The Subsurface Geology and Hydrothermal Alteration of the Dieng Geothermal Field, Central Java: A Progress Report

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Abstract. The Dieng geothermal system is volcano-hosted, and its reservoir is liquid-dominated. Thermal manifestations lay at about 2,000 m asl. Previous studies suggest that the field consists of three prospect areas, namely Sileri, Sikidang-Merdada, and Pakuwaja. Dieng Geothermal Field has serious problems with mineral scaling and corrosion in the production facility. The problems, to some extent, are related to the natural characteristics of the system. In our study, cuttings from 4 of 47 wells drilled in Dieng were examined using petrography and X-Ray Diffractometry techniques to better understand the subsurface geology of the Dieng Geothermal Field, including different types of hydrothermal alteration mineralogy. The wells MG-1, MG-2 and MG-3, and MG-4 are chosen to represent the prospect areas, respectively. In general, typical hydrothermal minerals in Dieng Geothermal Field formed by near-neutral pH fluids characterized by clays (smectite, illite, chlorite), silica (quartz, cristobalite), calcite, wairakite, pyrite, epidote, and actinolite. In wells MG-3 which are located in the Sikidang-Merdada area, acidic alteration such as anhydrite, pyrophyllite, and native sulfur are present. Most notably, anhydrite occurs from the near-surface down to depths >2,000 m. These findings indicate the existence of acidic fluids at the deeper parts of the Sikidang-Merdada area. Furthermore, we utilize subsurface geological data from other wells within all the three prospect areas to complement our review.

1. Introduction
The Dieng Geothermal Field is a liquid-dominated field located at about 80 km northwest of Yogyakarta, at an elevation of about 2,000 m asl. Dieng geothermal work area (Wilayah Kerja Panas Bumi/WKP) currently having 60 MWe installed capacity managed by PT. Geo Dipa Energi. Up to now, 47 wells have been drilled, with some reaching depths of >3 km. Dieng field has some serious problems in production facilities such as mineral scaling and corrosion. The problems, to some extent, are related to the natural characteristics of the system. This paper is part of our research aiming to analyze the interaction between the hydrothermal fluids and surrounding rocks which may shed light on the root of the problems. Cuttings recovered from 4 wells (2,400 to 3,100 m depth) were examined to better understand the subsurface geology and the distribution of hydrothermal minerals using petrography and X-Ray Diffractometry (XRD) techniques. The location of the research area is presented in Figure 1.
2. Samples and Analytical Methods
Sixty seven bags of cutting samples recovered from 4 (2,600 - 3,200 m depth) of the 47 wells drilled in Dieng were analyzed. The samples were first observed with the aid of hand lenses and a binocular microscope. The selected samples were then thin-sectioned and examined under a petrographic microscope to determine their lithology, primary and secondary mineralogy, and the styles and texture of alteration. An estimate of intensity of alteration in the samples, following [2]. Crosscutting relationship of hydrothermal minerals are difficult to recognize, due to the size of cuttings which very small. XRD techniques were employed to help determine the clay minerals. The stable well temperatures are used to model the present-day thermal regime of the system.

3. Field Overview

3.1. Geology
Physiographically the Dieng Geothermal Field is located within the North Serayu Range and is part of the Quaternary Volcanoes of Java [3]. The geology of Java is controlled by the subduction of the Indian-Australian plates below the Eurasian continental plates [1][4]. The island was affected by compressional forces associated with the Sunda orogeny in the late Neogen which produced plutonic intrusions and the uplift of the volcanic arc [1]. Dieng field is part of the Dieng Volcanic Complex comprising part of the NW-SE trending Quartenary volcanic chain, including the younger cones of Mt. Sundoro and Sumbing [5].

According to previous research [6], the Dieng field is located in a plateau that has elevation ranging from 1,600 and 2,100 m asl, enclosed by volcanic peaks rising to 2,200-2,565 m asl. The Dieng field is composed of a complex of late Quartenary to recent volcanic strato-cones, parasitic vents, and explosion craters. The oldest known volcanic activity formed the margin of the Dieng volcanic complex [7]. It also stated that the remnants of the ancient caldera of Mt. Prahu in the eastern margin marked the oldest
phase of the volcanic complex [5]. A smaller eruption center then emerged inside the SW part of the ancient caldera. The eruption centers from NW to SE are, Pagerkandang, Pangonan-Merdada, and Pakuwaja.

According to radiometric dating [8] [9], we conclude that the oldest volcanoes in Dieng volcanic complex are Prahu, Nagasari, and Bisma. It was active during the Late Pliocene. During the Late Pleistocene, after a major volcanic eruption in Prahu, some volcanic centers then emerged inside the area between Prahu, Nagasari, and Bisma. They are Pagerkandang and Pangonan-Merdada. The last phase of the complex is marked by the volcanic products of Kendil, Pakuwaja, and Seroja in the SE part as the youngest products of the complex. The systematic map showing the age and the distribution of volcanoes within the Dieng volcanic complex, as well as the location of manifestations and the studied wells, is presented in Figure 2.

![Systematic map of Dieng Geothermal Field](image)

**Figure 2.** Systematic map showing the age and the distribution of volcanoes within the Dieng volcanic complex, as well as location of manifestations and the studied wells (modified from IFSAR-DTM of Dieng geothermal field; radiometric age data based on [8] and [9]; wells from previous workers are KPS-1 from [10], GLP-XX from [11], and GRH-2 from [12]).
3.2. Thermal Manifestation
Thermal manifestations lie at about ~2,000 m asl and spatially associated with the NW-SE trending volcanic centers. They are dominated by solfataric and steam-heated fluid discharges including solfataras with a significant amount of sulfur deposit, fumaroles, gas discharges, acidic hot springs, mud pots, mud pools, altered grounds, and steaming grounds. The typical surface alteration minerals are kaolin, smectite, alunite, silica (quartz, cristobalite, tridymite), zeolite, sulfur, chalcanthite, and halotrichite [10]. Near-neutral pH fluid is rare, they are manifested in the Bitingan and Pulosari, in the northern and southwestern part of the field, respectively.

4. Discussion
4.1. Subsurface Geology
The knowledge of surface and subsurface geology of the Dieng field is obtained from the results of the previous workers, combined with the results of our study. Previous research suggested that the field consists of three prospect areas, namely Sileri, Sikidang-Merdada, and Pakuwaja [8]. To better understand the condition of the three prospect areas we selected 4 wells, namely MG-1, MG-2 and MG-3, and MG-4 to represent Sileri, Sikidang-Merdada, and Pakuwaja, respectively.

4.1.1. Stratigraphy. Stratigraphic division of the subsurface rocks follows those of [7] where it is divided into the Old Dieng, Middle-aged Dieng, and Young Dieng volcanic products. Detailed surface geology of the Dieng field was described by [13] where 23 volcanic products were recognized. Age dating and geochemistry of the subsurface rocks are not conducted during this study, therefore subsurface stratigraphic relationship was interpreted based on the observation at the characteristics and spatial association of the rocks with the volcanic products which referring to simpler division [7].

In general, the subsurface stratigraphy is composed of basaltic – andesitic lavas and pyroclastic rocks. Petrographic analyses made in this study shows, the subsurface rocks can be categorized into three groups: basaltic lava, andesitic lava, and biotite andesitic lava.

The basaltic lava consists of plagioclase (andesine-labradorite, with labradorite being predominant), pyroxene, and in places containing olivine, embedded in microcrystalline crystals of similar mineralogy, with opaque crystals and a glassy groundmass. These rock units are considered to be part of the Old Dieng products. Most likely, the Old Dieng products are the lowermost volcanic sequence encountered in the studied wells. However, the Old Dieng products are also found in MG-1 which is located in the northern part of the system, from near surface to the well bottom.

The andesitic lava, with pyroclastic rocks, are considered to be part of the Middle-aged Dieng products. The andesitic lava composed of andesine and pyroxene, set in a groundmass of microcrystalline plagioclase, with minor volcanic glass. The equivalent pyroclastic rocks have a similar composition. In the studied wells, these units were penetrated by the drill holes from the upper parts in MG-3 about 2,000 to 1,000 m asl, and thinning to the southeast in MG-2 and 4.

The biotite andesite lava consists of plagioclase (oligoclase-andesine), pyroxene, and biotite, embedded in microcrystalline plagioclase, opaque crystals, and a glassy groundmass. These units are considered to be part of the Young Dieng products and are encountered mainly in the upper parts of wells MG-2 and 4. A geological map of Dieng Geothermal Field is given in Figures 3.
Figure 3. Geological map of the Dieng geothermal field, Central Java (modified from Nurpratama [13]).

The diorite was encountered by wells MG-2 and MG-3, at about 2,000 m depths. Petrography shows that they are coarse-grained, with the primary mineralogy consists of andesine, pyroxene, and biotite. A cross-section showing the distribution of lithologic units, as well as the isotherms of the present-day temperatures is presented in Figure 4.
Figure 4. Cross-section from MG-1, 2, 3, and 4 showing the distribution of lithologic units, and the isotherms of the present-day temperatures (°C).
4.1.2. Geologic Structure. The primary evidence of undisturbed geological structures on the surface was difficult to recognize, due to the land use where most of the research area has been terraced for agricultural purposes. Therefore, the geological structures were interpreted from IFSAR-DTM.

Volcanic structures interpreted as crater rims are associated with Mts. Pagerkandang, Pangonan-Merda, Pakuwaja, and Seroja. These structures may be connected with the subsurface, as indicated by the existence of some losses of circulation in drilling. Well MG-1, situated in the northern rim of Pagerkandang crater, encountered total loss circulation from about 1,806 m to well bottom at 2,602 m depth. MG-3, sited in the southwestern rim of Pangonan-Merda crater, had a total loss circulation zone at the well bottom (3,102 m depth). MG-4 which located in the west of Pakuwaja crater also encountered a total loss of circulation zone at the well bottom (2,604 m depth).

NW-SE trending faults are evident from the alignment of the thermal manifestation areas. The active thermal manifestations are spatially associated with volcanic centers i.e., Sipandu, Sileri area (associated with Pagerkandang), Sikidang area (associated with Pangonan), and Pakuwaja. At present, these faults may still function as permeability providers, since the thermal associated with them are still active.

4.2. Subsurface Hydrothermal Alteration

4.2.1. Intensity of Alteration. Most of the subsurface rocks have been altered with the intensities of alteration ranging from 0.2 – 1.0. Pyroclastic rocks are more highly altered than lava. The phenocryst in lavas is usually more altered than the groundmass.

4.2.2. Style of Alteration. There are 3 styles of alteration in the subsurface rocks of the Dieng field, namely, replacement, leaching/dissolution, and direct deposition. Replacement and dissolution styles record the interaction between fluids and the host rocks, but the latter involves the removal of primary components without replacing them. In the subsurface, leaching is recognized in MG-1 and MG-3 from about 1,700 to 800 m asl. Replacement involves a mass exchange between primary components and the hydrothermal fluids. Minerals in the veinlets were directly deposited from the fluid that moves through the previously open spaces (fractures and/or cavities).

4.2.3. Hydrothermal Minerals. The identity and the distribution of hydrothermal minerals give clues about the past conditions of the system, most notably the thermal conditions. The past thermal structures of the Dieng system are deduced from the occurrence of temperature-dependent hydrothermal mineral that occurs in the field. These include actinolite, epidote, and wairakite. The use of the mineral geothermometers refers to [14] and [15].

The hydrothermal minerals encountered in the studied wells include clays (illite, smectite, halloysite, and chlorite), silica (quartz and cristobalite), calc-silicate (epidote, actinolite), zeolite (wairakite), and carbonate (calcite). These minerals formed from near-neutral pH fluids. However, acidic fluids were/have been present in the system. It is indicated by the presence of anhydrite at depth. Interestingly, well MG-3 which is located in the Sikidang-Merda area is also encountered pyrophyllite and native sulfur to the deeper part. The distribution of hydrothermal minerals with relative depth is given in Table 1.

The peak activity of the Dieng field was marked by the formation of epidote, indicating temperatures >250°C. Epidote is shallowest in MG-4 i.e 1,250 m asl, and deeper in the other wells. In well MG-1 which located in the Sileri area, epidote occurs at about 800 m asl. The downhole temperature here is less than 200°C. However, wairakite occurs in MG-1 at about 1,800 m depth, where the present-day temperature is about ~300°C. These phenomenon indicate the thermal and hydrology structures in the Sileri area, are quite complex. The Sikidang-Merda and Pakuwaja areas which are penetrated by MG-2 and MG-3, and MG-4, respectively, are most likely in thermal equilibrium with the present-day temperatures. Actinolite was found at about 500 m asl in MG-2, 3 and 4, in association with diorite intrusion. Actinolite indicates temperatures of >280°C [14] [15]. Examples for some petrographic
evidence of indicator minerals and the shallowest occurrence of some important hydrothermal minerals are presented in Figures 5 and 6, respectively.

The occurrence of anhydrite together with pyrophyllite and the presence of native sulfur in MG-3 from about 300 to 1300 m depths, indicating the possibility of acidic fluid input at depth in the Sikidang-Merdada area. Based on the distribution of the leached rocks in the studied wells, we conclude that acidic fluid was or has been circulating within the system.

The deep part of the Sikidang-Merdada area may have received magmatic fluids contribution. This finding agrees with [16], who reported that there is a corrosive steam zone in the Sikidang area, as characterized by a very high H₂S/CO₂ ratio in the gas, and presence of gaseous HCl. Examples for some megascopic and petrographic evidence of minerals which formed by the acidic fluid and the occurrence of anhydrite, sulfur, and leached rocks in the studied wells are presented in Figures 7 and 8, respectively.

Table 1. The relative distribution of subsurface hydrothermal minerals with depth.

| Relative Depths | Mineralogy | Well MG-1 | Well MG-2 | Well MG-3 | Well MG-4 |
|-----------------|------------|-----------|-----------|-----------|-----------|
| Shallow         |            | R | S | R | S | R | S | R | S |
| Calcite         |            | v | v | v | v | v | v | v | v |
| Quartz          |            | v | v | v | v | v | v | v | v |
| Cristobalite    |            | v | v | v | v | v | v | v | v |
| Adularia        |            | v | v | v | v | v | v | v | v |
| Pyrite          |            | D | D | D | D | D | D | D | D |
| Sulfur          |            | v | v | v | v | v | v | v | v |
| Anhydrite       |            | v | v | v | v | v | v | v | v |
| Hematite        |            | v | v | v | v | v | v | v | v |
| Smectite        |            | v | v | v | v | v | v | v | v |
| Chlorite        |            | v | v | v | v | v | v | v | v |
| Pyrophyllite    |            | v | v | v | v | v | v | v | v |

| Intermediate    |            | R | S | R | S | R | S | R | S |
| Sulfur          |            | v | v | v | v | v | v | v | v |
| Anhydrite       |            | v | v | v | v | v | v | v | v |
| Hematite        |            | v | v | v | v | v | v | v | v |
| Smectite        |            | v | v | v | v | v | v | v | v |
| Illite          |            | v | v | v | v | v | v | v | v |
| Chlorite        |            | v | v | v | v | v | v | v | v |
| Pyrophyllite    |            | v | v | v | v | v | v | v | v |

| Deep            |            | R | S | R | S | R | S | R | S |
| Calcite         |            | v | v | v | v | v | v | v | v |
| Quartz          |            | v | v | v | v | v | v | v | v |
| Adularia        |            | v | v | v | v | v | v | v | v |
| Epidote         |            | v | v | v | v | v | v | v | v |
| Actinonite      |            | v | v | v | v | v | v | v | v |
| Anhydrite       |            | v | v | v | v | v | v | v | v |
| Hematite        |            | v | v | v | v | v | v | v | v |

*R: Replacement; S: Space-fill; D: Disseminated
Figure 5. Examples of some indicator minerals under petrographic microscope. (A) Epidote partially replaces plagioclase. It indicates temperature of >250°C (MG-1/855 m). (B) Epidote, clinzoisite, and quartz are occur as a vug filling (MG-2/1600 m). (C) The occurrence of adularia as a high permeability indicator mineral (MG-3/2520 m). (D) Actinolite is a high temperature indicator mineral. It indicates temperature of 280°C (MG-3/2937 m).

Figure 6. Cross-section showing the shallowest occurrence of some important hydrothermal minerals, and the isotherms of the present-day temperatures (°C).
Figure 7. Examples of some megascopic and petrographic evidence of minerals which formed by acidic fluid in Dieng. (A) Glassy groundmass in tuff (MG-3/900 m) altered to pyrophyllite and microcrystalline quartz. (B) Anhydrite occurs as cavity fill in andesite (MG-3/1299 m). (C) Leaching/dissolution texture in fragment of tuff (MG-3/900 m) where acid sulfate fluids have leached the primary constituent of the rock. (D) Native sulfur has deposited at depth in basalt (MG-2/1060 m).

Figure 8. Cross-section showing the occurrence of anhydrite, pyrophyllite, native sulfur, and leached rocks.
5. Conclusions
Dieng Geothermal System was developed within the Dieng volcanic complex. In general, the subsurface stratigraphy is composed of basaltic – andesitic lavas and pyroclastic rocks. Diorite intrusion occurs beneath the Mt. Pangonan-Merdada. The intrusion was encountered in well MG-2 and 3.

The alteration mineralogy shows that the altering fluid was likely a near-neutral pH, but in parts, there has been some acidic fluid circulating in the system. In the deeper part, the acidic fluid was interpreted to be of magmatic type. This fluid formed anhydrite, pyrophyllite, and native sulfur, such as those found in well MG-3. This data has to be considered seriously in constructing the development strategy of the Dieng Geothermal Field. Further studies, involving fluids chemistry and stable isotope analyses of the minerals are suggested to better understand the characteristics of the system, especially the circulating fluid compositions.

The present-day temperatures (as represented by the isothermal lines, in Figure 3 and 4) shows that the main thermal focus of the Dieng geothermal system is located in the Sileri, Sikidang-Merdada and Pakuwaja areas. This coincides with the present-day active thermal manifestations in the Dieng field. Temperature-dependent minerals suggest that the prospect areas in the Dieng field are generally in equilibrium with the present-day temperature.

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