Updated Geologic Structures and Stratigraphy of the Darajat Geothermal Field in Indonesia

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Abstract. The main objectives of the evaluation of the geologic structures and stratigraphy of the Darajat geothermal field are to refine and update both the Darajat conceptual and geologic models. Re-interpretation of the borehole image logs, additional petrographic analysis of rock cuttings and cores, integration of subsurface data from the wells drilled during 2009-2011, and recent resource observations allowed definition of at least seven (7) lithologic units based on the dominant rock type. The updated stratigraphy of the reservoir was correlated with the surface rocks to develop a volcano-stratigraphy and geochronology of the Darajat geothermal system. The andesite-intrusive complex, which comprises the Darajat geothermal reservoir and the hypothesized sub-volcanic portion of an earlier liquid-dominated geothermal system, belongs to the Kendang Volcanics and makes up subsurface Units A and B. The interpretation of the major volcano-tectonic features and structures at Darajat was refined through the analysis of the Light Detection and Ranging (LIDAR) data/imagery that was acquired in 2014. The LIDAR Digital Elevation Model (DEM) hill-shade map shows several conspicuous volcanic vents in Puncak Cae, Gagak and Kiamis. The prominent Kendang Fault, which extends to the Kamojang Field in the northeast, might be a section of the ring structure of an earlier volcano, herein, called Kendang. Wellbore image data from several wells suggest that the Kendang Fault may dip at 70° eastward. Although needing further substantiation, we hypothesize that the decompression event that preceded the development of the steam-dominated geothermal reservoir at present might be related to the eruption of the Kendang volcano. The Gagak Fault is another prominent surface structure and believed to form during the eruption of the resurgent Gagak volcano after the eruption of the older Kendang volcano.

1. Introduction
The Darajat Field, located in West Java about 230 km southeast of Jakarta, is currently the largest steam-dominated geothermal resource in Indonesia. The Darajat geothermal field is located in the Quaternary volcanic center in West Java at an elevation of 1,750 – 2,000 m above sea level (ASL) (Figure 1). The geothermal investigations at Darajat began in the early 1970s while commercial production started in 1994 with the commissioning of the 55 MWe Unit I, which is owned and operated by Perusahaan Listrik Negara or PLN (the Indonesia state-owned power utility). The current installed electricity generation
capacity at Darajat is 271 MWe with the additions of Unit II (95 MWe) in 2000 and Unit III (121 MWe) in 2007; both Units II and III are owned and operated by Star Energy Geothermal Indonesia II, Ltd.

Figure 1. Location of the Darajat Geothermal Field in West Java, Indonesia.

The Darajat field is located in the Kendang volcanic complex that is a part of the Quaternary volcanic range in West Java, which includes the active Gunung Papandayan with the last eruption in 2002 and Gunung Guntur with the last eruption in 1840. The main Darajat reservoir is contained in the Andesite-Intrusive Complex, which is believed to be part of the heat source of the former hot water-dominated geothermal system [1]. A massive decompression event led to the demise of the water-dominated geothermal system and the Andesite-Intrusive Complex is the sub-volcanic portion of that geothermal system. The Andesite-Intrusive Complex consists of andesite lava and subordinate pyroclastic breccias intruded by diorite to micro-diorite dikes and sills [2].

This evaluation of the Darajat reservoir stratigraphy is aimed at developing a volcano-stratigraphy of the reservoir rocks and validating the subsurface extent of the mapped surface structures and lineaments at Darajat field. This study used the 2014 LIDAR data, borehole image logs, petrographic analysis of rock cuttings and cores, and other subsurface data from the 11 wells drilled during 2009-2011 campaign. The results of these analyses were used in targeting the wells currently drilled now, and the later updating of both the conceptual and geologic models of Darajat.

2. Update of surface and subsurface stratigraphy in Darajat Field

2.1. Surface Stratigraphy
Interpretation of the 2014 Light Detection and Ranging (LIDAR) data showed distinct drainage patterns at Darajat Field, e.g., rectangular, dendritic, etc., which were used to distinguish and map similar surface rock units. In northwest Darajat, the general dendritic pattern of the streams and rivers and flow direction were used to identify the older Kendang Volcanics from the younger Kamasan Volcanics.
The LIDAR Digital Elevation Model (DEM) and topography suggest at least three big volcanic vents in the general area including Kendang, Gagak and Kiamis. There are also young dacitic domes that may correlate with parasitic domes normally found in and around volcanoes (Figure 2).

Figure 2. Drainage patterns and surface rock units in the Darajat Field based on LIDAR data. Note that only the colored portion of the field has LIDAR data; the bottom portion is a part of the 2003 IKONOS map.

2.2. Subsurface Stratigraphy

The re-interpretation of the borehole image logs, petrographic analysis of rock cuttings and cores, and other subsurface data from wells drilled during 2009-2011 resulted in the delineation of at least seven (7) lithologic units based on the dominant rock type (Figure 3). About 12 volcanic facies or lithologic units were identified by previous workers [3] but re-analysis of rock samples and thin sections failed to identify the mafic basaltic lava flows, which constitute at least three volcanic facies in earlier analyses. The Gamma Ray (GR) logs show high GR values in the previously identified basaltic rocks suggesting that these lava flows are intermediate to felsic or have higher silica content than the typical basalts. A similar analysis of GR data [4] concluded that the silica-rich rhyolitic dacite marker at Salak Field has higher GR count.
Figure 3. Schematic diagram showing the interpreted stratigraphy and correlation between surface and subsurface rocks at Darajat Field. Both the Kamasan Volcanics and Rakutak Pyroclastics, located northwest and northeast of the production area, respectively, appear to be absent in subsurface rock samples. The thick dashed line denotes the decompression event hypothesized by [2] or the boundary in time between the then water-dominated geothermal system and the current vapor-dominated system.

The Andesite-Intrusive Complex, which comprises the Darajat geothermal reservoir and the hypothesized sub-volcanic portion of an earlier liquid-dominated geothermal system, belongs to the Kendang Volcanics and makes up subsurface Units A and B (Figure 3). Note that the diorite intrusions do not penetrate the Post-Kendang Volcanics or subsurface Unit C. Effective fractures, i.e., the fractures producing geothermal fluids, are more abundant in the lava flows and intrusives compared with the pyroclastics (next section) [3] reported that delineating the extent of the Andesite-Intrusive Complex is the key to finding permeability at Darajat Field.

3. Update of geologic structures in the Darajat Field
Analysis of the LIDAR also led to the refinement of the surface geology at Darajat as the LIDAR data revealed three noticeable surface structures, namely, Kendang, Gagak, and Ciakut (Figure 3). The prominent Kendang Fault, which extends to the Kamojang Field in the northeast, might be a section of the ring structure of an earlier volcano, here called Kendang. Although needing further substantiation, we hypothesize that the decompression event postulated by [2] might be related to the eruption of the Kendang volcano [5]. The Gagak Fault is another prominent surface structure and believed to form during the eruption of the resurgent Gagak volcano after the eruption of Kendang. Lastly, integration of the provisional reservoir stratigraphy delineated the Ciakut structure, which appears to be a product of a sector collapse inside the Gagak caldera (Figure 4). Work is underway to complete petrographic analysis of in-fill samples, identification of samples for possible age dating, and integration of these data into a coherent volcano-stratigraphy of the Darajat Field.
Figure 4. Surface geological map of the Darajat Field showing the interpreted structures based on LIDAR data and offset of reservoir rocks. Both the Kendang and Gagak structures are prominent on the surface while Ciakut is buried; structures are dashed where inferred. The LIDAR data covers the colored portion of the map only. Colors correspond with the subsurface rocks in Figure 3. The black polygon represents the production boundary; dashed when not constrained with well data.

[6] proposed that the unidentified fault, which runs from Papandayan to Guntur Volcano and called as “Garsela Fault,” shows two recent focal mechanism solutions of strike-slip and normal faulting. The Kendang Fault, interpreted to be part of the Garsela Fault, has a northeast-southwest trend from Darajat
to the Kamojang geothermal field and disappears near Guntur. Borehole image and core petrographic data from eight wells at Darajat suggest that the Kendang Fault dips about 70° eastward (Figure 5).

**Figure 5.** (1) Wells that are believed to have intersected the Kendang Fault, which is represented by the black concave plane. (2) Borehole image log of one of the wells showing micro-faults. (3) Thin section from DRJ-29 showing brecciation of the diorite at the depth where the Kendang Fault was believed to have been intersected. Other evidences used to interpret the easterly dip of the Kendang Fault include vertical and 70° slickensides in and sub-horizontal and sub-vertical fractures in cores and the relative location of high permeability feed zones encountered by the wells shown in (1).
4. Interpreted evolution of the Darajat Field

Integration of multiple datasets indicates that the Kendang Fault was already emplaced before the Kendang Volcano was borne. Magma appears to have used the Kendang Fault to reach the surface and form the composite Kendang strato-volcano. [7] concluded that the West Java orogeny occurred within Plio-Pleistocene was a big tectonic event. After the uplifting period, there was volcanic activity and we believe that this was when the Kendang Volcano was formed; this volcano consists of andesite lava flows and pyroclastic (Unit A). The Kendang Volcano eruption resulted in the destruction of almost the whole volcano similar to the sector collapse that occurred at Mount St. Helens (Figure 6).

![Figure 6. Conceptual model of the formation of the Kendang volcano and its later collapse. From the Kendang Fault, magma was able to ascend to the surface and formed the Kendang Volcano strato-volcano, and then it formed as sub-volcanic intrusion. Later eruption and sector collapse destroyed the volcano with the prominent ridge in west Darajat as the remnant of the volcano.](image)

After the eruption of the Kendang volcano, there was a period of quiescence before volcanism was reactivated. We believe that resurgent volcanism in the area produced the Gagak Volcano, which was formed within the Kendang caldera (Figure 7). Similar to the Kendang Volcano, the eruption of the Gagak Volcano produced a sector collapse destroying almost the whole volcano. This sector collapse is believed to have formed the Ciakut Fault that was later buried by post-Gagak Volcanics.
Figure 7. Conceptual model of the formation of the Gagak volcano and its later collapse. The Gagak Volcano is interpreted to have formed from the Kendang caldera because of resurgent volcanism. Similar with the Kendang Volcano, the Gagak Volcano erupted and experienced a sector.

Recent volcanism at Darajat Field is represented by dacitic crypto domes that are found only on the western side of the field. Crypto domes are common in large volcanoes and we believe that the crypto domes in west Darajat ascended through the zone of weakness created by the Kendang Fault. Note that the Kendang Fault is interpreted as part of the ring structure of the Kendang Volcano. The youngest activity of volcanism in the Darajat area is evidenced by the Kiamis Obsidian and rhyolitic tuff found in the northeast (Figure 8). Fresh, glassy obsidian can be found widely in this area.

Figure 8. Conceptual volcano-stratigraphy of the current Darajat geothermal field. The left figure shows the emplacement of the dacitic cryptodomes along the Kendang Fault in the western part of the Darajat field and movement along the Ciakut Fault, which is believed to be a buried structure. The right figure depicts the extrusion of the Kiamis Obsidian that is found northeast of the field.

The Kamasan Volcanics in northwest Darajat have not been encountered in wells but believed to be a smaller collapsed volcano as shown by its parallel drainage pattern (Figure 2). Similarly, the Rakutak Volcanics in the northeast has not been identified in all the wells drilled at Darajat but is believed to be older or similar age as the Post-Kendang Volcanics (Figures 2 and 3).

The geobody of micro-diorite intrusion and andesite lava, known as the Andesite Intrusive Complex, has been validated by the 3D joint inversion modeling of P wave (Vp) and density and using porosity as a constraint by Soyer et al. [8]. Figure 9 shows the top of the lava formation and the micro-diorite (MD)
intrusion with relatively lower Vp extending into the lower porosity and higher density lava formation. This relationship is probably expected because these rocks are generally more brittle and host higher fracture density when compared to the pyroclastics. [9] reported that wave velocity decreases when fracture density increases, phase changes from liquid to steam in the rock matrix, and with decrease in pressure and temperature. The Darajat field has been in commercial production since 1994 and continuous mass extraction has lowered reservoir pressure.

![Figure 9. Joint Vp-density inversion using cross-gradients to porosity shows delineation of the main intrusive body, MD, and extent of the lava flows. Collectively, these two units is called the Andesite-Intrusive Complex, which comprise the main geothermal reservoir at Darajat and believed to be the sub-volcanic portion of an earlier hot water hydrothermal system [2], the precursor of the current steam reservoir. White contours (>2.5 g/cc) represent the density model and judged representative of the lavas [8].](image)

5. Discussion and Conclusions
A simplified stratigraphy of the Darajat geothermal reservoir is proposed with seven lithologic units based on the dominant rock type. The mafic basaltic lava flows identified by previous workers were not found in this recent analysis. In addition, the use of the Volcanic Facies Model by [10] was not applied at Darajat Field because of the presence of multiple volcanic centers that make it harder to attribute the volcanic rocks to which particular vent or volcano.

Although an initial volcano-stratigraphy of the Darajat Field has been developed, this interpretation requires age dating to validate the relationship between the surface and reservoir rocks. The joint inversion study supports the geobody of the simple Andesite-Intrusive Complex located in the middle of the field. A next step is to distinguish older intrusions from younger intrusions possibly through thin section paragenesis and/or age dating.

The updated structures improve our understanding of the role of surface structures and lineaments in the reservoir and assist in drilling successful steam make-up wells. Before, there was a vague understanding of the role of these surface features in the geothermal reservoir. The Kendang Fault is obvious from the LIDAR data but the new interpretation of 70° dip eastward should help future well targeting and conceptual modeling. Similarly, delineation of the Gagak and Ciakut Faults explains in part the geochronology of volcanism at Darajat. Updating our understanding of the Darajat geothermal reservoir is an evergreen process as we interpret the reservoir’s performance and data from new wells.
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