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Geochemical Variations in Thermal Fluids after the Construction of Chingshui Geothermal Power Plant, Taiwan

Yi-Chia Lu, Sheng-Rong Song, Po-Hsiu Lin, Taguchi Sachihiro, Chyi Wang, Yu-Ming Lai, Tsung-Ren Peng, Hsiao-Fen Lee

Department of Geosciences National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan

D00224007@ntu.edu.tw

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ABSTRACT

The operation of a 3 MWe pilot geothermal power plant during 1981-1993 has resulted in changes in hot fluid chemistry in the Chingshui geothermal field. Long term sampling of discharged waters from production wells were analyzed for chemical and isotopic compositions since 1973. The results show increasing steam ratio and enthalpy, which suggests boiling during the first few years. Moreover, hydrogen and oxygen isotopic ratios of geothermal fluid became lighter. This suggests that meteoric water derived from higher elevation circulated into deeper levels during power plant operation period. Meanwhile, after the power plant shutdown cooler and shallower meteoric water may have seeped into the reservoir to cause slightly lowered temperatures, a decrease in chloride concentrations and heavier hydrogen and oxygen isotopic values. These changes in the characteristics of geothermal fluids suggest that discharging geothermal fluids for power generation had resulted to some geochemical fluctuations in the reservoir of the Chingshui geothermal field.

1. INTRODUCTION

In 1981, a 3 MWe pilot power plant was constructed as the first geothermal power plant of Taiwan in the Chingshui geothermal field after a long term exploration. A total of 18 wells, including 8 shallower (450-503m) and 10 deeper production ones (>1,500m) have been drilled since 1973. The production was later terminated in 1993 due to several issues, such as the low efficiency of steam production for a single flash geothermal power plant, scaling problems, lack of reinjection in the design, and declining capacity among others (Lin, 2000), resulting in more than 15 years of non-discharge.

For building a clean and sustainable geothermal power plant in 2020, more geological, geochemical and geophysical surveys were funded by the Ministry of Science and Technology (MOST) in 2008. Later, detailed renovation and well tests of the production wells, IC-5, IC-14 and IC-16, were performed by Jie-Yuan Technology Corporation in 2016.

We collected thermal fluids from wells IC-5, IC-14 and IC-16, during 2017-2018 for chemical and isotopic analyses, and compared with data recorded in the last 40 years. Then, we try to find the factors, such as boiling, fluid sources and water-rock interaction that may cause changes in the isotopic and chemical fluid compositions. Finally, the goals are to understand the evolution of thermal fluids after an operated geothermal system for designing a sustainable geothermal power plant with an efficient exploitation strategy in the future.

2. GEOLOGICAL SETTING

The Chingshui geothermal area is about 1.3-km^2, straddling the Chingshui River in northeastern Taiwan (Fig.1a). Two major regional faults, the Xiaonanao and Chingshuishi Faults, cut through rock formations in Chingshui area. The Xiaonanao is a south-dipping thrust fault with wide damaged zones evident along the Chilukeng River (Fig.1b; Tseng, 1978), which is associated with the Plio-Pleistocene Orogeny. The Chingshuishi Fault is a high angle strike-slip fault located along the Chingshui River. It was first deduced from geophysical data (Huang and Chuang, 1986), then a series of fault gouges close to the IC-16 were identified by the Jie-Yuan Technology Corporation, in 2018 (pink diamond points in Fig.1b).

3. ANALYTICAL METHODS

The concentrations of silica were treated by the molybdenum yellow colorimetric method and measured by a spectrophotometer at Fukuoka University. Compositions of carbonates and bicarbonates were analyzed by the 877 Titrino Plus made by Metrohm, Switzerland. The concentrations of anions and some of the cations, potassium, sodium, calcium, and magnesium were analyzed by 883 Intelligent Ion Chromatography made by Metrohm at Tatun volcano Observatory (TVO) and Department of Geosciences, National Taiwan University (NTU), respectively. Hydrogen and oxygen isotopes of water samples were analyzed with a Liquid-Water Isotope Analyzer (LWIA) produced by Los Gatos Research in the Department of Soil and Environmental Science, National Chung Hsing University.

4. RESULTS

The results show that the silica temperatures slightly increase by ~1℃ during the discharge period in all wells; and decrease by 1-2 ℃, 6-7℃, and 5-10℃ after long time of non-discharging, in wells IC-5, IC-14 and IC-16 (Fig. 2a).

Aqueous fluids in wells IC-5, IC-14 and IC-16 show increasing chloride concentrations and lighter isotopic values with time during the discharging period; but the non-discharging period resulted to a decrease in chloride concentrations by 50% with heavier isotopic values (Fig. 2b).

During the well testing, the stable isotopes in water became lighter as discharge continued. The δD values became lighter from -54.7 ‰ and -59.5 ‰ to -55.0 ‰ and -67.0‰, and the $\delta^{18}O$ lighter from -7.0 ‰ and -7.5 ‰ to -7.3 ‰ and -10.6 ‰. In contrast, theδD and the $\delta^{18}O$ values became heavier at about 2.4 ‰ to 14.5 ‰, and 1.4 ‰ to 4.4 ‰, respectively, after the non-discharging period (Fig. 2d).

In 2017, the calculated well bottom steam percentages were 3.5-3.9%, 11.3% and 19.5-20.5% for wells IC-5, IC-14, and IC-16, respectively, which were much higher than the initial state where no boiling or just slightly steam separation conditions Occurred.

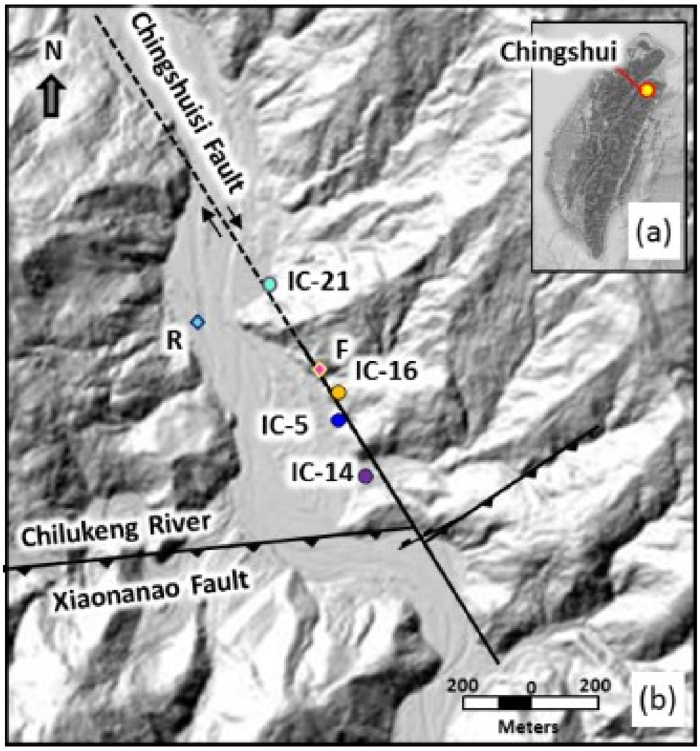

Figure 1: (a) The Chingshui geothermal field is located in the southwest of Ilan Plain. (b) The outcrops and the drilled wells, such as the IC-05, -14, -16, and -21, are predominantly distributed in a 1.3 km^2 area along the Chingshui River. The Xiaonanao, the Chingshuishi, and G faults cut across this area.

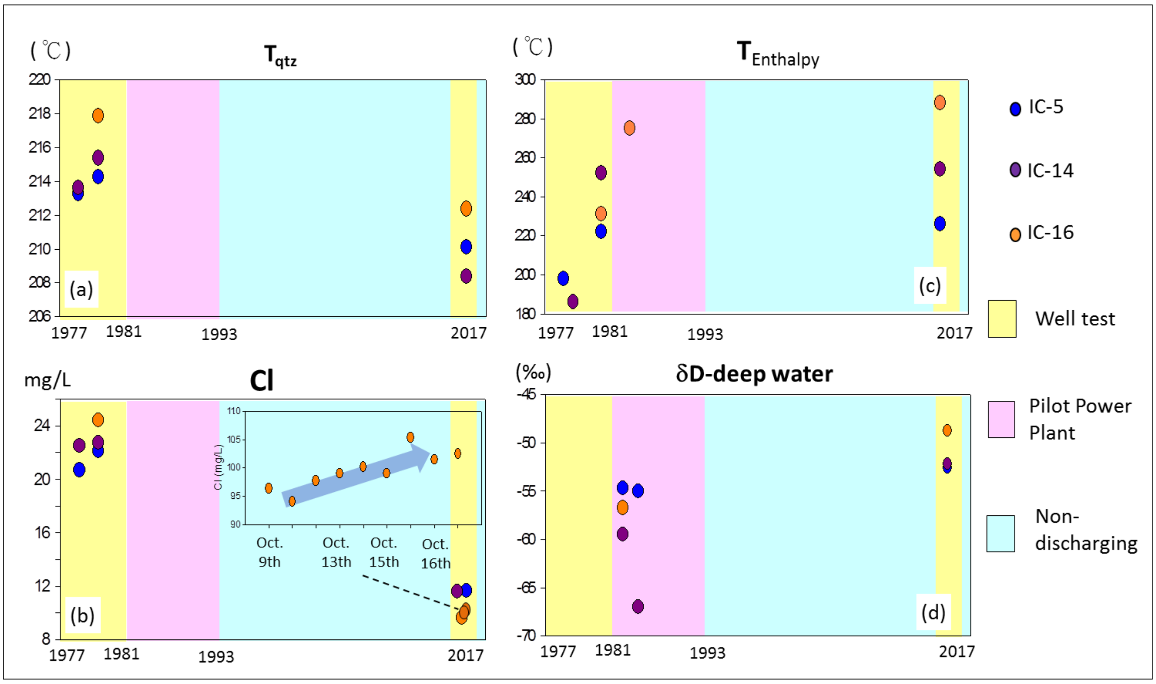

Figure 2: Plots of T_{qtz}, Cl^{-}, δD-deep water, and $T_{Enthalpy}$ vs. time.

5. DISCUSSION

5.1 Factors controlling the changes of chemical compositions

All wells occurred boiling widely since the discharging have begun, and the steam percentages did not come back to the initial state even long after the discharging stopped by the evidences of increases well bottom steam percentages and the enthalpy temperatures (Fig. 2c): from non-boiling conditions at197℃ in 1977 to 3.5-3.9% steam and 227℃in 2017 for well IC-05; from non-boiling at 188-205℃ in 1978 to 11.3% steam and 254 ℃ in 2017 for well IC-14, and from 17.2% steam at 277℃ in 1981 to 19.5-20.5% steam at 290℃ in 2017 for well IC-16. The increase in steam percentages and enthalpy temperatures imply that boiling occurred, because steam contains much higher enthalpy than thermal water. Moreover, bladed calcite crystals with gas-rich fluid inclusions, an indicator for boiling in a geothermal system (Simmons and Christenson, 1994), are abundant on the surface of open cracks and veins in the 2010 drilled cores of IC-21 (Lu et al., 2018).

Boiling can explain increasing chloride concentrations and silica temperatures of aqueous fluids in wells IC-5, IC-14.and IC-16. Moreover, comparing the 1981 and 2017 data, the distributions in oxygen and hydrogen isotopic plots, it shows that the boiling plays a significant role for isotopic changes. However, the lighter isotopic values of IC-5 and IC-14 during discharging period from 1981 to 1982, and the IC-16 discharging period in 2017, are not consistent with boiling behavior, because boiling only makes thermal fluids isotopic heavier. Therefore, it may be caused by another factor, such as source variation.

Deep circulation of hot water has been recognized in the Chingshui geothermal field. The meteoric water infiltrated into the subsurface from a catchment about 1,000 meters elevation from the southeast of the Chingshui area, then was heated by the deep rocks with higher geothermal gradient, or magmatic intrusion, and finally rising up to shallower reservoirs or discharged on the surface as hot springs (Liu et al., 1990). The higher the altitude of meteoric water infiltration is, the lighter the isotopic values will be in hot spring fluids (Chen, 1985; Liu et al., 1990). In general, because of increasing geothermal gradient with depth, fluids circulating into deeper formations have higher temperatures. Meanwhile, the deep circulation fluid has a higher concentration of Cl^-, contributed from either locally trapped brines or magmatic gases (Guo, 2012; Henley and Ellis, 1983).

We propose at discharging period, the fluid sources from a higher altitude and through a deeper circulation as suggested from lighter isotopic values, higher chloride concentrations, and higher reservoir temperature. Conversely, the cooler fluids come from lower altitudes then seeped into the reservoir as indicated by heavier isotopic values, lower chloride concentrations and lower reservoir temperature after a long period without discharge.

5.2 The characteristics of Chingshui Geothermal Field

Compared to the 1977-1979 well tests, thermal water production declined significantly in 2017. For example, hot water production rates decreased from 55.3 ton/hr in 1977 to 7.7 ton/hr in 2017 for well IC-5; from 38.7 ton/hr in 1978 down to 9.3 ton/hr in 2017 for well IC-14; and from 128.8 ton/hr in 1979 down to 9.6 ton/hr in 2017 for well IC-16.

Significant decline in thermal water production may be due to rapid overproduction of thermal fluids unmatched by the fluid residence time and rates of natural recharge. The residence time and rates of natural annual recharges are 15 years and 1.3×10^7 m^3/year based on tracer and interference tests (Fan et al., 2006); and 11.3-15.2 years and 5.0×10^5 - 6.7×10^5 m^3/year by analyzing naturally existing tritium and carbon-14 in groundwater, respectively (Cheng et al., 2010). Compared to these, total production is 664 ton/hr (5.8×10^6 ton/year) during the operation of the pilot geothermal power plant (Lin, 2000). Thus, it is obvious that the meteoric water circulation rate for recharging cannot meet the demand of geothermal production. Moreover, the fractured-control reservoir is small, only about 7.6×10^6 m^3 (Cheng et al., 2010), with limited amounts of hot fluids that are soon depleted by rapid discharging. Furthermore, re-injection of wastewater that could improve resource recovery was not implemented at that time. The Chingshui geothermal field is a fractured-controlled system with deeper heat sources, smaller reservoir volumes and lower heating rates than volcanic geothermal systems.

6. CONCLUSION

The Chingshui geothermal reservoir is a non-volcanic fractured-controlled geothermal system exploited for power generation for more than 10 years. The significant decline in well production may be due to the absence of re-injection, causing drops in reservoir pressure and serious boiling and scaling. Geochemically, the thermal waters show the lighter hydrogen and oxygen isotopic values, the higher concentrations of chloride, and the slightly higher silica temperatures in the wells, suggests that the sources of thermal fluids evolved from the shallower to deeper circulation due to the continuing discharging. With continued well discharge, the fluid source evolved from shallow to deep circulation as suggested by increasingly lighter hydrogen and oxygen isotopic values, higher chloride concentrations and slight increase in silica temperatures.

Conversely, after the pilot geothermal power plant was shut down and the wells stopped discharging, t local meteoric water seeped into the reservoir. This process resulted in aqueous fluids with heavier hydrogen and oxygen isotopic values, a decrease in chloride concentration by half, and lower reservoir temperatures in 2017 compared to the initial measurements. These results suggest heating residence times are not enough to go back to initial state. Moreover, the boiling and scales are occurred in formation rocks continuously.

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