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LECTURES ON GEOTHERMAL AREAS IN CHINA

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PREFACE

The UNU Visiting Lecturer in 2008 was Dr. Wang Kun, Senior Engineer and Deputy Director of the Geothermal Management Department at Tianjin Bureau of Land, Resources and Real Estate Management (TBLRREM), Tianjin, China. TBLRREM is responsible for the geothermal development, monitoring and utilization in Tianjin. Tianjin is the leading province in geothermal in China. In 2007, the space heating area was approximately 12 Mm^2 in Tianjin alone. Seventy geoscientists and engineers from China have graduated from the UNU-GTP and many of these are from Tianjin. Dr. Wang Kun is a former UNU-GTP Fellow (1998) and specialized in reservoir engineering. She obtained her BSc in numerical mathematics at Nankai University in Tianjin 1989, and her PhD in geology at Peking University 2005. She worked as a senior engineer at the Design Institute of Geothermal Exploration and Development until 2001, when she moved to the TBLRREM. Wang Kun is one of the leading geothermal reservoir engineers in China. She gave a series of lectures on geothermal development and resource management in China. Her lectures were excellent and well attended by members of the geothermal community in Iceland as well as the UNU Fellows and MSc Fellows.

Since the foundation of the UNU-GTP in 1979, it has been customary to invite annually one internationally renowned geothermal expert to come to Iceland as the UNU Visiting Lecturer. This has been in addition to various foreign lecturers who have given lectures at the Training Programme from year to year. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists have found time to visit us. Following is a list of the UNU Visiting Lecturers during 1979-2008:

1979 Donald E. White	United States	1994 Ladislaus Rybach	Switzerland
1980 Christopher Armstead	United Kingdom	1995 Gudm. Bödvarsson	United States
1981 Derek H. Freeston	New Zealand	1996 John Lund	United States
1982 Stanley H. Ward	United States	1997 Toshihiro Uchida	Japan
1983 Patrick Browne	New Zealand	1998 Agnes G. Reyes	Philippines/N.Z.
1984 Enrico Barbier	Italy	1999 Philip M. Wright	United States
1985 Bernardo Tolentino	Philippines	2000 Trevor M. Hunt	New Zealand
1986 C. Russel James	New Zealand	2001 Hilel Legmann	Israel
1987 Robert Harrison	UK	2002 Karsten Pruess	USA
1988 Robert O. Fournier	United States	2003 Beata Kepinska	Poland
1989 Peter Ottlik	Hungary	2004 Peter Seibt	Germany
1990 Andre Menjoz	France	2005 Martin N. Mwangi	Kenya
1991 Wang Ji-yang	China	2006 Hagen M. Hole	New Zealand
1992 Patrick Muffler	United States	2007 José Antonio Rodríguez	El Salvador
1993 Zosimo F. Sarmiento	Philippines	2008 Wang Kun	China

With warmest wishes from Iceland

Ingvar B. Fridleifsson, director, UNU-GTP

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THE TYPES, DISTRIBUTION AND BASIC CHARACTERISTICS OF GEOTHERMAL AREAS IN CHINA

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ABSTRACT

There are more than 3000 natural geothermal outcrops in China. The two high temperature geothermal areas in China include the Taiwan geothermal zone and the Himalayan geothermal zone. Low temperature geothermal areas are widely distributed in the vast area of Chinese mainland. The distribution of hot springs, geothermal wells and heat flow are controlled by geological structure. Taking the Ordos Basin and the Sichuang Basin as the centre, the geothermal areas in China can be divided into three sections: The eastern geothermal area, the western geothermal area and the middle geothermal area. The division of the Chinese geothermal areas correspond with the distribution pattern of the crustal thickness and the Moho-depth of Chinese mainland. The formation of the Chinese geothermal areas is affected by the geological evolution of the crust during plate motion of modern lithosphere; meanwhile, it is controlled by an isostatic gravity compensation function.

1. THE TYPES OF THE GEOTHERMAL AREAS IN CHINA

1.1 Hot springs and geothermal water areas

There are more than 3000 natural geothermal outcrops in China, with temperatures above 25°C (Limin Wang, 1992). More than 90% of them belong to low temperature geothermal resources (< 80°C), see Figure 1. The distributions of these hot springs are controlled by geological structures. Early in 1926 the geologist Prof. Zhang Hongzhao pointed out that the distribution of hot springs is closely linked to the geological structures similar to the network of veins. The research of the hot spring distribution is significant for revealing the rule of geological tectonics and facilitating geothermal exploration.

Based on the distribution of various geothermal outcrops around the world, such as volcanoes, hot springs, fumaroles and boiling mud ponds, as well as the distribution of geothermal boreholes and geothermal fields, structural geologists believe that geothermal distribution on the surface of the earth is dominated by the crustal tectonic movements, and that they are linearly distributed.

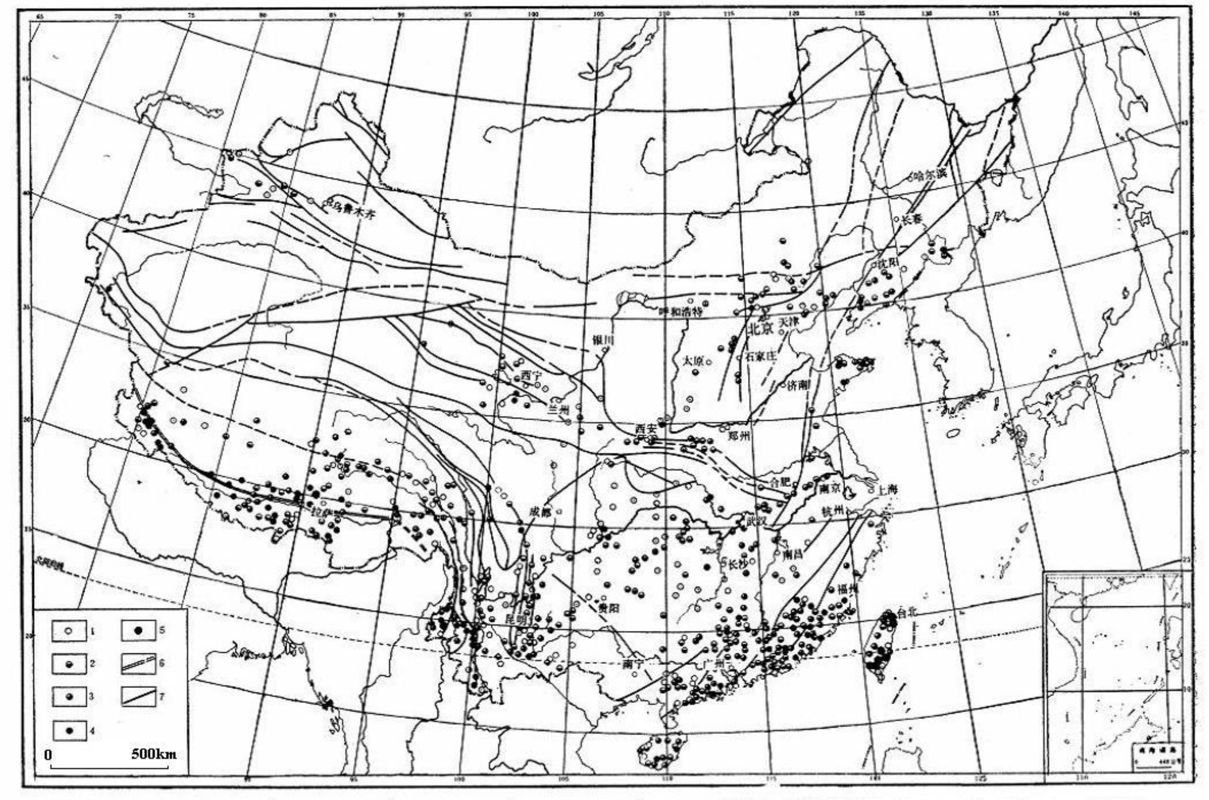

FIGURE 1: The distribution map of hot springs in China
(Huang Shangyao, Wang Jun, etc., 1981)

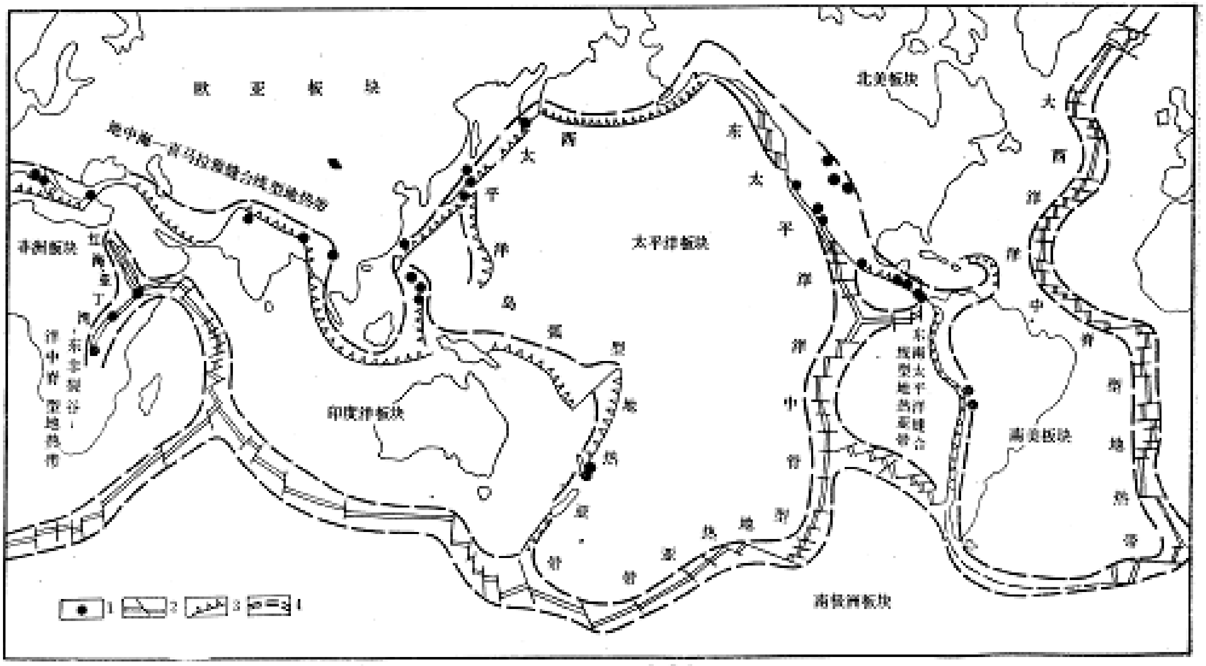

FIGURE 2: Relationship between geothermal belts and global plate tectonics. 1: high temperature geothermal field; 2: the accretion plate boundary, spreading-ridge province, continental rift valley and transform fault; 3: subducting plate boundary: boundary of the deep ocean trench and the volcanic island arc, the boundary in continental edge of the ocean trench and volcanic arc, and boundary of continental collision; 4: geothermal zone around the world.
(Huang Shangyao, Wang Jun, Wang Jiyang, 1983)

The geothermal areas in China can be divided into “high temperature areas” and “low temperature areas”, according to the wellhead temperature above and below 90°C, respectively.

1.2. High temperature geothermal areas on the plate margin and intraplate low temperature geothermal areas

Almost all of the high temperature areas are distributed in the active volcanic regions, younger than Tertiary age, around the world. There are more than 600 volcanoes in China; only few of them are active volcanoes. Therefore no high temperature geothermal areas are being developed in China, except in the Himalaya (from southern Tibet to western Sichuan and Yunnan) and the Taiwan geothermal areas. High temperature hot springs are densely spaced in these areas. Macao geothermal field in Taiwan is a part of the Western Pacific island arc geothermal zone. The geothermal fields in southern Tibet-western Sichuan-Yunnan are a part of the eastern extension of the Mediterranean-Himalayan suture zone (Figure 2). The high temperature geothermal areas in China are located on the plate margins of the modern lithosphere.

In the interior of the China plate, mainly low temperature geothermal areas are distributed. A part of them belongs to the fold system in the active tectonic zones in late Cenozoic (Figure 3), here the outcrops of hot spring are dense. Another part belongs to the basins between the fold systems, including the active blocks between the active structure zones. Underground geothermal water is abundant here. The borehole data shows that the temperatures normally reach 30~50°C at the depth of 1000 m and 55~80°C at the depth of 2000 m; Few wells reach 90~100°C. It is obvious that the basin geothermal zones are mainly low temperature.

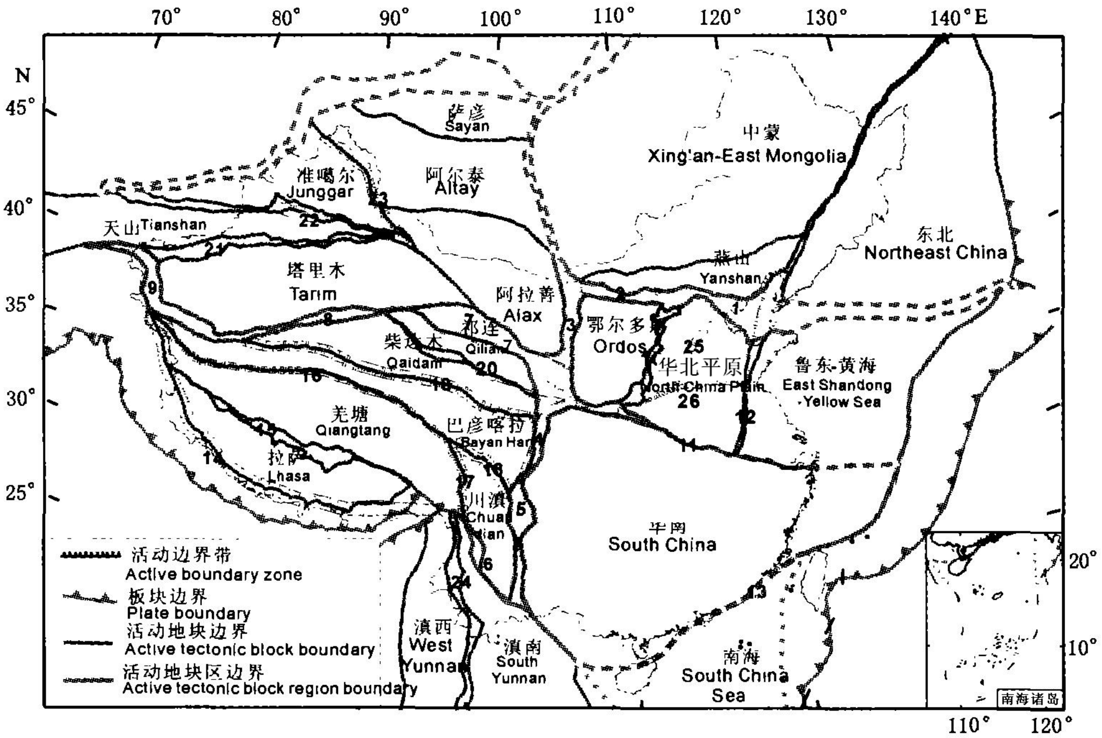

FIGURE 3: Distribution of active tectonic blocks and their boundaries. 1-26: the serial numbers of the active blocks. 1: Yan Mountai-Bohai Sea, 2: Yinshan Montain, 3: Helan Mountain, 4: Minshan-Longmen Mountain, 5: -Anning River-Xiaojiang Riber, 6: Honghe River, 7: Haiyuan-Qilian, 8: Aerjin, 9: West Kunlun, 10-Fen-Wei River, 11: Qinling-Dabieshan Mountain, 12: Tanlu, 13: Southeast coast, 14: Himalayan, 15: Karakorum-Jiali, 16: Mani-Yushu, 17: Source region of three rivers(Yellow river, Jinsha river and Lanchang river),18:Xianshui River,19: East Kunlun, 20:Wesat Qinling-Delingha, 21: Sounthern Tianshan,22: Northern Tianshan, 23: Fuyun, 24: Lancang River, 25: Huabei Plain, 26: Anyang-Heze-Linyi.
(Zhang Guomin, Ma Hongsheng, Wang Hui, etc.2005)

1.3 Brief characteristics of three types of geothermal zones

To sum up the above, China can be divided into three types geothermal zones: high temperature geothermal zones on plate margins, related to the active volcanoes; hot spring zones in fold systems related to active structure zones within the plate or in the block margin; and geothermal water zones in the basins related to the active blocks within the plate.

1.3.1 Plate marginal high temperature zones

High temperature zones on plate margins are located along the junction between the Western Pacific island arc and the Mediterranean-Himalayan suture zone in the global geothermal belt. Because the heat sources of volcanoes exist in the shallow part of the earth's crust, the local geothermal high heat flow anomalies can be observed here. Hot springs are common on the surface, and most with temperatures higher than 90°C. Also some high temperature geothermal activity can be found, such as hydrothermal explosion, geysers and boiling springs. Usually the temperature in these geothermal fields is higher than the local boiling point, most of them above 200-300°C. Under the influence of volcano-magmatic activity and the control of local geochemical conditions, the geothermal water is mainly acidic water of the Cl-Na type with low mineralization. It contains silicic acid, metasilicate, arsenic acid, carbon dioxide, sulphur dioxide, sulphurated hydrogen, hydrochloride gas and fluoride prussic acid gas, etc. The geothermal resources are abundant. Its isotopic components are close to the precipitation in recharge areas and belong to the modern meteoric water cycle.

1.3.2 Hot spring zones in fold systems

The artesian hot springs are exposed in low altitude structural fracture zones of the uplifted mountain areas and small scale inter-mountainous basins. The flow rate of a single spring generally is 20-200 m^3/day; few of them can reach more than 1000 m^3/day. The meteoric water is the primary recharge, and it circulates to the deep crust along tectonic fractures. The heat source comes from the natural geothermal gradient, only one or two high temperature areas are related to modern volcanics or magmatic residual heat. The geothermal water is mainly fracture-vein water of varying water quality and flow rate, with temperatures less than 80°C, except in few areas. The temperature increment is not evident with depth. The hot springs are of HCO_3-Na type and have weak alkalinity with low mineralization, usually less than 2 g/l. Cl-Na type water exists along the coastal area, and its TDS values can reach 10 g/l, with large contents of CO_2, nearly a hundred milligrams per litre. Hot springs often contain Sr, Ra, Al, F, B and SiO_2 etc., and H_2SiO_3, H_4SiO_4, F^- and Rn are typical elements.

1.3.3 Geothermal water zones in the basin

Geothermal water is abundant in the inner zone of large scale artesian basins, where the runoff circulation is low or stagnant. The reservoir lithology comprises clastic rock, carbonate rock and crystalline rock. There is a lack of natural springs but boreholes often have very high pressures. The heat source is the natural geothermal gradient, and the temperature and flow rate are relatively stable. The temperature lies on the geothermal gradient, gradually increasing with depth. They can reach 30-50°C at a depth of 1000 m, and 50-90°C at a depth of 2000 m. The flowrate of a single well is 100-500 m^3/day to 1000-2000 m^3/day. According to the formation conditions, the geothermal water in the basin can be classified into 2 types: Open circulation systems and closed or sealed systems. The former type is mainly derived from the precipitation since late Pleistocene. It has low TDS values, generally 1-2 g/l, only few with more than 30 g/l. The origin of the latter is a more complicated mixture of ancient meteoric water and sea water. Also it may be influenced by water-rock interaction, diagenesis or endogenesis and other geological process. The hydro-chemical types of the geothermal waters are mainly Cl-Na and Cl-Na-Ca type. Compared with modern meteoric water, the isotopic composition of ^2H is low but the chemical concentration Ca^{2+} is higher than that of modern sea water. Some of the waters accompanied by salt mineral deposit have the higher TDS values of 50-320 g/l in addition to H_2S gas, B, Li, K, Rb, Sr, etc. Others accompanied by hydrocarbon mineral deposit have TDS value of 50-150 g/l and are rich in methane, Br and I, etc.

2. DISTRIBUTION OF THE GEOTHERMAL AREAS IN CHINA

2.1 Trisection pattern of the geothermal areas in China

The Chinese geothermal exploration shows that the hot spring zones in fold systems and the geothermal water zones in the basins are controlled by geological tectonic, as for example, the foreland pediment, basin boundaries or inner deep tensional fractures, fracture zones at the anticline axis and boundaries of the graben structure, etc., commonly called “heat-controlling structures”. The geothermal features are usually well developed at the intersection of heat-controlling structures. Taking the Ordos Basin and the Sichuang Basin as the centre, the geothermal areas in China can be divided into three sections according to the strike of the geothermal zones (Figure 4 and 5): The eastern geothermal area, the middle geothermal area and the western geothermal area. The structural strike in the eastern geothermal area is mainly NE and NNE, and NW and EW. In the western area it is mainly NW and EW, and NE and NNE. In the middle area the strike is mainly SN, and EW. The division is called the “trisection pattern” of geothermal areas in China.

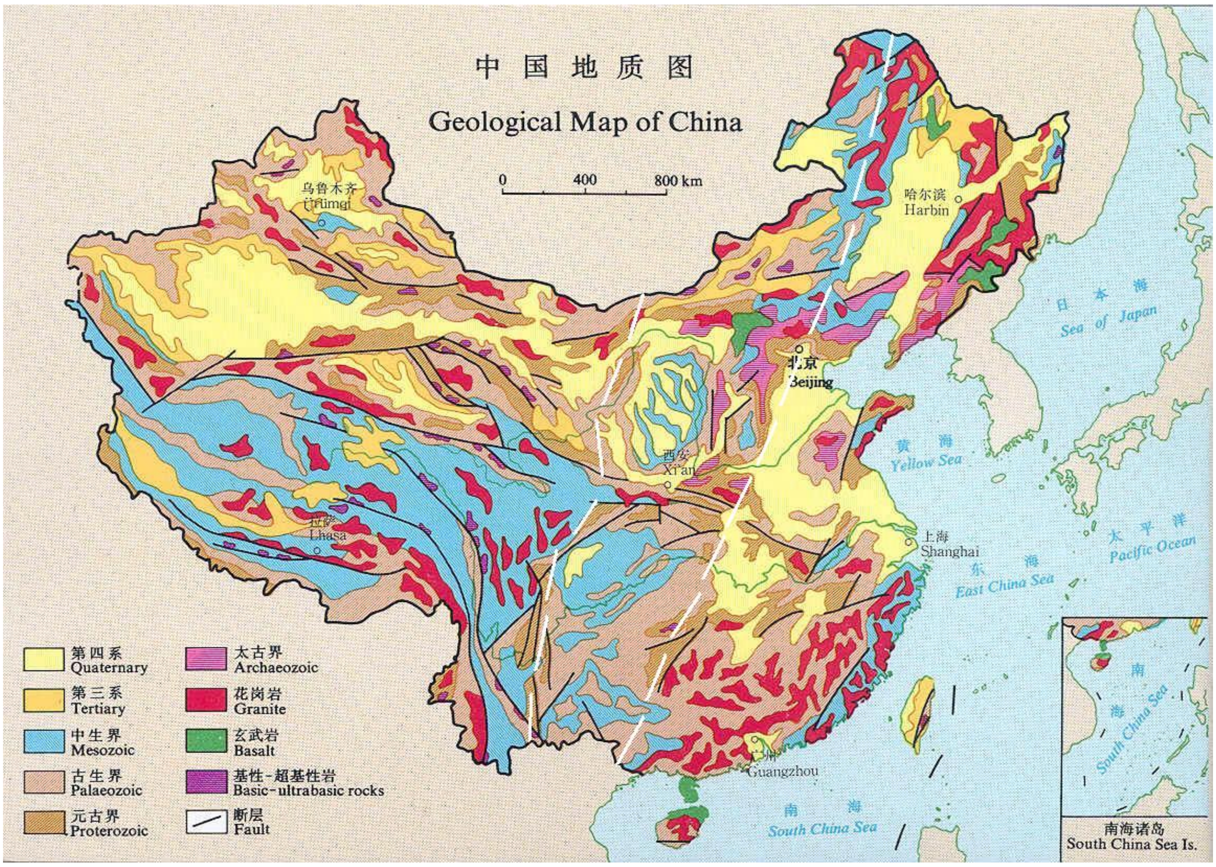

Figure 4: The geological map of the Chinese Mainland. The two white lines indicate the boundary of the trisection pattern of geothermal areas in China. The eastern line: Big Xinganling Mountain-Taihang Mountain-Wuling Mountain.The western line: Helan Mountain-Longmen Mountain-Tectonic Zone from north to south. (Geng Shufang, Fan Benxian, 1976)

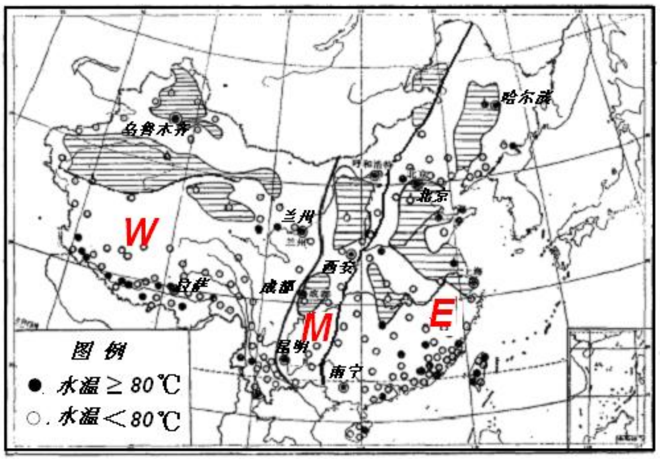

FIGURE 5: Trisection map of the geothermal areas in China. E-eastern geothermal area; M-middle geothermal area; W-western geothermal area.

2.1.1 Eastern geothermal area

In the eastern geothermal area, the fold system hot spring zone includes: a high temperature zone in Taiwan, and a low temperature zone at the south-eastern coastline and Jiaodong-Liaoning etc. The basin geothermal zones are the Songliao Basin, the Circum-Bohai Basin, the Jianghan Basin and the Nanyang Basin, etc. The main strike of the hot spring zones and geothermal zones are longitudinal, and secondly transverse. The most active heat-controlling structure is the Taiwan rift Fault, which is part of the Western Pacific island arc fracture belt. The Tancheng-Lujiang Fracture is the largest inland heat-controlling structure; The Taihang Mountain Fracture is the second largest.

2.1.2 Middle geothermal area

Generally, the middle geothermal area stretches north to south on the China Mainland. The main fold system hot spring zones include the Taihang Mountain, the Qinling Mountain, the Helan Mountain, the Longmen Mountain, the Big Snow Mountain etc. The main basin geothermal zones are located in the Ordos Basin and the Sichuan Basin. The strike of the hot spring zones and geothermal zones are in longitudinal and transverse directions. The active heat-controlling structures are the Qinling northern slope fracture, the BeiShan southern slope fracture, the Longmen Mountain Fracture and the Sanjiang Tectonic zone.

2.1.3 Western geothermal area

In the western geothermal area, the fold system hot spring zones include the Tianshan Mountain, the Qilian Mountain, the Kunlun Mountain Hot etc. The main basin geothermal zones are located in the Tarim Basin, the Junggar Basin and the Qaidam Basin etc. The largest and most active heat-controlling structure is Brahmaputra Fracture.

2.2. Heat flow distribution of the boundary and the inland in China

2.2.1 Heat flow distribution at the boundary in China

The average terrestrial heat flow of China is 63±16m W/m^2 (Chen Moxiang, Huang Shaopeng and Wang Jiyang, 1994), which is similar with the global continental statistic result. The southeast boundary of the Chinese mainland coincides with the plate boundary of the Philippine Sea and the Pacific. Meanwhile the India plate has severe influence upon the southwest of China. So in China, the southern boundary has a higher heat flow, while the heat flow at the northern boundary is lower.

According to the statistics of average and maximum values of heat flow, the high values in the southern boundary are: the Taiwan Island is 80-120 mW/M^2, the southeastern coastline is 75-80 mW/m^2, the Tengchong in Yunnan Province is 85-118 mW/m^2, and the southern Tibet (from Bangong Lake to the Shouthern part of the Nujiang Fracture) is 100-319 mW/m^2. The low values at the northern boundary are: the Xinganling Mountain < 40 mW/m^2, the Juggar Basin < 45 mW/m^2.

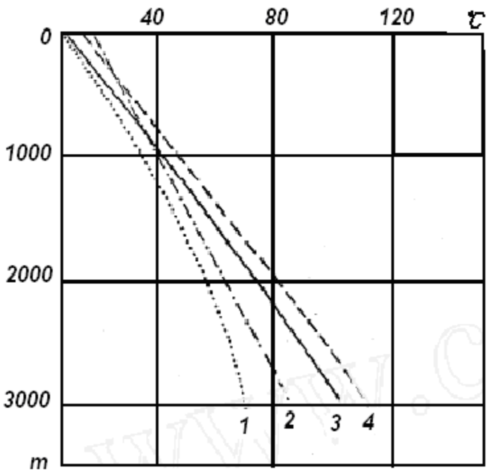

FIGURE 6: Relation of the hot water temperature and depth in main basins in China. 1-Junggar Basin, Tarim Basin and Jiuquan Basin; 2- Sichuan Basin; 3-Qaidam Basin, Ordos Basin; 4-Jianghan Basin, Huabei Basin, Subei Basin and Songliao Basin

2.2.2 Trisection pattern of the heat flow distribution in the interior

Except the two high heat flow areas mentioned above, the heat flow distribution in the interior is similar with the trisection pattern of the geothermal areas. The heat flow reduces stepwise from the eastern to the western area. The east area has a higher heat flow value. The average value is 62±13 mW/m^2 in the whole Huabei Mesozoic-Cenozoic fault basin, including the Xialiaohe Basin. The heat flow is 78±14 mW/m^2 in basement convex area and 51±8 mW/m^2 in the basement depression area. The distribution and changes of the heat flow can reflect the basement's tectonic features, as well as the tectonic pattern of alternating uplifts and depressions. The average value is 52±12 mW/m^2 in the middle area and 43±8m W/m^2 in the western area. Figure 6 shows that the temperature of the hot water decreases from east to west in sedimentary basin, which is consistent with the trisection pattern of the heat flow changes.

2.3. Trisection pattern of the character of the geothermal water

2.3.1 Low mineralization and deeply circulating hot water in the eastern geothermal area

The large scale Mesozoic-Cenozoic basins developed in the eastern geothermal area, i.e. the Huabei Basin (upper Tertiary), the Songliao Basin (upper Cretaceous). All of them constitute interbedded sands and clays filled with open deposits of river-lake facieses. Because of the large thickness (hundreds to 2000 m) and the high ratio of sand-clay layer, they are good clastic rock reservoirs.

In the Huabei Basin, the fractures and cavities are widely dispersed and developed in the carbonate rock reservoir beneath the upper Tertiary. In the local extensional stress regime, the tensional fractures and a series of graben structures of alternate uplifts and depressions are developed in the duality structure reservoir. Thus, the heat transfer property of the rock is distinctly different. After the reallocation of the heat flow during the transfer process, the local heat anomaly is formed in the cap rock of the uplift area, where the temperature gradient is higher than 4°C/100 m and the heat flow is more than 65 mW/m^2. The cap rock is comprises the shallow reservoir and its super stratum Quaternary sediments. The geothermal water is different from the groundwater in the shallow aquifer of the basin foreland. The latter belongs to the modern cycle of meteoric water. Geothermal water is the deep water cycle continuously recharged by ancient meteoric water since the latest glacial period. The low mineralization and deep seating are the main characteristics of the abundant geothermal water in the eastern geothermal area.

2.3.2 The low temperature and sealed fresh brine in the western geothermal area

The multi-layer hydrocarbon mine and the low temperature fresh brine are developed in the western geothermal area. Based on the hydro-geochemical and isotopic research, the origin of the brine is ancient sea water, sediment pore water created through diagenesis and huge amounts of crystallization water emerging from the transformation of gypsum into anhydrite. The fresh brine is sealed hot brine. The chronological studies of rare gas indicate that the residence time of the brine is close to the age of the surrounding rock.

2.3.3 Low temperature and highly concentrated hot brine in the middle geothermal area

In the middle geothermal area, there are several kinds of low temperature and highly concentrated hot brines. For example, the Sichuan Basin is formed in the compressional environment; the brine is widely distributed in the gas fields of the Sichuan Basin from the Sinian period to cretaceous period, but with different concentrations and genesis. The primary brines are the multi-type low temperature brines and highly concentrated hot brines in salt deposits, and the secondary brines are low temperature fresh brines and highly concentrated calcium chloride (CaCl) brines in hydrocarbon deposits[1].

3. THE CONTROLLING FACTORS ON THE DISTRIBUTION OF GEOTHERMAL AREAS IN CHINA

3.1 The history of the geotectonic evolution of the Chinese mainland

3.1.1 The geotectonic evolution process and the trisection pattern of geothermal areas in China

The Chinese mainland belongs to Asian Plate and is composed by several blocks. Since the Pliocene (3Ma) epoch, the pattern of crustal movements in China has been fixed (Figure 5). The macro geotectonic evolution can be described as a "teeterboard" process:

Considering the Ordos-Sichuan Basin as a main axis; Western China belonged to the Tethys Ocean in the Paleozoic period, and the landform is lower in the west compared to the east. In the Mesozoic period, the Qiangtang, the Gandise and the India massifs drifted from the southern mainland, then collided to form the suture with the Tarim massif. In the Cenozoic period, the Tethys Ocean evolved into the Qinghai-Tibet Plateau. During volcanic activity, the crust thickened and the topography increased. Later the Pacific Plate turned towards the north-west to dive beneath the plate of Philippine Sea, and to converge with the Eurasian plate. Meanwhile the Australian plate moved northwards, and the area near the Pacific Ocean is pulled apart in north to south direction making the crust thinner, decreasing the topography.

The "teeterboard" evolution of the Chinese mainland is the geological background for the formation of metal ore deposits, hydrocarbon deposits and salt deposits. Furthermore, it is the main controlling factor for the trisection pattern of the geothermal areas in China. The axis of the "teeterboard", the topographic high in the Ordos-Sichuan Basin affects the advance and retreat of the sea water. The ancient shelf of the shallow seashore occurs on both sides (east and west) of the high. Moreover, the formation of the sealed geothermal water in the Sichuan Basin is related to the closure of the Tethys since the Mesozoic period. The formation of the semi-open geothermal system in the Huabei Basin is related to an extensional stress field in the eastern area originating from the early Tertiary.

3.1.2 The geotectonic evolution and the heat flow distribution

The local heat flow is connected to the geotectonic evolution. According to on the statistic Pollack et al., 1993, the average heat flow value is 41±2.4 mW/m^2 for Archean units, 58±1.4mW/m^2 for Proterozoic units, 58-61mW/m^2 for Paleozoic units, 64±3.0 mW/m^2 for Mesozoic units and 64-97 mW/m^2 for Cenozoic units. In the eastern geothermal area in China, most of the average heat flow values are within the range of the heat flow in Cenozoic. This indicates that the eastern geothermal area is widely affected by Cenozoic tectonics. The effects on Taiwan and the south-eastern Coast are most intense. In the middle and western geothermal area, the high heat flow is most prominent in southern Tibet and the West Yunnan Province, affected by the collision of the India plate and Asian

[1] Classified by TDS(g/L) in water: fresh brine- TDS=30-150g/l, concentrated brine-TDS≥150g/l, saturated brine-TDS=320g/l, over-saturated brine-TDS≥320g/l, saturated and over-saturated brine is generally called highly concentrated brine.

mainland. The heat flow is lower in the other places. The average value of the heat flow in the Tarim Basin is only 44 mW/m^2 and close to the average value of cratons in Archean. Thus the effects of the tectonic events previous to the Cenozoic are rather distinct there.

3.2 Plate movement of the modern lithosphere

3.2.1 Plate movement controls the strike of the folded belts

Based on the theory of plate motion, there are three groups of horizontal driving forces in Chinese modern tectonic movements: The NNE trending compression created by the India plate (Figure 8); the convergence of the Pacific plate and the plate under the Philippine Sea towards the Asia plate (Figure 9); the resistance coming from the Russia plate in the north. Their joint actions bring about the trisection pattern of the folded belts.

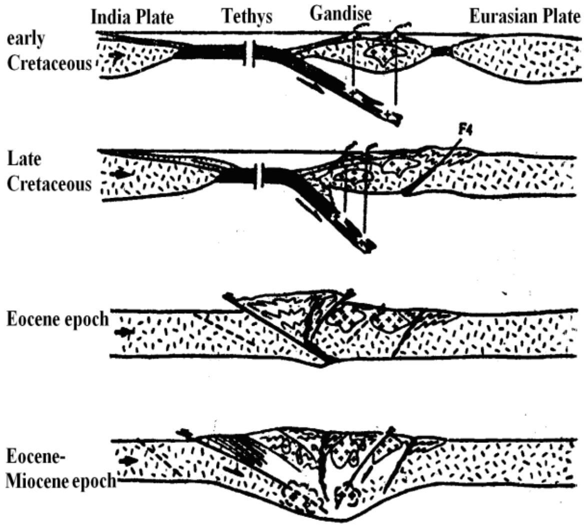

FIGURE 8: Sketch map of the collision between the Indian plate and Asian plate in Mesozoic-Cenozoic (Zhou Yunsheng,1981).

3.2.2 The strike of the folded belts dominates the strike of the hot springs and/or hot water zones.

The consistency in strike of the hot spring zones and folded belts should attribute to the heat transfer and water conductivity of the deep fractures along the folded belts. But the coherence between the hot water zones in the Basin and the folded belts is, not only, related to the concealed deep faults, but also to the changes in specific thermal conductivity in the rocks. For details, see the following.

3.2.3 The plate movement controls the heat flow distribution

Based on the theory of plate motion, molten mantle material extrudes at the mid-ocean ridges to forms new oceanic crust. The "new" crust gradually cools while spreading. At the ocean trenches, the oceanic crust dives into the asthenosphere of the upper mantle, and gradually disappears. The heat flow normally decreases from the mid-oceanic ridge to the trench, with highest heat flow values of 376.6 mW/m^2 and an average value of about 79.5 mW/m^2 at the mid-oceanic ridge. In the trench area, the average heat flow is only about 48.5 mW/m^2. Whereas, the lowest heat flow values in the basin are about 53.2 mW/m^2 (Lee, 1970)

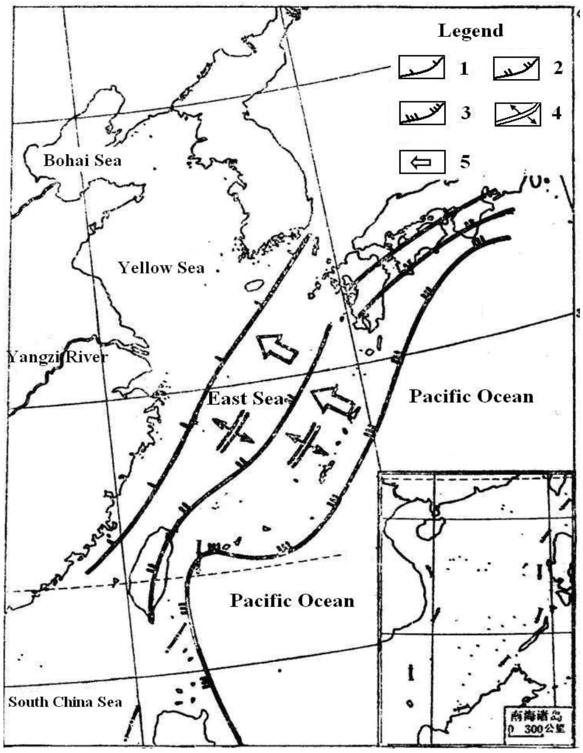

FIGURE 9: Sketch map of the Mesozoic-Cenozoic Subduction Zone of the West Pacific Ocean. 1: late Cretaceous; 2: early Mesozoic-Cenozoic subduction zone; 3: modern subduction zone; 4: back-arc rift basin; 5: subducting direction.
(Zhang Zhengkun, Ren Jishun, 1981)

3.2.4 The heat flow on the boundary of the Chinese mainland is affected by global geothermal belts.

As mentioned above, the heat flow is higher in the south and lower in the north on the Chinese mainland. The heat flow distribution is affected by the global geothermal belts, related to the tectonic magma activities in the collision zone, where the Indian plate and the Pacific plate collided with the Asian plate.

3.2.5 The trisection distribution pattern of the interior heat flow is related to the stress field.

On the basis of research on the strain rate fields of the China mainland through GPS data, both inner continuous deformation and block movement deformation exist within the china mainland. Continuous deformations mainly exist in the Qinghai-Tibet Plateau and the Tianshan Mountain, while inner deformations are less obvious and mostly occur in the fracture zones around the block boundary in the Junggar Basin, the Tarim Basin, the Ordos Basin, and in the north-east of China. The deformations of the blocks of the Yinshan-Yanshan Mountain, the Huabei Plain and the eastern Shandong-Huanghai Sea are inverted. This indicates that, the NNE trending compression by Indian plate is the main driving force of the inner deformation of the China mainland. The heat flow on the mainland decreases in an East-middle-west direction. The compression in western China and the extension in eastern China are the important factors creating the trisection.

3.3 The deep-crustal structure and isostatic gravity compensation function

3.3.1 The trisection pattern of crustal thickness and Moho-depth in the Chinese mainland

There are two gravity gradient belts on the Bouguer gravity anomaly map of the China mainland (Figure 10): HeLan Mountain – Longmen Mountain and Daxinganling Mountain-Taihang Mountain-Wuling Mountain. The deep-crustal structure of China mainland is divided into the trisection pattern by these two gravity gradient belts. With the centre of the Ordos–Sichuan Basin, the upper mantle is uplifted in the east and down-faulted in the west.

The map of the Moho-depth or crustal thickness in China (Figure 11) shows that same trisection pattern. The Moho is deeper in the west and shallower in the east. Its depth is about 45 km in the middle area, more than 60-70 km in the western area, and 38 km in the eastern area. The Moho depth gradually decreases towards the east and is only 8 km in Okinawa Trough (Yuan xuecheng, 1996; Huang Jiqing, 1980).

The trisection pattern of the geothermal areas corresponds with the distribution pattern of the crustal thickness and Moho depth of the China mainland.

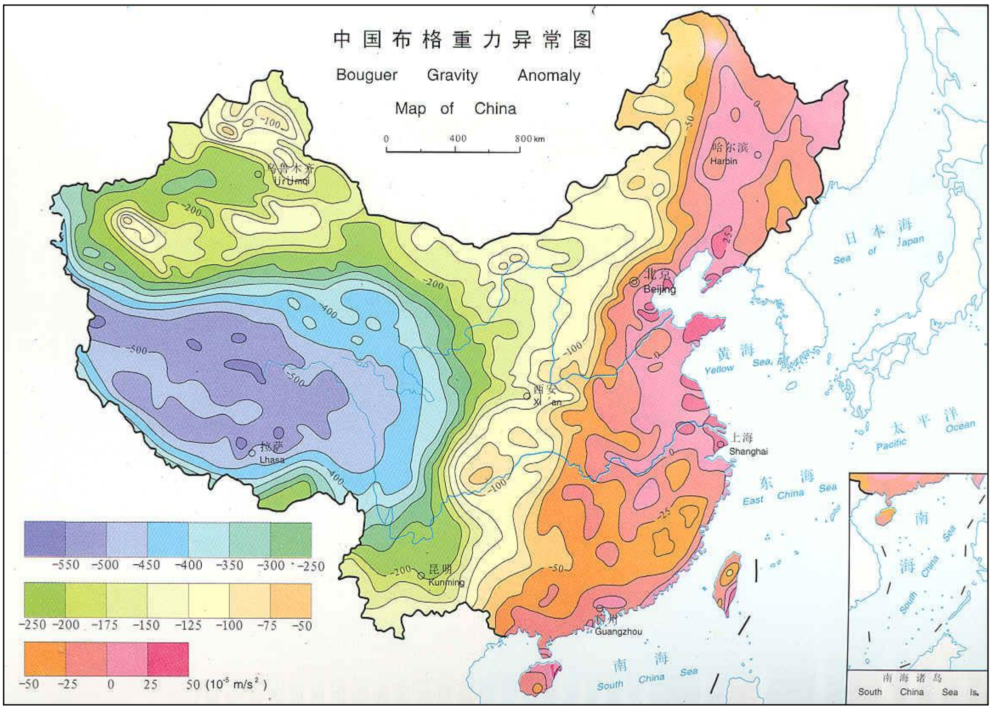

FIGURE 10: Bouguer gravity anomaly Map of China (Yuan Xuecheng, 1996)

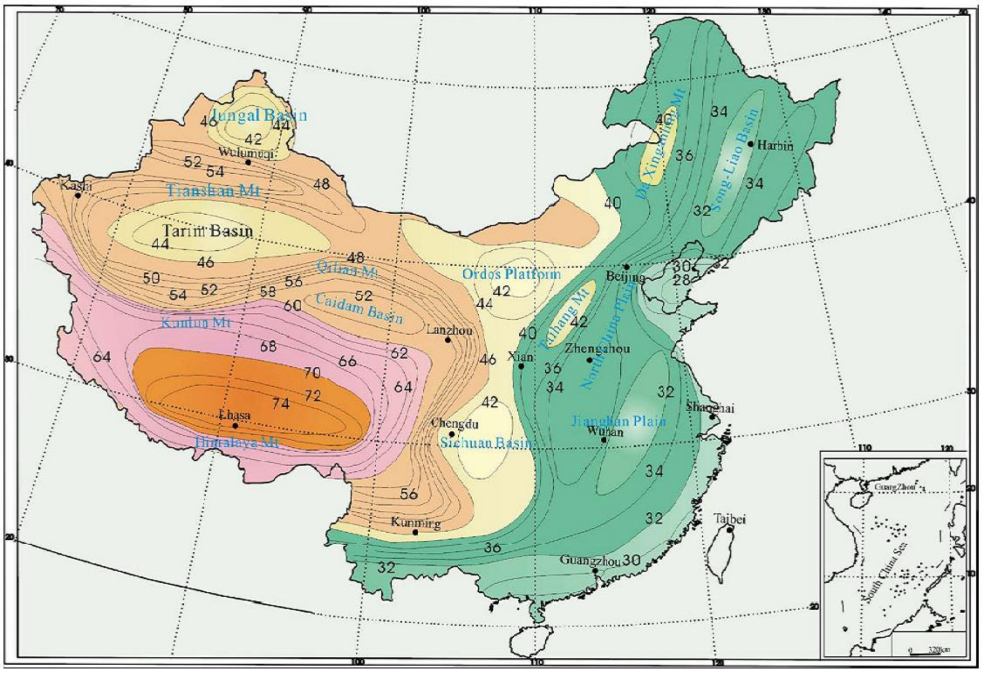

FIGURE 11: Map of the Moho-depth or crustal thickness in China
(Li Songlin, Walter Mooney, 2006).

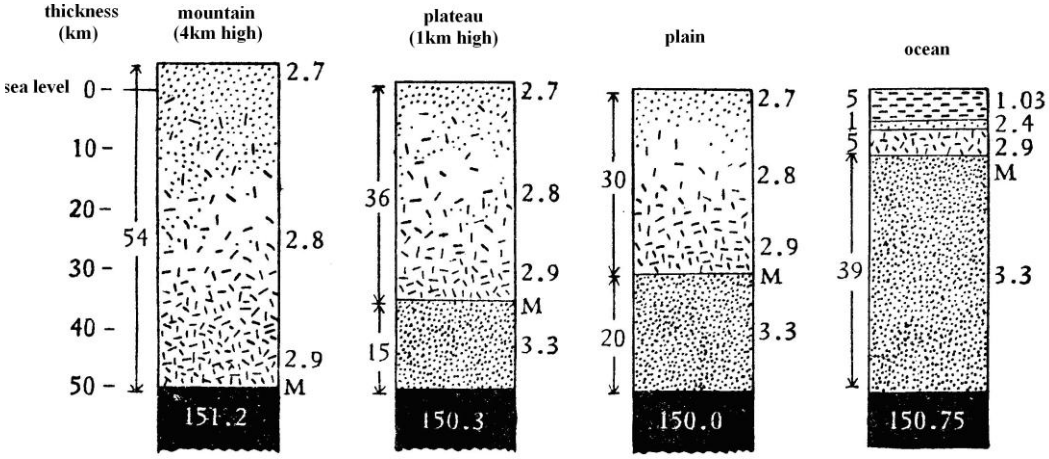

FIGURE 12: Four typical columnar sections of the relative positions of the Moho and isostatic compensation base levels.

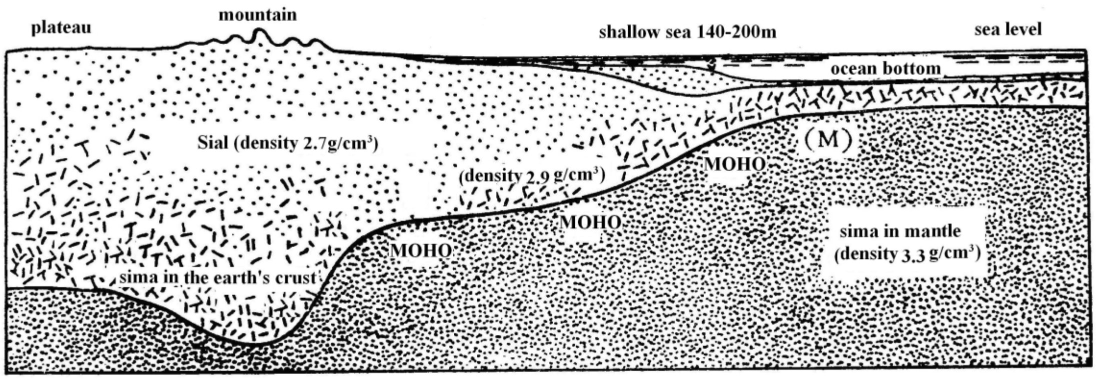

FIGURE 13: Sketch of the continental and oceanic isostatic compensation (Li Siguang, 1972).

3.3.2 The isostatic gravity compensation function

In the 1950s, the geologist Dr. Li Siguang pointed out that the modern China mainland topography is apparently correlative with the crustal thickness, and that the correlation is indeed associated with the formation. He subsequently developed the isostatic gravity compensation function, discussed in the formation of the modern China mainland topography.

Largely, the density of rocks increases with increasing depth in the earth's crust. The sediment density is 2.4 g/cm^3, the sima in the upper crust is 2.72.4 g/cm^3, the upper mantle is 3.32.4 g/cm^3. When the different morphological units of the continental crust and the oceanic crust reach an isostatic state (Figure 12), the base-level depth of the isostatic compensation should be accordant, with a difference is crustal thickness (the depth of upper mantle). The thickness of oceanic crust is about 11 km and the thicknesses on the craton are 30km on the plain, 36 km on the plateau and 54 km in the mountain area.

The western crust of the Chinese mainland is thickened by the compression and the eastern crust is thinned through extension. Isostasy is evidently changing. The inherent trend of crustal isostasy behaves as: crustal down-faulting as result of loading of sediments or continental glacier, and crustal rise due to mountain erosion, denudation or glacial melt-off. Through local elevation and subsidence and constant adjusting, the earth's crust reaches an isostatic state. The isostatic gravity compensation function brings up the trisection pattern of the topography, crustal thickness and Moho-depth of the Chinese mainland. Figure 13 shows the isostatic compensation between the continent and ocean. Moreover, factors such as heat flow changes react on the deep crustal structures.

3.3.3 The relation of geological evolution and crustal thickness to heat flow

On the stable continent, the heat flow increases from the paleostructures to the neotectonic regimes, and reflects the processes of the geological evolution. But in the active tectonic zone, the energy is redistributed. The temperature at depth has higher a horizontal gradient, so the relation between the crustal thickness and heat flow is complicated. Through research of heat flow and crustal thickness (Huang Shaopeng, 1992), the terrestrial heat flow is constituted by that of the earth's crust and the mantle. The crustal heat flow has a positive correlation with crustal thickness, while the mantle heat flow tends to lack correlation with its thickness. Thus the terrestrial heat flow is related to upwelling of the upper mantle and the associated thinning of the earth's crust in rift valley basins.

3.4 The rock's thermal conductivity

The thermal conductivity of rocks represents the rock's capacity for heat transfer, and is controlled by its constituents, structure, humidity, temperature and pressure, etc. Among the rock-forming minerals, the thermal conductivity of quartz is the higher (17.0 cal/cm·s °C) and of feldspar is the lower (4.5 cal/cm·s·°C). The geological age and the structure are the main controlling factors of thermal conductivity. Ancient crystalline rocks and compact rocks have higher thermal conductivity, while semi-consolidated or loose sediments in Cenozoic have lower thermal conductivities. The rock has higher thermal conductivity along the direction of the parallel texture plane, and the heat flow is concentrated areas of low resistivity. So the higher values of heat flow can be observed in the anticline axis and the upper part of other positive structures, where the thermal conductivity is higher, and where the upper loose stratum is thin. Thus, the average heat flow is 62±13 mW/m^2 in the Huabei Mesozoic-Cenozoic fault basin, 78±14 mW/m^2 in the basement uplift area and 51±8 mW/m^2 in the basement depression area. The distribution and changes of the heat flow primarily reflects the alternating normal and reverse faults in the basement structure.

4. CONCLUSION

1 There are two high temperature geothermal areas in China: the Taiwan geothermal zone and the Himalaya geothermal zone, which belong to the global geothermal belts.

2. Low temperature geothermal areas are widely distributed in the vast area of the Chinese mainland. The allocation of hot springs, geothermal wells and high heat flow areas are controlled by geological structure.

3. Taking Ordos - Sichuang Basin as the centre, the geothermal areas in China can be divided into three sections:

1. The Eastern geothermal area. The strike of the geothermal zone is mainly north-east. The local crustal stress field is extensional. The heat flow is high and the geothermal system is a low temperature hot water cycle.
2. The Western geothermal area. The strike of the geothermal zone is mainly north-west. The local crustal stress field has an extrusive nature. The heat flow is low in most areas, except the Himalayan high temperature geothermal zone. The geothermal system carries a low temperature freshwater brine in hydrocarbon mines with low mineralization water.
3. The Middle geothermal area. The strike of the geothermal zone is mainly north-south. The local crustal stress field has the extrusive nature. The geothermal system carries a low temperature and highly concentrated hot brine.
4. The trisection pattern of the Chinese geothermal areas is corresponding to the same distribution pattern as that of the crustal thickness and Moho-depth of the Chinese mainland, this represents an inner relationship among of them. The development of the Chinese

geothermal areas is affected by geological evolution of the crustal and by the isostatic gravity compensation function.

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LECTURE 2

BACKGROUND, HISTORY AND STATUS OF GEOTHERMAL UTILIZATION IN TIANJIN

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ABSTRACT

The Tianjin geothermal field is a typical low-temperature system, which is located in the middle-lower reaches of the Haihe River System on the North China plain. The geothermal distribution area is 8700 km^2, about 77% of the total Tianjin area. 10 geothermal anomalies are revealed. As a clean energy, the geothermal resource is widely used for space heating, potable water, agriculture etc. The annual production rate reaches 2450m^3 and the space heating area was about 12 Mm^2 in 2007. The geothermal reserves of 4 geothermal fields have been estimated with attainable resources of 5088×10^4 m^3/a in 2005. It is necessary to enhance the prospecting precision, expanding the exploitation area and strengthen the research on basic technology.

1. INTRODUCTION

Tianjin is located in the north-east of the North China Plain near Bohai Bay, west of the Pacific Ocean, at the lower reaches of Haihe River valley, with The Bohai Sea to the east and Yanshan Mountain to the north.

FIGURE 1: Location of Tianjin

Tianjin belongs to the warm temperature zone and has sub-humid continental monsoon climate. The four seasons are sharply distinguished, and this results in a great difference in temperature and a wide variety of scenery throughout the year. The average temperature in a year is over 12.3°C, and the frost-free period lasts about 200 days. On the average, the annual precipitation is about 600 mm, 75% of which

falls in June, July and August. The sunshine period is relatively long and the solar radiation is quite strong.

The present population of Tianjin is 1,236,700; the total area is 11,900 km^2. Tianjin has jurisdiction over 15 districts and 3 counties. With the largest artificial deep-water harbour and the largest port in the north of China, Tianjin port has the largest container dock groups, and the largest special docks for bulk grain and coke.

Tianjin has relatively rich energy resources, such as coal, oil, gas, geothermal; and thus has an advantage among the coastal cities in China. Its Bohai and Dagang Oil Fields are key state oil and gas projects, turning out 14,430,000 tons of crude oil and 830,000,000 m^3 of natural gas per year. Plentiful geothermal resources are available in Tianjin. Its reserves and utilization of these are ranked number one in China.

2. DISTRIBUTION AND CHARACTERISTICS OF GEOTHERMAL RESOURCES

2.1 Geology

Tianjin Geothermal field is located in a sedimentary-fault basin in the north of the North China Platform and is divided into a northern and a southern part by the Ninghe-Baodi fracture (Figure 2). Most of the area is covered by Quaternary strata. The outcrop of the base rock is limited to the mountain area in the north of Ji County. The northern part belongs to the secondary tectonic unit; the Jibao up-fold, in the Yanshan platform orogen. The southern part lies in the Bohai-Bay Basin. From west to east, the southern part constitutes three tectonic units; the Jizhong depression, the Cangxian upfold, and the Huanghua depression, that are cut into numerous tectonic blocks by several east-west, northwest and northeast trending fractures. On the whole, the centre part is uplifted with the low-lying part in the east and west. The anticline structure is the main regional trend. The main fractures are the Tianjin fracture in the west, the Cangdong fracture and the Baitangkou fracture in the east, and in the middle there are the Haihe and Chenglinzhuang fractures. Several faults accompany them. Most of the geothermal fields are located in the Cangxian uplift.

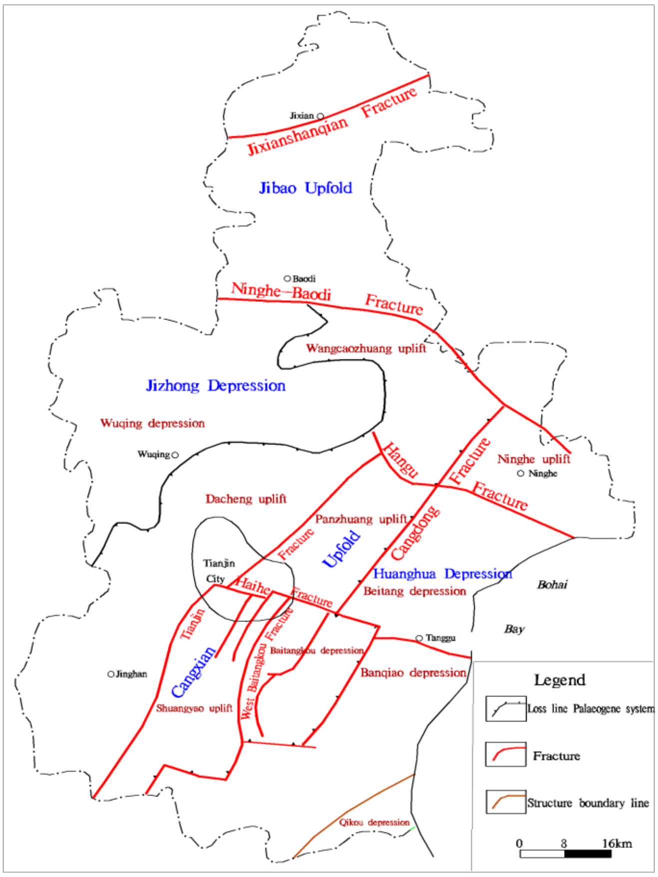

FIGURE 2: Sketch of geological tectonics in Tianjin

2.2 Strata in Tianjin

The general stratigraphy of Tianjin is presented in Table 1 (Tianjin Regional Geological Records, 1992).

TABLE 1: The general stratum of Tianjin

Geological age		Depositional formation	Diastrophism magmatism	Age (Ma)
Era	**System**			
Cainozoic	**Quaternary**	Continential plain, alluvial clastics, some lacustrine and marine deposits	Large depression	1.5±0.5
	Late Tertiary	Inland(near shore) salt and oil bearing lake clsastic	Basic magma effusives, dustpan basin	25±2
	Early Tertiary	Inland lake, red clastics	Basement fault, growth fault	66±2
Mesozoic	**Cretaceous**	Partial absence, inland basin, fluvial lacustrine clastics, intermediate pyroclastic rocks	General uplift	135±5
	Jurassic	Inland basin, coal-bearing calstics and volcanic rocks	Basic effusives, inland faulted basin, volcanic basin	200±5
	Triassic	Absent in late period, inland variegated clastic rocks	Orogen, inland small basin, intermediate magmatic emplacement	235±5
Late Palaeozoic	**Permian**	Continental coal-bearing, clastic rocks	Continental volcanic extrusion	285±5
	Carboniferous	Paralic coal-bearing clastics rocks	Inland large depression	350±5
	Devonian	-	General uplift	405±5
Early Palaeozoic	**Silurian**	-		440±10
	Ordovician	Neritic-littoral limestone, lagoonal dolomite, gypsum	Steady sinking, epicontinental sea	550±10
	Cambrian	Neritic-littoral limestone, sandy shale in early Cambrian		600±10
Late Proterozoic	**Sinian**	-	General uplift	800±50
	Qingbaikou	Neritic calcareous shale, littoral sandy shale, neritic limestone	Steady sinking, epicontinental sea	1000±50
Middle Proterozoic	**Jixianian**	Neritic limestone, littoral-neritic argillaccous carbonate, littoral magnesiaan carbonate, neritic shale		1400±50
	Changchengian	Littoral-neritic shale and dolomite, potassic volcanic rocks, littoral quartz sandstone and limestone, neritic shale, fluvial clastic rocks	Basement fault, submarine eruption, basic dike intrusion	1800±50
Early Proterozoic		?	Orogen	2500±50
Archaic		Basic to intermediate volcanic rocks, multilayered ferro-silicic iron rocks	Sealed folding, gneiss dome, granulite, migmatite	2900±50

2.3 Distribution of geothermal fields in Tianjin

There are 10 geothermal anomaly areas in Tianjin determined by temperature gradients of 3.5°C/100m (Figure 3). Seven of them are distributed in the Cangxian Up-fold. In Table 2 the temperature gradients of the cap rocks area are shown.

TABLE 2: Geothemal anomalies in Tianjin

Geothemal anomalies	Area (km^2)	Highest temperature gradients of cap rock (°C / 100m)
Wang Lanzhuang	534	8.0
Shanglingzi	315	8.3
Wanjia Matou	235	8.8
Pan zhuang	610	6.9
Zhouliangzhuang	180	5.5
Qiaogu	90	5.5
Kancaizhuang	20	5.5
Wangqingtuo	114	5.0
Shajingzi	190	4.5
Tangguantun	40	7.6

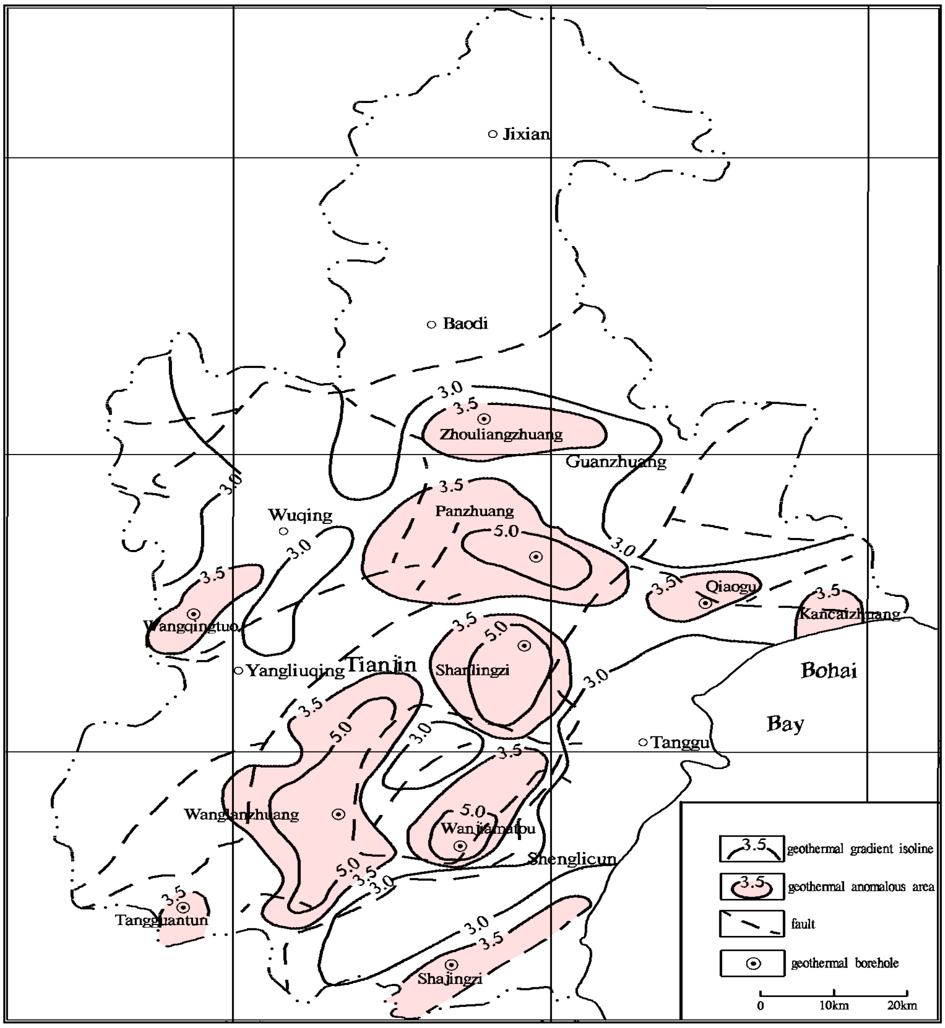

FIGURE 3: The location of geothermal anomaly areas in Tianjin

2.4 Characteristics of geothermal fields

Since the Holocene epoch, the regional sea level has ascended. Several times transgressions have supplied salty materials to the wedge-shaped water mass, which is shallow in the west and deeper in the east in the Quaternary aquifers. The increasing regional erosion has hindered the horizontal movement of geothermal water. The upward heat flow is obstructed by large, thick Quaternary stratum and water masses, and the sealing-off causes further heating of the geothermal water. Although the sealed water generally moves slowly, its velocity is considerable in decompression zones.

The geothermal water is mainly located in the Cangxian uplift range. It consists of “fractured karst geothermal water in bedrock”, accumulated in the medium Proterozoic Jixiannian Wumishan (Pt2W), lower Palaeozoic Cambrian (PzH) and Ordovician (PzO) reservoirs; and “porous geothermal water in clastic rock” that exists in Tertiary and Quaternary strata. Cold underground water deposits are located in fissures of the basement in front of the Yanshan Mountain and a shallow porous/fracture aquifer (500-800m depth) is located in the Tertiary and Quaternary strata. The isotope compositions show that the geothermal water is precipitation seepage that originate from the latest glacial period of upper Pleistocene (10000-21000B.P.) (Wang Kun, 2001), and has been sealed off since Holocene. It is a closed deep circulating system.

The geothermal water in fractures in the bedrock has a ^{14}C value (15-4.5 pmc), it is higher than that for water in the pores (7.6-4.5 pmc), and thus the geothermal water in the fractures is younger than the water in pores. After the long geological denudation period, the bedrock has a broad rim affected by weathering and well-developed fractures and dissolved cavities. Meanwhile there is a large outcrop area in the north and west mountains, which means that this is a semi-closed reservoir. On the other hand, the reservoirs in the Tertiary and Quaternary system are closed. Hereby, the deep circular geothermal system can be divided into (Wang Kun, 2001):

(1) Semi-open and semi-closed bedrock subsystems where the karst geothermal water is present;
(2) A closed clastic rock subsystem where geothermal water is present in pores.

Table 3 lists the hydro-geological characteristics of the main geothermal reservoirs in Tianjin (Song D. et al., 2007).

TABLE 3: The Hydro-geological characteristics of main geothermal reservoirs in Tianjin

Reservoir	Distibution	Depth (m)	Lithology	Flowrate (m^3/h)	Temp. (°C)	Hydro-chemistry	TDS (mg/L)
Nm group in late Tertiary	Widely spread in Southern plain	500-1200	Sandstone, silty sandstone	40-60	40-60	HCO_3-Na HCO_3·Cl-Na HCO_3·Cl·SO_4-Na	850-1800
Ng group in late Tertiary	Tanggu,Dagang, Wuqing District	1200-2400	Sanstone with gravel	80-120	65-87	Wuqing: CO_3-Na	1000-1400
						Tanggu:Cl·HCO_3-Na	1500-1800
						Dagang: Cl-Na	1500-2000
Ordovician	Urban area and the surrounding Disricts	950-1900	limestone	> 100	55-76	SO_4·Cl-Na·Ca	4000-6000
Cambrian	Local part	1300-1800	limestone	> 100	68-95	Cl·HCO_3-Na Cl·SO_4-Na	1700-1800
Jixianian in Middle Proterozoic	Widely spread on Cangxian Upfold	910-3190	Sandstone dolomite	> 100	74-103	North: HCO_3·SO_4-Na South: Cl·SO_4-Na	1000-2100

The Jixianian reservoir of the Middle Proterozoic is widespread in Tianjin. The depth to its upper boundary is 988-3000m. Over a 3-5 km width along the Baitangkou fault, the porosity reaches 5-7%. The flow rate is 100-200 m^3/h, and near the fracture it reaches almost 380m^3/h. The upper boundary of the reservoir is at progressively greater depths towards the west. The karst fracture is well developed in this reservoir and has formed strong storage abilities. It is the main productive reservoir in Tianjin. Along the Baitangkou faults, there is a water-abundant zone with a unit flow rate of 6-12m^3/h/m.

3. HISTORY OF GEOTHERMAL UTILIZATION IN TIANJIN

The earliest record of geothermal utilization comes from *The General Chronicle of District around Beijing*, which was published during the Qing Dynasty. Geologist Prof. Zhang Hongzhao refers to it in *The Summary of the Hot Springs in China* in 2006. It describes a hot spring that is located at the Jitou Mountain in Ji County, and people bathing in it to cure illnesses.

In early 1936, the first geothermal well was drilled in the centre of the urban area (Figure 4). It was drilled by the Beijing Museum (Tianjin Nature Museum at present), which was founded by the French naturalist Dr. E.·Licent (chinese name is Sang Zhihua), The well is located in the centre of the urban area, with a depth of 861m and an artesian discharge of 23 m^3/h. The wellhead temperature was 36°C. This well was pumped until the 1980s and was plugged in 1994.


FIGURE 4: Pumping test in situ of first geothermal well in 1936

From the 1950s till the end of the 1960s, some enterprises attempted to use geothermal resources on a small scale, such as for space heating, agriculture, textile mills and potable water.

Geothermal exploration started in the 1970s, at the proposal of Mr. Li Siguang, the former Minister of Geological and Mineral Resources. Through the geological survey of gravity, temperature and drilling, two geothermal anomalous areas were discovered in the urban area surrounding districts with an area larger than 1,000 km^{-2}. The geological institutions carried out a series of exploration and research on geothermal resources in the 1980s, with the financial support of the former Ministry of Geology and Mineral Resources and the United Nations Development Program (UNDP).

By the end of the 1980s, the geothermal resources were being used for space heating, greenhouses, hot springs, therapy and potable water in Tianjin. But the early geothermal utilization was simple and crude. The geothermal water was pumped directly into heating systems without heat exchangers. The heavy corrosion of pipelines and high temperature of waste water caused low heat efficiency and heat pollution.

Through the popularization of heat exchangers, frequency conversion, floor heating and automatic controlling techniques; and especially the success of reinjection tests in 1990s, the geothermal resources have been widely used in many cities for economic planning. Along with the rapid growth of the real estate market, demands for geothermal energy have increased enormously. Figure 5 shows

the fast increase in the number of geothermal wells and total area of space heating (Wang K., Han J., 2007).

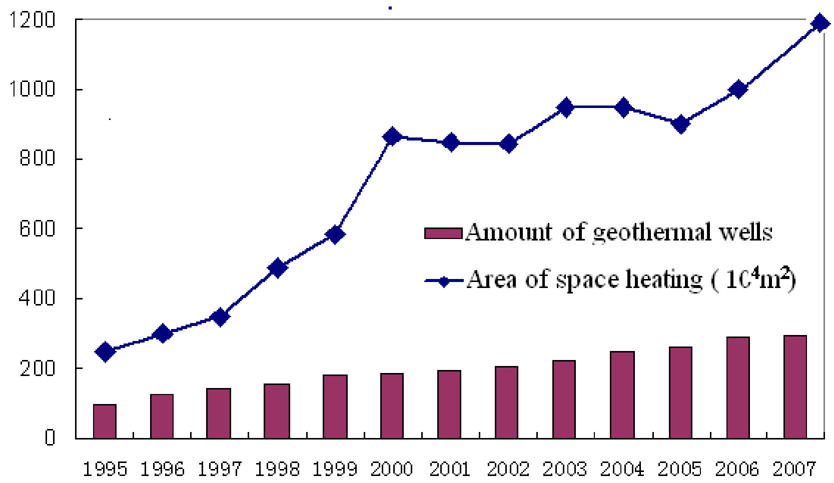

FIGURE 5: The number of geothermal wells and area of space heating in Tianjin

4. STATUS OF GEOTHERMAL UTILIZATION IN TIANJIN

4.1 Geothermal utilization in 2007

Compared with fossil fuels, geothermal energy has the benefits of lower running cost and it is environmentally friendly. By the end of 2007, there were 256 production wells and 38 reinjection wells in production in Tianjin (Zeng M. et al., 2007). The total production rate was 24,500,000m^3 with a reinjection rate of 4,620,000 m^3.

In 2007, the space heating areas covered 12Mm^2, or about 8% of the total heating area in winter (Figure 6). About 114 geothermal wells are used for space heating, mainly supplying to the urban area, Tanggu and Wuqing Districts etc. Every year, about 100,000 families and 850,000 people enjoy the luxury of tap water, geothermal swimming pools and physical therapy from geothermal resources.

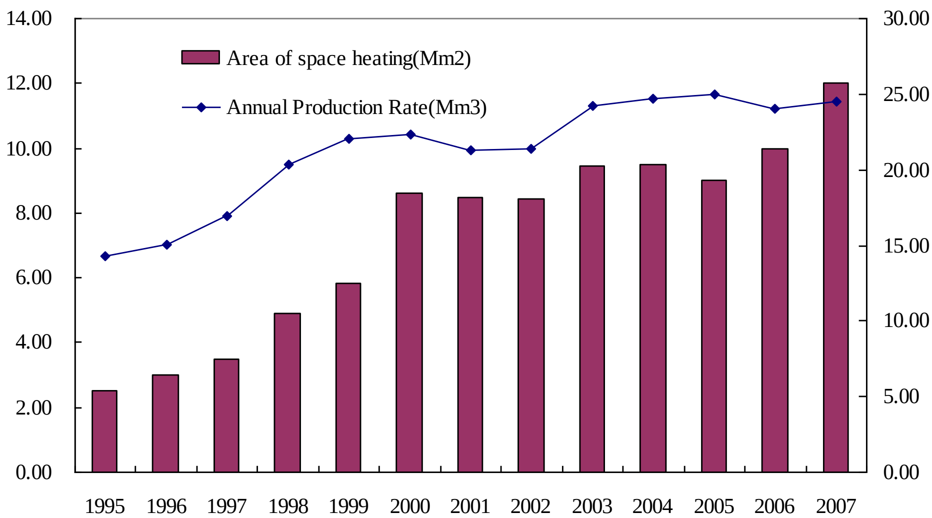

FIGURE 6: The growth of geothermal production rate and space heating area 1995-2007

Geothermal energy is used for space heating of residential and public buildings in Tianjin. It not only saves on investment and running cost, but also brings on evident environmental benefits. According

to incomplete statistics, the extent of geothermal space heating corresponds to replacing 215,600 tons of standard coal, reducing the discharge of coal dust by 1552 tons, sulphur dioxide by 6653 tons nitrogen dioxide by 1996.3 tons and carbon monoxide by 171,400 m^3.

4.2 Contribution of geothermal resources to local economic cooperation and development

China has a rich traditional hot spring culture, which makes geothermal resources one of the unique opportunities for recreational projects. In recent years, real estate and tourism have developed rapidly in Tianjin. The exploration and development of geothermal resources attract investment in hot spring vacation resort projects. Some large scale construction projects are under construction.

For example, the Zhouliangzhuang geothermal field is located in Baodi District, where there used to be deserted salty lands. There were only few farms and one village located there. As a result of the geothermal exploration, the first geothermal well was drilled in 2002 with a natural flow rate of 380m^3/h. The wellhead temperature is 103°C, and the artesian pressure is 4 Mpa. Now, a new town called Zhujiang Hot Spring Town has developed there. The total investment will be more than $140 millions. In 2007, the construction area reached 60 km^2 with a planned population of 200,000 inhabitants. The Hot Spring Town integrates the projects of villa construction, tourism, resorts, and convention and exhibition Centres. Two Universities have set up branches in the Town and started to recruit students in the summer of 2007.

FIGURE 7: Geothermal utilization in Tianjin

The governments of China and Singapore signed the agreement for the Sino-Singapore Eco-City project. The Sino-Singapore Eco City is located between the Tanggu and Hangu Districts of Tianjin's Binhai New Area. It is the second cooperation project after the Suzhou Industry Garden between

China and Singapore, occupying an area of 32 km^2. The construction will begin in July 2008 and will end in 2010. The maximum investment is estimated to be $4300 million. When completed, there will be 300,000 residents living and working in energy-efficient buildings in the Eco City. Besides preservation and restoration of natural ecology, green consumption and low carbon emissions, it is social cohesion that tops the list of features for the eco-city. The geothermal exploration and utilization have been planned.

5. CONCLUSIONS

The exploration and development of geothermal resources have played an important role in many aspects of Tianjin's economical development, such as attracting investment, improving environmental quality and standard of living, expanding tourism and developing industrial and agricultural production. Geothermal utilization brings about remarkable economic, social and environmental benefits,

The Tianjin Municipality puts great emphasis on geothermal resource management. The Geothermal Resources Development and Utilization Plan for Tianjin (2006-2010) were published in 2005. To meet the rapid increase in demand for geothermal resources, it is necessary to enhance the geothermal exploitation and strengthen the research on reinjection into the Tertiary system and the basement reservoir.

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GEOTHERMAL TRAINING PROGRAMME
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LECTURE 3

MANAGEMENT OF GEOTHERMAL RESOURCES IN TIANJIN

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ABSTRACT

The geothermal resources in Tianjin are classified as low-medium geothermal resources in sedimentary basins. As an environmentally benign energy resource, geothermal is widely used for space heating, potable water, agriculture etc. This paper gives a brief introduction to the laws, policies and processes concerning geothermal resources, exploration and development in Tianjin. The main contents of the Plan for Geothermal Development and Utilization in Tianjin are reviewed from a sustainable point of view. Policies encouraging the application of reinjection and integrated technologies are amply discussed and exemplified here.

1. INTRODUCTION

1.1 The laws and technical standards in China related to mineral and geothermal resources

The main laws and statutes related to the exploration, development and reinjection of mineral resources and geothermal resources are listed here.

1. Mineral Resources Law of The People’s Republic of China (Order No. 74 of the President of People's Republic of China)
2. Rules of Implementation of the Mineral Resources Law (Decree No.152 of State Council of People's Republic of China)
3. Regulation For Registering To Explore For Mineral Resources Using The Block System (Decree No.240 of State Council of People's Republic of China);
4. Regulations For Registering To Mine Mineral Resources (Decree No.241 of State Council of People's Republic of China)
5. Regulations For Transferring Exploration Rights and Mining Rights (Decree No.242 of State Council of People's Republic of China)
6. Regulations For Geological Data Management (Decree No.349 of State Council of People's Republic of China)
7. Provision For Collection and Management of Mineral Resources Compensation (Decree No.150,222 of State Council of People's Republic of China);
8. Others promulgated by related department.

The main technical standards and criterions are:

1. Standard for Drinking and Tap Water Quality (GB5749-2001);
2. Standard for Irrigation Farming Water Quality (GB5084-92);
3. Standard for Groundwater Quality (GB/T14848-93);
4. Standard for the Classification of Groundwater Resources (GB15218-94);
5. Demands For Modelling of Groundwater Resources Management (GB/T14497-93);
6. Geological Exploration Standard for Geothermal Resources (GB11615-89);
7. Appraisal Measures for Geothermal Resources (DZ40-85)
8. Others

1.2 Main contents

It is prescribed in the Mineral Resources Law of the People's Republic of China that:

1. Mineral resources shall be owned by the State. The State's ownership of mineral resources shall be exercised by the State Council.
2. Anyone who wishes to explore or mine mineral resources shall apply for and obtain upon approval, in accordance with law, the respective exploration and mining rights, and shall carry out the registration procedures.
3. The department in charge of geology and mineral resources under the State Council shall be responsible for supervising and administering the exploration and mining of mineral resources throughout the country. The department in charge of geology and mineral resources under the people's governments of the provinces, autonomous regions and municipalities directly under the central government shall be in charge of supervising and administering the exploration and mining of mineral resources within their respective administrative areas.
4. The State shall adopt the system so that exploration and mining rights are to be obtained with compensation.
5. Anyone who mines mineral resources must pay resource tax and mineral resource compensation of relevant provision of the State.

All the above prescriptions can be summarized as following: Firstly, mineral resources are owned by the State; secondly, the State implements the rights of the ownership, the utilization and the management of mineral resources, through the system of registration for mineral exploration, for examining and approving mineral mining, for obtaining exploration and mining rights with compensation. Thirdly, the State Council has licensed the practice of unified management of mineral resources, assigned to the whole country, to the department in charge of geology and mineral resources under the State Council (Tao Q., Hu J., 2007).

2. LAWS AND SYSTEM OF GEOTHERMAL MANAGEMENT IN TIANJIN

2.1 Provision of geothermal management in Tianjin

In order to strengthen geothermal management Tianjin Municipality set up a special department of geothermal management in 1994. Based on state laws and technical standards, the Provision of Geothermal Resources Management in Tianjin was promulgated in 1995; the Regulation of Mineral Resources in Tianjin was enacted in 2001.

With regard to the exploration and development of mineral resources, the department of geothermal resource management shall practise the policy of unified planning, rational distribution, exploration, rational mining and cascaded utilization. According to state and local laws and regulations a series of effective process have been established, including: permissions for exploring and mining geothermal resources, for examination and approval of the development plan and utilization proposal for geothermal resources, for supervision of the drilling of geothermal wells, for production evaluation of single geothermal wells, for annual investigation of issues regarding rational development and utilization of geothermal resources, for environmental protection and other obligations in accordance with the law, etc.

2.1.1 Registering to explore geothermal resources

Prior to exploration for mineral resources or drilling of geothermal wells, each exploration or drilling project shall be examined, approved, registered, and licensed by the department in charge of geology and mineral resources under the people's government of the Tianjin Municipality. It includes the following proceedings:

1. Application for exploration rights
2. Exploration-rights applicant shall pay a fee for the use of the exploration rights (hereafter referred to as the exploration fee) and a reimbursement fee for exploration rights.
3. Determination of the mineral resource areas for exploration with Block Registration System;
4. Period of validity for an exploration license is no more than 3 years
5. Obligations that exploration licensees should perform.

2.1.2 Registering to mine geothermal resources

Similar to geothermal resource exploration, mining projects shall be examined, approved, registered, and licensed by the department in charge of geology and mineral resources under the people's government of the Tianjin Municipality. It includes the following proceedings:

1. Application for mining rights;
2. Mining-rights applicant shall pay a mining fee and a reimbursement fee for mining rights;
3. Payment for geothermal resource compensation;
4. The length of time for a valid mining license shall be decided in accordance with the magnitude of the mining project, but shall be less than 30 years;
5. Obligations that mining concessioners should perform.

2.2 System of supervision and examination of geothermal production

The administrative department in charge of geology and mineral resources supervises and examines the geothermal production. The approving authority shall examine its application as to the limits of its mining area, the mining design or plan for mining, the production technique and safety and the environmental protection measures, in accordance with the law and relevant state provisions. The geothermal mining concessioners should adopt rational and scientific drilling techniques and rational production planning, to prevent overproduction and environmental pollution. For this purpose, the water level, temperature, flow rate and quality of geothermal wells should be monitored.

3. PLAN FOR GEOTHERMAL DEVELOPMENT AND UTILIZATION IN TIANJIN

With the increased geothermal development and utilization, the sustainable potential and economy of geothermal resources is emphasized in geothermal management. A Plan of Geothermal Development and Utilization for 2006—2010 has been compiled and authorized by the Tianjin Municipality (Song D., Wang K., Xu P. et al., 2006).

3.1 Regional division methods

Each reservoir is divided into three planning sub-areas, depending on its recoverable reserves and monitoring data (water level, pressure etc.) for the past year. The three sub-areas are: restricted productive zoning, permissible productive zoning, and geological survey zoning.

The restricted productive zoning is usually the geothermal field which has been producing for a long time and the annual production rate has approached increased the allowed recoverable reserves of the geothermal filed, and water level drawdown increases rapidly. In the allowable productive zoning, the annual production rate is less than the allowed recoverable reserves of the geothermal filed, the water level drawdown is less intense, and the resource potential is still considerable. The geological survey zoning means that little geological exploratory work has been carried out in the geothermal field.

3.2 Factors of planning

Several factors are involved in the Plan for Geothermal Development and Utilization for 2006-2010.

1. Through the application of heat pumps or other technology for saving energy, the temperature of waste water should be lowered to below 25°C for most geothermal utilities.
2. The annual reinjection rate will reach 6,000,000m^3, which account for 30% of the total production.
3. Some older geothermal utilities with low efficiency should be rebuilt, especially in zones of relatively poor production
4. Automatic metering and monitoring systems shall be set up by the end of 2010.
5. The government shall encourage scientific and technological research on the exploration and development of mineral resources, promote advanced technology and raise the scientific and technological level of geothermal exploration and development.

4. INCENTIVE POLICIES OF GEOTHERMAL REINJECTION AND CASCADED USE

Reinjection studies were started in Tianjin in the 1980s. After a series of tests, reinjection into the basement reservoir is now approved and considered a feasible way to maintain the reservoir’s pressure and prevent heat and chemical pollution by waste water.

In 1996, the administrative department revised the permit process for mining of geothermal resources. Space heating projects shall now involve reinjection when mining enterprises develop geothermal energy in a basement reservoir. Furthermore, the government took some measures to promote the drilling of reinjection wells and rebuilding old geothermal utilities. Initially, a 70% mineral resource compensation of the reinjection rate is exempt, if a doublet system is used. The mining concessioners can also apply for protection projects to get governmental subsidy (Wang K., Han J., 2007).

Now, there are about 38 doublet reinjection and production systems in Tianjin. The annual reinjection rate reaches 4.6Mm^3. Reinjection has become an important factor in geothermal management to ensure sustainable geothermal development.

5. ANALYSIS EXAMPLE

5.1 Demonstration projects on geothermal reinjection and cascaded utilization

The realty project of Haihe New World is located in the centre of the Urban area in Tianjin. The building area is 235,000m^2. The geothermal energy is used for space heating and tap water for more than 1600 families in this residential area. There are three geothermal wells. Two of them (WR93D, WR94D) are a reinjection and a production doublet systems respectively. Both are drilled into the dolomite carbonatite reservoir in Proterozoic strata. The third one (WR92) is in an Ordovician reservoir. The hydrological characteristics of three geothermal wells are listed in Table 1.

TABLE1: The Characteristics of geothermal wells in the Geothermal Utility Haihe New World.

Geothermal Well	Depth (m)	Wellhead Temp. (°C)	Flowrate (m^3/h)	TDS (mg/L)	Type
WR92	1388.6	48.5	43.92	>4000	Production
WR93D	3248.89	81.5	84.02	1830	Production
WR94D	3168	82	106.48	1830	Reinjection

All buildings in the residential area are heated by floor heating during winter. After the heat exchange, the waste geothermal water is reinjected. Geothermal water takes a 4,650 kW basic heat load, and the residual peak load of 5,600 kW is supplied by heat pumps during the coldest period. The heat supplied by the Ordovician geothermal well is used for tap water. Figures 1 and 2 show the geothermal utility and its technical flow-chart.

FIGURE 1: The geothermal utility of the Haihe New World Residential Area

The initial investment in this geothermal station is about $1,350,000. The annual overall operational cost for space heating is about $540,000, which is equal to $2.3 per unit area of space heating. Compared with space heating by coal-fire boilers, the initial investment in a geothermal utility is over $280,000 in excess, but its running costs saves about $130,000 every year. Meanwhile, the geothermal use can reduce the discharge of sulphur dioxide, nitrogen oxide, carbon dioxide and coal dust.

As one of the projects for mineral resource protection, the Haihe New World geothermal projects got the financial support of $340,000 from the Ministry of Finance in 2007 (Wang K., Han J., 2007).

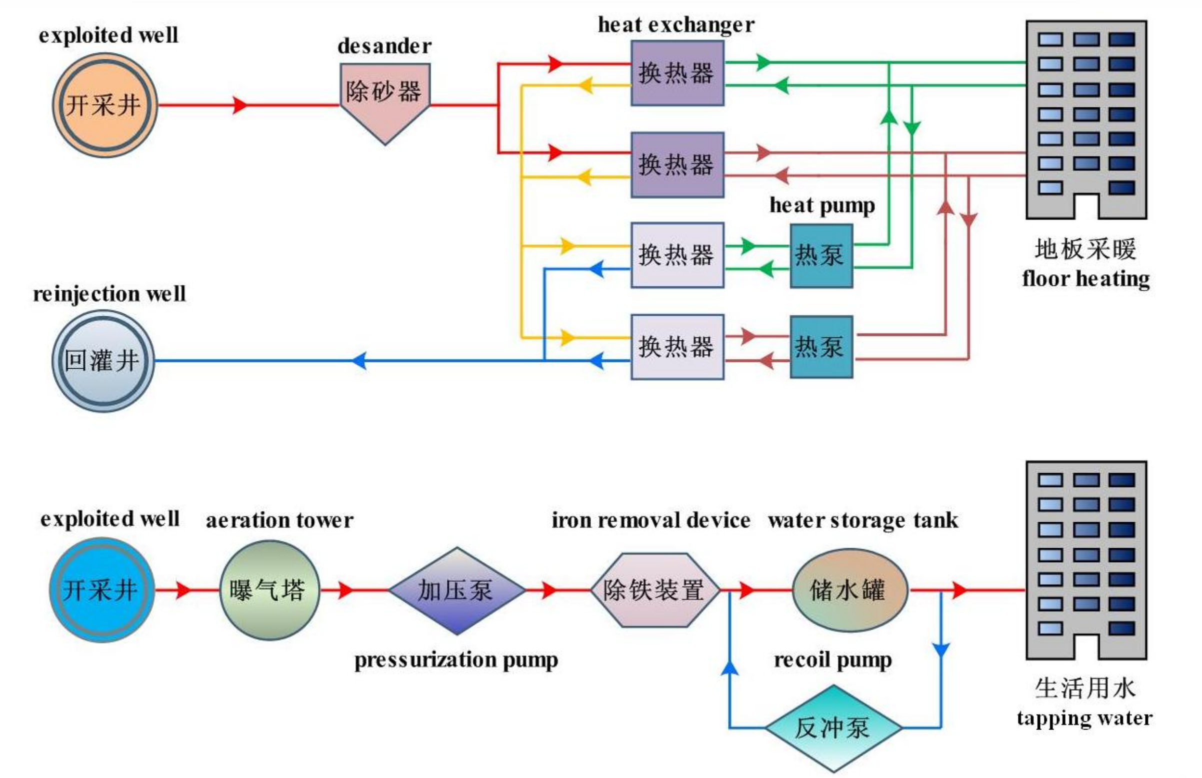

FIGURE 2: Flow-chart for the space heating system Haihe New World Residential Area

5.2 Discussion

Since 1996, all geothermal production from the basement reservoir is balanced by reinjection, employing a doublet well system. Many singlet production wells drilled before 1996 are, however, still used for production. The geothermal waste water is discharged into the sewage system directly after heat exchange. The large scale production has already resulted in a rapid drawdown of the water level. It is necessary and urgent to construct additional reinjection wells for the early singlet production wells in order to prolong the lifetime of these geothermal reservoirs.

However, the drilling of additional reinjection wells has been hampered by lack of funds and space. The facilities and technology employed in the early geothermal utility are simple and crude, and the construction cost of additional reinjection wells is high. Meanwhile, most production wells drilled before 1996 are located in the Urban area and in many cases there is not enough space to drill a reinjection wells. Therefore, the administrative departments in charge of geothermal resources and space heating have put forward a plan for recombining early production wells into doublet systems of reinjection and production wells in 2006. This proved successful in the Urban area. Through adjusting the heating system, 3 adjacent production wells located in three different residential areas were combined. One is selected as a reinjection well; the others are production wells and supply the space heating for three residential areas.

6. CONCLUSIONS

The policies and regulations are effective measures to promote exploration, development, utilization and protection of geothermal resources and to ensure the present and long-term requirements of city construction in Tianjin. Some related policies of geothermal management will be implemented in the future.

Since 2006, a unified system in which the geothermal mining-rights shall be paid for by the mining concessioner with a geothermal mining fee has been in operation. The mining fee shall be collected according to the standard of $1,000RMB per geothermal well per year. Anyone who applies for geothermal mining-rights to mineral deposits already discovered by the State, at the State's expense, shall pay, in addition to the mining fee, a reimbursement fee for mining rights which have been appraised and confirmed. The detailed specifications for managing the use of the funds mentioned above will be formulated in the near future by the department in charge of geothermal resources jointly with the department in charge of finance under the City Municipality.

Monitoring is the basic work for exploration, potential evaluation, development and management of geothermal fields. The automatic metering and monitoring will be in fully operational by the end of 2010. The monitoring and research on reinjection should be strengthened in the future.

Reinjection should be an essential part of sustainable geothermal utilization. But reinjection into the sandstone reservoir of the Tertiary system is still a great technical problem in Tianjin. Jointly with the department in charge of finance and space heating, some policies will be established for encouraging the combination and optimization of early geothermal utilization systems. Therefore, the development of geothermal resources will be continued.

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LECTURE 4

MONITORING AND RESOURCES EVALUATION OF THE GEOTHERMAL FIELDS IN TIANJIN

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ABSTRACT

Geothermal monitoring was initialized in the 1980s, in order to better develop and utilize the geothermal fields. After more than 20 years of continuous improvement the geothermal dynamic monitoring system has been set up in Tianjin. Meanwhile, the technical criterion for monitoring of low-medium geothermal field in Tianjin was compiled in 2006. The intelligent management Net PC system was installed to solve the difficulties in estimating collective costs and monitoring administration, research and development. The system can carry out real-time monitoring for all stages of development, raising the level of geothermal administration to a new level. It is very helpful for scientific planning and management of geothermal development and utilization in Tianjin. Based on the continuous geothermal monitoring, a new evaluation of geothermal resources in the plain area of Tianjin had been carried out from 2005 to 2007. The optimized plans are put forward for future geothermal development.

1. INTRODUCTION

Geothermal monitoring was initialized in the 1980s, in order to better develop and utilize the geothermal fields. After more than 20 years of continuous improvement, the geothermal dynamic monitoring system has been set up in Tianjin. Meanwhile, the technical criterion for monitoring of low-medium geothermal fields in Tianjin was compiled in 2006. The analyses and research of large dynamic pressures, temperatures and flow rates of the geothermal wells, are useful for scientific planning and management of the geothermal development and utilization in Tianjin.

In 1995, the administrative geothermal resources department began to finance geothermal monitoring in Tianjin. The geothermal wells were fewer than 50 in 1996, but in 2007 there were 291 wells (Song D., Wang K., Xu P. et al., 2007). Additionally, monitored area was gradually enlarged from the urban area to the whole jurisdiction of Tianjin. In the meantime, the monitoring methods and equipment have constantly been improved; from manual work in the beginning, till the current automatic metering of the production and reinjection rates in most geothermal wells. Remote automatic monitoring of water level, pressure, temperature, and flow rate has been carried out in some geothermal wells. The geothermal monitoring has become an important part for the geothermal utilization and research.

2. BASIC MONITORING CONTENTS

The geothermal observation net covers 15 districts and 2 counties in Tianjin.

2.1 Main contents

The main functions of geothermal monitoring include:

(1) Investigation of production status of every geothermal station, such as heating area or number of families using geothermal water; and condition of monitoring facilities, such as thermometers and pressure gauges of geothermal wells.
(2) Monthly collection of data on water level, temperature, and flow rate of production and reinjection wells.
(3) Chemical analysis, where water samples are taken from control wells during winter. The samples are representative of the main geothermal field, ranging from Tertiary to Proterozoic.
(4) Analyzing the technical problem of production and reinjection doublet system during the space heating period, and note taking on possible technical faults, such as the decline in reinjection rate, corrosion etc.
(5) Maintaining and updating the monitoring facilities.
(6) Predicting the development potential of the geothermal production and reinjection by modelling.

2.2 Technical criterion

(1) Geological exploration standards of geothermal resources (GB11615-89).
(2) Appraising measures of geothermal resources (DZ40-85).
(3) Technical standards of dynamic monitoring of low-medium geothermal resources in Tianjin (2005).

3. GENERAL STATUS OF GEOTHERMAL MONITORING IN TIANJIN

The administrative geothermal resources department finances the geothermal monitoring, according to the provisions of the management and the use of mineral resources. Fieldwork, such as; monitoring, investigation, maintenance and update of monitoring facilities, geophysical logging and geochemical sampling is based on the status of geothermal utilization and monitoring data from the previous year. After analyzing the water quality and interpreting the temperature and pressure logs, the annual report of geothermal monitoring is compiled. In 2007, 291 geothermal wells were monitored (Figure 1). Table 1 shows the detailed information about the monitoring of geothermal fields in 2007 (Zeng M. Ruan C. et al., 2007).

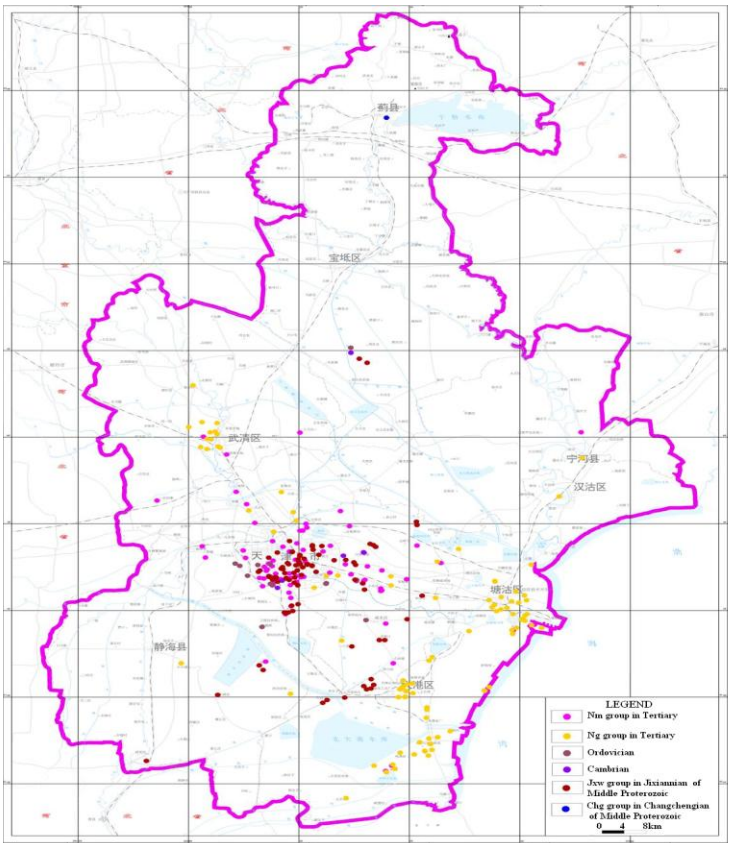

FIGURE 1: Location of geothermal wells in Tianjin

TABLE 1: Schedule of Geothermal Monitoring in 2007

Item	Contents			Unit	Workload
Fieldwork	Dynamic monitoring	Key wells	Water level, pressure, temperature, flow rate	wells × times	127×24
		Normal wells	Water level, pressure, temperature, flow rate	wells × times	164×12
	Investigation	Production / reinjection rate		wells	291
		Status of geothermal utilization		wells	291
		Monitoring facilities of geothermal wells		wells	291
		synchronous monitoring		wells × times	291×2
	Maintenance of monitoring facilities			wells	12
	Geochemistry	Amount of wells		wells	99
		Amount of wells		wells	11
	Geophysics logging	Temperature		wells	1
		Pressure		wells	1
Research work	Chemical analysis of geothermal fluid's quality			wells	99
	Logging Interpretation of geothermal wells			wells	1
	Monthly report and database			month	12
	Summarize of the synchronous monitoring			times	2
	Figures			figure	85
	Tables and graphs			sheet	45
	Annual report and information system			report	1

3.1 Routine monitoring work of geothermal wells

(1) Topographic measurements: Measuring the altitude of the base point of geothermal well is necessary to adjust the effects of ground elevation changes on the water level in geothermal wells.
(2) Static and dynamic water level measurements and measurements of corresponding temperatures in production and reinjection wells, instantaneous production and reinjection rate, and measurements of stable temperature when the well is pumping or during reinjection.
(3) Investigation of the geothermal utilization, such as utilization type and amount of usage, and temperature of feed water and waste water.
(4) Monthly and annual statistics of production rate and reinjection rate, in order to collect mineral resources compensation.
(5) Maintenance of the monitoring facilities, including: special tubes for water level measurements, precision of water level meters, flow rate meters, manometers, and thermometers.
(6) Identical monitoring in the beginning and at the end of the space heating period.

3.2 Terms of experiment analysis at lab

During the space heating period, in the winter, geochemical samples are taken from representative geothermal wells, in order to analyse the long-term changes in geothermal water quality. The analysis includes hydro-chemical analysis of sulphur, iron and isotope.

The layout of sampling points is decided by regional hydro-geological conditions, the reservoir, the recharge, the pathway of the geothermal flow, and the type of the utilization. The continuity of the data should also be regarded. The geochemistry analysis of geothermal fluid will be used for identifying the distributive characteristics, analyzing the origin and the recharge of the geothermal fluids.

3.3 Pressure and temperature logging in geothermal wells

Pressure and temperature logs from the geothermal wells, from several years of production or reinjection can not only provide information on the exact pressure and temperature conditions of the geothermal reservoir, but also the effects of the reinjection fluid upon the geothermal reservoir (Figure 2 and 3).

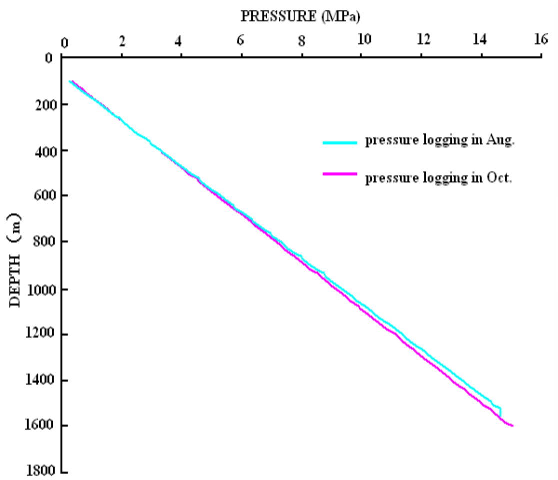

FIGURE 2: Pressure logging curves of reinjection well HX-25

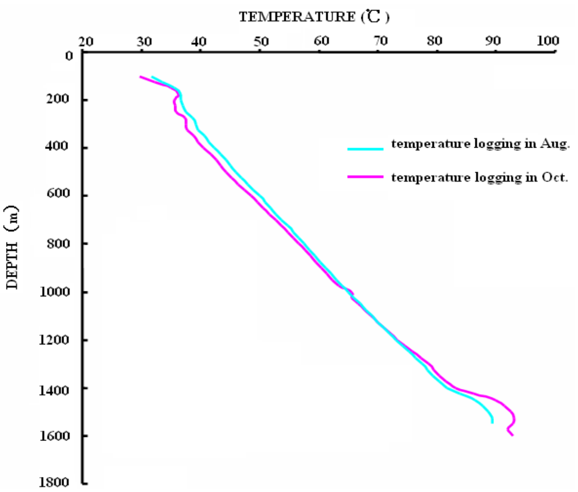

FIGURE 3: Temperature logging curves of reinjection well HX-25

3.4 Layout of key monitoring net

Because there are already more than 300 geothermal wells in 15 districts and 2 counties, and the water levels in most geothermal wells are observed manually few representative geothermal wells are selected to make up a key monitoring network. In order to obtain the data systematically and to analyse the dynamic nature of the geothermal resources objectively, the layout of a key monitoring network is planned as follows:

(1) *District and reservoir*: the observation points are chosen from the productive centre of the geothermal fields according to the geological conditions of the geothermal field and the development of the reservoir. Then the dynamic changes of geothermal development of every district, geothermal field and reservoir can be effectively monitored.
(2) *Geological tectonics*: the key observation points are distributed along the main fracture zones or tectonic elements.
(3) *Continuity and integration of data*: it is better to use data from long-term production wells, to avoid the effects caused by production start-up. Furthermore, the data should be continuously updated and integrated.

Usually the technicians monitor normal points and key points twice a month. In 2007, there were 127 key observation points, about 44% of the total number of geothermal wells in the area. There are 43 key points located in urban areas; the rest is in rural areas.

3.5 General analysis and annual reports

3.5.1 Monthly reports and the database

All observation data is collected and added to a geothermal monitoring database. From the analysis, a monthly report is compiled about the capability and performance of each geothermal well. The geothermal mining enterprises have access to these reports.

3.5.2 Synchronous monitoring

Since 2004, identical monitoring has been carried out in April and October (at the end and beginning of the space heating period). The data of the water level (Figure 4) and condition of the

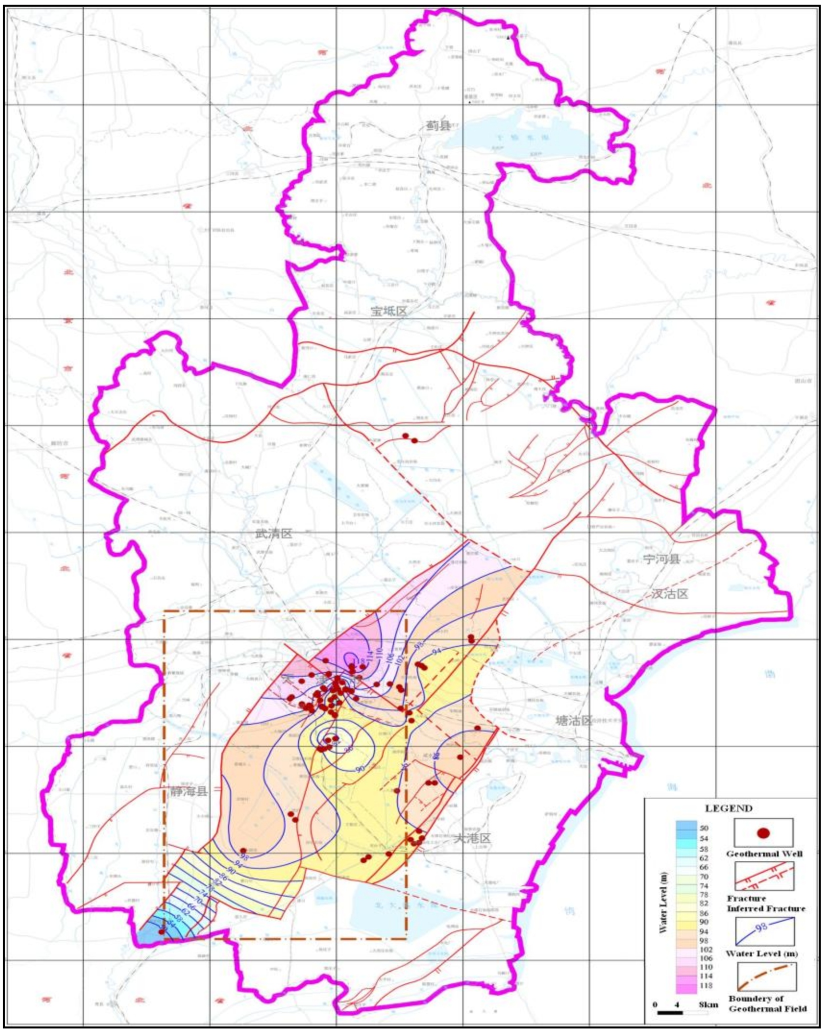

FIGURE 4: Contour of Water levels of Jxw reservoir in Proterozoic, 2007

monitoring facilities will immediately inform the geothermal mining enterprises of failure, so that they can examine and repair the equipment and, if necessary, install a submersible pump at a suitable depth.

3.5.3 Annual report

Mathematic modelling is an important tool to study the changes in geothermal reservoirs. Based on fieldwork, lab analysis and geophysical logging, combined with the historical changes of the geothermal reservoir, evolution in pressure, temperature and chemistry can be simulated and predicted by numeric modelling, presented in an annual report. Every short-term development potential of geothermal reservoirs has been predicted (Figure 5). Suggestions on geothermal development and management are put forward in the annual report.

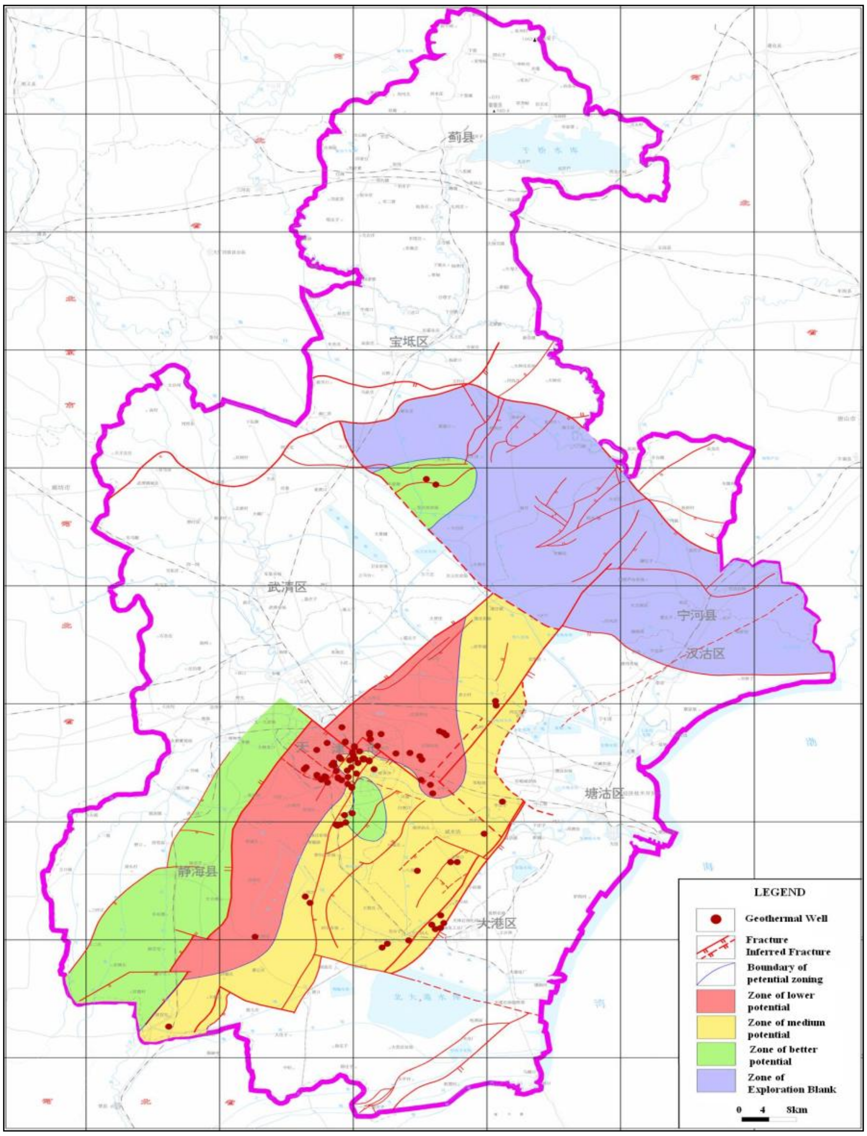

FIGURE 5: Zoning of development potential of Jxw reservoir in Proterozoic

4. AUTOMATIC METERING SYSTEM OF GEOTHERMAL WELLS

4.1 The components of the geothermal intelligent management system

4.1.1 Management information system

The Management information system (MIS) is based on management science, information science, computer science, statistics and operations. MIS can be used for collecting, transferring, storing, processing, and utilizing information. It is not only a technical system, but also a management system and it efficiently stores, processes and manages information (Guo C., Wang Q., Xu Y., 2001).

4.1.2 Geographical Information System

The Geographical Information System (GIS) is based on a geographical information databases. GISs collect, store, manage, operate, analyse, simulate and display space-related data, and through geographic analysis, providing dynamic geographical information that can be of great use for management. It gives comprehensive assessments, quantitative analyses on geothermal monitoring

(He M., Li C., Zhu J., et al, 2004). By using the functions of spatial data analysis, GIS create vector maps and find the direct relationship between map and data, i.e. GIS can create the map from the data and the data from the map. The system makes a detailed analysis of the information interprets the text data and maps it.

4.1.3 Intelligent information system

The Intelligent information system (IIS) is an application system where information technology and artificial intelligence technology are applied in specific fields. By using processing techniques and computer intelligence, IIS can solve process and logically analyse complex and large numbers of data. In the 1980s, operations research, with in-depth interdisciplinary research, was applied to management information systems as a new intelligent information discipline in the decision support system (DSS). Intelligent systems play an important role in realization of the intelligent judgment of the geothermal data. The systems send out warnings signals, when the geothermal station is improperly operated. This saves manpower and at the same time it limits the effect of human error.

4.1.4 Computer network

Network transmission is the media which transmit the collected information accurately and efficiently. Up to now, the most frequently used transmission system is the three-tier network composed by the network client, the server and the host. The outermost layer node of the typical three-tier network is a personal computer, which is connected to the local server. The computer stores data and manages external equipment used by the clients. As long as the manager has a computer, which has been connected to the three-tier system, (s)he will be able to retrieve the parameters from the local server and the host.

4.1.5 Wireless communications

The rapid evolution of communication technology is of great significant to the information system, especially the mobile communication (Wang H., 2007). Because of the built-in wireless computer modem, it is easier to connect computers to one another and thus to increase their capacity and adaptability.

4.2 Function of intelligent management system

The development of geothermal resources uses the monitoring capability of IMS, especially to monitor the production volume, production quality and the dynamic parameters. Its purpose is not only to collect the necessary dynamic data, but also to monitor the state of system operation and to manage the collected data. The management system server receives dynamic data from all remote data transmission terminals and organizes it. The software on the server analyses the data and assess the situation of the system operation.

Microsoft Access is used as a database platform and Visual Basic 6 as a development tool. In order to provide a humane management interface the geographical information system is included into the intelligent management system, so that all the property information of the geothermal sites can be closely linked to the spatial information, and visualization of the intelligent management system can be enhanced. The system includes historical data statistics, report creation, printing, trend forecasting, warnings and its disposal methods. The system can also be connected to any of the sites in order to monitor them.

To sum up, the upper-management system with powerful management functions and control methods has the function to support a variety of communication networks, communication methods and communication rules. Through monitoring all the geographical sites, the system can store information about the entire operation process. Therefore, in resource management, the factor of human error can be eliminated and it becomes a system with technical standardized management, as is shown in Figure 6.

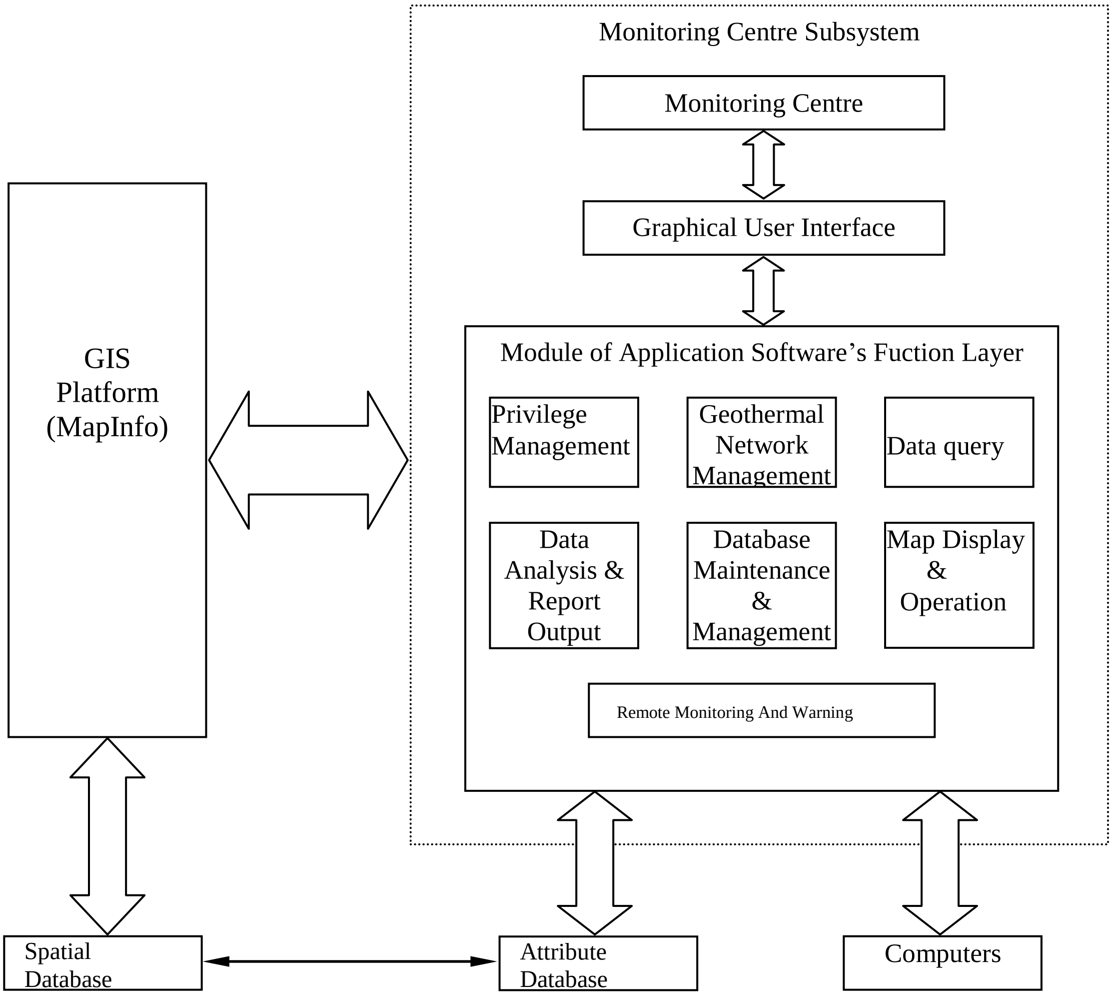

FIGURE 6: Configuration on the internet management systems

5. RESOURCES EVALUATION

5.1 The geological model of geothermal resources in the plain area

After more than 10 years of continuous geothermal monitoring, a new potential evaluation of the geothermal resources in Tianjin plain area has been carried out from 2005-2007(Figure 7).On the basis of the research on the geological conditions, the Earth's temperature field, the hydrodynamic field of geothermal fluids, geochemical analysis, geophysics exploration and well tests have been re-evaluated. The new geological model is set up for resources evaluation (Figure 8).

The Tianjin geothermal field is a typical sedimentary basin low-temperature system, common in eastern and north-eastern China. The main heat source is the superposition of convection heat flow from the upper mantle and radiogenic heat from the crust. The heat transfer is mainly by conduction but convection is effective locally due to the effect of different geological structures and lithologies.

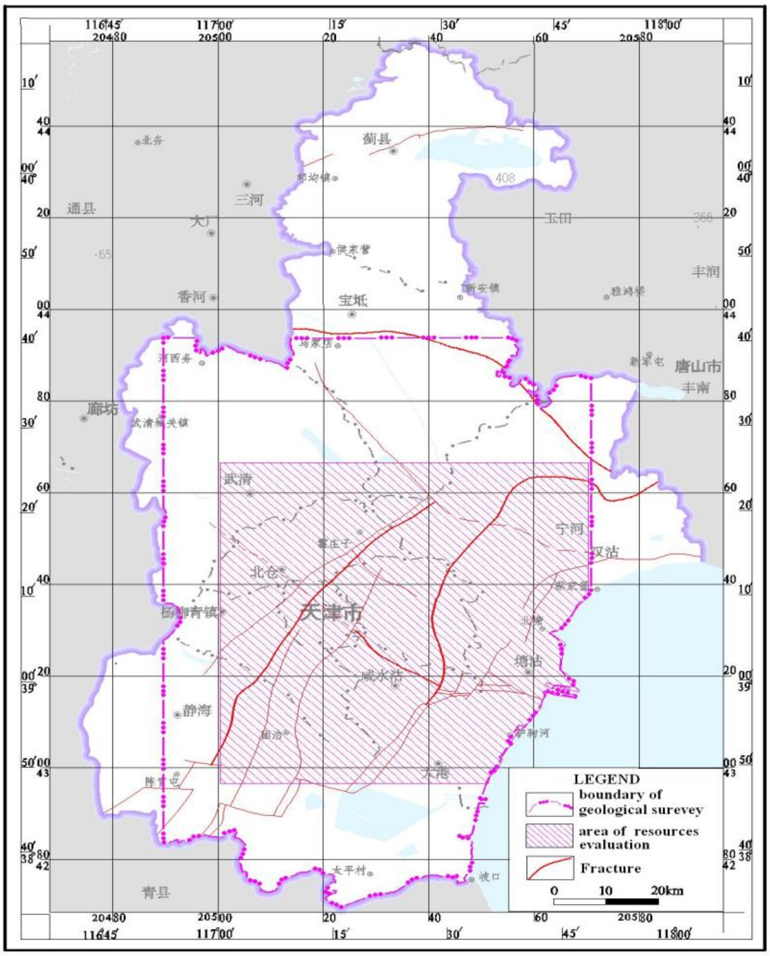

FIGURE 7: The working area of geothermal resources

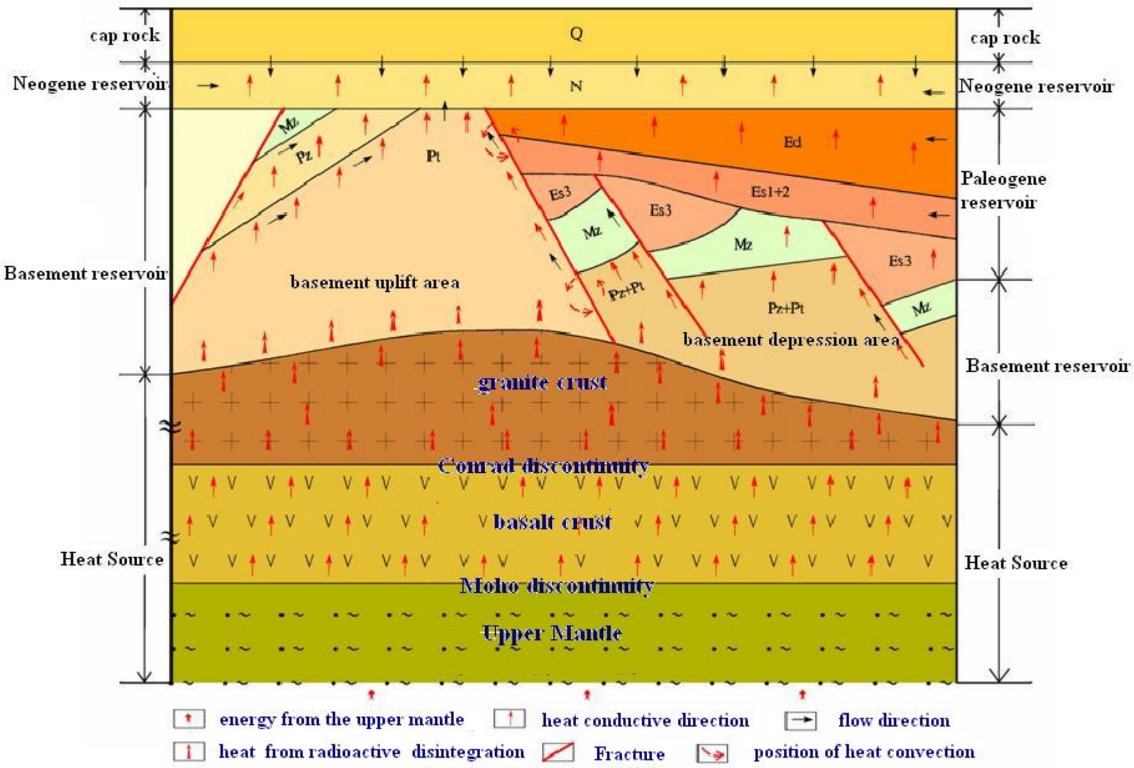

FIGURE 8: Geological geothermal model in Tianjin

Since the Holocene epoch, the regional sea level has ascended. Several transgressions supply the salty materials for the wedge-shaped salty water body, which is shallow in west and deeper in the east in the Quaternary aquifer. The rise of the regional base level of erosion hinders the horizontal movement of geothermal water. The upward heat flow is obstructed by a thick Quaternary stratum and the water mass. The sealing causes heating of the trapped geothermal water. Although the water moves slowly, the velocity is rather high in decompression zone (Wang K., 2005).

The geothermal water is mainly located in the range of the Cangxian uplift. The "geothermal karst fracture water in the bedrock", has accumulated in the medium Pro-terozoic Jixiannian Wumishan (Pt_2W), the lower Paleozoic Cambrian (PzH) and the Ordovician (PzO) reservoir; and the "gothermal pore water in clastic rock" exists in Tertiary and Quaternary formations. The cold underground water is deposited in the fissures of the basement in front of the Yanshan Mountain, and the shallow porous/fracture aquifer (500-800m depth) resides in Tertiary and Quaternary formations. From isotope analysis it is evident that the Tianjin geothermal water originates from ancient precipitation, with an age of 23 ~ 4 ka B.P. and has been sealed from Holocene to present. It is a closed deep circulation system.

The geothermal fracture water in the bedrock has ^{14}C value (15-4.5 pmc) larger than the value of pore water (7.6-4.5 pmc), indicating that the bedrock geothermal water is younger than pore water. After a long geological denudation period, the bedrock has a thick weathered surface and well-developed fractures and dissolved cavities. In the northern and western mountains there is a large outcrop area, and the reservoir is thus classified as a semi-closed reservoir. On the other hand, the reservoirs in Tertiary and Quaternary are closed systems. The deep circular geothermal system can be divided into (Wang K., 2001):

(1) semi-open and semi-closed bedrock subsystems, where the geothermal karst water exists;
(2) closed, clastic rock subsystem, where the geothermal pore water exists.

5.2 Potential Evaluation of geothermal resources in Tianjin

5.2.1 Neogene porous medium geothermal reservoir

The numerical modelling software Modflow is used to calculate the potential of the geothermal resources in Neogene porous medium reservoir. And its sub-program Interbed is used to calculate the sedimentation rate by coupling the hydrodynamic field of geothermal fluid.

It is assumed that the deepest water level will be shallower than -150m for the next 100 years of geothermal development in the Neogene reservoir, the total exploitable reserves in Neogene is 12.11×10^8 m^3, which is about 0.29% of the total reserve. The quantity of heat in the exploitable reserves is 11.12×10^{16} J, amounting to 3.08×10^{10}kWh, which is about 0.27% of the recoverable geothermal resources in Neogene.

In addition, the exploitable reserves of Minghuazhen Group in Neogene (Nm) are 6.8×10^8 m^3, which is about 0.23% of its totalreserves. The quantity of heat in the exploitable reserves is 4.93×10^{16} J with an average temperature of 41°C, amounting to 1.37×10^{10} kWh, which is about 0.17% of the recoverable geothermal resources in Nm.

And the exploitable reserves of Guantao Group in Neogene (Ng) are 5.31×10^8 m^3, which is about 0.43% of its totalreserves. The quantity of heat in exploitable reserves is 6.19×10^{16} J with an average temperature of 58°C, amounting to 1.71×10^{10} kWh, which is about 0.5% of the recoverable geothermal resources in Nm.

5.2.2 Basement carbonatite geothermal reservoir

The numerical modelling software AQUA3D is used to calculate the potential of the geothermal resources in the carbonatite reservoir, in the Ordovician and Wumishan Group of Jixianian in Proterozoic. The analytic model is used to calculate the potential of the geothermal resources in the Cambrian reservoir.

It is assumed that the deepest water level will be shallower than -200m in the nest 100 years of geothermal development in the basement reservoir. The total exploitable reserve in the basement is 15.63×10^8 m^3, which is about 0.69% of the total reserve. The quantity of heat in the exploitable reserves is 26.58×10^{16} J, amounting to 7.36×10^{10} kWh, which is about 1.61% of the recoverable geothermal resources in Neogene.

Hereinto, the exploitable reserves of geothermal fluid in Ordovician are 2.94×10^8 m^3, which is about 0.63% of its total reserves. The quantity of heat in the exploitable reserves is 5.13×10^{16} J with an average temperature of 80°C, amounting to 1.37×10^{10} kWh, which is about 0.69% of the recoverable geothermal resources in Ordovician.

And the exploitable reserves of geothermal fluid in Cambrian are 0.58×10^8 m^3, which is about 9.3% of its total reserves. The quantity of heat in the exploitable reserves is 0.93×10^{16} J with an average temperature of 81°C, amounting to 0.26×10^{10} kWh, which is about 9.3% of the recoverable geothermal resources in Cambrian.

The exploitable reserves of geothermal fluid in Wumishan Group of Jixianian in Proterozoic are 12.11×10^8 m^3, which is about 0.75% of its total reserves. The quantity of heat in exploitable reserves is 20.52×10^{16} J with an average temperature of 86°C, amounting to 5.68×10^{10} kWh, which is about 2.28% of the recoverable geothermal resources in it.

5.3 Optimizing plans for future geothermal development

5.3.1 Neogene porous medium geothermal reservoir

By estimating the geothermal utilization status, future plan, and geological condition, four kinds of schemes are designed to predict the water level changes in the future 10 and 30 years of geothermal production in the Nm and Ng groups in the Neogene reservoir (Hu Y., Lin L., Lin J., et al, 2007). Figure 9 shows the water level changes of the Ng group in the different schemes after 30years.

Scheme 1: Assuming that all geothermal wells will keep the same production rate of 722×10^4 m^3/a, as in 2004, for the next 30 years. Then the deepest water level of Ng group will be -135 m, in 2034, with an annual drawdown of about 1.0 m.

Scheme 2: Assuming that the total production rate of the Ng group will reaches 950×10^4 m^3/a, and that the number of geothermal wells and lay out of geothermal wells at present will not change in next 30 years. Then the deepest water level of the Ng group will be -155 m, in 2034, with an annual drawdown of about 1.73 m.

Scheme 3: Based on Scheme 2, where the total production rate of the Ng group is 950×10^4 m^3/a, but with the addition of 5 new geothermal wells in selected highly productive area. The deepest water level of the Ng group will be -138 m, in 2034, with an annual drawdown of about 1.33 m.

Scheme 4: Based on Scheme 3, where the total production rate of the Ng group is 950×10^4 m^3/a, but with the addition of 5 new geothermal wells in the peripheral regions, outside the highly productive area. The deepest water level of the Ng group will be -130 m, in 2034, with an annual drawdown of about 1.1m.

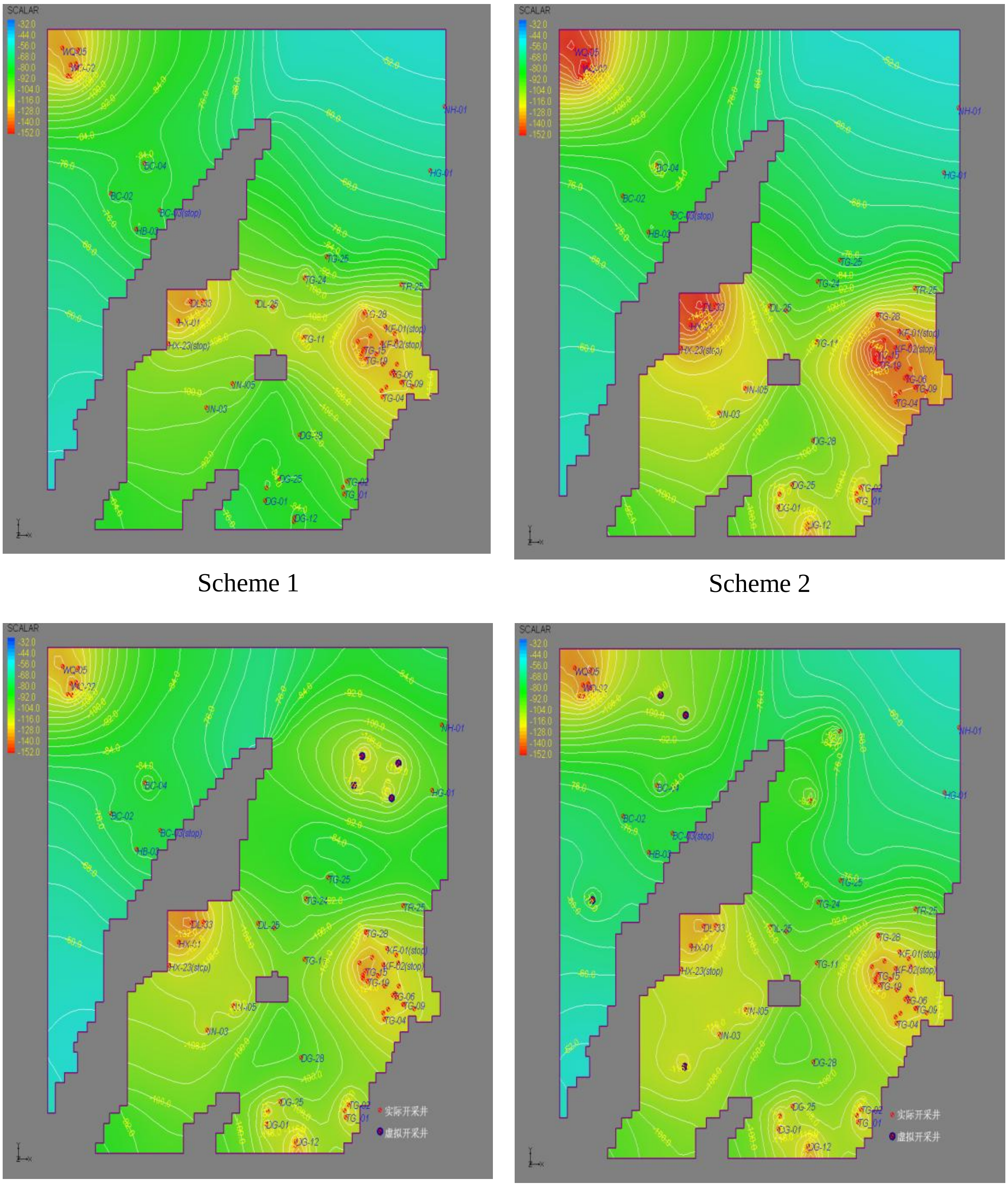

FIGURE 9: Water level contours of Ng group of different schemes in 2034
(Red dots are actual productive wells. Blue dots are virtual new geothermal wells in scheme 3 and 4)

By comparing the water level and its drawdown, it is obvious that Scheme 4 will be the optimized way for geothermal development in future. The dispersive layout of the production wells will slow down the water level drawdown from geothermal production.

5.3.2 Basement carbonatite reservoir in Paleozoic and medium Proterozoic

Simulations have been carried out based on the past 20 years of production history. Till now, there are 58 production wells and 18 reinjection wells in the Jixianian system. The optimized scheme is presented for the Wumishan Group of the Jixianian in Proterozoic from the calculation of four reinjection and production schemes (Hu Y., Lin L., Lin J., et al, 2007).

Scheme 1: Assuming that all geothermal wells will keep the present layout and the average production rate (80-120 m^3/h in winter) in 2004 in for the next 10 years. In the summer, the production rate is about 5-10% of that in the winter space heating time. All present reinjection wells are put into use with reinjection rate of 50-100 m^3/h. The total annual production rate will be $1270\times10^4\ m^3/a$, with a reinjection rate of $227.53\times10^4\ m^3/a$. Till 2014, the deepest water level will be -191.2 m, and the annual drawdown 5.2-7.4 m.

Scheme 2: Based on the present layout of geothermal production wells, and the addition of four new reinjection wells in the urban area. The annual production rate will stay at $1270\times10^4\ m^3/a$, but the reinjection rate increases to $362.53\times10^4\ m^3/a$. In 2014, the deepest water level will be -164.1 m.

Scheme 3: Keeping up the production rate of Scheme 2, but the four virtual reinjection wells are moved outside the urban area. Ten years later, the deepest water level will be -166.1 m.

Scheme 4: Based on Scheme 1, with the addition of eleven reinjection wells, five in the south of and north of the urban area respectively and one is in the urban area. The annual production rate will stay at $1270\times10^4\ m^3/a$, but the reinjection rate will increases to $542.53\times10^4\ m^3/a$. In 2014, the deepest water level will be -108.8 m.

Figure 10 shows the layout of reinjection wells in the four schemes. Compared with the others, Scheme four is the optimal scheme. Reinjection from the peripheral area of the highly productive centre will be a more effective way to maintain the reservoir pressure. But the possible distinct cooling resulting from the reinjection has not been assessed in the four schemes. The result of this is highly uncertain because the flow channels are unknown. Further research will be conducted in the future.

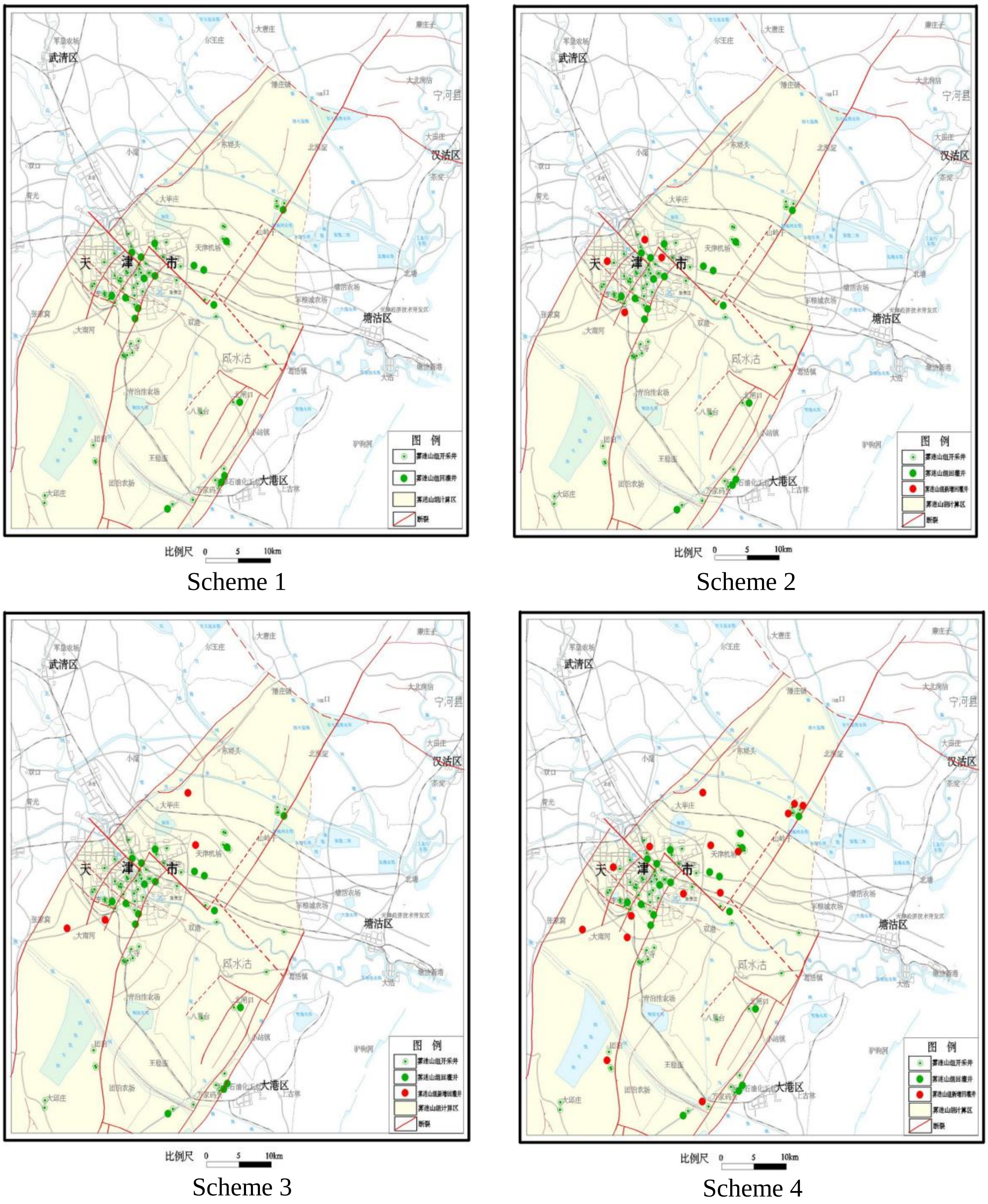

FIGURE 10: Layout of reinjection wells in four different schemes

6.CONCLUSION

Through the monitoring of geothermal fields for more than 20 years, it has become an important and necessary part to evaluate the geothermal potentials and to plan the geothermal development by utilizing information technology. It is also helpful in supplying guidance for mining enterprises on how to reasonably develop geothermal resources.

However, the water levels of most of the geothermal wells are observed manually due to very heavy corrosion of the monitoring equipment. The automatic observation equipment for water level still awaits improvement for more efficient data collection (Wang K., Han J., 2007).

With the increased geothermal development and utilization in Tianjin more monitoring points should be chosen, so that the nature and properties of the geothermal fields, as well as the response to long-term production and reinjection, can be obtained.

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GEOTHERMAL TRAINING PROGRAMME
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LECTURE 5

EXPERIENCE OF GEOTHERMAL REINJECTION IN TIANJIN AND BEIJING

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ABSTRACT

Reinjection has been widely applied in management of geothermal resources, and has become one of the routine applications of geothermal development in many geothermal fields. In China, reinjection tests started in 1974 in Beijing. But large scale reinjection of the geothermal waste water from heating systems was started in Tianjin in 1990's. Since 2000, reinjection has been considered an increasingly important aspect of geothermal resources management in Beijing and Tianjin.

At present, a number of reinjection projects are in operation in Tianjin and Beijing. As a result, the water level declining of geothermal wells has been greatly diminished. In Xiaotangshan geothermal field in Beijing, the water level has accurately stopped declining, since 2006, owing to reinjection and control on production of geothermal water.

In this paper, the reinjection history in Tianjin and Beijing will be summarized, and the experiences and problems of reinjection, including the distances between the production and reinjection wells, tracer test and monitoring of geothermal fields with reinjection, will be discussed.

1. INTRODUCTION

Geothermal is an environmentally benign energy source, widely used in many countries for power generation and direct use purposes, such as in space heating, bathing, swimming pools, fish farming, greenhouses, health spas and recreational facilities etc., bringing about significant economical and environmental benefits. Geothermal is a type of renewable energy, but it should not be over-exploited; or, the resources will be depleted, and will need a relatively long time to recover from improper management. Therefore, it is mandatory to implement proper management for the sustainable use of geothermal resources.

Reinjection has been widely used in the management of geothermal fields, and is becoming a routine application in many geothermal fields, since the first reinjection project was implemented in the famous Geysers area in 1969 (Axelsson & Stefansson, 1999). The purpose of geothermal reinjection is for (1) disposal of the waste geothermal fluid that may cause thermal and chemical pollution; (2) improvement of heat mining. Over 90% of the heat in the geothermal reservoirs is stored in the hot rock matrix; (3) stabilization of the production capacity of the geothermal field through the maintenance of the reservoir pressure (Liu, 1999).

Geothermal reinjection began as a method of disposing of wastewater from power plants in order to protect the surrounding environment. It was initialized as early as 1969 and 1970 at the Geysers area in California and in the Ahuachapan field in El Salvador, respectively. Presently there are a number of geothermal fields worldwide where reinjection is already a part of the operation, including the Geysers field in USA, the Larderrello field in Italy, the Berlin field in El Salvador, the Paris field in France, the Laugaland field in North Iceland etc. There are a number of other geothermal fields where reinjection tests have been carried out, and some of them may start production-scale reinjection soon.

There are abundant low enthalpy geothermal resources in China (high enthalpy geothermal only exists in Tibet and Taiwan). The resources are mostly used for health spas and recreation in southern China where there is no need for heating in the winter; in northern China, where the climate is colder, the resources are used for space heating and various other direct. For the past 30 years, geothermal utilization has been ever increasing, especially in the past 10 years and in large northern cities such as Beijing, Tianjin and Xi'an etc. With the expansion of geothermal utilization, some problems have arisen, i.e. the rapid decline of reservoir pressure in geothermal fields where the production is high. Reinjection is, therefore, considered as a measure for the sustainable use of geothermal energy.

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, a larger scale reinjection tests were carried out in this geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well with a depth of 1275 m. At the end of the 1980's, reinjection tests were carried out in the Tertiary sandstone reservoir in Tianjin. Since 1996, reinjection tests have also been implemented in the dolomite reservoir in Tianjin. Till now, there have been 13 production-reinjection doublets running in Tianjin. In 2004 and 2005, reinjection tests into the sandstone reservoir were carried out in Tianjin again. In 2001, reinjection tests were implemented in Xiaotanshan geothermal field north of Beijing, and in the Urban geothermal field in Beijing. Since then, production scale reinjection has been running in Xiaotangshan Geothermal field. Tests in both Tianjin and Beijing showed that reinjection is a feasible measure to ensure the sustainable use of geothermal resources in the two cities.

2. THE IMPORTANCE OF GEOTHERMAL REINJECTION

Beijing is rich in low-temperature geothermal, stored in limestone and dolomite reservoirs, and the identified area with geothermal potential is greater than 2760 km^2, divided on 10 geothermal fields, such as the ones in the southeast Urban area and Xiaotangshan (about 30 km north of the city centre). The temperature of the geothermal water in Beijing is 38-89°C. The geothermal water contains SiO_2 and other components that are good for human skin. Historically, hot spring water was used for bathing and for spas in Beijing. Large-scale geothermal use started in 1971 in Beijing, with the completion of the first geothermal well. After that, the number of geothermal wells increased rapidly, and the amount of geothermal water production increased with it. By 1985, the geothermal production increased to over 10 million m^3 annually, causing a rapid declining of reservoir pressure (water level). Therefore, strict measures were taken to control the amount of geothermal water subtraction since 1985. As a result, the water level decline has slowed down (Figure 1). At present, it is generally between 1 and 2.5 m annually, and it still threatens the sustainability of geothermal utilization in Beijing.

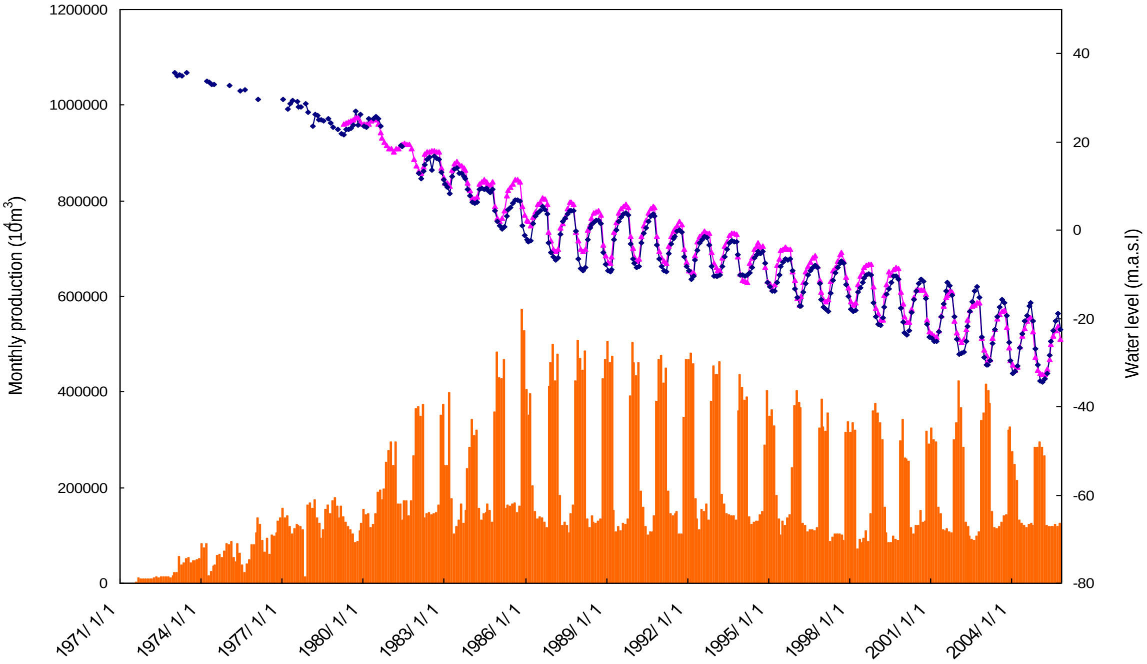

FIGURE 1: Historical water level change and monthly geothermal water production in the southeast Urban area, Beijing

This means that the net discharge of geothermal water, that is, the interval between production and reinjection of the geothermal systems should be under a certain limit. Otherwise, the water level of the geothermal wells will decline, and threaten the sustainability of the geothermal resource. It also means that if reinjection will not be carried out, the production should be lowered drastically. Therefore, it is essential to reinject the used geothermal water back into the geothermal reservoir.

The geothermal resources in Tianjin are low-enthalpy geothermal resources in sedimentary basins. The area with geothermal potential is about 8700 km^2, accounting for about 77% of the total area of the city. Geothermal water is stored in the Tertiary sandstone and karst-fractured dolomite. The temperature of the geothermal water ranges from 55 to 103°C. Geothermal is widely used for space heating, domestic hot water, fish farming and greenhouse, recreation etc. By the end of 2007, 294 geothermal wells (including 38 reinjection wells) were drilled in Tianjin, the deepest well being close to 4000 m deep. The production capacity of each well is 100 to 200 m^3/h. The annual production of geothermal water is 24.50 Mm^3.

Due to the large-scale development of the geothermal resources, the reservoir pressure decreases quickly in Tianjin, especially in the dolomite reservoir. Since 1997, the annual water level drawdown has been over 3 m. Currently the depth to the static water level in the geothermal wells varies between -40 m and -90 m, with an annual drawdown of 6-9 m (Figure 2). This suggests that the recharge to the reservoirs is rather limited. Meanwhile, the water level drawdown is lower than before 2004, due to the incrimination of the reinjection rate. Therefore, it is necessary to implement reinjection for maintaining the reservoir pressure and prolonging the life time of the geothermal wells.

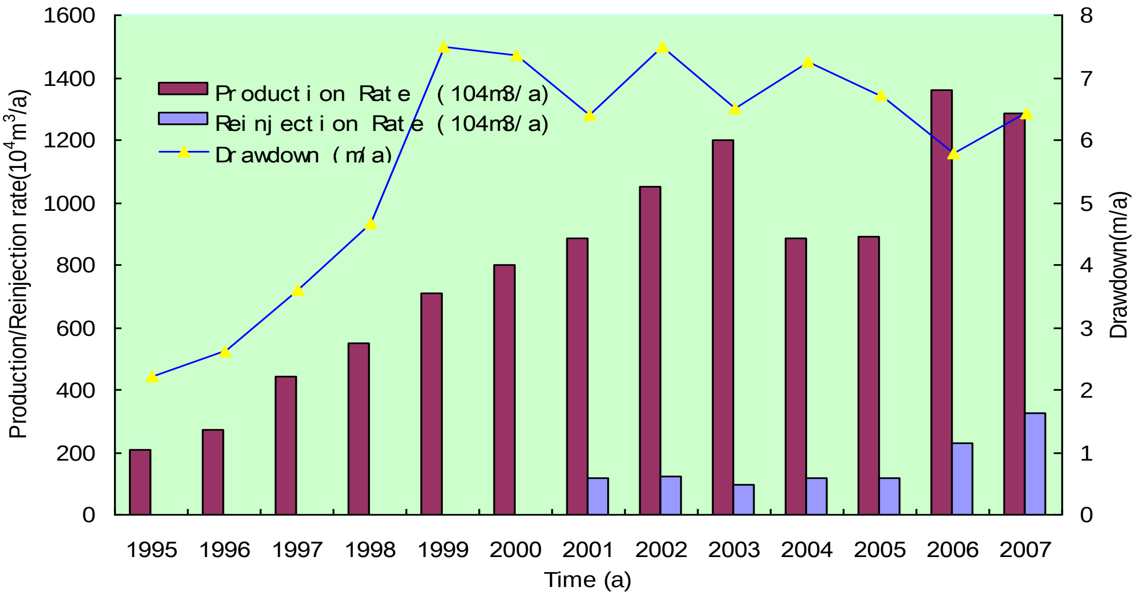

FIGURE 2: The history of water level drawdown v. geothermal water production and reinjection in the dolomite reservoir in the Tianjin urban area in 1995-2007.

3. APPLICATION IN TIANJIN

3.1 History of reinjection in Tianjin

Reinjection activity started in the early 1980's in Tianjin, and the history can be divided into 4 periods:

3.1.1 1980 - 1995

With the increase of geothermal water production, it was realized that reinjection might be a useful way to control the declining water level. In the beginning of the 1980's, studies on geothermal production-reinjetion doublet or production-reinjection well groups were carried out, and related numerical modelling on sandstone reinjection was conducted. Based on the results, reinjection tests, focused on reinjection into sandstone in the geothermal reservoir of the Tertiary System, were carried out in Dagang and Tanggu District in 1987-1989 and in 1995.

3.1.2 1995 - 1998

With the increase of geothermal water use from the dolomite reservoir, more attention was paid on reinjection into the dolomite reservoir in Tianjin. In 1995, the first production-reinjection doublet was drilled, and reinjection test was carried out in 1996-1997. The result showed that reinjection is technically feasible in the dolomite geothermal reservoir in Tianjin (Wang et al, 2001).

3.1.3 1998 - present

Based on the results of the reinjection tests for the dolomite reservoir, a few production and reinjection doublets were installed and operated in this period in Tianjin. In the same period of time, tracer tests were carried out for better understanding the movement and heating processes of the reinjected water. Monitoring of the doublets has become a routine, including flow rate, water level, temperature, and chemical contents. Numerical modelling was carried out for predicting the effect of reinjection. A technical standard for design and operation of geothermal reinjection was compiled, by summarizing the experiences of geothermal reinjection in Tianjin.

Since 2004, tests on reinjection into sandstone reservoirs were started again in Tianjin, due to the rapid decline of the water level in the sandstone reservoir.

3.2 Reinjection in dolomite reservoir

Most of the geothermal production /reinjection doublet systems in Tianjin are inside the urban area. Both of the production and reinjection wells were drilled into the dolomite reservoir which is widely dispersed in the Tianjin area (Wang et al., 2001).

Since the first geothermal production-reinjection doublet was put into operation during the winter (during the space-heating period) of 1999, 27 reinjection wells and 77 production wells have been drilled in this reservoir in Tianjin. All the doublet systems reinject under artesian conditions. All the geothermal water from the doublets is reinjected into the reservoir after the heating cycle. The amount of reinjection was 2.89×10^6 m^3 in 2007, accounting for about 24% of the total production from the geothermal reservoir. Although, that there are more geothermal production wells used for space heating than there are reinjection wells, and that production wells adjacent to reinjection wells influence the reservoir pressure around the reinjection wells, it can be observed that the water level close to reinjection wells declines much slower than in other parts. The average annual drawdown has decreased with increasing reinjection rates. Still, there have been no observable temperature changes in the surrounding production wells.

According to the geological conditions and the past 20 years of production history, a numerical model was set up for the geothermal system in the urban area in Tianjin, using the software package TOUGH2. The model was used to predict the changes of reservoir pressure in the geothermal system in the future, assuming that (1) all the geothermal wells will keep the average production rate in 2002 (80-120 m^3/h in winter, and 5-10% of the winter production rate in the summer); (2) all the 10 reinjection wells are put into use with a reinjection rate of 50-100 m^3/h for each well, and the annual amount of production is 1.3716×10^7 m^3 (deducting the amount of reinjection 1.7×10^6 m^3). It was predicted that the deepest water level in the reservoir will be 193 m below sea level. This means that the sustainability of the geothermal production cannot be realized if the present production and reinjection will be maintained in the future. If the present amount of reinjection increases with 150%, it was predicted that the deepest water level will be 138 m below see level in 2013 (Figure 3). This means that reinjection makes an effective measure to counteract the decline in reservoir pressure (Wang, 2005).

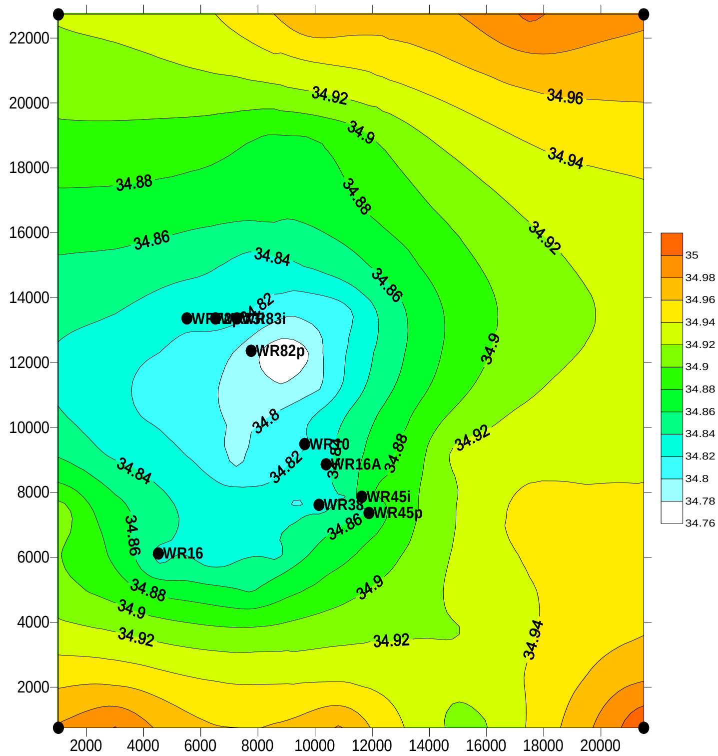

FIGURE 3: Contour map of calculated water level of the dolomite reservoir in Tianjin in Sept.2013, assuming the reinjection will increase 150%.

3.3 Tracer test

Reinjected cold water can extract additional thermal energy from the rock matrix and improve the heat mining from the geothermal reservoir. But it is not a simple decision to increase the amount of reinjection, because of the possible cooling of the production water. It is proposed that tracer test be carried out to study the connections between the production and reinjection wells and to predict the cooling effect by the increase of reinjection.

3.3.1 Tracer test in the winter of 1998 - 1999

To investigate the connections between the reinjection and production wells of the WR45 doublet, a tracer test was conducted in the winter of 1998-1999. 10 kg of potassium iodide (KI) was selected as the tracer. Meanwhile the chemical content of the water produced from the surrounding wells was monitored carefully. The resulting data are presented in Figure 4.

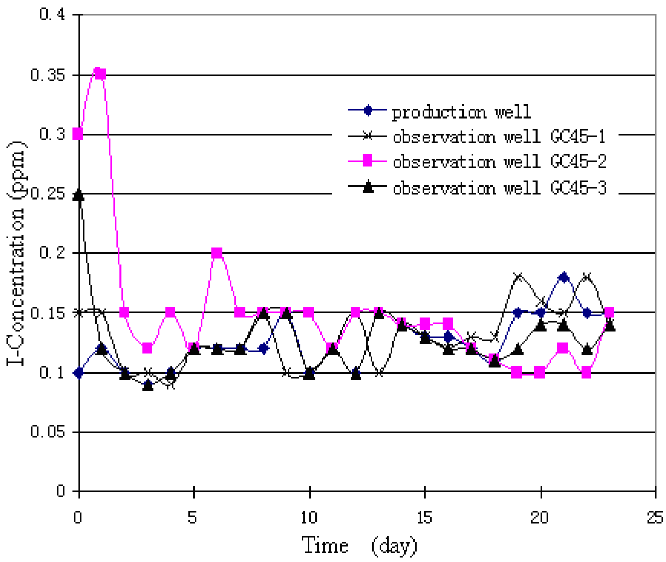

FIGURE 4: The recovery curves of the tracer concentration in the observation wells around WR45.

The monitoring data shows that the tracer concentration is almost constant in the production well, i.e. no noticeable recovery. On the other hand observation well GC45-2 shows some iodine recovery. This means that the hydrological connection between the production and reinjection well of doublet WR45 is indirect, but that there may be a direct (fast migration) channel between the reinjection well and other nearby geothermal production wells (such as production well GC45-1, which is about 2.5 km away from the reinjection well).

A mathematical model simulated the results from GC45-2 tries and assesses the nature and structure of the fractures connecting GC45-2 and the reinjection well. Figure 5 and Table 1 show the simulated recovery and model parameters, respectively. The simulation curve is composed of 4 pulses, corresponding to 4 flow channels/fractures. When the tracer was reinjected into the aquifer, it travelled rapidly along the most direct path, which had the smallest cross section. For this channel the tracer moved quickly to the production well and reached the maximum concentration in a very short time. If, on the other hand, the reinjected water diffuses into a large reservoir volume, only a small fraction of the tracer will be recovered and the time it takes it to reach peak value will be much longer. In the latter case, the thermal breakthrough time will not be a problem for the doublet system operation. Therefore, tracer tests are very important for understanding the mode of transport, flow channels, and fracture characteristics in the doublet production/reinjection systems.

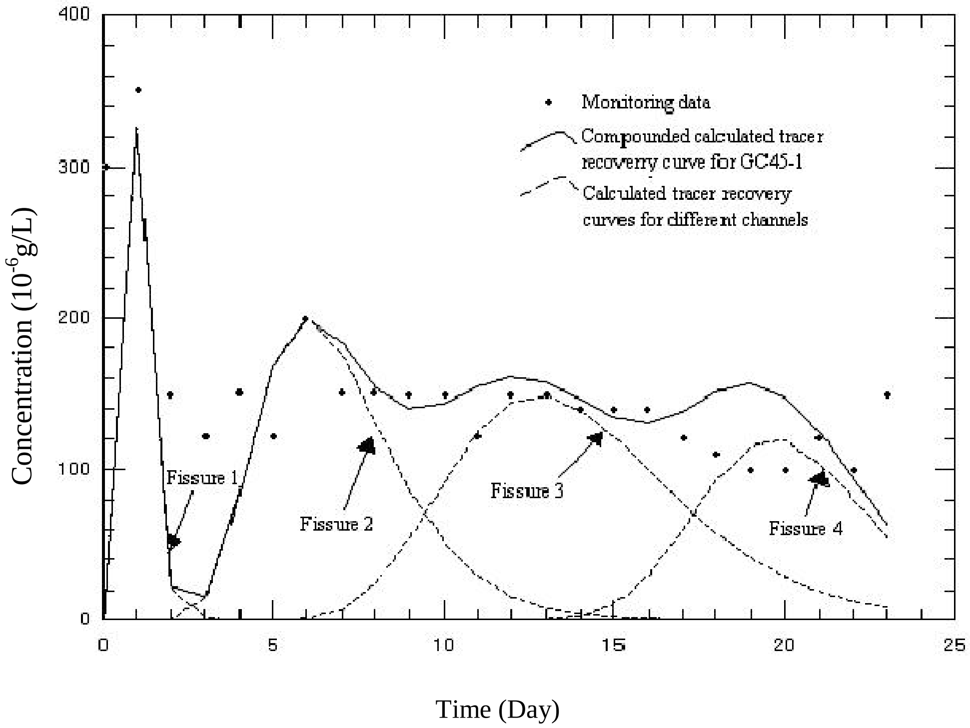

FIGURE 5: Calculated tracer recovery curves for observation well GC45-1. Each dashed line represents a different channel connecting the reinjection and production wells.

TABLE 1: Calculated parameters of the tracer test

	Cross section area Aφ (m^2)	Dispersivity α_L (m)	Mass recovered (%)
Fissure 1	1.50	356	20
Fissure 2	15.7	142	39
Fissure 3	29.5	10.1	10
Fissure 4	54.7	162	22

3.3.2 Tracer test in 2001

In the winter of 2001, another tracer test in the dolomite reservoir was carried out and the tracer used was the radioactive isotopic tracer (^{125}I, ^{35}S). The distance between the production and the observation well is more than 4km. The amount of tracer used was 350 mCi (1.3×1010Bq, ^{125}I). The entire tracer was applied instantaneously. The tracer break through time was about 3 days, and the peek time was at about 52 days (Figure 6). According to the deduction from the tracer tests, there is no premature thermal break through.

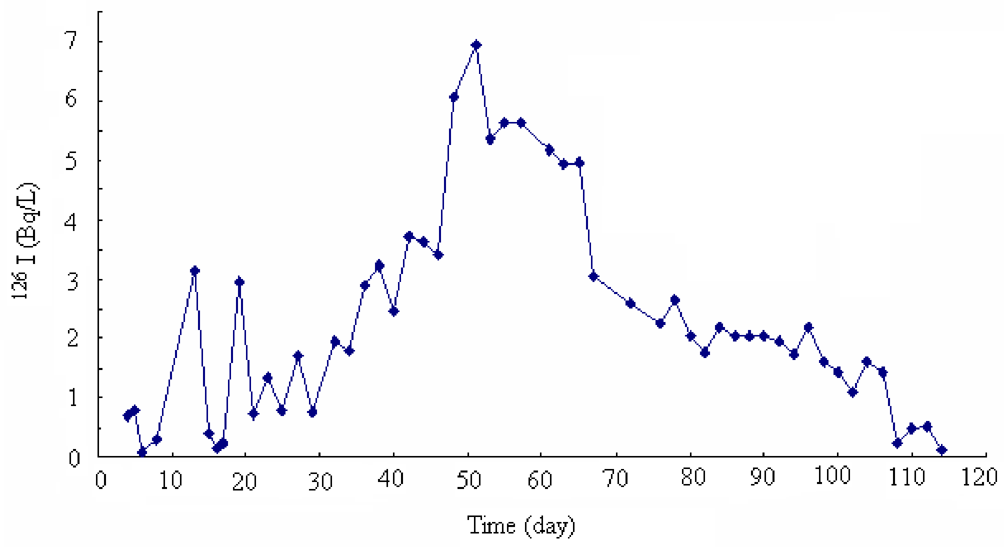

FIGURE 6: Tracer (^{125}I) recovery of a tracer test in 2001

3.4 Reinjection in sandstone reservoir

Through many years of research, the reinjection problems of dolomite reservoir have basically been solved. But the reinjection problems of sandstone reservoirs still exist, mainly at low reinjection rates and short duration times. The production from sandstone reservoirs exceeds 50% of the total geothermal production in Tianjin. Thus it is important to resolve the reinjection problems for the sustainable development and utilization of geothermal resources in Tianjin.

By the end of the 1980s, reinjection tests had been carried out in Tertiary sandstone reservoirs in Tianjin. During the tests about 30-50 m^3/h waste water was reinjected into the reservoir. But along with the reinjection, the reinjectivity quickly decreased. Tests of sandstone reinjection were carried out again in the winter of 2004-2005, and the results were similar to that of the previous tests. The reinjection tests were carried out in the Neogene Guantao formation sandstone reservoir in the Wuqing District, the Dongli District and the Dagang District, and reinjection well drilling technology, reinjection plugging problems and ground reinjection systems were studied here.

During the late Oligocene, North China Plain rose to the dustpan basin. And in the Miocene period the Yanshan uplift zone became the main source area. Because of the transport and deposition in lower river bends and braided rivers, clastic rocks formations arose of fluvial facies. It finally formed alluvial-pluvial fans and fluvial deposits well-distributed on the North China Plain. They mainly include mottle silt rocks and sand gravel rocks. The Neogene Guantao formation ultimately formed from clastic fluvial rocks with obvious sedimentary cycles, and they are mainly located in the Wuqing sag and the Huanghua depression in Tianjin. Clastic rocks in Tanggu, Beitang and the northwest of Xiaozhan are mainly of gravel facies, other parts are mainly of gravel and sand facies.

The top of the Guantao formation is a thick sand layer, the bottom is a gravel sand layer and its middle part is a silt stone layer. The total thickness is 200-600 m, of which the sand and gravel thickness amounts to 70-360 m. The porosity of the formation is 15%-32.4% and its permeability is $773\text{-}2631\times10^{-3}\ \mu m^2$. There is a well-formed gravel layer at the bottom of the Guantao formation, with a thickness of 30-60 m and a gravel diameter of 5 mm. The mean porosity is about 20%. Through exploration, deterring physical properties of rock samples, analyzing geothermal conditions and hydrological conditions, it is evident that the Guantao formation is a mid-low temperature heat storage layer created by normal consolidation processes. It also apparent that the source of its heat is from deep heat conduction and its water supply is from lateral runoff recharge.

The main problem with sandstone reijection in Tianjin is that the reinjectivity decreases fast with time, or the reinjectivity changes too much with time during the reinjection process. The clogging of reinjection wells is attributed to physical, chemical and biological factors.

3.4.1 Physics plugging

The filtered particles from the reinejection water has been analyzed by SEM (Scanning Electronic Microprobe) and X-ray diffraction in most of the wells. The result indicate that plagioclase, quartz, K-feldspar, FeS and ZnS seem to be the most common components carried on by the fluid, plus a certain number of possible other components, such as NaCl, $CaCO_3$.etc.

3.4.2 Chemistry plugging

There seem to be three types of minerals that potentially may precipitate during reinjection around the well bottom: quartz (chalcedony), calcite, Fe-Zn oxides (hydroxides) and sulphides. Among them, the Fe-Zn oxide and the sulphide have been found in samples of 25 wells. Also similar components have been discovered in filtration. This proves that the water is saturation in these components in these exploitation wells. It is assumed that iron and zinc comes from oxidation of the well tube and water conveying pipeline.

In order to prevent the suspended solid particle from entering the reservoir , and from blogging the passage, referring to successful experiences of water reinjection in oil wells, double deck cage screens is used when filling gravel into the geothermal well.

Meanwhile, In order to prevent physical and chemical jam, use is made of secondary filtration equipment in the reinjection system. The primary filtration is rough, the precision is of 50 μm, whereas, the secondary filtration is fine, with a precision of 3-5 μm. There are pressure cabins at the ends of the filtration pot. If there is a pressure difference in the cabins the finer particles will resort in the filter pack. In practice, the precision of the secondary filtration is high and its effect is good. To prevent gas blockage, there is a vent installed at the head of the reinjection well.

Two test sites were established in the Wuqing and Dongli districts, in 2004. Here, two reinjection wells have been drilled in the Guantao group reservoir. The two level filter system was used in the ground reinjection system, and productive reinjection tests have been conducted. In the Wuqing district the temperature of the reinjected fluid is 42 ~ 52°C, pumped at a reinjection rate with a decrease from 49 m3/h to 20 m3/h. The stable water level is at about 10 m depth. In the Dongli district the temperature of the reinjected fluid is 50°C, with a reinjection rate of about 16 m^3/h. The stable water level here is at about 15 m depth.

In summary, through the study of reinjection well-drilling technology and ground reinjection systems, some problems of physical and chemical reinjection plugging have been resolved, but decreasing reinjection rates remain a problem.

4. APPLICATION IN BEIJING

4.1 History of reinjection in Beijing

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, larger scale reinjection tests were carried out in the geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well at a depth of 1275 m. Hereafter, reinjection stopped in Beijing for a rather long time. In 2001, reinjection tests and demonstration projects started again. Recently, reinjection has been implemented on rather large scales and received significant results in Beijing. The geothermal reinjection history can be divided into 4 periods:

4.1.1 1974-1983

Because of the increase of geothermal water production in the early 1970’s, the water level of the geothermal wells declined rather fast. It was considered that reinjection would be an important measure to prolong the lifetime of the geothermal wells. In 1974, a short reinjection test was conducted in the famous Park of the Temple of Heaven in the southeast urban area. And in 1975, a short reinjection test was conducted again in the southeast urban area.

Until 1980, there were more than 30 geothermal wells in the southeast part of Beijing, the geothermal water production was about 3 million m^3/a, and the water level declining became more serious. Therefore, a larger scale reinjection test was carried out from June 4 to September 2, 1980. Cold groundwater of 15.5°C was reinjected into a 1060 m deep geothermal well in the southeast Urban area. In the 89 days of the reinjection test, about 60,000 m^3 of cold water was reinjected, and the temperature change inside the reinjection well was observed (Liu et al., 1981). After the 89 days, 40°C return geothermal water from a heating system was reinjected into a 1274.65 m deep geothermal well in the same area (Bai and Gong, 1984). In that period, reinjection tests focused on the time needed for the reinjected water to return to reservoir temperatures.

4.1.2 1983-2000

Geothermal reinjection activity stopped mostly because of financial problems, although the water level continued to decline in this period.

4.1.3 2001-2002

After 1999, with the fast development of geothermal utilization in Beijing, and the wide recognition of sustainable development, reinjection was again considered to counter the declining of water level drawdown. In 2001, a demonstration project of geothermal reinjection was carried out in the Xiaotangshan area. Return water from geothermal heating was reinjected back to the same geothermal reservoir through a well about 200 m away from the production well. This reinjection project operated smoothly in 2001 and 2002, and no cooling of the production temperature was observed (Liu, 2003).

In 2001, a reinjection test was also conducted in the southeast urban area in Beijing. Return water from a heating system was reinjected into a well that strikes a shallower geothermal reservoir 80 m away from the production well. Reinjection tests also started in 2002 at the south-eastern boarder of the same geothermal field (Liu, 2003).

4.1.4 2003-present

Since 2003, reinjection in Beijing has expanded rapidly. In the Xiaotangshan area, there were 6 reinjection wells in operation in 2006, and the amount of water reinjected was about 60% of the total production. Reinjection also expanded in other parts of Beijing during this period, and the role of reinjection in sustainable utilization of geothermal resources has been acknowledged.

4.2 Reinjection in the Xiaotangshan area

The reinjection in the Xiaotansgan began in 2001 in a hotel in the central part of the geothermal field. One of the two production wells at the hotel was converted into a reinjection well. The wells of the hotel were drilled in 1984 and 1996, respectively. The distance between the wells is about 200 m. The geothermal reservoir is in limestone of the Cambrian System and the dolomite of the Jixian System. The wells come across the same fault which is very important structure to the occurrence of geothermal in the vicinity of hotel. The reinjection was carried out from November 30, 2001 to March 27, 2002. In total 117 days. The temperature of the reinjected return water was 30-44°C. The flow rate of reinjection changed with the atmospheric temperature; it was approximately 800 m^3/d on the coldest days from January 8 to 20, 2002, and under 800 m^3/d on other days. The reinjectivity of the well did not decrease during the reinjection (Figure 7). The total amount of water reinjected was 73,331 m^3 for the duration of the heating season (Liu and Yan, 2006).

A tracer test was conducted during this reinjection test mentioned above. On January 8, 2002, 50 kg of KI was applied to the reinjection well instantaneously, 39 days after the reinjection started. 165 water samples from the production well were collected until space heating stopped. Samples were also collected from surrounding wells. No iodine was found in the samples. This indicates that there is not a direct pass between the reinjection and production wells, and that premature thermal breakthrough is not likely to happen in the production well (Liu, 2002).

When reinjection stopped, a submersible pump was installed in the reinjection well, intended to restore the reinjectivity of the well, in case of reduction. On April 15, 2002, the pump was started. At the beginning, the temperature of the water was around 30°C, and in an hour, the temperature rose to 63.5°C, and was thus nearly restored to its normal production temperature of 64°C.The reinjection test shows that the reinjectivity of the geothermal reservoir is rather good, and that the reservoir also has good capacity to reheat the reinjected colder water (Liu, 2006).

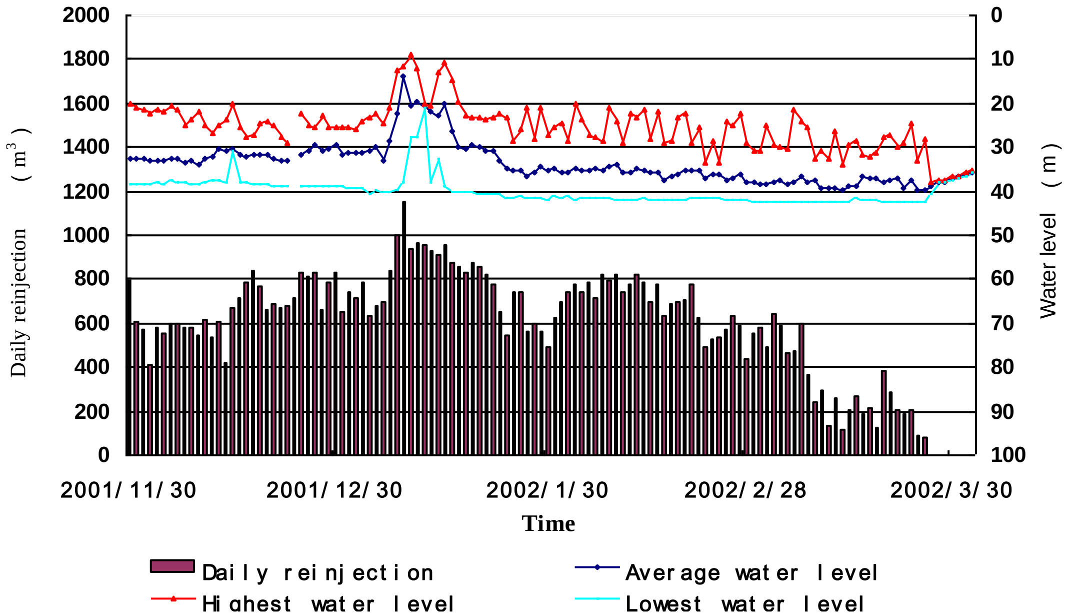

FIGURE 7: reinjection volume and water level changes of a reinjection well in the Xiaotangshan Geothermal Field during the heating season of 2001-2002

In the heating period of 2003-2004, a reinjection test was carried out in another hotel close to the one mentioned above. In 150 days, 1.48×10^5 m^3 of return water from the heating system was reinjected into a well drilled for reinjection purposes. The total amount of reinjection reached 2.48×10^5 m^3 throughout the heating season.

In the heating period of 2004-2005, four production-reinjection doublet systems were set up, by converting old production wells into reinjection wells, or by drilling new reinjection wells in the geothermal field. From November, 2004 to April, 2005, 10.2×10^5 m^3 of return water was reinjected into the geothermal reservoir, accounting for 36.5% of the total production (Liu and Yan, 2006).

In the heating period of 2005-2006, 6 reinjection wells were operating with return water from 8 production wells. There are two production-reinjection assemblages involving 2 production wells and

1 reinjection well each. The total quantity of reinjection was 1,322,778 m^3, accounting for 56.6 % of the annual production in the field.

In 2001-2002, the effect of the reinjection on the stabilization of the reservoir pressure was very little, because the amount of reinjection was small. With the increase of reinjection, the effect became more and more significant. In the 5 months from December, 2004 to April, 2005, the water level of the monitoring well (has been monitored for about 30 years) was higher than that for the same period in 2003 and 2004 (Figure 8), i.e. it rose 2.5 m. Considering that the water level decreased 1 to 1.5 m every year before the large scale reinjection, the effect was noteworthy.

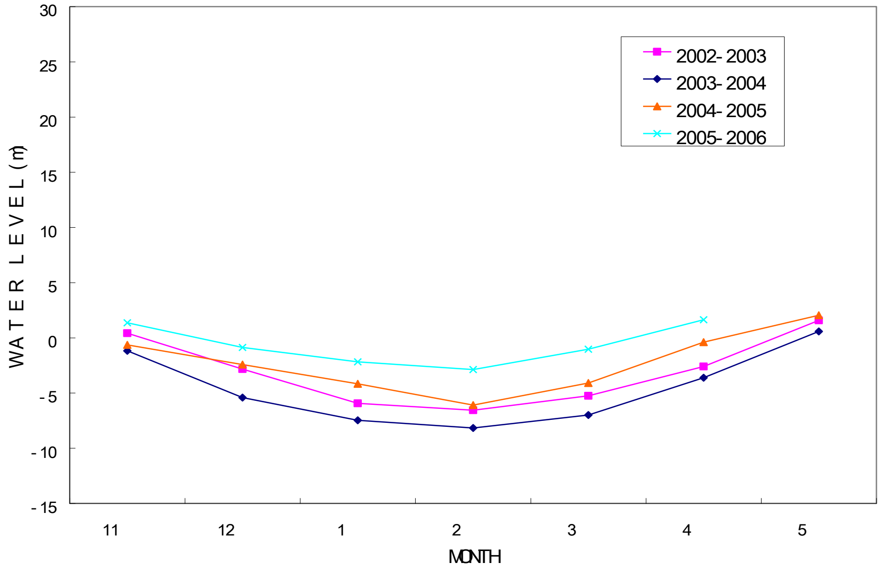

FIGURE 8: The water level of a monitoring well in Xiaotangshan geothermal field from 2002 to 2006

The reinjection in the Xiaotangshan geothermal field does not have observable influence on the temperature of the water in the production wells, although the distance between some of the production and reinjection wells is less than 200 m. It was also observed that the chemical composition of the geothermal water from the production wells did not change considerably. But the content of HCO_3^{2-} in the water pumped from one of the reinjection wells decreased, and the content of SO_4^{2-} increased. This may indicate convection, where the reinjected cold (heavy) water flows to deeper levels of the geothermal reservoir and that the hot water (light) from greater depths flows to the top of the reservoir.

4.4 Reinjection in other area in Beijing

Although geothermal reinjection tests have been carried out as early as 1974 in the urban area in Beijing, long term reinjection only started in early 2002 in an apartment building district about 5km south of Tiananmen Square. There are two geothermal reservoirs at different depths, both in dolomite, and separated by a shale layer of about 100 m thickness. Two wells, 90 m apart, were drilled in 2001 for the space heating of a 28,000 m^2 floor area (with the help of a heat pump system) and the reinjection of the return water from the heating system. The reinjection well is 1900 m deep, coming across the upper reservoir; the production well is 2054 m deep, completed for producing from the lower reservoir. The water temperatures from the reinjection well and the production well are 54°C and 59°C respectively. Both wells have good production capacity. The average flow rate of geothermal water in the heating system is 35 m^3/h. When all the return water was reinjected into the upper reservoir and the water level in the reinjection well rose 4 m on average. The test showed that the reinjectivity of the well is close to its productivity. This geothermal heating system, incorporated reinjection and heat pumps, has been running for more than 6 years, and ha not met any difficulties. It is also a good example for the cascaded use of geothermal resources (Liu, 2006).

Later, a few other reinjection wells were put into use in the southeast urban area and other geothermal fields in Beijing. Because the government encourages reinjection by subsidising, more developers are planning to start reinjection.

More tests and research, on wellhead facilities, and drilling and casing techniques of reinjection into sandstone reservoirs, are steadily progressing.

5. DISCUSSIONS

5.1 Distance of production and reinjection

Cooling of the reservoir caused by reinjection of colder fluid has been reported in a few high-enthalpy geothermal fields. For low-enthalpy geothermal fields, there have not been any such reports, not even in cases where the distance between production wells and reinjection wells is rather small. Therefore, it may be concluded that for production/reinjection doublets in low-enthalpy geothermal fields, one does not have to fear about cooling of the reservoir, if the distance between production and reinjection wells is greater than a few hundred meters, and the amount of reinjection is kept to a limit.

In designing the distance between reinjection and production wells of a doublet system, a few factors should be considered, including the type of geothermal reservoir, the geological structures of the geothermal field, the permeability and thickness of the reservoir, the direction of fluid flow, the temperature difference between the reservoir and reinjection water, the flow rate of reinjection etc.

But in cases where large numbers of reinjection wells and production wells will be placed among in rather small area, care has to be taken, and proper testing and modelling have to be carried out before any such reinjection project is initialized, to avoid premature thermal breakthrough.

5.2 Tracer test

Tracer tests can be a very good precaution for thermal breakthrough. Tracer testing is one of the most important aspects of geothermal reinjection, and it now a routine. Tracer tests can provide information about the flow paths and the flow velocity of the geothermal fluids between the reinjection and production wells. For fractured reservoirs, the volume of the aperture can be deduced from the tests. This information can be used to predict the cooling due to reinjection (Axelsson and Stefánsson, 1999). For large-scale reinjection projects or a greater number of production and reinjection wells in a relatively small area, it is strongly proposed that tracer test be carried out.

5.3 Monitoring

Monitoring is one of the most important elements for geothermal management. For a geothermal field with reinjection, a proper monitoring program is even more important. Besides the monitoring of reservoir pressure, temperature, production volume, and hydrochemistry; water level in reinjection wells, temperature of reinjection water, reinjection volume, and hydrochemistry of reinjection water should also be monitored. The purpose is to uncover changes in the geothermal system caused by reinjection, especially cooling of the reservoir.

6. CONCLUDING REMARKS

Reinjection is one of the most important aspects of sustainable management of geothermal resources. Reinjection tests were started as early as 1974 in Beijing. Reinjection of return water form geothermal heating systems has been applied in Tianjin since 1996 and in Beijing since 2001. The reinjection experiences show that it is significant in lowering the reservoir pressure, and improving the heat mining of the geothermal field. In the Xiaotangshan area in Beijing, the reinjection volume has reached about 60% of the geothermal water production. As a result, the water level of the geothermal field has stopped declining. This is a very good example of sustainable use of geothermal resources. It is proposed that reinjection be expanded in Beijing and Tianjin, as well as other geothermal fields in the world. However, reinjection is one of the most complicated technique of reservoir engineering, and pre-mature thermal break through should be avoided by the application of tracer tests and proper monitoring.

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LECTURE 2

BACKGROUND, HISTORY AND STATUS OF GEOTHERMAL UTILIZATION IN TIANJIN

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ABSTRACT

The Tianjin geothermal field is a typical low-temperature system, which is located in the middle-lower reaches of the Haihe River System on the North China plain. The geothermal distribution area is 8700 km^2, about 77% of the total Tianjin area. 10 geothermal anomalies are revealed. As a clean energy, the geothermal resource is widely used for space heating, potable water, agriculture etc. The annual production rate reaches 2450m^3 and the space heating area was about 12 Mm^2 in 2007. The geothermal reserves of 4 geothermal fields have been estimated with attainable resources of 5088×10^4 m^3/a in 2005. It is necessary to enhance the prospecting precision, expanding the exploitation area and strengthen the research on basic technology.

1. INTRODUCTION

Tianjin is located in the north-east of the North China Plain near Bohai Bay, west of the Pacific Ocean, at the lower reaches of Haihe River valley, with The Bohai Sea to the east and Yanshan Mountain to the north.

FIGURE 1: Location of Tianjin

Tianjin belongs to the warm temperature zone and has sub-humid continental monsoon climate. The four seasons are sharply distinguished, and this results in a great difference in temperature and a wide variety of scenery throughout the year. The average temperature in a year is over 12.3°C, and the frost-free period lasts about 200 days. On the average, the annual precipitation is about 600 mm, 75% of which

falls in June, July and August. The sunshine period is relatively long and the solar radiation is quite strong.

The present population of Tianjin is 1,236,700; the total area is 11,900 km^2. Tianjin has jurisdiction over 15 districts and 3 counties. With the largest artificial deep-water harbour and the largest port in the north of China, Tianjin port has the largest container dock groups, and the largest special docks for bulk grain and coke.

Tianjin has relatively rich energy resources, such as coal, oil, gas, geothermal; and thus has an advantage among the coastal cities in China. Its Bohai and Dagang Oil Fields are key state oil and gas projects, turning out 14,430,000 tons of crude oil and 830,000,000 m^3 of natural gas per year. Plentiful geothermal resources are available in Tianjin. Its reserves and utilization of these are ranked number one in China.

2. DISTRIBUTION AND CHARACTERISTICS OF GEOTHERMAL RESOURCES

2.1 Geology

Tianjin Geothermal field is located in a sedimentary-fault basin in the north of the North China Platform and is divided into a northern and a southern part by the Ninghe-Baodi fracture (Figure 2). Most of the area is covered by Quaternary strata. The outcrop of the base rock is limited to the mountain area in the north of Ji County. The northern part belongs to the secondary tectonic unit; the Jibao up-fold, in the Yanshan platform orogen. The southern part lies in the Bohai-Bay Basin. From west to east, the southern part constitutes three tectonic units; the Jizhong depression, the Cangxian upfold, and the Huanghua depression, that are cut into numerous tectonic blocks by several east-west, northwest and northeast trending fractures. On the whole, the centre part is uplifted with the low-lying part in the east and west. The anticline structure is the main regional trend. The main fractures are the Tianjin fracture in the west, the Cangdong fracture and the Baitangkou fracture in the east, and in the middle there are the Haihe and Chenglinzhuang fractures. Several faults accompany them. Most of the geothermal fields are located in the Cangxian uplift.

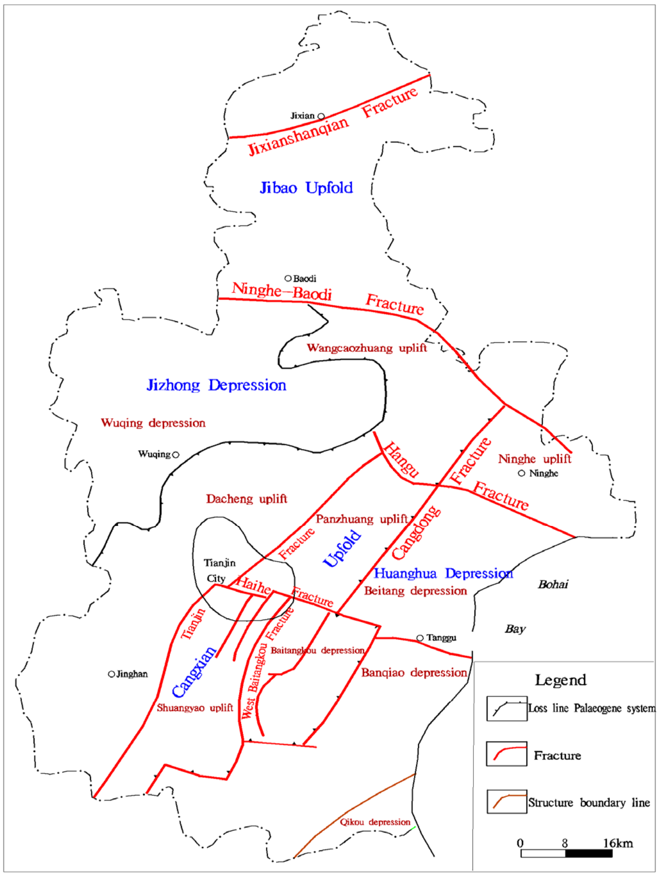

FIGURE 2: Sketch of geological tectonics in Tianjin

2.2 Strata in Tianjin

The general stratigraphy of Tianjin is presented in Table 1 (Tianjin Regional Geological Records, 1992).

TABLE 1: The general stratum of Tianjin

Geological age		Depositional formation	Diastrophism magmatism	Age (Ma)
Era	**System**			
Cainozoic	**Quaternary**	Continential plain, alluvial clastics, some lacustrine and marine deposits	Large depression	1.5±0.5
	Late Tertiary	Inland(near shore) salt and oil bearing lake clsastic	Basic magma effusives, dustpan basin	25±2
	Early Tertiary	Inland lake, red clastics	Basement fault, growth fault	66±2
Mesozoic	**Cretaceous**	Partial absence, inland basin, fluvial lacustrine clastics, intermediate pyroclastic rocks	General uplift	135±5
	Jurassic	Inland basin, coal-bearing calstics and volcanic rocks	Basic effusives, inland faulted basin, volcanic basin	200±5
	Triassic	Absent in late period, inland variegated clastic rocks	Orogen, inland small basin, intermediate magmatic emplacement	235±5
Late Palaeozoic	**Permian**	Continental coal-bearing, clastic rocks	Continental volcanic extrusion	285±5
	Carboniferous	Paralic coal-bearing clastics rocks	Inland large depression	350±5
	Devonian	-	General uplift	405±5
Early Palaeozoic	**Silurian**	-		440±10
	Ordovician	Neritic-littoral limestone, lagoonal dolomite, gypsum	Steady sinking, epicontinental sea	550±10
	Cambrian	Neritic-littoral limestone, sandy shale in early Cambrian		600±10
Late Proterozoic	**Sinian**	-	General uplift	800±50
	Qingbaikou	Neritic calcareous shale, littoral sandy shale, neritic limestone	Steady sinking, epicontinental sea	1000±50
Middle Proterozoic	**Jixianian**	Neritic limestone, littoral-neritic argillaccous carbonate, littoral magnesiaan carbonate, neritic shale		1400±50
	Changchengian	Littoral-neritic shale and dolomite, potassic volcanic rocks, littoral quartz sandstone and limestone, neritic shale, fluvial clastic rocks	Basement fault, submarine eruption, basic dike intrusion	1800±50
Early Proterozoic		?	Orogen	2500±50
Archaic		Basic to intermediate volcanic rocks, multilayered ferro-silicic iron rocks	Sealed folding, gneiss dome, granulite, migmatite	2900±50

2.3 Distribution of geothermal fields in Tianjin

There are 10 geothermal anomaly areas in Tianjin determined by temperature gradients of 3.5°C/100m (Figure 3). Seven of them are distributed in the Cangxian Up-fold. In Table 2 the temperature gradients of the cap rocks area are shown.

TABLE 2: Geothemal anomalies in Tianjin

Geothemal anomalies	Area (km^2)	Highest temperature gradients of cap rock (°C / 100m)
Wang Lanzhuang	534	8.0
Shanglingzi	315	8.3
Wanjia Matou	235	8.8
Pan zhuang	610	6.9
Zhouliangzhuang	180	5.5
Qiaogu	90	5.5
Kancaizhuang	20	5.5
Wangqingtuo	114	5.0
Shajingzi	190	4.5
Tangguantun	40	7.6

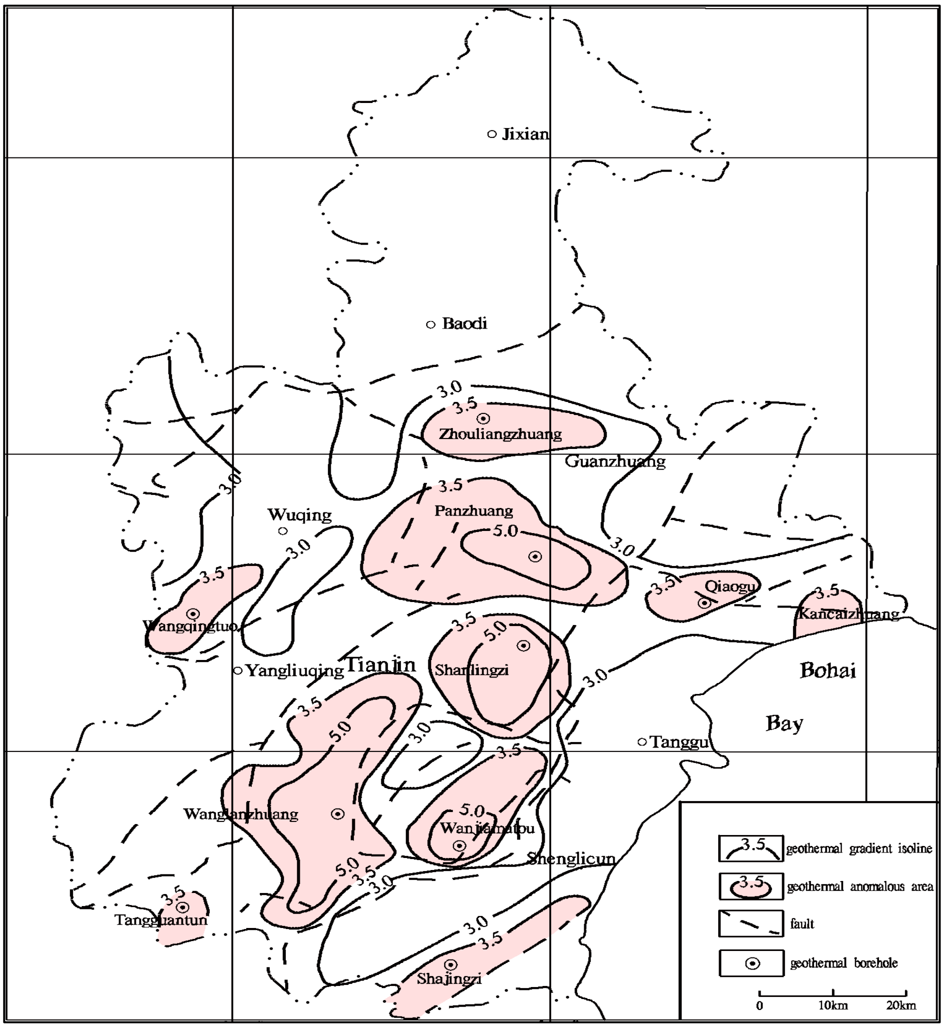

FIGURE 3: The location of geothermal anomaly areas in Tianjin

2.4 Characteristics of geothermal fields

Since the Holocene epoch, the regional sea level has ascended. Several times transgressions have supplied salty materials to the wedge-shaped water mass, which is shallow in the west and deeper in the east in the Quaternary aquifers. The increasing regional erosion has hindered the horizontal movement of geothermal water. The upward heat flow is obstructed by large, thick Quaternary stratum and water masses, and the sealing-off causes further heating of the geothermal water. Although the sealed water generally moves slowly, its velocity is considerable in decompression zones.

The geothermal water is mainly located in the Cangxian uplift range. It consists of "fractured karst geothermal water in bedrock", accumulated in the medium Proterozoic Jixiannian Wumishan (Pt2W), lower Palaeozoic Cambrian (PzH) and Ordovician (PzO) reservoirs; and "porous geothermal water in clastic rock" that exists in Tertiary and Quaternary strata. Cold underground water deposits are located in fissures of the basement in front of the Yanshan Mountain and a shallow porous/fracture aquifer (500-800m depth) is located in the Tertiary and Quaternary strata. The isotope compositions show that the geothermal water is precipitation seepage that originate from the latest glacial period of upper Pleistocene (10000-21000B.P.) (Wang Kun, 2001), and has been sealed off since Holocene. It is a closed deep circulating system.

The geothermal water in fractures in the bedrock has a ^{14}C value (15-4.5 pmc), it is higher than that for water in the pores (7.6-4.5 pmc), and thus the geothermal water in the fractures is younger than the water in pores. After the long geological denudation period, the bedrock has a broad rim affected by weathering and well-developed fractures and dissolved cavities. Meanwhile there is a large outcrop area in the north and west mountains, which means that this is a semi-closed reservoir. On the other hand, the reservoirs in the Tertiary and Quaternary system are closed. Hereby, the deep circular geothermal system can be divided into (Wang Kun, 2001):

(1) Semi-open and semi-closed bedrock subsystems where the karst geothermal water is present;
(2) A closed clastic rock subsystem where geothermal water is present in pores.

Table 3 lists the hydro-geological characteristics of the main geothermal reservoirs in Tianjin (Song D. et al., 2007).

TABLE 3: The Hydro-geological characteristics of main geothermal reservoirs in Tianjin

Reservoir	Distibution	Depth (m)	Lithology	Flowrate (m^3/h)	Temp. (°C)	Hydro-chemistry	TDS (mg/L)
Nm group in late Tertiary	Widely spread in Southern plain	500-1200	Sandstone, silty sandstone	40-60	40-60	HCO_3-Na HCO_3·Cl-Na HCO_3·Cl·SO_4-Na	850-1800
Ng group in late Tertiary	Tanggu,Dagang, Wuqing District	1200-2400	Sanstone with gravel	80-120	65-87	Wuqing: CO_3-Na	1000-1400
						Tanggu:Cl·HCO_3-Na	1500-1800
						Dagang: Cl-Na	1500-2000
Ordovician	Urban area and the surrounding Disricts	950-1900	limestone	＞100	55-76	SO_4·Cl-Na·Ca	4000-6000
Cambrian	Local part	1300-1800	limestone	＞100	68-95	Cl·HCO_3-Na Cl·SO_4-Na	1700-1800
Jixianian in Middle Proterozoic	Widely spread on Cangxian Upfold	910-3190	Sandstone dolomite	＞100	74-103	North: HCO_3·SO_4-Na South: Cl·SO_4-Na	1000-2100

The Jixianian reservoir of the Middle Proterozoic is widespread in Tianjin. The depth to its upper boundary is 988-3000m. Over a 3-5 km width along the Baitangkou fault, the porosity reaches 5-7%. The flow rate is 100-200 m^3/h, and near the fracture it reaches almost 380m^3/h. The upper boundary of the reservoir is at progressively greater depths towards the west. The karst fracture is well developed in this reservoir and has formed strong storage abilities. It is the main productive reservoir in Tianjin. Along the Baitangkou faults, there is a water-abundant zone with a unit flow rate of 6-12m^3/h/m.

3. HISTORY OF GEOTHERMAL UTILIZATION IN TIANJIN

The earliest record of geothermal utilization comes from *The General Chronicle of District around Beijing*, which was published during the Qing Dynasty. Geologist Prof. Zhang Hongzhao refers to it in *The Summary of the Hot Springs in China* in 2006. It describes a hot spring that is located at the Jitou Mountain in Ji County, and people bathing in it to cure illnesses.

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FIGURE 4: Pumping test in situ of first geothermal well in 1936

From the 1950s till the end of the 1960s, some enterprises attempted to use geothermal resources on a small scale, such as for space heating, agriculture, textile mills and potable water.

Geothermal exploration started in the 1970s, at the proposal of Mr. Li Siguang, the former Minister of Geological and Mineral Resources. Through the geological survey of gravity, temperature and drilling, two geothermal anomalous areas were discovered in the urban area surrounding districts with an area larger than 1,000 km^{-2}. The geological institutions carried out a series of exploration and research on geothermal resources in the 1980s, with the financial support of the former Ministry of Geology and Mineral Resources and the United Nations Development Program (UNDP).

By the end of the 1980s, the geothermal resources were being used for space heating, greenhouses, hot springs, therapy and potable water in Tianjin. But the early geothermal utilization was simple and crude. The geothermal water was pumped directly into heating systems without heat exchangers. The heavy corrosion of pipelines and high temperature of waste water caused low heat efficiency and heat pollution.

Through the popularization of heat exchangers, frequency conversion, floor heating and automatic controlling techniques; and especially the success of reinjection tests in 1990s, the geothermal resources have been widely used in many cities for economic planning. Along with the rapid growth of the real estate market, demands for geothermal energy have increased enormously. Figure 5 shows

the fast increase in the number of geothermal wells and total area of space heating (Wang K., Han J., 2007).

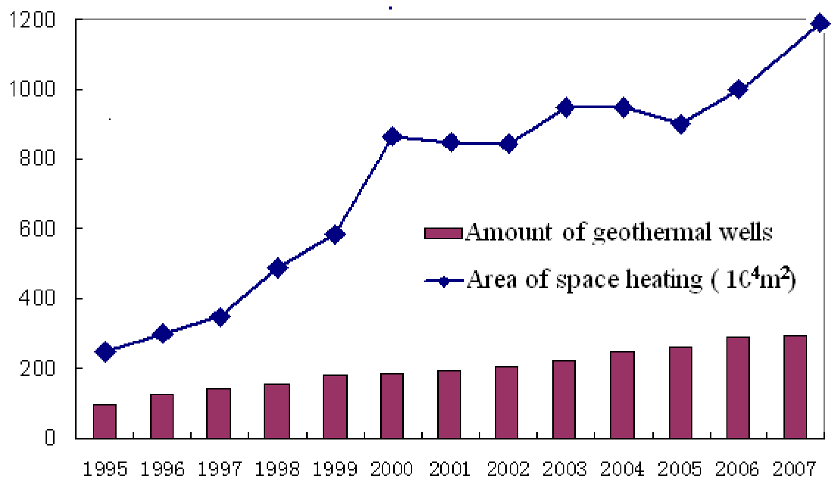

FIGURE 5: The number of geothermal wells and area of space heating in Tianjin

4. STATUS OF GEOTHERMAL UTILIZATION IN TIANJIN

4.1 Geothermal utilization in 2007

Compared with fossil fuels, geothermal energy has the benefits of lower running cost and it is environmentally friendly. By the end of 2007, there were 256 production wells and 38 reinjection wells in production in Tianjin (Zeng M. et al., 2007). The total production rate was 24,500,000m^3 with a reinjection rate of 4,620,000 m^3.

In 2007, the space heating areas covered 12Mm^2, or about 8% of the total heating area in winter (Figure 6). About 114 geothermal wells are used for space heating, mainly supplying to the urban area, Tanggu and Wuqing Districts etc. Every year, about 100,000 families and 850,000 people enjoy the luxury of tap water, geothermal swimming pools and physical therapy from geothermal resources.

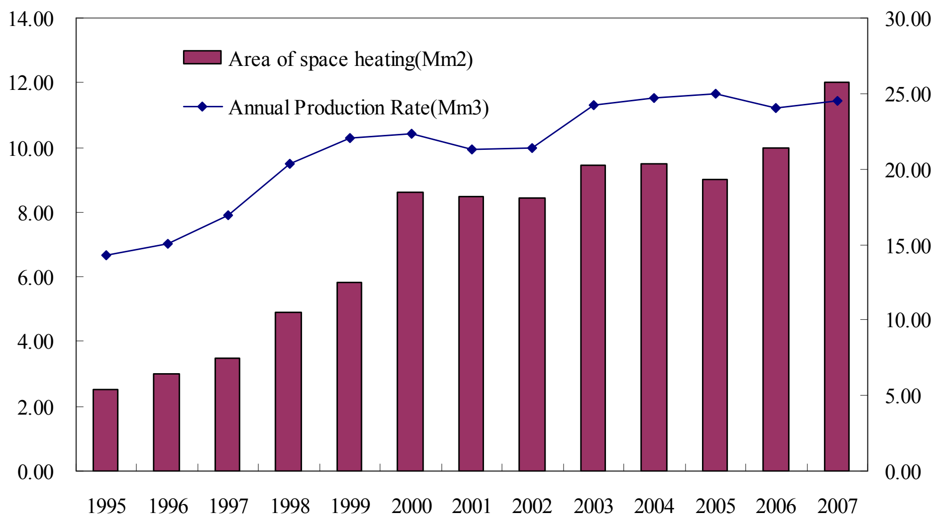

FIGURE 6: The growth of geothermal production rate and space heating area 1995-2007

Geothermal energy is used for space heating of residential and public buildings in Tianjin. It not only saves on investment and running cost, but also brings on evident environmental benefits. According

to incomplete statistics, the extent of geothermal space heating corresponds to replacing 215,600 tons of standard coal, reducing the discharge of coal dust by 1552 tons, sulphur dioxide by 6653 tons nitrogen dioxide by 1996.3 tons and carbon monoxide by 171,400 m^3.

4.2 Contribution of geothermal resources to local economic cooperation and development

China has a rich traditional hot spring culture, which makes geothermal resources one of the unique opportunities for recreational projects. In recent years, real estate and tourism have developed rapidly in Tianjin. The exploration and development of geothermal resources attract investment in hot spring vacation resort projects. Some large scale construction projects are under construction.

For example, the Zhouliangzhuang geothermal field is located in Baodi District, where there used to be deserted salty lands. There were only few farms and one village located there. As a result of the geothermal exploration, the first geothermal well was drilled in 2002 with a natural flow rate of 380m^3/h. The wellhead temperature is 103°C, and the artesian pressure is 4 Mpa. Now, a new town called Zhujiang Hot Spring Town has developed there. The total investment will be more than $140 millions. In 2007, the construction area reached 60 km^2 with a planned population of 200,000 inhabitants. The Hot Spring Town integrates the projects of villa construction, tourism, resorts, and convention and exhibition Centres. Two Universities have set up branches in the Town and started to recruit students in the summer of 2007.

FIGURE 7: Geothermal utilization in Tianjin

The governments of China and Singapore signed the agreement for the Sino-Singapore Eco-City project. The Sino-Singapore Eco City is located between the Tanggu and Hangu Districts of Tianjin's Binhai New Area. It is the second cooperation project after the Suzhou Industry Garden between

China and Singapore, occupying an area of 32 km^2. The construction will begin in July 2008 and will end in 2010. The maximum investment is estimated to be $4300 million. When completed, there will be 300,000 residents living and working in energy-efficient buildings in the Eco City. Besides preservation and restoration of natural ecology, green consumption and low carbon emissions, it is social cohesion that tops the list of features for the eco-city. The geothermal exploration and utilization have been planned.

5. CONCLUSIONS

The exploration and development of geothermal resources have played an important role in many aspects of Tianjin's economical development, such as attracting investment, improving environmental quality and standard of living, expanding tourism and developing industrial and agricultural production. Geothermal utilization brings about remarkable economic, social and environmental benefits,

The Tianjin Municipality puts great emphasis on geothermal resource management. The Geothermal Resources Development and Utilization Plan for Tianjin (2006-2010) were published in 2005. To meet the rapid increase in demand for geothermal resources, it is necessary to enhance the geothermal exploitation and strengthen the research on reinjection into the Tertiary system and the basement reservoir.

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LECTURE 2

BACKGROUND, HISTORY AND STATUS OF GEOTHERMAL UTILIZATION IN TIANJIN

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ABSTRACT

The Tianjin geothermal field is a typical low-temperature system, which is located in the middle-lower reaches of the Haihe River System on the North China plain. The geothermal distribution area is 8700 km^2, about 77% of the total Tianjin area. 10 geothermal anomalies are revealed. As a clean energy, the geothermal resource is widely used for space heating, potable water, agriculture etc. The annual production rate reaches 2450m^3 and the space heating area was about 12 Mm^2 in 2007. The geothermal reserves of 4 geothermal fields have been estimated with attainable resources of 5088×10^4 m^3/a in 2005. It is necessary to enhance the prospecting precision, expanding the exploitation area and strengthen the research on basic technology.

1. INTRODUCTION

Tianjin is located in the north-east of the North China Plain near Bohai Bay, west of the Pacific Ocean, at the lower reaches of Haihe River valley, with The Bohai Sea to the east and Yanshan Mountain to the north.

FIGURE 1: Location of Tianjin

Tianjin belongs to the warm temperature zone and has sub-humid continental monsoon climate. The four seasons are sharply distinguished, and this results in a great difference in temperature and a wide variety of scenery throughout the year. The average temperature in a year is over 12.3°C, and the frost-free period lasts about 200 days. On the average, the annual precipitation is about 600 mm, 75% of which

falls in June, July and August. The sunshine period is relatively long and the solar radiation is quite strong.

The present population of Tianjin is 1,236,700; the total area is 11,900 km^2. Tianjin has jurisdiction over 15 districts and 3 counties. With the largest artificial deep-water harbour and the largest port in the north of China, Tianjin port has the largest container dock groups, and the largest special docks for bulk grain and coke.

Tianjin has relatively rich energy resources, such as coal, oil, gas, geothermal; and thus has an advantage among the coastal cities in China. Its Bohai and Dagang Oil Fields are key state oil and gas projects, turning out 14,430,000 tons of crude oil and 830,000,000 m^3 of natural gas per year. Plentiful geothermal resources are available in Tianjin. Its reserves and utilization of these are ranked number one in China.

2. DISTRIBUTION AND CHARACTERISTICS OF GEOTHERMAL RESOURCES

2.1 Geology

Tianjin Geothermal field is located in a sedimentary-fault basin in the north of the North China Platform and is divided into a northern and a southern part by the Ninghe-Baodi fracture (Figure 2). Most of the area is covered by Quaternary strata. The outcrop of the base rock is limited to the mountain area in the north of Ji County. The northern part belongs to the secondary tectonic unit; the Jibao up-fold, in the Yanshan platform orogen. The southern part lies in the Bohai-Bay Basin. From west to east, the southern part constitutes three tectonic units; the Jizhong depression, the Cangxian upfold, and the Huanghua depression, that are cut into numerous tectonic blocks by several east-west, northwest and northeast trending fractures. On the whole, the centre part is uplifted with the low-lying part in the east and west. The anticline structure is the main regional trend. The main fractures are the Tianjin fracture in the west, the Cangdong fracture and the Baitangkou fracture in the east, and in the middle there are the Haihe and Chenglinzhuang fractures. Several faults accompany them. Most of the geothermal fields are located in the Cangxian uplift.

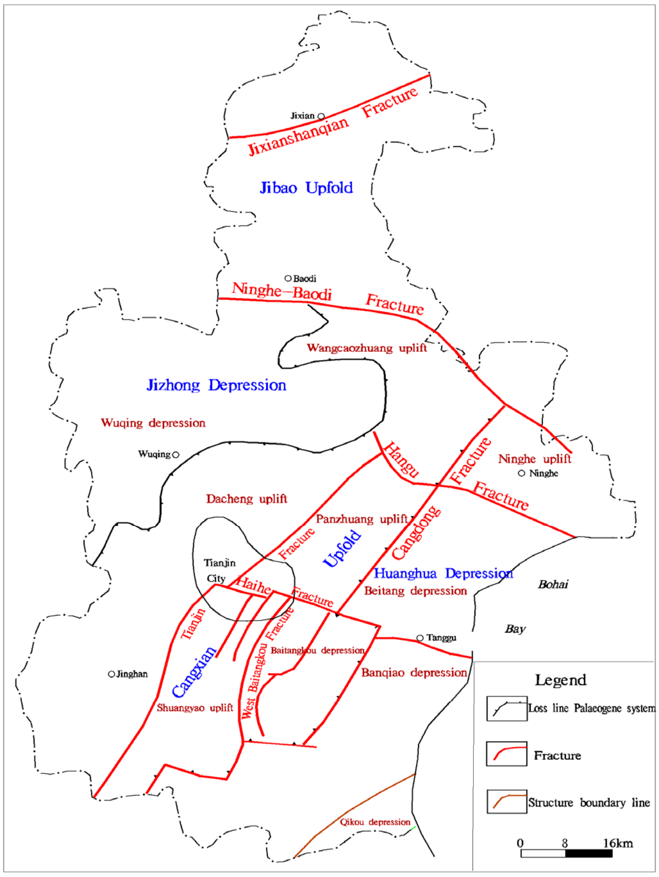

FIGURE 2: Sketch of geological tectonics in Tianjin

2.2 Strata in Tianjin

The general stratigraphy of Tianjin is presented in Table 1 (Tianjin Regional Geological Records, 1992).

TABLE 1: The general stratum of Tianjin

Geological age		Depositional formation	Diastrophism magmatism	Age (Ma)
Era	**System**			
Cainozoic	**Quaternary**	Continential plain, alluvial clastics, some lacustrine and marine deposits	Large depression	1.5±0.5
	Late Tertiary	Inland(near shore) salt and oil bearing lake clsastic	Basic magma effusives, dustpan basin	25±2
	Early Tertiary	Inland lake, red clastics	Basement fault, growth fault	66±2
Mesozoic	**Cretaceous**	Partial absence, inland basin, fluvial lacustrine clastics, intermediate pyroclastic rocks	General uplift	135±5
	Jurassic	Inland basin, coal-bearing calstics and volcanic rocks	Basic effusives, inland faulted basin, volcanic basin	200±5
	Triassic	Absent in late period, inland variegated clastic rocks	Orogen, inland small basin, intermediate magmatic emplacement	235±5
Late Palaeozoic	**Permian**	Continental coal-bearing, clastic rocks	Continental volcanic extrusion	285±5
	Carboniferous	Paralic coal-bearing clastics rocks	Inland large depression	350±5
	Devonian	-	General uplift	405±5
Early Palaeozoic	**Silurian**	-		440±10
	Ordovician	Neritic-littoral limestone, lagoonal dolomite, gypsum	Steady sinking, epicontinental sea	550±10
	Cambrian	Neritic-littoral limestone, sandy shale in early Cambrian		600±10
Late Proterozoic	**Sinian**	-	General uplift	800±50
	Qingbaikou	Neritic calcareous shale, littoral sandy shale, neritic limestone	Steady sinking, epicontinental sea	1000±50
Middle Proterozoic	**Jixianian**	Neritic limestone, littoral-neritic argillaccous carbonate, littoral magnesiaan carbonate, neritic shale		1400±50
	Changchengian	Littoral-neritic shale and dolomite, potassic volcanic rocks, littoral quartz sandstone and limestone, neritic shale, fluvial clastic rocks	Basement fault, submarine eruption, basic dike intrusion	1800±50
Early Proterozoic		?	Orogen	2500±50
Archaic		Basic to intermediate volcanic rocks, multilayered ferro-silicic iron rocks	Sealed folding, gneiss dome, granulite, migmatite	2900±50

2.3 Distribution of geothermal fields in Tianjin

There are 10 geothermal anomaly areas in Tianjin determined by temperature gradients of 3.5°C/100m (Figure 3). Seven of them are distributed in the Cangxian Up-fold. In Table 2 the temperature gradients of the cap rocks area are shown.

TABLE 2: Geothemal anomalies in Tianjin

Geothemal anomalies	Area (km^2)	Highest temperature gradients of cap rock (°C / 100m)
Wang Lanzhuang	534	8.0
Shanglingzi	315	8.3
Wanjia Matou	235	8.8
Pan zhuang	610	6.9
Zhouliangzhuang	180	5.5
Qiaogu	90	5.5
Kancaizhuang	20	5.5
Wangqingtuo	114	5.0
Shajingzi	190	4.5
Tangguantun	40	7.6

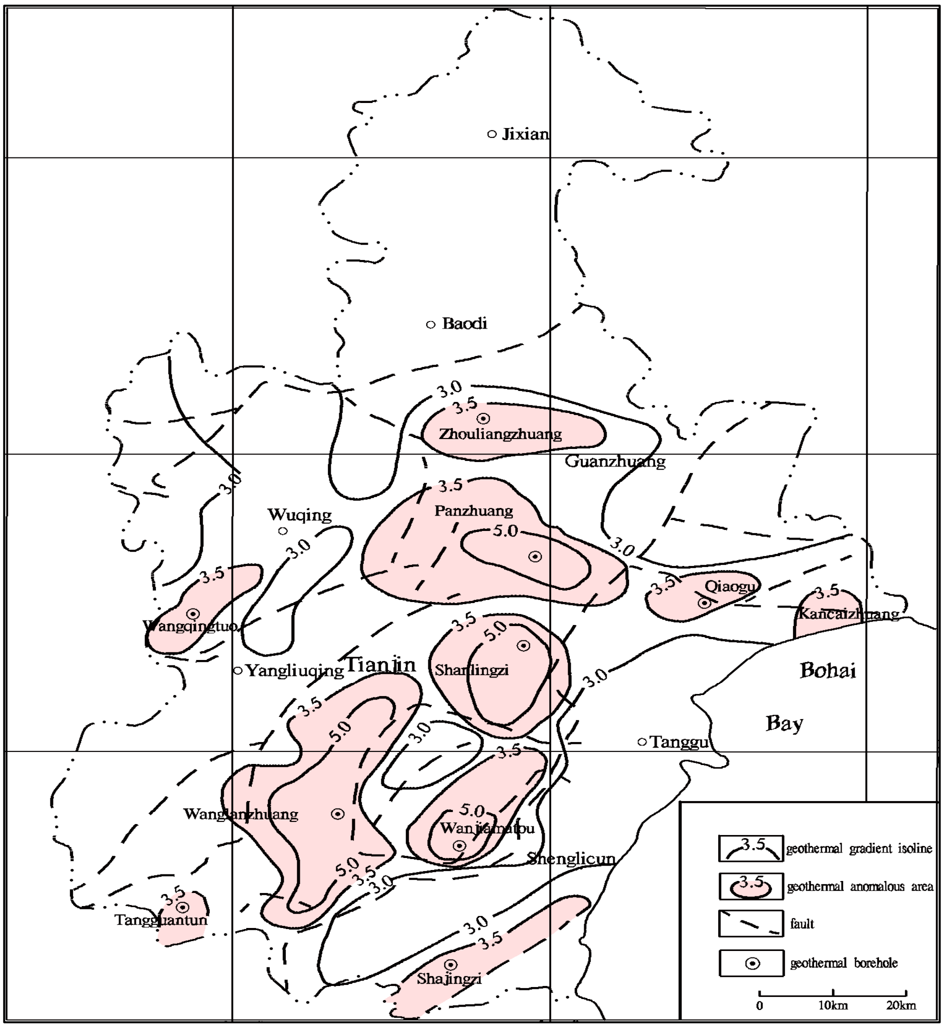

FIGURE 3: The location of geothermal anomaly areas in Tianjin

2.4 Characteristics of geothermal fields

Since the Holocene epoch, the regional sea level has ascended. Several times transgressions have supplied salty materials to the wedge-shaped water mass, which is shallow in the west and deeper in the east in the Quaternary aquifers. The increasing regional erosion has hindered the horizontal movement of geothermal water. The upward heat flow is obstructed by large, thick Quaternary stratum and water masses, and the sealing-off causes further heating of the geothermal water. Although the sealed water generally moves slowly, its velocity is considerable in decompression zones.

The geothermal water is mainly located in the Cangxian uplift range. It consists of "fractured karst geothermal water in bedrock", accumulated in the medium Proterozoic Jixiannian Wumishan (Pt2W), lower Palaeozoic Cambrian (PzH) and Ordovician (PzO) reservoirs; and "porous geothermal water in clastic rock" that exists in Tertiary and Quaternary strata. Cold underground water deposits are located in fissures of the basement in front of the Yanshan Mountain and a shallow porous/fracture aquifer (500-800m depth) is located in the Tertiary and Quaternary strata. The isotope compositions show that the geothermal water is precipitation seepage that originate from the latest glacial period of upper Pleistocene (10000-21000B.P.) (Wang Kun, 2001), and has been sealed off since Holocene. It is a closed deep circulating system.

The geothermal water in fractures in the bedrock has a ^{14}C value (15-4.5 pmc), it is higher than that for water in the pores (7.6-4.5 pmc), and thus the geothermal water in the fractures is younger than the water in pores. After the long geological denudation period, the bedrock has a broad rim affected by weathering and well-developed fractures and dissolved cavities. Meanwhile there is a large outcrop area in the north and west mountains, which means that this is a semi-closed reservoir. On the other hand, the reservoirs in the Tertiary and Quaternary system are closed. Hereby, the deep circular geothermal system can be divided into (Wang Kun, 2001):

(1) Semi-open and semi-closed bedrock subsystems where the karst geothermal water is present;
(2) A closed clastic rock subsystem where geothermal water is present in pores.

Table 3 lists the hydro-geological characteristics of the main geothermal reservoirs in Tianjin (Song D. et al., 2007).

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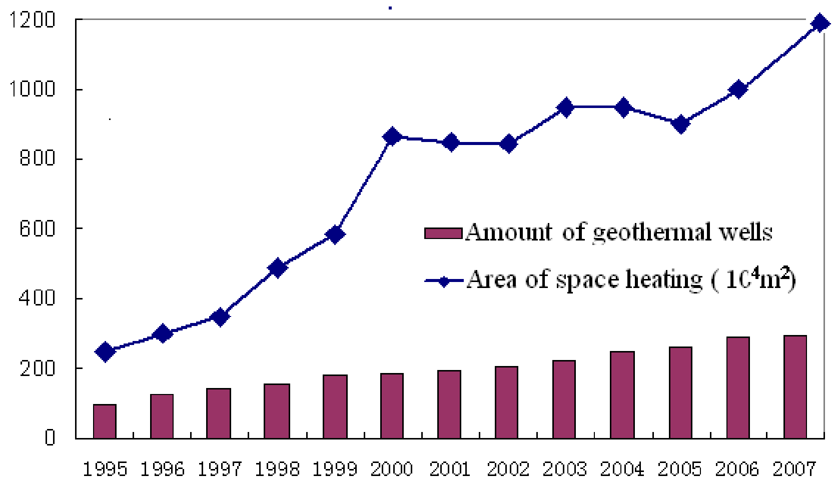

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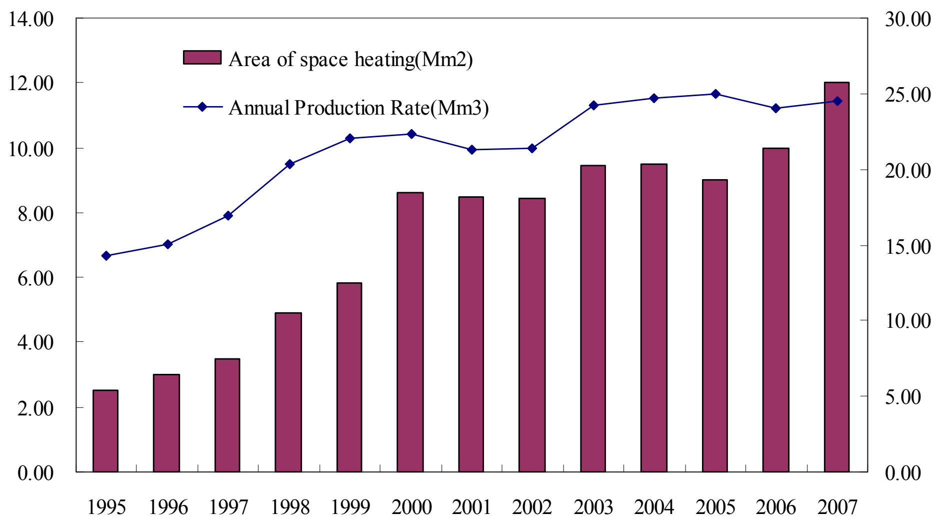

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LECTURE 3

MANAGEMENT OF GEOTHERMAL RESOURCES IN TIANJIN

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ABSTRACT

The geothermal resources in Tianjin are classified as low-medium geothermal resources in sedimentary basins. As an environmentally benign energy resource, geothermal is widely used for space heating, potable water, agriculture etc. This paper gives a brief introduction to the laws, policies and processes concerning geothermal resources, exploration and development in Tianjin. The main contents of the Plan for Geothermal Development and Utilization in Tianjin are reviewed from a sustainable point of view. Policies encouraging the application of reinjection and integrated technologies are amply discussed and exemplified here.

1. INTRODUCTION

1.1 The laws and technical standards in China related to mineral and geothermal resources

The main laws and statutes related to the exploration, development and reinjection of mineral resources and geothermal resources are listed here:

1. Mineral Resources Law of The People's Republic of China (Order No. 74 of the President of People's Republic of China)
2. Rules of Implementation of the Mineral Resources Law (Decree No.152 of State Council of People's Republic of China)
3. Regulation For Registering To Explore For Mineral Resources Using The Block System (Decree No.240 of State Council of People's Republic of China);
4. Regulations For Registering To Mine Mineral Resources (Decree No.241 of State Council of People's Republic of China)
5. Regulations For Transferring Exploration Rights and Mining Rights (Decree No.242 of State Council of People's Republic of China)
6. Regulations For Geological Data Management (Decree No.349 of State Council of People's Republic of China)
7. Provision For Collection and Management of Mineral Resources Compensation (Decree No.150,222 of State Council of People's Republic of China);
8. Others promulgated by related department.

The main technical standards and criterions are:

1. Standard for Drinking and Tap Water Quality (GB5749-2001);
2. Standard for Irrigation Farming Water Quality (GB5084-92);
3. Standard for Groundwater Quality (GB/T14848-93);
4. Standard for the Classification of Groundwater Resources (GB15218-94);
5. Demands For Modelling of Groundwater Resources Management (GB/T14497-93);
6. Geological Exploration Standard for Geothermal Resources (GB11615-89);
7. Appraisal Measures for Geothermal Resources (DZ40-85);
8. Others.

1.2 Main contents

It is prescribed in the Mineral Resources Law of the People's Republic of China that:

1. Mineral resources shall be owned by the State. The State's ownership of mineral resources shall be exercised by the State Council.
2. Anyone who wishes to explore or mine mineral resources shall apply for and obtain upon approval, in accordance with law, the respective exploration and mining rights, and shall carry out the registration procedures.
3. The department in charge of geology and mineral resources under the State Council shall be responsible for supervising and administering the exploration and mining of mineral resources throughout the country. The department in charge of geology and mineral resources under the people's governments of the provinces, autonomous regions and municipalities directly under the central government shall be in charge of supervising and administering the exploration and mining of mineral resources within their respective administrative areas.
4. The State shall adopt the system so that exploration and mining rights are to be obtained with compensation.
5. Anyone who mines mineral resources must pay resource tax and mineral resource compensation of relevant provision of the State.

All the above prescriptions can be summarized as following: Firstly, mineral resources are owned by the State; secondly, the State implements the rights of the ownership, the utilization and the management of mineral resources, through the system of registration for mineral exploration, for examining and approving mineral mining, for obtaining exploration and mining rights with compensation. Thirdly, the State Council has licensed the practice of unified management of mineral resources, assigned to the whole country, to the department in charge of geology and mineral resources under the State Council (Tao Q., Hu J., 2007).

2. LAWS AND SYSTEM OF GEOTHERMAL MANAGEMENT IN TIANJIN

2.1 Provision of geothermal management in Tianjin

In order to strengthen geothermal management Tianjin Municipality set up a special department of geothermal management in 1994. Based on state laws and technical standards, the Provision of Geothermal Resources Management in Tianjin was promulgated in 1995; the Regulation of Mineral Resources in Tianjin was enacted in 2001.

With regard to the exploration and development of mineral resources, the department of geothermal resource management shall practise the policy of unified planning, rational distribution, exploration, rational mining and cascaded utilization. According to state and local laws and regulations a series of effective process have been established, including: permissions for exploring and mining geothermal resources, for examination and approval of the development plan and utilization proposal for geothermal resources, for supervision of the drilling of geothermal wells, for production evaluation of single geothermal wells, for annual investigation of issues regarding rational development and utilization of geothermal resources, for environmental protection and other obligations in accordance with the law, etc.

2.1.1 Registering to explore geothermal resources

Prior to exploration for mineral resources or drilling of geothermal wells, each exploration or drilling project shall be examined, approved, registered, and licensed by the department in charge of geology and mineral resources under the people's government of the Tianjin Municipality. It includes the following proceedings:

1. Application for exploration rights;
2. Exploration-rights applicant shall pay a fee for the use of the exploration rights (hereafter referred to as the exploration fee) and a reimbursement fee for exploration rights;
3. Determination of the mineral resource areas for exploration with Block Registration System;
4. Period of validity for an exploration license is no more than 3 years;
5. Obligations that exploration licensees should perform.

2.1.2 Registering to mine geothermal resources

Similar to geothermal resource exploration, mining projects shall be examined, approved, registered, and licensed by the department in charge of geology and mineral resources under the people's government of the Tianjin Municipality. It includes the following proceedings:

1. Application for mining rights;
2. Mining-rights applicant shall pay a mining fee and a reimbursement fee for mining rights;
3. Payment for geothermal resource compensation;
4. The length of time for a valid mining license shall be decided in accordance with the magnitude of the mining project, but shall be less than 30 years;
5. Obligations that mining concessioners should perform.

2.2 System of supervision and examination of geothermal production

The administrative department in charge of geology and mineral resources supervises and examines the geothermal production. The approving authority shall examine its application as to the limits of its mining area, the mining design or plan for mining, the production technique and safety and the environmental protection measures, in accordance with the law and relevant state provisions. The geothermal mining concessioners should adopt rational and scientific drilling techniques and rational production planning, to prevent overproduction and environmental pollution. For this purpose, the water level, temperature, flow rate and quality of geothermal wells should be monitored.

3. PLAN FOR GEOTHERMAL DEVELOPMENT AND UTILIZATION IN TIANJIN

With the increased geothermal development and utilization, the sustainable potential and economy of geothermal resources is emphasized in geothermal management. A Plan of Geothermal Development and Utilization for 2006—2010 has been compiled and authorized by the Tianjin Municipality (Song D., Wang K., Xu P. et al., 2006).

3.1 Regional division methods

Each reservoir is divided into three planning sub-areas, depending on its recoverable reserves and monitoring data (water level, pressure etc.) for the past year. The three sub-areas are: restricted productive zoning, permissible productive zoning, and geological survey zoning.

The restricted productive zoning is usually the geothermal field which has been producing for a long time and the annual production rate has approached increased the allowed recoverable reserves of the geothermal filed, and water level drawdown increases rapidly. In the allowable productive zoning, the annual production rate is less than the allowed recoverable reserves of the geothermal filed, the water level drawdown is less intense, and the resource potential is still considerable. The geological survey zoning means that little geological exploratory work has been carried out in the geothermal field.

3.2 Factors of planning

Several factors are involved in the Plan for Geothermal Development and Utilization for 2006-2010.

1. Through the application of heat pumps or other technology for saving energy, the temperature of waste water should be lowered to below 25°C for most geothermal utilities;
2. The annual reinjection rate will reach 6,000,000m^3, which account for 30% of the total production;
3. Some older geothermal utilities with low efficiency should be rebuilt, especially in zones of relatively poor production;
4. Automatic metering and monitoring systems shall be set up by the end of 2010;
5. The government shall encourage scientific and technological research on the exploration and development of mineral resources, promote advanced technology and raise the scientific and technological level of geothermal exploration and development.

4. INCENTIVE POLICIES OF GEOTHERMAL REINJECTION AND CASCADED USE

Reinjection studies were started in Tianjin in the 1980s. After a series of tests, reinjection into the basement reservoir is now approved and considered a feasible way to maintain the reservoir's pressure and prevent heat and chemical pollution by waste water.

In 1996, the administrative department revised the permit process for mining of geothermal resources. Space heating projects shall now involve reinjection when mining enterprises develop geothermal energy in a basement reservoir. Furthermore, the government took some measures to promote the drilling of reinjection wells and rebuilding old geothermal utilities. Initially, a 70% mineral resource compensation of the reinjection rate is exempt, if a doublet system is used. The mining concessioners can also apply for protection projects to get governmental subsidy (Wang K., Han J., 2007).

Now, there are about 38 doublet reinjection and production systems in Tianjin. The annual reinjection rate reaches 4.6Mm^3. Reinjection has become an important factor in geothermal management to ensure sustainable geothermal development.

5. ANALYSIS EXAMPLE

5.1 Demonstration projects on geothermal reinjection and cascaded utilization

The realty project of Haihe New World is located in the centre of the Urban area in Tianjin. The building area is 235,000m^2. The geothermal energy is used for space heating and tap water for more than 1600 families in this residential area. There are three geothermal wells. Two of them (WR93D, WR94D) are a reinjection and a production doublet systems respectively. Both are drilled into the dolomite carbonatite reservoir in Proterozoic strata. The third one (WR92) is in an Ordovician reservoir. The hydrological characteristics of three geothermal wells are listed in Table 1.

TABLE1: The characteristics of geothermal wells in the geothermal utility of Haihe New World

Geothermal Well	**Depth (m)**	**Wellhead Temp. (°C)**	**Flowrate (m^3/h)**	**TDS (mg/L)**	**Type**
WR92	1388.6	48.5	43.92	>4000	Production
WR93D	3248.89	81.5	84.02	1830	Production
WR94D	3168	82	106.48	1830	Reinjection

All buildings in the residential area are heated by floor heating during winter. After the heat exchange, the waste geothermal water is reinjected. Geothermal water takes a 4,650 kW basic heat load, and the residual peak load of 5,600 kW is supplied by heat pumps during the coldest period. The heat supplied by the Ordovician geothermal well is used for tap water. Figures 1 and 2 show the geothermal utility and its technical flow-chart.

FIGURE 1: The geothermal utility of the Haihe New World Residential Area

The initial investment in this geothermal station is about $1,350,000. The annual overall operational cost for space heating is about $540,000, which is equal to $2.3 per unit area of space heating. Compared with space heating by coal-fire boilers, the initial investment in a geothermal utility is over $280,000 in excess, but its running costs saves about $130,000 every year. Meanwhile, the geothermal use can reduce the discharge of sulphur dioxide, nitrogen oxide, carbon dioxide and coal dust.

As one of the projects for mineral resource protection, the Haihe New World geothermal projects got the financial support of $340,000 from the Ministry of Finance in 2007 (Wang K., Han J., 2007).

5.2. Discussion

Since 1996, all geothermal production from the basement reservoir is balanced by reinjection, employing a doublet well system. Many singlet production wells drilled before 1996 are, however, still used for production. The geothermal waste water is discharged into the sewage system directly after heat exchange. The large scale production has already resulted in a rapid drawdown of the water

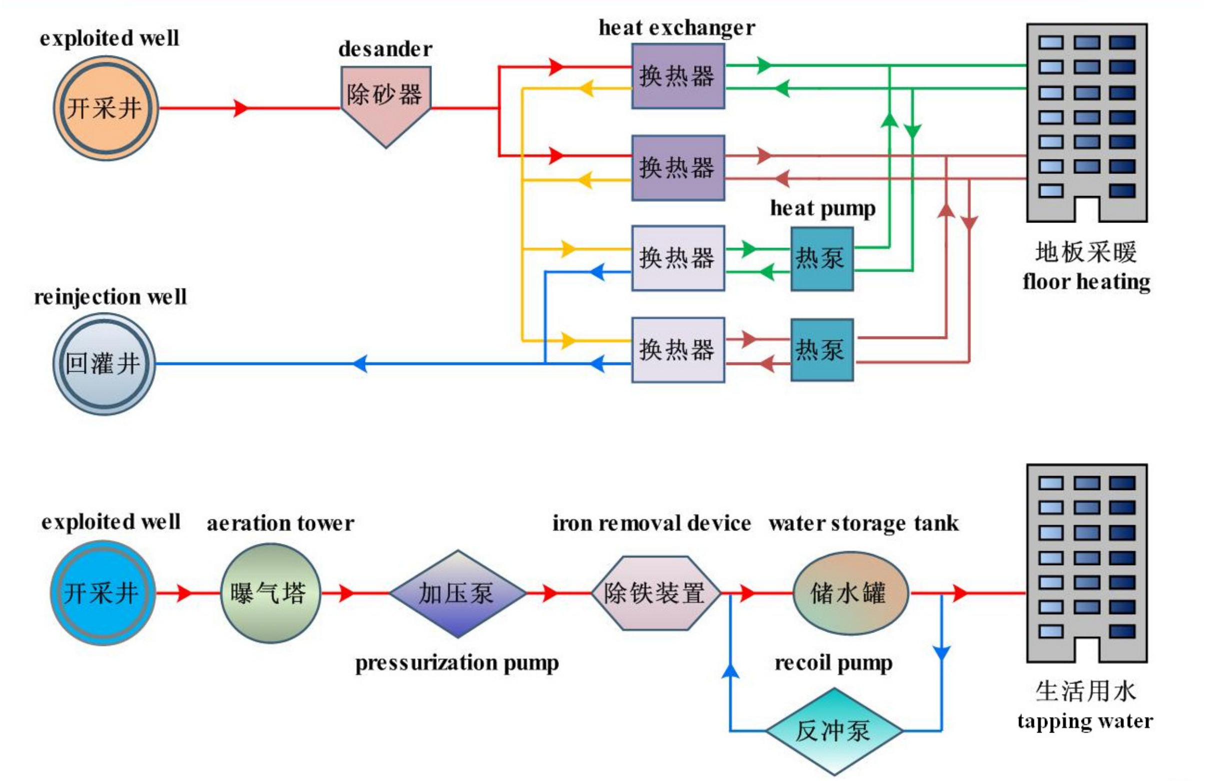

FIGURE 2: Flow-chart for the space heating system Haihe New World Residential Area

level. It is necessary and urgent to construct additional reinjection wells for the early singlet production wells in order to prolong the lifetime of these geothermal reservoirs.

However, the drilling of additional reinjection wells has been hampered by lack of funds and space. The facilities and technology employed in the early geothermal utility are simple and crude, and the construction cost of additional reinjection wells is high. Meanwhile, most production wells drilled before 1996 are located in the Urban area and in many cases there is not enough space to drill a reinjection wells. Therefore, the administrative departments in charge of geothermal resources and space heating have put forward a plan for recombining early production wells into doublet systems of reinjection and production wells in 2006. This proved successful in the Urban area. Through adjusting the heating system, 3 adjacent production wells located in three different residential areas were combined. One is selected as a reinjection well; the others are production wells and supply the space heating for three residential areas.

6. CONCLUSIONS

The policies and regulations are effective measures to promote exploration, development, utilization and protection of geothermal resources and to ensure the present and long-term requirements of city construction in Tianjin. Some related policies of geothermal management will be implemented in the future.

Since 2006, a unified system in which the geothermal mining-rights shall be paid for by the mining concessioner with a geothermal mining fee has been in operation. The mining fee shall be collected according to the standard of $1,000RMB per geothermal well per year. Anyone who applies for geothermal mining-rights to mineral deposits already discovered by the State, at the State's expense, shall pay, in addition to the mining fee, a reimbursement fee for mining rights which have been appraised and confirmed. The detailed specifications for managing the use of the funds mentioned above will be formulated in the near future by the department in charge of geothermal resources jointly with the department in charge of finance under the City Municipality.

Monitoring is the basic work for exploration, potential evaluation, development and management of geothermal fields. The automatic metering and monitoring will be in fully operational by the end of 2010. The monitoring and research on reinjection should be strengthened in the future.

Reinjection should be an essential part of sustainable geothermal utilization. But reinjection into the sandstone reservoir of the Tertiary system is still a great technical problem in Tianjin. Jointly with the department in charge of finance and space heating, some policies will be established for encouraging the combination and optimization of early geothermal utilization systems. Therefore, the development of geothermal resources will be continued.

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LECTURE 4

MONITORING AND RESOURCES EVALUATION OF THE GEOTHERMAL FIELDS IN TIANJIN

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ABSTRACT

Geothermal monitoring was initialized in the 1980s, in order to better develop and utilize the geothermal fields. After more than 20 years of continuous improvement the geothermal dynamic monitoring system has been set up in Tianjin. Meanwhile, the technical criterion for monitoring of low-medium geothermal field in Tianjin was compiled in 2006. The intelligent management Net PC system was installed to solve the difficulties in estimating collective costs and monitoring administration, research and development. The system can carry out real-time monitoring for all stages of development, raising the level of geothermal administration to a new level. It is very helpful for scientific planning and management of geothermal development and utilization in Tianjin. Based on the continuous geothermal monitoring, a new evaluation of geothermal resources in the plain area of Tianjin had been carried out from 2005 to 2007. The optimized plans are put forward for future geothermal development.

1. INTRODUCTION

Geothermal monitoring was initialized in the 1980s, in order to better develop and utilize the geothermal fields. After more than 20 years of continuous improvement, the geothermal dynamic monitoring system has been set up in Tianjin. Meanwhile, the technical criterion for monitoring of low-medium geothermal fields in Tianjin was compiled in 2006. The analyses and research of large dynamic pressures, temperatures and flow rates of the geothermal wells, are useful for scientific planning and management of the geothermal development and utilization in Tianjin.

In 1995, the administrative geothermal resources department began to finance geothermal monitoring in Tianjin. The geothermal wells were fewer than 50 in 1996, but in 2007 there were 291 wells (Song D. et al., 2007). Additionally, monitored area was gradually enlarged from the urban area to the whole jurisdiction of Tianjin. In the meantime, the monitoring methods and equipment have constantly been improved; from manual work in the beginning, till the current automatic metering of the production and reinjection rates in most geothermal wells. Remote automatic monitoring of water level, pressure, temperature, and flow rate has been carried out in some geothermal wells. The geothermal monitoring has become an important part for the geothermal utilization and research.

2. BASIC MONITORING CONTENTS

The geothermal observation net covers 15 districts and 2 counties in Tianjin.

2.1 Main contents

The main functions of geothermal monitoring include:

(1) Investigation of production status of every geothermal station, such as heating area or number of families using geothermal water; and condition of monitoring facilities, such as thermometers and pressure gauges of geothermal wells.
(2) Monthly collection of data on water level, temperature, and flow rate of production and reinjection wells.
(3) Chemical analysis, where water samples are taken from control wells during winter. The samples are representative of the main geothermal field, ranging from Tertiary to Proterozoic.
(4) Analyzing the technical problem of production and reinjection doublet system during the space heating period, and note taking on possible technical faults, such as the decline in reinjection rate, corrosion etc.
(5) Maintaining and updating the monitoring facilities.
(6) Predicting the development potential of the geothermal production and reinjection by modelling.

2.2 Technical criterion

(1) Geological exploration standards of geothermal resources (GB11615-89).
(2) Appraising measures of geothermal resources (DZ40-85).
(3) Technical standards of dynamic monitoring of low-medium geothermal resources in Tianjin (2005).

3. GENERAL STATUS OF GEOTHERMAL MONITORING IN TIANJIN

The administrative geothermal resources department finances the geothermal monitoring, according to the provisions of the management and the use of mineral resources. Fieldwork, such as; monitoring, investigation, maintenance and update of monitoring facilities, geophysical logging and geochemical sampling is based on the status of geothermal utilization and monitoring data from the previous year. After analyzing the water quality and interpreting the temperature and pressure logs, the annual report of geothermal monitoring is compiled. In 2007, 291 geothermal wells were monitored (Figure 1). Table 1 shows the detailed information about the monitoring of geothermal fields in 2007 (Zeng M. Ruan C. et al., 2007).

3.1 Routine monitoring work of geothermal wells

(1) Topographic measurements: Measuring the altitude of the base point of geothermal well is necessary to adjust the effects of ground elevation changes on the water level in geothermal wells.
(2) Static and dynamic water level measurements and measurements of corresponding temperatures in production and reinjection wells, instantaneous production and reinjection rate, and measurements of stable temperature when the well is pumping or during reinjection.
(3) Investigation of the geothermal utilization, such as utilization type and amount of usage, and temperature of feed water and waste water.

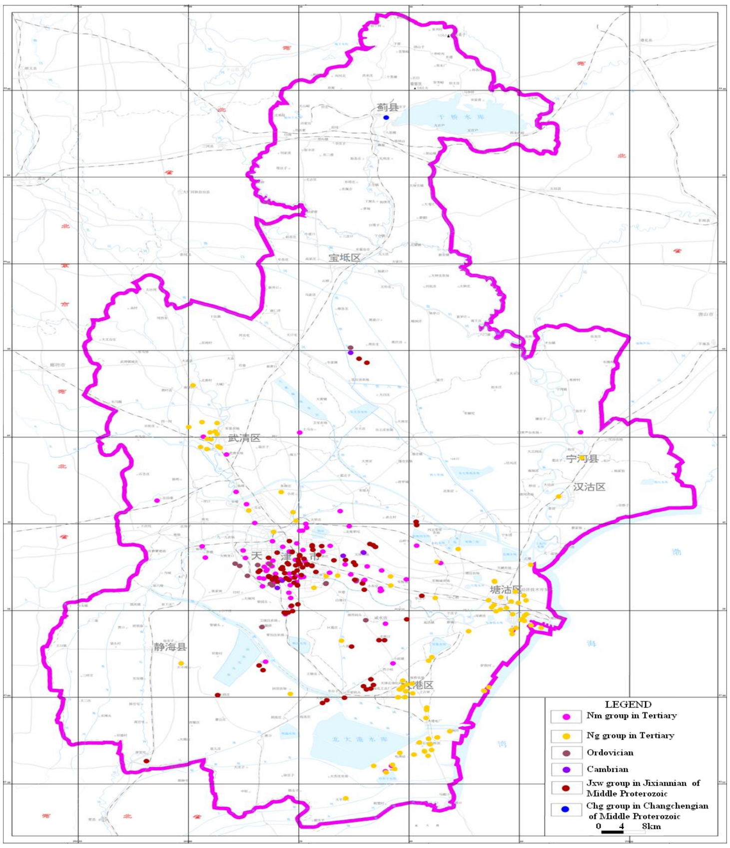


FIGURE 1: Location of geothermal wells in Tianjin

TABLE 1: Schedule of geothermal monitoring in 2007

Item	Contents			Unit	Workload
Fieldwork	Dynamic monitoring	Key wells	Water level, pressure, temperature, flow rate	wells × times	127×24
		Normal wells	Water level, pressure, temperature, flow rate	wells × times	164×12
	Investigation	Production / reinjection rate		wells	291
		Status of geothermal utilization		wells	291
		Monitoring facilities of geothermal wells		wells	291
		synchronous monitoring		wells × times	291×2
	Maintenance of monitoring facilities			wells	12
	Geochemistry	Amount of wells		wells	99
		Amount of wells		wells	11
	Geophysics logging	Temperature		wells	1
		Pressure		wells	1
Research work	Chemical analysis of geothermal fluid's quality			wells	99
	Logging Interpretation of geothermal wells			wells	1
	Monthly report and database			month	12
	Summarize of the synchronous monitoring			times	2
	Figures			figure	85
	Tables and graphs			sheet	45
	Annual report and information system			report	1

(4) Monthly and annual statistics of production rate and reinjection rate, in order to collect mineral resources compensation.
(5) Maintenance of the monitoring facilities, including: special tubes for water level measurements, precision of water level meters, flow rate meters, manometers, and thermometers.
(6) Identical monitoring in the beginning and at the end of the space heating period.

3.2 Terms of experiment analysis at lab

During the space heating period, in the winter, geochemical samples are taken from representative geothermal wells, in order to analyse the long-term changes in geothermal water quality. The analysis includes hydro-chemical analysis of sulphur, iron and isotope.

The layout of sampling points is decided by regional hydro-geological conditions, the reservoir, the recharge, the pathway of the geothermal flow, and the type of the utilization. The continuity of the data should also be regarded. The geochemistry analysis of geothermal fluid will be used for identifying the distributive characteristics, analyzing the origin and the recharge of the geothermal fluids.

3.3 Pressure and temperature logging in geothermal wells

Pressure and temperature logs from the geothermal wells, from several years of production or reinjection can not only provide information on the exact pressure and temperature conditions of the geothermal reservoir, but also the effects of the reinjection fluid upon the geothermal reservoir (Figure 2 and 3).

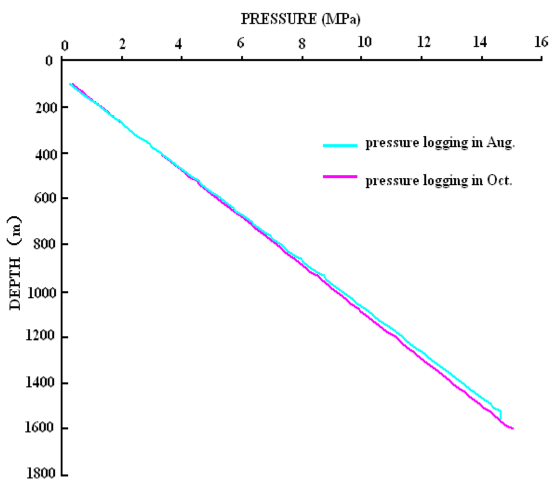


FIGURE 2: Pressure logging curves of reinjection well HX-25

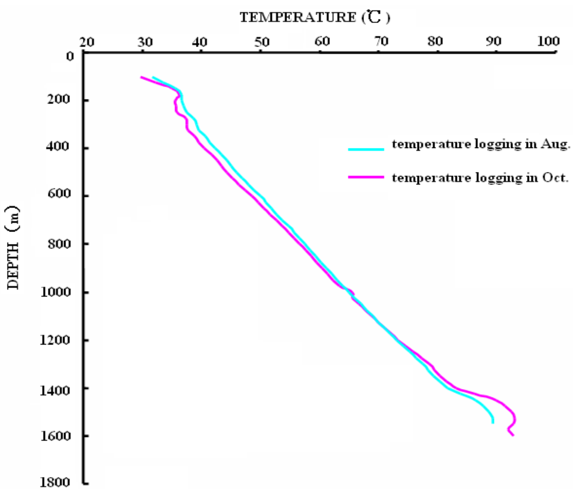


FIGURE 3: Temperature logging curves of reinjection well HX-25

3.4 Layout of key monitoring net

Because there are already more than 300 geothermal wells in 15 districts and 2 counties, and the water levels in most geothermal wells are observed manually few representative geothermal wells are selected to make up a key monitoring network. In order to obtain the data systematically and to analyse the dynamic nature of the geothermal resources objectively, the layout of a key monitoring network is planned as follows:

(1) *District and reservoir*: the observation points are chosen from the productive centre of the geothermal fields according to the geological conditions of the geothermal field and the development of the reservoir. Then the dynamic changes of geothermal development of every district, geothermal field and reservoir can be effectively monitored.
(2) *Geological tectonics*: the key observation points are distributed along the main fracture zones or tectonic elements.
(3) *Continuity and integration of data*: it is better to use data from long-term production wells, to avoid the effects caused by production start-up. Furthermore, the data should be continuously updated and integrated.

Usually the technicians monitor normal points and key points twice a month. In 2007, there were 127 key observation points, about 44% of the total number of geothermal wells in the area. There are 43 key points located in urban areas; the rest is in rural areas.

3.5 General analysis and annual reports

3.5.1 Monthly reports and the database

All observation data is collected and added to a geothermal monitoring database. From the analysis, a monthly report is compiled about the capability and performance of each geothermal well. The geothermal mining enterprises have access to these reports.

3.5.2 Synchronous monitoring

Since 2004, identical monitoring has been carried out in April and October (at the end and beginning of the space heating period). The data of the water level (Figure 4) and condition of the monitoring facilities will immediately inform the geothermal mining enterprises of failure, so that they can examine and repair the equipment and, if necessary, install a submersible pump at a suitable depth.

3.5.3 Annual report

Mathematic modelling is an important tool to study the changes in geothermal reservoirs. Based on fieldwork, lab analysis and geophysical logging, combined with the historical changes of the geothermal reservoir, evolution in pressure,

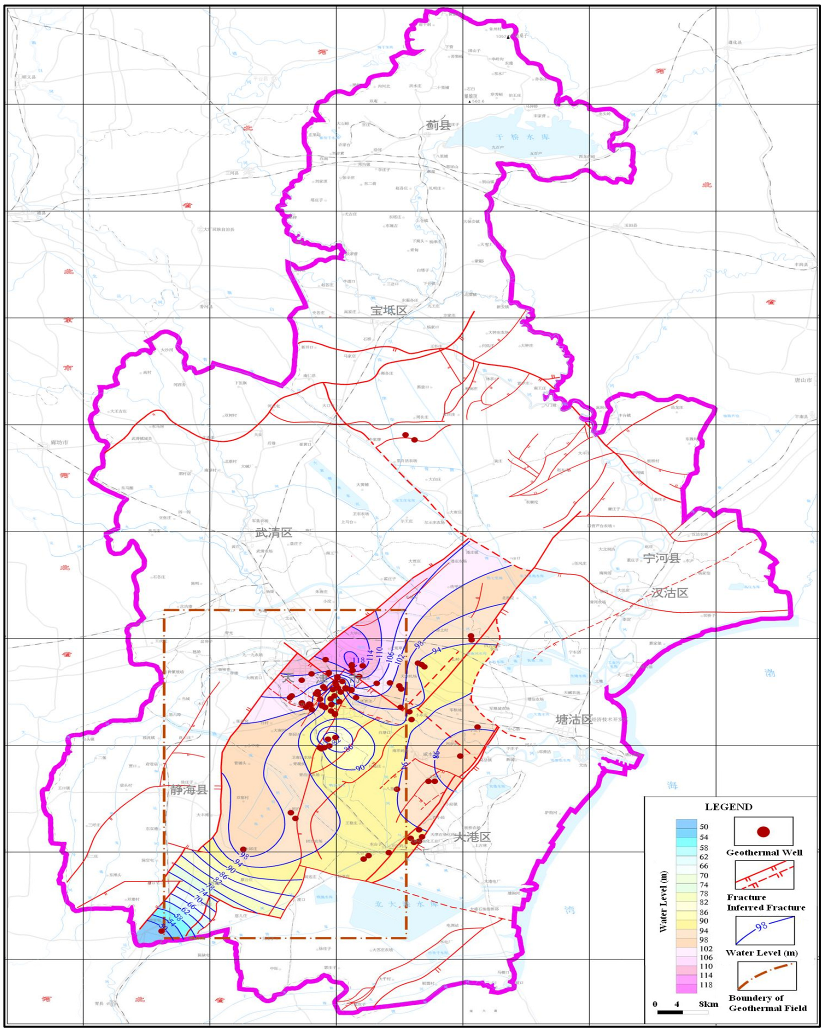


FIGURE 4: Contour of water levels of Jxw reservoir in Proterozoic, 2007

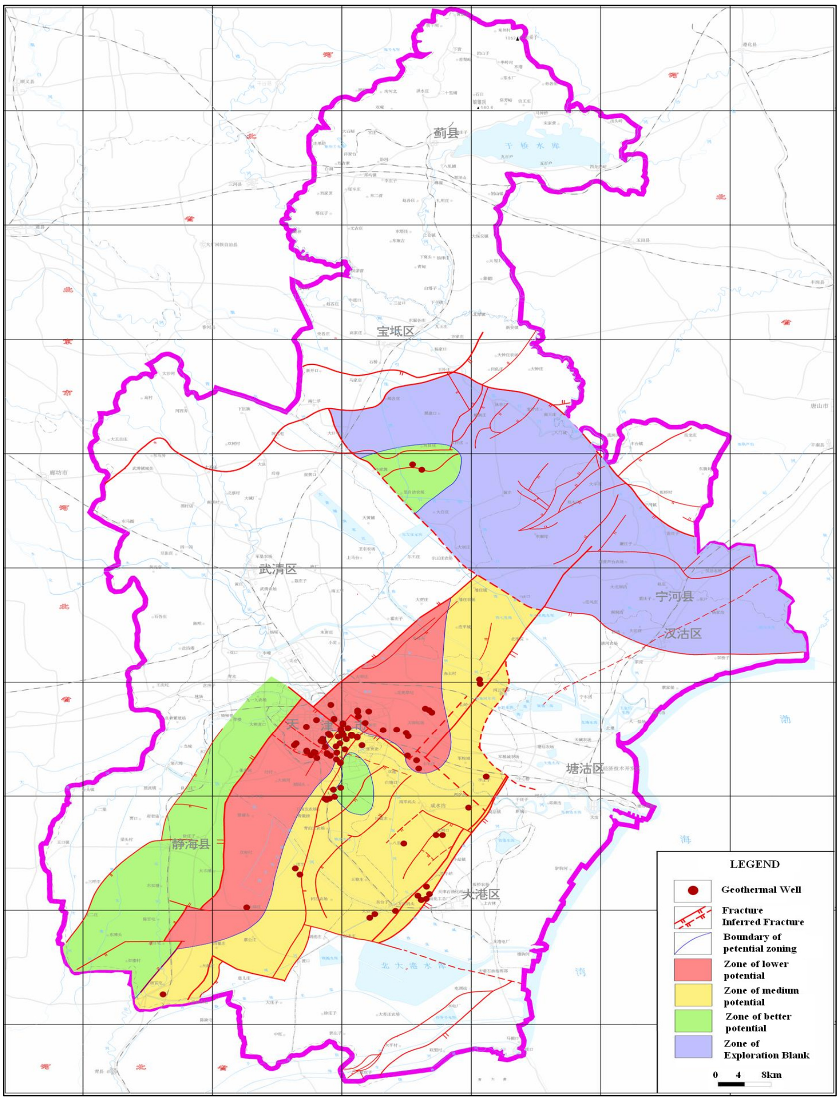


FIGURE 5: Zoning of development potential of Jxw reservoir in Proterozoic

temperature and chemistry can be simulated and predicted by numeric modelling, presented in an annual report. Every short-term development potential of geothermal reservoirs has been predicted (Figure 5). Suggestions on geothermal development and management are put forward in the annual report.

4. AUTOMATIC METERING SYSTEM OF GEOTHERMAL WELLS

4.1 The components of the geothermal intelligent management system

4.1.1 Management information system

The management information system (MIS) is based on management science, information science, computer science, statistics and operations. MIS can be used for collecting, transferring, storing, processing, and utilizing information. It is not only a technical system, but also a management system and it efficiently stores, processes and manages information (Guo C. et al., 2001).

4.1.2 Geographical Information System

The Geographical Information System (GIS) is based on a geographical information databases. GISs collect, store, manage, operate, analyse, simulate and display space-related data, and through geographic analysis, providing dynamic geographical information that can be of great use for management. It gives comprehensive assessments, quantitative analyses on geothermal monitoring

(He M., Li C., Zhu J., et al, 2004). By using the functions of spatial data analysis, GIS create vector maps and find the direct relationship between map and data, i.e. GIS can create the map from the data and the data from the map. The system makes a detailed analysis of the information interprets the text data and maps it.

4.1.3 Intelligent information system

The intelligent information system (IIS) is an application system where information technology and artificial intelligence technology are applied in specific fields. By using processing techniques and computer intelligence, IIS can solve process and logically analyse complex and large numbers of data. In the 1980s, operations research, with in-depth interdisciplinary research, was applied to management information systems as a new intelligent information discipline in the decision support system (DSS). Intelligent systems play an important role in realization of the intelligent judgment of the geothermal data. The systems send out warnings signals, when the geothermal station is improperly operated. This saves manpower and at the same time it limits the effect of human error.

4.1.4 Computer network

Network transmission is the media which transmit the collected information accurately and efficiently. Up to now, the most frequently used transmission system is the three-tier network composed by the network client, the server and the host. The outermost layer node of the typical three-tier network is a personal computer, which is connected to the local server. The computer stores data and manages external equipment used by the clients. As long as the manager has a computer, which has been connected to the three-tier system, (s)he will be able to retrieve the parameters from the local server and the host.

4.1.5 Wireless communications

The rapid evolution of communication technology is of great significant to the information system, especially the mobile communication (Wang H., 2007). Because of the built-in wireless computer modem, it is easier to connect computers to one another and thus to increase their capacity and adaptability.

4.2 Function of intelligent management system

The development of geothermal resources uses the monitoring capability of IMS, especially to monitor the production volume, production quality and the dynamic parameters. Its purpose is not only to collect the necessary dynamic data, but also to monitor the state of system operation and to manage the collected data. The management system server receives dynamic data from all remote data transmission terminals and organizes it. The software on the server analyses the data and assess the situation of the system operation.

Microsoft Access is used as a database platform and Visual Basic 6 as a development tool. In order to provide a humane management interface the geographical information system is included into the intelligent management system, so that all the property information of the geothermal sites can be closely linked to the spatial information, and visualization of the intelligent management system can be enhanced. The system includes historical data statistics, report creation, printing, trend forecasting, warnings and its disposal methods. The system can also be connected to any of the sites in order to monitor them.

To sum up, the upper-management system with powerful management functions and control methods has the function to support a variety of communication networks, communication methods and communication rules. Through monitoring all the geographical sites, the system can store information

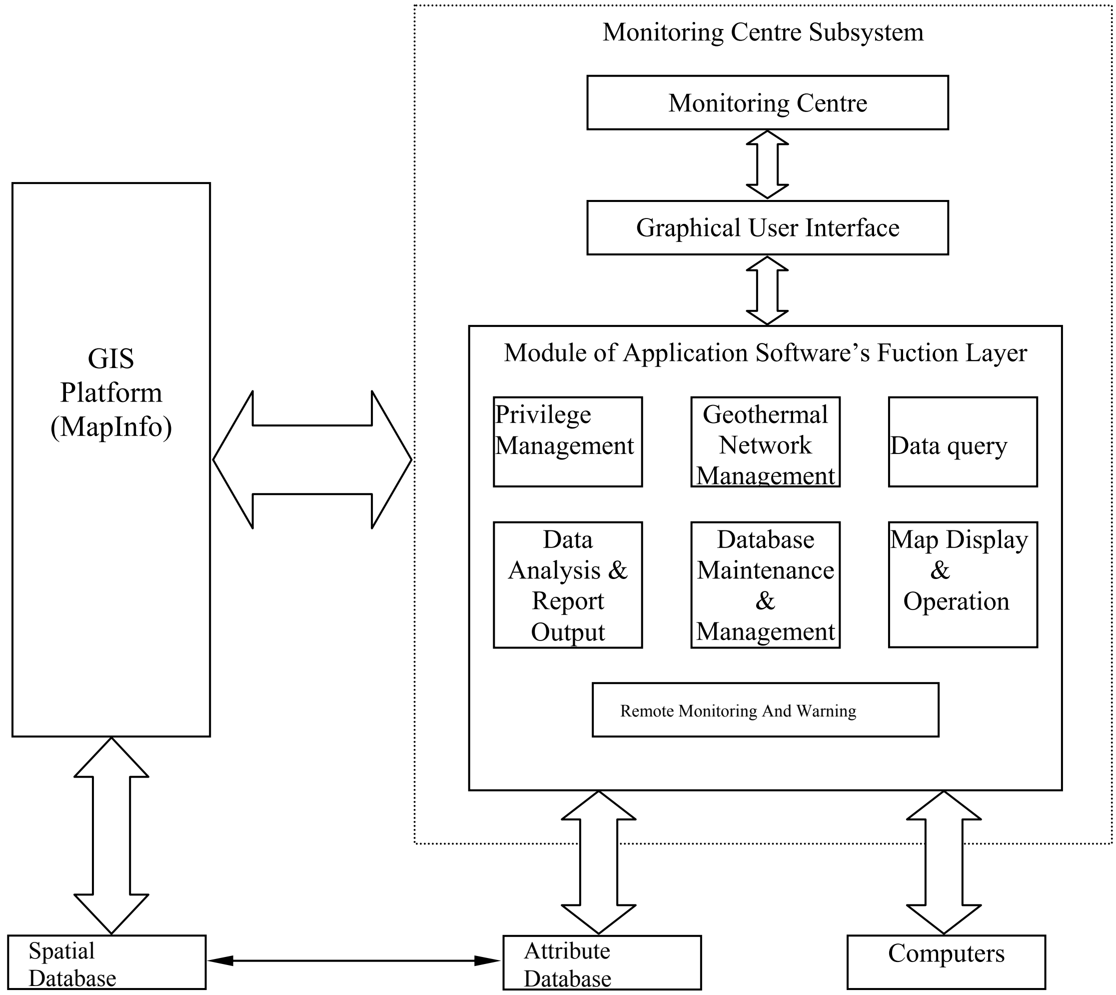


FIGURE 6: Configuration on the internet management systems

about the entire operation process. Therefore, in resource management, the factor of human error can be eliminated and it becomes a system with technical standardized management, as is shown in Figure 6.

5. RESOURCES EVALUATION

5.1 The geological model of geothermal resources in the plain area

After more than 10 years of continuous geothermal monitoring, a new potential evaluation of the geothermal resources in Tianjin plain area has been carried out from 2005-2007(Figure 7).On the basis of the research on the geological conditions, the Earth's temperature field, the hydrodynamic field of geothermal fluids, geochemical analysis, geophysics exploration and well tests have been re-evaluated. The new geological model is set up for resources evaluation (Figure 8).

The Tianjin geothermal field is a typical sedimentary basin low-temperature system, common in eastern and north-eastern China. The main heat source is the superposition of convection heat flow from the upper mantle and radiogenic heat from the crust. The heat transfer is mainly by conduction but convection is effective locally due to the effect of different geological structures and lithologies.

Since the Holocene epoch, the regional sea level has ascended. Several transgressions supply the salty materials for the wedge-shaped salty water body, which is shallow in west and deeper in the east in the Quaternary aquifer. The rise of the regional base level of erosion hinders the horizontal movement of geothermal water. The upward heat flow is obstructed by a thick Quaternary stratum and the water mass. The sealing causes heating of the trapped geothermal water. Although the water moves slowly, the velocity is rather high in decompression zone (Wang K., 2005).

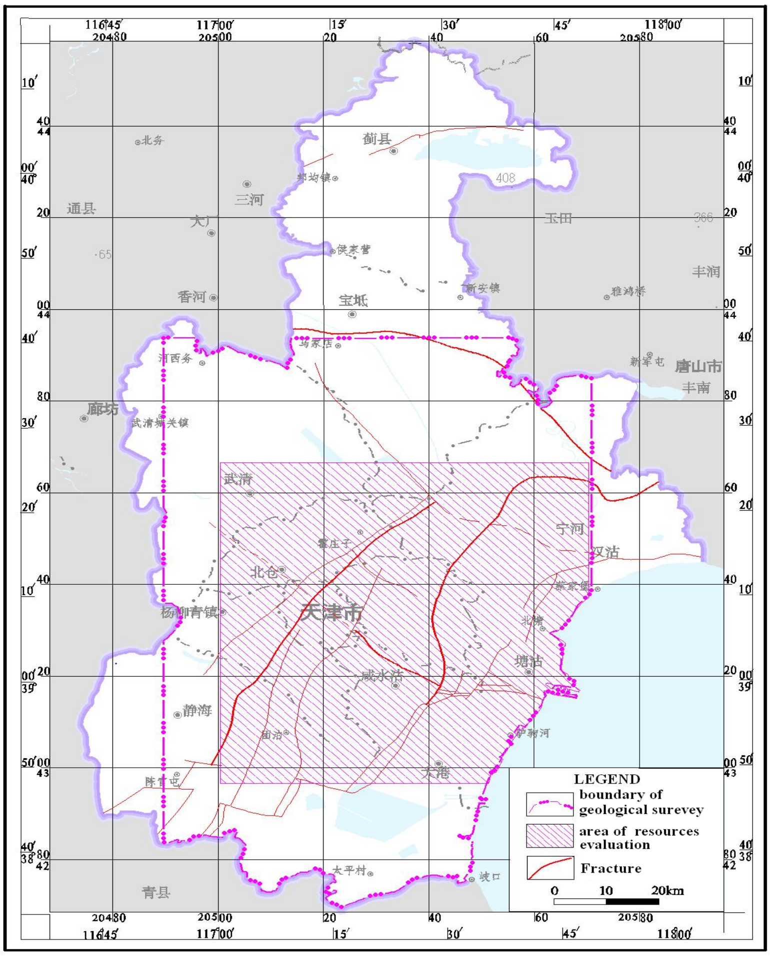


FIGURE 7: The working area of geothermal resources

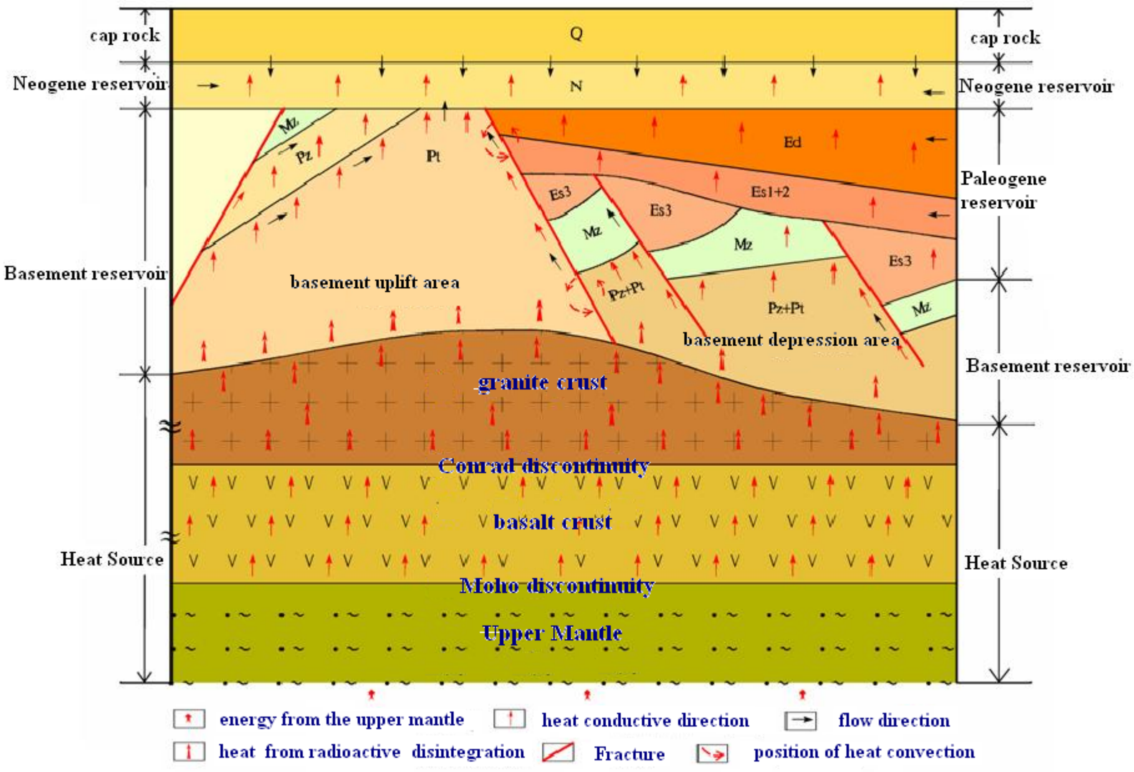


FIGURE 8: Geological geothermal model in Tianjin

The geothermal water is mainly located in the range of the Cangxian uplift. The "geothermal karst fracture water in the bedrock", has accumulated in the medium Pro-terozoic Jixiannian Wumishan (Pt_2W), the lower Paleozoic Cambrian (PzH) and the Ordovician (PzO) reservoir; and the "gothermal pore water in clastic rock" exists in Tertiary and Quaternary formations. The cold underground water is deposited in the fissures of the basement in front of the Yanshan Mountain, and the shallow porous/fracture aquifer (500-800m depth) resides in Tertiary and Quaternary formations. From isotope analysis it is evident that the Tianjin geothermal water originates from ancient precipitation, with an age of 23 ~ 4 ka B.P. and has been sealed from Holocene to present. It is a closed deep circulation system.

The geothermal fracture water in the bedrock has ^{14}C value (15-4.5 pmc) larger than the value of pore water (7.6-4.5 pmc), indicating that the bedrock geothermal water is younger than pore water. After a long geological denudation period, the bedrock has a thick weathered surface and well-developed fractures and dissolved cavities. In the northern and western mountains there is a large outcrop area, and the reservoir is thus classified as a semi-closed reservoir. On the other hand, the reservoirs in Tertiary and Quaternary are closed systems. The deep circular geothermal system can be divided into (Wang K., 2001):

(1) Semi-open and semi-closed bedrock subsystems, where the geothermal karst water exists;
(2) Closed, clastic rock subsystem, where the geothermal pore water exists.

5.2 Potential evaluation of geothermal resources in Tianjin

5.2.1 Neogene porous medium geothermal reservoir

The numerical modelling software Modflow is used to calculate the potential of the geothermal resources in Neogene porous medium reservoir. And its sub-program Interbed is used to calculate the sedimentation rate by coupling the hydrodynamic field of geothermal fluid.

It is assumed that the deepest water level will be shallower than -150m for the next 100 years of geothermal development in the Neogene reservoir, the total exploitable reserves in Neogene is 12.11×10^8 m^3, which is about 0.29% of the total reserve. The quantity of heat in the exploitable reserves is 11.12×10^{16} J, amounting to 3.08×10^{10}kWh, which is about 0.27% of the recoverable geothermal resources in Neogene.

In addition, the exploitable reserves of Minghuazhen Group in Neogene (Nm) are 6.8×10^8 m^3, which is about 0.23% of its totalreserves. The quantity of heat in the exploitable reserves is 4.93×10^{16} J with an average temperature of 41°C, amounting to 1.37×10^{10} kWh, which is about 0.17% of the recoverable geothermal resources in Nm.

And the exploitable reserves of Guantao Group in Neogene (Ng) are 5.31×10^8 m^3, which is about 0.43% of its totalreserves. The quantity of heat in exploitable reserves is 6.19×10^{16} J with an average temperature of 58°C, amounting to 1.71×10^{10} kWh, which is about 0.5% of the recoverable geothermal resources in Nm.

5.2.2 Basement carbonatite geothermal reservoir

The numerical modelling software AQUA3D is used to calculate the potential of the geothermal resources in the carbonatite reservoir, in the Ordovician and Wumishan Group of Jixianian in Proterozoic. The analytic model is used to calculate the potential of the geothermal resources in the Cambrian reservoir.

It is assumed that the deepest water level will be shallower than -200m in the nest 100 years of geothermal development in the basement reservoir. The total exploitable reserve in the basement is 15.63×10^8 m^3, which is about 0.69% of the total reserve. The quantity of heat in the exploitable reserves is 26.58×10^{16} J, amounting to 7.36×10^{10} kWh, which is about 1.61% of the recoverable geothermal resources in Neogene.

Hereinto, the exploitable reserves of geothermal fluid in Ordovician are 2.94×10^8 m^3, which is about 0.63% of its total reserves. The quantity of heat in the exploitable reserves is 5.13×10^{16} J with an average temperature of 80°C, amounting to 1.37×10^{10} kWh, which is about 0.69% of the recoverable geothermal resources in Ordovician.

And the exploitable reserves of geothermal fluid in Cambrian are 0.58×10^8 m^3, which is about 9.3% of its total reserves. The quantity of heat in the exploitable reserves is 0.93×10^{16} J with an average temperature of 81°C, amounting to 0.26×10^{10} kWh, which is about 9.3% of the recoverable geothermal resources in Cambrian.

The exploitable reserves of geothermal fluid in Wumishan Group of Jixianian in Proterozoic are 12.11×10^8 m^3, which is about 0.75% of its total reserves. The quantity of heat in exploitable reserves is 20.52×10^{16} J with an average temperature of 86°C, amounting to 5.68×10^{10} kWh, which is about 2.28% of the recoverable geothermal resources in it.

5.3 Optimizing plans for future geothermal development

5.3.1 Neogene porous medium geothermal reservoir

By estimating the geothermal utilization status, future plan, and geological condition, four kinds of schemes are designed to predict the water level changes in the future 10 and 30 years of geothermal production in the Nm and Ng groups in the Neogene reservoir (Hu Y., Lin L., Lin J., et al, 2007). Figure 9 shows the water level changes of the Ng group in the different schemes after 30years.

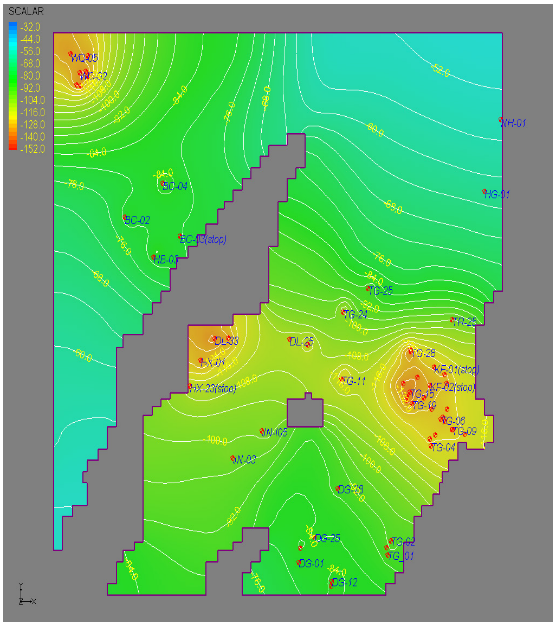
Scheme 1: Assuming that all geothermal wells will keep the same production rate of 722×10^4 m^3/a, as in 2004, for the next 30 years. Then the deepest water level of Ng group will be -135 m, in 2034, with an annual drawdown of about 1.0 m.

Scheme 2: Assuming that the total production rate of the Ng group will reaches 950×10^4 m^3/a, and that the number of geothermal wells and lay out of geothermal wells at present will not change in next 30 years. Then the deepest water level of the Ng group will be -155 m, in 2034, with an annual drawdown of about 1.73 m.

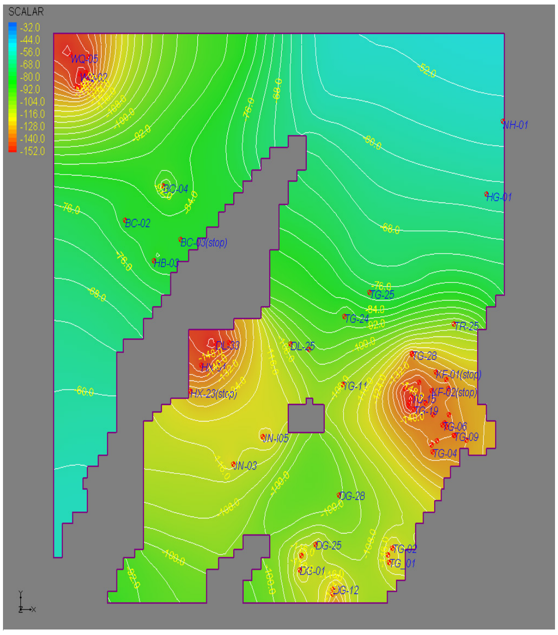
Scheme 3: Based on Scheme 2, where the total production rate of the Ng group is 950×10^4 m^3/a, but with the addition of 5 new geothermal wells in selected highly productive area. The deepest water level of the Ng group will be -138 m, in 2034, with an annual drawdown of about 1.33 m.

Scheme 4: Based on Scheme 3, where the total production rate of the Ng group is 950×10^4 m^3/a, but with the addition of 5 new geothermal wells in the peripheral regions, outside the highly productive area. The deepest water level of the Ng group will be -130 m, in 2034, with an annual drawdown of about 1.1 m.

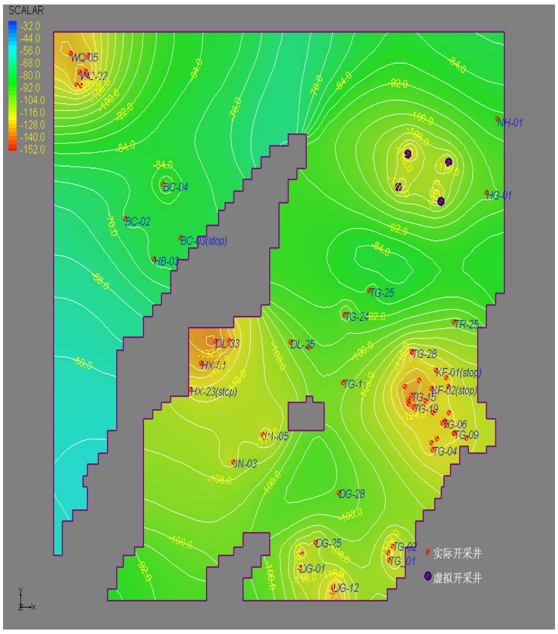
By comparing the water level and its drawdown, it is obvious that Scheme 4 will be the optimized way for geothermal development in future. The dispersive layout of the production wells will slow down the water level drawdown from geothermal production.



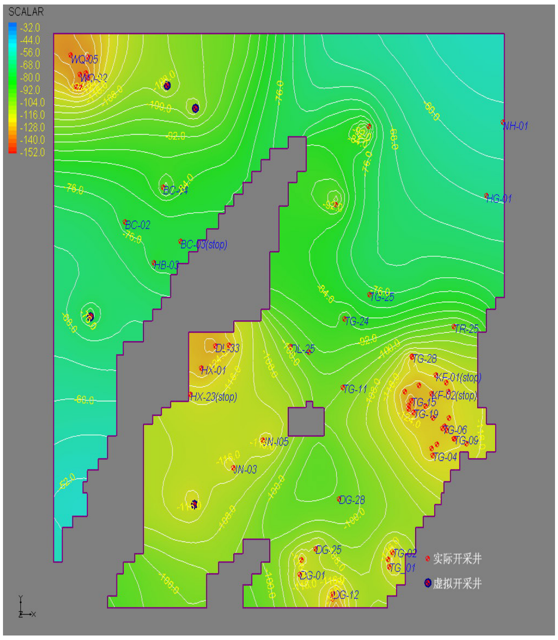
Scheme 1



Scheme 2



Scheme 3



Scheme 4

FIGURE 9: Water level contours of Ng group of different schemes in 2034
(Red dots are actual productive wells. Blue dots are virtual new geothermal wells in scheme 3 and 4)

5.3.2 Basement carbonatite reservoir in Paleozoic and medium Proterozoic

Simulations have been carried out based on the past 20 years of production history. Till now, there are 58 production wells and 18 reinjection wells in the Jixianian system. The optimized scheme is presented for the Wumishan Group of the Jixianian in Proterozoic from the calculation of four reinjection and production schemes (Hu Y., Lin L., Lin J., et al, 2007). Figure 10 shows the layout of reinjection wells in the four schemes.

Scheme 1: Assuming that all geothermal wells will keep the present layout and the average production rate (80-120 m^3/h in winter) in 2004 for the next 10 years. In the summer, the production

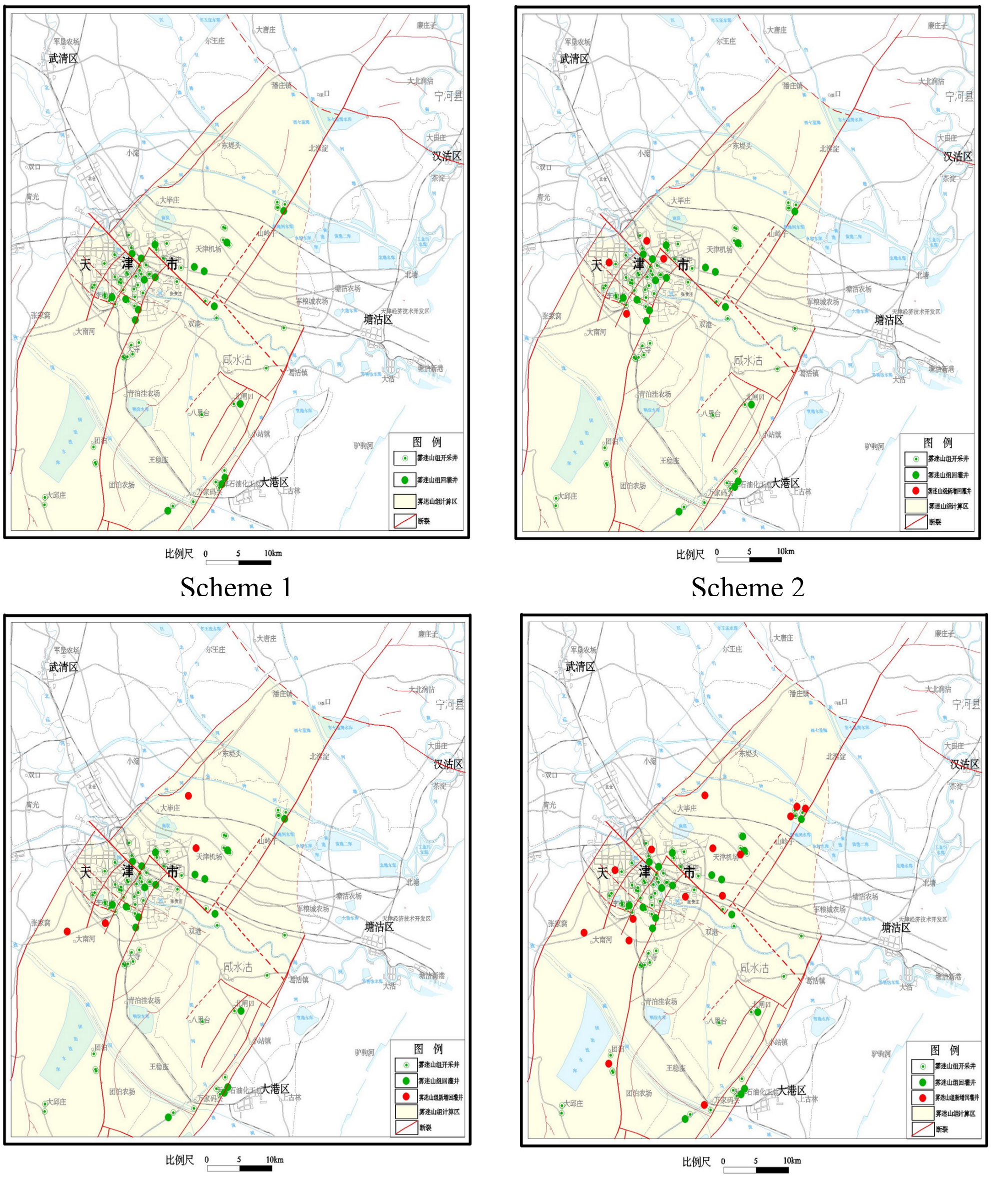

Scheme 1
Scheme 2
Scheme 3
Scheme 4

FIGURE 10: Layout of reinjection wells in four different schemes

production rate is about 5-10% of that in the winter space heating time. All present reinjection wells are put into use with reinjection rate of 50-100 m^3/h. The total annual production rate will be $1270\times10^4\ m^3/a$, with a reinjection rate of $227.53\times10^4\ m^3/a$. Till 2014, the deepest water level will be -191.2 m, and the annual drawdown 5.2-7.4 m.

Scheme 2: Based on the present layout of geothermal production wells, and the addition of four new reinjection wells in the urban area. The annual production rate will stay at $1270\times10^4\ m^3/a$, but the reinjection rate increases to $362.53\times10^4\ m^3/a$. In 2014, the deepest water level will be -164.1 m.
Scheme 3: Keeping up the production rate of Scheme 2, but the four virtual reinjection wells are moved outside the urban area. Ten years later, the deepest water level will be -166.1 m.

Scheme 4: Based on Scheme 1, with the addition of eleven reinjection wells, five in the south of and north of the urban area respectively and one is in the urban area. The annual production rate will stay at $1270\times10^4\ m^3/a$, but the reinjection rate will increases to $542.53\times10^4\ m^3/a$. In 2014, the deepest water level will be -108.8 m.

From Figure 10, the layout of reinjection wells in the four schemes, compared with the others, Scheme four is the optimal scheme. Reinjection from the peripheral area of the highly productive centre will be a more effective way to maintain the reservoir pressure. But the possible distinct cooling resulting from the reinjection has not been assessed in the four schemes. The result of this is highly uncertain because the flow channels are unknown. Further research will be conducted in the future.

6. CONCLUSIONS

Through the monitoring of geothermal fields for more than 20 years, it has become an important and necessary part to evaluate the geothermal potentials and to plan the geothermal development by utilizing information technology. It is also helpful in supplying guidance for mining enterprises on how to reasonably develop geothermal resources.

However, the water levels of most of the geothermal wells are observed manually due to very heavy corrosion of the monitoring equipment. The automatic observation equipment for water level still awaits improvement for more efficient data collection (Wang K., Han J., 2007).

With the increased geothermal development and utilization in Tianjin more monitoring points should be chosen, so that the nature and properties of the geothermal fields, as well as the response to long-term production and reinjection, can be obtained.

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LECTURE 5

EXPERIENCE OF GEOTHERMAL REINJECTION IN TIANJIN AND BEIJING

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ABSTRACT

Reinjection has been widely applied in management of geothermal resources, and has become one of the routine applications of geothermal development in many geothermal fields. In China, reinjection tests started in 1974 in Beijing. But large scale reinjection of the geothermal waste water from heating systems was started in Tianjin in 1990's. Since 2000, reinjection has been considered an increasingly important aspect of geothermal resources management in Beijing and Tianjin. At present, a number of reinjection projects are in operation in Tianjin and Beijing. As a result, the water level declining of geothermal wells has been greatly diminished. In Xiaotangshan geothermal field in Beijing, the water level has accurately stopped declining, since 2006, owing to reinjection and control on production of geothermal water.

In this paper, the reinjection history in Tianjin and Beijing will be summarized, and the experiences and problems of reinjection, including the distances between the production and reinjection wells, tracer test and monitoring of geothermal fields with reinjection, will be discussed.

1. INTRODUCTION

Geothermal is an environmentally benign energy source, widely used in many countries for power generation and direct use purposes, such as in space heating, bathing, swimming pools, fish farming, greenhouses, health spas and recreational facilities etc., bringing about significant economical and environmental benefits. Geothermal is a type of renewable energy, but it should not be over-exploited; or, the resources will be depleted, and will need a relatively long time to recover from improper management. Therefore, it is mandatory to implement proper management for the sustainable use of geothermal resources.

Reinjection has been widely used in the management of geothermal fields, and is becoming a routine application in many geothermal fields, since the first reinjection project was implemented in the famous Geysers area in 1969 (Axelsson & Stefansson, 1999). The purpose of geothermal reinjection is for (1) disposal of the waste geothermal fluid that may cause thermal and chemical pollution; (2) improvement of heat mining. Over 90% of the heat in the geothermal reservoirs is stored in the hot rock matrix; (3) stabilization of the production capacity of the geothermal field through the maintenance of the reservoir pressure (Liu, 1999).

Geothermal reinjection began as a method of disposing of wastewater from power plants in order to protect the surrounding environment. It was initialized as early as 1969 and 1970 at the Geysers area in California and in the Ahuachapan field in El Salvador, respectively. Presently there are a number of geothermal fields worldwide where reinjection is already a part of the operation, including the Geysers field in USA, the Larderrello field in Italy, the Berlin field in El Salvador, the Paris field in France, the Laugaland field in North Iceland etc. There are a number of other geothermal fields where reinjection tests have been carried out, and some of them may start production-scale reinjection soon.

There are abundant low enthalpy geothermal resources in China (high enthalpy geothermal only exists in Tibet and Taiwan). The resources are mostly used for health spas and recreation in southern China where there is no need for heating in the winter; in northern China, where the climate is colder, the resources are used for space heating and various other direct. For the past 30 years, geothermal utilization has been ever increasing, especially in the past 10 years and in large northern cities such as Beijing, Tianjin and Xi'an etc. With the expansion of geothermal utilization, some problems have arisen, i.e. the rapid decline of reservoir pressure in geothermal fields where the production is high. Reinjection is, therefore, considered as a measure for the sustainable use of geothermal energy.

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, a larger scale reinjection tests were carried out in this geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well with a depth of 1275 m. At the end of the 1980's, reinjection tests were carried out in the Tertiary sandstone reservoir in Tianjin. Since 1996, reinjection tests have also been implemented in the dolomite reservoir in Tianjin. Till now, there have been 13 production-reinjection doublets running in Tianjin. In 2004 and 2005, reinjection tests into the sandstone reservoir were carried out in Tianjin again. In 2001, reinjection tests were implemented in Xiaotanshan geothermal field north of Beijing, and in the Urban geothermal field in Beijing. Since then, production scale reinjection has been running in Xiaotangshan Geothermal field. Tests in both Tianjin and Beijing showed that reinjection is a feasible measure to ensure the sustainable use of geothermal resources in the two cities.

2. THE IMPORTANCE OF GEOTHERMAL REINJECTION

Beijing is rich in low-temperature geothermal, stored in limestone and dolomite reservoirs, and the identified area with geothermal potential is greater than 2760 km^2, divided on 10 geothermal fields, such as the ones in the southeast Urban area and Xiaotangshan (about 30 km north of the city centre). The temperature of the geothermal water in Beijing is 38-89°C. The geothermal water contains SiO_2 and other components that are good for human skin. Historically, hot spring water was used for bathing and for spas in Beijing. Large-scale geothermal use started in 1971 in Beijing, with the completion of the first geothermal well. After that, the number of geothermal wells increased rapidly, and the amount of geothermal water production increased with it. By 1985, the geothermal production increased to over 10 million m^3 annually, causing a rapid declining of reservoir pressure (water level). Therefore, strict measures were taken to control the amount of geothermal water subtraction since 1985. As a result, the water level decline has slowed down (Figure 1). At present, it is generally between 1 and 2.5 m annually, and it still threatens the sustainability of geothermal utilization in Beijing.

This means that the net discharge of geothermal water, that is, the interval between production and reinjection of the geothermal systems should be under a certain limit. Otherwise, the water level of the geothermal wells will decline, and threaten the sustainability of the geothermal resource. It also

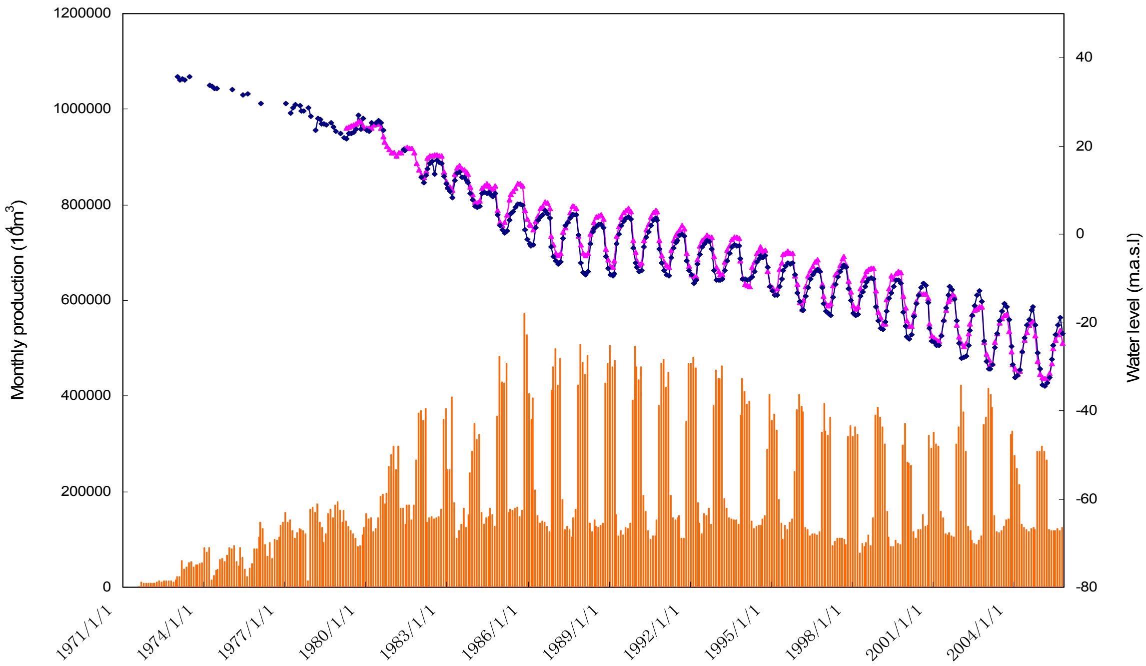

FIGURE 1: Historical water level change and monthly geothermal water production in the southeast Urban area, Beijing

means that if reinjection will not be carried out, the production should be lowered drastically. Therefore, it is essential to reinject the used geothermal water back into the geothermal reservoir.

The geothermal resources in Tianjin are low-enthalpy geothermal resources in sedimentary basins. The area with geothermal potential is about 8700 km^2, accounting for about 77% of the total area of the city. Geothermal water is stored in the Tertiary sandstone and karst-fractured dolomite. The temperature of the geothermal water ranges from 55 to 103°C. Geothermal is widely used for space heating, domestic hot water, fish farming and greenhouse, recreation etc. By the end of 2007, 294 geothermal wells (including 38 reinjection wells) were drilled in Tianjin, the deepest well being close to 4000 m deep. The production capacity of each well is 100-200 m^3/h. The annual production of geothermal water is 24.50 Mm^3.

Due to the large-scale development of the geothermal resources, the reservoir pressure decreases quickly in Tianjin, especially in the dolomite reservoir. Since 1997, the annual water level drawdown has been over 3 m. Currently the depth to the static water level in the geothermal wells varies between -40 m and -90 m, with an annual drawdown of 6-9 m (Figure 2). This suggests that the recharge to the reservoirs is rather limited. Meanwhile, the water level drawdown is lower than before 2004, due to the incrimination of the reinjection rate. Therefore, it is necessary to implement reinjection for maintaining the reservoir pressure and prolonging the life time of the geothermal wells.

3. APPLICATION IN TIANJIN

3.1 History of reinjection in Tianjin

Reinjection activity started in the early 1980's in Tianjin, and the history can be divided into 4 periods:

3.1.1 1980 - 1995

With the increase of geothermal water production, it was realized that reinjection might be a useful way to control the declining water level. In the beginning of the 1980's, studies on geothermal

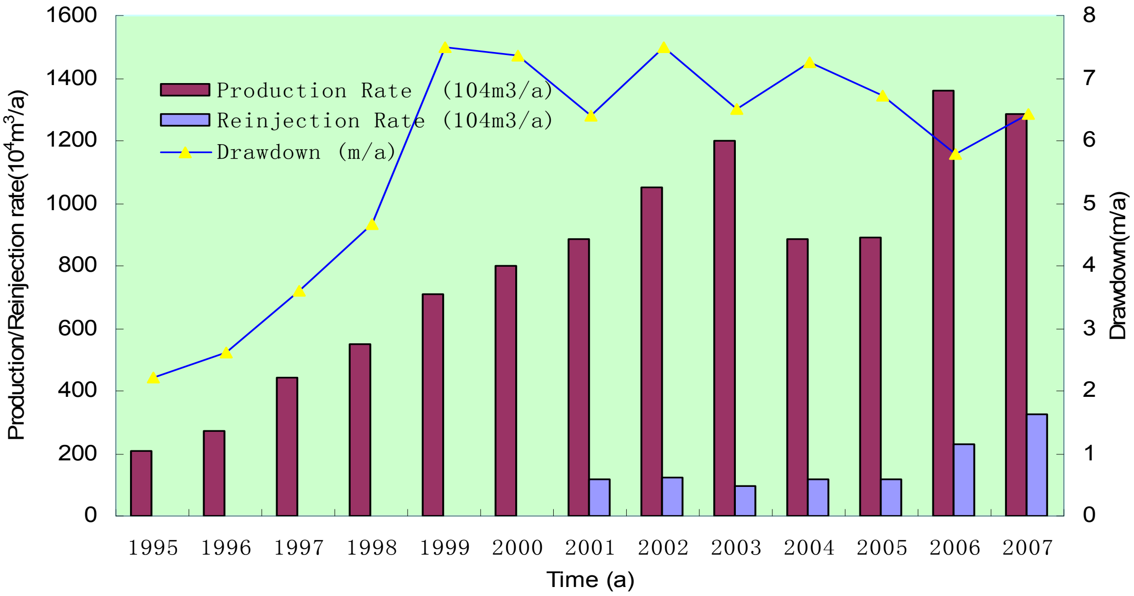

FIGURE 2: The history of water level drawdown v. geothermal water production and reinjection in the dolomite reservoir in the Tianjin urban area in 1995-2007.

production-reinjection doublet or production-reinjection well groups were carried out, and related numerical modelling on sandstone reinjection was conducted. Based on the results, reinjection tests, focused on reinjection into sandstone in the geothermal reservoir of the Tertiary System, were carried out in Dagang and Tanggu District in 1987-1989 and in 1995.

3.1.2 1995 - 1998

With the increase of geothermal water use from the dolomite reservoir, more attention was paid on reinjection into the dolomite reservoir in Tianjin. In 1995, the first production-reinjection doublet was drilled, and reinjection test was carried out in 1996-1997. The result showed that reinjection is technically feasible in the dolomite geothermal reservoir in Tianjin (Wang et al, 2001).

3.1.3 1998 - present

Based on the results of the reinjection tests for the dolomite reservoir, a few production and reinjection doublets were installed and operated in this period in Tianjin. In the same period of time, tracer tests were carried out for better understanding the movement and heating processes of the reinjected water. Monitoring of the doublets has become a routine, including flow rate, water level, temperature, and chemical contents. Numerical modelling was carried out for predicting the effect of reinjection. A technical standard for design and operation of geothermal reinjection was compiled, by summarizing the experiences of geothermal reinjection in Tianjin.
Since 2004, tests on reinjection into sandstone reservoirs were started again in Tianjin, due to the rapid decline of the water level in the sandstone reservoir.

3.2 Reinjection in dolomite reservoir

Most of the geothermal production /reinjection doublet systems in Tianjin are inside the urban area. Both of the production and reinjection wells were drilled into the dolomite reservoir which is widely dispersed in the Tianjin area (Wang et al., 2001).

Since the first geothermal production-reinjection doublet was put into operation during the winter (during the space-heating period) of 1999, 27 reinjection wells and 77 production wells have been drilled in this reservoir in Tianjin. All the doublet systems reinject under artesian conditions. All the geothermal water from the doublets is reinjected into the reservoir after the heating cycle. The amount of reinjection was 2.89×10^6 m^3 in 2007, accounting for about 24% of the total production from the geothermal reservoir. Although, that there are more geothermal production wells used for space heating than there are reinjection wells, and that production wells adjacent to reinjection wells influence the reservoir pressure around the reinjection wells, it can be observed that the water level close to reinjection wells declines much slower than in other parts. The average annual drawdown has decreased with increasing reinjection rates. Still, there have been no observable temperature changes in the surrounding production wells.

According to the geological conditions and the past 20 years of production history, a numerical model was set up for the geothermal system in the urban area in Tianjin, using the software package TOUGH2. The model was used to predict the changes of reservoir pressure in the geothermal system in the future, assuming that (1) all the geothermal wells will keep the average production rate in 2002 (80-120 m^3/h in winter, and 5-10% of the winter production rate in the summer); (2) all the 10 reinjection wells are put into use with a reinjection rate of 50-100 m^3/h for each well, and the annual amount of production is 1.3716×10^7 m^3 (deducting the amount of reinjection 1.7×10^6 m^3). It was predicted that the deepest water level in the reservoir will be 193 m below sea level. This means that the sustainability of the geothermal production cannot be realized if the present production and reinjection will be maintained in the future. If the present amount of reinjection increases with 150%, it was predicted that the deepest water level will be 138 m below see level in 2013 (Figure 3). This means that reinjection makes an effective measure to counteract the decline in reservoir pressure (Wang et al., 2005).

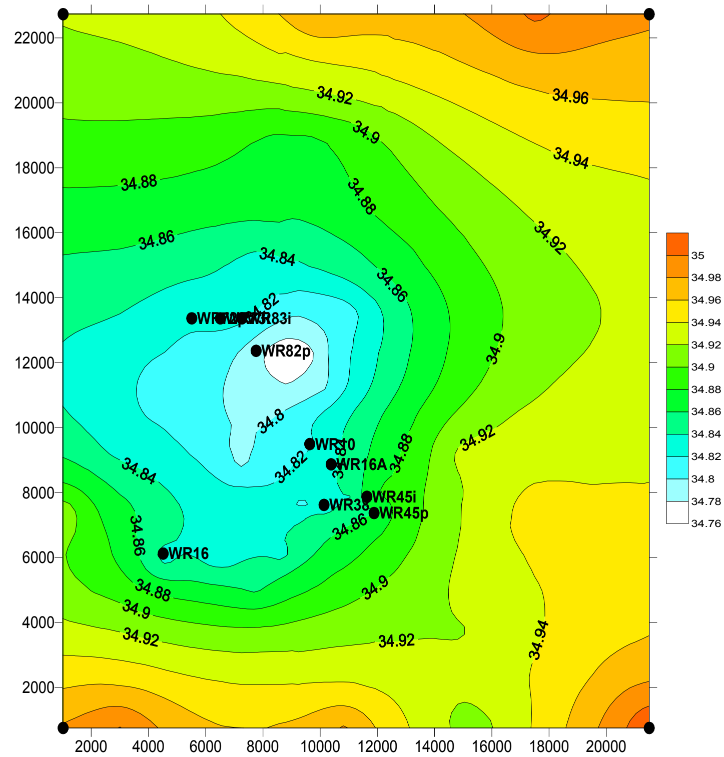

FIGURE 3: Contour map of calculated water level of the dolomite reservoir in Tianjin in Sept.2013, assuming the reinjection will increase 150%

3.3 Tracer test

Reinjected cold water can extract additional thermal energy from the rock matrix and improve the heat mining from the geothermal reservoir. But it is not a simple decision to increase the amount of reinjection, because of the possible cooling of the production water. It is proposed that tracer test be carried out to study the connections between the production and reinjection wells and to predict the cooling effect by the increase of reinjection.

3.3.1 Tracer test in the winter of 1998 - 1999

To investigate the connections between the reinjection and production wells of the WR45 doublet, a tracer test was conducted in the winter of 1998-1999. 10 kg of potassium iodide (KI) was selected as the tracer. Meanwhile the chemical content of the water produced from the surrounding wells was monitored carefully. The resulting data are presented in Figure 4.

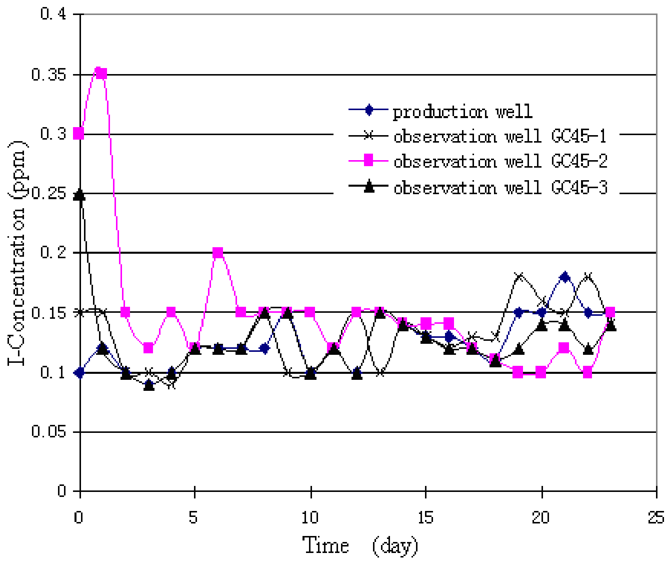

FIGURE 4: The recovery curves of the tracer concentration in the observation wells around WR45

The monitoring data shows that the tracer concentration is almost constant in the production well, i.e. no noticeable recovery. On the other hand observation well GC45-2 shows some iodine recovery. This means that the hydrological connection between the production and reinjection well of doublet WR45 is indirect, but that there may be a direct (fast migration) channel between the reinjection well and other nearby geothermal production wells (such as production well GC45-1, which is about 2.5 km away from the reinjection well).

A mathematical model simulated the results from GC45-2 tries and assesses the nature and structure of the fractures connecting GC45-2 and the reinjection well. Figure 5 and Table 1 show the simulated recovery and model parameters, respectively. The simulation curve is composed of 4 pulses, corresponding to 4 flow channels/fractures. When the tracer was reinjected into the aquifer, it travelled rapidly along the most direct path, which had the smallest cross section. For this channel the tracer moved quickly to the production well and reached the maximum concentration in a very short

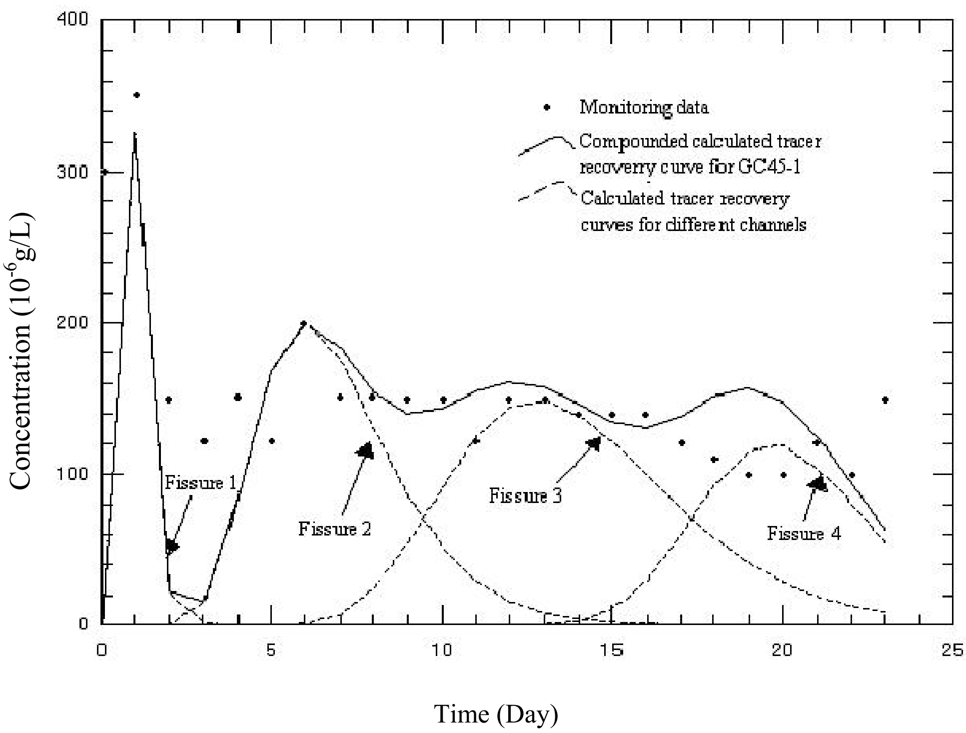

FIGURE 5: Calculated tracer recovery curves for observation well GC45-1. Each dashed line represents a different channel connecting the reinjection and production wells.

time. If, on the other hand, the reinjected water diffuses into a large reservoir volume, only a small fraction of the tracer will be recovered and the time it takes it to reach peak value will be much longer. In the latter case, the thermal breakthrough time will not be a problem for the doublet system operation. Therefore, tracer tests are very important for understanding the mode of transport, flow channels, and fracture characteristics in the doublet production/reinjection systems.

TABLE 1: Calculated parameters of the tracer test

	Cross-section area Aφ (m^2)	**Dispersivity α_L (m)**	**Mass recovered (%)**
Fissure 1	1.50	356	20
Fissure 2	15.7	142	39
Fissure 3	29.5	10.1	10
Fissure 4	54.7	162	22

3.3.2 Tracer test in 2001

In the winter of 2001, another tracer test in the dolomite reservoir was carried out and the tracer used was the radioactive isotopic tracer (^{125}I, ^{35}S). The distance between the production and the observation well is more than 4km. The amount of tracer used was 350 mCi (1.3×1010Bq, ^{125}I). The entire tracer was applied instantaneously. The tracer break through time was about 3 days, and the peek time was at about 52 days (Figure 6). According to the deduction from the tracer tests, there is no premature thermal break through.

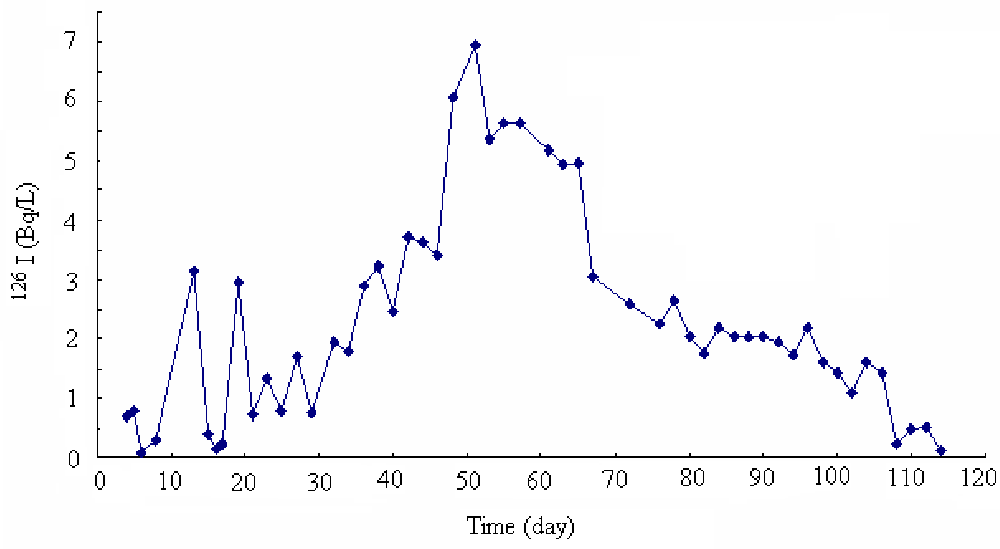

FIGURE 6: Tracer (^{125}I) recovery of a tracer test in 2001

3.4 Reinjection in sandstone reservoir

Through many years of research, the reinjection problems of dolomite reservoir have basically been solved. But the reinjection problems of sandstone reservoirs still exist, mainly at low reinjection rates and short duration times. The production from sandstone reservoirs exceeds 50% of the total geothermal production in Tianjin. Thus it is important to resolve the reinjection problems for the sustainable development and utilization of geothermal resources in Tianjin.

By the end of the 1980s, reinjection tests had been carried out in Tertiary sandstone reservoirs in Tianjin. During the tests about 30-50 m^3/h waste water was reinjected into the reservoir. But along with the reinjection, the reinjectivity quickly decreased. Tests of sandstone reinjection were carried out again in the winter of 2004-2005, and the results were similar to that of the previous tests. The reinjection tests were carried out in the Neogene Guantao formation sandstone reservoir in the Wuqing District, the Dongli District and the Dagang District, and reinjection well drilling technology, reinjection plugging problems and ground reinjection systems were studied here.

During the late Oligocene, North China Plain rose to the dustpan basin. And in the Miocene period the Yanshan uplift zone became the main source area. Because of the transport and deposition in lower river bends and braided rivers, clastic rocks formations arose of fluvial facies. It finally formed alluvial-pluvial fans and fluvial deposits well-distributed on the North China Plain. They mainly include mottle silt rocks and sand gravel rocks. The Neogene Guantao formation ultimately formed from clastic fluvial rocks with obvious sedimentary cycles, and they are mainly located in the Wuqing sag and the Huanghua depression in Tianjin. Clastic rocks in Tanggu, Beitang and the northwest of Xiaozhan are mainly of gravel facies, other parts are mainly of gravel and sand facies.

The top of the Guantao formation is a thick sand layer, the bottom is a gravel sand layer and its middle part is a silt stone layer. The total thickness is 200-600 m, of which the sand and gravel thickness amounts to 70-360 m. The porosity of the formation is 15%-32.4% and its permeability is 773-2631×10^{-3} μm^2. There is a well-formed gravel layer at the bottom of the Guantao formation, with a thickness of 30-60 m and a gravel diameter of 5 mm. The mean porosity is about 20%. Through exploration, deterring physical properties of rock samples, analyzing geothermal conditions and hydrological conditions, it is evident that the Guantao formation is a mid-low temperature heat storage layer created by normal consolidation processes. It also apparent that the source of its heat is from deep heat conduction and its water supply is from lateral runoff recharge.
The main problem with sandstone reijection in Tianjin is that the reinjectivity decreases fast with time, or the reinjectivity changes too much with time during the reinjection process. The clogging of reinjection wells is attributed to physical, chemical and biological factors.

3.4.1 Physical plugging

The filtered particles from the reinejection water has been analyzed by SEM (Scanning Electronic Microprobe) and X-ray diffraction in most of the wells. The result indicate that plagioclase, quartz, K-feldspar, FeS and ZnS seem to be the most common components carried on by the fluid, plus a certain number of possible other components, such as NaCl, $CaCO_3$.etc.

3.4.2 Chemical plugging

There seem to be three types of minerals that potentially may precipitate during reinjection around the well bottom: quartz (chalcedony), calcite, Fe-Zn oxides (hydroxides) and sulphides. Among them, the Fe-Zn oxide and the sulphide have been found in samples of 25 wells. Also similar components have been discovered in filtration. This proves that the water is saturation in these components in these exploitation wells. It is assumed that iron and zinc comes from oxidation of the well tube and water conveying pipeline.

In order to prevent the suspended solid particle from entering the reservoir , and from blogging the passage, referring to successful experiences of water reinjection in oil wells, double deck cage screens is used when filling gravel into the geothermal well.

Meanwhile, In order to prevent physical and chemical jam, use is made of secondary filtration equipment in the reinjection system. The primary filtration is rough, the precision is of 50 μm, whereas, the secondary filtration is fine, with a precision of 3-5 μm. There are pressure cabins at the ends of the filtration pot. If there is a pressure difference in the cabins the finer particles will resort in the filter pack. In practice, the precision of the secondary filtration is high and its effect is good. To prevent gas blockage, there is a vent installed at the head of the reinjection well.

Two test sites were established in the Wuqing and Dongli districts, in 2004. Here, two reinjection wells have been drilled in the Guantao group reservoir. The two level filter system was used in the ground reinjection system, and productive reinjection tests have been conducted. In the Wuqing district the temperature of the reinjected fluid is 42 ~ 52°C, pumped at a reinjection rate with a decrease from 49 m3/h to 20 m3/h. The stable water level is at about 10 m depth. In the Dongli district the temperature of the reinjected fluid is 50°C, with a reinjection rate of about 16 m^3/h. The stable water level here is at about 15 m depth.

In summary, through the study of reinjection well-drilling technology and ground reinjection systems, some problems of physical and chemical reinjection plugging have been resolved, but decreasing reinjection rates remain a problem.

4. APPLICATION IN BEIJING

4.1 History of reinjection in Beijing

In China, the earliest geothermal reinjection tests were started in the urban area of Beijing in 1974 and 1975. In 1980, larger scale reinjection tests were carried out in the geothermal area: cold ground water and return geothermal water was reinjected into a geothermal well at a depth of 1275 m. Hereafter, reinjection stopped in Beijing for a rather long time. In 2001, reinjection tests and demonstration projects started again. Recently, reinjection has been implemented on rather large scales and received significant results in Beijing. The geothermal reinjection history can be divided into 4 periods.

4.1.1 1974-1983

Because of the increase of geothermal water production in the early 1970's, the water level of the geothermal wells declined rather fast. It was considered that reinjection would be an important measure to prolong the lifetime of the geothermal wells. In 1974, a short reinjection test was conducted in the famous Park of the Temple of Heaven in the southeast urban area. And in 1975, a short reinjection test was conducted again in the southeast urban area.

Until 1980, there were more than 30 geothermal wells in the southeast part of Beijing, the geothermal water production was about 3 million m^3/a, and the water level declining became more serious. Therefore, a larger scale reinjection test was carried out from June 4 to September 2, 1980. Cold groundwater of 15.5°C was reinjected into a 1060 m deep geothermal well in the southeast Urban area. In the 89 days of the reinjection test, about 60,000 m^3 of cold water was reinjected, and the temperature change inside the reinjection well was observed (Liu et al., 1981). After the 89 days, 40°C return geothermal water from a heating system was reinjected into a 1274.65 m deep geothermal well in the same area (Bai and Gong, 1984). In that period, reinjection tests focused on the time needed for the reinjected water to return to reservoir temperatures.

4.1.2 1983-2000

Geothermal reinjection activity stopped mostly because of financial problems, although the water level continued to decline in this period.

4.1.3 2001-2002

After 1999, with the fast development of geothermal utilization in Beijing, and the wide recognition of sustainable development, reinjection was again considered to counter the declining of water level drawdown. In 2001, a demonstration project of geothermal reinjection was carried out in the Xiaotangshan area. Return water from geothermal heating was reinjected back to the same geothermal reservoir through a well about 200 m away from the production well. This reinjection project operated smoothly in 2001 and 2002, and no cooling of the production temperature was observed (Liu, 2003).

In 2001, a reinjection test was also conducted in the southeast urban area in Beijing. Return water from a heating system was reinjected into a well that strikes a shallower geothermal reservoir 80 m away from the production well. Reinjection tests also started in 2002 at the south-eastern boarder of the same geothermal field (Liu, 2003).

4.1.4 2003-present

Since 2003, reinjection in Beijing has expanded rapidly. In the Xiaotangshan area, there were 6 reinjection wells in operation in 2006, and the amount of water reinjected was about 60% of the total production. Reinjection also expanded in other parts of Beijing during this period, and the role of reinjection in sustainable utilization of geothermal resources has been acknowledged.

4.2 Reinjection in the Xiaotangshan area

The reinjection in the Xiaotansgan began in 2001 in a hotel in the central part of the geothermal field. One of the two production wells at the hotel was converted into a reinjection well. The wells of the hotel were drilled in 1984 and 1996, respectively. The distance between the wells is about 200 m. The geothermal reservoir is in limestone of the Cambrian System and the dolomite of the Jixian System. The wells come across the same fault which is very important structure to the occurrence of geothermal in the vicinity of hotel. The reinjection was carried out from November 30, 2001 to March 27, 2002. In total 117 days. The temperature of the reinjected return water was 30-44°C. The flow rate of reinjection changed with the atmospheric temperature; it was approximately 800 m^3/d on the coldest days from January 8 to 20, 2002, and under 800 m^3/d on other days. The reinjectivity of the well did not decrease during the reinjection (Figure 7). The total amount of water reinjected was 73,331 m^3 for the duration of the heating season (Liu and Yan, 2006).

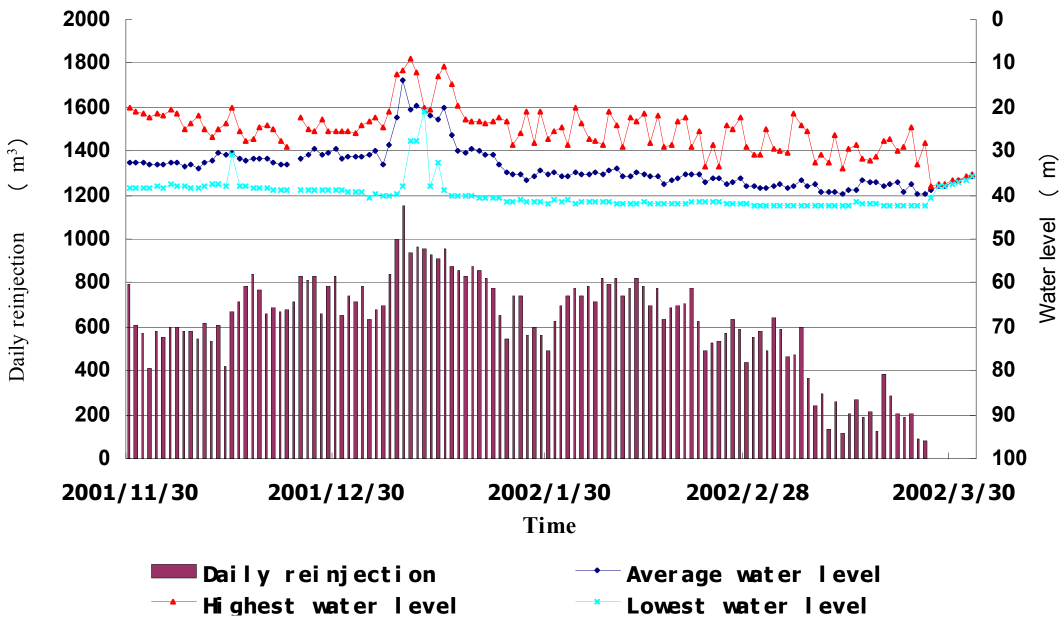

FIGURE 7: reinjection volume and water level changes of a reinjection well in the Xiaotangshan Geothermal Field during the heating season of 2001-2002

A tracer test was conducted during this reinjection test mentioned above. On January 8, 2002, 50 kg of KI was applied to the reinjection well instantaneously, 39 days after the reinjection started. 165 water samples from the production well were collected until space heating stopped. Samples were also collected from surrounding wells. No iodine was found in the samples. This indicates that there is not a direct pass between the reinjection and production wells, and that premature thermal breakthrough is not likely to happen in the production well (Liu, 2002).

When reinjection stopped, a submersible pump was installed in the reinjection well, intended to restore the reinjectivity of the well, in case of reduction. On April 15, 2002, the pump was started. At the beginning, the temperature of the water was around 30°C, and in an hour, the temperature rose to 63.5°C, and was thus nearly restored to its normal production temperature of 64°C.The reinjection test shows that the reinjectivity of the geothermal reservoir is rather good, and that the reservoir also has good capacity to reheat the reinjected colder water (Liu, 2006).

In the heating period of 2003-2004, a reinjection test was carried out in another hotel close to the one mentioned above. In 150 days, 1.48×10^5 m^3 of return water from the heating system was reinjected into a well drilled for reinjection purposes. The total amount of reinjection reached 2.48×10^5 m^3 throughout the heating season.

In the heating period of 2004-2005, four production-reinjection doublet systems were set up, by converting old production wells into reinjection wells, or by drilling new reinjection wells in the geothermal field. From November, 2004 to April, 2005, 10.2×10^5 m^3 of return water was reinjected into the geothermal reservoir, accounting for 36.5% of the total production (Liu and Yan, 2006).

In the heating period of 2005-2006, 6 reinjection wells were operating with return water from 8 production wells. There are two production-reinjection assemblages involving 2 production wells and 1 reinjection well each. The total quantity of reinjection was 1,322,778 m^3, accounting for 56.6 % of the annual production in the field.

In 2001-2002, the effect of the reinjection on the stabilization of the reservoir pressure was very little, because the amount of reinjection was small. With the increase of reinjection, the effect became more and more significant. In the 5 months from December, 2004 to April, 2005, the water level of the monitoring well (has been monitored for about 30 years) was higher than that for the same period in 2003 and 2004 (Figure 8), i.e. it rose 2.5 m. Considering that the water level decreased 1 to 1.5 m every year before the large scale reinjection, the effect was noteworthy.

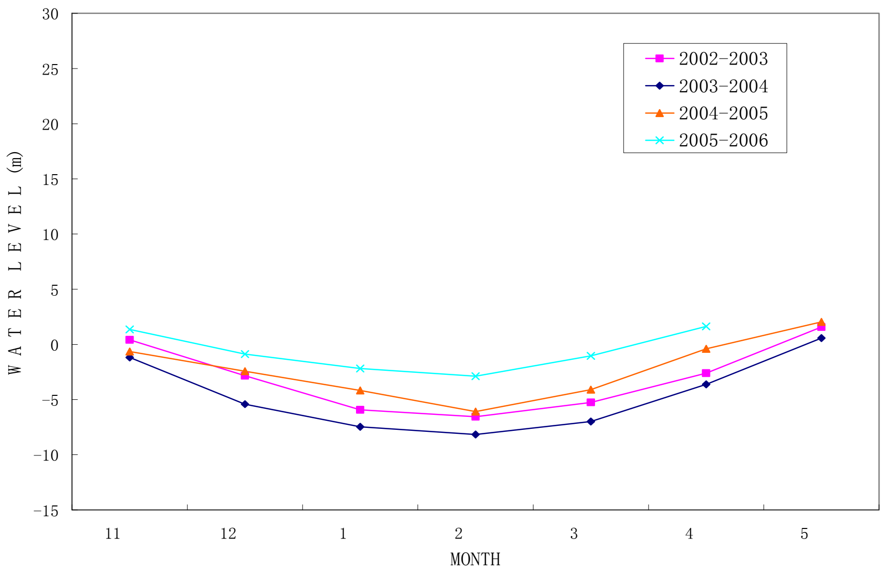

FIGURE 8: The water level of a monitoring well in Xiaotangshan geothermal field from 2002 to 2006

The reinjection in the Xiaotangshan geothermal field does not have observable influence on the temperature of the water in the production wells, although the distance between some of the production and reinjection wells is less than 200 m. It was also observed that the chemical composition of the geothermal water from the production wells did not change considerably. But the content of HCO_3^{2-} in the water pumped from one of the reinjection wells decreased, and the content of SO_4^{2-} increased. This may indicate convection, where the reinjected cold (heavy) water flows to deeper levels of the geothermal reservoir and that the hot water (light) from greater depths flows to the top of the reservoir.

4.3 Reinjection in other area in Beijing

Although geothermal reinjection tests have been carried out as early as 1974 in the urban area in Beijing, long term reinjection only started in early 2002 in an apartment building district about 5km south of Tiananmen Square. There are two geothermal reservoirs at different depths, both in dolomite, and separated by a shale layer of about 100 m thickness. Two wells, 90 m apart, were drilled in 2001 for the space heating of a 28,000 m^2 floor area (with the help of a heat pump system) and the reinjection of the return water from the heating system. The reinjection well is 1900 m deep, coming across the upper reservoir; the production well is 2054 m deep, completed for producing from the lower reservoir. The water temperatures from the reinjection well and the production well are 54°C and 59°C respectively. Both wells have good production capacity. The average flow rate of geothermal water in the heating system is 35 m^3/h. When all the return water was reinjected into the upper reservoir and the water level in the reinjection well rose 4 m on average. The test showed that the reinjectivity of the well is close to its productivity. This geothermal heating system, incorporated reinjection and heat pumps, has been running for more than 6 years, and ha not met any difficulties. It is also a good example for the cascaded use of geothermal resources (Liu, 2006).

Later, a few other reinjection wells were put into use in the southeast urban area and other geothermal fields in Beijing. Because the government encourages reinjection by subsidising, more developers are planning to start reinjection.

More tests and research, on wellhead facilities, and drilling and casing techniques of reinjection into sandstone reservoirs, are steadily progressing.

5. DISCUSSIONS

5.1 Distance of production and reinjection

Cooling of the reservoir caused by reinjection of colder fluid has been reported in a few high-enthalpy geothermal fields. For low-enthalpy geothermal fields, there have not been any such reports, not even in cases where the distance between production wells and reinjection wells is rather small. Therefore, it may be concluded that for production/reinjection doublets in low-enthalpy geothermal fields, one does not have to fear about cooling of the reservoir, if the distance between production and reinjection wells is greater than a few hundred meters, and the amount of reinjection is kept to a limit.

In designing the distance between reinjection and production wells of a doublet system, a few factors should be considered, including the type of geothermal reservoir, the geological structures of the geothermal field, the permeability and thickness of the reservoir, the direction of fluid flow, the temperature difference between the reservoir and reinjection water, the flow rate of reinjection etc.

But in cases where large numbers of reinjection wells and production wells will be placed among in rather small area, care has to be taken, and proper testing and modelling have to be carried out before any such reinjection project is initialized, to avoid premature thermal breakthrough.

5.2 Tracer test

Tracer tests can be a very good precaution for thermal breakthrough. Tracer testing is one of the most important aspects of geothermal reinjection, and it now a routine. Tracer tests can provide information about the flow paths and the flow velocity of the geothermal fluids between the reinjection and production wells. For fractured reservoirs, the volume of the aperture can be deduced from the tests. This information can be used to predict the cooling due to reinjection (Axelsson and Stefánsson, 1999). For large-scale reinjection projects or a greater number of production and reinjection wells in a relatively small area, it is strongly proposed that tracer test be carried out.

5.3 Monitoring

Monitoring is one of the most important elements for geothermal management. For a geothermal field with reinjection, a proper monitoring program is even more important. Besides the monitoring of reservoir pressure, temperature, production volume, and hydrochemistry; water level in reinjection wells, temperature of reinjection water, reinjection volume, and hydrochemistry of reinjection water should also be monitored. The purpose is to uncover changes in the geothermal system caused by reinjection, especially cooling of the reservoir.

6. CONCLUDING REMARKS

Reinjection is one of the most important aspects of sustainable management of geothermal resources. Reinjection tests were started as early as 1974 in Beijing. Reinjection of return water form geothermal heating systems has been applied in Tianjin since 1996 and in Beijing since 2001. The reinjection experiences show that it is significant in lowering the reservoir pressure, and improving the heat mining of the geothermal field. In the Xiaotangshan area in Beijing, the reinjection volume has reached about 60% of the geothermal water production. As a result, the water level of the geothermal field has stopped declining. This is a very good example of sustainable use of geothermal resources. It is proposed that reinjection be expanded in Beijing and Tianjin, as well as other geothermal fields in the world. However, reinjection is one of the most complicated technique of reservoir engineering, and pre-mature thermal break through should be avoided by the application of tracer tests and proper monitoring.

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