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THE RESERVOIR OF THE RENDINGAN-ULUBELU-WAYPANAS GEOTHERMAL SYSTEM

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ABSTRACTS

The Rendingan-Ulubelu-Waypanas (RUW) geothermal system, is dominated by products of Quaternary and Tertiary volcanism (the Tanggamus volcanism) consisting mainly of andesitic lavas and pyroclastics. Thermal manifestations occur over a distance of more than 15 km within the Ulubelu graben and southwest of Mt. Waypanas.

Six exploration wells encountered temperatures from 50 to 220 ^oC and penetrated rocks that mostly also occur at the surface. Microearthquake epicenters were determined using a random analysis method as velocity structures are not known. Gravity data were interpreted using 'iterative forward modeling' and deconvolution methods and gave consistent results. Ground magnetic data revealed the effects of deeper bodies. The Mt. Rendingan pyroclastics and andesite lavas, Mt. Kukusan basaltic andesite lavas and Mt. Kabawok pyroclastics are normally magnetised.

The magnetic interpretation, together with results from the mapping of surface manifestations, microearthquake study and previous Schlumberger resistivity surveys, show that the RUW geothermal system is a single unit, covering an area of about 150 km^2. Measured well temperatures and pressures, hydrothermal mineralogy, and the thermal characteristics of fluids trapped in inclusions indicate that in the central part of the system, perched meteoric water and steam condensate occurs above 250 m depth (450 m a.s.l.). Between about 250 m and 550 m depth (450 m and 150 m a.s.l.) the reservoir contains vapor with two phases occurring from about 600 m to 800 m depth (100 m a.s.l. to 100 m b.s.l.). Alkali chloride water with a near neutral pH and a low concentration of dissolved carbon dioxide occurs below 800 m depth (100 m b.s.l.). A pronounced temperature reversal in well UBL1 indicates an inflow of cooler water at about 700 m depth; this is probably meteoric water descending a fault zone. Convection occurs below 800 m depth, consistent with the presence here of high permeability indicating minerals (i.e. adularia and albite). The dimensions of the RUW geothermal system have changed spatially and temporally during its life, but the sequence, chronology and directions of the changes are incompletely known.

INTRODUCTION

The Rendingan-Ulubelu-Waypanas (RUW) geothermal system is near circular in shape, as revealed by its magnetic signature, and extends over a distance of 15 km at the southern end of the Sumatra Fault Zone in Tanggamus, Lampung. Formerly this system was known as Ulubelu. However, Pertamina[1] suggested it should be separated into the two parts, the northern (Rendingan) and southern (Ulubelu) areas. With extension of the survey area to include its Waypanas manifestations, this combined study area is now called the Rendingan-Ulubelu-Waypanas (RUW) geothermal system.

The study of this area used geological, geophysical and paleohydrological methods to obtain a four dimensional picture of the reservoir. Geological assessment consisted of surface studies, including field surveys of hydrothermal manifestations and rock sampling; cores and cuttings were examined in hand specimen and petrographically, boreholes drilled, downhole temperatures and pressures measured and interpreted. Geophysical work consisted of micro-earthquake, gravity and magnetic data that have been analyzed to interpret the RUW reservoir. The microearthquake analysis contributed information that helped characterize the hydrothermal system. The gravity data helped reveal the distribution and dimensions of host rocks within the geothermal system and nearby, and the magnetic studies the extent of the geothermal system with respect to its rock alteration intensity. Interpretation of paleohydrology is based upon drillhole measurements, the hydrothermal minerals and the thermal characteristics of fluids trapped in inclusions that record former conditions in the reservoir.

METHODOLOGY

Glimpses of the RUW reservoir can be recognised from its surface expression. The geothermal system is situated within areas of high relief, around 1600 to 400 m, but moderately steep terrain occurs in its central part, mostly from 700 m to 800 m. The lowest places are south and southwest of (the RUW) hydrothermal manifestations, at about 400 m (Figure 1).

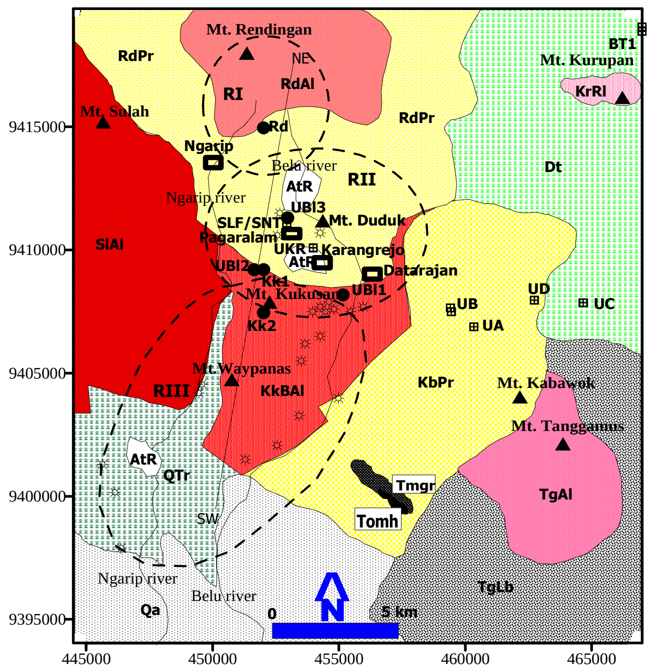

Figure 1. Extent of the Reservoir boundaries model of the Rendingan-Ulubelu-Waypanas (RUW) geothermal system approximated from surface manifestations, microearthquake data, gravity and magnetic anomalies, and resistivity studies. Full line ellipse is Ulubelu caldera marked by F1 and F5. Dashed line ellipses are geothermal prospects (RI, Rendingan; RII, Ulubelu; RIII, Waypanas). Qa: Alluvium, AtR: Altered rocks, TgAl: Tanggamus andesite lavas, KrRl: Kurupan rhyolite lavas, Dt: Dacite tuff, RdAl: Rendingan andesite lavas, RdPr: Rendingan pyroclastics, TgLb: Tanggamus laharic breccia, KbPr: Kabawok pyroclastics, DdDl: Duduk Dacite lavas, KkBAl: Kukusan basaltic andesite lavas, SlAl: Sulah andesite lavas, QTr: Pumiceous tuff (Ranau Formation), Tmgr: Granodiorite, Tomh: Hulusimpang Formation. Filled circles (Kk1): bore holes; stars: hot springs or fumaroles; triangles: summits of mountains; squares: petrographic samples. Boxes are villages. White crosses are locations of the seismic stations that recorded the analog data of microearthquake events. Black crosses are the locations of seismic stations that recorded digital data. Full and dashed lines are confirmed and inferred faults, respectively. Contour scale gravity anomalies are in 50 $\mu N\ kg^{-1}$. Contour scale magnetic anomalies are in 50 nT. Contour scale resistivity anomalies are in Ωm. The coordinates are given in terms of the Indonesian map (m) standard metric grid referred to as Dittop TNI-AD [2].

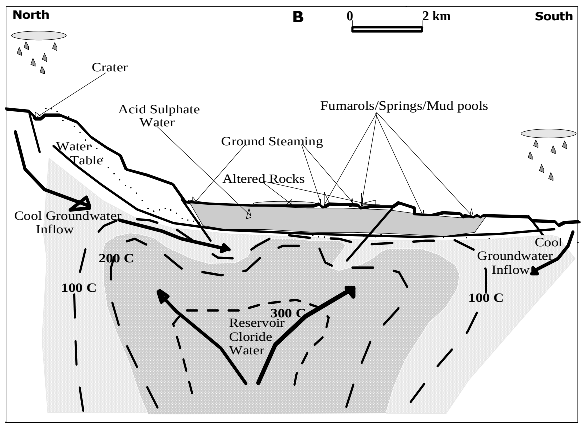

Figure 2. Model of the hydrology of the present Rendingan-Ulubelu-Waypanas (RUW) geothermal system along a section NE-SW (Figure 1). Contour values are temperature in ^{o}C.

The Rendingan manifestations occur on steep terrain between 1600 and 900 m, from north to south. Only steaming ground appears there, but relict hydrothermal minerals occur near well Rd. The Ulubelu manifestations, situated in the central area within moderately steep terrain, are mostly between 800 and 700 m. Manifestations here include fumaroles, hot pools, hot mud pools, H_2S discharges, bubbles of CO_2, steaming ground, silicified country rocks, silica sinter, silica residue and acid thermal waters at temperatures between 45 and 100^{o} C. The Waypanas manifestations between 700 and 400 m south of Mt. Kukusan to the southwest of Mt. Waypanas have the same types of manifestations.

Thermal fluids ascend through host andesites beneath sinters within moderately steep terrain in the central part of the study area, close to Pagaralam village (Ulubelu manifestations). But some out-flows discharge 7 to 15 km to the south and southwest of the study area (Waypanas manifestations) at lower elevations (Figure 1).

RESULT AND DISCUSSION

EXTENT OF THE RESERVOIR

(1) The RUW geothermal system (Figure 1) is a large system, covering an area of about 150 km^2. Evidence for its extent includes surface manifestations that are widespread from the northern part of the Ulubelu manifestations, close to Pagaralam village, southward to the southern part of the Waypanas (Figure 1). The manifestations include thermal discharge features and altered rocks within the Ulubelu caldera, extending along the Belu and Ngarip rivers to southern Mt. Waypanas (Figure 1).

(2) The Rendingan microearthquake swarm, which occurred in February 1993 [3], is probably a result of hydrothermal activity. Assuming this to be true, its conclude that well Rd penetrated part of the geothermal reservoir. This is also consistent with the occurrence of hydrothermal minerals at shallow depths in this well.

(3) A gravity low situated at the northern part of the study area, below well Rd within the Mt. Rendingan andesite lavas (RdAl) and Mt. Rendingan pyroclastics (RdPr), may represent a permeable fracture zone (Pbr). The magnetic data indicate that hydrothermally demagnetised rocks, surrounding well Rd, extends from the Ulubelu caldera southward to the vicinity of Mts. Kukusan and Waypanas.

RELATIONS BETWEEN THE RENDINGAN, ULUBELU AND WAYPANAS GEOTHERMAL FIELDS

Although the surface manifestations are concentrated in three places (i.e. the Rendingan, Ulubelu and Waypanas manifestations; Figure 1), thermal activity was once more widespread within the Rendingan-Ulubelu-Waypanas (RUW) geothermal system and was probably contiguous between the Rendingan and Ulubelu areas and also probably between Ulubelu and Waypanas. Past thermal activity in the three areas is indicated by the occurrence of the surface manifestations and relict hydrothermal minerals. Therefore, I think the evidence presented in this thesis shows that this is one system, as delineated on Figures 1 and 2.

The microearthquake activity and gravity data obtained near well Rd reflect the presence of the Rendingan reservoir. However, no data indicate a direct connection between Rendingan and the Ulubelu-Waypanas fields. The microearthquake swarm occurred mainly in the Rendingan area. The spatial and hydrological relationships between the Rendingan and Ulubelu and Waypanas thermal areas are such that they likely comprise a single geothermal system, the Rendingan-Ulubelu-Waypanas (RUW) system. However, an area of high resistivity[4] occurs between the Rendingan and Ulubelu manifestations, so perhaps it is only at shallow depths that they are separate.

STRUKTUR, PERMEABILITY AND HYDROLOGYOF THE RESERVOIR

Fluid flows in geothermal reservoirs occurs mainly through fractures of various lengths and widths[5]. Permeability in the RUW geothermal reservoir is probably provided by faults and unconformities. Permeability and buoyancy are the key parameters that affect convection in porous media[6] and both are needed. A rock permeability of approximately 10^{-15} m^2 is required for convection in geothermal reservoirs at about 200 to 250 ^oC but this reduces to about 10^{-16} m^2 when the reservoir temperature is 350 ^oC because of enhanced buoyancy and lower fluid viscosity[7]. Therefore the vertical permeability must be greater than 10^{-15} m^2 within the RUW reservoir. The hydrological condition, as delineated in Figures 2, show domains dominated by vapor, two phases and liquid water. Figure 2 summarizes the hydrology of the present RUW geothermal system.

The major fault trends are NW-SE and NE-SW (Figure 1). The principal fault system affecting the Rendingan manifestations (R I) (Figure 1) includes faults F8 and F5. Cool meteoric water supplied to the reservoir near here could descend, from the Mt. Rendingan crater into the central Rendingan reservoir, close to well Rd, also intersected by fault F5.

The Ulubelu manifestations (R II) (Figure 1) are affected by faults F1, F2, F3, F4, F5, and F6. F1 is a normal fault that affects most of this area. Normal fault F2 occurs in the southwest part of this area. A strike slip fault, F3, provides a permeable zone that connects the Ulubelu and Waypanas reservoirs. A strike slip fault F4 supplies cool water from the higher elevations in the northwest (The normal faults F5 and F6 northeast of this reservoir also provide permeability and supply cool water to the system together with fault F1. The Ulubelu manifestations close to Pagaralam village and well UBL3 are probably supplied by fluid that ascends near here.

The Waypanas manifestations are intersected by a fault system that includes faults F3, F7, F10, F11, F12, F14, F15 and F16. The Ulubelu and Waypanas areas are probably connected hydrothermally by the strike slip faults F3 and F11. Faults F10 and F11 supply cool water to this system from the higher elevations in the southeast (see Figure 1). An additional supply of cool water moves through faults F3, F7 and F13 (see Figures 1 and 2).

Fluid in the permeable fracture zone surrounding well Rd probably derive from near the summit of Mt. Rendingan to the north and the area surrounding Mts. Kukusan and Waypanas in the southern part (Figure 2 along section NW-SE in Figure 1).

PRESENT CHARACTER OF THE RUW RESERVOIR

The downhole temperatures and pressures, hydrothermal mineralogy, the thermal characteristics of fluids trapped in inclusions and geophysical data in the RUW geothermal system provide information about the thermal character of its reservoir.

The system has perched water or steam condensate above 250 m depth (450 m a.s.l.), vapor occurs between about 250 m and 550 m depth (450 m and 150 m a.s.l.), two phases from about 600 m to 800 m depth (100 m a.s.l. to 100 m b.s.l.) and alkali chloride water below this, near well UBL3. The water level is at 600 m depth in wells UBL1 (150 m a.s.l.) (Figure 2) and UBL3 (100 m a.s.l.) (Figure 2) and at 400 m depth in well UBL2 (450 m a.s.l.) (Figure 2). Convection occurs below 800 m depths in the reservoir near wells UBL1 and UBL3. However, a pronounced temperature reversal indicates inflow of cooler water at about 700 m depth , probably meteoric water descending though fault F11 (Figure 2). Convection below 800 m depth is also consistent with the occurrence of the high permeability characteristic minerals (i.e. adularia and albite) in rocks below 800 m. In wells UBL2 and UBL3, adularia and albite occur from 500 and 600 m depths respectively, consistent with the present water levels in these wells.

Downwell temperature profiles in wells Rd, Kk1, Kk2, UBL1, UBL2 and UBL3 indicate the thermal regime within the RUW geothermal system. The temperature profile in well Rd shows a temperature gradient of 110 ^{o}C/km. This value indicates that the heat here moves only by conduction [8]. It also higher than the regional value heat flow in Iceland 80-100 ^{o}C/km [9].

The temperature gradients in wells Kk1 and Kk2 are 140 and 200 ^{o}C/km respectively. Wells UBL1, UBL2 and UBL3 are characterized by very high temperature gradients in their uppermost 200 m. These are 420, 220 and 500 ^{o}C/km respectively. Some of the hydrothermal minerals in drill cuttings (e.g. illite, wairakite, prehnite and epidote) indicate high-temperature hydrothermal fluids (> 210^{o} C), although it is by no means certain that these represent the present thermal regime (see section 7). The composition of the deep fluid that produced the observed alteration was alkali chloride water. The mineralogy and fluid inclusion geothermometry results yield the hydrological conditions summarized in Table 1. Comparison of T.bore, T.minerals and Th values, indicates that the deep reservoir is still liquid hotter than 180^{o} C. Generally, the fluid inclusion data also indicate high reservoir temperatures and boiling conditions. The average homogenization temperatures (Ths) are mostly between about 200^{o} C and 250^{o} C. The occurrence of both vapor rich and two-phase inclusions in the same samples indicates boiling occurred while inclusions were being trapped. The water involved in the fluid/rock interactions was very dilute with apparent salinities from 0.0 to 0.9 wt. % NaCl (Table 1). The microearthquake activity and gravity data may indicate the closeness of well Rd to a permeable fracture zone. Temperatures

Table 1. Summary of fluid properties of RUW geothermal system deduced from alteration mineralogy and fluid inclusion geothermometry

Alteration Type	Indicated Temperature (^oC)	pH	Fluid Origin
Silica Sinter	~ 100 (at surface) > 180 (at depth)	6 to 7	Chloride waters discharging at the surface
Epidote-wairakite Adularia-quartz	> 210	Neutral	Deeply derived upflowing alkali-chloride water. Salinity < 0.9 wt% NaCl equiv.
Kaolinite	< 140	2 to 5	Steam condensate

measured in well Rd indicate a conductive gradient, in the caprock here. This conclusion is consistent with the resistivity data of Suharno (2000) (see Figure 1).

CHANGES IN RESERVOIR CONDITIONS

The surface manifestations, downwell data, hydrothermal mineralogy and fluids trapped in inclusions record changes in the hydrology of the reservoir, although the sequence and directions of changes are incompletely known.

The presence of the hydrothermal feldspars and some other hydrothermal minerals indicate that the altering water had a near neutral pH. Epidote, prehnite and laumontite (in veins) could only have formed from a liquid of close to neutral pH and of alkali chloride composition. The relationship between the occurrence of calcite and calc-silicate minerals indicates that the deep water had a low concentration of dissolved carbon dioxide. The waters were undersaturated in sulphate, as indicated by the absence of anhydrite and other sulphate minerals. The widespread calcite in veins indicates CO_2 loss from boiling or effervescence.

The compares Th, T.mineral and T.bore, and indicates that the differences between the average homogenization temperatures and present-day temperatures are within 20^o C, while the differences between the hydrothermal mineral deduced temperatures and the present-day temperatures are > 20^o C.

This implies that cooling has occurred since the minerals deposited and the inclusions were trapped .

The mineralogy, fluid inclusions and surface manifestation assessments indicate that conditions in the RUW geothermal system changed spatially and temporally during its lifetime. Erosion has now exposed hydrothermal minerals that formed deep within the geothermal reservoir during an earlier stage of activity. Alkali chloride waters close to boiling temperature and of neutral pH water once discharged at the surface, as is shown by the presence of silica sinter now changed to quartz. At an unknown time waters discharged at the surface changed to pHs between 2 and 4, at temperatures between 45 and 100^o C. Differences between the measured downhole temperatures, which are lower than those indicated by the hydrothermal mineral and fluid inclusion geothermometers, implies cooling of > 20^o C has occurred since the minerals deposited. Overprinting by kaolinite and calcite of quartz also supports the suggestion that the thermal system has been cooling.

The mineralogical evidence incompletely records some of the changes in the thermal regime. Table 1 is a summary of the hydrological conditions deduced from the mineralogy and fluid inclusion geothermometry. Erosion exposed rocks that contain calc-silicate minerals (i.e. epidote, wairakite and prehnite) produced by neutral pH waters at greater depth. The piezometric surface likely dropped in response to movements within the caldera or graben collapse and probably other factors such as climate change also affected the hydrology. I interpret the geothermal evolution of the RUW geothermal system as follows:

The first thermal activity started at an unknown time with the interaction of andesites with near neutral pH waters. This is recorded by assemblages with chlorite, illite, smectite and vermiculite. Rainwater descended, producing near neutral pH, alkali chloride waters by reacting with the andesites in the reservoir. These waters ascended deeply penetrating fractures generated around the Ulubelu caldera or graben faults. These waters were hotter than 260^o C in the reservoir and discharged at the ground surface as hot pools, hot springs and deposited silica sinter (opal-A that later changed to quartz).

A progressive lowering of the piezometric surface caused steam condensate to occupy shallow levels in the reservoir, as revealed by alteration overprints and the occurrence together of acid water and silica sinter.

Displacements on fault F5 in the northern part of Ulubelu caldera affected the hydrology of the geothermal system. Their cumulative effect was to progressively lower the piezometric surface, and create an acid sulphate zone above the new piezometric surface within the earlier reservoir filled with dilute alkali chloride waters.

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