The Yangbajing geothermal field and the Yangyi geothermal field: two representative fields in Tibet, China

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ABSTRACT

In recent several decades, there has been growing geothermal energy utilization in the world. As one of the most important countries considered high in potential for geothermal development, China is in possession of abundant high-temperature geothermal resources, most of which are distributed in Tibet Autonomous Region and western Yunnan Province. In Tibet, the Yangbajing and Yangyi geothermal fields are two representative fields with magmatic chambers as heat sources, and both of them are located in the Yangbajing-Dangxiong basin, a Cenozoic rift basin that belongs to the Dangxiong-Yangbajing-Duoqing active tectonic belt. In this paper, the geological evolution process of the Yangbajing-Dangxiong basin was summarized, based on which the general situation and the geothermal geology of the Yangbajing and Yangyi geothermal fields were introduced. Moreover, surface water pollution induced by geothermal wastewater drainage at Yangbajing and geothermal spring discharge at Yangyi was also discussed briefly. A great deal of detailed work, such as decontamination before geothermal wastewater drainage, should therefore be done as one of the parts in the geothermal water resource management schemes at Yangbajing and Yangyi to prevent their surface water environment from further deterioration.

1. INTRODUCTION

Since the 20th century, with the rapid development of human society, energy has become an extremely important issue with which human being have to deal. As a renewable energy, geothermal energy has attracted more and more attentions in the countries where there are abundant geothermal resources, such as the United States, Iceland, Italy, Japan, China, etc. Although most geothermal reservoirs are located in the deep underground with no visible clues showing above ground, sometimes geothermal energy can find its way to the surface in the form of volcanoes, fumaroles (holes where volcanic gases are released), and hot springs or geysers. According to the data from Geothermal Energy Association (2007), the exploitable worldwide geothermal energy resources amount to between 65.576 and 138.131 GW of electrical generation capacity using enhanced technology. So far geothermal energy has been used by people in different ways, including direct use or district heating systems (use hot water from thermal springs or reservoirs near the surface), geothermal heat pumps (use stable ground or water temperatures near the earth's surface to control building temperatures above ground), and electricity generation.

Geothermal energy is also a kind of comparatively clean energy. Compared with other kinds of energy, such as

coal, petroleum, or natural gas, the use of geothermal energy has much smaller adverse environmental impacts. Direct use and heating applications have almost no negative impact on the environment. As far as geothermal power plants are concerned, their emission levels of harmful gases are very low since they do not generate electricity by burning fuel. A geothermal power plant approximately releases less than 1 % of carbon dioxide emission of a fossil fuel plant with equivalent power output. Furthermore, although H₂S can be naturally found in geothermal steam and water, it can be removed by the scrubber systems of geothermal plants, so the emission of sulfur compounds from geothermal plants that can result in acid rain is 97 % less than that from fossil fuel plants. However, there are also some environmental problems resulting from the use of geothermal energy. For example, during the construction of a geothermal power plant, the land stability in the surrounding region may be affected in different extents, which is especially a concern with Enhanced Geothermal Systems where water is injected into hot dry rock without water before. For another example, geothermal waters from reservoirs may contain some harmful trace elements with very high concentrations, such as fluorine, boron, mercury, arsenic, antimony, etc. If they are drained immediately into rivers after use, the water quality of these rivers may be deteriorated.

In recent years, geothermal energy has been widely generated in over 20 countries around the world including the United States, Iceland, Italy, Germany, Turkey, France, Netherlands, Lithuania, New Zealand, Mexico, El Salvador, Nicaragua, Costa Rica, Russia, the Philippines, Indonesia, Japan, and China. In China, geothermal behaviors have been found almost in every province. However, hightemperature hydrothermal systems are mainly distributed in Tibet and western Yunnan, as a major part of the Mediterranean-Himalayas geothermal belt. According to a literature by Liao and Zhao (1999), there are 129 hydrothermal systems with reservoir temperature more than 150 °C in Tibet, among which 12 systems have reservoir temperature more than 200 °C. Some of these hydrothermal systems such as the Yangbajing geothermal field, the Naqu geothermal field, and the Langjiu Geothermal field have ever been used for electricity generation. However, there are also some high-temperature geothermal fields with huge potential for electricity generation where no systematic investigation has been done, such as the Yangyi geothermal field whose location is very adjacent to the Yangbajing geothermal field. In fact, the Yangbajing and Yangyi geothermal fields are two representative fields in Tibet where magmatic heat source is responsible for the formation of high-temperature reservoirs. So the aim of this paper is to introduce the general situation and the geothermal geology of these two fields, based on the analysis of the geological evolution process of the Yangbajing-Dangxiong basin where Yangbajing and Yangyi are located. Furthermore, the surface water

pollution induced by the geothermal wastewater drainage at Yangbajing and the geothermal spring discharge at Yangyi was also discussed briefly in this paper.

2. GEOLOGICAL EVOLUTION OF THE YANGBAJING-DANGXIONG BASIN

As so-called "world ridge", the Tibet Plateau is the largest and latest one in the world. During the long geological evolution, especially after the Mesozoic era, numerous large-scale tectonic movements have occurred in this plateau. Since the Quaternary, the Tibet Plateau has been raised sharply, which resulted in the formation of a series of nearly N-S stretching tensile active tectonic belts.

The Dangxiong-Yangbajing-Duoqing active tectonic belt is one of the most representative tectonic belts in Tibet. Along the belt, many Cenozoic rift basins were formed where a lot of intensive hydrothermal activities occurred. These hydrothermal areas include Luoma, Tuoma, Gulu, Dongweng, Dangxiong, Qucai, Laduogang, Gariqiao, Xumai, etc., among which the most famous two are Yangbajing and Yangyi located in the Yangbajing-Yangyi basin (Fig. 1), a sub-basin of the Yangbajing-Dangxiong basin.

The geological evolution process of the Yangbajing-Dangxiong basin where the Yangbajing and Yangyi geothermal fields are located had attracted the attentions of many relative institutions and scholars. According to Wu et al. (2003), the tectonic and topographic evolution of the Yangbajing-Dangxiong basin includes six consecutive phases: Late Oligocene to Early Miocene (28-20 Ma), Early Miocene (20-18 Ma), Middle-Late Miocene (18-8 Ma), Late Miocene to Early Pliocene (8-5 Ma), Pliocene to Early Pleistocene (5-2 Ma), and after Early Pleistocene (1.5-0 Ma). The detailed descriptions of these phases are as follows (Wu et al., 2003).

(1) Late Oligocene to Early Miocene (28-20 Ma). During this phase, the Kangdese and Pangduo thrusting structures were formed with the Kangdese-Lhasa land block being strongly extruded. The intense regional tectonic activities resulted in an alternative distribution of fault-block mountains and depressed basins (Fig. 2-a).

(2) Early Miocene (20-18 Ma). The long-term extrusion pressing induced that the thickness of local earth crust was doubled, and this in turn elevated ground surface to an altitude of 4500-5500 m. At the same time, due to the increase of the crust thickness, a local molten granite was formed at the depth of 17-20 km (Fig. 2-b).

(3) Middle-Late Miocene (18-8 Ma). The large-scale local molten process was continuing, resulting in that a large amount of granite magma was emplaced and crystallized into hard rocks along the Nyenchen Tonglha Mountains. With the buoyancy of magma, the Nyenchen Tonglha Mountains began to rise slowly, and in both sides of the Mountains, the Pangduo and Namu land blocks were relatively descending (Fig. 2-c).

(4) Late Miocene to Early Pliocene (8-5 Ma). A regional detachment occurred between the Nyenchen Tonglha land block and the southeastern Yangbajing-Dangxiong-Pangduo land block, during which a large-scale NE-SW stretching structural surface with a dip angle of about 30° was also formed. It was named as the Nyenchen Tonglha ductile shear zone (NSZ) that consists of granitic mylonite (Fig. 2-d).

(5) Pliocene to Early Pleistocene (5-2 Ma). During this phase, with the sharp rise of the Nyenchen Tonglha Mountains, the land blocks in its both sides correspondingly declined. In this way was the Yangbajing-Dangxiong basin formed. Furthermore, a group of NE-SW stretching normal faults with high dip angle was also formed in the two sides of the Yangbajing-Dangxiong basin (Fig. 2-e).

(6) After Early Pleistocene (1.5-0 Ma). The Yangbajing-Dangxiong graben was further depressed, which lowered the average altitude of the depression center to about 4400 m. Several major NW-SE stretching strike-slip faults were formed during this period. A palaeo-lake with an area of $100,000 \text{ km}^2$ (namely the present Namu Lake) occurred to the northwest of the Nyenchen Tonglha Mountains, and with the subsequent shrink of this palaeo-lake, a series of lacustrine terraces took shape as well. So far, the topography of the Yangbajing-Dangxiong basin, the Nyenchen Tonglha Mountains, and the Namu Lake presents its today's appearance (Fig. 2-f).

Moreover, it is also worth noting that a large-scale international collaboration project INDEPTH (International Deep Profiling of Tibet and the Himalayas) was carried out during 1992-2002 to investigate the geological structure in southern Tibet. According to INDEPTH, there were four bright spots of seismic reflection (Angang bright spot, Yangbajing bright spot, Nyenchen Tonglha bright spot and Dangxiong bright spot) along the measuring line from Nimu to Yangbajing to Dangxiong (Fig. 3), and one of these four bright spots, the Yangbajing bright spot below the Yangbajing geothermal field, should be the geophysical reflection of the water-retaining molten granite with the depth of 15-25 km and the thickness of 20 km (Zhao et al., 2002), which is responsible for the formation of reservoirs at Yangbajing.

3. THE YANGBAJING GEOTHERMAL FIELD

Yangbajing, located to the northwest of Lhasa city, Tibet, western China (Fig. 1), is a geothermal system with the highest reservoir temperature in China, the measured downhole temperature being up to 329.8 °C at exploration borehole ZK4002 (Duo, 2003). The study area belongs to temperate semiarid monsoon climate area. The mean annual air temperature at Yangbajing is 2.5 °C in the past 40 years, the highest and lowest recorded air temperature being 23.4 and -25.7 °C respectively. The atmospheric pressure ranges between 0.580 and 0.609 atm, with an average value of 0.597 atm. The mean annual rainfall is 382.8 mm, with 65% rainfall in July and August.

There was strong manifestation of hydrothermal activity in the study area, including hydrothermal explosion, boiling spring, hot spring, warm spring, hot lake, fumarole, steaming ground, hydrothermal alteration zone, and hot spring silica sinter. According to Li et al. (2003), before the first Yangbajing geothermal power plant was built (in 1981), there were about 30 warm springs with the temperature between 20 and 60 °C, about 20 hot springs between 60 and 86 °C, and 4 boiling springs higher than 86 °C at Yangbajing where the water boiling temperature is 86 °C. A hot water lake with an area of 7350 m² and a depth of more than 5 m was also formed in and around a former hydrothermal explosion crater located in the south area of the field. Besides the crater responsible for the formation of the hot water lake, 6 other hydrothermal explosion craters were found as well. Moreover, steaming ground also appeared together with hot springs and boiling springs, where sinters were usually distributed as the remnants of early hydrothermal activities.

However, after the Yangbajing geothermal power plant was put into use, almost all of the primary hydrothermal manifestations, including boiling spring, hot spring, warm spring, and hot lake, disappeared under the effect of longterm intensive exploitation of geothermal resource. At Yangbajing, the first pilot electric generating facility of 1 MW was installed in September of 1977, and was successful in generating electricity. In 1981 and 1986, the first and second geothermal power plant was constructed respectively. In 1996, the only deep well (ZK4001) for geothermal electric power generation using deep fluid was drilled to the deep reservoir. At present, the total installed electricity generating capacity is up to 24.18 MW (9 MW from the first power plant and 15.18 MW from the second power plant). There are all together 34 geothermal production wells in the Yangbajing field. At present, 13 wells drilled to shallow reservoir plus 1 well (ZK4001) drilled to deep reservoir, are used for electricity generation.

As mentioned above, before the Yangbajing geothermal power plants were built, the geothermal waters in the study area were discharged as boiling springs, hot springs and warm springs. The discharge of these spring waters into surface environment with high B, As, and F concentrations induced the enrichment of these elements in soils and pasture plants, and therefore resulted in the death of domestic animals (Tong et al., 2000). Moreover, according to the investigation by Tong and Zhang (1981), there was a boiling spring vent in the center of the Zangbo River, and the water quality of the river was therefore directly affected by the spring at that time. However, after the operation of the power plants, all of the boiling, hot and warm springs (including the boiling spring in the center of the Zangbo River) vanished because of long-term overexploitation of the geothermal fluids. Now, all the production wells drilled in the south area of the geothermal field by the power plants are no longer in use, because the geothermal water table there has been declining and is now below the perforated pipe of the wells. So, at present, the geothermal waters have no immediate impacts on the Zangbo River located in the south area of the field. However, the hot wastewaters generated by the geothermal power plants have been discharged immediately into the Zangbo River, resulting in the contamination of the river water.

According to our field investigation in 2006 (Guo et al., 2008), the Zangbo river water at the nearest downstream of the wastewater drainage exit of the first geothermal power plant has much higher B, As and F concentrations than the upstream of the river. B, As, and F are harmful to human health at high concentration levels, and their upper limits of concentration in drinking water recommended by the World Health Organization (WHO) are 0.5, 0.01, and 1.5 mg/L respectively (Dotsika et al., 2006; Gaus et al., 2003; Daniele, 2004; Saxena and Ahmed, 2001). Although the Zangbo River has certain self-purification capability due to the dilution of river waters and contaminant sorption onto riverbed sediments, the B, As and F in the river waters have indeed caused harmful effects on human health. Both the workers in the Yangbajing geothermal power plants and the villagers living near the geothermal field have suffered from baldness or teeth erosion in their middle age due to drinking of the river water (Sun and Ta, 1997; Li et al., 2003). Therefore, decontamination before discharge of geothermal wastewaters into the river is urgently needed to protect the health of dwellers at and downstream of Yangbajing. Alternatively, artificial recharge of the geothermal wastewaters into the reservoir is another environment-friendly and effective way, because it can not only prevent surface environment from contamination, but also maintain the geothermal fluid pressure for sustained exploitation of geothermal energy. But the reinjection is costly and requires high technology, and therefore detailed works are needed to find out feasible reinjection scheme.

4. THE YANGYI GEOTHERMAL FIELD

Yangyi, located 72 km northwest of Lhasa city, Tibet, western China (Fig. 1), is a geothermal system having very high reservoir temperatures, with the highest measured well temperature of 207.2 °C at borehole 208 (The Geothermal Geological Team of Tibet, 1990). In the early and middle 1980s, a preliminary multidisciplinary survey, comprising geological, geothermal, geophysical and hydrogeological investigations, was made at Yangyi by the Geothermal Geological Team of Tibet. According to the results of the magneto-telluric survey, a low resistivity (3-10 Ω ·m) body is present at a depth of 9-15 km, possibly consisting of a water-retaining, partially molten granite. In other words, there may exist a relatively shallow magmatic heat source at Yangyi that may contribute heat and chemical components to the overlying hydrothermal system. Among the 15 boreholes drilled at Yangyi in the late 1980s, four (Well No.200, No.203, No.208, and No.403) were considered to have the potential for electricity generation with a total of 30 MW for the whole geothermal field. One of these wells, well No.208, had a total production of water and steam up to 400 t/h and it was estimated that the electricity generation potential of this well could reach 10 MW.

Although electricity generation at Yangyi is feasible, the high-temperature geothermal fluids have not been exploited to generate electricity so far. All the geothermal wells drilled by the Geothermal Geological Team of Tibet have been abandoned, though hot water and steam are still flowing out from some of them. For sustainable exploitation of the geothermal energy at Yangyi, more detailed hydrogeological and geochemical work is urgently needed.

The Yangyi geothermal field is located to the west of Yangyi Village, Dangxiong County of Tibet. It belongs to the Yangbajing-Yangyi basin where the world famous Yangbajing geothermal field, with the highest reservoir temperature in China, is also located. The topography of the Yangyi geothermal field is high in the west and the south and low in the east and the north, with altitudes between 4550 and 5050 m. The major river of the area is the Luolang River that flows from south to north and drains into the Lhasa River, a tributary of the Brahmaputra River. Other smaller streams include the Qialagai Stream, the Nangzeng Stream, and the Bujiemu Stream that are tributaries of the Luolang River. The climate in the study area is semiarid plateau meadow climate. The mean annual air temperature at Yangyi is 1.1 °C, with the highest and lowest recorded air temperature of 21.0 and -31.9 °C respectively. The atmospheric pressure ranges between 0.544 and 0.570 atm, with an average value of 0.560 atm. The mean annual rainfall is 414.1 mm, with 85 % of it between July and September. It is worth noting that the geographical and climatic features of the Yangyi field are very similar to those of the Yangbajing field.

In the Yangyi geothermal field, there are three areas where hydrothermal activities occur extensively, as described in detail below.

(1) The Qialagai Valley gate area. This area is the largest active geothermal area in the Yangyi field. There are about fifty boiling and hot springs with temperatures higher than 85 °C, the boiling point at Yangyi. The discharges of these springs are between 0.001 and 0.5 L/s. Fumaroles and steaming ground are also distributed in this area. In addition, a great deal of spring sinter can be found from the Qialagai Valley gate to the west bank of the Luolang River, with all of the boiling and hot spring waters discharging into the Qialagai Stream and then into the Luolang River.

(2) The area between the Nangzeng Valley and the Qialagai Valley. The major hydrothermal manifestations include boiling springs, fumaroles, steaming ground and intensified hydrothermal alteration. The discharges of the springs in this area are between 0.001 and 0.05 L/s, much lower than those in the Qialagai Valley gate area. The main types of hydrothermal alteration are montmorillonization, kaolinization and alunitization.

(3) The Bujiemu Valley gate area. Four springs with water temperature between 35 and 86 °C are distributed in this area (Liao and Zhao, 1999). The discharges of these springs are around 0.001 L/s. There are 7 geothermal resource exploration wells drilled by the Geothermal Geological Team of Tibet along the Bujiemu Valley. From these wells abandoned after exploration work, hot water and steam are still flowing out.

According to our field investigation in 2007, the concentrations of most chemical constituents in the geothermal waters at Yangyi are much higher than those in surface waters. The average concentrations of some harmful constituents such as B. As, and F can be up to 42.9, 2.0, and 19.2 mg/L respectively. The geothermal waters from both thermal springs and abandoned geothermal wells discharge into the Qialagai Stream, the Nangzeng Stream, and the Bujiemu Stream, and finally into the Luolang River, which is the only drinking water source for all villagers living in the Yangyi village. Thus, the water quality variations induced by the discharge of geothermal waters are vitally important for the health of local residents. Our measurements show that the B and As concentrations in waters downstream of the Luolang River are slightly higher than the drinking water standards, and therefore may have adverse health effects on local people. Great care should therefore be taken in the geothermal water resource management at Yangyi.

5. CONCLUSION

The Yangbajing and Yangyi geothermal fields are two representative fields with magmatic chambers as heat sources in Tibet, western China. These two fields are located in the Yangbajing-Dangxiong basin, a Cenozoic rift basin that belongs to the Dangxiong-Yangbajing-Duoqing active tectonic belt. The tectonic and topographic evolution Yangbajing-Dangxiong basin includes six of the consecutive phases: Late Oligocene to Early Miocene (28-20 Ma), Early Miocene (20-18 Ma), Middle-Late Miocene (18-8 Ma), Late Miocene to Early Pliocene (8-5 Ma), Pliocene to Early Pleistocene (5-2 Ma), and after Early Pleistocene (1.5-0 Ma). Surface water pollution induced by geothermal wastewater drainage at Yangbajing and geothermal spring discharge at Yangyi has attracted more and more attention of relative agencies and scholars. A great deal of detailed work, such as decontamination before geothermal wastewater drainage, should be done as one of the parts in the geothermal water resource management schemes at Yangbajing and Yangyi to prevent their surface water environment from further deterioration.

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Figure 1: Locations of the Yangbajing and Yangyi geothermal fields







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c. Middle-late Miocene 18-8 Ma



d. Late Miocene to - Early Pliocene 8-5 Ma



e. Pliocene to Early Pleistocene 5-2 Ma



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Legends: HH: High Himalayas crystalline rock zone; YZS: Brahmaputra suture zone; NQT: Nyenchen Tonglha Mountains; YBJ: Yangbajing graben; MFT: Main front fault; MBT: Main border fault; MCT: Main central fault; MHT: Main Himalayas reverse fault; STD: Southern Tibet depart system; KM: Kangma Dome; GTS: Kangdese thrusting structure; RTS: Renbu thrusting structure; ABS: Angang bright spot; YBS: Yangbajing bright spot; NBS: Nyenchen Tonglha bright spot; DBS: Dangxiong bright spot; Moho: Mohorovicic discontinuity.

Figure 3: Tectonic pattern in southern Tibet (Cite from Zhao et al., 2002)