

Identification of meteoric water incursion to a high-temperature geothermal reservoir by rare earth elements and isotope oxygen-18 analyses

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1. Introduction

In this study, we use Principal Component Analysis (PCA) to establish a relationship among rare earth elements (REE), $\delta^2\text{H}$, and $\delta^{18}\text{O}$ for clarifying mixing process in the reservoir from previous recharge study by Shoedarto et al. (2020). PCA has been frequently applied to processing geochemical and other types of geoscience data to enhance the interpretability of the components as combinations of multiple variables (Grunsky, 1997; Cheng et al., 2009). Amongst several geochemistry methods, the H^2 and O^{18} are widely known to identify meteoric mixing in the reservoir. On the other hand, REEs have been well studied as geochemical tracers in aqueous environments (e.g., Willis and Johannesson, 2011).

The samples were obtained from seven active geothermal wells in a high-temperature transitional liquid to vapor reservoir, that is located geothermal field in the Southern Bandung, West Java, Indonesia. This power plant has been generating 275 MWe over the past twenty years. Monitoring of the reservoir performance is critical to minimize any undesirable effects in a timely manner.

2. Methods

All of the samples were taken from the transitional zone except for the GA-12 (Fig. 1) which was sampled from the liquid zone. They were analyzed for the REEs using an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS, Agilent 7500cx, Agilent Technologies, U.S in Research Institute for Humanity and Nature, Kyoto) and for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analyses in Kyoto University using water isotope analyzer based on cavity ring-down spectroscopy (L2130-i, Picarro Inc., U.S.). The δ denotes the ratio of the sample to the standard VSMOW.

The variations in Ce, Eu, and total REEs are the result of inherited source rock signatures and water rock interaction (WRI) through the recorded sorption and from their REEs anomalies. To identify the anomalies by considering the geological setting, normalization to known materials such as Post Archean Australian Shale (PAAS; McLennan, 1989) is indispensable.

The REEs, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data compositions were converted into real number space by log-ratio transform. By applying PCA function in the Origin program, the data were reoriented to the greatest axis of variances which becomes the 1st and 2nd principal components (PCs) in a bivariate plot (Fig. 3).

3. Calculation

The isotopic shift ratios for both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ from the surface to the reservoir, δ_i , can be calculated as follow (D'Amore et al., 1993):

$$\delta_i = \delta_l - x_v \times 1,000 \ln a$$

where x_v and a denote vapor fraction and fractionation factor of the isotope at a specific temperature between liquid and vapor, respectively.

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ fractionations between liquid and vapor in the reservoir can be expressed as:

$$\delta^2\text{H}_{\text{res}} = \delta^2\text{H}_{\text{sep}} - x_v \times 1,000 \ln a (\delta^2\text{H}_{\text{sep}})$$

$$\delta^{18}\text{O}_{\text{res}} = \delta^{18}\text{O}_{\text{sep}} - x_v \times 1,000 \ln a (\delta^{18}\text{O}_{\text{sep}})$$

where the subscripts “res” and “sep” denote the reservoir and separator, respectively. In the temperature range from 0 to 374.1 °C, $\ln a$ values for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are approximated by polynomial equations of temperature T (in K, Horita and Wesolowski 1995) as:

$$1,000 \ln a (\delta^2\text{H}) = 1,158.8 (T^3/10^9) - 1,620.1 (T^2/10^6) + 794.84 (T/10^3) - 161.04 + 2.9992 (10^9/T^3);$$

$$1,000 \ln a (\delta^{18}\text{O}) = -7.685 + 6.7123 (10^3/T) - 1.6664 (10^6/T^2) + 0.35041 (10^9/T^3).$$

4. Results and Discussion

The results of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analyses reveal that there are two groups of well fluids in Fig. 1. WY-1, GA-11, and GA-12 wells had undergone water-rock interaction (WRI), with GA-12 at the most advanced stage. The waters of PB-1, GA-3, GA-13, and WY-2 are on the mixing line with PB-1 as the most diluted well as it is located near to the Local Meteoric Water Line (LMWL).

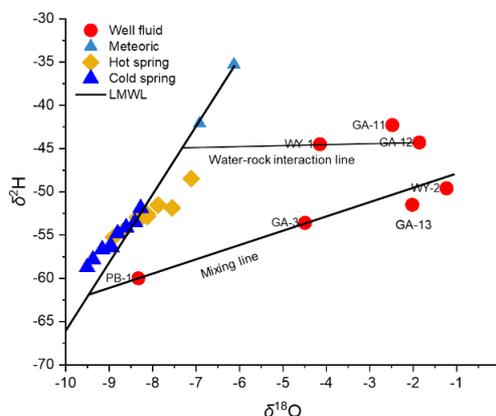


Figure 1. Two groups of water-rock interaction (WRI) and mixing are characterized by the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analyses.

Fluids that had been contacted with oxic environment (recent meteoric recharge) usually show negative Ce anomalies. From the spider diagram in Fig. 2, surprisingly the most diluted PB-1 and GA-3 have no sign of negative Ce anomalies. Normalizing to PAAS gives a clear anomaly of HREE (heavy REE) enrichments relative to LREE (light REE) as well as negative Ce anomalies and positive Eu anomalies for most of the well samples (Fig. 2). Enrichments in HREE are resulted from stable complexes forming with some ligands and stay longer in the solutions. This implies that all the fluid samples had interacted longer with reservoir rocks.

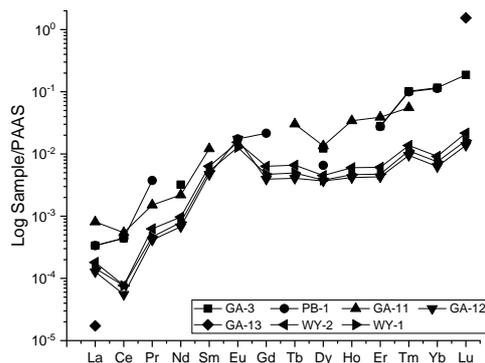


Figure 2. All samples showing HREE enrichments relative to LREE, negative Ce (except for PB-1, GA-2, GA-3, and GA-5 wells) and positive Eu anomalies.

GA-12, GA-3, and PB-1 are well spread out along the PC1 axis in Fig. 3A, meanwhile a factor-loading plot in Fig. 3B shows that the most significant variables for the component 1 are the HREE and wells from the WRI group. Gd, Dy, Er, Tm, Yb, and Lu are better distributed along the PC1 axis. Eu including the rest of the REEs and $\delta^{18}\text{O}$ are spread out along the PC2 axis in Fig. 3B.

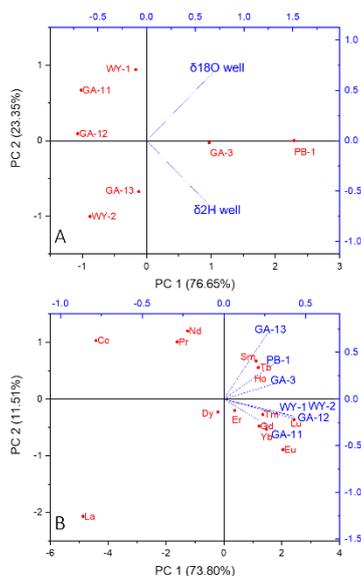


Figure 3. The mixing wells PB-1 and GA-3 are well plotted in the PC1 of the bivariate $\delta^2\text{H}$ and $\delta^{18}\text{O}$ plot (A), meanwhile the WRI wells, GA-13 and WY-2 are located along the PC2. Based on the REEs, the loading plot of the WRI group strongly influences PC1, while the mixing wells have more influences in PC2 (B).

Positive Eu anomalies in the WRI group from Fig. 2 show that reservoir fluids had undergone hydrothermal alteration and removal of Eu from the hot fluids during the precipitation of secondary minerals. This is in agreement with the finding that Eu and Tm account for the most influential elements in the WRI group. From the score plot in Fig. 3B, the mixing group GA-3, GA-13, and PB-1 are positively correlated to only the middle REEs (Sm, Tb, and Ho). Conclusively, the mixing and WRI groups are responsible for clustering their REEs and $\delta^{18}\text{O}$ samples.

5. Conclusion

Even though the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analysis present signs for probable meteoric incursion for the wells in the mixing line, there is still no correlation with the oxic environments from Ce anomalies. It seems that the mixing process in the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ diagram are dominated by non-meteoric water fluids such as condensate fluids. Mixing of meteoric recharge in PB-1 and GA-3 was confirmed with the score plot of PC1 that covered 77% of the variation. For this reason, the linear mixing in Fig. 1 is not supposed to pass through the GA-13 and WY-2 as there are more complex process other than mixing with colder fluid in those wells.

On the other hand, oxic environment from the negative Ce is oppositely correlated with the WRI group. Hence, wells in the WRI group have no contact with recent meteoric water in the great depth. The HREE enrichments from the spider diagram suggest solid hint of hydrothermal alteration and WRI for all the samples. The WRI process in the reservoir that is reflected the WRI group have positive correlation with not only Eu, but also Gd, Dy, Er, Tm, Yb, and Lu. Those HREE could be significant for WRI in the next research. The approach using PCA for reservoir monitoring to ascertain whether colder water incursion could be predicted from the classification groups was explored.

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