Geological and Isothermal 3-D Model of Blawan-Ijen Geothermal System

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Abstract. The Blawan-Ijen is one of the geothermal prospects in the eastern part of Java island, Indonesia. This prospect is situated in the caldera called the Kendeng caldera. The Blawan-Ijen has geothermal manifestations in two different locations, the Ijen crater in the southeast and Blawan in the northern part of the caldera. These manifestations are estimated to have different reservoirs. Different manifestations of characteristic and lithological complexity in the Kendeng caldera make the geothermal system contained in the caldera less known. Therefore, a 3D model was built on understanding the geometries of the Blawan-Ijen geothermal system. In this research, the model is limited to the geological and isothermal model. The data used in building the models are based on the literature and research data that has been done previously. Geological and isothermal models were built using Leapfrog Geothermal software. The 3D conceptual model provides a general overview of the geometries of the Blawan-Ijen geothermal system. The isothermal model shows temperature anomalies and their possible distribution.

1. Introduction
In the initial stages of exploration, the conceptual model of the geothermal system is used to understand the geological conditions and processes that occur in the geothermal system, especially about temperature, pressure, and fluid flow. This conceptual model is generally built based on the integration of geosciences (geology, geochemistry, and geophysics) and well data. This conceptual model will continue to be updated with increasing information or data. Conceptual models are generally limited to 2D models. However, this 2D model has limited information, especially regarding the geometry of the geothermal system. Therefore, the delineation of geothermal systems in 3D models is a way to better understand geothermal systems [1].

The case study in this research was conducted on the Blawan-Ijen geothermal prospect. The Blawan-Ijen is one of the geothermal prospects in the eastern part of Java island, Indonesia. Research in this area has been widely carried out on geology, geochemistry, and geophysics. The Blawan-Ijen prospect is currently in the stage of exploration well drilling. The slim hole was drilled vertically until 2000 m depth and discovered a high temperature of about 283°C [2]. Subsurface 3D models in the Blawan-Ijen area will be built based on data from previous research. This paper only discusses the construction of the geological and isothermal model.

2. Geothermal System of Blawan-Ijen
The Blawan-Ijen geothermal system is associated with active volcanic and a caldera (Kendeng caldera). The Blawan-Ijen geothermal system is controlled by a local (volcanic) structure in the form of the Kendeng Caldera and a regional structure (tectonic) of a north-south fault fracture followed by volcanic
eruption cones directed at the west-east and northwest-southeast faults. The geothermal system in a caldera can be found as long as eruption activity continues. If silicic magma bodies are formed, these resources have a life span of several million years after the last volcanic activity. The amount of a hydrothermal system that can be utilized depends on the level of the permeable zone under the caldera or in the caldera deposit. In most calderas that contain thick and dense tuff deposits, the hydrothermal system is limited to caldera ring fractures and faults that intersect the caldera, which form a permeability zone [3].

The existence of the Blawan-Ijen geothermal system is indicated by the appearance of surface manifestations in the Ijen Craters and Blawan. Manifestations around the Ijen Crater consist of acid crater lakes, acid hot springs, and fumaroles [4]. The acid crater lake has a temperature >30°C and a pH <1 [5]. The acid crater lake has about 1000 x 600 m and 200 m depth [6]. The chemical content in acid crater lakes is controlled by the continuous interaction of meteoric water with crater rocks. The presence of gas vents at the bottom of the lake also controlled the chemical content in the fluid of crater lakes [7]. This crater lake and deeper thermal system are the sources of the manifestation of acid hot springs on the western slope of the Ijen Crater. The hot springs have an acidic pH (pH<1) and a temperature that varies from 20-30°C [5]. Fluids from both crater lake and acid hot springs have SO₄-C₁ type. Fumarole activity can be found in the southeast of Ijen Crater. This fumarole has a high discharge with temperatures varying from 200°C [4,6] at several vents and about 600°C coming out on the silicic dome [8]. The manifestation of Blawan's hot springs is located in Blawan village, in the northern part of Kendeng Caldera. This manifestation has a temperature of around 35-50°C with a neutral pH (pH>~6). This hot spring has the fluids' chemical characteristics of the HCO₃-SO₄ type [9–11].

Some wells that have been drilled in the Blawan-Ijen area are slim holes. The ISH-01 slim hole well in the south reach a temperature of 80°C at a 500 m depth. At the same depth, alteration minerals (epidote) are found, estimated to be alteration minerals from extinct systems [9]. The other slim hole (IJ-X) is to

**Figure 1.** Geological map of Blawan-Ijen modification from Sujanto et al. (1988).
The north of the previous slim hole. This slim hole reaches a 2000 m depth and indicates a temperature of 283°C with neutral fluid. High temperatures are also strengthened by the presence of alteration minerals such as epidote found at depths of 1782-2000 m [2]. Figure 1 shows the distribution of the lithological unit and some manifestations in the Blawan-Ijen geothermal area.

3. Data and Method
The data used in this modeling are topography data, geology, geochemistry, and well data. The topographic data used in this modeling is based on DEMNAS with a spatial resolution of about 8 m and bathymetry data from Ijen Crater, as described by Takano et al. [6]. This data is used to build topography in the Leapfrog Geothermal software. A detailed geological survey in the Blawan-Ijen area was conducted by Sitorus (1990) and Sujanto (1988) and produced a surface geological map [12,13]. This surface geology map and cross-section are used as input data to build 3D geological models in Leapfrog Geothermal software. There are about 70 lithology units on this map, but this unit will be simplified by coloring based on rock sources to aid modeling. Subsurface temperature distribution, other than based on the well data, is obtained from the results of temperature estimation given by Saputra (2006) [1]. By this method, the subsurface temperature of the conductive layers can be determined. This method uses surface manifestation temperature data and estimated temperature from the reservoir based on geochemical data. This temperature value will then be interpolated using Leapfrog Geothermal software to provide subsurface temperature distribution in the area. The boundary of the model is limited in the Kendeng caldera area, and the bottom elevation of the model is limited to -1000 masl.

4. Results and Discussion
The results of 3D geological modeling in the Blawan-Ijen area can be seen in Figure 2. The modeling results are arranged based on volcano stratigraphy, as described in the Sitorus (1990). Figure 2 (A) shows a geological model in the early stages of Kendeng caldera formation. Figure 2 (B) is a geological model that shows the Blawan lake sediments and the product of resurgent dome activity (Mt. Blau). Figure 2 (C) is a geological model at the stage of volcano formation along the Kendeng caldera rim. The caldera rim volcano consists of Mt. Jampit, Mt. Ringgih, Mt. Suket, Mt. Rante, Mt. Pawenan and Mt. Merapi (from old to young). Figure 2 (D-F) is a post-caldera stage with several cinder cones formed inside the caldera with an east-west orientation. Figure 2 (G) shows the final 3D geological model of Blawan-Ijen. The 3D geological model shows very complex rock layers near the surface as a result of post-caldera volcanic activity. Complex lithology and lack of structure in the middle part of the caldera may be the cause of the absence of surface manifestations in this area. Based on this model, reservoir rocks are estimated to be the volcanic layer of Old Ijen composite cone with lithology consist of a pyroclastic flow, pyroclastic fall, and lava flow with andesitic-basaltic characteristics.

The results of the isothermal model can be shown in Figure 3. The isothermal models are categorized based on their temperature: high temperature (>225°C), moderate temperature (125-225°C), and low temperature (<125°C). Based on the model results, the high-temperature distribution can be seen to tend toward the Ijen Crater. This is possible because Ijen Crater is an active crater found in the Blawan-Ijen area. Besides, the Ijen crater has intense manifestation activity, such as fumaroles. Another possibility is that this high-temperature trend corresponds to the lineament of several cinder cones formed in the caldera. The lineament is likely to have good permeability so that it becomes a magma path to exit and form the cinder cone. This high temperature may be related to the presence of heat sources in the subsurface and was once correlated with cinder cones on the surface. This possibility still needs to be examined in more detail, especially with the lack of data used in this study. Geophysical data and other well data may provide a more detailed overview of the subsurface.
Figure 2. The results of 3D geological modeling in the Blawan-Ijen area, the above models are sorted from A to F based on volcano stratigraphy in Sitorus (1990). A) the initial stage of caldera formation, B) Blawan lake formation and resurgent dome (Mt Blau) activity, C) volcanic formation along the caldera rim, D-F) cinder cone formation in the caldera, and G) final 3D geological model of Blawan-Ijen geothermal area.
Figure 3. Isothermal model of Blawan-Ijen geothermal area. (A) N-S cross section through Blawan manifestation in the north and Wurung Crater in the south, (B) NW-SE cross section through Ijen crater in the southeast and Blawan manifestation in the northwest, and (C) E-W cross section through Ijen Crater in the west and well IJ-X.
5. Conclusion

The 3D geological and isothermal models show the geometry of the Blawan-Ijen geothermal system and its possible distribution. With limited data used in this 3D model, it is sufficient to provide a subsurface overview of the Blawan-Ijen geothermal system. The heat source of the Blawan-Ijen geothermal system is estimated to be magma associated with volcanic activity on the surface. This interpretation is supported by 3D isothermal model, which shows the correlation of high temperature with volcanic cones on the surface, such as Wurung Crater and Ijen Crater. Based on 3D lithological model, reservoir of this geothermal system is estimated to be old Ijen volcanic products. The absence of manifestations in the center part of the caldera is thought to be due to newer volcanic products with impermeable properties. This 3D model can be updated with increasing data to provide more detailed subsurface information. Further research and the addition of data can provide a more accurate model, so this model can be used as a guide in developing Geothermal fields in the future.

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