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Stable Isotopes Study of Wayang Windu Geothermal Field, Indonesia

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ABSTRACT

Wayang Windu geothermal field is located in West Java (Indonesia) and is associated with Quaternary active volcanoes. The geothermal system is transitional between liquid and vapor dominated systems. We have collected samples from hot springs and deep wells to analyze naturally occurring isotope compositions, i.e. δD, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$. The compositions of δD and $\delta^{18}O$ suggest that fluid from thermal manifestations and deep fluids are of meteoric origin. Deep fluids may have recharged from a lower altitude than fluids of the thermal manifestations. $^{87}Sr/^{86}Sr$ ratios of the fluid samples vary between 0.7046 – 0.7058 and are in agreement with $^{87}Sr/^{86}Sr$ ratios of Sunda arc calc-alkaline volcanic rocks.

1. INTRODUCTION

Wayang Windu is located about 35 km south of Bandung, the capital of West Java province. The geothermal field stretches along a series of Quaternary volcanoes (Mt. Malabar, Mt. Puncak Besar, Mt. Gambung, Mt. Bedil, Mt. Wayang and Mt. Windu, Fig. 1). Several thermal manifestations including fumaroles, hot springs, mud pools and altered ground are situated along the slopes of the mountain range. Fumaroles located between Mt. Wayang and Mt. Windu show temperatures between 93°C to 96°C, and are therefore slightly superheated compared to the normal water boiling point at altitudes of 2000 m. Hot springs located in altitudes between 1495 m and 1985 m reach temperatures from 41°C to 88°C. Water discharge hot springs are of bicarbonate type, except for hot springs located near the fumaroles, which discharge acid sulfate water (Ganda and Hantono, 1992; Bogie et al, 2008).

The lithology at Wayang Windu consists of four main units, which were subdivided by Alzwar et al. (2004) into the older Malabar-Bedil andesite unit, the Kancana lavas unit, the Malabar-Tilu volcanic unit, and the younger Wayang volcanic unit. According to Bogie et al (2008), the geothermal system at Wayang Windu is classified as transitional between vapor and liquid dominated systems.

In this study, we present stable water isotope (^{2}H and ^{18}O) and Sr isotope data to define the recharge area and analyze water-rock interaction affecting the composition of the geothermal waters. Stable water isotopes were employed to define natural recharge area for fluids of the reservoir and groundwater discharging at the surface manifestations. Coplen et al (2000) summarized several factors that affect fractionation of stable water isotopes, i.e. temperature, amount effect, altitude effect, latitude effect, and seasonal variation. Among those factors, altitude and amount effects are the most prominent considering the nature and climate in Indonesia and thus have been applied previously to define the recharge altitudes of reservoir fluids (e.g. Abidin and Wandowo, 1993; Abidin et al, 2005; Riogilang et al, 2012).

Hendrasto (2005) investigated the recharge area of Wayang Windu geothermal field by stable water isotopes. Based on his results he suggested that deep fluids are recharged in elevations between 1317 m and 1606 m above sea level (asl), while the recharge area for hot springs is located in elevations between 1987 m and 2837 m asl. Hendrasto's approach used monthly rainfall data collected during the rainy season from October 2004 to January 2005, which only covered about 50% of annual rainfall, thus might be less representative for the average rainfall composition in the area of Wayang Windu. In the current study, the recharge area was determined based on established rainfall data in Java (e.g. Abidin and Wandowo, 1993; Abidin, 2003 and PATIR – BATAN, 2007-2008) to obtain a better coverage of precipitation of about 80% of the annual rainfall amount (6 to 11 months observation).

In addition to the stable water isotope data, we investigated Sr isotopes to elucidate water-rock interaction in shallow and deep aquifer systems (e.g. McNutt, 2000; Woods et al, 2000; Shand et al, 2009; Graham, 1992; Peiffer et al. 2011; Millot et al. 2012). The application of $^{87}Sr/^{86}Sr$ ratios to deduce sources of solutes in geothermal systems are based on several advantages (1) Sr concentrations are usually sufficiently high in natural waters for isotope analysis with high precision (2) Sr substitutes for Ca, which is a major constituent of rocks, and (3) ^{87}Sr is the decay product of ^{87}Rb, thus the $^{87}Sr/^{86}Sr$ ratio varies in different minerals depending on their Rb content and age. The Sr isotope ratio therefore provides an important tool to identify dissolving mineral phases and unlike the light water isotopes, Sr isotopes are not measurably fractionated during water-rock interaction. These characteristics of the Sr isotope system are beneficial for tracing pathways of Sr in rocks and waters.

2. METHOD

2.1 Sampling

Water samples were collected from hot springs, cold springs and deep wells for stable water isotope and Sr isotope analysis. Samples from production wells were collected using a Weber separator to separate steam and brine for $\delta^{2}H$ and $\delta^{18}O$ analysis (Arnorsson et al, 2006). In addition, cutting samples from the deep wells representing the feed zones were analyzed.

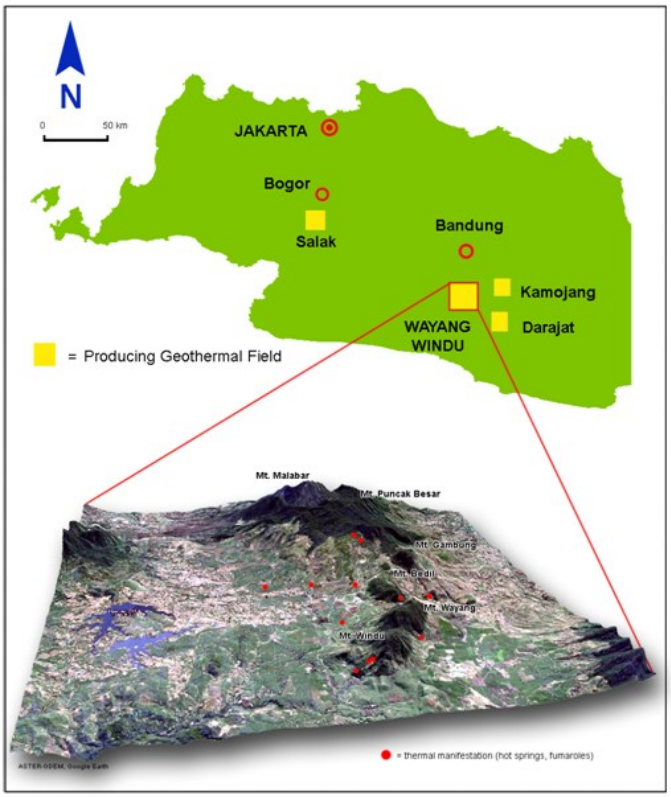

Figure 1: Location of Wayang Windu geothermal field, Indonesia.

2.2. Analysis

Water isotopes were analyzed using a LGR liquid water analyzer at BATAN isotope laboratory Indonesia, standardized against SMOW. The analytical error for $\delta^{18}O$ determination is ± 0.1 ‰, while for $\delta^{2}H$ it is ± 0.9 ‰. Results from separated brine and steam were corrected using the following mass balance formula (Giggenbach, 1991):

$$\delta_o = y.\delta_{SCS} + (1\text{-}y).\delta_{SPW} \quad (1)$$

where δ_o is the original isotope composition, δ_{scs} is the isotope composition in the separated steam fraction, δ_{spw} is the isotope composition in the respective separated brine sample, and y is the steam fraction, calculated using following formula:

$$y = \frac{H_d - H_l}{H_v - H_l} \quad (2)$$

where H_d, H_l and H_v are the enthalpies of total discharge, separated liquid and separated vapor, respectively, at the separation temperature.

Sr isotope ratios ($^{87}Sr/^{86}Sr$) were measured using Thermal Ionization Mass Spectroscopy (TIMS) at the Geoscience Center, University of Göttingen. Water samples were pre-concentrated by evaporation before ion exchange chromatography. Separation of Sr from other cations was carried out using ion-exchange chromatography following the procedure outlined in Wiegand (2009). Purified Sr fractions were loaded onto out-gassed Re filaments using 0.25 N H_3PO_4. $^{87}Sr/^{86}Sr$ ratios were corrected for instrumental fractionation using the natural $^{88}Sr/^{86}Sr$ ratio of 8.375209. Routine standard measurements yielded 0.71039 ± 0.00002 (2σ: n = 30) for the NBS9^{87} Sr standard. Only distilled reagents were used for chemical sample preparation. Blanks were less than 0.5 ng for Sr. The reproducibility of the individual $^{87}Sr/^{86}Sr$ ratio is equal to or less than 0.00002 (2σ)

3. RESULTS

$\delta^{18}O$ values of hot spring samples range between -7.74 ‰ and -4.47 ‰ while for deep fluids $\delta^{18}O$ values vary between -4.64 ‰ and 2.04 ‰ (after correction as outlined in eq. 1 and 2). $\delta^{2}H$ values of the hot springs vary between -51.4 ‰ and -41.2 ‰, while for deep fluids $\delta^{2}H$ values are more enriched and vary between -39.7 ‰ and -33.3 ‰. Generally, the results show a pattern similar to the previous study carried out by Hendrasto (2005). However, stable water isotope compositions are more depleted and scattered for the hot springs in the previous study compared to our study. This difference may be due to the different sampling period during September 2004 in Hendrasto's study, whereas in the present study water samples were collected in June, and therefore may reflect a seasonal effect.

$^{87}Sr/^{86}Sr$ ratios of hot springs vary between 0.70463 and 0.70526, whereas the deep fluids show higher ratios of 0.70469 to 0.70576. Additional cutting samples from the deep wells have $^{87}Sr/^{86}Sr$ ratios between 0.70442 and 0.70524.

4. DISCUSSIONS

4.1 Water isotopes and recharge area

The correlation between $\delta^{18}O$ and $\delta^{2}H$ of Wayang Windu fluids is presented in Fig. 2. The local meteoric water line is given by the following equation (Hendrasto, 2005):

$$\delta^{2}H = 7.91\ \delta^{18}O + 12.98 \quad (3)$$

Stable water isotope data of thermal manifestations and production wells plot in two distinct groups. Most of hot spring samples are located close to the local meteoric line together with local groundwater samples, suggesting that the thermal waters discharging at the hot springs are mostly fed by groundwater of shallow sources. The acid hot spring (Kawah Wayang) has a very enriched isotopic composition likely due to surface evaporation. Fluid samples from the production wells show a trend towards magmatic andesitic waters (Giggenbach, 1992), which suggests that magmatic water is introduced into the deep fluids. The deep fluids trend line intersects the local meteoric water line at a different position ($\delta^{18}O$ = -6.21 ‰, $\delta^{2}H$ = -39.0 ‰) compared to the hot springs ($\delta^{18}O$ = -7.5 ‰, $\delta^{2}H$ = -50.0 ‰), suggesting that both thermal water from manifestations and deep fluids are of meteoric origin but were recharged at different altitudes. Because of the altitude effect, the more enriched isotopic values of the deep fluids point to a lower recharge elevations than for the hot springs.

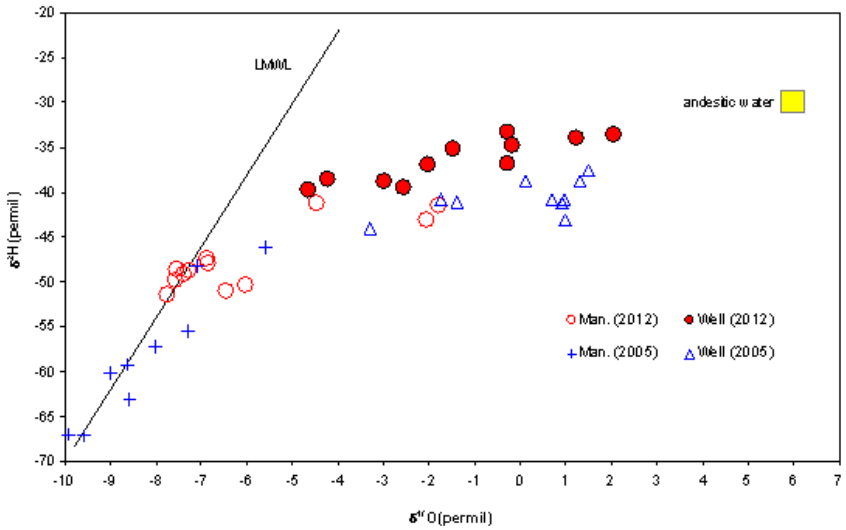

Figure 2. $\delta^{18}O$ vs $\delta^{2}H$ of Wayang Windu fluids (red circles: data this study; blue symbols: data from Hendrasto (2005). Man = thermal manifestetation (hot spring and fumarole).

Hendrasto (2005) estimated a recharge area for deep fluids between 1317 m and 1606 m asl using rainwater isotope compositions from different altitudes. However, the data points were poorly correlated (r^2 = 0.29) thus leading to a higher uncertainty for the predicted recharge area. For the data analyzed in the current study, better correlation (r^2 = 0.76) was obtained. To estimate the recharge area based on the present data, three approaches were made based on the following assumptions:

(1) The altitude effect in Wayang Windu does not significantly differ from other places in Java. A number of isotope hydrology studies carried out by Abidin (2003) and PATIR – BATAN (2006, 2007 and 2008) including several places in Java and Bali showed typical relationships between elevation and isotopic values for the studied areas of 0.20-0.43 ‰ (avg. 0.29 ‰) per 100 m for $\delta^{18}O$ and 1.5 - 2.6 ‰ (avg. 2.12 ‰) per 100 m for $\delta^{2}H$. The average values were used to estimate the elevation difference of the recharge area for the deep fluids and hot springs. Based on the difference of 1.3 ‰ and 12 ‰ for $\delta^{18}O$ and $\delta^{2}H$ of deep fluid and hot spring samples (intersection with the local meteoric water line), respectively, the difference in the recharge elevations for the deep fluids and the hot springs was estimated to 426 – 528 m.

(2) Most of the isotopic data from the hot springs plot close to the local meteoric water line together with local cold springs, suggesting minor contributions of deep fluids. Chemical classifications of the hot springs, i.e. bicarbonate waters (Ganda and Hantono, 1992; Bogie et al, 2008), also suggest a dominant shallow component.

(3) The groundwater recharge elevation must not be lower than the highest hot spring elevation. The highest elevation for the hot springs is at Kawah Burung, i.e. 1985 m, thus local groundwater was recharged at elevations above about 2000 m.

Based on this approach, the altitude of the recharge area for the deep fluids was estimated to 1460-1660 m (figure 3), slightly narrower compared to the previous study by Hendrasto (2005). The northern part of the recharge area for deep fluids is smaller compared to the western or southern area of the geothermal field, therefore suggesting that the northern part of Wayang Windu, which is recently being developed, may have limited natural supply of meteoric water, which might be considered for the exploitation and reinjection program.

4.2. Strontium isotopes

Sr isotope distributions of the cutting samples show greater variation for the older Loka unit (0.7044 to 0.7051) compared to the younger Pangalengan and Waringin units (~0.7052) likely related to variable geochemical composition of the mostly andesitic

rocks in the area (Bogie et al., 2008). $^{87}Sr/^{86}Sr$ ratios of Sunda arc calc-alkaline rocks range from 0.70407 to 0.70579 (Whitford, 1975) and are in good agreement with the Sr isotope results of this study for both cuttings and fluid samples.

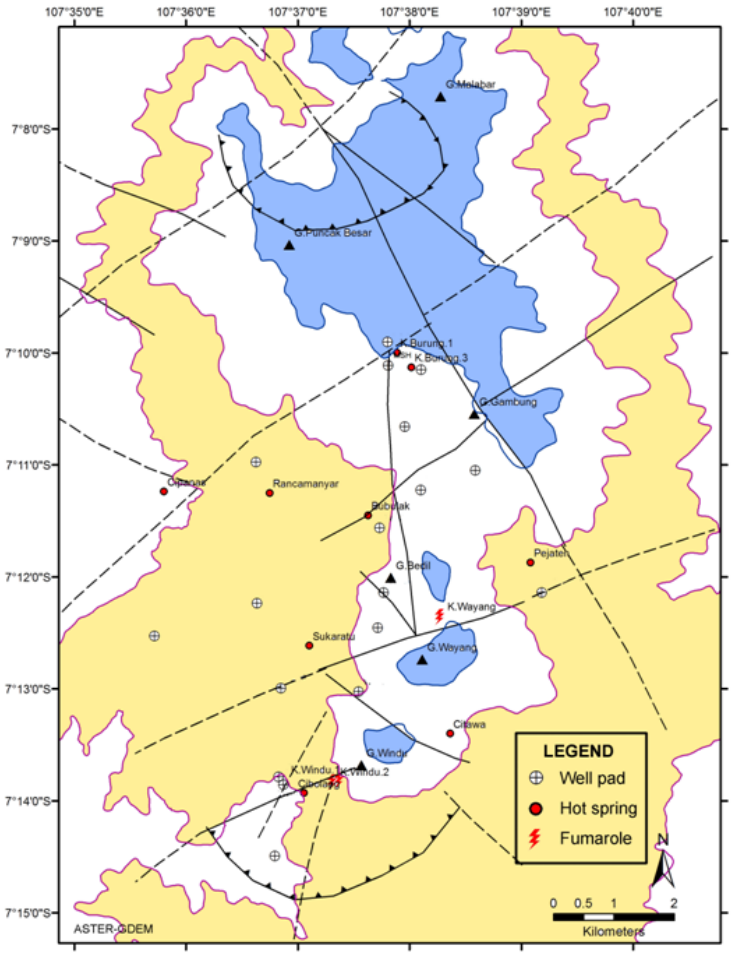

Figure 3. Estimated recharge area for deep fluids (yellow) and hot springs (blue), based on water isotope data. The structural map is based on Alzwar et al. (2004).

$^{87}Sr/^{86}Sr$ ratios of hot and cold springs vary between 0.7046 and 0.7053, while deep fluids show a slightly wider range of $^{87}Sr/^{86}Sr$ ratios from 0.7044 and 0.7058. Based on those results a considerable heterogeneity in the Sr isotopic composition of dissolving minerals in the reservoir rocks and at the surface is suggested. The lithological and mineralogical variation of the andesitic rocks was investigated by Abrenica et al (2010) and Susanto et al. (2011). Apart from primary volcanic minerals like plagioclase and pyroxene, several secondary alteration products were identified, including quartz, chlorite, calcite, zeolites, montmorillonite, wairakite. Sr may be found as a substitute of Ca in Ca-bearing minerals like plagioclase, pyroxenes, calcite, zeolites (wairakite), and montmorillonite. Fig. 4 shows the relationship between $^{87}Sr/^{86}Sr$ ratios and Sr concentrations from fluids and cutting samples analyzed in this study.

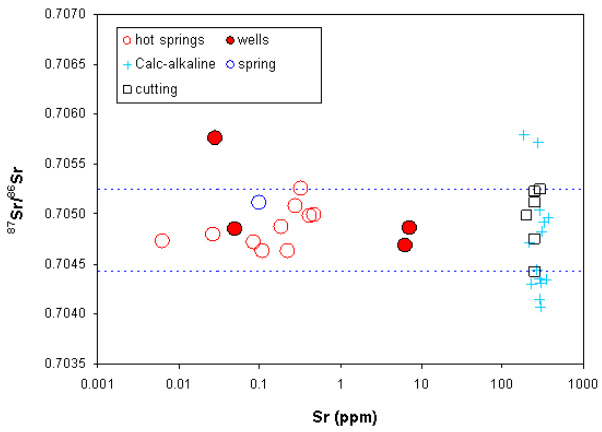

Figure 4. Sr concentration (ppm) vs $^{87}Sr/^{86}Sr$ ratio from Wayang Windu thermal fluids and cuttings. Sunda arc calc-alkaline rocks (Whitford, 1975) are plotted for comparison.

5. CONCLUSION

Based on water isotope composition, thermal fluids in Wayang Windu are of meteoric origin but have two different recharge areas. The deep fluids were recharged from lower altitudes (1460-1660 m) than the fluids of the hot springs (above 1985 m). The approach used in this study can be applied to delineate recharge altitude, provided a good database for isotope data of precipitation exists for the investigation area. $^{87}Sr/^{86}Sr$ ratios of Wayang Windu fluid samples vary between 0.7046 – 0.7058 and are in good agreement with $^{87}Sr/^{86}Sr$ ratios of cutting samples from wells and Sunda arc calc-alkaline volcanic rocks. Mineral dissolution is the main process controlling the $^{87}Sr/^{86}Sr$ ratio in Wayang Windu fluids.

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