

## Application Water Geothermometry on Geothermal Systems in Taiwan

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### ABSTRACT

Using geochemical signatures from water samples as a proxy for geothermal exploration has been applied for years. Determining the temperature of a reservoir is crucial for geothermal power generation. This paper's goal is the application of geothermometry to metamorphic and sedimentary regions of Taiwan.

For the reservoir temperature, the result of quartz geothermometer are consistent with fix aluminum and degassing condition of multicomponent geothermometer. The reservoir temperature values of quartz geothermometer display 211°C, 182°C, 134°C, 229°C, 234°C, 205°C, 235°C, and 227°C in the A, B, C, D, E, F, G, and H samples of the Chingshui geothermal field, respectively. The reservoir temperature values of multicomponent geothermometer present 278°C, 190°C, 98°C, 176°C, 218°C, 198°C, 251°C, and 204°C in the A, B, C, D, E, F, G, and H samples of the Chingshui geothermal field, respectively. The reservoir temperature values are 100°C, 100°C, and 63.1°C by quartz geothermometer in the Chonglun, Kuantzeling, and Liuchungshi, respectively. The reservoir temperature values are 100°C, 100°C, and 74.5°C by fix aluminum and degassing condition of multicomponent geothermometer in the Chonglun, Kuantzeling, and Liuchungshi, respectively.

### 1. INTRODUCTION

The geothermal reservoir temperature is important factor for exploration. The water geothermometry is a useful tool for calculating the reservoir temperature including the silica, Na-K, Na-K-Ca, Na-Li, K-Mg, and multicomponent geothermometers (Fournier and Rowe, 1966; Verma, 2000; Karingithi, 2009; Reed, 1982; Reed and Spycher, 1984). However, the silica and multicomponent geothermometers often are applied on the geothermal field of world.

In this study, we would apply these two geothermometries on the geothermal field of Taiwan. The first one is to collect waters and rocks of the Central Range Slate Belt (metamorphic rock) and Western Foothills (sedimentary rock). The second aspect is to analyze the minerals of rocks and major elements and stable isotope of water. The third is estimating the temperature of reservoir by the Geochemistry Workbench software.

### 2. GEOLOGICAL SETTING AND SAMPLE SITES

In the geological physiographic provinces of Taiwan Island from the north to the south, which include (1) the Coastal Range, the northern extend of Luzon arcs, consisting of sedimentary and volcanic rocks; (2) the Longitudinal Valley, the plate boundary between the Eurasian and Philippine Sea Plates; (3) the eastern Central Range, a pre-Tertiary metamorphic complex rock, containing the Yuli belt and western Tailuko belt; (4) the western Central Range composed of argillite, including the Backbone Range and the Hsuehshan Range belts; (5) the Western Foothills, the fold-and-thrust belt, consisting of clastic Oligocene-Pleistocene sedimentary rocks, and; (6) the Coastal Plain containing younger sediment deposits (Figure 1a) (Ho, 1988).

The Chingshui geothermal field is situated in the Backbone Ridge belt that is major composed of Miocene slate (Figure 1b). Several natural occurring hot springs found along the Chingshui River as well as geothermal wells. Those hot springs and wells are located in the Lushan Formation which is divided into two formation members including Chingshuihu member and Jenrse member. The Chingshuihu member is composed of slate or phyllite, and it is divided into three beds including the beds of Lsc, Lsc and Lsc. On the other hand, The Jenrse member is composed of alteration argillite and meta-sandstone, and it is divided into four beds involving in the beds of Lsj, Lsj, Lsj and Lsj. The Kuantzeling area is located in the Western Foothills that is major consist of Pleistocene sedimentary rock. In that area, there is near the Chukou fault, and major composed of shale formation (Figure 1c).

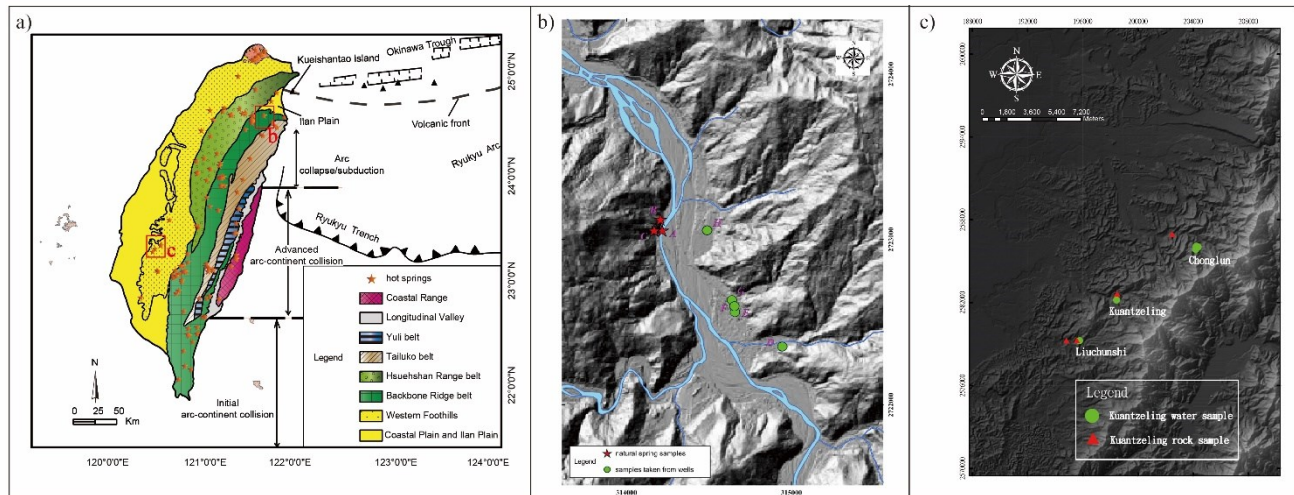


Figure 1: (a) The geological physiographic provinces of Taiwan Island and this study areas. (b) The geothermal waters locations of Chingshui geothermal field. (c) The sampling sites of Kuantzeling area.

### 3. SAMPLING AND ANALYTICAL METHODS

#### 3.1 Sampling method

In this study, all collected water samples were filtered through 0.22- $\mu$ m cellulose filters in the field and stored in high-density polyethylene (HDPE). And, we measured the pH value, total dissolved solids and temperature of sample in situ by the handheld instrument. However, for cation analysis, we not only filtered the sample but also added ultra pure  $\text{HNO}_3$  to prevent precipitation in the field. In laboratory, the Yttrium is added in these samples as the internal standard.

The anions and cations were measured using an ion chromatograph (IC, Type Met Rohm) and an inductively coupled plasma-atomic emission spectrometer (ICP-AES, Type Jobin-Yvon ULTIMA2), respectively. The uncertainties were less than 3 % for the former and less than 2 % for the latter.

The analysis of mineral assemblages of host rock were be conducted by the X-ray Diffraction.

#### 3.2 Silica geothermometer

In this study, we applied geothermometers of different silica species including the quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite. These equations as the following

(a) Quartz geothermometer (maximum steam loss)(Fournier, 1977)

$$t^{\circ}\text{C} = \frac{1522}{5.75 - \log(\text{SiO}_2)} - 273.15 \dots\dots\dots(1)$$

(b) Quartz geothermometer (no steam loss) (Fournier, 1977)

$$t^{\circ}\text{C} = \frac{1309}{5.19 - \log(\text{SiO}_2)} - 273.15 \dots\dots\dots(2)$$

(c) Chalcedony geothermometer(Fournier, 1977)

$$t^{\circ}\text{C} = \frac{1032}{4.69 - \log(\text{SiO}_2)} - 273.15 \dots\dots\dots(3)$$

(d)  $\alpha$ -Christobalite geothermometer(Fournier, 1977)

$$t^{\circ}\text{C} = \frac{1000}{4.78 - \log(\text{SiO}_2)} - 273.15 \dots\dots\dots(4)$$

(e)  $\beta$ -Christobalite geothermometer(Fournier, 1977)

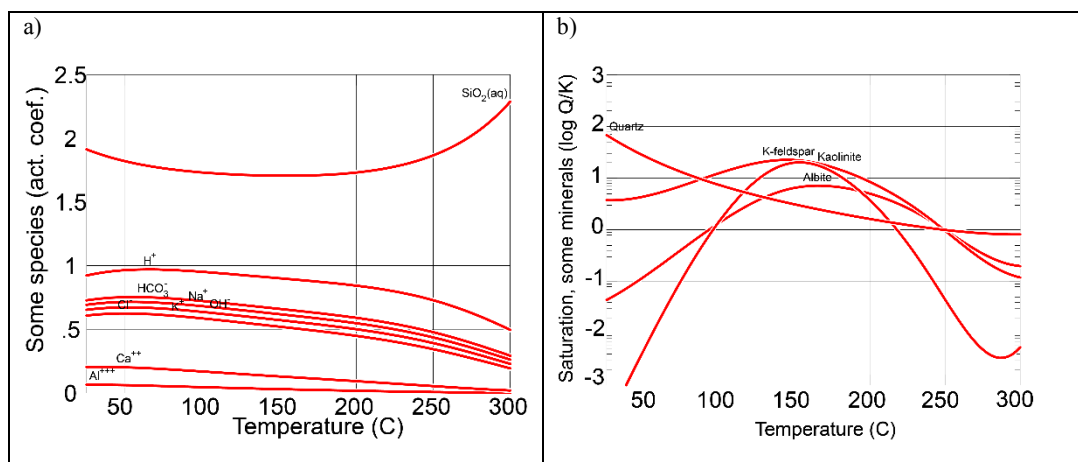
$$t^{\circ}\text{C} = \frac{781}{4.51 - \log(\text{SiO}_2)} - 273.15 \dots\dots\dots(5)$$

where  $t^{\circ}\text{C}$  is temperature estimated by  $\text{SiO}_2$  ( $^{\circ}\text{C}$ ), and  $\text{SiO}_2$  is the total amount of silicon dioxide in water ( $\text{mg}/\text{kg}$ ).

There are four assumptions for applying silica geothermometer. They are (a) the equilibrium between water and rock is valid, (b) no other water body enters as water ascending to the surface, (c) no precipitation occurs as water reach the surface, and (d) there is an unlimited supply for silicon dioxide.

### 3.3 Multicomponent geothermometer

This study calculates the reservoir temperature by Geochemistry Workbench software. The figure 2 displays principle of multicomponent geothermometer.



**Figure 2: (a) The software can also calculate the ion activity (Q) at each temperature. In general, the greater the activity of the large elements the faster the reaction rate. (b) Referring to the formula  $\log Q/K$  we can calculate at each temperature whether there is saturation, unsaturation or equilibrium. (Bethke, 2007)**

## 4. RESULTS AND DISCUSSION

### 4.1 Field observation

The pH values of three outcrops are 9.2, 8.03 and 6.14 in A, B and C of Chingshui geothermal field, respectively. The temperature of in situ are  $96^{\circ}\text{C}$ ,  $91.1^{\circ}\text{C}$  and  $63.2^{\circ}\text{C}$  in A, B and C of Chingshui geothermal field, respectively. The pH values of five drill wells are 8.2, 7.84, 8.18, 7.65 and 8.67 from D, E, F, G and H of Chingshui geothermal field, respectively. The temperature of in situ are  $96.4^{\circ}\text{C}$ ,  $64.3^{\circ}\text{C}$ ,  $94.6^{\circ}\text{C}$ ,  $84.5^{\circ}\text{C}$  and  $75.4^{\circ}\text{C}$  from D, E, F, G and H of Chingshui geothermal field, respectively (Figure 3).

The pH values are 7.45, 7.82 and 8.07 in Chonglun, Kuantzeling and Liuchungshi, respectively. The temperature of in situ are  $32.8^{\circ}\text{C}$ ,  $67.1^{\circ}\text{C}$  and  $45.4^{\circ}\text{C}$  in Chonglun, Kuantzeling and Liuchungshi, respectively (Figure 3).

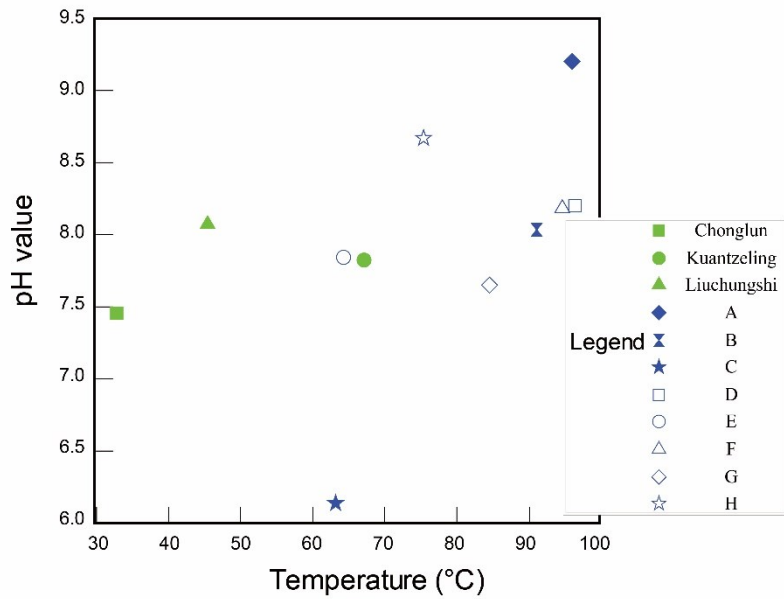


Figure 3: The pH value v.s. temperature in Chingshui geothermal field and Kuangzuling area.

#### 4.2 Major elements characteristics of thermal water

According to the major elements concentration, this paper classified into two types in Chingshui geothermal field and Kuangzuling area. The thermal water of Chingshui geothermal field belongs to Na-HCO<sub>3</sub> water, the hot spring of Kuangzuling area is Na-Cl water (Figure 4).

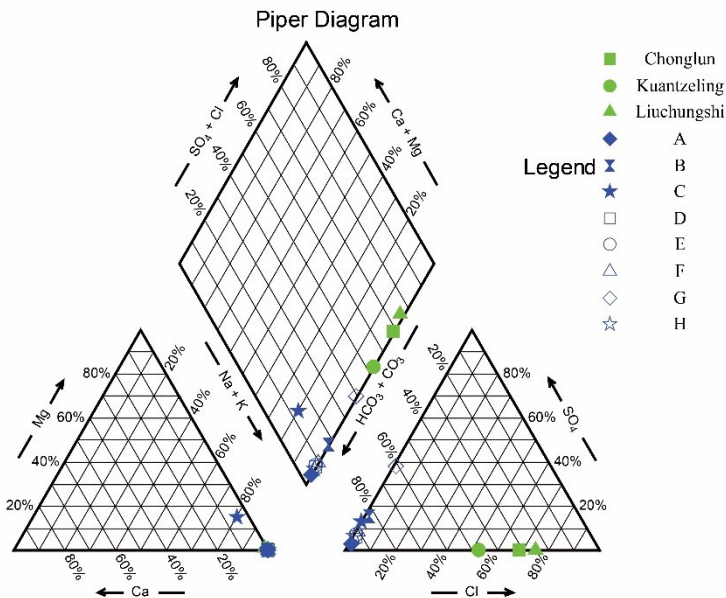


Figure 4: The Piper diagram of Chingshui geothermal field and Kuangzuling area.

#### 4.3 Mineral assemblages of host rock

In the Chingshui geothermal field, the mineral assemblages of slate formation are composed of quartz, chlorite, kaolinite, illite, feldspar, and their percentages are 15%, 22%, 28% and 5%, respectively (Figure 5).

In the Kuangzuling area, the mineral assemblages of shale formation are composed of quartz, chlorite, kaolinite, illite, feldspar, and their percentages are 13%, 33%, 52% and 2%, respectively (Figure 6).

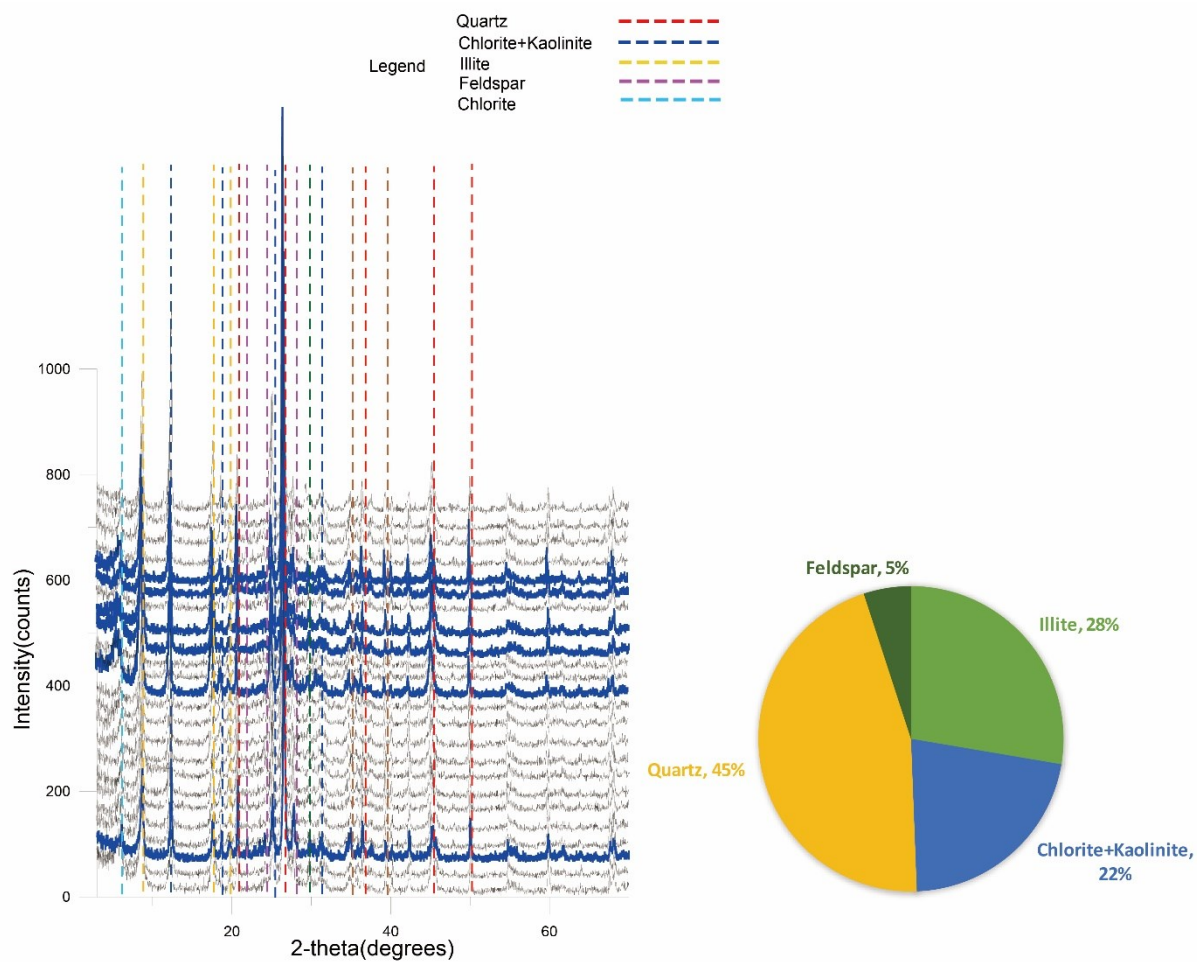
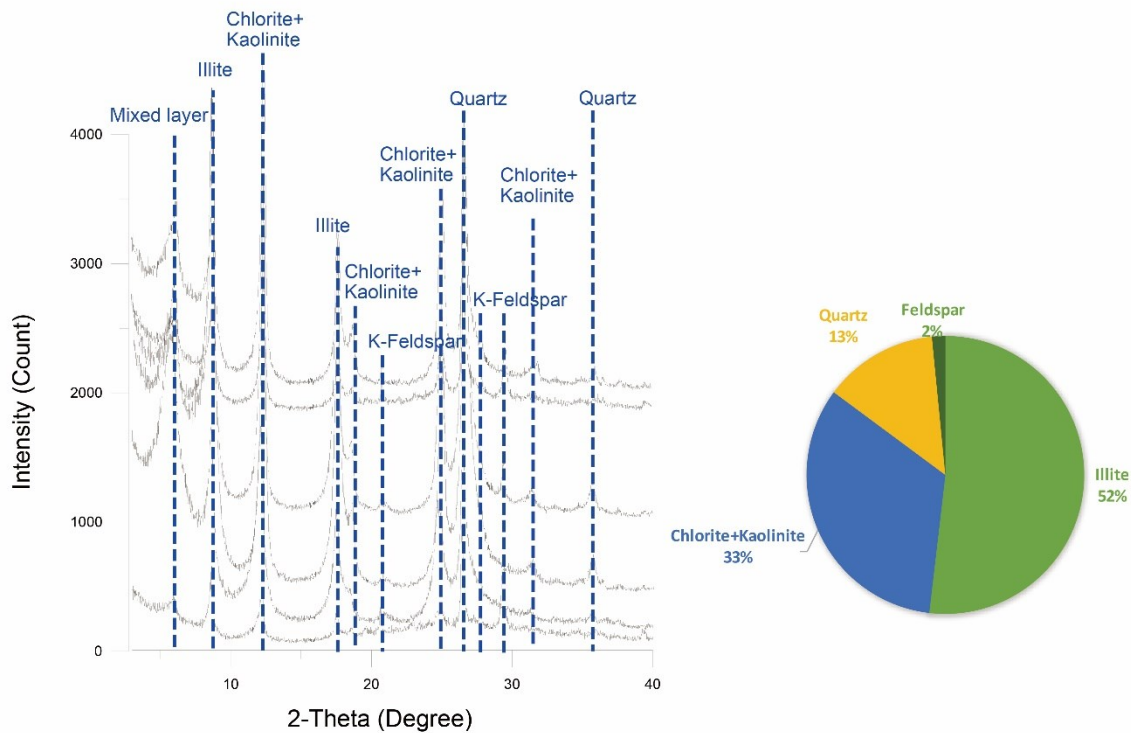


Figure 5: The XRD pattern and percentage of mineral assemblage in the Chingshui geothermal field.



**Figure 6: The XRD pattern and percentage of mineral assemblage in the Kuangzuling area.**

#### 4.4 Geothermometer

For A sample of the Chingshui geothermal field, the results present 193.1°C, 210.9°C, 195.1°C, 162.7°C and 112.7°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For B sample of the Chingshui geothermal field, the results present 170°C, 182.2°C, 161.4°C, 132.6°C and 82.7°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For C sample of the Chingshui geothermal field, the results present 129.6°C, 133.5°C, 106.4°C, 82.8°C and 34.4°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For D sample of the Chingshui geothermal field, the results present 207.8°C, 229.4°C, 217.2°C, 182.5°C and 132.6°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For E sample of the Chingshui geothermal field, the results present 211.7°C, 234.4°C, 223.3°C, 187.9°C and 138.1°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For F sample of the Chingshui geothermal field, the results present 188.1°C, 204.7°C, 187.6°C, 156.1°C and 106.1°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For G sample of the Chingshui geothermal field, the results present 212°C, 234.8°C, 223.7°C, 188.3°C and 138.5°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For H sample of the Chingshui geothermal field, the results present 206.1°C, 227.3°C, 214.7°C, 180.3°C and 130.4°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For fix aluminum and degassing condition of multicomponent geothermometer, the results display 278°C, 190°C, 98°C, 203.8°C, 195.5°C, 217.5°C, 198°C and 250.5°C in A, B, C, D, E, F, G and H of Chingshui geothermal field, respectively (Figure7).

In the Chonglun, the temperature present 100.7°C, 99.7°C, 69.6°C, 49.4°C and 2.8°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. In the Kuangzuling, the result present 100.6°C, 99.5°C, 69.4°C, 49.2°C and 2.6°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. In the Liuchungshi, the results display 63.1°C, 59.6°C, 24.6°C, 8.1°C and -35.5°C by quartz (maximum steam loss and no steam loss), chalcedony,  $\alpha$ -christobalite, and  $\beta$ -christobalite, respectively. For fix aluminum and degassing condition of multicomponent geothermometer, the results display 100°C, 100°C and 74°C in the Chonglun, Kuangzuling, Liuchunshi (Figure8).

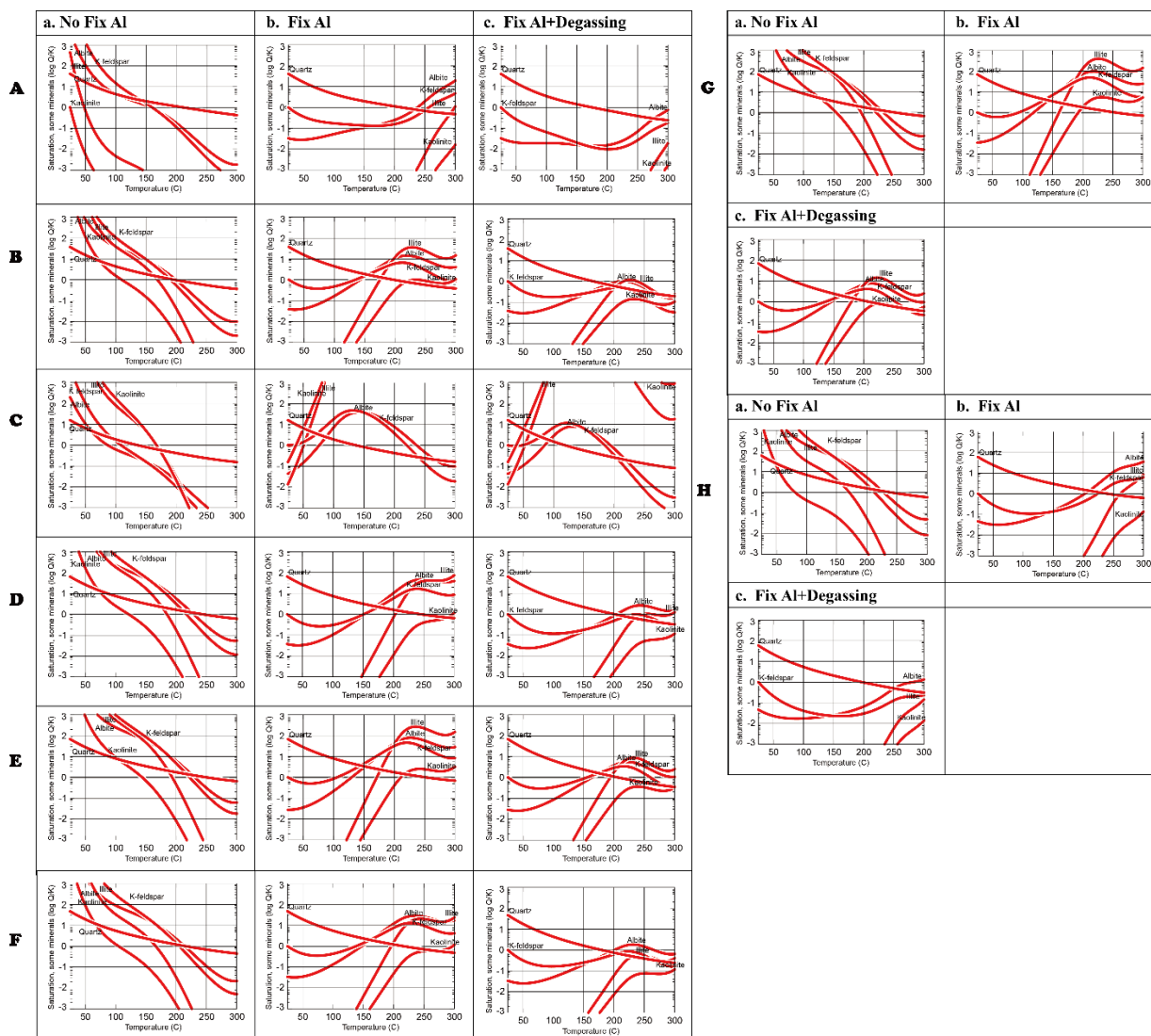


Figure 7: In the Chingshui geothermal field, the reservoir temperature is estimated by Geochemistry Workbench software.

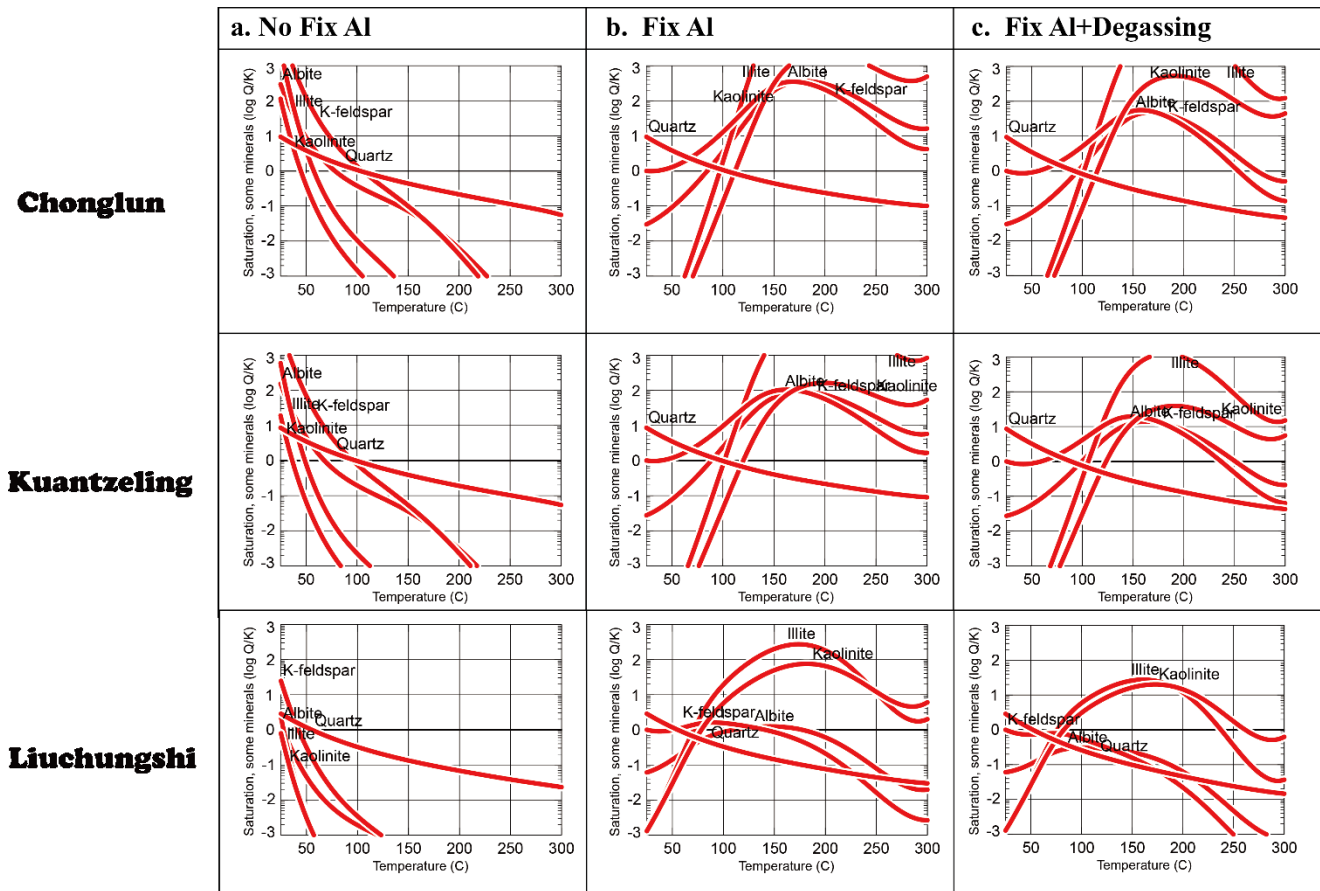


Figure 8: In the Kuantzing area, the reservoir temperature is estimated by Geochemistry Workbench software.

## 5. CONCLUSION

- (1) According to the major elements concentration, this paper classified into two types in Chingshui geothermal field and Kuangzuling area. The thermal water of Chingshui geothermal field belongs to Na-HCO<sub>3</sub> water, the hot spring of Kuangzuling area is Na-Cl water.
- (2) For the XRD results, the mineral assemblages are composed of quartz, chlorite, kaolinite, illite, feldspar in the Chingshui geothermal field and Kuantzing.
- (3) For the reservoir temperature, the result of quartz geothermometer are consistent with fix aluminum and degassing condition of multicomponent geothermometer.

## REFERENCES

- Bethke, C. M. (2007). *Geochemical and biogeochemical reaction modeling*. Cambridge University Press.
- Fournier, R. O., & Rowe, J. J. (1966). Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells. *American Journal of Science*, 264(9), 685-697.
- Fournier, R. O. (1977). Chemical geothermometers and mixing models for geothermal systems. *Geothermics*, 5(1-4), 41-50.
- Ho, Chung-Sun (1988). *An Introduction to the Geology of Taiwan explanatory text of the geologic map of Taiwan*. Central Geological Survey, MOEA, 2nd edition, 1-192.
- Karingithi, C. W. (2009). *Chemical geothermometers for geothermal exploration*. Short Course IV on Exploration for Geothermal Resources: United Nations University, Geothermal Training Program, Lake Vaivasha, Kenya, 1-22.
- Reed, M. H. (1982). Calculation of multicomponent chemical equilibria and reaction processes in systems involving minerals, gases and an aqueous phase. *Geochimica et Cosmochimica Acta*, 46(4), 513-528.
- Reed, M., & Spycher, N. (1984). Calculation of pH and mineral equilibria in hydrothermal waters with application to geothermometry and studies of boiling and dilution. *Geochimica et Cosmochimica Acta*, 48(7), 1479-1492.
- Verma, M. P. (2000). Chemical thermodynamics of silica: a critique on its geothermometer. *Geothermics*, 29(3), 323-346.

