Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Deep groundwater cycle in Xiongxian geothermal field

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Keywords: Groundwater cycle; Geothermal system; Karstic reservior; Isotope; Xiongxian; China

ABSTRACT

The deep karstic aquifer containing hot water is ideal for space heating and maybe also for geothermal power generation. The hot water is characterized by high single-well yield, low salinity, gravity injection and less impact on environment when it is exploited. In order to run a karstic geothermal field sustainably, it is of high importance to identify the local groundwater circulation pattern in the field. Here we take Xiongxian geothermal field as an example to get insights into the characteristics of local groundwater circulation in karstic aquifers. Groundwater samples and surface water samples were collected, and analyzed for their hydro-chemical and isotopic contents. Results show that the TDS of groundwater in karstic aquifers is between 1.9 and 2.6 g/L. According to the data of water table, the local groundwater flow direction is from Southwest to Northeast. This is confirmed by the TDS data, which increases gradually in this direction. However, this is orthogonal to the regional groundwater flow direction that is from Northwest to Southeast. This phenomenon highlights the control of aquifer lithology and geological structures on the groundwater flow field. Isotopic data illustrates some oxygen isotope shifts, although the reservoir temperature is less than 90 ℃. Finally, a conceptual model is proposed to depict the deep groundwater cycle in Xiongxian geothermal field, which will serve as a basis for the further simulated model for exploitation strategy and could be used as a reference in similar karstic aquifers.

1. INTRODUCTION

The geothermal energy available from the Earth is potentially enormous, spanning a wide range of heat sources including hydrothermal resources and hot dry rock (HDR) energy. Among them, the hydrothermal systems taking advantage of heated groundwater is the kind in wide use.

Sufficient production of groundwater with constant temperature is most crucial for large scale utilization of hydrothermal resources. In this regard, the deep karstic aquifer containing hot water is ideal for space heating and maybe for geothermal power generation. The features of high single-well yield, low salinity, gravity injection and less impact on environment characterize the exploitation of karstic aquifers. In China, more than 80% of geothermal water is obtained from karstic aquifers (Pang et al., 2012).

Xiongxian geothermal field is located in Niutuozhen uplift, which has a total area of 640 km^2, with the area within Xiongxian territory being around 320 km^2. The recoverable heat in Xiongxian geothermal field is estimated to be 2.5 × 10^{18} J (Huang et al., 2012; Liu et al, 2014). Geothermal water in Xiongxian has been used for more than 30 years, with reservoir temperature ranging from 50°C to 95°C. The geothermal energy is mainly used for space heating, bathing and greenhouse agriculture. Space heating starts from November 15th every year and ends on March 15th the next year.

With the rapidly growing demand for energy, and increasing concern for climate change, large use of geothermal energy is highly expected. But overexploitation may cause resource depletion and other environmental problems (Duan et al., 2011). Taking Xiongxian as an example, we note that the water table has dropped by 30 m from 2001 to 2009. After 2009, many injection wells were installed in order to maintain the water table. For the sustainable use of geothermal water in Xiongxian, subsurface characterization is critical, while the research on deep groundwater cycle could serve as a basis.

2. STUDY AREA

Xiongxian lies in the North China Plain (NCP). It is at a distance of 108 km from Beijing and 100 km from Tianjin (Fig. 1). The Xiongxian geothermal system is situated in the Niutuozhen uplift, which is located north of the Jizhong Depression, and is a part of the Bohai Bay Basin (BBB). The BBB, one of the major petroleum and gas producing areas in eastern China, covers Bohai Bay and coastal areas with an area of about 200,000 km^2. It is a large Mesozoic - Cenozoic intra-cratonic sedimentary basin filled by continental sediments of Paleocene, Neogene and Quaternary ages. It was formed in the Tertiary on the basement of the North China Platform, and consists of many separate Paleogene faulted depressions. During the Neogene, the whole area subsided and became united into a great depression (Pang et al., 2013).

The boundary of the Niutuozhen Uplift consists of four main faults (Fig. 1 and Fig .2). They are the Niudong fault, the Niunan fault, the Rongcheng fault and the Daxing fault, which were created by folding movement from the Late Jurassic to the Cretaceous, during the Himalayan movement. The Xiongxian geothermal system is located in the southwest from the larger Niutuozhen geothermal system. The main geothermal reservoirs are porous Tertiary sandstone and karst-fissured dolomite bedrock. The strata of the Xiongxian geothermal system and surroundings include Quaternary and Tertiary formations in Cainozoic, Jixian System and Changcheng System in Proterozoic and Archaeozoic.

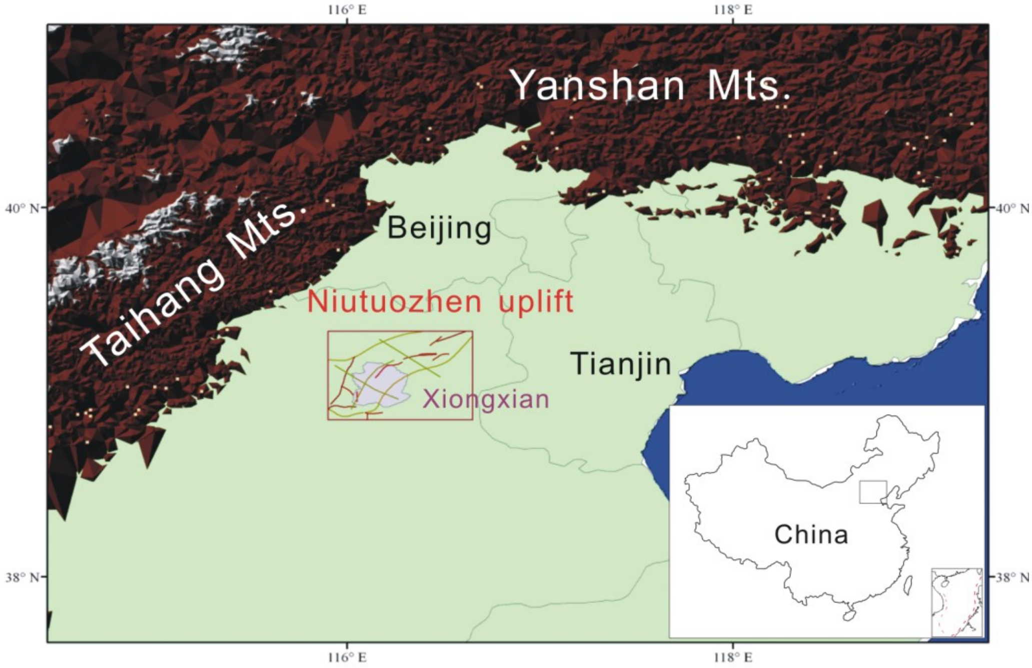

Figure 1 Locations of Niutuozhen uplift and Xiongxian geothermal field in China. The red block scheme illustrates the Niutuozhen uplift with faults as boundaries. The orchid polygon shows the extent of Xiongxian.

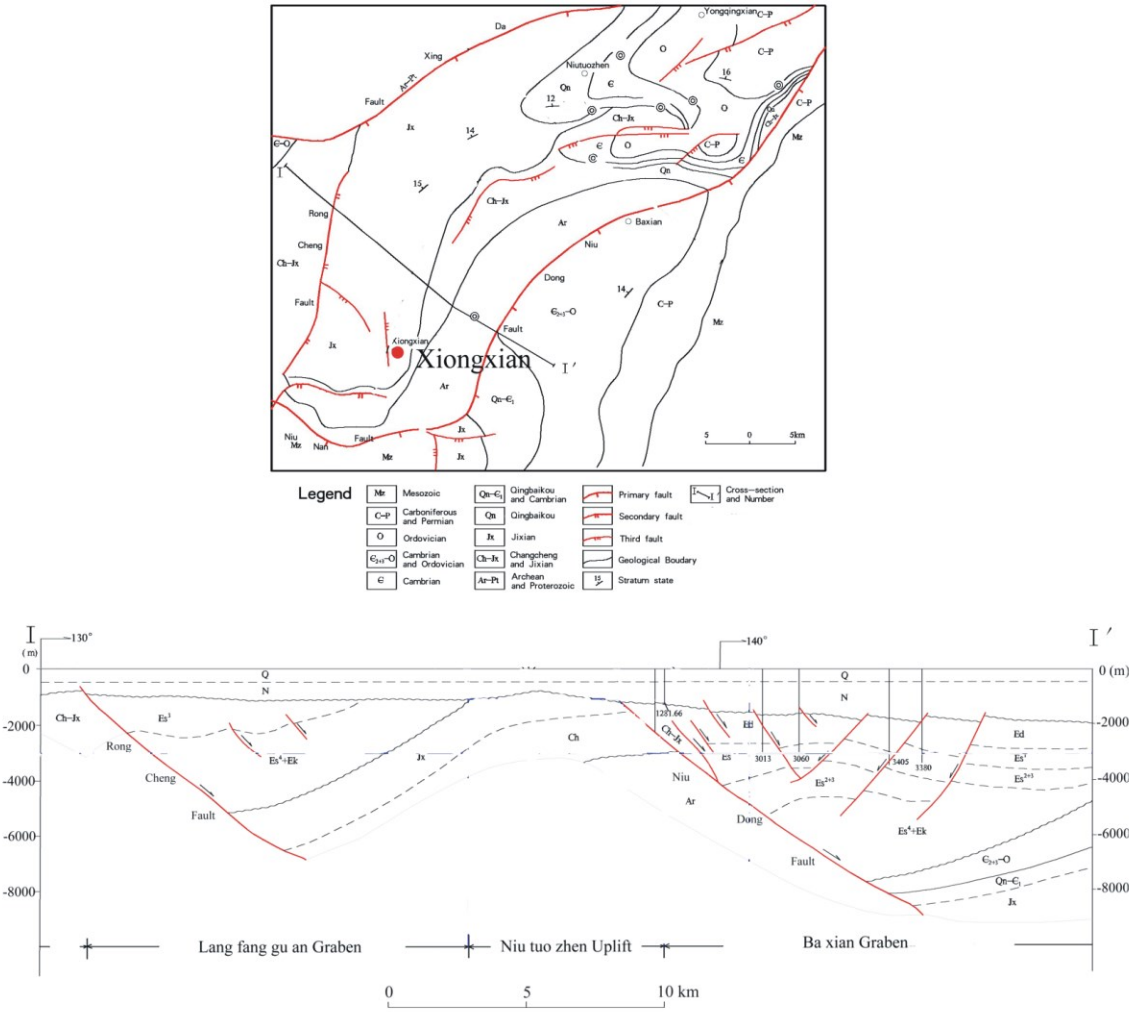

Figure 2 Tectonic map and a cross section of Xiongxian geothermal field in Niutuozhen uplift (Reivsed from Ma et al., 1990).

3 SAMPLING AND ANALYSES

Samples of hot and cold waters were collected in Xiongxian geothermal field in 2013. Field parameters, including pH, dissolved oxygen (DO), Eh, electrical conductivity (EC) and temperature were recorded at the time of sample collection. Samples were later analyzed in the Water Isotopes and Water-Rock Interaction Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences. δ^2H and δ^{18}O were measured on a laser absorption water isotope spectrometer analyzer (Picarro L2120-i). All δ^2H and δ^{18}O values are expressed related to Vienna Standard Mean Ocean Water (V-SMOW) in ‰, and the measurement precision was 0.5 and 0.1‰ for δ^2H and δ^{18}O, respectively. The analysis of water chemistry was completed using ion chromatography in Analytical Laboratory of Beijing Research Institute of Uranium Geology. The methods for cation measurements are taken from the National Analysis Standard DZ/T0064.28-93 while for anions are from DZ/T0064.51-93. Alkalinity was measured on automatic titrator (785 DMP™). Analytical precision was 3% of concentration based on reproducibility of samples and standards and detection limit was 0.1 mg/L.

4. RESULTS AND DISCUSSION

4.1 Groundwater flow direction

Water table of geothermal water in the karstic reservoirs was measured in May, 2013, two months after the four month long pumping period for space heating. Given the consistency of surface elevation of each well, the groundwater depth is used to map the groundwater flow direction. Groundwater is found to move toward northeast in the urban region of Xiongxian geothermal field (Fig. 3). The spatial variation of Total dissolved solids (TDS) was then used to determine the groundwater flow direction in a larger extent from Rocheng uplift to Xiongxian uplift, according to the recognition that TDS escalates following the movement of groundwater.

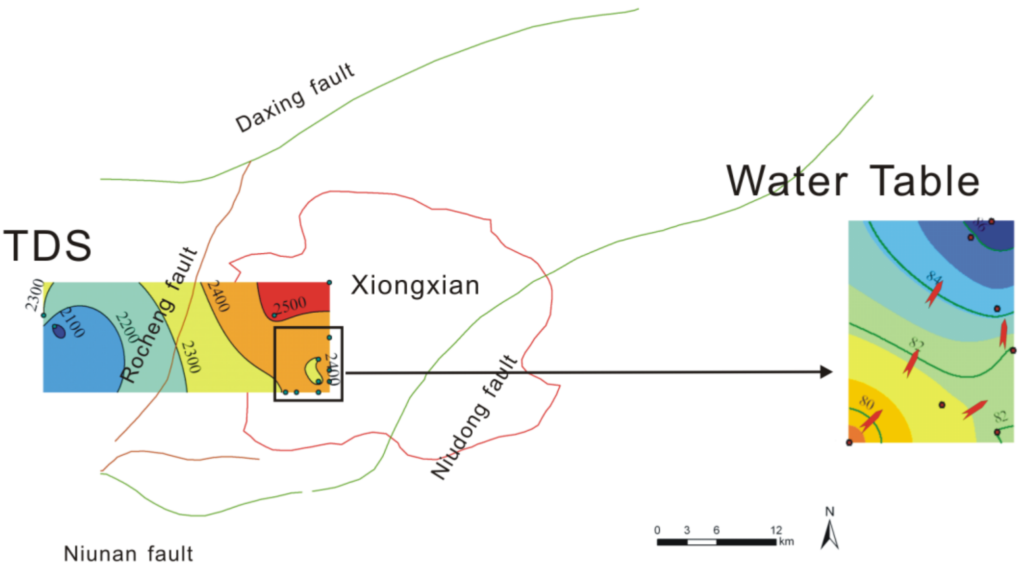

Figure 3 Groundwater flow direction indicated by water table and TDS in the study area.

Interestingly, the local groundwater flow direction we found in Xiongxian geothermal field is not consistent but orthogonal to the regional flow direction, which is from northwest towards southeast. Zhou et al. (1989) found that recharge for Niutuozhen uplift is from Taihang and Yanshan Mountains with two major flow paths: one is through the Langfang-Guan sag in the north, and the other is from Xushui sag and Rocheng uplift in the west. With their findings in mind, one can see a groundwater jet stream comes from the west in Figure 3. Meaningfully, it turns to northeast in the urban region of Xiongxian, which actually refers to the axis of south Niutuozhen uplift. As was claimed above, Niutuozhen uplift is encircled by several normal faults. Among them, Niudong and Niunan faults in the east and south are identified as barriers of weak groundwater conductivity (Zhou et al., 1989). Such a barrier forces groundwater to move northeast in the axis of the uplift and decelerate gradually to the boundary surrounded by low permeability sandstone. Then the hindered movement of groundwater in the horizontal domain enhances its flow in the upward direction, when the so-called leakage recharge occurs. The finding of groundwater flow justifies the existence of higher temperature groundwater in the top of Niutuozhen uplift and its cap rock consisted of Neogene reservoirs. Ma et al. (1990) pointed out that TDS in the Neogene reservoirs above the axis of Niutuozhen uplift is larger than TDS in other parts within the same region, which confirms our explanation on groundwater flow. The leakage recharge between different deep aquifers will be further demonstrated in the following sessions based on hydro-chemical and isotopic data.

4.2 Water-rock interaction

Stable isotopes of different water bodies including cold water in quaternary aquifers and thermal water in Neogene and Jixianian aquifers are used to illustrate water-rock interaction and hydraulic connectivity between them. Classifications can be easily found due to the distinct behaviors of the isotopic locations in Fig. 4. Cold water with water table less than 200 m is more enriched in isotopes than cold water with water table more than 200 m. The radiocarbon ages of them are less than 10000 years and more than 14000 years, respectively (Table 1). As a counterpart research on shallow groundwater in North China Plain (NCP), Chen et al. (2003) claimed that groundwater recharged by precipitation in the late Pleistocene have ranges of −9.4 to −11.7‰ for δ^{18}O and

−76‰ to −85‰ for δ^2H values, while groundwater recharged by precipitation in the Holocene have ranges of are −7.7‰ to −10.2‰ of δ^{18}O and −63‰ to −73‰ for δ^2H values, respectively. The differences of isotopic data suggest that groundwater beneath and above the depth of 200 meters are in independent systems with weak hydraulic connectivity between them.

Table 1 TDS and radiocarbon age of groundwater in different aquifers

	Quaternary (<200 m)	Quaternary(>200 m)	Neogene*	Jixianian
TDS (mg/L)	300 - 600	100 - 500	500 - 1500	1900 - 2600
Age (ka)	<10	14 - 25	25 - 30	31 - 36

*The data of Neogene geothermal water is cited from Ma et al. (1990)

The isotopic values of Neogene thermal water are well between those of the two groups of cold water differentiated by depth (Fig. 4). By contrast, Jixianian thermal water illustrates a clear trend of oxygen shift. The phenomenon of oxygen shift is very common in high temperature geothermal system as a result of ^{18}O exchange between groundwater and reservoir rocks (Clark and Fritz, 1997). It may also be observed in the middle-low temperature geothermal system by exchanging ^{18}O of groundwater with reservoir carbonates over long residence time and low water-rock ratios (Qin et al., 2005). Besides the oxygen isotope change, the hydrogen values of Jixianian thermal water seem larger than those of Quaternary groundwater with depth larger than 200 m. According to our analysis above, precipitation in the late Pleistocene has lower values of δ^{18}O and δ^2H due to the cooler climate. Thus Jixianian groundwater with an age of 31 – 36 ka (Table 1) should be more depleted in or close to groundwater isotopes in the Quaternary with depth larger than 200 m. The reason might be related to the releasing of CH_4 in a reducing environment, where many oil and gas fields are adjacent. Further evidences should be presented in this regard.

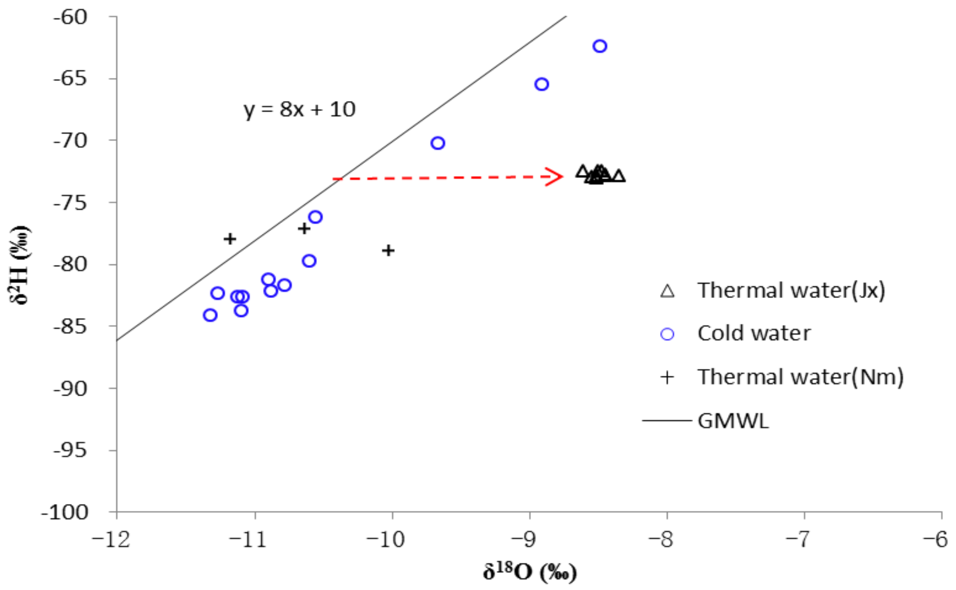

Figure 4 Stable isotopes of different water bodies in Xiongxian geothermal field. The solid line represents the global meteoric water line (GMWL). The dashed line shows the oxygen shift of thermal water in the Karstic reservoir.

4.3 Conceptual model

Based on the geological, hydrogeological and hydrogeochemical data, a conceptual model of deep groundwater cycle is proposed. During the cooler climate in the late Pleistocene, precipitation in the Taihang and Yanshan Mountains infiltrated, went through Langfang-Guan sag, Xushui sag and Rongchen uplift and finally turned to be the regional recharging source for Niutuozhen uplift from Northwest. On the local scale, after that the groundwater moved into Xiongxian geothermal filed, south Niutuozhen uplift, they were blocked by Niudong and Niunan faults in the east and south and then turns to move toward northeast in the horizontal domain and upward in the vertical domain. Leakage recharge may occur between Neogene and Jixianian aquifers.

5. CONCLUSIONS

Recharge mechanisms and timing for Xiongxian geothermal field have been considered on the basis of multiple isotopic and hydrochemical tracers. Several key aspects of the system are elucidated by the available data:

(1) On the local cycle, groundwater flow direction is found to change from northwest to northeast in the axis of Niutuozhen uplift as a result of tectonic structure. The change of flow direction enhances the heat convergence in Niutuozhen uplift and even aquifers in its cap rocks.

(2) Groundwater in the Xongxian geothermal field was recharged by precipitation in the late Pleistocene, whose isotopes are more depleted than those in the Holocene.

(3) The long residence time of more than 30 ka for geothermal water causes to a weak oxygen shift, which implies the occurrence of water-rock interaction.

ACKNOWLEDGEMENTS

This study is supported by the National Natural Science Foundation of China (Grant 41372257). The authors appreciate the International Postdoctoral Exchange Fellowship Program China and Project funded by China Postdoctoral Science Foundation for the financial support of this work.

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