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Characteristics of Hydrothermal Alteration in Part of the Northern Vapor-Dominated Reservoir of the Wayang Windu Geothermal Field, West Java

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ABSTRACT

The Wayang Windu geothermal field is transitional between liquid-dominated and vapor-dominated conditions. A petrologic study of 522 core and cutting samples from four wells was undertaken. Three of the wells intersect the northern vapor-dominated reservoir at Wayang Windu. The fourth does not and has been used to make a comparison. The aim of the study is to characterize the alteration of the vapor-dominated reservoir in order to see if this yields useful information regarding its formation and how it may be best utilized. The samples were subjected to petrography, X-ray diffraction and fluid inclusion analyses. The results of this study show that the hydrothermal alteration above and within part of the northern vapor-dominated zone of Wayang Windu can be grouped into four main zones consisting of: (1) smectite zone (occurring at the surface down to ~700m depth); (2) transition zone (present at depths between 700m – 900m); (3) illite zone (~900m to ~1390m); and (4) amphibole zone (>1390m depths), although this zone may be restricted to the vicinity of a dyke. There are also zones of advanced argillic alteration. The presence of amphibole, epidote and wairakite, along with high temperature advanced argillic alteration, within a lower temperature vapor-dominated zone reflects earlier alteration episodes formed when this part of the system was more magmatically-related and water-dominated. Alteration associated with the current vapor-dominated conditions in the reservoir could not be clearly identified. However, there is overprinting above the reservoir where a condensate zone has formed.

1. INTRODUCTION

A number of geothermal fields in Indonesia have been recently noted to be partially vapor-dominated, or at least to be evolving towards a vapor-dominated system. These include the Karaha-Telaga Bodas (Allis and Moore, 2000), Patuha (Layman and Soemarinda, 2003), and Wayang Windu fields (Bogie et al., 2008) which are all situated in West Java (Figure 1). It is also worth noting that these currently "evolving" geothermal fields are not far from the Kamojang and Darajat vapor-dominated fields.

The area considered in this study is part of the Wayang Windu geothermal field located some 40 km south of Bandung, West Java. The geothermal system is associated with an extinct stratovolcano in the north called Gunung (G.) Malabar and the G. Wayang and G. Windu volcanoes further south (Figure 2).

The rocks typically found in the field include andesitic lava flows, flow breccias, lahars, and a variety of pyroclastic rocks ranging from tuffaceous breccias to massive lapilli and crystal tuff. Heat is considered to be provided by an intrusive complex at depth that is mainly identified from gravity surveys (Kusumah et al., in prep), although only a minor amount of intrusives in the form of dykes have been found in the wells..

The surface thermal manifestations in Wayang Windu include fumaroles, hot springs and altered ground, which are mainly located along mapped structures on the surface. The hot springs are generally neutral bicarbonate in chemistry with variable amounts of sulfate (5-65%) and have temperatures ranging from ambient to 66°C. Fumaroles have temperatures of 93°C, the local boiling point. Acid-sulfate pools are associated with the fumaroles.

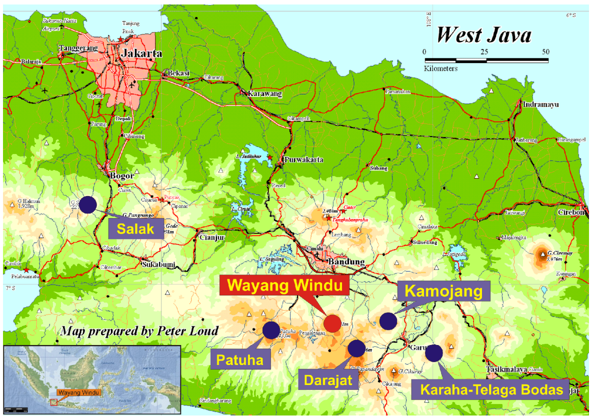

Figure 1: Location of geothermal fields in West Java, Indonesia

Chemical analyses of the brine from the field's deep liquid-dominated reservoir and gas discharges of the wells reveal that the system is composed of three regions with distinct chloride and NCG contents. The region southwest of G. Windu is characterized by Cl concentrations of 6,000-8,000 ppm and NCG contents of 10 wt%. The sector near G. Wayang is characterized by higher Cl (12,000-13,000 ppm), but lower NCG contents (0.5-4.5%). The sector close to G. Gambung has similar Cl contents to the Wayang region, but the NCG are slightly lower (0.36-2.6%) (Bogie et al., 2008). A fourth region further to the northwest associated with G. Puncak Besar indicated by MT and gravity surveys has been successfully drilled in the vapor-dominated zone, and is also low in gas, but since the well did not reach the deep liquid reservoir salinity data is not available.

Initial production drilling in the southern part of the field focused upon the deep liquid-dominated reservoir. However, more productive wells were drilled further north, where a widespread, shallow, pre-exploitation, vapor-dominated reservoir is present. The last round of drilling that provided the majority of samples for this study concentrated on targeting this vapor-dominated zone.

This paper presents the characteristics of hydrothermal alteration in the part of Wayang Windu beneath the southern slopes of G. Malabar and describes part of the system's northern vapor-dominated reservoir in terms of its mineralogy, temperature, and fluid composition.

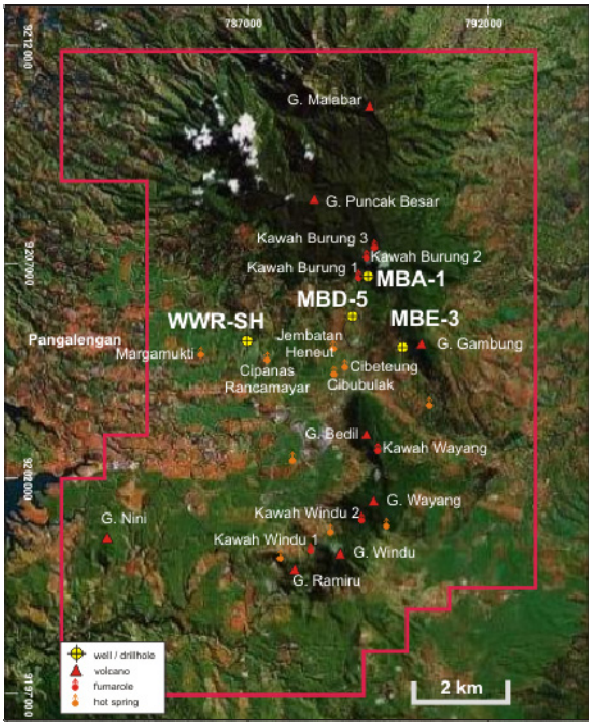

Figure 2: Landsat image of the Wayang Windu geothermal field. The wells studied are WWR-SH, MBD-5, MBA-1 and MBE-3

2. SAMPLING AND METHODS

Samples at 3 m intervals were examined from four wells. WWR-SH is a slim hole drilled in 1997 during the first round of drilling. It lies outside of the vapor-dominated reservoir and was extensively cored. It thus serves as a good comparison well to the other three wells (MBA-1, MBD-5 and MBE-3), which were drilled as large diameter production wells during the 2006 to 2007 drilling campaign. A total of 522 core and cutting samples were examined. These were prepared for thin section microscopy, X-ray diffraction and fluid inclusion analyses.

3. RESULTS

3.1 Subsurface Geology

Megascopic and petrographic examinations of the cores and cuttings indicate that the rocks at depth mainly comprise of repetitive sequences of lava/coarse pyroclastics and tuffs of basaltic andesite to andesite compositions, except for MBA-1, which intersected a microdiorite porphyry dyke at the bottom at around 1390 m TVD (true vertical depth). The dyke is characterized by a porphyritic texture with traces of plagioclase, hornblende and minor pyroxene 1 to 3 mm long as phenocrysts. The subsurface rocks and the nature of their deposition based on borehole images of the four wells examined imply that they have come from at least two distinct eruptive centers. The south-dipping lavas and tuffs in the upper portions of the wells have come from the G. Malabar volcanic center in the north, while the northwest-dipping lavas and tuffs at the lower portions of the wells may have come from a buried volcanic center to the southeast.

3.2 Subsurface Hydrothermal Alteration

The alteration minerals in the northern Wayang Windu can be classified into two suites based on the chemistry of the altering fluids: neutral pH and acid. The neutral-pH fluid alteration suite is grouped into zones based on the occurrence and distribution of alteration minerals with depth. The zones defined include: smectite zone, transition zone, illite zone and amphibole zone. Similarly, the occurrences of acid fluid alteration minerals with depth are classified into: cristobalite zone, kaolinite±alunite zone, kaolinite + calcite + cristobalite/quartz + pyrite zone and a pyrophyllite+diaspore+anhydrite zone. The distribution of these alteration zones in the subsurface is illustrated in Figure 3.

The neutral-pH fluid alteration assemblage generally dominates the entire well sections. The cristobalite and kaolinite±alunite and kaolinite + calcite + cristobalite/quartz + pyrite zones are found above the vapor-dominated reservoir and the pyrophyllite+diaspore+anhydrite zone is found in MBA-1 within and just above the vapor-dominated reservoir. The advanced argillic alteration occurs as an overprint. In wells MBA-1, MBD-5 and MBE-3, kaolinite + silica +anhydrite +alunite + natro-alunite + pyrite occur with smectite + calcite at depths between 50 to 650 m TVD. In MBA-1, on the other hand, pyrophyllite, anhydrite and diaspore are present at depths from around 700 to 1250 m TVD and occur with illite, quartz, chlorite(-smectite), epidote, wairakite, calcite, pyrite, amphibole and cordierite.

The mineral assemblage zones that characterize the subsurface of northern Wayang Windu can be classified as argillic, propylitic or advanced argillic type of alteration. In general, argillic alteration consisting predominantly of smectite and minor illite-smectite is widespread in the caprock at depths <800 m TVD of the four wells examined (Figure 3).

Within the vapor-dominated reservoir, propylitic alteration is largely present. The minerals that occur within the reservoir include abundant chlorite (-smectite), illite, quartz, epidote, wairakite and occasional pyrite, calcite and albite. The reservoir section in MBA-1 and MBE-3 is characterized by abundant illite, whereas the reservoir in MBD-5 is dominated by illite-smectite (Figure 3).

The presence of epidote and wairakite within the vapor-dominated zone indicates that the altering fluid was liquid (Browne, 2007, written comm.) and these minerals are generally uncharacteristic of steam-dominated reservoir conditions. Petrographic examination reveals that the epidote and wairakite in the steam zone are unaltered. Based on the occurrence and nature of these minerals in the reservoir, it is clear that the secondary minerals present at depth are not in equilibrium with the current conditions. This point is reinforced by the fact that WWR-SH, which was drilled outside of the vapor-dominated zone and the other wells, which were drilled into the vapor dominated zone, have very similar alteration assemblages. These evidences point to the fact that the vapor zone in the northern Wayang Windu was liquid-dominated at initial state.

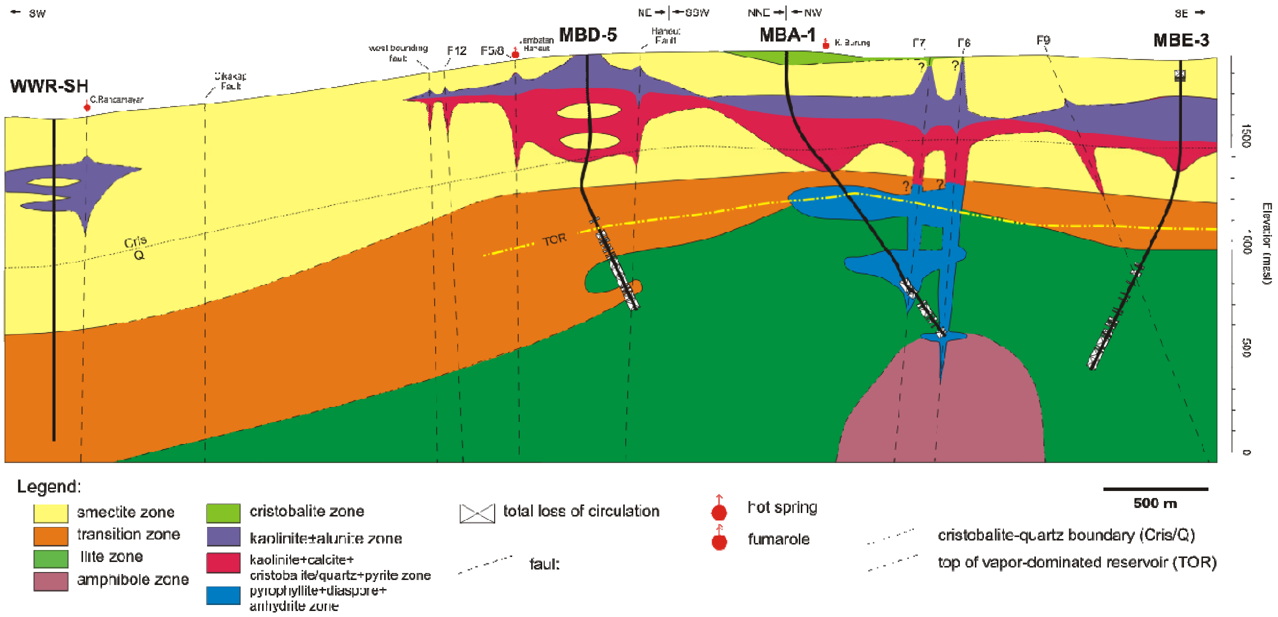

Figure 3: Subsurface distribution of alteration zones on the southern flank of Gunung Malabar, Wayang Windu. The dash-dot lines indicate the inferred extent of the alteration zones

There are however very distinct changes above the vapor-dominated reservoir with widespread overprinting of the original smectite zone by the cristobalite zone, kaolinite±alunite zone and kaolinite + calcite + cristobalite/quartz + pyrite zone. This overprint is found in all four wells, but is most strongly developed in those which intersected the vapor-dominated reservoir. As discussed below, this overprint can be interpreted to be indicative of boiling beneath it. However, given the lower elevation of the top of the overprint in WWR-SH in comparison to the other wells there may be (or have been) an outflowing perched acid aquifer running from above the vapor-dominated zone out towards WWR-SH. Bogie et al. (2008) have previously recognized this overprint and noted that it has reduced the conductivity of the clay cap of the system as indicated by the MT survey.

The existence of wairakite strongly suggests boiling at depth and has also been found in the Karaha-Telaga Bodas vapor-dominated zone (Allis and Moore, 2000). Boiling is also indicated by the presence of vapor-rich fluid inclusions hosted in quartz, calcite, epidote and wairakite vein minerals.

3.3 Fluid Inclusion Work

Due to a limited number of good samples for fluid inclusion analysis, only crystals from MBD-5 and MBA-1 were examined. The samples that provided measurable inclusions are hosted in quartz, calcite and wairakite and are generally filled by a mixture of liquid and vapor of varying proportions. In all of the samples, vapor-rich fluid inclusions were observed.

Homogenization temperatures of primary fluid inclusions in quartz and calcite from MBD-5 suggest that the fluid was trapped at temperatures between 240°C and 280°C. As the inclusions are likely to have been trapping a two-phase fluid the lower temperatures may be more reflective of trapping temperatures.

Ice melting temperature measurements of fluid inclusions in MBD-5 reveals that the hydrothermal fluid had salinities ranging from 0.53 to 1.05 wt% NaCl whereas the fluid inclusions in MBA-1 had salinities of 0.87 – 4.91 wt% NaCl. In comparison, the salinity of the current deep liquid reservoir in this area is 3.3 wt% NaCl. Once gas contents are taken into account the current deep reservoir has higher salinities than those that originally prevailed within the vapor-dominated zone prior to its boil off, as would be expected.

4.2 Subsurface Permeability

The alteration minerals in the vapor-dominated reservoir do not reflect current conditions so they can not be expected to reflect current permeability, particularly since alteration mineralogy associated with vapor-dominated conditions can not be clearly identified.

4.3 Subsurface Temperature

Similarly to permeability, the identified alteration minerals within the vapor-dominated reservoir can not indicate current temperatures, but since there are measured temperatures available, the mineralogy deduced temperatures can be used to establish any changes with time. The following temperature ranges were used for the temperature stability of the minerals: smectite + cristobalite (<100°C); smectite + quartz (100° - 180°C); illite-smectite mixed layer (180° - 220° C); illite (>240° C); kaolinite (< 260°C); pyrophyllite (> 260°C); diaspore (> 280°C); and amphibole (>280°C), (Reyes, 1990; Kingston Morrison Ltd., 1997).

Figure 4 shows that the measured temperature profiles in MBD-5, MBA-1 and WWR-SH. It should be noted that the temperatures in the interval between 1100 and 1600 m asl in MBD-5 do not reflect reservoir conditions due to steam reflux in the casing. It is likely that the temperatures in this interval in MBD-5 are similar to the other wells off the MBD pad, which are similar to that in MBA-1. If this is the case there has been little change in temperature with formation of the vapor-dominated zone and the lower fluid inclusion homogenization temperature is closest to the trapping temperature.

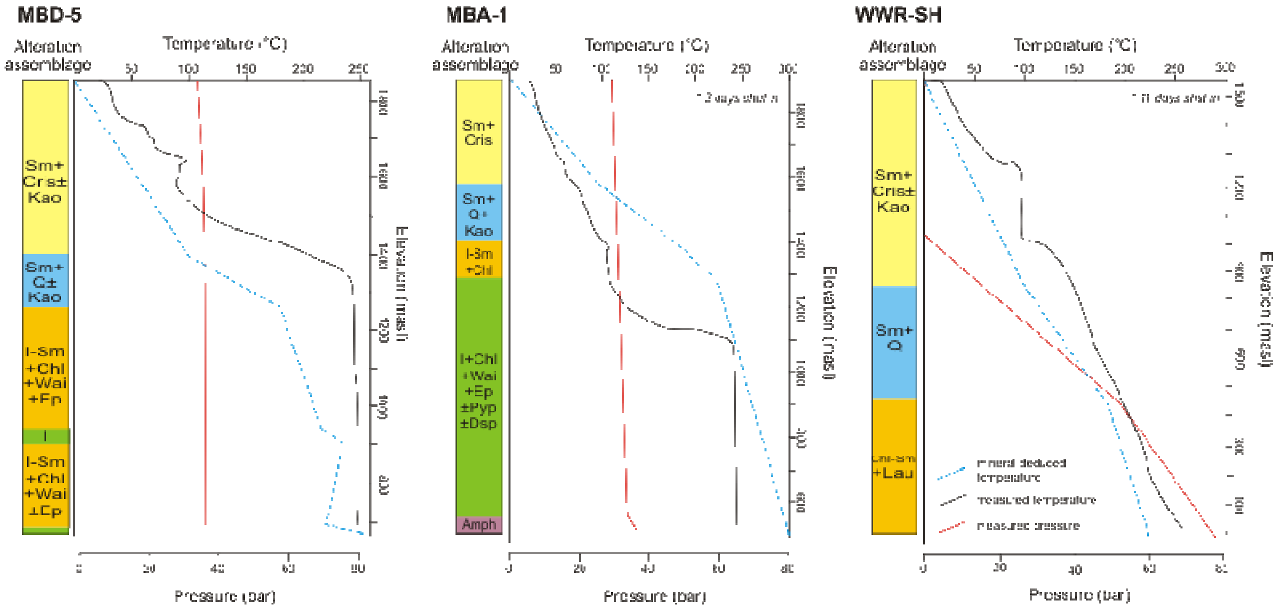

Figure 4: Comparison of downhole and mineral-deduced temperatures. Pressure-temperature measurements are obtained from downhole measurements made by Star Energy Geothermal (Wayang Windu) Ltd. *Note that the MBD-5 temperatures between 1100 and 1600 masl are not representative of the reservoir temperatures because of steam reflux in the casing. The reservoir temperatures in MBD-5 are more likely to be similar to those in MBA-1.*

The measured temperatures in MBA-1 are now cooler than those indicated by the mineralogy. This is consistent with an early, more magmatic-related stage of the system's development associated with the presence of intrusive rocks and a high temperature advanced argillic alteration assemblage.

WWR-SH shows a near conductive measured temperature profile, with the formation of some steam just above its water level, which since the water level is being defined by the piezometric surface rather than being the actual top of the reservoir does not reflect reservoir temperatures. The reservoir temperature profile is therefore nearly parallel to, but hotter than, the temperature profile deduced from the mineralogy. The area around WWR-SH thus appears to be conductively heating, and thus possibly indicating a high overall conductive heat flow in the general area.

4.4 Hydrothermal Fluid Composition

Four types of hydrothermal fluids are indicated to have been present to account for the various mineral assemblages. The most common one is a saline neutral-pH fluid. The others involve acidic hydrothermal fluids, two of which occur where there are low temperatures and have a low temperature alteration assemblage and hence are recent or current. The other contains minerals indicative of much higher temperatures than currently prevailing and are relict. A point reflected in the chemistry of the wells in which there are no indications of highly acid fluids in the vapor-dominated reservoir.

The presence of acid minerals in the subsurface indicates several processes occurring at depth. For example, the assemblage kaolinite + alunite + natro-alunite + opal/tridymite/cristobalite/quartz + anhydrite + pyrite that is found at depths of ~50m – 300 m TVD in MBD-5 and WWR-SH and at ~200 m – 500 m in MBE-3 and MBA-1 is likely to have been produced by steam-heated acid-sulfate waters formed where steam condenses into oxygenated ground waters. The sulfate is derived from the oxidation of H_2S in the vadose zone. The formation of steam-heated acid sulfate waters relates to boiling of chloride fluids at depth (Nicholson, 1993).

The assemblage kaolinite + calcite + cristobalite/quartz + pyrite is likewise formed by acid steam condensate but unlike the acid-sulfate solutions that formed the previous assemblage, these minerals are produced by carbonic acid waters formed by steam and gas condensation into poorly-oxygenated subsurface groundwaters (Nicholson, 1993).

Deeper occurrences of pyrophyllite and diaspore MBA-1 are likely to have been produced by condensed magmatic volatiles early in the system's evolution. An equivalent stage of evolution may be found at Patuha or Karaha-Telaga Bodas, where the current presence of acidic magmatic volatiles is reported (Allis and Moore, 2000; Layman and Soemarinda, 2003)

CONCLUSIONS

To sum up, the upper parts of the present geothermal system beneath the southern slopes of Gunung Malabar is characterized by the following:

- The volcanic rocks in the subsurface come from at least 2 eruptive centers (i.e. from the north and southeast). The reservoir rocks comprise mostly of tuffaceous rocks which originated from the southeast volcanic edifice.
- Prograde occurrence of clays and acid fluid produced minerals with depth are observed in the 4 wells.
    - Clays are present in the following order: smectite, illite-smectite mixed-layer, illite
    - Acid minerals occur in the following order: kaolinite±alunite,anhydrite, kaolinite + calcite + cristobalite/quartz + pyrite, diaspore + pyrophyllite, pyrophyllite
- In general, the rocks of the steam zone in MBE-3 are composed mainly of illite, while those of MBD-5 are made up of illite-smectite mixed-layer. MBA-1, on the other hand, has rocks composed mostly of illite with sporadic distributions of pyrophyllite, diaspore and anhydrite.

- The characteristics of some subsurface alteration minerals (e.g. wairakite, epidote) within the vapor-dominated reservoir indicate disequilibrium with the present conditions.
- Past temperature of up to 300°C in places, dropped to pre-exploitation temperatures of ~250°C.
- Severe boiling which may have resulted from continuous steam extraction have caused the formation of an extensive steam zone.
- Deep advanced argillic alteration is relict, however shallow advanced argillic alteration above the reservoir formed in response to the boil off and is ongoing.

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Mineral Abbreviations:

Amph	Amphibole	I-Sm	Illite-smectite
Chl	Chlorite	Ka	Kaolinite
Chl-Sm	Chlorite-smectite	Lau	Laumontite
Cris	Cristobalite	Sm	Smectite
Dsp	Diaspore	Pyp	Pyrophyllite
Ep	Epidote	Q	Quartz
I	Illite	Wai	Wairakite