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Oxygen Isotope and Ranking Faults Analyses to Delineate Water-rock Interaction Processes in a High-Temperature Geothermal System

Riostantieka Mayandari*, Yohei Tada*, Koki Kashiwaya*, Katsuaki Koike*, Irwan Iskandar**, M.N. Heriawan**, S. Notosiswoyo** and Dwiyoga Malik***

*Graduate School of Engineering, Kyoto University, Katsura C1-2-215, Kyoto 615-8540, Japan.
E-mail: shoedarto.mayandari.56r@st.kyoto-u.ac.jp
**Faculty of Mining and Petroleum Engineering, Institute Technology of Bandung, Bandung, Indonesia
*** Star Energy Geothermal (Wayang Windu) Ltd., Wisma Barito Star Energy Tower, Jakarta, Indonesia

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1. Introduction

According to Lumb (1981), one of the main objectives of geothermal explorations is to locate productive zones or upflow zones to ascertain an existence of useful geothermal production field. Wayang Windu geothermal field is a recognized high-temperature field in Indonesia and characterized by a transitional liquid to vapor system that has installed the capacity of 135 MWe.

The purpose of this study is to clarify the possible correlated signatures between productive zones and oxygen isotopes of the reservoir fluid in the northern part of the area, due to its numerous high-ranked faults compared to the southern part.

2. Methods

According to previously study from Star Energy, the most productive zones were specified based on the appearances of the best-fitted faults from the integration of surface and subsurface structures (Star Energy, 2015). An integrated study of geological structures has been conducted by Star Energy Geothermal (Wayang Windu) Ltd. for almost 15 years. Star Energy used image data analyses such as surface lineaments from satellite images and aerial photos. These lineaments were then verified by the field data on thermal manifestations, surface structure evidences, and stream conductivities. Before they arranged a surface structure identification, they suggested structure rankings from their analyses on structure identifications. In addition, some production data such as feed zones, steam-kick spots, loss zones, and open fractures were selected to verify the subsurface structure identification. Finally, Star Energy confidentially proposed the best fitted of the fault ranking based on the integrated data from major surface and subsurface structures. They were generated from series of cross-sections to identify the presence and location of faults. Several faults were then identified as the best ranked faults such as Haneut, Kijang, Cibitung, Cibitung 1, and Gambung Selatan Faults. The second best-ranked faults was also recognized as well as the third and fourth best-ranked faults. These results will be integrated with geochemistry interpretations.

Additionally, methods used in this study include field work, water and isotope sampling, laboratory analyses, and their interpretations. There are two-types data as:

A. Primary data including water geochemistry and isotopes sampling from 7 hot springs, 3 fumaroles, and 16 well heads.
B. Secondary data consist of Wayang Windu geothermal field map from Bogie et al. (2003).

Chemical properties were analyzed to obtain isotopes of $\delta^{18}O$ and $\delta^{2}H$ ratios by a Picarro instrument. All these surface data were used to calculate the values of isotopes in the reservoir isotopes fractionation calculation (Eq. 2 and Eq. 3) from Truesdell (1977) op cit. Nuti (1992).

3. Calculation

Such subsurface processes like boiling, mixing, steam heating, surface evaporation, conduction, and water-rock interaction can change the isotopic content of the geothermal waters to somewhat lower or higher than that of the local precipitation because the oxygen contents are exchanged between host rocks (Nicholson, 1993). Calculation of stable isotope values in the reservoir is obtained by heat and mass balance approach:

$$Hl,res = Hl,t\ (1\text{-}y) + Hv,t\ (y) \quad (1)$$

$$\delta l,res = \delta l,t\ (1\text{-}y) + \delta v,t\ (y) \quad (2)$$

Hl,res refers to liquid entalphy in the reservoir; Hl,t denotes liquid entalphy in the given temperature; Hv,t denotes vapor entalphy in the given temperature; δl,res denotes liquid isotopes ratio in the reservoir; δl,t denotes liquid isotopes ratio in the given temperature; δv,t denotes vapor isotopes ratio in the given temperature; y is vapor fraction; and (1-y) or x is liquid fraction.

Equation 2 can be reformed to δl,t = δl,res + (y) 1.000 ln α, by changing the value factor isotopic fractionation δl-δv to ≈ 1.000 ln α where 1.000 ln α is a function of temperature. This function was derived from Horita and Wesolowski equation (1995) in 0°C to the critical temperature 374°C (T in K):

$$1.000 \ln l - v(O) = -7{,}685 + 6{,}7123\left(\frac{10^3}{\mathrm{T}}\right) - 1{,}6664\left(\frac{10^6}{T^2}\right) + 0{,}35041\left(\frac{10^9}{T^3}\right) \quad (3)$$

$$1.000 \ln l - v(\mathrm{H}) = 1.158{,}8\left(\frac{T^3}{10^9}\right) - 1.620{,}1\left(\frac{T^2}{10^6}\right) + 794.84\left(\frac{T}{10^3}\right) - 161.04 + 2{,}9992\left(\frac{10^9}{T^3}\right) \quad (4)$$

Those equations mean when the parent fluid moves towards a shallower depth, the temperature will be decreased and the $\delta^{18}O$ fractionation factor will be increased slightly. Changes in fractionation factors will substitute δ¹⁸O values in boiling production wells into lighter δ¹⁸O values.

Stable isotope compositions of surface manifestations are ranged from -8.76‰ to -5.93‰ for $\delta^{18}O/^{16}O$, and are -58.81‰ to -47.29‰ for $\delta^{2}H/^{1}H$. Meanwhile stable isotope compositions in each wells are ranged from +0.4‰ to -4.57‰ for $\delta^{18}O/^{16}O$ and -34.55‰ to -44.75‰ for $\delta^{2}H/^{1}H$. By using deep well liquid data from Bogie et al. (2003), where T is 300°C, the values of $\delta^{18}O/^{16}O$ parent fluid is calculated as 1.97‰ and -0.87‰ for $\delta^{2}H/^{1}H$.

4. Results and Discussion

As host rocks have relatively heavy isotopic ratios, it causes the oxygen shifting of the well fluids as we can see from the values of Wayang fumarole and production wells in Figure 1. These exchange processes are greatly accelerated in high temperature zones, where less oxygen shift is anticipated in low to intermediate temperature zones. Parent fluid of deep liquid reservoir was generated from meteoric water which was heated by steam from boiling processes in the depth (yellow line). Meanwhile fluids from production wells were initiated from meteoric water, which had undergone water and rocks interactions (green line), and were also resulted from the condensation from deep seated parent fluid steam (purple line).

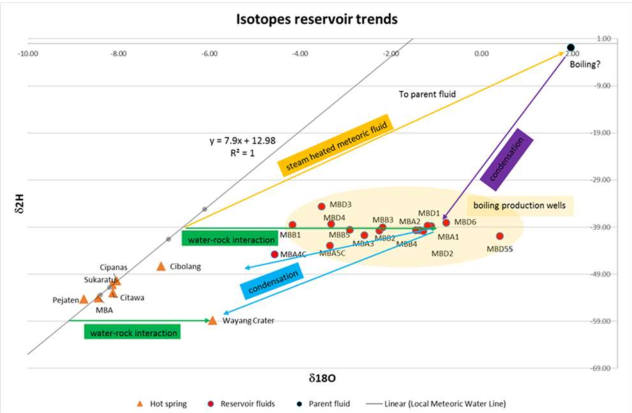

Figure 1. Meteoric water is the source of surface manifestations and the reservoir, meanwhile Wayang fumarole gained the steam from condensation process of boiled production fluids.

Figure 2 introduces the 1st ranked faults in red lines, and 2nd ranked faults in yellow lines. Meteoric water is presumably seeped through the 1st ranked faults such as Haneut Fault which is responsible for water-rock interaction processes in MBD5 and Wayang fumarole as well as Kijang Fault for MBA2, MBA3, also MBD1; and Cibitung 1 Fault for MBD4 (Figure 2). Meanwhile, the water-rocks interaction processes of MBB3 and MBB5 are under control of the intersections of 2nd ranked in the northern part. Wayang fumarole sits in Haneut Fault which possibly develops its steam that connected with MBD5 and MBB5, since they are located in the same fault.

5. Conclusion

Wayang Windu reservoir fluids were derived from its local meteoric water. Predominant subsurface processes based on isotopic analyses are water-rocks interaction, condensation, meanwhile boiling process need to be supported by other analyses. The best-fitted faults based on integrated data from major surface and subsurface structures from Star Energy are correlated to the results of stable isotope compositions in the reservoir. Subsurface processes from isotope composition especially water-rock interaction process could be a supportive signature of the quality of the faults, whether they are surficial or subterraneously connected.

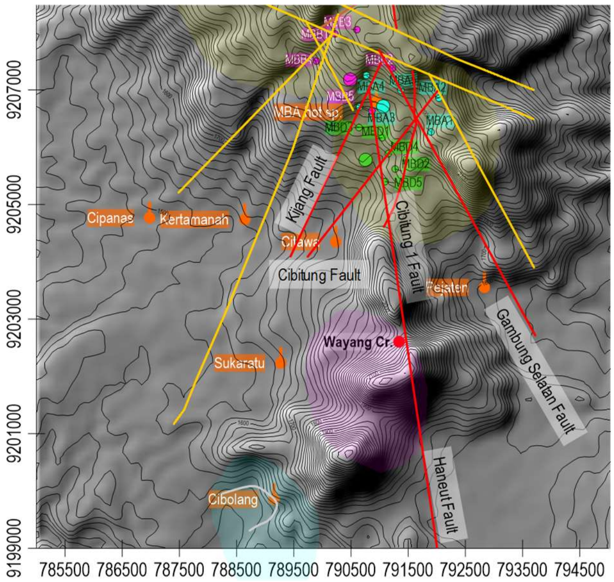

Figure 2. Those first-ranked faults (red-colored lines) are confirmed with oxygen isotope analyses.

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