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Application of Integrated Multicomponent Geothermometry to a Tengchong Geothermal Field, Southwestern China

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ABSTRACT

Geothermal reservoir temperature is an important parameter of geothermal research and development. Classical geothermometers have been commonly applied to determine geothermal temperatures. When the deep geochemical signatures are masked by effects of gas loss, mixing and/or dilution, these “classical” geothermometers often give inaccurate results. The integrated multicomponent geothermometry (IMG) coupled with numerical optimization is able to reconstruct deep fluid chemical composition and give relatively reasonable results. Using the IMG simulation method, we have investigated geothermal reservoir temperatures for a Tengchong geothermal field in Southwestern China. The results show that the reservoir temperature in the study area ranges from 206 to 250 degrees Celsius, which is consistent with field observations during geothermal exploration. The results of the quartz geothermometer are closest to the IMG results. Therefore, we believe the optimized IMG is the most credible geothermometry in this study area. Al and Mg concentrations have significant impact on precipitation and dissolution of minerals. Accurate selection of reservoir rock minerals is the key for the success of the use of the integrated multicomponent geothermometry.

1. INTRODUCTION

Chemical geothermometer has been applied in estimating geothermal temperature for decades, the main theory is to analyze the relationship between chemical composition and temperature to estimate the geothermal temperature. The most commonly used chemical geothermometer is classical geothermometer, such as silica geothermometer (Fournier and Potter, 1982), Na-K ratio geothermometer (Fournier, 1979), Na-K-Ca ratio geothermometer (Fournier and Truesdell, 1973) and K-Mg ratio geothermometer (Giggenbach, 1988). However, these methods are based on the assumption that signatures of deep fluid have not been covered up by gas loss, mixing and/or dilution when geothermal fluids ascending to ground surface.

Integrated multicomponent geothermometer (IMG) is based on the theory of multiple mineral saturation index analysis of the fluid in a variety of dissolved components. Compared with the classical geothermometer, the advantage of IMG is based on the complete fluid analysis, numerical calculation and reliable thermodynamic theory, it can be used in most of geochemical systems. But the IMG requires detailed chemical and mineral data, so its application frequency is much lower than classical geothermometer (Ding, 2013).

Based on the above problems, choosing Tengchong geothermal field as the research area, this paper uses the IMG to rebuild the chemical composition of deep fluid to estimate more accurate temperature. In addition, we discuss the influence of gas loss, mixing/dilution, different mineral combination and concentration of Al, Mg on adjusting geothermal temperature.

2. GEOLOGICAL SETTINGS

Yunnan Tengchong volcanic region is located in the edge of the Eurasian plate and Indian plate. In this field, late Cenozoic volcanic activity and modern fracture tectonic activity are frequent. There are a lot of granite rich in radioactive elements, providing a rich source of heat for the region (Tong and Zhang, 1989).

Rehai geothermal field is one of the most active geothermal field in Tengchong volcanic region, it has high reputation both at home and abroad. Rehai geothermal field is located in the southwest of Tengchong county, with a total area of nearly 10 km^2, in northcentral zone of Tengchong-Longchuan hydrothermal activity region. It includes a wider range area, high intensity, and complete types of large geothermal field in Tengchong (Figure 1a, b). The formation of Rehai geothermal field is closely related to the recent volcanic activity, and the fracture development zone is helpful to guide water thermal conductivity. This geothermal field covers all types from low temperature to boiling spring. There are some high temperature springs (≥80^{o}C~<local boiling point), including Laogunguo, Dagunguo, Xiaogunguo, Yanjingquan, Diretiyanqu, Zhenzhuquan, Huaitaijing, and Gumingquan. Others are medium and low temperature springs (≥25^{o}C~<80^{o}C), such as Dabaiyan, Xianrenzaotang, Zhongxiaosi, Shizitang, and Yangjiapo. The remaining springs are steaming ground and gas holes, including Zhonghuangdimian, Huangguoqing, and Shapo-Songmuqing (Guo, 2013).

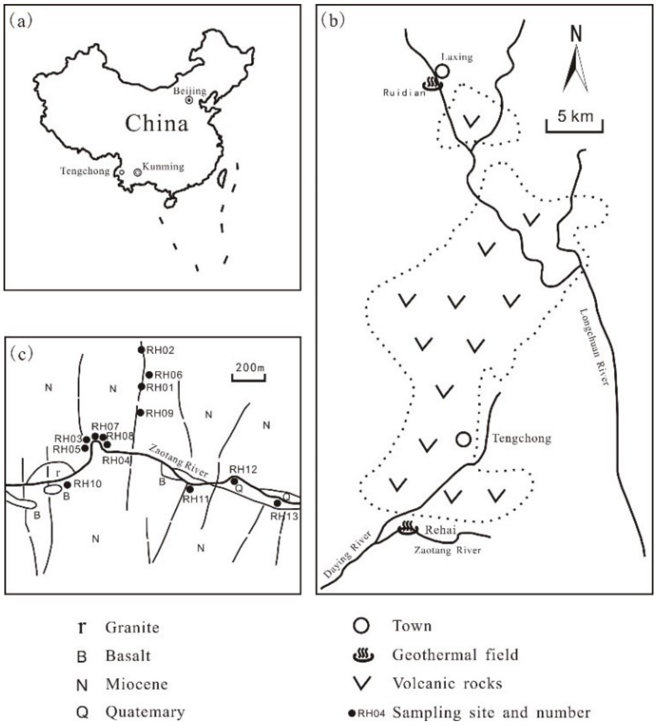


Figure 1: (a and b) Location of the Rehai geothermal field; (c) Sampling sites in the Rehai geothermal field (According to Liu et al., 2014).

3. WATER CHEMICAL COMPOSITION

Water sample data used in this study come from the analysis of field water samples (Liu, 2014). A total of 13 water samples were collected near Zaotang River, Rehai geothermal field, Tengchong County (Figure 1c). Chemical compositions of water sample are listed in Table 1.

As can be seen from the Table 1, in most water samples main cations are Na^+ and K^+, while concentrations of Ca^{2+} and Mg^{2+} are very low. Main anions are Cl^- and HCO_3^-, SO_4^{2-} is the main anion only in RH03 and RH06, but RH05 has three main anions or CO_3^{2-}, Cl^- and HCO_3^-. The pH value of RH06 is 2.6, the rest of samples are weak acid or weak alkaline (6.4 ~ 9.2). In all water samples, RH03 and RH06 are different, because they have high concentration of SO_4^{2-} and low concentrations of Na^+, Cl^- and HCO_3^-. As the local shallow groundwater has low concentrations of Na^+, Cl^- and HCO_3^-, we speculate that due to the degassing effect some of gas loss carrying a lot of H_2S and SO_2 reacting with shallow groundwater generated acid with lots of SO_4^{2-} when it ascends to ground surface.

Table 1: List of aqueous concentrations of the major spring waters from Rehai geothermal field (mg/L).

Sample no.	Location	T/°C	pH	HCO_3^-	CO_3^{2-}	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	SiO_2
RH01	Dagunguo	96	8.3	1131.9	35.6	35.2	725.0	1.0	0.0	689.0	123	889.8
RH02	Laogunguo	91	6.8	561.0	36.0	23.9	325.0	0.9	0.0	252.0	53.1	360.0
RH03	Zhenzhuquan	96	6.4	5.6	0.0	128.2	39.2	2.3	0.4	67.7	15.9	262.0
RH04	Gumingquan	96	8.9	759.7	122.3	18.6	651.0	1.4	0.0	573.2	107	677.0
RH05	Yanjingquan	94	8.9	499.8	190.5	15.3	413.6	0.3	0.0	474.5	83.9	678.7
RH06	Diretiyanqu	88	2.6	0.0	0.0	682.0	5.9	30.2	1.3	14.8	24.1	316.9
RH07	Huaitaijingzuo	88	8.4	857.3	40.8	20.1	558.6	1.5	0.1	538.3	96.8	304.0
RH08	Huaitaijingyou	88	7.6	628.5	0.0	38.3	454.6	1.6	0.0	400.4	71.1	491.0
RH09	Xiaogunguo	82	7.5	982.9	12.9	20.5	174.8	11.8	1.4	112.2	33.6	260.5
RH10	Wumingquan1	49	9.2	517.8	127.3	32.7	344.7	1.1	0.3	389.3	72	581.2
RH11	Wumingquan2	66	6.9	665.4	1.1	52.1	279.5	2.4	0.1	334.2	51.9	330.0
RH12	Wumingquan3	90	8.2	615.6	35.1	23.8	279.5	2.4	0.2	338.7	50.9	350.0
RH13	Wumingquan4	70	8.3	701.7	63.0	34.0	361.9	4.9	0.5	375.4	68.9	280.0

4. APPROACH OF INTEGRATED MULTICOMPONENT GEOTHERMOMETRY

4.1 Mineral assemblage and thermodynamic data

For the case of Rehai near Tengchong volcanic region, a mineral assemblage was selected on the basis of XRD analyses of cuttings from Lin's research (Lin, 2014). From this published data, the rock of geothermal reservoir is Yanshanian granite. Quartz, albite, microcline, clinochlore, muscovite, calcite, tremolite, laumontite, and montmorillonite-Ca are present in this granite.

The thermodynamic database SOLTHERM.H06 (Reed and Palandri, 2006) was used in this simulation, which has been validated in many types of hydrothermal systems.

4.2 Simulation program

In this study, we used a reservoir temperature simulation program GeoT, developed by Spycher et al. (2014) of Lawrence Berkeley National Laboratory. Using complete fluid analyses, GeoT calculates the saturation indices of minerals (log(Q/K)) over a range of temperatures (e.g., 25-300°C), the saturation indices are graphed as a function of temperature, and the clustering of log(Q/K) curves near zero at any specific temperature is inferred to yield the reservoir temperature. This computer program combines the multicomponent chemical geothermometry method by Reed and Spycher (1984) and deep fluid reconstruction to correct any dilution/mixing and gas loss on the way to the ground surface. Meanwhile, this software employs a set of objective criteria to estimate reservoir temperatures to reduce errors in judging clustering of computed log(Q/K) curves on fairly subjective “eyeballing”. Coupled with numerical optimization using PEST, GeoT can estimate unknown or poorly known input parameters.

Input parameters include specific minerals, concentrations of aqueous species, gas composition, initial temperature, steam fraction of discharge, etc. We use IMG (GeoT-PEST) to simulate a total of 13 samples in Tengchong.

5. RESULTS

5.1 Example application

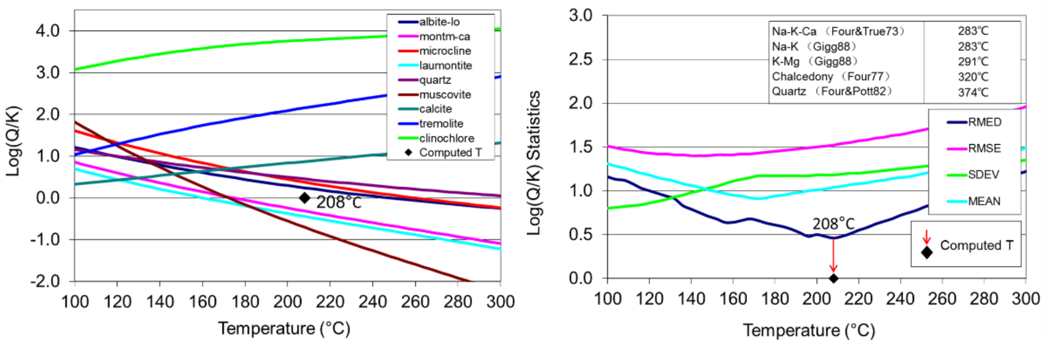
Because of the lack of deep drilling, there is no accurate data about reservoir temperature of Rehai field near Tengchong region. The maximum reported wellbore temperature is less than 200°C in our research area, it is below the results reported by previous investigators using a variety of methods. This is probably because most drillings are shallow, only a few deep drillings may not touch the real geothermal reservoir (Zhang and Duan, 2005). Guo (2013) used Na-K geothermometer and Si-enthalpy graphic method to estimate the reservoir temperature, and the result is 250°C. Using a variety of classical geothermometers and a lot of chemistry data, Tong and Zhang (1989) obtained an average value of 215±28°C. Integrating Na-K geothermometer, SiO_2 geothermometer and carbon isotope geothermometer, Shang (2000) gave a temperature range of 250±7°C. Synthesizing results of previous investigations, the range of 200-250°C is reasonable temperatures in Rehai geothermal field near Tengchong volcanic region.

RH01 (Dagunguo) is the most famous and representative geothermal spring, so we choose RH01 as an example. Due to the absence of Al concentration in the given data, according to previous experience an approximate value (0.05 mg/L) is given by Zhang et al. (2004). As Mg concentration is too low to detect, it is assumed that the concentration of Mg is minimum detectable value (0.01 mg/L). (Figure 2a) computed saturation indices (SI) graphed as a function of temperature, the clustering near zero occurs around 208°C. (Figure 2b) is measure of clustering: median (RMED), mean root square error (RMSE), standard deviation (SDEV) and average (MEAN) of absolute SI values. The equilibrium temperature is inferred from the temperature at which RMED is minimum (Spycher et al., 2014). As shown in (Figure 2b), RMED result is 0.46, and the other statistical results are even higher than 1, there are a lot of errors without deep fluid reconstruction. (Figure 2b) also shows the classical geothermometer predictive value, they are all higher than 280°C, beyond the predictable range.

In the selected 9 minerals, six are aluminosilicate minerals (albite-low, montm-ca, microcline, laumontite, muscovite, clinochlore). Al concentration is an important factor in determining the Al-containing minerals equilibrium, but in reality Al concentration is often missing or inaccurate. Pang et al. (2010) pointed out that the error in Al data will destroy the original mineral equilibrium. If we turn down the Al concentration, all Al-containing minerals log(Q/K) curves will move to unsaturated state, but other minerals do not change. So we must correct Al concentration to apply the IMG method. For the same reason, the concentration of Mg should be also corrected.

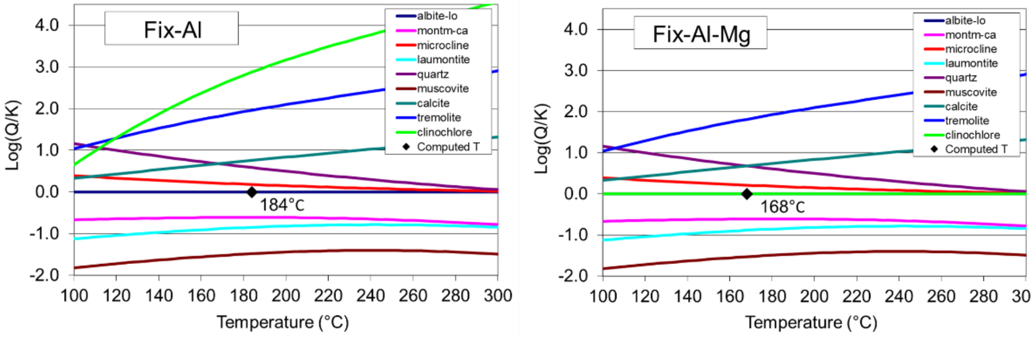
Fix-Al method refers to that the equilibrium is interdependence if some minerals contain a same component in a geothermal system. When Al concentration is inaccurate or unknown, we can assume that aqueous Al is fixed to a particular Al-containing mineral at different temperatures, then use the obtained Al concentration to calculate log(Q/K) value of other Al-containing minerals. The same approach applies to the Mg concentration. Forcing Al concentration to equilibrium with albite-low, the result is 184°C shown in Figure 2c, the curves do not have a clustering in a specific temperature. We continue to apply the Fix-Al method and force Mg concentration to equilibrium with clinochlore, the result is 168°C shown in Figure 2d, but the curves do not focus on any specific temperature. The above results show that the Fix-Al method is not always effective.

The GeoT could couple with external software to optimize the clustering, so we use PEST to estimate the parameters. The parameters estimated by optimization are Al and Mg concentration; the dilution/concentration factor (‘cfact’, representing dilution when its value is >1); and also the steam fraction (‘sf’, the fraction of gas in the total discharge). The following average gas composition was estimated from analyses of gas samples from geothermal wells (Shangguan et al., 2000) to reconstitute the ‘pre-boiled’ fluid composition: 99.86 mol% H_2O (wet gas); and 95.41 mol% CO_2, 0.43 mol% H_2, 0.023 mol% H_2S, 0.01 mol% CH_4 (dry gas).



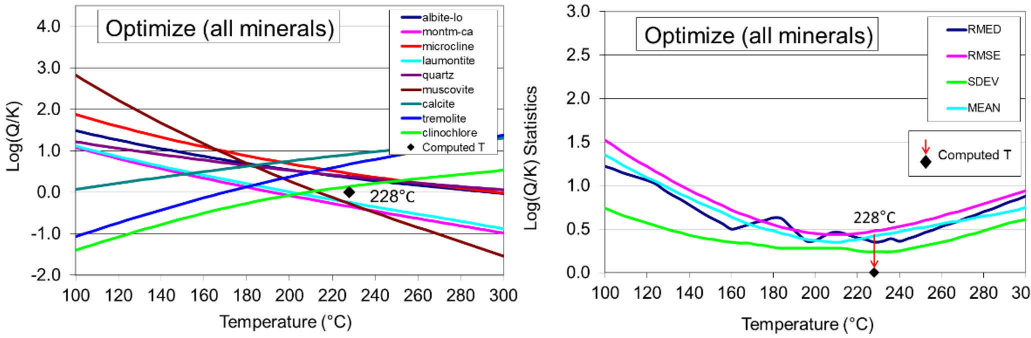
(a) Mineral saturation index variation with temperature for base case.

(b) Statistical analysis for base case (including the results of classical geothermometers).



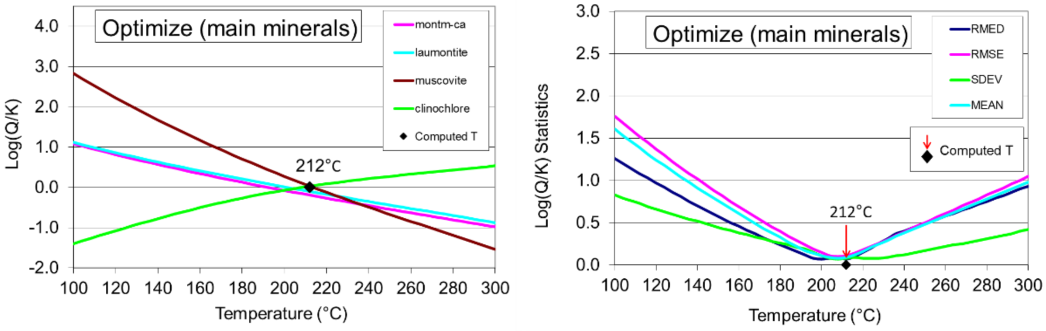
(c) Mineral saturation index variation with temperature for Fix-Al case.

(d) Mineral saturation index variation with temperature for Fix-Al-Mg case.



(e) Mineral saturation index variation with temperature for numerical optimization case.

(f) Statistical analysis for numerical optimization case.



(g) Mineral saturation index variation with temperature for numerical optimization case(considering the main minerals).

(h) Statistical analysis for numerical optimization case (considering the main minerals).

Figure 2: The results of Dagunguo geothermal spring in using the Integrated Multicomponent Geothermometry.

We use numerical optimization on the IMG (GeoT-PEST) to estimate the RH01 water sample, the corrected value is 0.23mg/L of Al concentration, 0.05μg/L of Mg, dilution factor of 1, steam fraction of 0.04. Figure 2e shows the corrected clustering of curves, the result is obviously getting better from Figure 2f, in this case the optimized-IMG resulted temperature is 228°C. It is not difficult to see that the range of equilibration temperatures obtained with each individual mineral is over 100°C, which shows that we do not need to consider all the minerals, because they may not achieve equilibrium in a small range of temperature. Considering only the main minerals (montm-ca, laumontite, muscovite, clinochlore) yields a temperature of 212°C (Figure 2g), and the spread in temperatures computed with these four minerals is smaller (20°C) than the previous, this result is quite reasonable. Figure 2h shows the statistic result that the lowest statistic value points to 212°C, and the value of RMED is 0.066 (a good result). From what has been discussed above, the numerical optimization and fluid reconstruction achieved a success in this case.

5.2 Other geothermal springs

Using the same method, we simulated other water samples in Rehai geothermal field, all the simulation results are reasonable. As shown in Table 2, the resulted temperatures are between 206°C and 250°C, the average temperature and standard deviation is 229±14°C. As can be seen from Table 2, most of samples are affected by gas loss, this process will take away CO_2 and other gases, pH value will rise according to carbonate equilibrium. RH04, RH05 and RH10 have the highest pH value (8.9, 8.9, 9.2), we speculate that it may be due to the loss of CO_2 and need to add back gas loss to rebuild the chemical equilibrium, so the results verified the assumption that these three samples have the highest ‘sf’ values (0.39, 0.31, 0.43).

RH01, RH02, RH06 and RH09 have similar results (212°C, 212°C, 216°C, 206°C), and their locations are close, they may share a common fracture channel. The concentration factor of RH06 is 1.30, it can use to correct dilution effect. On the contrary, RH02 has a dilution factor of 0.9 to correct concentration effect. RH03, RH04, RH05, RH07 and RH08 have similar results (250°C, 250°C, 246°C, 224°C, 240°C) as well, and they located in a same river bend. Except RH03 they all have steam fractions of 0.39, 0.31, 0.20, 0.11, indicating that gas loss is a common process in this group of springs. The other samples were all taken from springs near Zaotang River, including RH10, RH11, RH12 and RH13. The resulted temperatures are very similar: 234°C, 228°C, 230°C and 224°C, respectively.

The comparison of the IMG simulated temperatures with classical geothermometer results is shown in Figure 3. We can see that quartz geothermometer results are closet to IMG results. Na-K geothermometer results are much higher than IMG results. Na-K-Ca geothermometer, which aims to correct the abnormal high results by Na-K geothermometer, has a better result than Na-K geothermometer. Due to the missing or inaccurate Mg data, K-Mg geothermometer results do not draw on the Figure 3. We can see from Table 2 that the K-Mg geothermometer results are generally higher, because it usually used in the Mg-rich and low-temperature geothermal field.

Table 2: List of temperatures calculated from classical geothermometers, simulated from the optimized multicomponent geothermometry, and values of parameters estimated by numerical optimization. cfact, concentration/dilution factor; sf, steam fraction. The Al concentration is in mg/L, and the Mg concentration in μg/L. Temperature is in degrees Celsius. Tstdev, standard deviation of these temperatures.

Sample no.	pH	T_{quartz}	$T_{Na\text{-}K}$	$T_{Na\text{-}K\text{-}Ca}$	$T_{K\text{-}Mg}$	T_{geoT}	T_{stdev}	Optimized parameters			
								Al	Mg	cfact	sf
RH01	8.3	359	283	283	523	212	9	0.23	0.05	1.00	0.04
RH02	6.8	210	300	269	308	212	10	0.19	0.90	0.90	0.08
RH03	6.4	221	311	239	235	250	6	0.80	1.60	1.30	0.00
RH04	8.9	238	288	271	370	250	9	0.35	0.50	1.00	0.39
RH05	8.9	251	283	284	382	246	12	0.32	0.26	1.00	0.31
RH06	2.6	238	631	319	119	216	66	2.70	1300	1.30	0.00
RH07	8.4	209	284	272	381	224	6	0.28	0.50	1.20	0.20
RH08	7.6	227	283	259	378	240	8	0.42	0.22	0.83	0.11
RH09	7.5	194	338	244	322	206	9	0.42	0.27	1.00	0.08
RH10	9.2	219	287	263	306	234	9	0.40	1.20	1.00	0.43
RH11	6.9	209	270	242	329	228	5	0.40	0.50	1.00	0.11
RH12	8.2	214	267	240	332	230	4	0.34	0.45	1.11	0.20
RH13	8.3	204	286	249	358	224	6	0.35	0.45	1.20	0.18

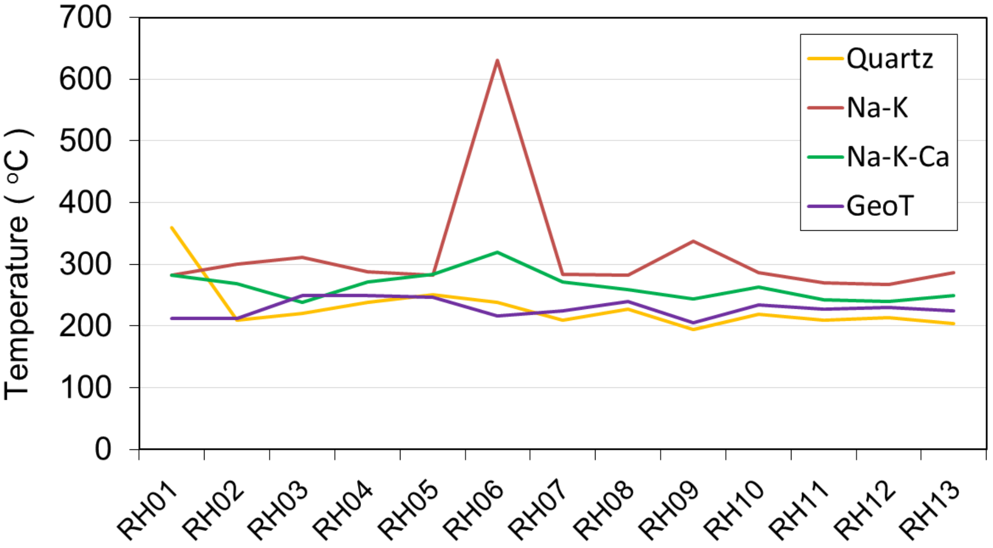


Figure 3: Comparison of temperatures obtained from the integrated multicomponent geothermometry with those calculated from ion based geothermometers for different springs in Tengchong Geothermal Field.

6. CONCLUSION

Using the integrated multicomponent geothermometry (IMG) coupled with numerical optimization, we have investigated geothermal reservoir temperatures for a Tengchong geothermal field in Southwestern China. Main conclusions can be drawn as follows:

(1) The reservoir temperatures of Rehai geothermal field near Tengchong volcanic region, obtained from the optimized-IMG method, range from 206 to 250°C, the average temperature and standard deviation is 229±14°C. Temperatures calculated from quartz geothermometer are closet to the IMG results, which may be the highest credible classical geothermometer for this study area.

(2) The Al and Mg concentrations are generally lower than detectable range, but they can greatly affect the precipitation and dissolution of minerals. Dilution and gas loss will occur generally when geothermal fluid ascending to ground surface. Reconstruction of chemical composition and accurate selection of reservoir rock minerals are the key for the success of the use of the integrated multicomponent geothermometry.

(3) The optimized IMG can give a relatively reasonable result when the deep geochemical signatures are masked by effects of gas loss and/or dilution. Using the IMG together with classical geothermometers can significantly increase confidence in reservoir temperature estimations.

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