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The Application of Na-K-Mg, Na-K/Mg-Ca and K-Mg/Quartz Diagrams to Evaluate Water Geochemistry in West Java Geothermal Prospects, Indonesia

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ABSTRACT

There are about 20 geothermal prospects reported in West Java. Eight of them are existent geothermal fields such as Kamojang, Darajat, Wayang Windu, and Salak-Awibengkok. The rest is still in an exploration stage to get to know their geothermal system properties with geological, geophysical, and geochemical surveys. Geochemical surveys are used to evaluate characteristic of manifestastions, type of fluid and geothermometers. During this time, water geochemistry is used just to know geothermometers without considering equilibrium of fluid and to understand fluid process in either deep or shallow levels.

This study focus on the evaluation of water geochemistry with Na-K-Mg ternary, Na-K/Mg-Ca and K-Mg/Quartz diagrams to compare temperatures of equilibration between each other, to consider the equilibrium of fluid and to understand deep and shallow processes in some of the West Java geothermal prospects such as Tanggeung, Jampang, Tangkuban Perahu, Papandayan, Mt. Kromong, Mt. Ciremai, and Panulisan. The K-Mg/Quartz diagram was compared to low temperature geothermometers to eliminate invalidity of each geothermometer, which could be caused by dilution process, equilibration with amorphous silica or some residual effect of an acid zone. The Na-K/Mg-Ca diagram combines the Na-K geothermometer with equilibration of the system Mg-Ca. Both of them are usually used to know the influence of shallow and low temperature processes. The preliminary results show that a part of the hot and warm springs in West Java geothermal prospects have fluids which do not come from a reservoir and undergone dilution or mixing process. The other group of the thermal discharges is characterized by a brine that comes from deep liquid geothermal water with small influence of dilution or mixing process. Three graphical techniques were used to show the shallow and deep temperature structure of each prospect with some explanation about equilibrium and processes of fluid up rise from deep to surface.

1. INTRODUCTION

West Java is the biggest geothermal province in Indonesia, with a potential of 6,101 MW or 22% from total geothermal Indonesia potential (Fadillah et al., 2013). West Java geothermal prospects are divided in two categories: existent and non-existent geothermal fields. Eight geothermal fields have been producing electricity (Kamojang, Darajat, Wayang Windu, Awibengkok-Salak, Patuha, Karaha Bodas, Cibuni, and Ciater). The rest of West Java geothermal prospects are green fields which are currently in an exploration stage with geological, geophysical, and geochemical surveys.

This paper presents an evaluation of obtained results from a water geochemistry survey, which helps to understand properties such as characteristic of manifestations, type of fluid, location of upflow and outflow zones. The goal of this study is to assess through water geochemistry the equilibrium of the fluid. Furthermore, data is also used to compare and deduce the temperature of equilibration at depth or shallow levels of selected hot or warm springs using the Na-K-Mg ternary diagram and the Na-K/Mg-C and K-Mg/Quartz geothermometers in some of the non-existent and green fields geothermal prospects in West Java. These West Java geothermal prospects are Tanggeung (with Cibungur, Leles, Panyindangan, and Leuwilutung warm springs), Jampang (Cibubuay, Cimandiri Barat, Cimandiri Timur, and Cipanas), Papandayan (Cilayu, Ciarinem-1 and 2), Tangkuban Perahu (Maribaya, Kancah, Batugede and Batukapur), Mt. Kromong (Banyupanas, Goamacan, Simeut, Mt. Kuda, and Cipanas), Mt. Ciremai (Liang Panas and Sangkanhurip) and Panulisan prospect (Figure 1). Currently, solute geothermometers are based on silica and alkali contents such as Na/K, K-Mg, and Na-K-Ca. These geothermometers tend to overestimate temperatures without a proper consideration and checking of equilibration conditions. The interpretation of these geothermometers can make us believe in an initial assessment of the presence of a deep, high temperature resource in a geothermal system on these geothermal fields, but it is needed to consider the water-rock interaction condition. Finally, the evaluation and assessment process of water geochemistry can be used to estimate the geothermal resource potential in West Java.

2. METHODOLOGY

In the preliminary investigation, we selected some hot and warm springs data in West Java, using the ESDM Jabar inventory data (ESDM Jabar, 2013) and many other published papers such as Haryanto et al. (2009), Hamzah et al. (2011), Herdianita and Priadi (2008). Some unpublished data were also used (Triyono, 2012). We choose twenty three manifestations, which then were divided into seven prospects. There are many methods to assess reservoir temperatures such as water geothermometer based on an equation, gas (equation and graphic), isotopes (equation) and water geothermometers based on graphics. We want to prove that these graphical techniques can give a good, reliable and accurate result if gas geochemistry data is not available.

The major anions are plotted in a SO_4-Cl-HCO_3 diagram to determine the fluid type as a first step to describe a geothermal system. Fluid type can tell us the type of thermal water, reservoir or condensate fluid. This diagram can help to define and distinct between upflow and outflow zones of prospect areas. The fluid type is usually in line with the ion balance (IB) percentage. Mature water such as chloride type water is in line with low IB; contrariwise condensate water is in line with high IB. Water samples are also plotted in Na-K-Mg ternary diagram, Na-K/Mg-Ca and K-Mg/Quartz diagrams to check fluid-rock equilibrium and infer deep temperature, which usually will help to deduce resource potential. Solute geothermometers based on equations cannot recognize fluid equilibrium. Overall, comparing geothermometers will be used to evaluate a right reservoir temperature for each prospect and understand each geothermal system, which could be of interest for further, integrated surveys.

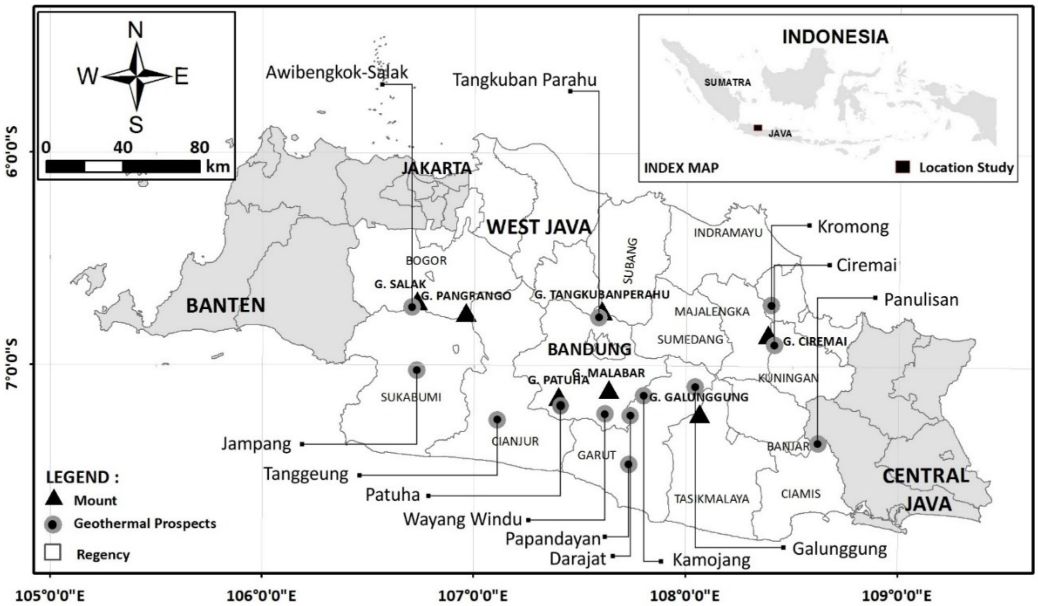

Figure 1: Map of Geothermal prospects in West Java with a total potential of about 6,101 MW. Existing geothermal fields, which have been generating electricity are Wayang Windu, Kamojang, Darajat, and Awibengkok-Salak. G: Gunung (Mount).

3. GEOTHERMAL PROSPECTS AND THEIR GEOCHEMICAL CHARACTERISTICS

We selected some hot and warm springs of West Java geothermal prospects to know geochemical characteristics of theirs geothermal systems. Hydrothermal- type systems follow the classification of Herdianita et al. (2012). A review of geochemical characteristics for each prospect is given below about the type of fluid, temperature, pH, ionic balance, outflow or upflow zones and some other characteristics. Fluid type and symbology follow the classification described by Hochstein et al. (2010) with additional class.

3.1 Tanggeung Prospect (Cianjur)

Tanggeung prospect is associated with structural geology. Cimandiri Fault is one of the major structures in West Java. This structure spread out from Sukabumi to Cianjur. Tanggeung prospect is located 30 km west of Cianjur City or 240 km southwest of Bandung (Figure 1). This prospect have four warm springs named as Panyindangan, Leuwilutung, and Leles with temperatures ranging from 40 to 65°C, whereas Cibungur is a hot spring with a temperature of 70°C (Table 1). The ionic balance of thermal waters is in the range 0,5 to 6,5%. The thermal discharges are mostly neutral pH, chloride-sulfate waters as shown in Figure 2 and are likely the product from the absorption of magmatic gases (especially H_2S gas) in groundwater, followed by dissolution of host rocks and they are assumed to reflect conditions with a neutralization zone in deep (Giggenbach, 1988). H_2S condensation in groundwater and fluid-rock equilibrium occurred in partial equilibrium as shown in a Na-K-Mg diagram (Figure 3). Whereas, Leles warm spring is a sulfate water (volcanic water) with a neutral pH (6,75). This may indicate that spring water is derived from volcanic fluids containing high H_2S and low HCl, which is completely neutralized by the reaction with host rocks. This characteristic of Leles is refer to reverse explanation about Kancah chloride spring in Nasution et al, (2004), although the input geochemistry data is wrong. Dissolution of rocks yields alteration minerals such as montmorillonite, which was mentioned by Haryanto et al. (2009). Montmorillonite or smectite appears to have been formed at neutral pH. These springs are flowing out from contacts of lithology or fractures of andesitic basaltic lavas, which are normal along Cibuni River at Tanggeung district.

3.2 Jampang Prospect (Sukabumi)

The Jampang geothermal prospect is associated with the Cimandiri Fault like Tanggeung project. The prospect is located at Central Jampang District, Sukabumi and about 35 km to the south of the Awibengkok geothermal production field (Figure 1). Warm springs are located between 47 to 170 masl, indicated by the presence of warm springs along the Cimandiri river. Bicarbonate-sulfate (neutral pH condensate) warm springs are found in Cibubuay, Cipanas, Cimandiri barat and timur which are controlled by the Cimandiri normal fault. This green field is also called Cimandiri geothermal prospect (Hamzah et al., 2012). Warm springs are characterized by a neutral pH, temperatures of around 38 to 42°C and an ionic balance between 1,0 to 3,5%, except by Cibubuay with an ionic balance of 10% (Table 1). The rocks are mainly sediments with some of the units appearing to be carbonates and volcano-clastics.

3.3 Papandayan Prospect (Garut)

Papandayan prospect is related with the Mount Papandayan, Garut, West Java (Figure 1). The mount is one of several hydrothermal systems associated with Quaternary andesitic volcanoes like Mt. Salak and Tangkuban Perahu. This mountain has had explosive eruptions, like the one in November 2002 (Utama et al., 2012). Related with this phenomenon is the appearance of manifestations in surface, almost around the peak of the crater such as fumaroles with an average temperature of 90°C and acid springs which are influenced by magmatic volatiles or H_2S condensation into shallow ground water. Thermal springs which are identified as outflows of Papandayan are Cilayu and Ciarinem-1 and 2 springs with a range of temperature from 40 to 60°C and an ionic balance between 1,0 to 3,0% (Table 1). Cilayu is located near Mount Kendang, about 25 km to the southwest from Mt. Papandayan. Whereas, Ciarinem spring is located at Mount Angsana's flank, near Ciarinem River at Pameungpeuk, Garut. There is no alteration in Cilayu which has neutral pH, chloride type waters with presence of silica sinter. Ciarinem has silica sinter also, although it is a neutral pH, sulfate water with a range of pH of 7.4 to 8.0. There is a chance that sulfate waters occurred in long-term periods, so the water had interacted with surrounding rocks and then shallow neutralization it is possible (Herdianita and Priadi, 2008).

3.4 Tangkuban Perahu Prospect (Bandung)

Tangkuban Perahu is a well-known mountain in Bandung, West Java (Figure 1). Same as Papandayan, Tangkuban Perahu is a hydrothermal system associated with Quaternary andesitic volcanoes. The latest eruption was an explosive eruption in November 2012. Tangkuban Perahu has many bicarbonate (neutral pH condensate) thermal manifestations such as Maribaya, Batukapur-Sagalaherang and Batugede. Kancah on the contrary is sulfate type water (Figure 2). Most of thermal discharges have ionic balance between 0 and 1% except Kancah with a 13%. The high ionic balance value in thermal discharges does not mean they are not suitable to be interpreted, but just less confidence on the results. These manifestations include fumaroles, solfataras and steaming grounds at Domas, Ratu Crater and other craters at the summit of the mountain. Kancah has acid pH (pH<3) and sulfate type water (Table 1), but Nasution et al, (2004) described this spring as chloride type water. There is wrong geochemistry data in Nasution et al, (2004). Kancah and the other manifestations at the summit of mount Tangkuban Perahu area inferred to be in the upflow zone, while the rest of hot springs are located in the outflow of Tangkuban Perahu geothermal prospect. The presence of fumaroles and steaming ground with a range of temperature from 25 to 95°C at the summit of the mountain suggests the existence of a high temperature system on Tangkuban Perahu. Gas geothermometers from fumaroles gave an estimate of reservoir temperature above 250°C (Utama et al., 2012). Tangkuban Perahu concession area was awarded to PT. Tangkuban Perahu Geothermal Power (TPGP) in 2009.

3.5 G. Kromong Prospect (Cirebon)

Mt. Kromong is a hydrothermal system hosted in a sedimentary basin which has high TDS and chloride contents (Herdianita et al, 2012). It is a parasitic cone located between 300-500 masl at the northern slope of Ciremai, Kuningan, West Java (Figure 1). Basement of Kromong is composed of Tertiary sedimentary rocks overlaid by Quaternary rocks. The inferred reservoir zone by gravity measurements is beneath the northern part of Mt. Kromong (ESDM Jabar, 2013). Reservoir fluid of Kromong is mainly derived from meteoric waters and then heated by the heat source. Chloride water is found on Goamacan and Banyupanas warm springs, which are interpreted as outflow thermal discharges. These springs have a range of temperature from 54 to 57°C and neutral pH; they are Na-Cl waters with a composition of Na and Cl from 2400 to 4200 mg/kg (Table 1). Cipanas, Simeut, and Mt. Kuda warm springs in the southern part are not like Goamacan and Banyupanas. These spring are condensate waters which appears in the flanks associated to acid (pH<3) sulfate waters for Cipanas with a pH value of 2.69 (0 mg/kg of HCO_3^-) and bicarbonate waters (neutral pH condensate) for Mt. Kuda (0 mg/kg of SO_4^{2-}) and Simeut (Figure 2). Most of Kromong thermal discharges have an ionic balance (IB) between 0.9 to 2.5% (Table 1).

3.6 G. Ciremai Prospect (Kuningan)

Mt. Ciremai is one of the highest stratovolcanoes in West Java and it has a volcanic hydrothermal system associated with Quartenary andesitic volcanoes. Liang Panas and Sangkanhurip warm springs are outflows from the Ciremai geothermal prospect at the eastern and southern parts of Mount Ciremai. Temperature of these springs is 36 and 47°C, respectively and both have neutral pH, Na-Cl waters with high composition of Na and Cl from 1200 to 3400 mg/kg (Figure 2 and Table 1). Steam discharge in the form of fumaroles and steaming ground is appearing at the peak of Mt. Ciremai with temperatures about 90°C and shows an upflow zone and high temperature system (Pertamina, 1985 op.cit., Herdianita et al., 2010). Ciremai concession area was awarded to PT. Jasa Daya Chevron in 2011.

3.7 Panulisan Prospect (Ciamis)

Panulisan is located at the Banjar District, Ciamis Regency, West Java (Figure 1). The hydrothermal system of Panulisan prospect is an isolated warm spring with unknown source hydrothermal system. Actually, there are four thermal discharges at Panulisan, but only one data sample is available and reliable. The thermal discharges appear along Cijalu and Cinagara river with a temperature range from 44 to 52°C, and neutral pH, sulfate chloride type (Figure 2). The explanation about inconsistence of the warm spring as described above.

4. DISCUSSION

4.1 Na-K-Mg Ternary Diagram

Na-K-Mg ternary diagram consist of a fast-responding K-Mg system with a slowly re-equilibrating Na-K system to evaluate the degree of attainment of fluid-rock equilibrium. This ternary plot is a powerful tool to: (1) make a distinction between water suitable and unsuitable for the application of ionic solute geothermometers, (2) assess deep equilibrium temperature and (3) evaluate re-equilibrium and mixing effects on a large number of water samples (Marini, 2004). The position of data points for Tanggeung discharges points to attain partial equilibrium in the Na-K-Mg ternary diagram (Figure 3). Temperature ($T_{K\text{-}Mg}$) for all Tanggeung thermal discharges is maximal around 100°C for the described conditions at shallow levels (Figure 3). On the other hand, these waters are sulfate and chloride-sulfate as shown in Figure 2, thus $T_{K\text{-}Na}$ is not valid to be applied. Papandayan hot springs, Ciarinem 1 and 2, like Tanggeung thermal discharges fall into the partial equilibrium area, but have sulfate water type with $T_{K\text{-}Mg}$ around 100°C. Almost all data points of Tangkuban Perahu, Jampang, Ciremai and Kromong thermal discharges plot close to the Mg corner, so their Na-K temperatures have lower reliability (Giggenbach, 1988). This fact doesn't apply for the Goamacan and Banyupanas thermal discharges of Kromong. Both of them, and Cilayu (Papandayan) with chloride type water, have points to attain of partial equilibrium. On the contrary, chloride type waters of Ciremai discharges are Sangkanhurip and Liang Panas, which plotted far from the full equilibrium line, not having even a partial equilibrium. Their high Mg content suggests a water-rock interaction process to reflect an immature nature of the water (dilute water), possibly affected by the absorption of dissolved rock (Reyes et al., 1993). Refer to Figure 3, $T_{Na\text{-}K}$ of around 190°C for Goamacan and Banyupanas and a $T_{K\text{-}Mg}$ of around 140°C for Goamacan, 120°C for Banyupanas and Cilayu, and around 80°C for Sangkanhurip and Liang Panas. Mg can respond faster to decreasing temperature than Na, thus $T_{K\text{-}Mg}$ in shallow levels is still reliable to be applied (Giggenbach, 1986). Panulisan have differences from others springs. Samples of these discharges are close to the full equilibrium line indicating an intersection between $T_{Na\text{-}K}$ and $T_{K\text{-}Mg}$ lines with a temperature of 100°C for Panulisan. It means that Panulisan water discharges were occurring in equilibrium conditions either in deep or shallow level.

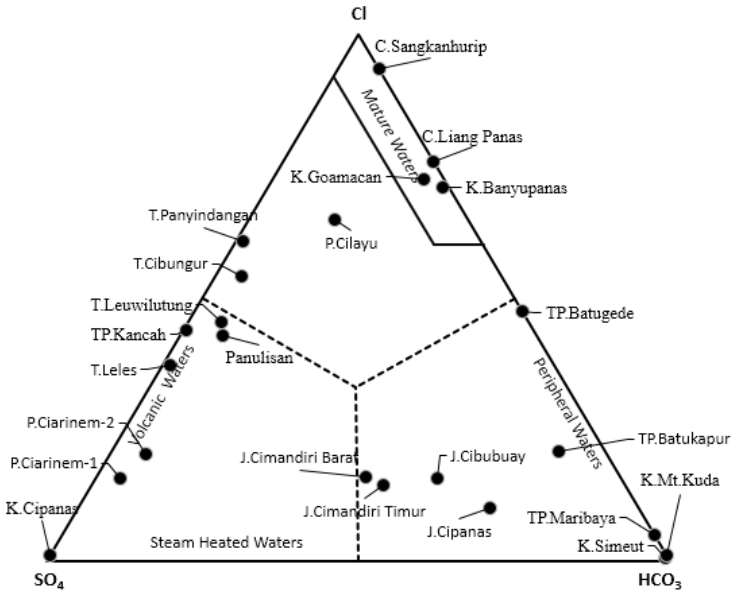

Figure 2: SO_4-Cl-HCO_3 Ternary Diagram (Giggenbach, 1988) of samples of West Java Geothermal Prospects. Samples name follow Table 1.

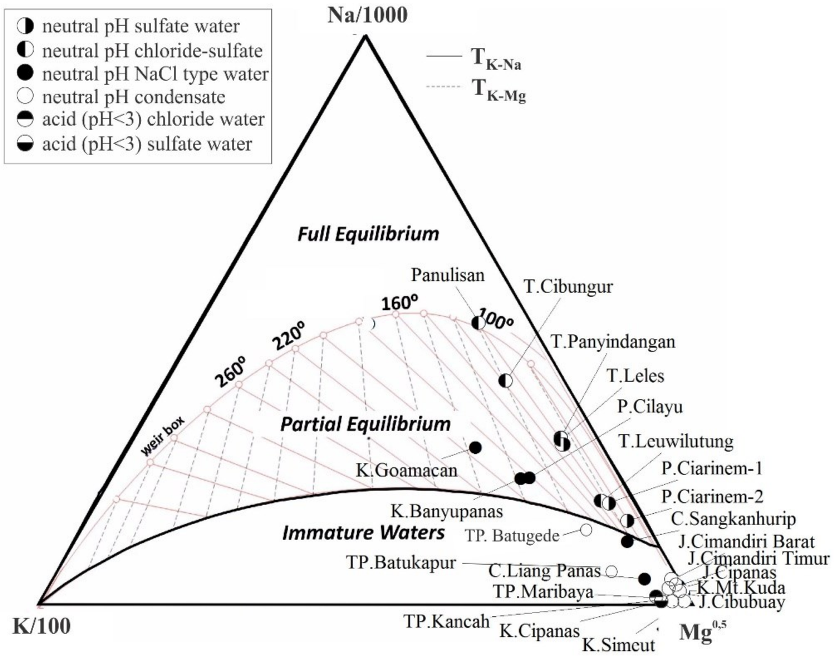

Figure 3: Na-K-Mg Ternary Diagram (Giggenbach, 1986) of samples of West Java Geothermal Prospects. Samples name follow Table 1. Type of fluid follows the classification described by Hochstein et al. (2010) with additional class.

4.2 Na-K/Mg-Ca Diagram

For this work we prefer to rely on the Na-K-Mg ternary diagram and neglect the Na-K/Mg-Ca plot. The Na-K/Mg-Ca diagram combines the Na-K geothermometer with equilibration of the system Mg-Ca to know about the interaction of the water with rock at shallow levels, mixing with lower temperature aquifers, steam heating and acidification through oxidation of H_2S (Giggenbach and Glover, 1992). Slow, Na-K system shows water-rock equilibration temperatures to reflect conditions at deeper levels, while faster equilibration geothermometers, based on dissolved silica and K/Mg (see next subsection) contents provide information on temperatures at shallow levels (Giggenbach, 1988). Geothermal fluids consist of Na, K, Mg, Ca and other anions. These elements can be derived by rock dissolution, which is caused by acidic condensate and minor magmatic constituent, from crustal rocks to attain the fluid-rock equilibrium, or usually called full equilibrium. Interaction between the rising fluids and host rocks produce cations and anions which interacts with fluids until they are equilibrated completely (Giggenbach, 1988).

Table 1: Chemical analyses of selected water samples from geothermal prospects in West Java (all concentrations in mg/kg). Classification of prospects follow ESDM Jabar (2013) and location of samples follow Figure 1. Reference for data: (a) Haryanto, et al. (2009), (b) Hamzah, et al. (2011), (c) Herdianita, N.R., and Priadi, B. (2008), (d) Triyono, S. (2011), (e) (f) and (g) ESDM Jabar (2013). Samples name cited is listed by capital T, J, P, TP, K, C in column 2 which refer to T: Tanggeung, J: Jampang, P: Papandayan, TP: Tangkuban Perahu, K: Kromong, C: Ciremai. Type fluid symbol: c: chloride, s: sulfate, b: bicarbonate, c-s: chloride-sulfate, and b-s: bicarbonate-sulfate water.

Prospect/ Samples	T (°C)	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	SO_4^{2-}	SiO_2	Type Fluid	IB (%)
Tanggeung [(a)]												
T.Cibungur	52.70	7.42	227.30	5.09	56.60	0.09	320.93	24.69	248.55	87.98	c-s	6.49
T.Leles	66.60	6.75	455.50	8.72	374.48	1.06	608.71	17.25	1008.99	44.07	s	0.45
Panyindangan	38.70	6.80	980.90	17.43	503.61	4.71	1606.09	24.64	1012.29	29.90	c-s	1.36
Leuwilutung	70.00	7.56	698.31	17.38	321.58	8.66	874.47	101.66	954.68	92.05	c-s	1.46
Jampang [(b)]												
J.Cibubuay	38.40	7.65	75.00	0.79	26.10	12.97	36.27	127.80	68.80	78.80	b-s	10.80
imandiri Barat	42.10	7.77	87.15	0.92	28.56	3.32	45.72	124.50	118.00	78.80	b-s	2.43
mandiri Timur	42.30	7.65	87.85	0.80	24.47	6.28	43.74	141.30	118.00	65.10	b-s	3.69
J.Cipanas	38.20	7.56	76.33	0.54	22.84	6.31	27.83	179.90	65.40	54.50	b-s	1.01
Papandayan[(c)]												
P.Cilayu	53.50	6.80	1000.00	61.43	75.74	8.20	1213.60	257.60	402.03	156.76	c	2.80
.Ciarinem-1	59.60	7.90	265.00	5.61	270.20	1.34	177.50	45.02	912.63	64.18	s	1.04
.Ciarinem-2	40.90	7.40	265.00	4.29	240.00	2.20	213.00	60.02	778.83	63.51	s	1.25
Tangkuban Perahu[(d)]												
P.Maribaya	-	6.36	118	28.3	145	91.8	59.6	1130	0.2	187	b	1.0
TP.Kancah	-	2.86	48.8	37.2	71.2	21.4	230	2	291	114	s	13.0
P.Batugede	-	6.53	1340	91.4	131	63.1	1560	1730	0.2	149	b	0.0
P.Batukapur	-	6.74	310	65	50.2	43.4	229	791	82.9	198	b	0.0
Mt. Kromong[(e)]												
.Banyupanas	56.80	7.98	2366.81	161.69	233.93	44.67	3323.80	1306.53	47.40	42.37	c	2.63
.Goamacan	53.80	7.72	2817.00	197.27	346.36	29.27	4224.40	1413.52	189.00	51.03	c	0.34
K.Simeut	38.50	6.82	58.32	5.51	82.10	53.89	4.20	650.63	3.28	144.72	b	1.62
K.Mt.Kuda	37.50	7.97	114.78	6.98	36.12	22.68	5.58	520.45	0.00	127.40	b	0.87
K.Cipanas	34.10	2.65	13.32	4.90	15.76	2.29	2.00	0.00	192.00	58.90	s	1.93
Mt. Ciremai[(f)]												
.Liang Panas	36.2	6.4	1.250.00	136.00	122.40	612.00	3347.50	1056.00	4.05	148.00	c	1.10
Sangkanhurip	47.4	7.00	1.412.00	55.00	151.00	115.00	2627.00	182.00	0.50	182.00	c	1.73
Panulisan[(g)]												
Panulisan	43.00	7.4	813.64	12.80	330.40	0.49	834.89	132.09	985.00	66.00	s-c	6.12

Most of water discharges from Tanggeung (Leuwilutung, Panyindangan, Cibungur, Leles) and Papandayan (only Ciarinem-1 and 2) have equilibrated fluids (Figure 4). These samples plot close to the full equilibrium line and represent equilibration with crustal rocks or mineral solution equilibrium (Reyes et al., 1993). The fluids have attained water-rock equilibrium at temperatures (T_{Na-K}) about 120-140°C. The Na-K temperature, as described above, is likely to reflect conditions at deeper levels. Sangkanhurip and Liang Panas neutral pH chloride waters are totally different with high Mg contents around 112-612 mg/kg. Extensive interaction with rocks cause that fluids are controlled by the dissolution of rocks or rather than mineral-solution equilibrium. The point marked "rock dissolution" in Figure 4with x= 0.8 and y=0.8 is based on several averages of x= 10 K/(10 K +Na) and y= 10 Mg/(10 M+Ca) ratios for the mean x and y ratio of dissolved volcanic rocks, including Cipanas and Kancah, Maribaya and Batukapur springs. Rock dissolution in highly immature water generally is caused by volcanic waters (Reyes et al., 1993) like Cipanas-Kromong or Kancah (acid pH<3, sulfate water) which are completely neutralized by the interaction with surrounding rocks. Data point for Maribaya, Batukapur, Batugede (Tangkuban), Simeut and Kuda (Kromong) and all of Jampang discharges (Cibubuay, Cipanas, Cimandiri barat dan timur) show high Mg/Ca ratios corresponding to rock dissolution followed by deposition of K-rich secondary minerals such as clays and zeolites like laumontite at low temperatures (Giggenbach et al., 1994). The point marked at x=0.28 and y=0.95 represents "seawater". Batu Gede and Sangkanhurip samples are near this point. Batugede water is most likely marine pore waters from the Subang Formation, while Sangkanhurip is most likely connate waters from Tertiary sedimentary rocks (Djuri, 1973 op cit Herdianita et al, 2010). One of the G.Kromong (Banyupanas) samples points to Batu Gede composition but is partially equilibrated. The whole set of water are HCO_3 -water as suggested by Figure 2, which rises to the surface slowly. The next cluster in Figure 4 is related to neutral pH, Na-Cl type waters (Cilayu, Goamacan, and Banyupanas) which not attain to the equilibrium line but just had been re-equilibrated, so these waters plot in a transition area from rock dissolution to rock-fluid equilibrium. Respond to change is shown by general trend line. Overall, equilibrium temperatures estimated using Na-K/Mg-Ca geothermometer are 120-140°C for Papandayan, 140°C for Tanggeung, 120°C for Panulisan, 80°C for Jampang and uncertain temperature for Tangkuban, Kromong and Ciremai because their samples not attain equilibrium.

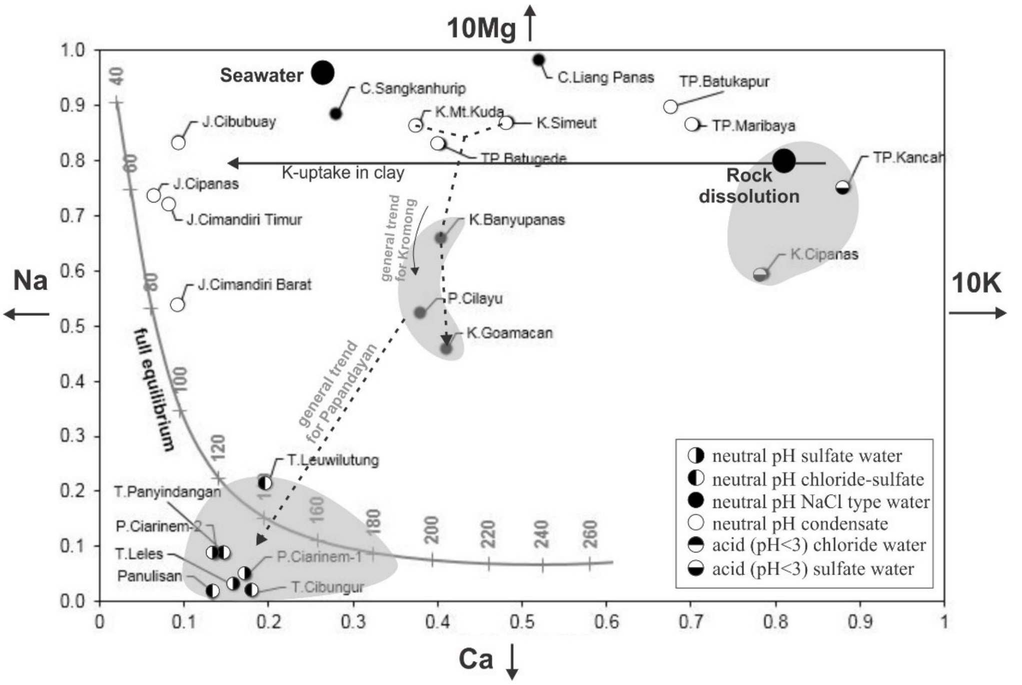

Figure 4: Plot of 10 K/(10 K+Na) versus 10 Mg/(10 Mg+Ca), C_i in mg/kg or Na-K/Mg-Ca Diagram (Giggenbach and Glover, 1992, modified) of some thermal discharges in West Java geothermal prospects. For sample names see Table 1. Type of fluid follow the classification type as described by Hochstein et al. (2010) with additional class.

4.3 K-Mg and Quartz (Conductive) Diagram

As discussed in the previous subsection, K-Mg/Quartz (conductive) diagram can only provide low temperature estimates. This diagram was compared to low temperature geothermometers to eliminate invalidity of each geothermometer, which could be caused by dilution process, equilibration with amorphous silica or some residual effect of an acidic zone (Powell and Cumming, 2010). The chemical system between K-Mg and dissolved silica can respond fast to temperature changes. Condensate water are found in Cipanas, Cibubuay, Cimandiri Barat and Timur (Jampang), Simeut and Kuda (Kromong), Maribaya (Tangkuban) whereas Cilayu, Ciarinem 1 and 2 (Papandayan), Cipanas (Kromong), Leuwilutung, Cibungur, Leles, Panyindangan (Tanggeung), Batugede (Tangkuban) and Panulisan are outflow discharges. Kancah (Tangkuban), Sangkanhurip and Liang Panas (Ciremai) are another group which plot between amorphous silica and the equilibrium line. The reason is probably due to an extensive water-rock interaction process during fluid rise to the surface for Sangkanhurip and Liang Panas, and residual effects of acidic fluids for Kancah. Sangkanhurip and Liang Panas thermal waters have aqueous silica concentrations which are controlled by saturation with silica polymorph (amorphous silica is the most soluble silica polymorph) of intermediate solubilty (Marini, 2004). Data points for Goamacan and Banyupanas move to downwards because a loss of silica and disequilibrium or re-equilibrium as shown in Figure 4. Whereas, data points for Cipanas (Kromong) are still doubtful. Condensate water has equilibrated with amorphous SiO_2 with a temperature of equilibrium between 40 and 60°C. The rest of results are unreliable. Another group is outflow discharges in equilibrium with chalcedony with equilibrium temperatures between 70 and 170°C. Overall, equilibrium temperatures are taken and proposed as K-Mg and silica geothermometer of 110°C for Tangkuban, 120°C for Papandayan, 110°C for Tanggeung and Panulisan, 130°C for Kromong, and 80°C for Ciremai. Whereas for Jampang is unreliable.

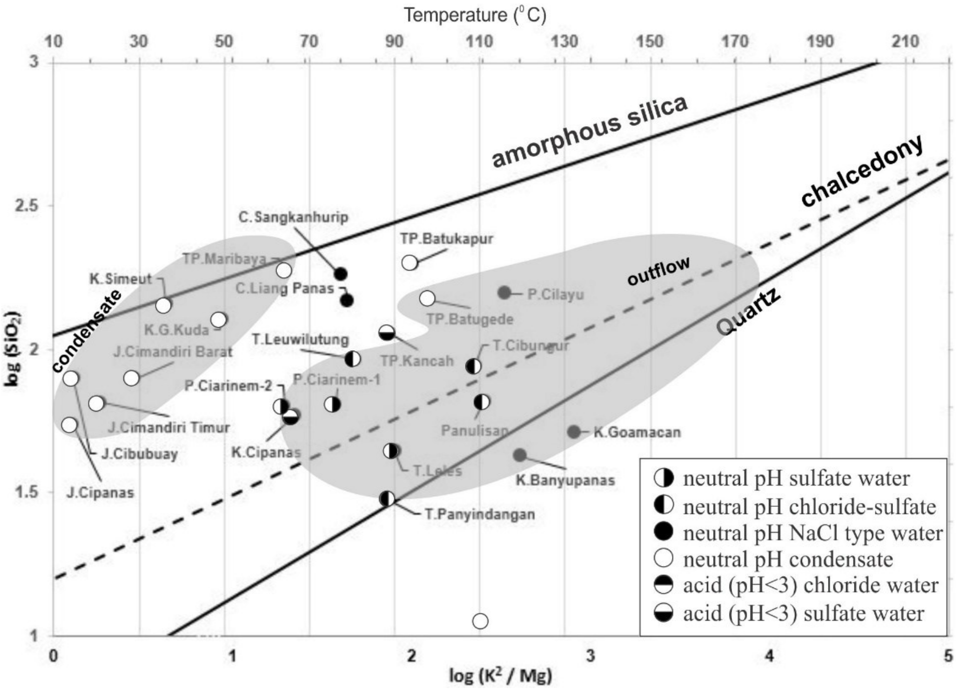

Figure 5: Plot of log (K^2/Mg) versus log (SiO_2) (Giggenbach and Glover, 1992) of some thermal discharges in West Java geothermal prospects. Sample name follow Table 1. Type of fluids follows the classification described by Hochstein, et al. (2010) with additional class. G: Gunung (Mount).

4.4 Common Solute Geothermometers

Referring to pH, ionic balance and type of fluid, solute geothermometer of Cipanas are not valid to be used. Solute geothermometer based on equation show that there are three different equation, quartz-based and cations-based are Na, K, Ca, and Mg. There is no combination of quartz and cation geothermometers. Geothermometer calculation results of Na-K, either from Fournier (1979) or Giggenbach (1988) geothermometer, have a relative overestimate of temperature. Otherwise, Na-K-Ca-Mg corrected and K-Mg geothermometers show reservoir temperature too low. Quartz geothermometers have relative normal temperature result. This equation is good for sub-boiling hot springs. Quartz geothermometers in some hot springs have values less than 150°C, so that temperature is not valid. If the chalcedony geothermometer has values less than 100°C is the same, not valid. The last, reservoir temperature have to be estimated by amorphous silica. The trend of invalidity of some solute geothermometers usually made many geochemists to become unsure to decide the right subsurface temperature. With three geothermometers based on graphical techniques as discussed above, invalidity of each geothermometer can minimize this effect. The important thing of these geothermometers is consider equilibrium of fluids.

5. CONCLUSION

Twenty three water samples in West Java were used to know the temperature of equilibrium and some processes in either deep or shallow levels. This water geochemistry study is divided into seven prospects. There are two hydrothermal systems that are associated with the Cimandiri Fault, namely Tanggeung and Jampang. Three hydrothermal systems are associated with Quaternary andesitic volcanoes (Papandayan, Tangkuban Perahu and Ciremai Mountain). One hydrothermal system is hosted in a sedimentary rock basin (Kromong) and an isolated warm spring, with unknown origin hydrothermal system, is Panulisan.

The preliminary results show that most of thermal discharges in West Java geothermal prospects have thermal waters which do not come from a reservoir and undergone dilution or mixing process and also extensive interaction with surrounding rocks such as Simeut, Sangkanhurip, Liang Panas, all thermal discharge of Jampang, all thermal discharge of Tangkuban Perahu except Kancah. These hot springs are inferred as condensate waters. Thermal waters that come from a reservoir fluid with a small effect of dilution or mixing are found in Cilayu, Goamacan, and Panulisan. The thermal discharges of Tanggeung are mostly neutral pH, chloride-sulfate waters except by Leles which is volcanic water, while Papandayan are mostly sulfate waters except by Cilayu with neutral pH, chloride waters. All of Jampang discharges are bicarbonate water, Ciremai are chloride water, and Panulisan is chloride-sulfate. However, Kromong and Tangkuban discharges are separated into two types of waters. Part of Kromong discharges is chloride water, and others are bicarbonate and sulfate, while Tangkuban are sulfate and bicarbonate water. Their characteristics can be used to assess geothermal resources in each prospect. Water-rock equilibrium is an important aspect to be considered to produce a reliable and acceptable reservoir temperature estimate. Closer the fluids are to equilibrium conditions, more reliable are our estimates of deep and shallow process of fluids. Thus, thermal water can be estimated correctly and accurately. A combination of three graphical techniques (Na-K-Mg, Na-K/Mg-Ca, and K-Mg/Quartz) gives less uncertainty about the use of geothermometers to be applied confidently in geothermal resources assessment of West Java prospects. These graphical techniques are more reliable than equation solute geothermometers to the assessment of reservoir temperature and hence for determine geothermal potential. These techniques consider processes of fluid from reservoir to surface, while equation geothermometers just give results without consider subsurface process. Overall, equilibrium temperatures are taken and proposed from three graphical techniques as above for the whole set of Tanggeung discharges with an average temperature of 140°C, Jampang temperature of 80°C, Papandayan range of temperature of 120-140°C, Kromong temperature average of 190°C, Ciremai temperature of 80°C and Panulisan range of temperature of 110-120°C. Based on water chemistry, geothermometry of Tangkuban Perahu is still doubtful. However, all solute geothermometer based on graphical techniques have to be compared with gas geothermometers, if any. Tangkuban, Ciremai, and Papandayan are active volcanoes which have fumaroles in the summit. So, three prospects of those probably have deep temperature higher than 225°C as expected for high temperature systems. Equilibrium temperatures as discussed for those prospects, probably just define shallow conditions before thermal discharges appear in surface. In shallow levels, Tanggeung and Kromong temperature of equilibrium is about 100°C and 130 to 140°C, while Panulisan has deep and shallow temperature as above.

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REFERENCES

ESDM Jabar : Evaluasi Prospek Panas Bumi Jawa Barat dan Penyusunan Skema Pengembangannya, Internal Report, prepared for ESDM office, unpublished (2013).

Fadillah, A., Nugraha, T., and Gumilar, J.: West Java Geothermal Update, *Proceedings,* 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2013).

Giggenbach,W.F.: Graphical techniques for the evaluation of water/rock equilibration conditions by use of Na, K, Mg, and Ca contents of discharge waters, *Proceedings*, 8th NZ Geothermal Workshop, Auckland, (1986).

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

Giggenbach, W.F., and Glover., R.B.: Tectonic Regime and Major Processes Governing The Chemistry of Water and Gas Discharges From The Rotorua Geothermal Field, New Zealand, Geothermics, Vol 21, (1992), 121-140.

Giggenbach, W.F., Sheppard, D.S., Robinson, B.W., Stewart, M.K., and Lyon, G.L.: Geochemical Structure and Position of The Waiotapu Geothermal Field, New Zealand, Geothermics, Vol 23, (1994), 599-644.

Hamzah, I., Herdianita, N.R., and Saffitri, Y.: Sistem Panas Bumi Cimandiri :Asal dan Karakteristik. *Proceedings*, 11th Annual Indonesian Geothermal Association Meeting and Conference, Lampung (2011).

Haryanto, A.D., Rosana, M.F., Sunarie, and C.Y.: Potensi Panas Bumi Sebagai Sumberdaya Energi Terbarukan Di Kecamatan Tanggeung, Kabupaten Cianjur, Laporan Akhir Penelitian, Hibah Penelitian Strategis Nasional, Jurusan Teknik Geologi, Universitas Padjajaran (2009).

Herdianita, N.R., and Priadi, B.: The Chemical Composition of Thermal Waters at Ciarinem and Cilayu, Pameungpeuk, West Java-Indonesia, ITB J. Sci. Vol 39 A, No. 1, 2008, 49-61.

Herdianita, N.R., Julinawati, T., and Amorita, I.E.: Hydrogeochemitry of Thermal Water from Surface Manifestation at Gunung Ciremai and Its Sorrounding, Cirebon, West-Java-Indonesia, *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010).

Herdianita, N.R., Situmorang, J., Mussofan, W., and Hamzah, I.: Geothermal Resource of Java, *Proceedings*, Australian Geothermal Energy Conference, Melbourne (2012).

Hochstein, M.P., Simanjuntak, J., and Sudarman, S.: Geothermal Prospects of the Eastern Banda Arc Islands (Indonesia), *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010).

Nasution, A., Kartadinata, M.N., Kobayashi, T., Siregar, D., Sutaningsing, E., Hadisantono, R., and Kadarstia, E.: Geology, Age Dating and Geochemistry, of The Tangkuban Perahu, Geothermal Area, West Java, Indonesia, J. Geothermal Res.Soc. Japan, Vol 26, (2004), 285-303.

Powell, T., and Cumming, W.: Spreadsheets For Geothermal Water and Gas Geochemistry, *Proceedings*, 35th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2010).

Reyes, A. G., Giggenbach, W. F., Saleras, J. R. M., Salonga, N. D. and Vergara M. C.: Petrology and geochemistry of Alto Peak, a vapor-cored hydrothermal system, Leyte Province, Philippines. *Geothermics,* Vol. 22, (1993), 479-519.

Triyono, S.: Well Targetting for Tangkuban Parahu Geothermal Project. Internal Report: prepared for PT Tangkuban Perahu Geothermal Power, Indonesia Power, unpublished (2011).

Utama, A.P., Dwinanto, A., Hikmi, M., Irsamukti, R., and Situmorang, J.: Green Field Geothermal System in Java, Indonesia, *Proceedings,* 1st ITB Geothermal Workshop, Bandung (2012).