMENTAL ISOTOPES AND INTERACTION OF GEOTHERMAL WATER WITH THE SEDIMENTS

3.1 Stable Isotope Composition and Origin of the Geothermal Waters

The stable isotope compositions of the geothermal waters in Guanzhong Basin are shown in Fig.4, the δ^2H values range from -94.7 to -80.4‰, and the δ^{18}O values range from approximately -11.8 to -3.1‰, except for one sample from Lintong with higher δ^2H values of -65.7‰ and δ^{18}O values of -9.6‰, due to different water circulation pathways (Qin, et al., 2005). For the groundwater in the Qinling Mts. front, δ^2H and δ^{18}O values range from -91.9 to -65.1‰ and -9.42 to-12.6‰; for the groundwater in the North Mts. Front, the values are-36.4 to -85.0‰ and -5.6 to -11.6‰ (Ma, et al., 2008); for precipitation, the values are -6.1 to -5.2‰ and -36.4 to -33.4‰. Groundwaters in the southern and northern rim of the basin fall on the LMWL, while the geothermal waters in Xi'an and Xianyang exhibit a significant δ^{18}O shift up to 10‰ as compared to their projected original composition at the LMWL.

Comparison of δ^2H shows that geothermal waters in Xi'an and Xianyang are of different origin, though the two geothermal fields are very close by from each other, the δ^2H of Xi'an geothermal water is similar to the groundwater in the Qinling Mts. front, while Xianyang geothermal water is similar to the groundwater in the North Mts. front, indicating the same recharge source, respectively. Deuterium excess of the geothermal waters shows a decreasing trend from the periphery to the center of the basin (Ma et al., 2008), which also supports this recharge model. According to this model, the calculated recharge elevation for Xianyang geothermal water range between 700 and1000 m, corresponding to the North Mts.; while for Xi'an it is from 1500 to 2800m, corresponding to the north slope of the Qingling Mts. Oxygen shift generally occurs in geothermal systems with reservoir temperatures higher than 250℃, however, in Xi'an and Xianyang geothermal fields in the Guanzhong Basin characterized by relatively low reservoir temperatures in the range of 40-120℃, significant oxygen shift up to 10‰ has been observed, which is unusual in geothermal systems of the same kind. The δ^{18}O shift indicates intensified water-rock interactions in the geothermal reservoirs, and may reflect a relatively closed geological environment with limited connection to the modern recharge water.

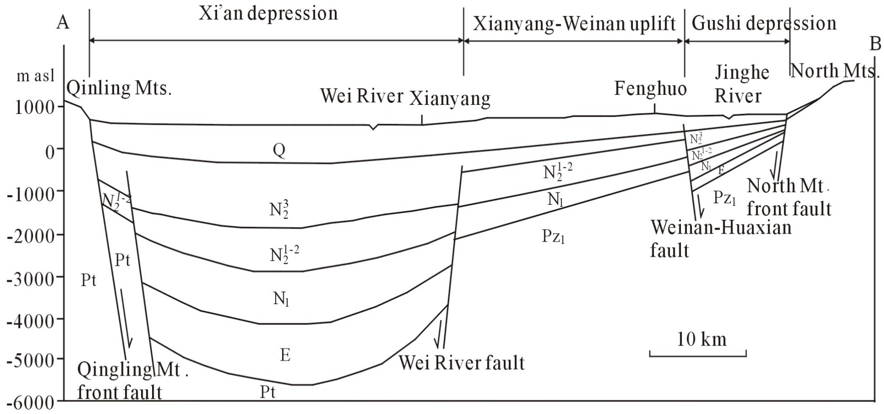

Fig.2: A geological cross section of Guangzhong Basin (A-B cross section as indicated in Fig. 1)

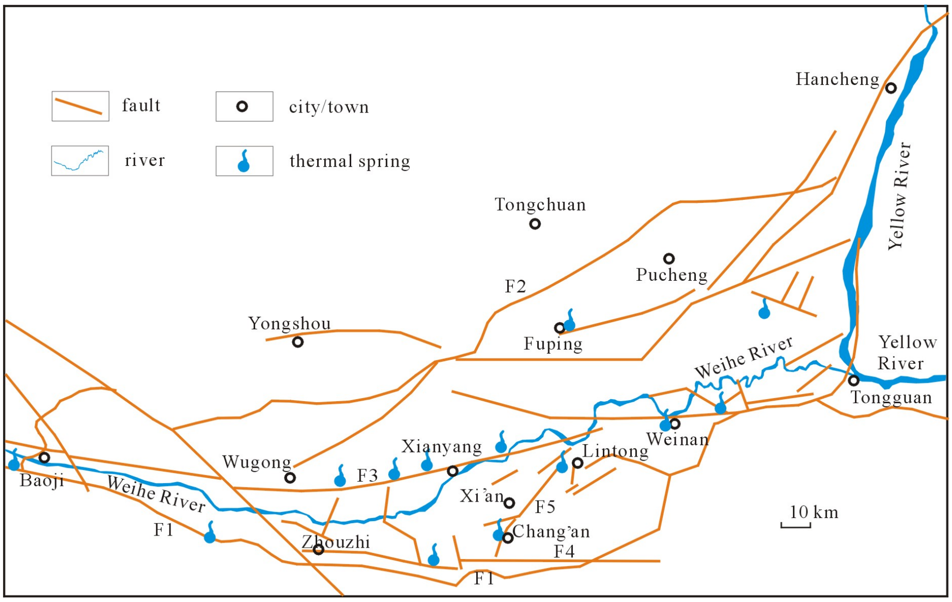

Fig.3: Geological structures and geothermal localities in Guanzhong Basin. F1: Qinling Mt. front fault; F2: North Mt. front fault (south); F3: Wei River fault; F4:Yuxia fault;F5: Chang'an-Lintong fault

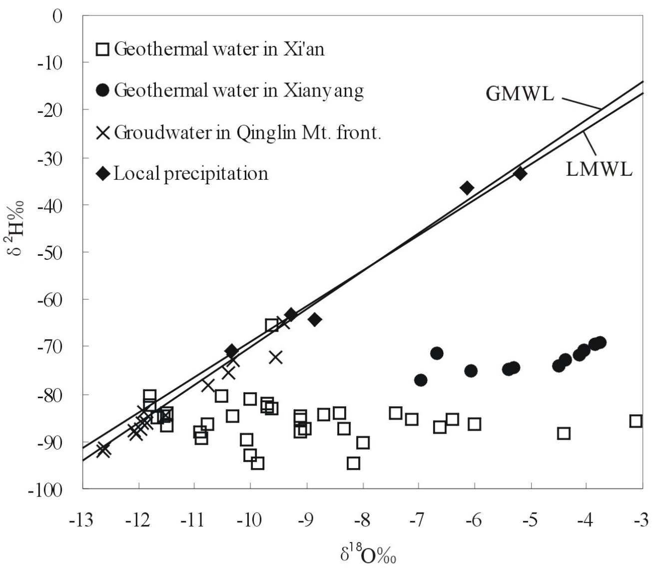

Fig.4: δ2H-δ18O plot showing the stable isotope composition of the geothermal waters in the Guanzhong Basin. The Local Meteoric Water Line (LMWL), based on the data from the GNIP network at Xi'an station is δ2H= 7.5δ18O+ 6.1.

Data indicated by open squares are from Qin, et al.(2005) and Ma, et al.(2008), data indicated by crosses and circles are from Ma, et al.(2008).

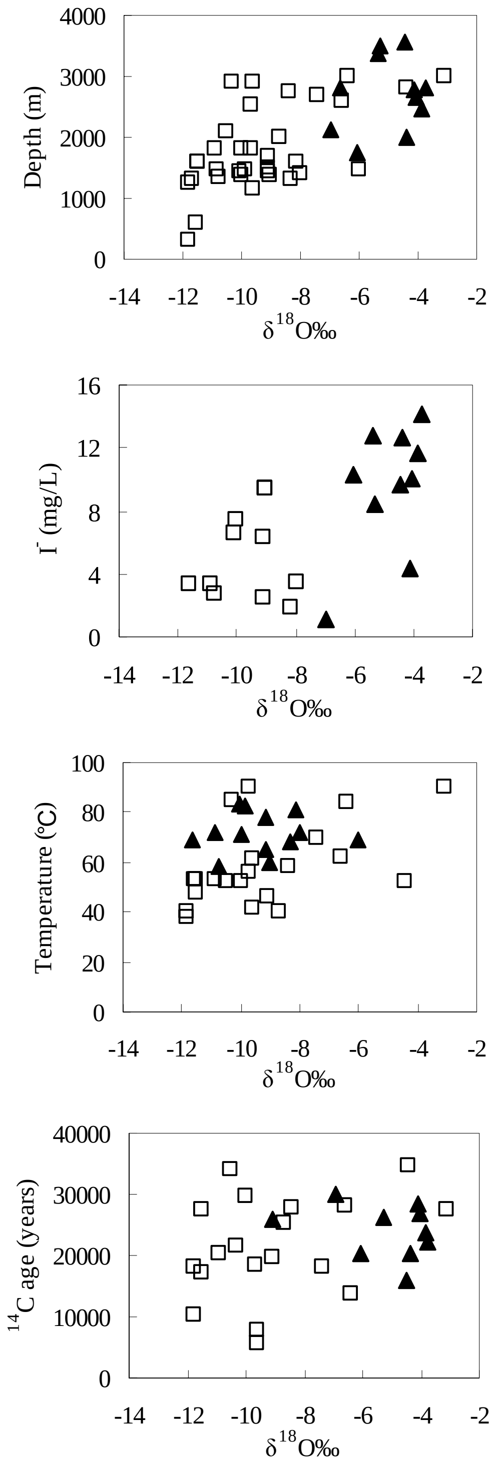

Fig.5: Xi'an and Xianyang geothermal waters. Variations in depth, I, temperature and ^{14}C age vs. $\delta^{18}O$, data indicated by open squares are from Qin, et al. (2005) and Ma, et al (2008), solid triangles are from Ma, et al. (2008).

For geothermal water samples from Xi'an and Xianyang, increase in temperature, depth, ^{14}C age, TDS, I^- (Fig.5), H_2S and $\delta^{34}S$ (Ma, et al., 2008) can be clearly observed when $\delta^{18}O$ shift grows, the occurrence of I^- and H_2S represents a relatively isolated and reducing environment favering the biological-deoxidization processes, and are more enriched in Xi'an than in Xianyang. $\delta^{34}S$ enrichment may be caused by the reduction of SO_4^{2-} under a relatively isolated environment, following the reaction such as: $SO_4^{2-}+2C+2H_2O \rightarrow H_2S+2HCO_3^-$ and may account for the fact that the main anions in Xi'an is SO_4^{2-} , while in Xiangyang is Cl^-, and having a higher content of H_2S. Hence, Xianyang geothermal field may be even more closed compared to Xi'an.

3.2 Mechanisms for the Oxygen Shift in Geothermal Waters

Generally speaking, the degree of oxygen shift is determined by reservoir temperature, water-rock interaction time and water/rock ratio of the system.

3.2.1 Reservoir Temperature

The increase of temperature has two main effects on isotope exchange. At elevated temperatures, the equilibrium fractionation of ^{18}O between minerals and water is reduced, thus increasing the initial degree of disequilibrium; the rate of isotope exchange is also accelerated. Fig.5 shows that $\delta^{18}O$ increases with the increase of wellhead temperature. To study the effect of temperature on $\delta^{18}O$ shift, calculation of the reservoir temperature is needed. Ma, et al. (2008) estimated the reservoir temperature of Xianyang geothermal water to be 144.6-170℃ using the Na-K-Mg diagram. A mature water sample of 3000m depth from Xi'an geothermal field was used to calculate the reservoir temperature using the FixAl method (Pang and Reed, 1998), the calculated temperature is 130℃ (Fig.6).

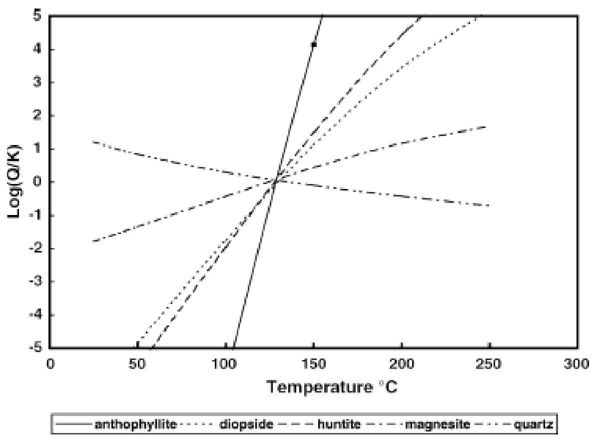

Fig.6: Plot of log (Q/K) vs. temperature (℃) for a mature water sample from Xi'an geothermal field, showing that the equilibrium temperature between water and minerals at a depth of 3000m is 130℃.

3.2.2 Water-Rock Ratio

Fig.7 shows that HCO_3^- and ^{14}C increase with the increase of $\delta^{13}C$, illustrating that $\delta^{13}C$ enrichment is correspondent to the carbonate dissolution , indicating that $\delta^{13}C$ in the geothermal waters has two main sources: soil CO_2 and reservoir rock carbonates. It has also been found that SiO_2 increases with $\delta^{18}O$ in the geothermal waters from Xi'an geothermal field. Hence dissolution of silicate and carbonate take place and may participate in the water-rock ^{18}O exchange in the central part of the basin.

Exchange of ^{18}O between water and calcite may be the dominant process due to the low fractionation factor for ^{18}O exchange between water and calcite at temperatures lower than 100℃, and the lesser temperature dependence of the fractionation factor for calcite-water compared to that for quartz–water or kaolinite-water exchange.

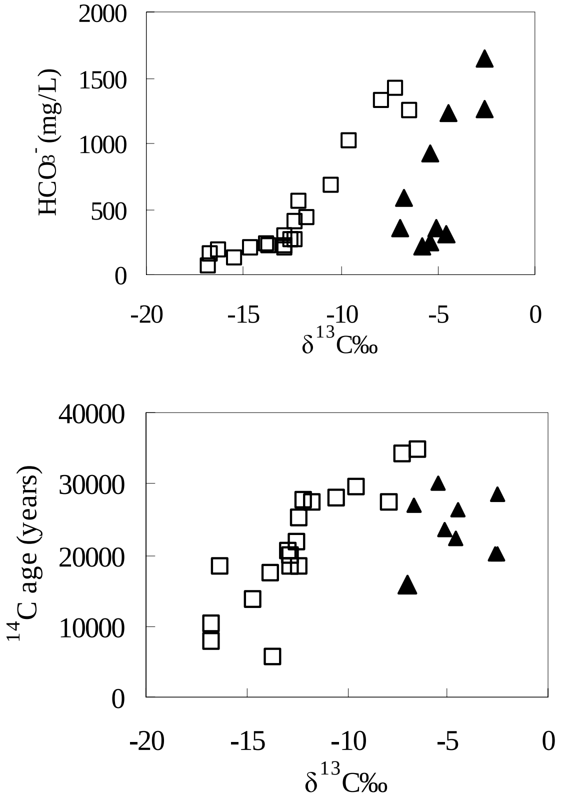

Fig.7: Xi'an and Xianyang geothermal waters. Plots of δ^{13}C vs. HCO_3^- and δ^{18}O.

Using the equilibrium fractionation factors of O'Neil et al.(1969) for the calcite–water system, the values of δ^{18}O of the geothermal water were calculated over the measured temperature range.

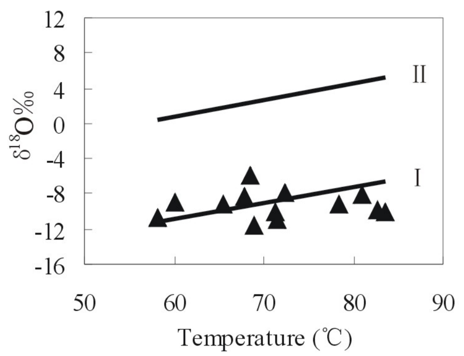

Fig.8: Xianyang geothermal waters. δ^{18}O vs. wellhead temperatures. calcite equilibrium curve (I) corresponds to δ^{18}O = 11.3‰ and curve II to δ^{18}O = 22.3‰.

It is shown in Fig.8 that in the temperature range of 58-84℃ the general trend of δ^{18}O versus temperature falls on the equilibrium line I defined by an assumed δ^{18}O value for calcite of 11.3‰ but lies below equilibrium line II defined by the value of δ^{18}O assumed for calcite of 23.3‰, a value widely observed for non-metamorphosed limestones. The scatter of the data around line I may result from: (i) water-rock ratio (ii) incomplete equilibration due to the low temperature at which the exchange reaction occurs; (iii) metamorphism of reservoir rocks; (iv) variation in isotopic composition of reservoir rocks. The assumed δ^{18}O value for calcite at equilibrium is lower than that for Xi'an, which is 14.5‰ (Qin et al., 2005), which may have resulted from these processes.

The water-rock ratios can be calculated choosing the mature water samples with maximum δ^{18}O shifts for Xi'an and Xiangyang geothermal fields, according to the basis of ^{18}O isotope mass balance,

$$\delta^{18}O_{total} = \frac{R}{(1+R)\delta^{18}O_{water-ini}} + \frac{R}{(1+R)\delta^{18}O_{carbonate-ini}}$$

$$= \frac{R}{(1+R)\delta^{18}O_{water-final}} + \frac{R}{(1+R)\delta^{18}O_{carbnate-final}}$$

the water-rock ratio is derived from,

$$R = \frac{\left(\delta^{18}O_{carbonate-ini} - \delta^{18}O_{carbonate-final}\right)}{\left(\delta^{18}O_{water-final} - \delta^{18}O_{water-ini}\right)}$$

Values for the equation are: $\delta^{18}O_{carbonate-final}$ is 9‰, according to the carbonate nodules in the tertiary reservoirs of the Guangzhon Basin (Ding and Yang, 2000), $\delta^{18}O_{carbonate-ini}$ is 30‰, $\delta^{18}O_{water-ini}$ and $\delta^{18}O_{water-final}$ for Xi'an are -12.2 and -3.1‰, and -10.0‰ and -3.7‰ for Xianyang.

The calculated water-rock ratio for Xi'an is 2.3, and is 3.3 for Xianyang. Assuming a rock density of 2.65 g/cm^3, the carbonate is about 10% by volume fraction, a porosity of 14% for Xi'an , and 19% for Xianyang are derived, these porosity values are in accordance with the data from oil and gas exploration. It has been identified that the carbonate cements account for 10%-30% of the Tertiary reservoir rock by volume, thus about 16%-50% of them has evolved in the interaction with the geothermal waters.

3.3 Time Span of Water-Rock Interaction

It's showed in Fig.5 that δ^{18}O shifts increase with the increasing ^{14}C age, indicating that the geothermal water residence time may play a role in ^{18}O exchange. The uncorrected ^{14}C age for Xianyang geothermal water is in the range of 15,788-30,142 years (Ma, et al., 2008), while 5,489-34,700 years for xi'an (Qin, et al., 2005). Taking ^{14}C dilution by the exchange of carbon isotopes between the DIC (dissolved inorganic carbon) and carbonate minerals in the reservoir matrix into consideration, ^{14}C ages of Xi'an geothermal water were corrected by Fontes-Garnier model chosen on the basis of the hydrogeochemical evolution characteristics (Table 1).

time is, the larger the oxygen shift will be. Besides, temperature is the most important parameter for water-rock interactions, the higher the temperature, the easier the oxygen shift to take place. In order to distinguish the relative significance of water-rock interaction time and temperature in the δ^{18}O shift, or water rock interaction, the following statistical analysis has been performed. In the exercise, we have ignored the effect of water-rock ratio, for simlicity.

Table 1: Carbon-14 age and oxygen shift of geothermal waters in Xi'an

Sample number	Well depth(m)	^{13}C (‰)	$\delta^{18}O$ (‰)	^{14}C (pmc)	T-well -head (℃)	T-SiO_2 (℃)	Uncorrected age(10^4a)	Corrected age(10^4a)	$\delta^{18}O$ shift (‰)
GZH-1	2701	-16.3	-7.4	10.4	70	96	1.87	1.62	4.6
GZH-2	2100	-7.2	-10.5	1.5	52	83	3.47	2.50	1.5
GZH-3	1800	-9.5	-10	2.5	52	74	3.05	2.34	2.0
GZH-4	3001	-14.6	-6.4	18.0	84	112	1.42	1.06	5.6
GZH-5	1800	-12.3	-9.7	10.1	56	80	1.90	1.41	2.3
GZH-6	2900	-12.5	-10.3	6.8	85	120	2.22	1.74	1.7
GZH-7	3004	-7.9	-3.1	3.3	90	136	2.82	1.84	8.9
GZH-8	2012	-12.3	-8.7	4.3	40	81	2.60	2.12	3.3
GZH-9	300	-16.7	-11.8	28	40	72	1.05	0.84	0.2
GZH-10	2800	-6.4	-4.4	1.3	52	124	3.59	2.42	7.6
GZH-11	2588	-10.5	-6.6	3.1	62	114	2.87	2.24	5.4
GZH-12	1500	-12.8	-9.1	8.5	46	94	2.04	1.58	2.9
GZH-13	2748	-12.1	-8.4	3.2	58	116	2.85	2.34	3.6
GZH-14	1590	-11.7	-11.5	3.3	48	83	2.82	2.29	0.5
GZH-16	2900	-16.7	-9.6	38.1	61	97	0.80	0.56	2.4
GZH-17	1801	-12.9	-10.9	8.0	53	83	2.09	1.64	1.1
GZH-18	1600	-13.8	-11.5	11.6	52.6	80	1.78	1.40	0.5
GZH-19	1160	-13.6	-9.6	50.5	42	84	0.56	0.16	2.4
GZH-20	1250	-12.8	-11.8	10.4	37.5	71	1.87	1.43	0.2

Generally speaking, the longer the water-rock interaction The relationship of $\delta^{18}O$ shift (Δ), which is defined as the shift from the initial $\delta^{18}O$ of -12‰ (on LMWL), with water-rock interaction time (t) and reservoir temperature (T) of individual water samples based on SiO_2 geothermometry (Qin, et al., 2005) is statistically analyzed by multiple linear regression, yielding,

$$\Delta = 0.102T + 0.128t - 6.887$$

The predicted and observed oxygen shift for geothermal waters from Xi'an is shown in Fig.9.

Normalization of all the variables gives

$$\Delta_S = 0.815T_S + 0.034A_S - 2.886 \cdot 10^{-7}$$

It can be readily inferred that the coefficient of reservoir temperature accounts for 96% of the total coefficients; hence reservoir temperature is the dominant factor controlling the ^{18}O shift. Kinetic effects are secondary.

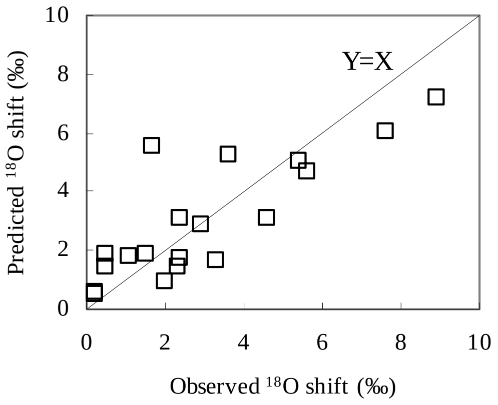

Fig.9: Predicted and observed oxygen shift for geothermal waters in Xi'an

4. GENETIC MODEL OF THE GEOTHERMAL FIELDS IN THE GUANGZHONG BASIN

The Guanzhong Basin is a Cenozoic rift basin. It develops along with the uplift of the Tibet Plateau, undergoing a process of strike slip pull apart succeeded by rises and falls. Upwelling of the asthenosphere results in a high heat flow background serving as the stable heat source for the geothermal fields in the Guanzhong Basin. During the development of the rift basin, there formed tensional fault systems with faults of different scales and massive Cenozoic sediments. These faults can server as conduits for geothermal water flow or storage space for water and heat, and have controlled the development and distribution of the geothermal fields. The massive Cenozoic strata can act as caprock and also provide a favorable storage space for water and heat.

The geothermal waters in the Guanzhong Basin are recharged by precipitation from the mountaineous areas on both sides of the basin. The recharged water flows to the central part of the basin though the fractured zones and aquifers at different rates, cycles deeply and is heated by the host rocks, and remaines in the fractured zone and aquifers. The major geothermal fields are developed in the centre of the basin where the groundwater retention zone is located. The distinct isotopic composition of geothermal waters between Xi'an and Xianyang reflects that the two are separate systems and that the controlling influence of the fault structures is the dominant factor.

5. IMPLICATIONS FOR GEOTHERMAL REINJECTION AND SUSTAINABLE DEVELOPMENT

The residence time of the major geothermal waters is relative long, mostly in the range of 11-35 thousand years. Furthermore, the tensional faults in the basin may connect different geothermal reserviors, shallow cold water or surface water. Large scale exploitation of the geothermal water may lead to the decline of the reservoir pressure and the change of the flow field, thus imposing the risk of the mixing of geothermal waters with shallow cold water or surface water through water-transmitting faults or by leaking though the aquitards, resulting in the cooling of the reservoirs. Thus a production-reinjection exploitation mode must be adopted for the sustainable use of the geothermal resources.

The Tertiary reservoir of the basin has a porosity of about 9%-28%, and a permeability of about 2-30μm^2. It has been argued that sandstone reservoirs with porosity and permeability less than 20% and 500μm^2 may have a poor injectivity (Seibt, 2003), moreover, reinjection may cause formation damage due to the unconsolidated reservoir rocks, resulting in the decrease of the reservoir injectivity.

However, geothermal reservoirs in the basin are rich in carbonate cements, with a volume ratio of 10%-30%; additive can be injected into the reservoirs to enhance the water-rock interactions and improve the hydraulic property when necessary, realizing effective reinjection.

6. CONCLUSIONS

1) The Guanzhong Basin geothermal fields are formed in an active rift basin, where extensive faulting and a high heat flow background are observed. The larger fault system in the central part of the basin with strong activity controls the development and the distribution of the geothermal fields.

2) The geological environment of the major geothermal fields in the central part of the basin is relatively closed with slow water recharge rates, mainly on the scale of tens of thousand of years. Individual geothermal systems with limited hydraulic connections are developed due to the control of fractures.

3) The remarkable and unusual $\delta^{18}O$ shifts in geothermal water at temperatures mostly below 100□ are result of water rock interaction. The extent of shift is controlled mainly by temperature, rather than residence time of water in contact with the rock. Carbonate in the formation sediments with a low porosity, ensuring a low water-rock ratio, play a key role in the process.

4) In order to ensure sustainable use of the geothermal resources, geothermal waste water re-injection must be implemented. However, the physical property of the reservoirs may cause a relatively poor injectivity. In light of the high content of carbonate cement in the reservoir rocks, there is a potential for improving the injectivity though chemical stimulation.

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