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ANALYZING THE LONG-TERM EXPLOITATION STABILITY OF BEIJING GEOTHERMAL FIELD FROM GEOTHERMAL WATER CHEMISTRY

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ABSTRACT

The Xiaotangshan geothermal field in Beijing, as one of the earliest explored low-temperature geothermal field in China, has been exploited for about 30 years and the reservoir pressure has declined with the increasing production rate. For the sustainable development of geothermal field, it is necessary to analyze its long-term exploitation stability. The changes of isotopic and chemical compositions in geothermal water have been employed to analyze the exploitation condition. By comparing the changes of chemical compositions in geothermal water between the natural state and the production period, it was found that the concentration of Ca^{2+}, Mg^{2+} and HCO_3^- were increasing while K^+, Na^+, Cl^-, SO_4^{2-} and TDS were decreasing after geothermal field development began. The concentration of chemical compositions in geothermal water monitored at wells throughout 3 years shows a linear relation with the monthly production rate. Also, the content of deuterium, oxygen-18 and tritium in geothermal water changes with the reservoir pressure and well production. It suggested that the recharge process of geothermal field had been changed and the cold groundwater entered the reservoir. The reservoir temperature given by geothermometer decreased due to intense production although there was no monitored temperature change at wellhead. The geothermal field seems to have been depleting. For the long-term exploitation, the present production rate should be reduced for geothermal recover.

1. INTRODUCTION

The Xiaotangshan low-temperature geothermal field is located about 27 km north of the Beijing city. Before 1975, it was a geothermal area with the surface manifestation of warm springs. The first geothermal well was drilled in 1975 after the thermal springs disappeared, and since then the geothermal development has grown very quickly. Most geothermal explored works had been carried out from 1975 to 1985. During this period, 25 geothermal wells were drilled, tested and sampled, allowing the initiation of a detailed study for a better knowledge of the geothermal field. Geothermal water is mainly used for spa, bathing, space heating and green house.

The earliest investigation of geothermal fluid chemistry in this geothermal field began in 1961 and lasted to 1967. Samples were taken from springs once a season. Since full-scale production in 1980, several research programs have been carried out for developing geothermal water. Many researchers have worked on the geothermal field from different aspects. Yang Qilong and Zhang Daofu (1985) gave a conceptual model based on the information from the geothermal exploration. Zheng Keyan et al. (1989) presented the origin of thermal water and its circulation by studying the distribution of chemical compositions from geothermal water and confirmed the recharge process by isotopic studies. Yao Zujin (1992) suggested that " the flowing alternation" is responsible for the changes of fluid chemistry during exploitation.

Generally, the changes of chemical compositions in geothermal fluid should reflect the changes of reservoir condition during the geothermal exploitation. The purpose of present work is to report on a study of the fluid chemistry in the geothermal field. Attention was focused on the reservoir response to the production. Three main questions were addressed. How did the thermal water chemical compositions change after intense exploitation? What changes of reservoir condition can be learned from water chemical compositions? Is the geothermal field depleting now?

2. THE XIAOTANGSHAN HYDROTHERMAL SYSTEM IN BEIJING

The Xiaotangshan geothermal field lies in the Jingxi upwarp. It is bordered by the Yanshan fold zone in the north, by the Huangzhuang-Gaoliying fault and Beijing downwarp in the east. The terrestrial heatflow in this area is about 50-30 mW/m^2. The Jurassic formation in the southern of the geothermal field and the Quaternary formation, overlying the geothermal reservoir, are considered to be caprock. The geothermal reservoir is consisted of carbonate rocks, from Middle Proterozoic Jixian system to Lower Palaeozoic Cambrian (Figure 1). The buried depth of reservoir varies from 61.7 m to 388 m and the water temperature ranges from 30 to 69 deg. C.

The chemistry of thermal water is of HCO_3-SO_4-Na-Ca type, with relatively high alkalinity, F and tritium but low TDS (542-699 mg/l). ^{14}C dating revealed that the thermal water is about 17,900 years old. The content of deuterium and oxygen-18 in geothermal water are obviously lower than that of local cold groundwater in Quaternary aquifer. Table 1 shows the chemical compositions of thermal water and cold groundwater. The isotopic studies (Zheng Keyan et al., 1989) confirmed that the geothermal system is recharged in correspondence to the mountains about 50 km to 100 km away in north and north west, where there is a reservoir formation outcrop. The regional aquifer formations outcrop locally in correspondence to structural highs, representing recharge areas for ground water circulation. Most of the thermal springs are found close to the boundaries of these outcrops and often located in zones of high water level. The infiltrated water flows initially inside the aquifer and heated to high temperature during deep circulation. The geochemical and isotopic data suggest that regional circulation is the primary source of the water delivered by the springs at the geothermal field. Low salinity water and the presence of tritium, however, indicate that local infiltration should be present

At natural state, geothermal water was discharged by springs. A natural discharge of 72 l/s was estimated from the thermal springs in the field. In 1989 the production was 84 l/s and the water level was 37 m above sea level. By 1989, the production from the field has been increased to 110 l/s, and the water level was 31m. The warm spring No.1 has its water temperature at 50 deg. C and the flow rate of 10.42 l/s. The flow rate had decreased distinctly in 1974, then it diminished. Well No.1 was drilled to the depth 76.5 m at 15 m southeast of spring No.1 in 1975, with temperature 52 deg. C at wellhead. With increasing production, especially after 1980, the discharge from the field exceeded the recharge, resulting in an increasing drawdown. During 1987-1989, the annual production has been relatively constant, causing the water level in the field to fall in a pseudosteady state, indicating a limited resource.

3. CHANGES OF RESERVOIR CONDITIONS INFERRED FROM GEOTHERMAL WATER CHEMISTRY DURING THE PRODUCTION

Changes in the chemical compositions of the fluid from geothermal reservoirs are often an early indicator of important future developments. Intense production of geothermal water could cause the changes in reservoir conditions. The chemical changes of geothermal fluids from the spring and production well provide an insight for the production effects. A single sample analysis of geothermal water provides little information about the dynamics of a system, several sample analyses provide, however, a powerful tool in geothermal studies. Samples in the field had taken from natural spring No.1 before it disappeared in 1974 and from well No.1 during 1985-1990. The statistics of the chemical compositions from two periods show that the concentration of HCO_3, Ca and Mg has increased while F, SO_4, Cl, SiO_2 and TDS decreased (Table 2). A possible explanation is that the thermal water mixing with a few percent of cold water is takings place. This can therefore be an early sign of cooling in the reservoir that will become more noticeable in the future. This probably was caused by higher production rate resulting in a reservoir change to adjust to the high production.

The geothermal water components can be traced by chemical, isotopic and physical parameters. Mixing of two waters can be indicated in a plot of one conservative species against another. The plot generally shows a well-defined mixing line that extends from the composition of one end member to that of the other. If the cold end member is very dilute, then F, B, Li and Cl are considered to be conservative. Deuterium, because there is negligible hydrogen in rocks, is generally conservative in water. Figure 2 shows that Li, B, F and deuterium as a function of Cl provide the best-defined line, indicating the mixing of two type waters. One type is high in Li, B, F and Cl but low in deuterium, the second end-member is low in all these elements except deuterium. Thus Cl was selected as the major reference. Figure 3 presents plots of various compositions against Cl. It indicates that two water types mixing in varying ratios, a saline one with relatively high K, Na, SiO_2, Cl, SO_4, Li, B, F, and a fresh water with relatively high Ca, Mg and HCO_3.

The fit line of the tritium against Cl, T=-3.97Cl + 136.11, may be extrapolated to a point of zero tritium, the Cl concentration at this point, 34.28 mg/kg, is most possibly close to the value of the saline warm water from a deep circulation over a long period. The lowest Cl concentration of the local shallow groundwater is estimated 8.86mg/kg, which may represent the Cl in fresh end-member. According to the fit line, the corresponding tritium content is 100.94 TU, in good agreement with 96.62—111.52 TU in cold groundwater.

Monitoring the chemical changes of geothermal fluids from the production wells is very useful to estimate various kinds of changes in reservoir conditions. With the increasing production rate, the reservoir pressure declined gradually. The geothermal water recharge, thermal water component, local water-rock equilibrium and the temperature will be changed. These effects could be determined from the fluid chemistry changes during the production. After 1975, the reducing Cl concentration in production well indicated the effect of the recharged low Cl cold water. Figure 4 shows the relations between the monthly production rate and major chemical ion concentration, isotopic content from well No.1. The production rate has positive correlation with Ca, Mg, HCO_3, and negative correlation with Na, SO_4, Cl, SiO_2 and pressure. With the increasing production rate, the Na, SO_4, Cl, SiO_2 concentration decrease, while Ca, Mg, HCO_3, tritium, deuterium and oxygen-18 increase. Thus, the production water is a mixture of warm waters enriched Na, SO_4, Cl, SiO_2 and cold water enriched Ca, Mg, HCO_3, tritium, deuterium and oxygen-18. Their fractions in the production water varied with reservoir pressure. It indicated that the recharge of high temperature water with high Cl concentration had changed. This was a clear indication that the cold fresh water with low chloride content entered into the thermal system. The negative correlation of stable isotopes with the production rate suggested that the recharge average altitude tended to be lower and the recharge took place near the geothermal field. The tritium vs. production rate plot reveals that the younger recharge water, probably cold water, is increasing in the well with increasing production rate.

The changes in the chemical compositions of geothermal water often precede cooling of the geothermal reservoir, and data obtained by chemical monitoring of fluids may therefore give a warning in time for preventive actions. The geothermometers provide the tools for detecting the reservoir temperature change. Even with their inherent uncertainties, geothermometers can be very useful for estimating approximate temperature in geothermal systems and for investigating effects of water-rock partial re-equilibration during upflow. The increasing Mg, in general, and decreasing $K/\sqrt{Mg}$ and $Li/\sqrt{Mg}$, are very sensitive indicators and of mixing of high- and low-temperature waters. Figure 5 shows the changes in $K/\sqrt{Mg}$ (Giggenbach, 1988), $Li/\sqrt{Mg}$ (Kharaka and Mariner, 1989) and chalcedony (Arnorsson et. al., 1983) geothermometer temperature. Disagreement among $K/\sqrt{Mg}$, Li/√Mg and chalcedony may result from mixing of different waters without water-rock re-equilibration after mixing. Even so, the geothermometers can be used as reference for studying the temperature change resulted from production. Although the water temperature monitored has been nearly constant after 15 years production in the field, the chalcedony geothermometer shows that the reservoir temperature has decreased since production.

4. CONCLUSIONS

The production rate of geothermal water during utilization greatly exceeded the natural replenishment in Xiaotangshan geothermal field. This caused reservoir pressure draw-down with subsequent change of reservoir conditions. The chemical studies of geothermal waters both in springs and wells show that HCO_3, Ca and Mg have increased while F, SO_4, Cl, SiO_2 and TDS decreased after geothermal exploitation. The chemical composition changes of thermal water monitored during production suggested that the cold water recharge was increasing and the produced thermal water from wells was a mixture of two type waters. The isotopic studies indicated the recharge location became close to the field and the younger water with tritium was produced from the wells. Although the temperature at wellhead has not obviously decreased, the temperature given by geothermometers shows that the reservoir is cooling. The geothermal field seems to have been depleting. For long-term production, the production should be cut down for the geothermal field recovered.

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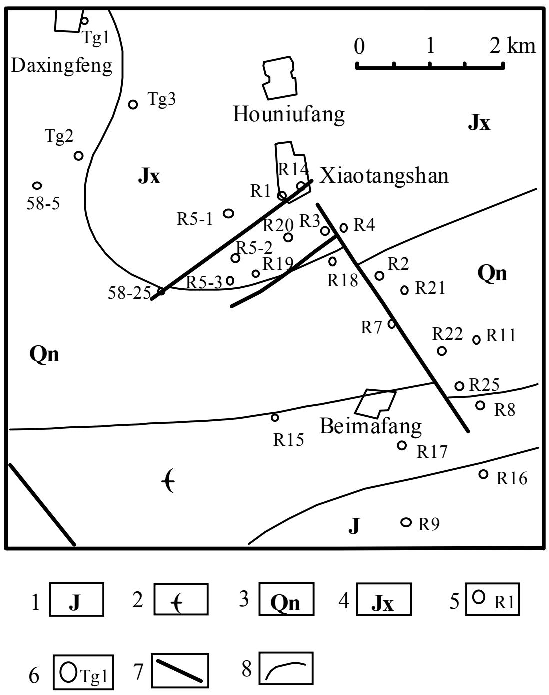
Table 1.The chemical compositions of waters in ppm from the Xiaotangshan geothermal field.

Well No.	1	4	7	8	9	11	12	Qincheng (cold spring)	Daxingfeng (cold spring)
Temp. (•).	52	48.52	54.5	49	44	59	53.7		
K	14.17	17.50	20.56	16.94	14.94	15.56	15.94	1.73	0.64
Na	78.28	87.59	89.66	93.79	71.66	80.76	79.72	6.14	7.27
Ca	45.09	51.10	47.09	49.70	49.10	43.09	47.09	55.11	58.12
Mg	13.74	13.37	14.59	15.80	14.59	12.16	15.20	17.63	7.05
Li	0.244	0.322	0.356	0.326	0.288	0.280	0.30		
Cl	26.59	33.68	39.00	35.45	23.04	31.97	33.68	8.86	8.86
SO_4	70.88	83.82	84.41	100.94	95.59	83.82	82.35	20.53	8.24
HCO_3	274.58	292.88	305.09	298.98	271.53	247.12	283.73	228.81	201.36
F	6.82	6.30	6.30	6.3	6.06	6.55	6.26	1.71	0.00
SiO_2	32.80	38.00	40.00	40.00	30.00	40	32.00	13.20	22.00
HBO_2	0.80	0.84	0.84	0.80	0.72	0.80	0.80	0.00	0.00
CO_2 free	8.80	11.00	8.80	13.2	8.80	8.80	8.80		
^3H(TU)	21.88	31.16	21.67	30.17	29.77	34.90	28.46	92.62	111.52
δD‰	-73.1	-78.2	-76.6	-79.0	-78.2	-74.4	-76.3	-63.6	-62.7
$\delta^{18}O$‰	-10.56	-11.07	-10.93	-11.06	-11.31	-10.63	-10.86	-8.91	-8.53
pH	6.9	6.85	7.00	6.95	6.90	6.92	6.90	7.25	7.2
TDS	563.94	625.72	648.26	660.00	579.60	562.59	599.70	366.26	328.36

Table 2. Comparisons of water chemistry from warm spring No.1 in 1960s and Well No.1 in 1980s (from Yao 1992).

Sampling date (Number)	Statistics	K+Na	Ca	Mg	HCO_3	SO_4	Cl	F	SiO_2	pH	TDS
1962-01—1967-03 (21)	Average	92.52	42.12	14.66	287.12	74.1	30.18	6.6	34.34	7.53	586.04
	Standard deviation	4.12	1.03	0.77	9.38	8.13	1.57	0.57	3.85	0.33	14.63
	Deviation coefficent	0.043	0.025	0.052	0.033	0.109	0.052	0.09	0.112	0.04	0.025
1987-06—1990-05 (21)	Average	92.88	42.47	15.58	286.17	65.43	28.10	6.1	34.52	7.26	572.92
	Standard deviation	4.02	1.52	1.31	10.09	4.54	1.45	0.31	2.48	0.27	13.16
	Deviation coefficent	0.043	0.036	0.084	0.035	0.069	0.051	0.05	0.072	0.03	0.131



1. Jurassic andesite. 2. Limestone of Paleozoic Cambrian 3. Shale of Proterozoic Qingbaikou system. 4. Dolomite of Proterozoic Jixian system. 5. Borehole. 6. Geothermal well 7. Fault. 8. Boundary of formation

Figure 1. The geological structure in Xiaotangshan geothermal field

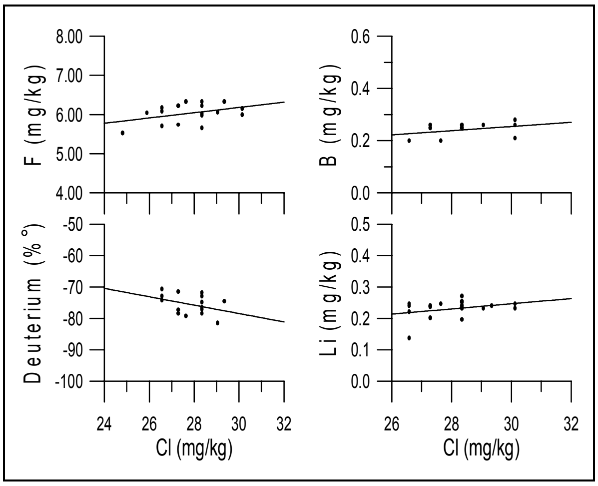


Figure 2. Aplot of Cl against F, Li, B and δD in geothermal water in the Xiaotangshan field

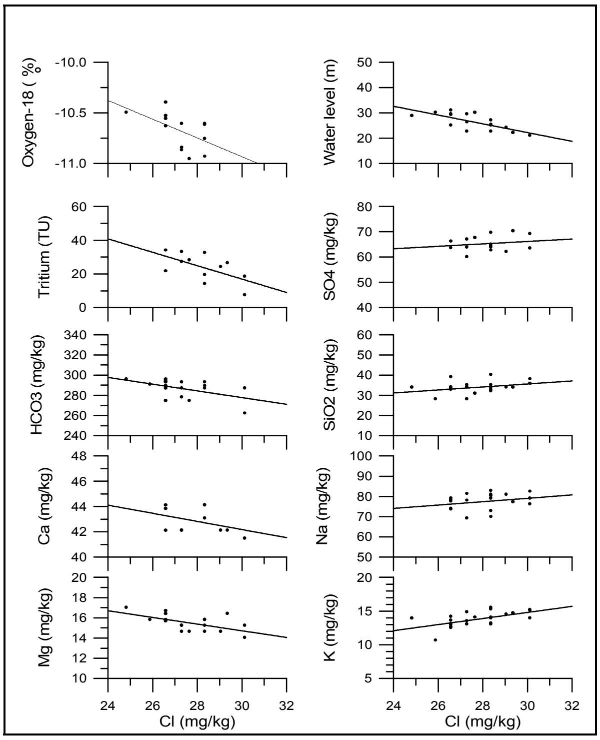


Figure 3. The correlations of various ions and water level as a function of chloride in production Well No.1.

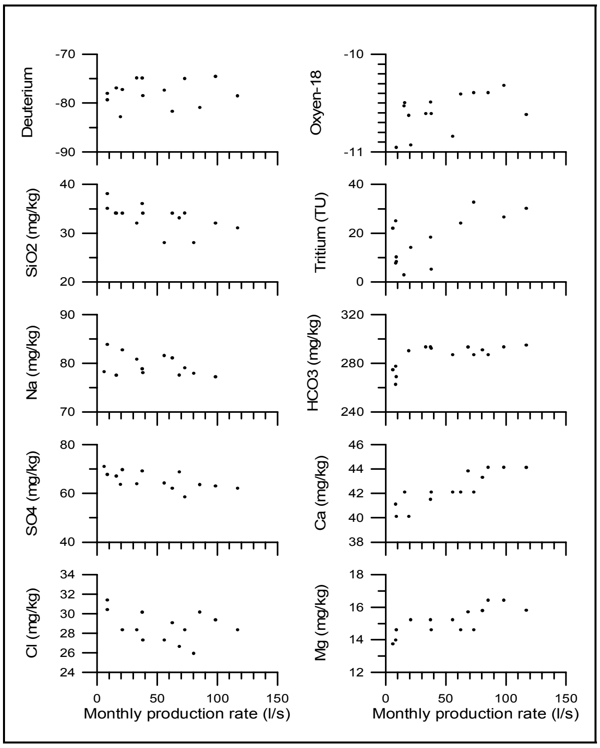


Figure 4. The changes of selected ions in geothermal water from Well No. 1 with monthly production rate.

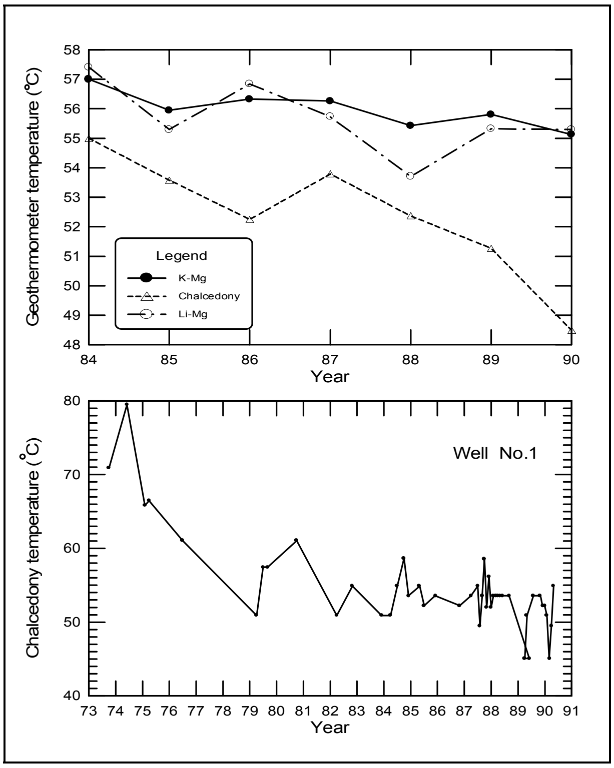


Figure 5. Changes in geothermometer temperature with time in production water at Xiaotangshan field