Journal of Applied Geology, vol. 2(2), 2017, pp. 59–69
DOI: http://dx.doi.org/10.22146/jag.39979

Hydrogeochemical Characterization of Geothermal Water in Arjuno-Welirang, East Java, Indonesia

Vanadia Martadiastuti[1], Agung Harijoko*[1], I Wayan Warmada[1], and Kotaro Yonezu[2]

[1]*Department of Geological Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia*
[1]*Department of Earth Resources Engineering, Kyushu University, Japan*

ABSTRACT. Arjuno-Welirang Volcanic Complex (AWVC) is one of geothermal fields which located in East Java province, Indonesia. It belongs to a Quarternary volcanic arc and has potential for development of electricity. The field is situated in a steep volcanic terrain and there are only few geothermal manifestations, i.e., hot springs, fumaroles, solfataras, steaming ground and hydrothermal alteration. This study aims to classify the type and source of geothermal fluid and to estimate the reservoir condition of Arjuno-Welirang geothermal system. Data are obtained from collecting water samples including hot springs, cold springs, river waters and rain water, then they are analyzed using ICP-AES, titration and ion chromatography. All thermal waters have temperatures from 39.5–53°C and weakly acidic pH (5.2–6.5). Cangar and Padusan hot springs show bicarbonate water, formed by steam condensing or groundwater mixing. On the other hand, Songgoriti shows Cl-HCO_3 type, formed by dilution of chloride fluid by either groundwater or bicarbonate water during lateral flow. All of the waters represent immature waters, indicating no strong outflow of neutral Cl-rich deep waters in AWVC. Cl/B ratios show that all water samples have a similar mixing ratio, showing they are from common fluid sources. However, Padusan and Songgoriti have higher Cl/B ratios than Cangar, suggesting that geothermal fluids possibly have reacted with sedimentary rocks before ascending to the surface. All waters were possibly mixed with shallow groundwater and they underwent rock-water reactions at depth before ascending to the surface. An estimated temperatures reservoir calculated using CO_2 geothermometer yielded temperatures of 262–263 °C based on collecting of fumarole gas at Mt. Welirang crater. According to their characteristics, Cangar and Padusan are associated with AWVC, while Songgoriti is associated with Mt. Kawi.

Keywords: Water chemistry · Geothermal · Arjuno-Welirang · East Java · Indonesia.

1 INTRODUCTION

Understanding the type and origin of geothermal system is important in the geothermal exploration. Arjuno-Welirang field located in East Java province, Indonesia, about 70 km southwest of Surabaya (Figure 1), belongs to an undeveloped geothermal prospect. This geothermal system has a steep volcanic terrain and having scarce of geothermal manifestations. Consequently, a proper data collection and an integrated water characterization should be done in the poor geothermal manifestations such as Arjuno-Welirang area, in order to construct the thermal water hydrology.

2 GEOLOGY

2.1 Tectonic setting

Java island is situated on the southeast edge of the Eurasian Plate at the Sundaland margin in which Sundaland is the continental core of southeast Asia (Sribudiyani *et al.*, 2003). Subduction of the Indonesia-Australia Plate be-

*Corresponding author: A. HARIJOKO, Department of Geological Engineering, Gadjah Mada University. Jl. Grafika 2 Yogyakarta, Indonesia. E-mail: aharijoko@ugm.ac.id

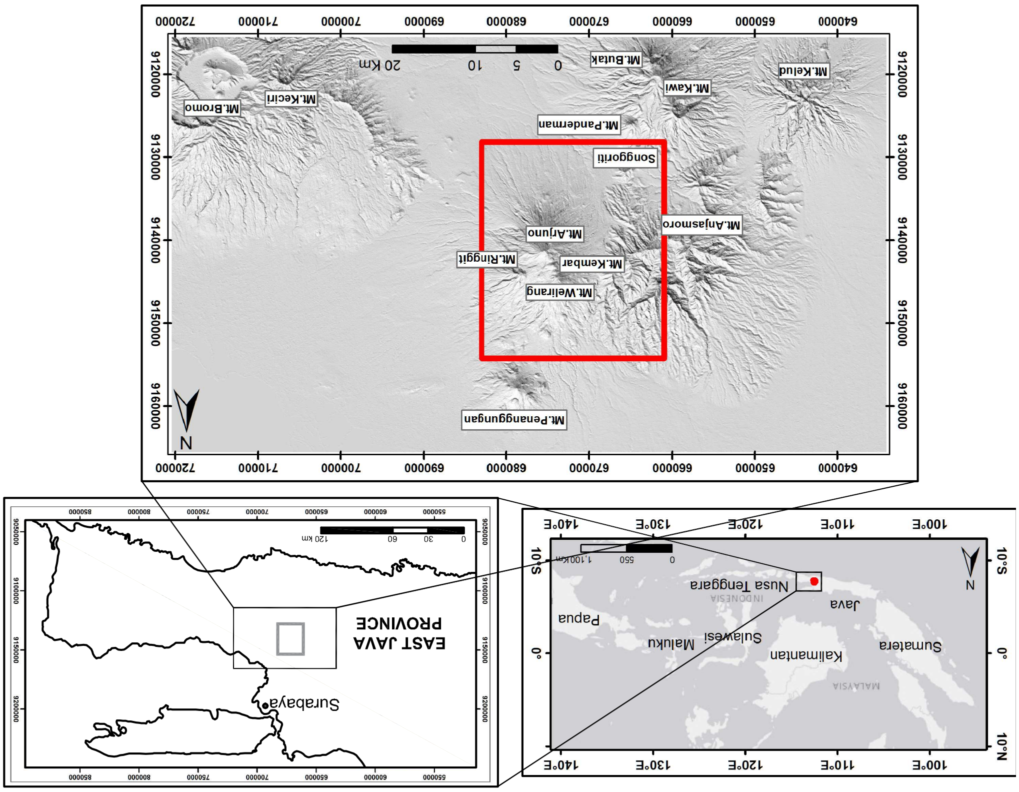

Figure 1: Location of Arjuno-Welirang geothermal field.

neath the Eurasian Plate has created the Java trench where located to the south of Java from Middle Miocene to the present-day (Hall, 2002). This subduction results in Sunda volcanic arc, although volcanic activity was not continuous for all of this period (Smyth *et al.*, 2008). As a consequence of the Miocene – present subduction, Java island contains the products of active and ancient volcanism which distributed along the length of the island (Smyth *et al.*, 2005).

2.2 Regional geology

East Java can be subdivided into four parts (Figure 2), broadly parallel to the elongation of the island (Smyth *et al.*, 2008), such as: Southern Mountains Arc, a volcanic arc was mainly built by andesites (van Bemmelen, 1949) from Middle Eocene – Miocene in southern Java; Kendeng Basin, the basin was filled with volcaniclastic turbidites and pelagic mudstones (Untung and Sato, 1978) which formed in deep marine (Darman and Sidi, 2000) and has an age range of Middle Eocene – Miocene (de Genevraye and Samuel, 1972); Sunda Shelf, an area was composed by shallow marine clastic and extensive carbonate sedimentary rocks and was formed from Eocene to Pliocene (Ardhana, 1993); and Modern Volcanic Arc, this arc is mainly built on Kendeng Basin but locally overlap the edge of Southern Mountains Arc. The active volcanoes are composed by Quaternary basaltic andesite (Nicholls *et al.*, 1980) and was built upon deep marine volcaniclastic rocks and mudstone. The study area belongs to Modern Volcanic Arc province.

2.3 Geology and geochemistry of Arjuno-Welirang volcanic complex

Geological and geochemical surveys have been done in Arjuno-Welirang geothermal field. However, the drilling exploration has never been conducted in that area. Arjuno-Welirang geothermal field has a high enthalpy and it is associated with Quaternary stratovolcanoes (Hadi *et al.*, 2010).

Arjuno-Welirang Volcanic Complex (AWVC) comprises several volcanoes, i.e., Old AWVC (Mt. Ringgit, Mt. Bulak, Mt. Pundak and Mt. Tunggangan) and Young AWVC (Mt. Arjuno, Mt. Welirang, Mt. Kembar-I, Mt. Kembar-II and Mt. Bakal). Geologically, this area is composed by andesitic-basaltic lavas, pyroclastic and volcaniclastic rocks (Figure 2). The NNW–SSE alignment of volcanic craters show

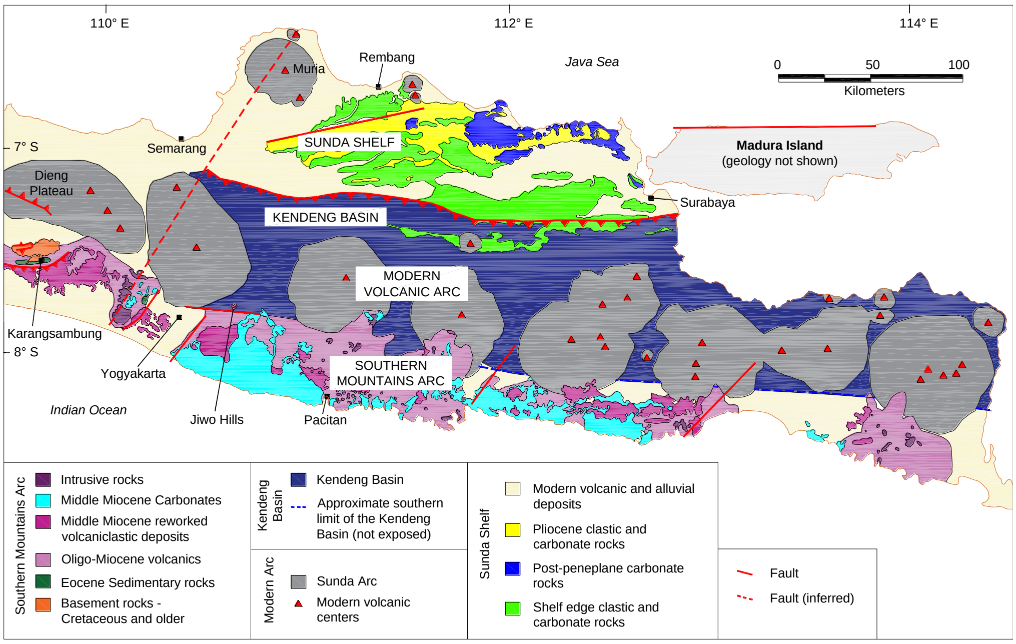

Figure 2: Geological map of East Java, depicting the main geological provinces and stratigraphic units (modified from Smyth *et al.*, 2008). The study area belongs to Modern Volcanic Arc province.

that the forming of AWVC is controlled by geological structures. The structures are dominated by NE–SW, NW–SE, N–S, E–W normal-sinistral and normal-dextral faults. Moreover, strike-slip fault and volcanic structures (ring fractures and collapse zones) are also can be found in this area (Utama, 2017).

Geochemical survey has been done in Arjuno-Welirang field. Fumaroles in Plupuh Crater (Mt.Welirang) has measured temperature of 137°C, however, the estimated reservoir temperature from that fumarole using CO_2 gas geothermometer by D'Amore and Panichi (1987) yielded temperature up to 260°C (Hadi *et al.*, 2010).

2.4 Geothermal Manifestations

Geothermal manifestations in AWVC are characterized by hot springs (Padusan and Cangar), fumaroles-solfataras (Mt. Welirang summit) and altered ground (flank of Mt. Pundak and Mt. Welirang, respectively). Hadi *et al.* (2010) and Utama (2017) also found fumaroles (Mt. Kembar-I and Mt. Kembar-II summits, respectively), steaming ground in the flank of Mt. Kembar-II and altered ground in Mt. Kembar-I and Mt. Kembar-II summits, respectively. The NW–SE and N–S faults control the appearance of the geothermal manifestations (Hadi *et al.*, 2010; Utama, 2017). Songgoriti hot spring is located in the flank of Mt. Kawi around 16 km southwest of AWVC.

3 SAMPLES AND ANALYTICAL METHODS

3.1 Samples

Twenty-four water samples were collected in Arjuno-Welirang geothermal prospect, including 7 hot springs, 8 cold springs, 8 river waters, and 1 rain water (Figure 3). Based on the sampling locations, there are 3 groups of thermal water samples, such as: Cangar (CG 1 and 2), Padusan (PD1, 2, 3 and 4), and Songgoriti (SG1).

Water sampling was complemented by in-situ measurement of temperature, pH, electric conductivity (EC), and total dissolved solid (TDS). All of water samples were filtered through 0.45 mm membrane filters prior to storage in 100 mL of sterile high-density polyethylene bottles (HDPE). At each water sampling location, water sample was collected into 2 bottles, i.e. for cation and anion analyses. In this study, HCO_3 concentrations were not measured during collecting water samples, but they were measured in laboratory.

3.2 Analytical methods

Samples for cation (Li^+, Na^+, K^+, Mg^{2+} and Ca^{2+}), silica (SiO_2) and boron (B) analyses were collected in HDPE (High Density Polyethylene) bottles that had been acidified with a few mL of

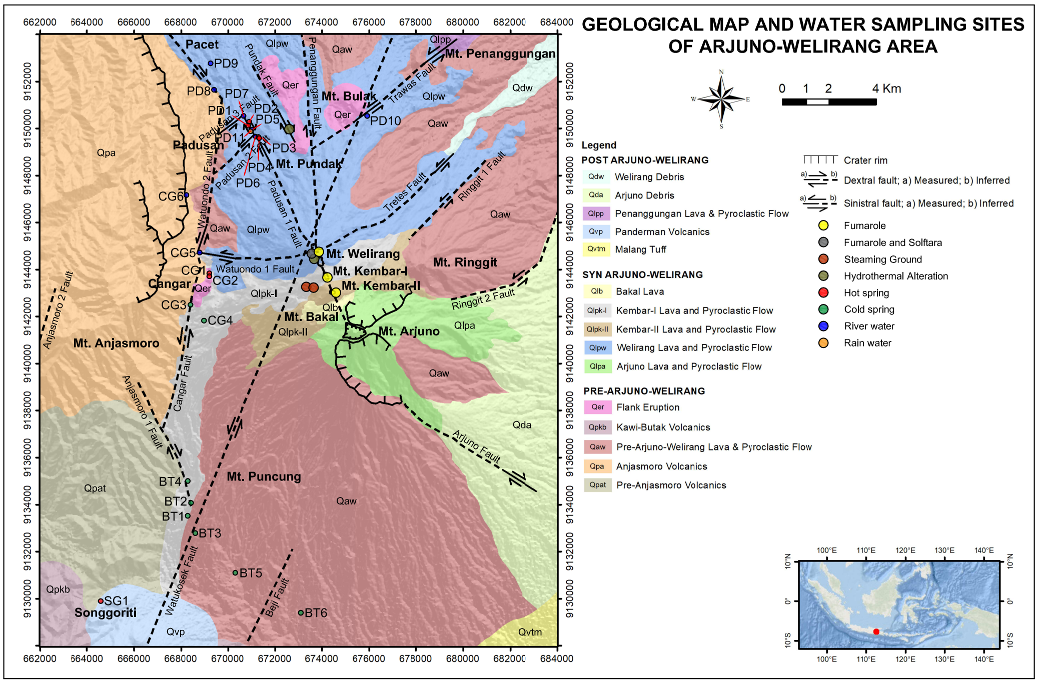

Figure 3: Geological map, geothermal manifestation sites (modified from Santosa and Suwarti, 1992; Santosa and Atmawinata, 1992; Utama, 2017), and sampling water sites in Arjuno-Welirang geothermal field.

concentrated HNO_3 until the pH of water sample becomes <3 (Nicholson, 1993). Besides that, the filtered and un-acidified samples were collected for anion (Cl^-, SO_4^{2-} and HCO_3^-) analysis. SiO_2 and B were analyzed using ICP-AES (Optima 5300 DV), HCO_3^- was analyzed by titration with 0.05 M HCl, while cations (Li^+, Na^+, K^+, Mg^{2+} and Ca^{2+}) and anions (Cl^- and SO_4^{2-}) were analyzed by using ion chromatography (Dionex ICS-90). ICP-AES, titration, and ion chromatography analyses were conducted at Economic Geology Laboratory, Department of Earth Resources Engineering, Kyushu University, Japan. Before conducting those analyses, the instruments were calibrated with standard solutions to confirm standard values and detection limits for each element.

4 RESULTS AND DISCUSSION

4.1 Results

There are three groups of hot springs in the study area such as Padusan and Cangar are found in the flank of AWVC and Songgoriti is found in the flank of Mt. Kawi which located in the southwest of AWVC. Water chemistry data from 24 water samples are given in Table 1. The analytical error (ionic balance) between cations and anions for this analysis is less than 10 %. Based on ionic balance comparisons, the water chemistry data are applicable to some interpretations. All thermal waters have temperatures from 39.5–53°C and weakly acidic pH (5.2–6.5).

Distribution of major elements (showing with stiff diagram) for the water samples are shown Figure 4. According to the distribution of the geochemical characteristics, the thermal water samples in Cangar, Padusan and Songgoriti show different characteristics. Cangar hot springs have relatively high HCO_3^-, Padusan hot springs have higher major elements (HCO_3^-, Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+} and Mg^{2+}) concentrations than Cangar, while Songgoriti has very high Na^+ and Cl^- concentrations.

4.2 Discussion

4.2.1 General hydrogeochemical characteristics

Hydrogeochemical characteristics are defined by the dominant cation-anion and depicted in semi-logarithmic Schoeller diagram (Figure 5). The diagram shows that all hot springs (except Songgoriti) have higher concentrations of Na, K, Ca, Mg, Cl, HCO_3, SO_4, SiO_2 and B than cold waters (including cold springs, river waters and rain water). At Songgoriti hot spring, all the constituents are high, but SO_4 is very low. High Ca, Mg and HCO_3 compositions

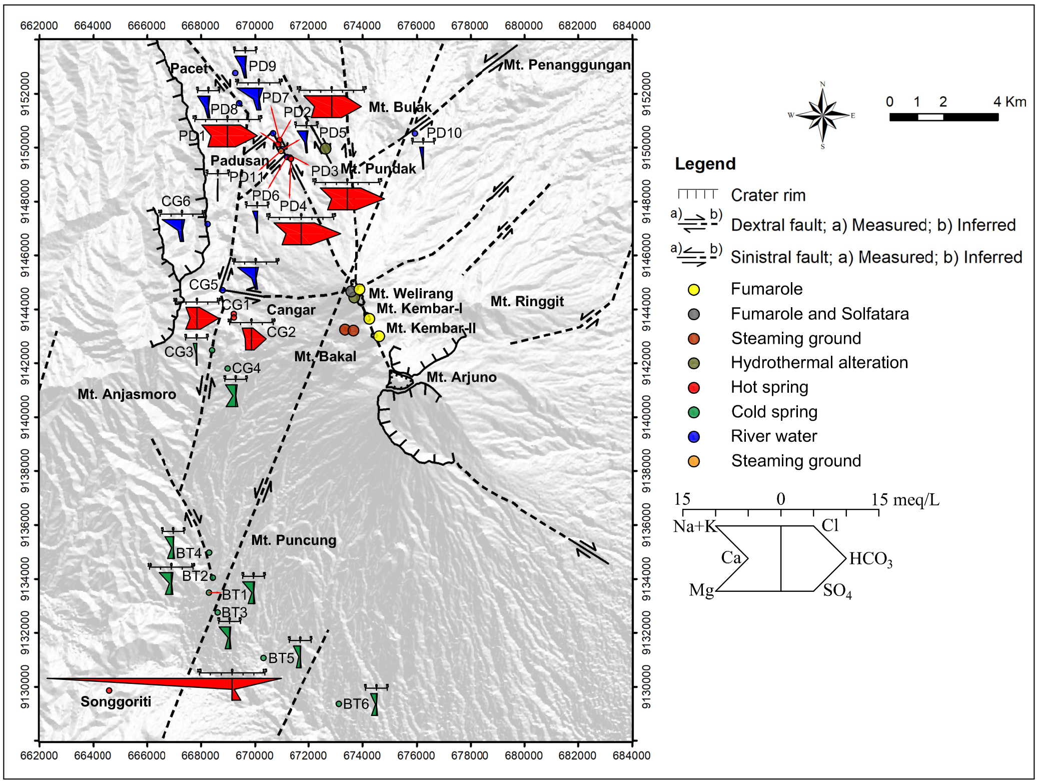

Figure 4: Distribution of geochemical characterististics showing with stiff diagram in Arjuno-Welirang geothermal field.

in the hot springs indicate that possibly they were mixed with near-surface groundwater, because the hot springs are particularly low in Ca and Mg (Truesdell, 1991), and HCO_3 is the typical main anion in most of cold water samples (Uzelli *et al.*, 2017). All of waters show similar patterns, it suggests that the waters are mixed with same fluids, however, they possibly have different degrees of mixing. Songgoriti hot spring points out has higher Ca, Mg and HCO_3, indicating it underwent more mixing with groundwater than Padusan and Cangar. In addition, Padusan also have higher Ca, Mg and HCO_3, suggesting they experience more mixing than Cangar.

4.2.2 *Relative Cl, SO_4 and HCO_3 contents*

Chemical compositions of the water samples are also plotted (Figure 6) on the Cl–SO_4–HCO_3 diagram (Giggenbach, 1988). Based on the Cl–SO_4–HCO_3 diagram, all of the water samples (including Cangar and Padusan hot springs) are classified as bicarbonate water, except Songgoriti belongs to Cl–HCO_3 type. Bicarbonate water are products of steam-heating and gas condensation into poorly-oxygenated subsurface groundwaters. The water is formed by reactions between dissolved CO_2 and host rock. Their chemistry is unrelated to equilibria in the deep reservoir, so that this water is not suitable for geothermometer (Nicholson, 1993).

Cangar and Padusan hot springs are weakly acidic pH (5.2–6.5), suggesting the waters have reacted with the local rocks, either in the shallow reservoir or during lateral flow. Mg^{2+} concentration in these waters are relatively high (>0.1 mg/L), indicating near surface reactions of leaching Mg from the local rock, or dilution by groundwater (Nicholson, 1993).

Bicarbonate waters have a strong affinity with meteoric waters, probably degassed gases such as CO_2 and/or H_2S are absorbed in the shallow groundwater (Taguchi *et al.*, 2014). As we can see in the Figure 3, these waters were found around the flank of AWVC, furthermore, they are associated with travertine ($CaCO_3$) which is found near Padusan hot springs.

On the other hand, Songgoriti belongs to Cl–HCO_3 type, formed by dilution of chloride fluid by either groundwater or a bicarbonate water during lateral flow. This thermal water has near-neutral pH (i.e., 6.5) with higher concentration of chloride and bicarbonate.

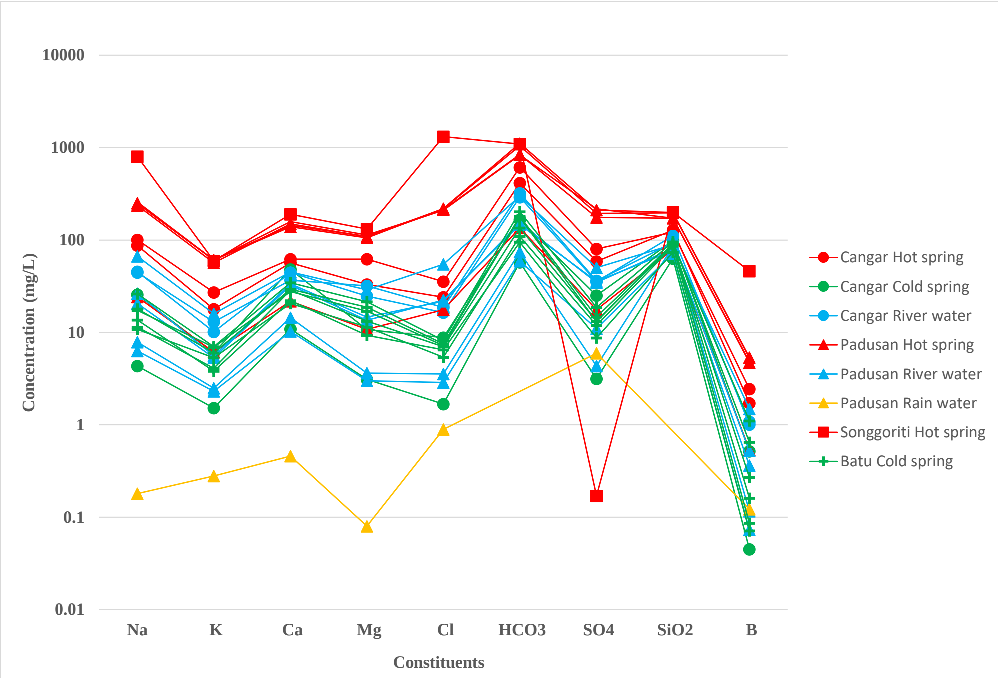

Figure 5: Semi-logarithmic Schoeller diagram for water samples in Arjuno-Welirang area.

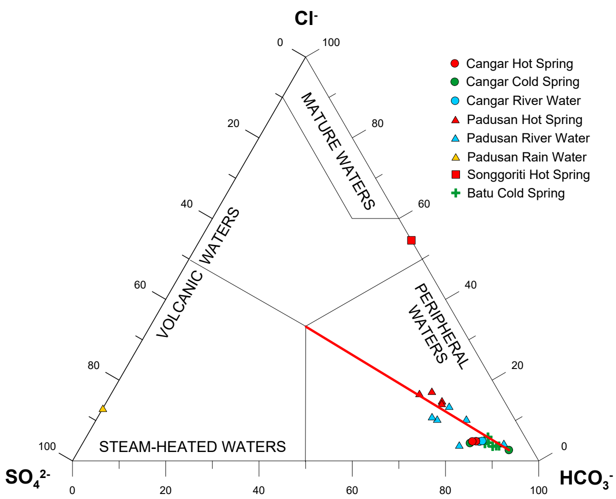

Figure 6: Cl-SO_4-HCO_3 diagram (Giggenbach, 1988) of water samples from Arjuno-Welirang area.

Songgoriti hot spring has very high Cl concentration up to 1313 mg/L (Table 1), assuming the geothermal fluids have already reacted with sedimentary rocks before ascending to the surface. As we know that AWVC and Mt. Kawi lie on Kendeng Basin which composed by deep marine sedimentary rocks (Figure 2). Conversely, the hot spring has very low SO_4 (0.17 mg/L), indicating it is not formed by steam condensation into near-surface waters (Nicholson, 1993).

In Figure 6, all of hot and cold water samples (except Songgoriti) show a linier trend tends to volcanic waters, showing with the red line. It probably the waters are derived from volcanic waters which accumulated in the crater lake of AWVC.

4.2.3 *Relative Cl, Li and B contents*

Cl, Li and B are important conservative constituents which may be used as a tracer for the initial deep rock dissolution process and as reference to evaluate the possible origin of geothermal fluid. Moreover, Li is the alkali metal probably least affected by secondary processes (Giggenbach, 1991). The relative Cl, Li and B contents of water samples in Arjuno-Welirang area are shown in Figure 7. Based on Cl–Li–B diagram, all of water samples have much higher Cl and B contents, suggesting either addition of Cl and B before, during or after the rock dissolution process, or loss of Li (Giggenbach, 1991). Li is possibly taken up into clays in near-surface reactions (Nicholson, 1993), where halloysite is found near Padusan hot spring.

Cl/B ratios can be used to indicate common reservoir source for waters (Nicholson, 1993) and to evaluate mixing between thermal and non-thermal waters (Arnorsson and Andresdottir, 1995). The trend line indicates that there

Table 1: Chemical composition of water samples in Arjuno-Welirang area.

Sample ID	Location	Fluid type	Temp (°C)	pH	EC (mS/cm)	TDS (mg/L)	SiO_2 (mg/L) ICP-AES	B	HCO_3^- (mg/L) Titration	Cl^- (mg/L) IC	SO_4^{2-}	Li^+	Na^+	K^+	Mg^{2+}	Ca^{2+}
CG-1	Cangar	Hot spring	46.2	6.4	1070	450	122	2.44	612	35.5	80.2	*n.d*	100.1	27.1	62.0	62.1
CG-2	Cangar	Hot spring	39.5	6.2	750	350	128	1.72	413	24.0	58.7	*n.d*	87.0	17.8	32.9	56.4
CG-3	Cangar	Cold spring	17	7.0	170	70	63	0.05	57	1.7	3.2	*n.d*	4.3	1.5	3.1	10.9
CG-4	Cangar	Cold spring	22	6.4	390	190	99	0.52	165	8.8	25.0	*n.d*	25.6	6.0	10.7	48.0
CG-5	Cangar	River water	22	6.5	450	240	111	1.01	291	16.4	35.5	*n.d*	45.3	10.1	24.7	44.6
CG-6	Cangar	River water	23.2	8.3	510	240	93	1.08	322	18.6	36.3	*n.d*	44.3	13.0	31.9	36.8
PD-1	Padusan	Hot spring	46.2	6.1	2050	1020	172	4.72	841	212.0	175.7	0.1	236.0	56.4	108.7	149.2
PD-2	Padusan	Hot spring	46.5	5.8	2080	1020	172	4.81	831	210.0	217.0	0.1	257.0	60.6	113.2	158.3
PD-3	Padusan	Hot spring	53	5.2	1730	610	196	5.29	1046	217.0	194.0	0.2	248.0	60.6	109.1	144.4
PD-4	Padusan	Hot spring	51.4	6.5	2290	1100	198	5.36	1111	219.0	211.0	0.2	250.0	60.9	105.8	139.0
PD-5	Padusan	River water	23	7.7	270	120	79	0.54	135	17.6	17.6	*n.d*	24.2	6.1	10.8	21.7
PD-6	Padusan	River water	22	6.5	130	60	85	0.12	74	3.6	4.3	*n.d*	7.9	2.5	3.6	14.4
PD-7	Padusan	River water	23	6.2	640	310	89	1.48	298	54.5	50.0	*n.d*	66.6	15.9	28.8	45.2
PD-8	Padusan	River water	23	7.5	340	170	81	0.52	153	21.7	34.8	*n.d*	26.3	5.6	14.6	33.6
PD-9	Padusan	River water	23.3	7.9	320	150	77	0.36	146	22.4	35.6	*n.d*	20.6	5.3	13.5	32.4
PD-10	Padusan	River water	20.6	5.7	90	40	72	0.07	59	2.9	11.0	*n.d*	6.3	2.3	3.0	10.3
PD-11	Padusan	Rain water	23	4.9	30	*n.d*	*n.d*	0.12	*n.d*	0.9	5.9	*n.d*	0.2	0.3	0.1	0.5
SG-1	Songgoriti	Hot spring	46	6.5	1690	1880	200	45.95	1091	1313.0	0.2	1.6	800.0	59.5	131.5	190
BT-1	Batu	Cold spring	22	6.3	340	170	91	1.11	180	7.5	14.7	*n.d*	17.9	6.0	18.7	29.3
BT-2	Batu	Cold spring	22	7.0	380	150	96	0.65	203	8.2	18.6	*n.d*	26.1	7.0	21.4	34.4
BT-3	Batu	Cold spring	21	7.0	300	150	90	0.27	176	7.2	13.1	*n.d*	17.3	6.9	17.0	27.6
BT-4	Batu	Cold spring	21	7.0	260	140	90	0.16	135	7.0	13.2	*n.d*	11.4	4.1	13.2	28.6
BT-5	Batu	Cold spring	21	7.0	210	110	86	0.09	109	5.4	11.9	*n.d*	10.8	5.3	11.4	20.6
BT-6	Batu	Cold spring	22	7.0	210	100	73	0.07	95	6.5	8.7	*n.d*	13.6	3.8	9.3	22.0

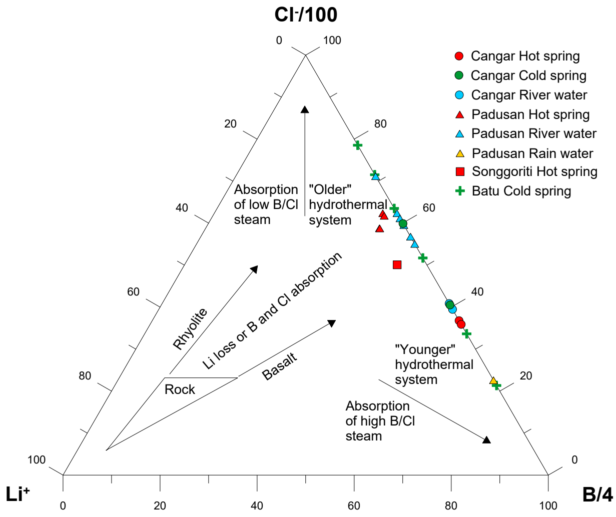

Figure 7: Cl-Li-B diagram (Giggenbach, 1988) of water samples from Arjuno-Welirang area.

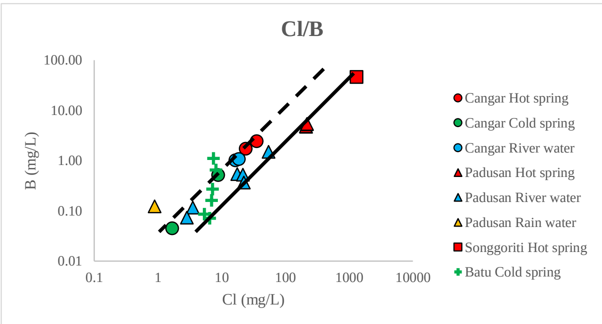

Figure 8: Plots of Cl vs. B concentrations for water samples in Arjuno-Welirang area.

is direct hydraulic connection between the non-thermal waters and geothermal systems (Han *et al.*, 2010).

Figure 8 shows two linier mixing trends among all the waters in Arjuno-Welirang field. Padusan and Songgoriti are in the same trend line (continuous line), while Cangar has different trend line (dashed line). Padusan and Songgoriti have higher Cl/B ratios than Cangar, assuming Cangar experienced more intensively mixing/dilution with shallow groundwater than Padusan and Songgoriti. However, those trend lines have similar patterns, indicating that all water samples have similar Cl/B ratios and they are from common fluid sources and formed by rock dissolutions with similar rocks, i.e., andesitic-basaltic rocks. Although they are affected by rock dissolutions, they are not added by different constituents or formation waters.

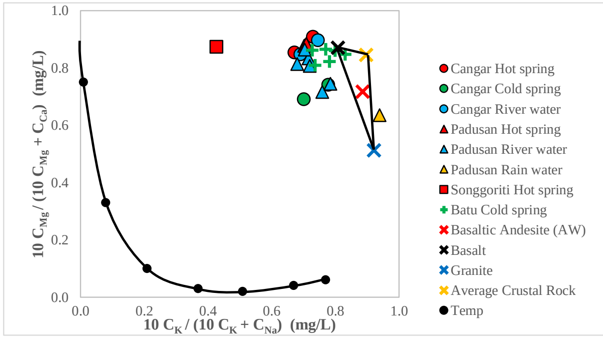

Figure 9: Plots of Na-K vs. Mg-Ca concentrations for water samples in Arjuno-Welirang area.

4.2.4 *Relative Na, K, Mg and Ca contents and estimated reservoir temperature*

Na–K and Mg–Ca contents can give information the process and origin of the waters. Figure 9 shows all waters are plotted far from full equilibrium line, representing the composition of waters are not attained water-rock equilibrium with a rock of average crustal composition (Giggenbach, 1988). Moreover, all waters are plotted near local rocks of AWVC, i.e., andesitic-basaltic rocks (red cross). Assuming cation compositions of the waters are from local rock dissolutions and absorption of hot magmatic gasses by condensates during rock dissolutions (Hochstein and Sudarman, 2015).

Subsurface reservoir temperature is an important parameter in evaluating the formation and utilization potential of a geothermal energy resource. Geothermometry techniques can be used to estimate reservoir temperature (Arnorssoon, 1983; Giggenbach, 1988; Han *et al.*, 2010).

Geothermometry methods can be calculated using either cation or silica concentrations. Na–K (cation) geothermometer resulting "slow" water-rock equilibration temperatures and are likely to reflect conditions at deeper levels (Giggenbach and Glover, 1992). This geothermometer is based on a concentration ratio, thus it is less affected by dilution and boiling (Nicholson, 1993). On the other hand, silica geothermometer represents fast water-rock equilibration and usually providing information on temperatures at shallow levels (Giggenbach and Glover, 1992). This geothermometer is dependent on an absolute concentration, therefore, it is affected by physical processes such as boiling and dilution/mixing (Nicholson, 1993). Consequently, silica geothermometers is not suitable for estimating reservoir temperature in Arjuno-Welirang geothermal system.

The degree of chemical equilibration between geothermal fluids and rocks can be estimated using Na–K–Mg diagram (Giggenbach, 1988). All of water samples including Cangar, Padusan and Songgoriti, belong to immature water (Figure 10), representing there is no strong outflow of neutral Cl-rich deep waters in AWVC. Consequently, reservoir temperature cannot be inferred by the hot springs in this field (Nicholson 1993; Taguchi *et al.*, 2014).

Disregarding the immature waters, estimating reservoir temperature using a ternary plot of Na/1000–K/100–$Mg^{1/2}$ proposed by Giggenbach (1988) depicts that all of water samples (except Songgoriti) have estimated temperatures up to ±325°C (showing with the blue dashed lines), while Songgoriti has an estimated temperature of ±225°C, showing with the green dashed lines (Figure 10). According to the Na–K–Mg diagram on the right side, all of water samples (except Songgoriti) are plotted in a linier trend line. It suggests that Cangar, Padusan and the cold waters have similar mixing ratios.

The immature waters represent that cation compositions are inequlibrated, therefore, cation geothermometry cannot be applied to estimate reservoir equilibrium temperatures using thermal spring in this geothermal systems. Geothermal fluid in this area are derived from advective flow of diluted condensates over the upper flanks and foothill region of volcanoes with high relief. In strato-volcanic geothermal system, acidic manifestations up-slope and minor neutral pH springs down-slope are common (Hochstein and Sudarman, 2015). In fact, some acidic manifestations such as advanced argillic alterations, fumaroles, solfataras and steaming ground are found near top of AWVC, moreover, some bicarbonate hot springs whose near-neutral pH (5.2–6.5) and argillic alteration are found in down-slope of AWVC.

Due to immature waters are not suitable for water (solute) geothermometers, estimated temperatures reservoir can be calculated using gas geothermometer in AWVC geothermal system. Collecting and analyzing gas were not conducted in this study, thus, gas geothermometer cannot be calculated. Nevertheless, Hadi *et al.* (2010) mentioned the estimated reservoir temperature of AWVC was around 262–263°C using CO_2 geothermometer (D'Amore and Panichi, 1987) based on collecting of fumarole gas at crater Mt. Welirang.

According to the type of fluids and the difference of estimated reservoir temperatures, Cangar and Padusan might be formed in different system with Songgoriti. Cangar and Padusan hot springs are probably associated with Arjuno-Welirang Volcanic Complex (AWVC), while Songgoriti is possibly associated with Mt. Kawi which is located in the southwest of AWVC (see Figures 1 and 3).

5 Conclusions

Cangar and Padusan hot springs (pH 5.2–6.5) show bicarbonate water, it is product of steam-heating and gas condensation or groundwater mixing. This water is formed by reactions with host rocks in the shallow reservoir or during lateral flow and neutralize the initial acidity by advective flow or diluted condensates, so that the water becomes near-neutral pH. Cangar, Padusan and cold waters are possibly associated with volcanic waters, indicating these waters underwent rock-water reactions at depth. On the other hand, Songgoriti belongs to $Cl-HCO_3$ type, formed by dilution of chloride fluid by either groundwater or a bicarbonate water during lateral flow.

Based on Cl/B ratios, all water samples have similar patterns, indicating those waters have similar Cl/B ratios and are possibly from common fluid sources. However, Padusan and Songgoritihave higher Cl/B ratios than Cangar, assuming Cangar experienced more intensively mixing/dilution with shallow groundwater than Padusan and Songgoriti. The waters were possibly mixed with shallow groundwater before ascending to the surface, due to the hot springs have relatively high Ca, Mg and HCO_3 concentrations. Moreover, all water samples are might be affected by local rock dissolutions, i.e., andesitic-basaltic rocks. However, they are not added by different constituents or formation waters.

All water samples including Cangar, Padusan and Songgoriti belong to immature water,

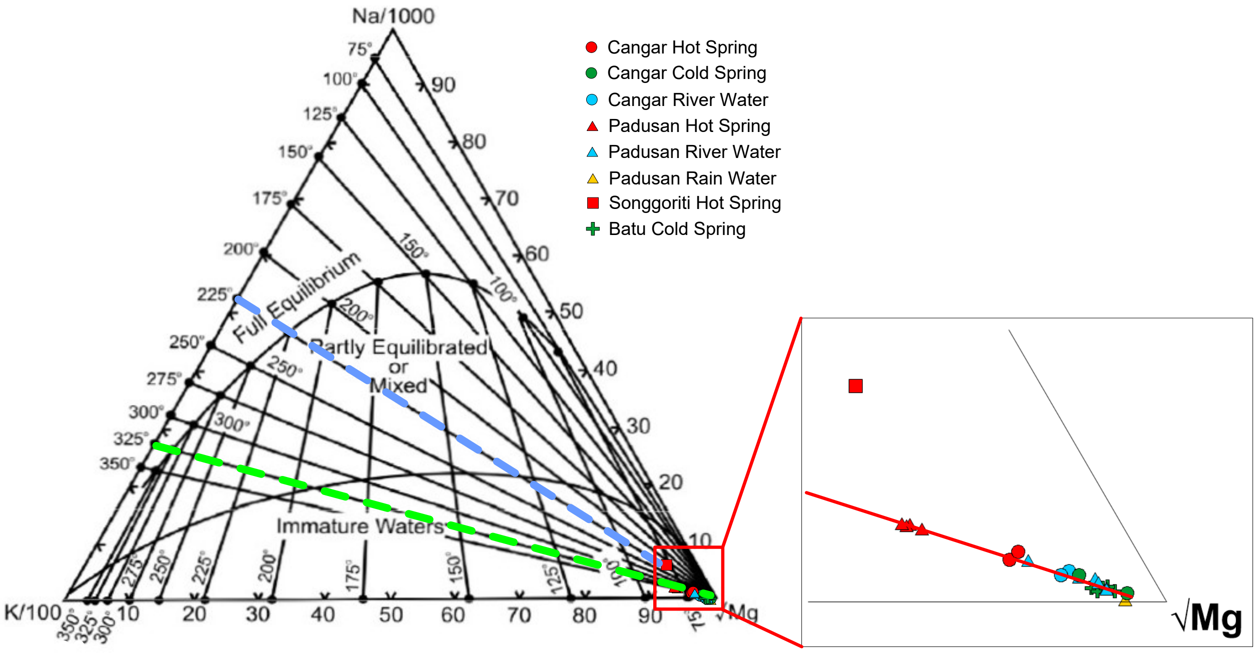

Figure 10: Na-K-Mg diagram (Giggenbach, 1988) of water samples from Arjuno-Welirang area.

indicating there is no strong outflow of neutral Cl-rich deep waters in AWVC. This water type is difficult to estimate reservoir temperature using both cation and silica geothermometer. Consequently, estimated temperatures reservoir calculated using CO_2 geothermometer yielded temperatures of 262–263°C based on collecting of fumarole gas at Mt. Welirang crater.

According to their characteristics, it can be postulated that Cangar and Padusan have a different system with Songgoriti. Cangar and Padusan hot springs are probably associated with Arjuno-Welirang Volcanic Complex (AWVC), while Songgoriti is possibly associated with Mt. Kawi which is located in the southwest of AWVC.

ACKNOWLEDGEMENTS

This research was financially supported by Grant Research Fund for scientific research from Universitas Gadjah Mada, Indonesia, and Indonesia Endowment Fund for Education (Lembaga Pengelola Dana Pendidikan/LPDP). It was also supported by Department of Earth Resources Engineering, Kyushu University, Japan, especially to Economic Geology Laboratory and Energy Resources Laboratory for analyzing the water samples. The authors are also grateful to Ms. Rie Yamashiro from Energy Resources Laboratory, Department of Earth Resources Engineering, Kyushu University, Japan, for her help during conducting analyses. We also thank to Mr. Sachihiro Taguchi from Department of Earth System Science, Faculty of Science, Fukuoka University, Japan, for his helpful suggestions. The manuscript greatly benefited from Mr. Mochamad Nukman as a reviewer who gives helpful comments.

REFERENCES

Ardhana, W. (1993) A Depositional Model for The Early Middle Miocene Ngrayong Formation and Implications for Exploration in The East Java Basin: Jakarta, Proceedings of the 22nd Indonesian Petroleum Association Annual Convention, 395–443 pp.

Arnorrson, S. (1983) Chemical Equilibria in Icelandic Geothermal Systems: Implications for Chemical Geothermometry Investigations. Geothermics 12: 119-128p.

Arnorrson, S. and Andresdottir, A. (1995) Processes Controlling the Distribution of Boron and Chloride in Natural Waters in Iceland. Geochim. Cosmochim. Acta 59(20): 4125-4146 pp.

D'Amore, F. dan Panichi, C. (1987) Geochemistry in geothermal exploration. In: Economides, M. and

Ungemach, P. (eds) Applied geothermics, Wiley & Sons, New York, 69–89pp.

Darman, H. dan Sidi, F.H. (2000) An Outline of The Geology of Indonesia, Ikatan Ahli Geologi Indonesia, Jakarta, 54-58p.

de Genevraye, P., and Samuel, L. (1972) The Geology of Kendeng Zone (East Java): Jakarta, Proceedings of the First Indonesian Petroleum Association Annual Convention, 17–30pp.

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

Giggenbach, W.F., 1991, "Chemical Techniques in Geothermal Exploration" in: D'Amore, F. (Ed.), Applications of Geochemistry in Geothermal Reservoir Development, UNITAR/UNDP on Small Energy Resources, Rome, 119-142pp.

Giggenbach, W.F. and Glover, R.B. (1992) Tectonic Regime and Major Processes Governing the Chemistry of Water and Gas Discharges from the Rotorua Geothermal Field, New Zealand, Geothermics, 21, No.1/2, 121-140 pp.

Hadi, M.N., Kusnadi, D., and Sugianto, A. (2010) Penyelidikan Terpadu Geologi, Geokimia and Geofisika Daerah Panas Bumi Arjuno-Welirang, Kabupaten Mojokerto and Malang, Provinsi Jawa Timur (in Bahasa), Center for Geological Resouces, Indonesian Ministry of Energy and Mineral Resources, Bandung, 1-11 pp.

Hall, R., 2002, Cenozoic Geological and Plate Tectonic Evolution of SE Asia and the SW Pacific: Computer-Based Reconstructions, Model and Animations: Journal of Asian Earth Sciences 20: 353–434pp.

Han, D.M., Liang, X., Jin, M.G., Currell, M.J., Song, X.F., Liu, C.M. (2010) Evaluation of Groundwater Hydrochemical Characteristics and Mixing Behavior in the Daying and Qicun Geothermal Systems, Xinzhou Basin. Journal of Volcanology and Geothermal Research 189: 92–104pp.

Hochstein, M.P. and Sudarman, S. (2015) Indonesian Volcanic Geothermal Systems, Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, 1–11pp.

Nicholls, I.A., Whitford, D.J., Harris, K.L., and Taylor, B. (1980) Variation in the Geochemistry of Mantle Sources for Tholeiitic and Calc-alkaline Mafic Magmas, Western Sunda Volcanic Arc, Indonesia: Chemical Geology 30: 177–199pp.

Nicholson, K. (1993) Geothermal Fluids : Chemistry and Exploration Technique, Springer-Verlag, Berlin, 39–218p.

Santosa, S. and Atmawinata, S. (1992) Geological Map of the Kediri Quadrangle, Jawa, scale 1:100000, Geological Research and Development Centre, Bandung.

Santosa, S. and Suwarti, T. (1992) Geological Map of the Malang Quadrangle, Jawa, scale 1:100000, Geological Research and Development Centre, Bandung.

Smyth, H., Hall, R., Hamilton, J.P., and Kinny, P. (2005) East Java: Cenozoic Basins, Volcanoes and Ancient Basement: Jakarta, Proceedings of the 30th Indonesian Petroleum Association Annual Convention, 251–266p.

Smyth, H.R., Hall, R., Nichols, G.J. (2008) Cenozoic Volcanic Arc History of East Java, Indonesia: The Stratigraphic Record of Eruptions on an Active Continental Margin, The Geological Society of America, Special Paper 436, 199–222p.

Sribudiyani, Muchsin, N., Ryacudu, R., Kunto, T., Astono, P., Prasetya, I., Sapiie, B., Asikin, S., Harsolumakso, A.H., and Yulianto, I. (2003) The Collision of The East Java Microplate and Its Implication for Hydrocarbon Occurences in The East Java Basin, Proceedings of Indonesia Petroleum Association, Jakarta.

Taguchi, S., Vaquilar, R.L., Laguerta, E.P., Bornas, M.A.V., Solidum Jr., R.U., Reyes, P.J.D., Mirabueno, M.H.T., Daag, A.S., Bariso, E.B., Okuno, M. (2014) Geochemical Characteristics of Hot Springs in Bulusan Volcanic Complex, Southern Luzon, Philippines, Scientific Journal of Fukuoka University 44, 2nd reprint, September 2014, 129–142p.

Truesdell, A.H. (1991) "Effects of Physical Processes on Geothermal Fluids" in: D'Amore, F. (Ed.) Applications of Geochemistry in Geothermal Reservoir Development, UNITAR/UNDP on Small Energy Resources, Rome, 71–90pp.

Untung, M., and Sato, Y. (1978) Gravity and Geological Studies in Java, Indonesia: Geological Survey of Indonesia and Geological Survey of Japan Special Publication 6, 207p.

Utama, H.W. (2017) Vulkanisme and Struktur Geologi Daerah Panas Bumi Kompleks Gunung Api Arjuno-Welirang, Provinsi Jawa Timur (in Bahasa), unpublished thesis manuscript from Graduate Program of Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, 1–137p.

Uzelli, T., Baba, A., Mungan, G.G., Dirik, R.K., Sozbilir, H. (2017) Conceptual Model of the Gulbahce Geothermal System, Western Anatolia, Turkey: Based on Structural and Hydrochemical Data, Journal of Geothermics 68: 67–85pp.

van Bemmelen, R.W. (1949) The Geology of Indonesia Volume 1A, Government Printing Office, The Hague, Netherlands, 25–30p.