Geothermal Prospect Review in the Western Part of Salak Volcano, West Java, Indonesia

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Abstract. The Ertankian Geothermal Prospect is located in the southern area of Bogor District, West Java, Indonesia. From 1982 through the end of 1983, Unocal Geothermal of Indonesia, Ltd. (UGI) conducted extensive geological, geochemical, and geophysical surveys that outlined Ertankian as a potential geothermal field on the flanks of the Salak Volcano. This volcano forms the north-eastern part of the Salak-Perbakti-Gagak Volcanic Massif, which consists of Upper Pleistocene to Recent stratovolcanoes, parasitic vents, and phreatomagmatic craters. The exploration survey included, magnetotelluric and gravity surveys, water geochemistry, thermal manifestation gas, ion, and isotope analyses, and geological, photo-geological interpretation, and photogrammetry interpretation. Kawah Ertankian is a vigorous fumarole area with numerous superheated and boiling steam vents, boiling acid sulfate hot springs, and large areas of acid-altered ground. Elemental sulfur is common around many of the vents. Steam from the Ertankian Fumaroles contains 7 mol% H2S and the maximum reservoir temperature obtained from the NAH-CO2 gas geothermometer was 525°F. The Ertankian Hot Springs have acid sulfate character and yield little information about the underlying hydrothermal system. Bicarbonate chloride warm springs occur on the northern flanks of the Salak Volcano at northwest and northeast locations and interpreted as the outflow product of Ertankian Geothermal System. Extensive areas of low resistivity are distributed across most of the Ertankian Geothermal Prospects. Low resistivity zones are observed around the Kawah Ertankian thermal manifestation complex and broaden to the far northwestern warm spring and Gunung Perbakti in the southwest. The shallowest base of the conductor is observed in the area near Kawah Ertankian and probably extends towards the northwest in the Alpha-19 well area. Towards the south and southwest, a significant deepening of base of the clay cap is observed. The observed resistivity trend coincides with and parallels to the NW-SE South and North Ertankian Faults, which may be the outflow pathway of the hydrothermal system. The lower rock conductance values and deepening of the clay cap base toward the southwest indicate a lower possibility of connection to the main Salak geothermal system. Considering the geological, geochemical, and geophysical data, the Ertankian Geothermal Prospect is presumed to be an encouraging area for further studies.

1. Introduction

The Salak Geothermal Field is located in West Java, about 70 km south of Jakarta, Indonesia along the Sunda Volcanic Arc (Figure 1). It is situated in a mountainous area with elevation ranging from about
950 to 1,500 m above sea level (ASL). It is the largest operating geothermal field in Indonesia with an installed capacity of 377 MWe [1]. Six power plants are operated in Salak with 180 MWe from the PLN Units-I/II/III and 197 MWe from the Star Energy Geothermal Salak Units IV/V/VI. The commercial resource is spatially associated with andesitic-to-rhyolitic volcanism that has occurred over the past 330 ka, especially silicic volcanism that were erupted in the last 280 ka along a major NNE-trending structure. The Salak geothermal field is a water-dominated reservoir with distributed permeability, benign chemistry, low-to-moderate non-condensable gas (NCG) content, and moderate-to-high temperatures (240–312°C) resource with high fracture permeability, moderate porosity (mean = 10.6%) and moderate-to-low matrix permeability (geometric mean = 0.026 md) [2].

The Ertankian Geothermal Prospect is located on the eroded western flank of the Salak Stratovolcano. The eruptive centers in this volcano shifted progressively from east to west with the most recent volcanism represented by Gunung Sumbul (Figure 2), a volcanic spine or dome built on the western remnants of Salak volcano’s crater rim. No magmatic eruptions are known during historic time, but a number of historic phreatic events have occurred in the Ertankian fumarolic area on the volcano’s west flank [3].

2. Tectonic Setting
The Salak Volcano (2,211 m) is a large andesite volcano that has been built up during the Quaternary and located within the central volcanic belt of West Java, in the district of Bogor. The volcanoes of the Salak region are part of the Sunda island arc system that stretches from the Andaman Islands north of Sumatra to Flores in the Banda Sea and has developed as a result of the 6-7 cm northward migration and consequent subduction of the Indo-Australian Plate beneath the Eurasian. The tectonic features of the area of interest have been described in detail by Hamilton (1979). Beneath Java (and Salak volcano) the crust is ~20 km thick and has a ‘quasi-continental’ seismic velocity structure, intermediate between continental and oceanic. The south-eastern boundary of Sundaland (Southeast Asian continental part of the Sunda block/Eurasian plate with pre-tertiary basement) is located in West Java [4]. However, due to limited knowledge of the precise structure and composition of the Java crust, the exact location and nature of this boundary remain unknown.

Figure 1. Map of West Java showing the Salak (also known as Awibengkok) and other producing geothermal fields (dashed polygons) in the general area. The Ertankian Geothermal Prospect is located northeast of the Salak Geothermal Field. Also shown here are the Salak-Perbakti-Gagak-Halimun Volcanoes and Cianten Caldera features.
3. Geology
The Salak Volcano is the largest and most easterly cone in the Salak-Perbakti-Gagak-Halimun Volcanic Massif, an agglomeration of late Pleistocene to recent stratocones, parasitic vents, and phreatic craters (Figure 1). Historically, volcanic activity at Salak Volcano has been limited to a number of phreatic explosions occurring at side vents on the flanks of the volcano. The summit of Salak Volcano is characterized by the appearance of a crater that opens to the southwest and associated with a sector collapse. The central crater is breached on the west side, and explosive eruptions about 300 years ago formed a second crater (Kawah Ertankian) within which a number of phreatic explosions have occurred between 80- and 40-years BP [5].

Lavas from the Salak Volcano were erupted 1.2 to 0.28 MYBP (and possibly later) and vary in composition from older olivine basalts to younger andesite and subordinate dacite [3]. Volcanic products of Salak volcano can be divided into two main groups based on eruption location, rocks erupted from the central vent (CVG/Central Vent Group) and those erupted from flank or side vents (SVG/Side Vents Group) [6]. The CVG, which dominates the volcanic deposits at Salak volcano, consists of multiple lava flows and pyroclastic units.

Two dominant fracture trends are present in the area of interest and strike NE-SW and NW-SE (Figure 2). These dominant fracture trends are also found in the commercial Salak geothermal field. The Salak-Pelabuhan Ratu regional fault, which trends NE-SW and extends more than 7 km south of Salak volcano, is relatively parallel with the Salak Volcano sector collapse wall. The NW-trending fractures intersect the NE set in the vicinity of Kawah Ertankian and Gunung Sumbul. This structural intersection may well have controlled the location of the Ertankian hydrothermal system. The NW-trending faults appear to channel shallow outflow and surface discharge from the hydrothermal reservoir and may also constitute boundaries of the deep reservoir. Another prominent lineament is the NW-SE trending Perbakti Structure, an inferred fault, located between the Salak Geothermal Field in the west and the Ertankian Geothermal Prospect in the east. This inferred fault intersects Gunung Perbakti in the far south and could have an important role for the Salak and Ertankian Geothermal Fields.

4. Surface Thermal Manifestation
The Ertankian Fumarole area is a major surface thermal manifestation complex situated on the west flank of the Salak volcano. Numerous superheated and boiling steam vents exist in this vigorous fumarolic area with native sulfur being deposited around many of the vents (solfatara) and large areas of acid-altered ground. Warm springs occur 5 km to the northwest and downhill from Ertankian at Beta and on the northern flank of Salak Volcano at Gamma. The fumaroles are typically high gas (>4 % weight) and high H2S (>6 % mole) with no indication of excess chloride from its steam condensate and yield geothermometer temperatures of 525°F (Table 1). The Beta Hot Spring gas is dominantly CO2 and, despite its relatively high helium isotope, appears to be distal from the Ertankian hydrothermal system based on its chemistry and gas geothermometry. Gas from the Gamma thermal manifestation is rich in methane and yields low geothermometer estimates.

The Ertankian Hot Spring has an acid sulphate character and yields little information about the underlying hydrothermal system (Table 2 and Figure 3). The Beta and Gamma springs are mixed bicarbonate-chloride types with significant concentrations of Mg and Ca, which are typical of vents peripheral to the high-temperature hydrothermal systems (or springs not related to high-temperature systems) and, hence, provide little direct information about the geothermal reservoir. The significant chloride component, however, is indicative of NaCl fluid in the reservoir and, therefore, probable liquid-dominated conditions somewhere within the system.
Figure 2. Salak Volcano is the largest and most easterly cone in the Salak-Perbakti-Gagak Volcanic Massif. Ertankian Geothermal Prospect is located in the western part of the Salak Stratovolcano (marked by Kawah Ertankian occurrence).

Table 1. Surface gas composition in the Ertankian Geothermal Prospect area.

|            | Ertankian | Beta    | Gamma   | Alpha  |
|------------|-----------|---------|---------|--------|
| Vent T°F   | 271       | 120     | 110     | 266    |
| CO₂        | 89.6      | 99.4    | 72.7    | 92.8   |
| CH₄        | 0.666     | 0.305   | 8.72    | 0.4    |
| H₂         | 1.8       | <0.001  | 0.001   | 0.45   |
| N₂         | 0.843     | 0.128   | 16.9    | 0.54   |
| NH₃        | 0.218     | <0.001  | <0.03   | 0.1    |
| H₂S        | 6.86      | 0.204   | 1.38    | 5.67   |
| CO₂/H₂S    | 13.1      | 487     | 53      | 16.4   |
| CO₂/CH₄    | 135       | 326     | 8       | 232    |
| Geothermometer °F | 525 | 336 | 81 | 453 |
Table 2. Hot spring composition in the Ertankian Geothermal Prospect area.

|                | Ertankian | Beta | Gamma |
|----------------|-----------|------|-------|
| Vent T°F bp    | 120       | 110  |       |
| pH             | 4.6       | 6.7  | 6.7   |
| Na             | 49        | 292  | 346   |
| K              | 3         | 62   | 40    |
| Ca             | 63        | 140  | 80    |
| Mg             | 27        | 120  | 73    |
| Cl             | 92        | 320  | 580   |
| SO₄            | 7436      | 3    | 7     |
| HCO₃           | 139       | 1130 | 550   |
| F              | -         | -    | -     |
| B              | 4008      | 15   | 25    |
| SiO₂           | 188       | 160  | 140   |
| NH₄            | 2700      | -    | -     |
| Cl/B           | 0.02      | 21.3 | 23.2  |

Figure 3. The ternary plots show spring samples from the Ertankian (red square), Zeta (pink square), Beta (blue square), and Gamma (green square) thermal manifestations. (a) Cl-SO₄-HCO₃ ternary indicates that the Ertankian Spring is typical of sulfate, Zeta is chloride, and Beta and Gamma springs are mixed bicarbonate-chloride waters. (b) Na-K-Mg ternary shows all springs are immature while Zeta, believed as the best representation of liquid level of the Alpha Geothermal System at surface, is the only one in partial equilibrium state.

A significant aspect of the Ertankian fumarole chemistry is the stable isotope composition of steam condensate (Figure 4). The Ertankian steam contains much heavier hydrogen and oxygen than local meteoric water indicating a significant non-meteoric component in the reservoir fluid. The presence of the non-meteoric component implies a strong flux of the component into the geothermal reservoir.
relative to meteoric water influx during the historical life of the system [3]. Possible origins of the thermal fluid are old formation water and/or magmatic water.

![Figure 4. Stable isotope composition of steam condensate. The Ertankian steam condensate exhibits magmatic input as shown by the mixing line connecting the SMOW with the magmatic vapor isotope content.](image)

5. Geophysics
A geophysical survey was conducted in 1983 in the area of interest during the exploration by UGI. In this survey, magnetotelluric (MT) stations were distributed around the broader prospect area toward the east region of the prospect in the vicinity of Kawah Ertankian area. Although the survey was conducted with a wide coverage, a number of the magnetotelluric (MT) stations were not used because of the low signal-to-noise ratio and absence of a static shift correction on the data. In 2004, another MT survey coupled with Time-Domain Electro-Magnetic (TDEM) measurement was conducted; however, the survey mainly concentrated in the Alpha production area and did not give significant improvement to the data coverage in the eastern portion of the Ertankian prospect (Figure 5).
An extensive area of low resistivity is distributed across most of the Ertankian prospect area. Low resistivity zones are found around the Ertankian thermal manifestation complex and broaden to far northwestern warm spring in Beta and Gunung Perbakti in the southwest (Figure 6). These low resistivity zones can be due to several types of clay-rich deposits such as volcaniclastic clays, sedimentary basin clay deposits, or smectite/argillic clay alteration overlying a geothermal system. Within the Ertankian prospect, the low resistivity layers that are near to and appear to be associated with surface thermal manifestations are believed to most likely represent the signature of a clay cap over a geothermal reservoir or outflow from a geothermal reservoir.

A standard way to view the characteristics of the low resistivity layer is to contour the elevation of the base of the conductor layer (Figure 6). In the case of Ertankian, the elevation of the base of <10 ohm-m layer was determined from the 1D MT models from each of the MT stations. The typical areas of interest are where the shallow base of conductor coincides with active thermal areas because often the shallowest and thinnest part of the clay cap is located over the part of reservoir where the high temperatures are also the shallowest. Figure 6 shows that the shallowest base of the conductor is observed in the area near the Ertankian fumarole and possibly extends to the northwest towards the Alpha area. Towards the south and southwest from Ertankian, a significant deepening of the base of the clay cap is observed. Moreover, there is minimal information to describe the area east of the Ertankian thermal area as the latest MT stations were located west of the Ertankian prospect.
Figure 6. The elevation of the base of clay cap from 1D MT model is shallowest around the Ertankian prospect area. The same shallow base of the conductive layer is found in the commercial Alpha Geothermal Field.

In addition to the information from the base of the conductor, the total conductance map shows the highest value is in east Ertankian thermal area although there are not many MT stations in this general area (Figure 7). The higher conductance region indicates higher intensity of conductance and trends in a similar NW-SE direction toward Alpha-19 as the trend of the shallow conductor. The observed resistivity trends parallel to the NW-SE oriented South and North Ertankian inferred faults, which probably act as pathways of the outflow of system.
Figure 7. The total conductance at 1,000 m ASL shows higher conductance or higher intensity of the conductor at the Ertankian Geothermal Prospect that trends along the South and North Ertankian inferred structures.

Several cross-sections were constructed to illustrate the subsurface distribution of the clay cap at Ertankian to determine the possible aerial extent of the prospect. The Ertankian-2 profile, which passes along the Beta Hot Spring and extends through the Ertankian Fumarole towards the southeast, shows a continuous “semi-flat” conductor that extends from Ertankian to the northwest and possibly delineating the outflow of the hydrothermal system (Figure 8). The extension of the clay cap towards the southeast is unconstrained because of the lack of MT stations (i.e., a distant station shows weak conductance).
Figure 8. NW-SE cross-section showing the extent of the Ertankian Geothermal System towards the northwest. The extent of the hydrothermal system to the southeast is uncertain because of poor data coverage.

Meanwhile, the Ertankian-3 profile describes the area from north to south across the Ertankian thermal area (Figure 9). The shallowest portion of the clay cap is observed directly below the Ertankian fumarole and abruptly deepens as it extends towards the north. The conductor in the north is typical of basin type clays and not part of geothermal interest. The clay cap base also dips towards the south typical of geothermal systems in volcanic settings. The prospect size in the north and south are defined by the geometry of the clay cap in each region and is about 8.25 km².

Figure 9. N-S cross-section showing the geometry of the Ertankian Geothermal Prospect. The highly conductive clay in the north is typical of basin clays and not of geothermal interest.

6. Conclusions
The Ertankian Geothermal Prospect is about 6 km northeast of the currently producing Alpha Geothermal Field. This geothermal prospect is manifested by a large fumarolic complex on the west flank of Salak Volcano. Integration of geology, geochemistry, and geophysics data indicates that there is significant geothermal potential in the Ertankian area. In Java, most geothermal fields are spatially associated with Quaternary volcanic complexes and there is a trend that the bigger geothermal systems are mainly located proximally or <10 km from a volcano’s peak [7].
The Ertankian Geothermal System is developed with the inferred upflow located beneath the Ertankian fumarole and outflows towards the Beta bicarbonate hot spring in the northwest as shown in the Figure 10. Prominent NW-SE inferred faults appear to control the outflow location, as indicated also by the trend of the base of low resistivity. Numerous superheated and boiling steam vents exist in this vigorous fumarolic area with some solfataras depositing native sulfur. The fumaroles are typically high gas (>4 wt.% NCG) and high H2S (>6 % mole) with no indication of excess chloride from their steam condensate. However, the high δ3He and heavier δ3D and O18 indicate a geothermal fluid with magmatic input. Additional 3G data is recommended to fully characterize and delineate the system including additional geologic and structural mapping, satellite imagery analysis, and MT survey especially east of the prospect. As phreatic explosions have occurred in the last 50 years, a detailed study of potential hazards should also precede any major development.

Figure 10. Mapview and NW-SE cross-section showing the conceptual model of Ertankian Geothermal Field based on the integration of geological, geophysical and geochemical data.

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