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Hydrothermal Features of the Neogene Guantao Sandstone Porous Geothermal Reservoir in the North China Basin

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ABSTRACT

Utilization of low-temperature (<150°C) geothermal water, particularly produced from sedimentary geothermal systems, plays an increasingly important role in direct energy use and provides an alternative energy source to fossil fuels in China. As the demand for direct use of sedimentary geothermal resources in China has been increasing in recent years, their sustainable utilization has become a requirement as well as a challenge for local geothermal production. Neogene Guantao sandstone geothermal reservoirs play an important role in geothermal utilization in China, mainly for space heating. However, due to heavy development and very limited recharge, fast water level drawdown occurs in most of the sandstone reservoirs in China once their utilization starts. Reinjection of the return water back into the underground has become an effective means to counteract the drawdown. This study is a part of an ongoing PhD project, aiming to contribute to the understanding of sustainable utilization of sandstone geothermal resources, in particular the reinjection of return water into sandstone reservoirs. In this paper, geological conditions, and property of the Guantao sandstone reservoir in North China basin will first be introduced. This is then followed by a description of Guantao sandstone geothermal production and reinjection history of the main production areas in North China basin.

1. INTRODUCTION

Low-temperature geothermal resources are being more widely used as a direct energy source, providing a viable alternative to fossil fuels. By 2019, there were a total of 88 countries that used geothermal energy directly with an estimation of the installed thermal power for direct utilization equals to around 107 727 MWth , and a growth of 52% in the past 5-6 years (Lund and Toth, 2021). The utilization of geothermal resources is already quite great in China, especially for direct use, with a total installation of 40 610 MWth and energy use of 443 492 TJ/Yr (Tian et al., 2020; Lund and Toth, 2021). Among various types of geothermal systems(Saemundsson et al., 2009), deep permeable sedimentary systems found in many major sedimentary basins are widely distributed in contrast to the limited distribution of volcanic high-temperature geothermal systems (Limberger et al., 2018). They are governed by heat conduction and usually supply low-temperature geothermal water. By now sedimentary geothermal resources are used extensively in Europe and in China. There are several sedimentary basins in Europe that are exploited for geothermal energy, including the Aquitaine basin, Molasse basin, Paris basin, Vienna basin, Pannonian basin, and N-German basin (Lopez et al., 2010; Vernier et al., 2015; Weber et al., 2015; Goldbrunner and Goetzl, 2019). In China, 15 known major low temperature sedimentary basin geothermal systems can provide a total geothermal resource estimate of around 3×10^{22} J and a total extractable resource estimated of about 5.3×10^{21} J. Among those basins, the North China basin is the second top potential area based on the total estimated geothermal resources, with the other four basins are the Sichuan basin, Hehuai basin, Fenwei basin and Erdos basin. Based on the lithology of reservoir formation rocks, there are two main types of productive sedimentary reservoir: one is Palaeogene - Neogene porous sandstone reservoir and the other one is Cambrian - Ordovician karst fractural carbonate rock reservoir. Compared to carbonate reservoirs, e.g., up to a 9000m bury depth in the Huanghua depression in North China basin, sandstone reservoirs usually have shallower bury depth up to around 3000m, which is an appropriate depth for geological survey and economical drilling. The geothermal exploitation of sandstone reservoirs in China can be traced back to 1970s. Provinces and cities like Tianjin, Shandong, Hebei located in the North China basin provide typical examples where direct use of sedimentary geothermal resources, e.g. for space heating, can be highly beneficial (Zheng et al., 2015; Zhu et al., 2015; Zhang et al., 2019).

Despite geothermal resources are generally considered as renewable energy sources worldwide (Bodvarsson, 1982), when talking about "renewability", the double nature of geothermal resources should be considered carefully (Rybach et al., 1999; Stefansson, 2000; Axelsson, 2010, 2011; Axelsson et al., 2020; Rybach, 2021). Sedimentary geothermal resources can usually be treated as partly renewable or slowly renewable energy sources due to the relatively insignificant energy current compared to the vast stored energy, and their renewability is mainly supported by heat conduction (Stefansson, 2000; Axelsson, 2011). For sandstone geothermal reservoirs with limited natural recharge of water and very slow heat renewability, utilization adhering to weak sustainability (Axelsson, 2011) can be considered, by allowing some deterioration of one of the sustainability pillars (Ketilsson et al., 2010) under a time frame of 100 - 300 years (Axelsson et al., 2005), based on the application of reinjection as a man-made addition to the limited natural recharge (Axelsson, 2008). Reinjection is the most efficient method to maintain the reservoir water pressure and ensure the sustainable utilization of sandstone geothermal resources (Axelsson, 2008, 2012). Extensive research has focused on solving the problem of sandstone reinjection, which manifests itself in rapidly decreasing injection capacity due to scaling, clogging and corrosion, in addition to the cold-front breakthrough, which can cool production wells and thus reduce their productivity (Seibt and Kellner, 2003; Axelsson, 2008; Diaz et al., 2016; Su et al., 2018; Markó et al., 2021; Zheng et al., 2023). The reinjection capacity could be maintained after using various approaches, such as, improved reinjection well construction (Seibt and Kellner, 2003), efficient maintenance of reinjection systems, conducting different kinds of testing, application of different modelling techniques as well as using geochemical methods (Axelsson, 2008; Lopez et al., 2010; Røgen et al., 2015).

The success of sandstone reservoir reinjection makes the sustainable development of the sandstone geothermal resources to be possible. This study is a part of an ongoing PhD project, aiming to contribute to the understanding of sustainable utilization of sandstone geothermal resources, in particular the reinjection of return water into sandstone reservoirs. The geothermal sandstone reservoirs of the Neogene Guantao Formation are selected as the subject of this study, due to their long production history and the fact that they are the main sandstone geothermal production layers in China at present. In this paper, geological conditions and property of the Guantao sandstone reservoir in North China basin will first be introduced. This is then followed by a description of Guantao sandstone geothermal production and reinjection history of the main production areas in North China basin. Based on this understanding, further study will focus on the assessment of the sustainable yield of the Guantao sandstone reservoir, with and without reinjection. It is aiming to build a numerical model in the size of the whole North China basin and then make predictions for assess the sustainable yield of the Guantao reservoir in a large scale of production and reinjection.

2. TECTONIC SETTINGS AND STRATIGRAPHY OF THE NORTH CHINA BASIN

The North China basin is surrounded by large uplifts such as Taihang mountain uplift, Yan mountain uplift, Luxinan uplift, and Ludong uplift. The interior of the basin is further divided into depressions and uplifts divided by large deep faults (Figure 1(a)). The North China Basin is a Mesozoic-Cenozoic intraplate rift basin that represents the destruction of the North China craton. The basin is a Cenozoic pull-apart basin over a Mesozoic graben. The Archaean, Proterozoic, Paleozoic, and Mesozoic strata constitute the basement of the basin, on which thick Cenozoic strata are deposited. The Cenozoic has a rather considerable variation in thickness; the thickness of the deepest part of the depression can reach thousands of meters, while it diminishes progressively from the edge of the depression to the uplift. Affected by the new Cathaysia tectonic system, the bedrock fault structure in the area was developed under a high activity intensity, and the main directions of the fault development were NNE, NE, and EW, followed by NW. The fault structures are all hidden type, and the major deep heat controlling faults include the Taihang piedmont fault, the Cangdong fault, the Niudong fault, the Maxi fault, the Liaokao fault, the Tanlu fault, the Zhuoxian - Baodi - Leting fault, and the Qiguang fault (Zhang et al., 2015).

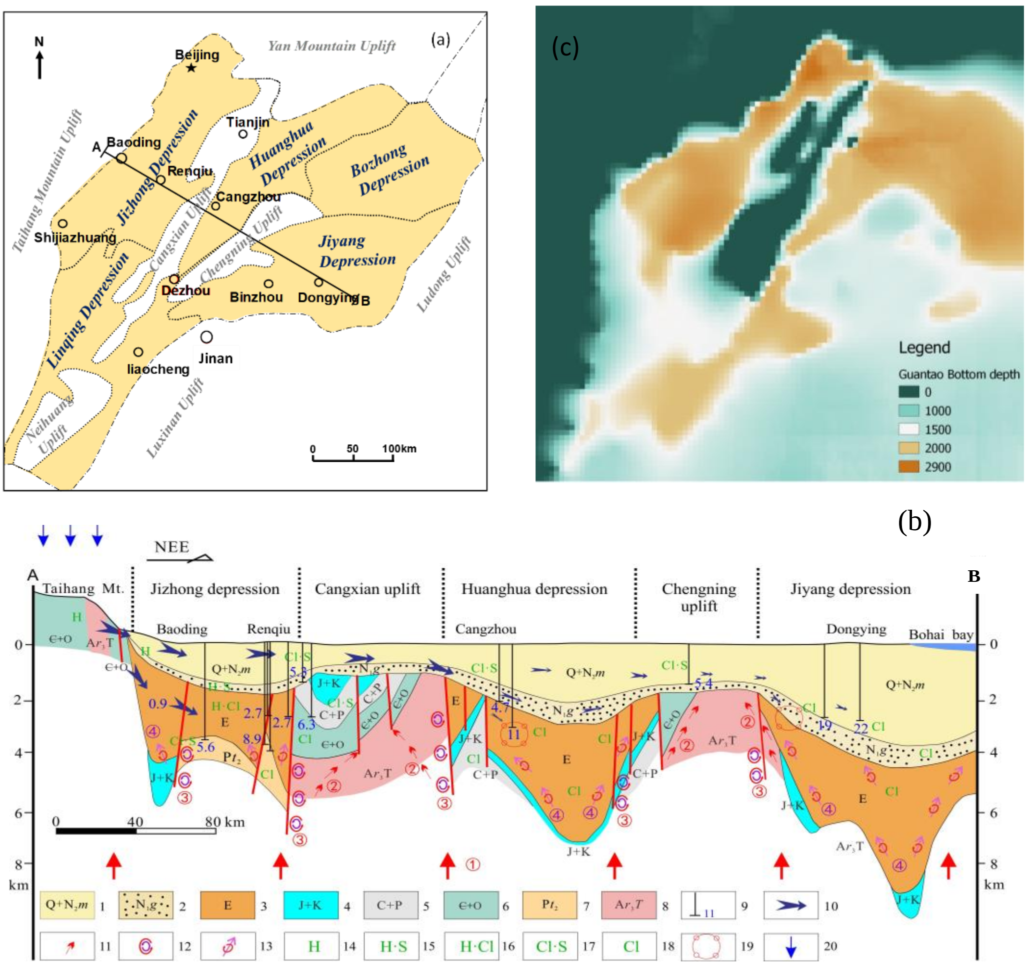

Figure 1: Sketch maps showing (a) the geological and tectonic setting of the North China basin, (b) vertical structures of the lithology and (c) the distribution of the Guantao sandstone Formation. Maps (a) and (b) are modified from Zhang, 2015, Map (c) information from Zhang et al, 2013; Liu et al., 2021 and Yang et al, 2022

From the old to the new, the main strata in the basin are: the Neoarchean Taishan group granitic gneiss (Ar_3T); the dolostone, mudstone and sandstone of Mesoproterozoic Changcheng-Jixian system (Pt_2); the limestone of lower Palaeozoic Cambrian-Ordovician (Є-O); the mudstone, sandstone and coal seam of upper Palaeozoic Carboniferous-Permian (C-P); the mudstone and sandstone of Mesozoic Jurassic-Cretaceous (J-K); the Paleogene mudstone, siltstone, fine sandstone, oil shale (E); the mudstone, medium sandstone and conglomerate of Neogene Guantao formation (Ng); the clay and sand of Neogene Minghuazhen formation (Nm); and the Quaternary sand and clay (Q). Among these strata, the dolostone of Mesoproterozoic Changcheng-Jixian system (Pt_2) (Wang et al., 2018; Wu et al., 2018), the lower Palaeozoic Cambrian-Ordovician limestone (Є-O) (Zhang et al., 2015; Kang et al., 2022), and the sandstone-conglomerate of Neogene Guantao formation (Ng) are the main reservoirs in the basin, with productive geothermal water aquifers (Fig. 1(b)).

3. HYDROTHERMAL FEATURES OF GUANTAO FORMATION IN THE NORTH CHINA BASIN

In general, geothermal systems found in the North China basin are governed by heat conduction and usually supply low-temperature geothermal water (40~90°C). The area with higher temperatures corresponds to the uplift zone, and the area with lower temperatures corresponds to the depressed zone. Within a depth of 3000 m, geothermal reservoirs of significance exploration are mainly Neogene Minghuazhen sandstone Formation, Guantao sandstone Formation, Paleogene Dongying sandstone Formation and Proterozoic-Paleozoic carbonate rock Formation. Among them, the production depth of Paleogene-Neogene groundwater is generally between 900 and 3000 m (Figure 1(b)).

3.1 Sandstone Geothermal Reservoirs and Distribution of Guantao Sandstone Formation

Sandstone reservoirs are mainly found in the depression area of the North China basin and the Paleogene-Neogene sandstone reservoirs are generally well preserved. In the uplift areas, sandstone thermal reservoirs are often missing, e.g., Guantao Formation is missing in the Cangxian uplift. The buried depth of the bottom of Minghuazhen Formation is around 1000-1800 m in Jizhong and Huanghua depressions, 800-1400 m in Linqing depression and 700-1100 m in Jiyang depression. The depth of the bottom of Guantao Formation is 1100-2100 m in the Jizhong and Huanghua depressions and is 1000-1700 m in Linqing and Jiyang depressions (Figure 1 and 3). Vertically, the depth of burial of the sandstone geothermal reservoir in the Minghuazhen formation, the Guantao formation, and the Dongying formation gradually gets deeper, the rock layers get denser, and the conditions for water circulation get worse. The aquifer depth from surface to around 2500 m is more open with stronger runoff. Then it will be followed by a relatively closed transition zone at the depth around 2500 to 3000m and aquifer located below 3000m is more in a closed flow system. In most of the cases, geothermal water from Guantao Formation is extracted from the depth between around 900 m to 2000 m deep in this area (Kang et al., 2022). Figure 1(c) depicts the distribution of the Guantao Formation throughout the whole North China basin, with Tianjin Municipality, Hebei Province, and Shandong Province.

The Guantao sandstone formation is distributed widely in the plain area of Hebei province with a size of 52 000 km^2, except for Niutuozhen uplift, Dacheng uplift and Cangxian uplift. The average depth of the formation bottom is around 1400 to 1600m, with a maximum depth of 2200 to 2400m in some depression areas (e.g., Huanghua depression) and a minimum depth of less than 1000m (e.g., Cangtai uplift). The average thickness of the whole formation is 200-400 m with a maximum of 500 -800 m. Thickness of the main sandstone reservoir (aquifer) is 80 – 200 m. Reservoir temperature in general is 50 – 60 °C and can be more than 75°C in the Jizhong depression. The geothermal water type is mainly HCO_3·Cl-Na type and Cl-Na type (Figure 2) with a pH value between 7.1 – 8.8. The TDS of the geothermal water varies a lot, which is less than 2 – 3 g/l in the west part of the plain area but more than 5g/l in the east part (Zhang et al., 2013).

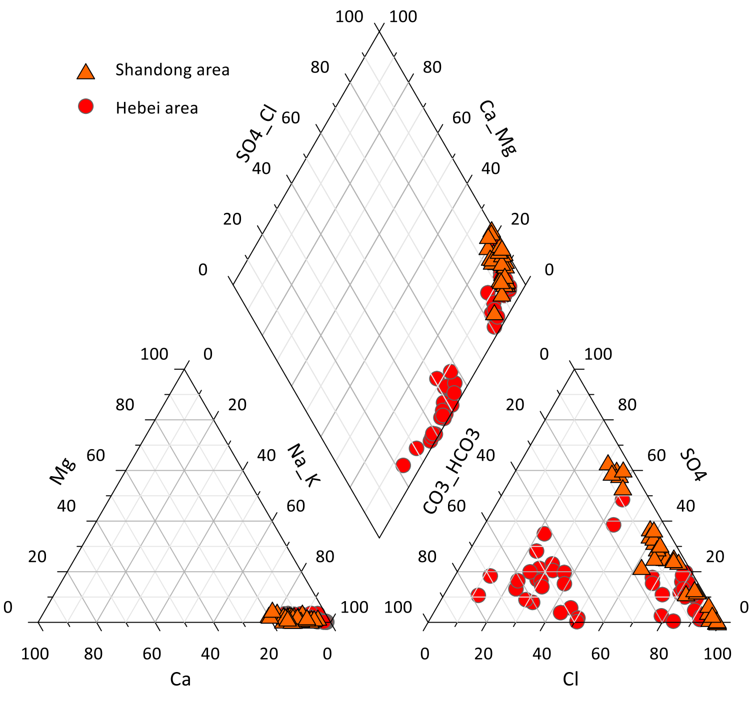

Figure 2: Piper diagram of the water samples from Guantao sandstone reservoir in Hebei and Shandong areas(Data from Kang et. al, 2021 and Li et al, 2015)

In Tianjin, Guantao formation is missing in the uplift area located near the middle area of the city and can be found constantly in the depressions on both sides of the middle uplift area. The total size of it is around 8500 km^2 with the depth of the bottom of the formation is around 1000 – 2700 m. Thickness of the main sandstone reservoir (aquifer) is 100 – 200 m with a wellhead water temperature around 48 – 82 °C. The geothermal water type is mainly $HCO_3 \cdot Cl$-Na type and HCO_3-Na type with a pH value between 7.4 – 8.6. The TDS of geothermal water in general is around 0.5 – 2 g/l and can be up to 6g/l in some cases (Liu et al., 2021).

In Shandong Province, Guantao formation distributed throughout the North Shandong Plain area except in the eastern part of the Guangrao County, with a total area of about 38 000 km^2. Its burial depth gradually deepens from the southwest to the northeast, generally exceeding 2000 m in the depression, with a thickness around 200 - 700 m. The main reservoir is the coarse-grained sandstone and glutenite in the lower parts of the Guantao Formation (Ng_2 in Figure 3), with a general thickness of 50 -150 m. The water temperature is generally 50–90° C with a pH value between 7.1 – 8.1. The main water type of the hot water is Cl-Na type in the east part and $Cl \cdot SO_4$-Na type in the west with the TDS value ranging from 4 to 18.5 g/l (Kang et al., 2022; Yang et al., 2022).

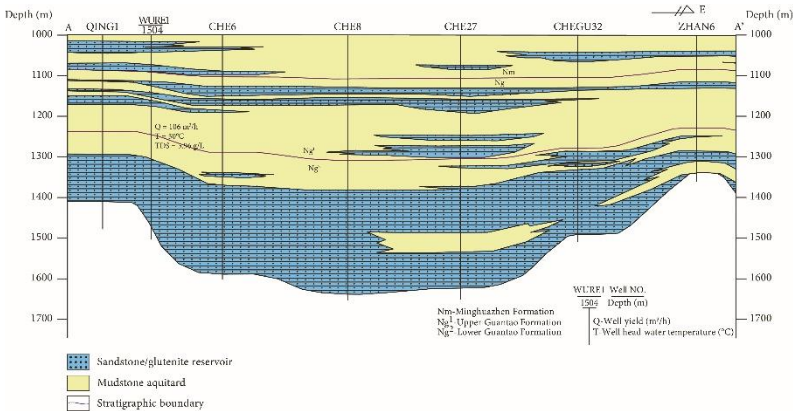

Figure 3: Lithology and distribution of the Guantao sandstone reservoir (Kang et al., 2022)

3.2 Heat Sources and Origins of Geothermal Water

The formation of geothermal water in the region is affected by mantle structure, magmatic activity in the deep part of the crust; geological structure, stratigraphic lithology and groundwater activity in the shallow part of the crust, and is related to factors such as caprocks, geothermal reservoir space, heat sources and geothermal water supply sources (Chen, 1988). The caprock of the Guantao formation geothermal reservoir is a soft layer composed of clay and sand of loose sedimentary layers of Quaternary Pingyuan and Minghuazhen formations. Heat sources mainly come from normal deep crust and upper mantle conducting heat flow and deep magma heat. The large and deep ultra-crustal faults such as Cangdong, Liaocheng-Lankao and Guangrao-Qihe faults, play an important role in communication and conduction of magma heat source in deep crust and upper mantle, and constitute a good channel for underground heat flow. Guantao reservoir is usually defined as a relatively close system. The recharge of geothermal water is very limited and has been considered mainly from the depositional water and the connate water, which are preserved when the basin sediments are formed. Another part of the recharge source is the precipitation in the remote mountainous recharge areas after the formation of sediments during the long geological period (Zhou et al., 2007). From Figure 4, it can be seen the geothermal water composition in this type of reservoir might be modified by water-rock interaction and the thermal water from coastal area has some possible water mixing. The thermal gradient of the basin is mainly controlled by the geological structure, cap rock thickness and hydrogeological conditions. In general, the distribution of the thermal anomaly is related to the regional tectonic line, which is northeast direction. The high value of the geothermal gradient in the plain area is generally greater than 3.5°C/100m. The relatively low-value area corresponds to the depression area with a value of less than 3.0°C/100m (Liu et al., 2021; Kang et al., 2022).

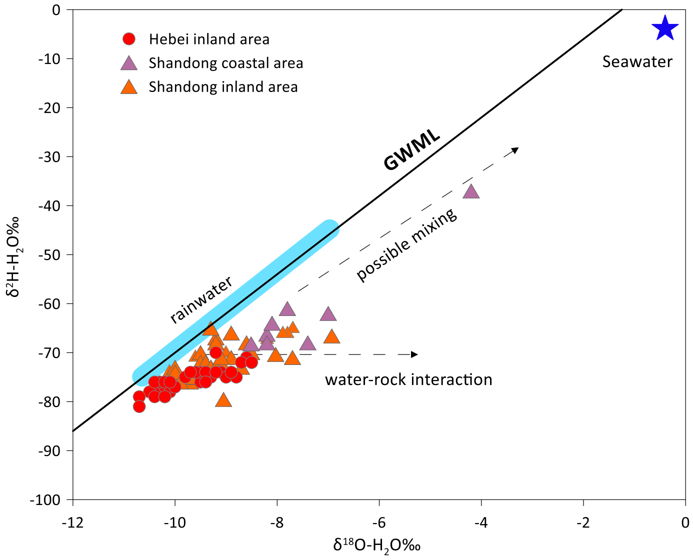

Figure 4: Relationship between δ^2H and $\delta^{18}O$ values of the water samples. The values for local meteoric water (blue area), the global meteoric water line (GWML), and the trends for possible mixing and water–rock interactions are also shown. (Data from Kang et. al, 2021 and Li et al, 2015)

3.3 Production and Reinjection History of Guantao Geothermal Reservoirs

Figure 5 shows historical water level changes of the Guantao reservoirs in correspondence to production and reinjection The large-scale development of geothermal resources in Tianjin started in the 1990s. It is mainly for direct use in space heating, hot spring physiotherapy, aquaculture, industry, and agriculture. The main production areas are in the Jizhong depression and Huanghua depression tectonically, which are urban city center, Wuqing, Tanggu and Dagang etc. Affected by years of intensive production of geothermal water, there is a water level depression area appeared from the urban center area expanding to the rural area. The water level depth of geothermal water from Guantao Formation in the urban center is around 15- 20 m in early 1990s, later was 40 – 50 m in 1999 and then continuously decreasing to 110- 140m until 2019. The water level of various reservoirs started to rise after 2019 with the continuing growth in reinjection and shutdown of unlicensed geothermal wells, for example, the water level rose up back to about 80 m in Guantao Formation. There have been more than 200 drillings for reinjection thus far. After reinjection, the water's temperature can stay between 60 and 80 °C without noticeably dropping (Liu et al., 2021). However, further research should be done to determine how the temperature changes in the event of increased production demand and large-scale reinjection.

The average water level depth of production area of Guantao reservoir was generally around 50-60 meters in Hebei around year 2015, with a decreasing speed of 8.7 m/year. The maximum water level depth was larger than 100 m in the central areas of the Jizhong depression with a decreasing level of 12 m/year and the minimum water level depth was about 20 m in the southwestern part of the Linqing depression, with a decreasing level of 8m/year. During that time, there were around 720 geothermal wells drilled into Guantao reservoirs with a yearly production rate of around 70 000 000 m^3. It is mainly for direct use in space heating, bathing and aquaculture (Liu, 2017). Reinjection also took place in Hebei for sustainable development of geothermal. However, reinjection in Guantao formation is still in the stage of experimental research. More research needs to be done to determine how the reservoirs will be impacted when large-scale reinjection begins.

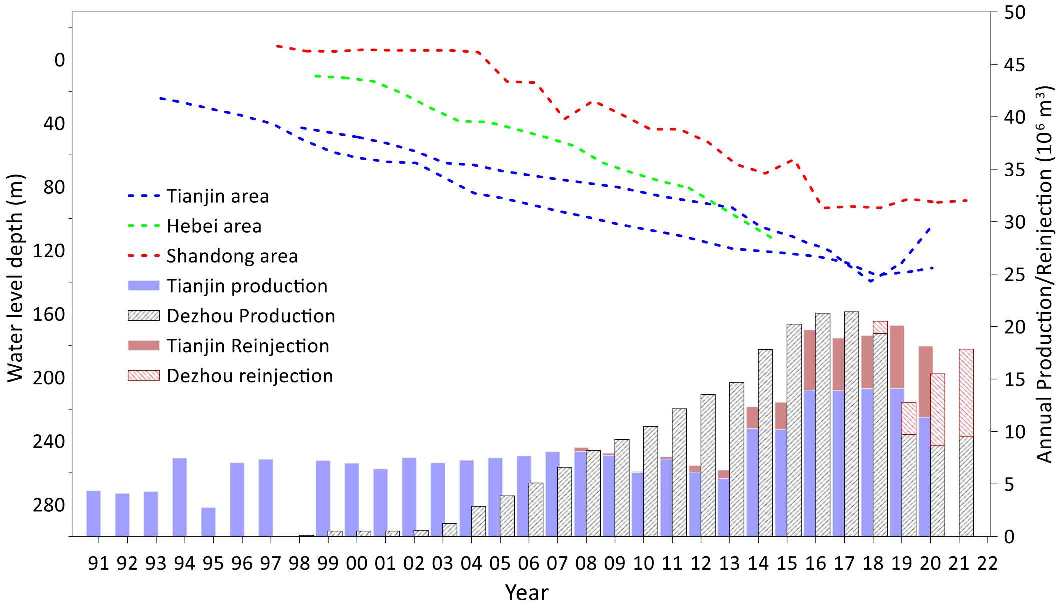

Figure 5: Relationship between water level and production/reinjection rate in Tianjin, Hebei and Shandong. The water level depth variations show typical production fields in the three provinces. Historical annual production and reinjection of Tianjin area and Dezhou area, Shandong are shown, to give a general idea of how production and reinjection effect the water level changes. (Data of Tianjin area are from Yin, et. al, 2023, Hebei area from Li et al, 2015)

In the early 2000s, the exploitation of the geothermal water in the Guantao Formation was very small in Shandong. Geothermal water level was in a natural self-flowing state with a constant water level depth ranging from 14m above the surface to 40 m in different locations. The general flow direction of the geothermal water in the Guantao Formation was from southwest to northeast of the plain area in North Shandong. In the past 20 years, as the demand of using geothermal water has increased, more production of geothermal water caused several water level depression zones to form. These depression cones are in the urban city areas of Liaocheng, Dezhou, Linqing, and Pingyuan, and have changed the natural flow direction. Take Dezhou city as an example, in the natural state before production, most of the wells in the urban Dezhou reservoir were artesian, with an artesian water level height of 7-8 m above the ground surface and a free-flow rate of 8-11 L/s (Kang et al., 2019). Since 2006 the water level in central urban Dezhou has dropped from 8.3 m artesian height in 1997 to 93 m below ground surface in 2017, with an annual decrease of 8.2 m from 2013 to 2017. Meanwhile, as the water level has dropped, well productivity has also decreased. After 2017, production of geothermal water in urban Dezhou area has been reduced rapidly due to local policy requiring reinjection of all return water for the purpose of sustainable utilization. The production units which cannot perform reinjection have, therefore, been shut down until they can fulfill the reinjection requirement. The reinjection rate has increased obviously after 2019, reaching almost 90% of the production rate in 2021. As a result, the water level in the reservoir has shown an increasing trend, rising back to 78 m depth in 2021 (Zheng et al., 2023). For sustainable development of geothermal, there are several reinjection experiments that take place in Shandong and have successful results. However, reinjection in Guantao formation is still in the stage of experimental research. More research needs to be done to determine the water level response of the sandstone reservoir to long-term, large-scale production and return water reinjection. Then, an assessment of the sustainable production potential needs to be made.

4. CONCLUSION

The Guantao sandstone geothermal reservoir distributes throughout the North China basin, with Tianjin Municipality, Hebei Province, and Shandong Province, with a total area of about 98 000 km^2. The depth of the formation bottoms varies between depression and uplift areas, which is around 2000 to 2400m in depression areas and a minimum depth of less than 1000m – 1400 in uplift areas. The reservoir rock type is mainly coarse-grained sandstone with a thickness of around 50 – 200 m.

Guantao geothermal systems found in the North China basin are governed by heat conduction and usually supply low-temperature geothermal water between 40~90°C. The distribution of the thermal anomaly is related to the regional tectonic direction, and the high value of the geothermal gradient in the plain area is generally greater than 3.5°C/100m. The geothermal water type is mainly $HCO_3\cdot Cl$-Na type, HCO_3-Na type, $Cl\cdot SO_4$-Na type and Cl-Na type with a pH value between 7 – 8.8. The TDS of geothermal water varies a lot but with large numbers, which can be up to 5- 18 g/l.

Development of geothermal resources obtain from Guantao sandstone reservoir can be traced back to the 1990s. Since the 2000s, the water level draw-down has increased fast in the main production areas, mainly located in the urban areas, attributed to heavy development, and limited recharge. Reinjection return water or other sources of water back to Guantao reservoir is a prerequisite of further development of this type of aquifer and has been done in Tianjin, some part in Dezhou, Shandong and Hebei. However, in most locations in the North China Basin, reinjection is still in the experimental stage. More research is still required to determine how to maintain the reinjection capacity, prevent the water level from decreasing, and evaluate the sustainable yield with large-scale reinjection without the result in thermal breakthrough.

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