ESTIMATION OF THE PREFERRED GEOTHERMOMETER FOR TAIWAN'S PREDOMINANTLY SLATE GEOTHERMAL RESERVOIRS OF THE CHINGSHUI REGION, TAIWAN

Huei-Fen Chen[1*], Hua-Lin Liu[1],Yi-Hua Huang[2], Sheng-Rong Song[2] and Chia-Mei Liu[3]

1. National Taiwan Ocean University, Keelung 20224, Taiwan, R.O.C.
2.Natioanl Taiwan University, Taipei 10617, Taiwan, R.O.C.
3. Chinese Culture University, Taipei 11114, Taiwan, R.O.C.
*e-mail: diopside0412@yahoo.com.tw

ABSTRACT

Estimation of the geothermal energy contained within geothermal reservoirs using geothermometers is a well-established practice. The most commonly used geothermometers at hot-spring environments are SiO_2, Na-K and Na-K-Ca. The preferred geothermometer varies with the type of environment in which it is to be used. In Taiwan, geothermal reservoirs of the Chingshui Region of northeastern Taiwan exist in predominantly slate environments. Therefore, this study examines water-rock interactions in a slate environment to determine the best geothermometer for measuring reservoir temperature. Water-rock interaction experiments at between 100 and 300°C were conducted for varying time periods with the longest duration being 60 days. The varying duration were given for equilibria to be established. Cations: Si^{4+}, Na^+, K^+, Ca^{2+}, Mg^{2+} and anions: F^-, Cl^-, PO_4^{3-}, SO_4^{2-}, Br^-, NO_3^- were analyzed after water-rock reactions had taken place and steam and liquid products had passed from the reaction chamber into a separate collection chamber in a two-tank autoclave setup. The concentrations of Si^{4+}, Na^+, F^-, PO_4^{3-}, and SO_4^{2-} varied positively with increased temperature. Cations, Ca^{2+} and Mg^{2+}, however, showed a negative relationships. Others were independent of temperature variation. These results were compared to a variety of silica, Na-K and Na-K-Ca geothermometers. The comparative results supported silica geothermometers as giving the most accurate representation of the slate environment of the Chingshui region, northeastern Taiwan. The Na-K and Na-K-Ca geothermometers did not fit the results of experiments. Further comparisons with downhole temperature testing at geothermal reservoirs in the region showed that steam conditions were very close to the results achieved. The result of these experiments strongly support a silica geothermometers as the appropriate tool for estimating temperature conditions in the slate environment on Taiwan's northeastern hot-springs region.

Keywords: geothermometer, hot spring, silica, slate

1. INTRODUCTION

Evaluating the temperature of a geothermal reservoir is key to estimating its thermal content. Recently, a successful inversion technique was developed to create a 3D interpretation of magnetotelluric (MT) data. This successful model is a useful tool for geothermal reservoir exploration (Uchida and Sasaki, 2006; Yasukawa, 2013). However, understanding the temperature of a geothermal reservoir is critical to successful exploration, because it is the primary determinant of efficiency and type of power generator required. Since coring is an expensive method of determining temperature within a geothermal reservoir, geochemical methods looking at the chemical composition of hot springs or isotopic chemistry of vapor have been developed as alternative methods (Karingithi, 2009). The most common approaches use geothermometers of SiO_2, Na-K, and Na-K-Ca and so on (White, 1970; Fournier and Rowe, 1966; Fournier and Truesdell, 1973, 1974; Fournier, 1977, 1979; Fournier and Potter, 1982).

While geothermometers are widely used, convenient and comparatively inexpensive (Fournier, 1981, 1989; Fournier and Truesdell, 1970), few studies discuss the relative suitability of geothermometers for particular environments. In Taiwan, past research by Cherng (1978) used a Na-K-Ca geothermometer in hot springs of Yilan while later Liu (2002) used a SiO_2 geothermometer in the same region. Unfortunately, the two studies delivered different temperature results leaving us a question of the exact temperature. Later, Liu et al. (2015) used silica geothermometers to evaluate a broader selection of hot springs areas for a potential geothermal power plant at three zones on the Yilan Plains, Sanxing, Dongshan and Wujie. Using a silica geothermometer was expected to better constrain results to assist with evaluating locations. Regardless, it is still unclear why Na-K-Ca and SiO_2 geothermometers produce such obvious differences in temperature results. To help with developing a reliable standard suited to local conditions, this study proposes a water-slate interaction experiment to give a suitable geothermometer for measuring temperature within geothermal reservoirs in the predominantly slate environments of northeastern Taiwan's geothermal reservoirs.

2. METHOD

Five grams of slate grain sieved through 4 mesh and 8 mesh were reacted with 280 ml pure water for different durations (short and long). Experimental temperatures ranged from 100°C to 300°C under saturated vapor pressure (Fig. 1). Two connected autoclaves separated by a valve were used to conduct the experiments. Initially, 280 ml of pure water was injected into the first autoclave and 200 ml of pure water into the second. When the reaction reached the desired duration at high temperature, the valve was opened and vapor and water passed from the first to second vessel. A filter with 5μm pore size was installed in the gate between the two vessels. The reaction solids was immediately preserved in vessel one, and liquids was removed to vessel two. In this two-vessel reaction, the oversaturated solution in the first vessel should be immediately diluted in the second vessel. This method effectively prevents the solution reacting with rocks in the first vessel and secondary minerals precipitating during cooling.

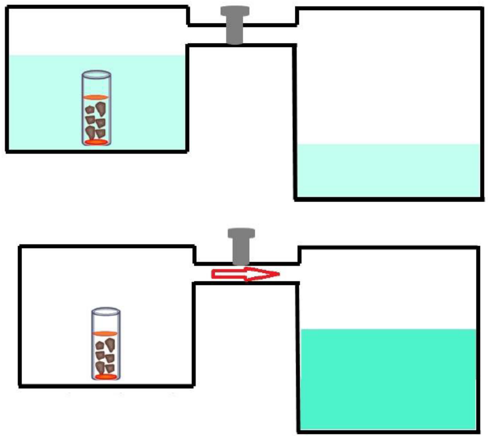

Figure 1. Illustration of water-rock interaction setup

The gathered diluted solution from vessel two was filtered through a 0.2 μm membrane and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) for cations and ion-exchange chromatography (IC) for anions. The cations measured were: Si^{4+}, Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} while the anions were: F^{-}, Cl^{-}, PO_4^{3-}, SO_4^{2-}, Br^{-}, and NO_3^{-}. Secondary minerals on the slate rocks of the first vessel were measured by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) to understand equilibrium phases.

3. RESULTS AND DISCUSSIONS

3.1 Silica Geothermometers

The silica geothermometer was first proposed by White et al. (1956) and White (1970). Consequent researchers examined the application of silica geothermometes correcting for SiO_2 solubility in equilibrium with quartz (Fournier 1977; Fournier and Potter, 1982), chalcedony (Arnórsson et al., 1983), and amorphous silica (Fournier and Marshall, 1983). Other researches discussed the temperature limits of proposed equations (Arnórsson et al., 1983; Nicholson, 2012). Arnórsson et al. (1983) suggesting that for temperatures between 120°C and 180°C, equations should use chalcedony solubility. Moreover, many past researches have used silica geothermometers for estimating geothermal reservoir temperatures (Chen, 1985; Liu, 2002; Karingithi, 2009; Kuo et al., 2015; Lee et al., 2015; Liu et al., 2015)

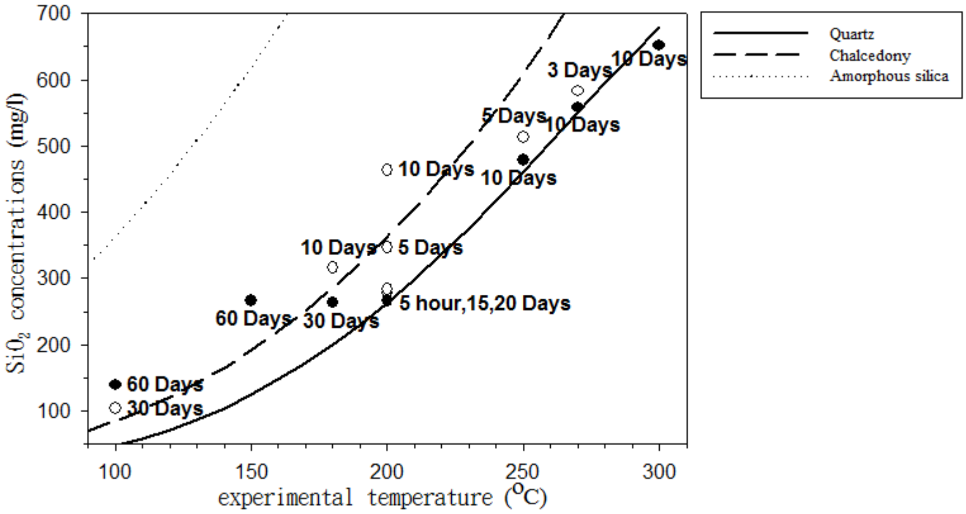

Figure 2. Experimental temperatures and silica concentrations compared to silica solubility with quartz (Fournier and Potter, 1982), chalcedony (Arnórsson et al., 1983), and amorphous silica (Fournier and Marshall, 1983).

Our experimental results show a positive correlation between real reaction temperatures and SiO_2 concentration using silica geothermometers (Fig. 2). In Figure 2, the empty circle means the experiment of shorter reaction time, and the solid circle means that of longest reaction time with more reached equilibrium condition. For examples of 200°C , the silica concentration increased from 5 hours to 10 days, but it decreased to an equilibrium concentration in 15 days and 20 days. So, we must test in varying duration for determinate equilibrium concentration in each temperature experiment. When temperatures were higher than 200°C, the quartz geothermometer was very accurate, but when the temperatures were lower 180°C, the chalcedony geothermometer was more accurate. That means that between 180~200°C, there is a transitional zone in which silica concentration is difficult to confirm.

***3.2** Na-K and Na-K-Ca Geothermometers*

In other studies, researchers have considered the Na/K ratio as being independent of spring water evaporation as the concentrations of all these ions would decline during evaporation. In these studies, equilibrium of albite and orthoclase were used to calculate the geothermometer (White, 1965; Ellis and Wilson, 1960). Later, revised equations of these relations were proposed by others (Fournier, 1979; Arnorsson, 1983; Nieva and Nieva, 1987; Giggenbach, 1988). In present research, the Na-K geothermometer is well established and has been shown to be particularly relevant in measuring waters from high temperature chloride springs (Muraoka et al., 2007; Karingithi, 2009; Nicholson, 2012). However, Na-K equilibrium of feldspar is unstable in high concentration Ca^{2+} environments. This anomaly led to the development of a geothermometer based on the relationship between the Na-K equilibrium and introduced calcium ions (Fournier and Truesdell, 1973). This empirical Na-K-Ca geothermometer has the advantage of not high thermal regions (Truesdell, 1976; Cherng, 1978; Muraoka et al., 2007; Karingithi, 2009; Nicholson, 2012).

Curiously, in our experiments, neither the Na-K nor Na-K-Ca geothermometer shows a positive correlation with our experimental temperatures (Fig. 3). When we calculated the experimental ion concentration to the geothermometers of Na-K and Na-K-Ca, we discovered that they (empty and solid circles) show reverse relationship with our experimental temperatures. This opposite results is due to the equilibrium minerals involved in the water-slate interaction that were illite and chlorite and not feldspar by SEM and EDS analysis.

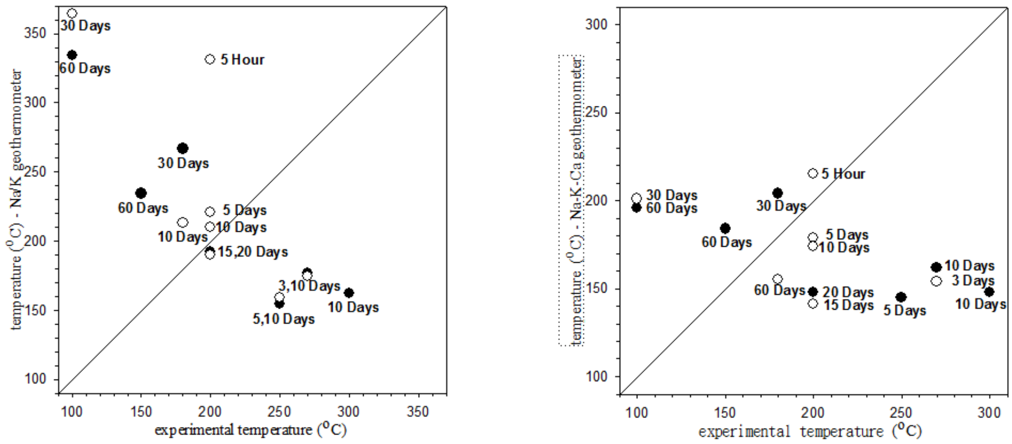

Figure 3. The real experimental temperatures compared to the calculted temperature by Na-K geothermometer (Giggenbach, 1988), and Na-K-Ca geothermometer (Fournier and Truesdell, 1973).

The results above indicate the suitability of the SiO_2 geothermometer in the slate dominated regions of the Central Mountain Range over Na-K or Na-K-Ca geothermometers. To further validate our findings and elaborate on the results, actual temperatures of hot spring recorded at the bottom of borehole in Chingshui regions (IC 1 to 16) were used for comparison with our results (Fig. 4). Actual temperatures (black circles) distribute between the quartz geothermometer of steam-loss (red triangles) and non steam-loss (blue squares) zones at temperatures higher than 180°C, and the real temperature is closer to the steam-loss equation. However, the real temperature is closer to chalcedony geothermometer (green inverted triangles) at temperature below 180°C.

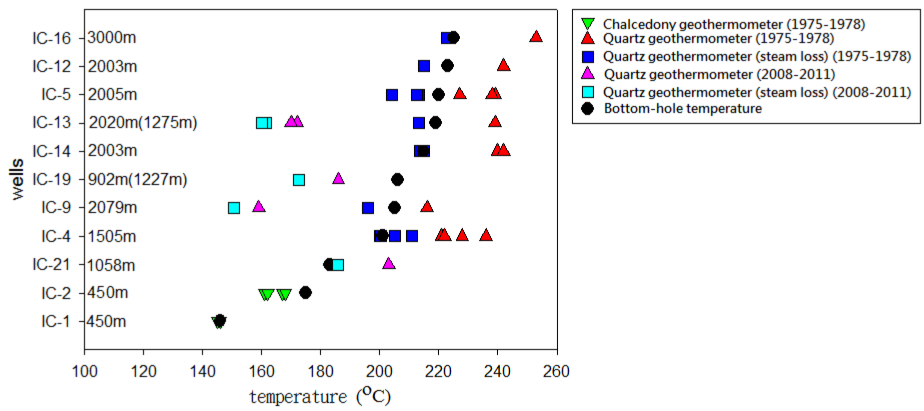

Figure 4. Comparing real detected temperatures at hot springs at the bottoms of cores with the silica geothermometer of quartz (Fournier and Potter, 1982) and chalcedony (Arnórsson et al., 1983) equations.

4. CONCLUSION

The results of this research show an error under the quartz geothermometer of 1~6°C for temperatures 200~300°C. This error is higher under the chalcedony geothermometer at temperatures 100~180°C. Mineral phase issues mean Na/K and Na-K-Ca geothermometers are not suitable for use in the slate environments of Taiwan. Real detected temperatures of hot springs in bottom of boreholes are only a little higher than the steam-loss equation of silica geothermometer in the Chingshui region of Taiwan. The results strongly support using silica geothermometers for temperature estimations in geothermal reservoirs of the predominantly slate regions of Taiwan's Central Mountain Range.

REFERENCES

Arnórsson, S., Gunnlaugsson, E. and Svavarsson, H. (1983) The chemistry of geothermal waters in Iceland. III. Chemical geothermometry in geothermal investigations. *Geochimica et Cosmochimica Acta* **47**, 567-577.

Chen, C.H. (1985) Water-Rock Interaction Chemical characteristics of thermal waters in the Central Range of Taiwan, R.O.C. *Chemical Geology* **49**, 303-317.

Cherng, F.P. (1978) Geochemical Exploration of Hot Spring Areas In Taiwan,*Ming and Metallurgy*, 22 (4), 72-83. (in Chinese)

Ellis, A.J. and Wilson, S.H. (1960) The geochemistry of alkali metal ions in the Wairakei hydrothermal system. *New Zealand Journal of Geology and Geophysics* **3**, 593-617.

Fournier, R.O. (1977) Chemical geothermometers and mixing models for geothermal systems.

*Geothermics***5**, 41-50.

Fournier, R.O. (1979) A revised equation for the Na/K geothermometer. *Geothermal Resources Council Transactions* **3**, 221-224.

Fournier, R.O. (1981) Application of water geochemistry to geothermal exploration and reservoir engineering, *Geothermal systems: principles and case histories*. Chichester, Sussex, England and New York, Wiley-Interscience, pp. 109-143.

Fournier, R.O. (1989) Lectures on geochemical interpretation of hydrothermal waters. UNU *Geothermal Training Programme.*

Fournier, R.O. and Marshall, W.L. (1983) Calculation of amorphous silica solubilities at 25° to 300°C and apparent cation hydration numbers in aqueous salt solutions using the concept of effective density of water. *Geochimica et Cosmochimica Acta* **47**, 587-596.

Fournier, R.O. and Potter, R.W. (1982) Revised and expanded silica (quartz) geothermometer, *Geothermal Resources Council Bulletin* **11**, 3-12.

Fournier, R.O. and 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* **26**4, 685-697.

Fournier, R.O. and Truesdell, A.H. (1970) Chemical indicators of subsurface temperature applied to hot spring waters of Yellowstone National Park, Wyoming, U.S.A. *Geothermics* **2**, Part 1, 529-535.

Fournier, R.O. and Truesdell, A.H. (1973) An empirical Na-K-Ca geothermometer for natural waters. *Geochimica et Cosmochimica Acta* **37**, 1255-1275.

Fournier, R.O. and Truesdell, A.H. (1974) Geochemical indicators of subsurface temperature. Part II. Estimation of temperature and fraction of hot water mixed with cold water. U.S. *Geological Survey* **2**, 263-270.

Giggenbach, W.F. (1988) Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. *Geochimica et Cosmochimica Acta* **52**, 2749-2765.

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, pp. 1-22.

Kuo, C.H., Liu, C.M., Song, S.R. and Tsai, Y.W. (2015) Application Silica Heat Flow on Geothermal Water Circulation Depth of the Chingshui Geothermal Field, Taiwan, Fourtieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 1-6.

Lee, B.H., Lin, C.K., Chuang, C.W., Liu, L.W., Lee, H.J. and Liu, C.H. (2015) A Test of Calcium

Carbonate Scale Inhibition in Chingshui Geothermal Field, Taiwan, Proceedings World Geothermal Congress 2015, Melbourne, Australia, pp. 1-8.

Liu, C.M. (2002) Silica heat flow and thermal structure of southern Taiwan, master thesis of National Taiwan University, Institute of Geosciences, 93pp. (in Chinese)

Liu, C.M., Chiang, H.T., Kuo, C.H., Song, S.R. and Tsai, Y.W. (2015) Integrating Geothermometer and High Resolution Thermometer to Characterize the Geothermal Characteristics of Ilan Plain, Taiwan, *Fourtieth Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, pp. 1-6.

Muraoka, H., Sakaguchi, K.,Shiro, T.,SoKen-Hiroshi, S.,Shigeno,Mizugaki, K. (2007) Japan's hydrothermal system Atlas, *AIST Geological Survey of Japan*, 110p.

Nicholson, K. (2012) **Geothermal Fluids: Chemistry and Exploration Techniques**. Springer Berlin Heidelberg.

Nieva, D. and Nieva, R. (1987) Developments in geothermal energy in Mexico—part twelve. A cationic geothermometer for prospecting of geothermal resources. *Heat Recovery Systems and CHP 7*, 243-258.

Truesdell, A.H. (1976) Summary of section III geochemical techniques in exploration, *Proceedings of the 2nd UN Symposium on the Development and Use of Geothermal Resources*. Lawrence Berkeley Laboratory, Berkeley, California, pp. liii-lxxix.

Uchida, T. and Sasaki, Y. (2006) Stable 3-D inversion of MT data and its application to geothermal exploration, *Exploration Geophysics*, **37**, 223-230.

White, D.E. (1965) Saline waters of sedimentary rocks. In: Fluid in Subsuface Environments -*Am. Assoc. Pet. Geologists, Mem.*, Young and Galley editors, **4**, 342-360.

White, D.E. (1970) Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources, *Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources*. IIRG, CNR, Pisa, Italy, p. 58-80.

White, D.E., Brannock, W.W. and Murata, K.J. (1956) Silica in hot-spring waters. *Geochimica et Cosmochimica Acta* **10**, 27-59.

Yasukawa, K., Ishido, T., Matsubayashi, O., Uchida, T., Sakaguchi, K. and Matsuyama, K. (2013) Interpretation of MT and SP survey results at Minami-Izu geothermal field, Japan, *Proceedings of 38th Workshop on Geothermal Reservoir Engineering*, Stanford, California.