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The Application of Three-Dimensional Gravity Inverse Modelling to Reconstruct the Caldera Setting of Ulubelu Geothermal Fied

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ABSTRACT

Ulubelu field, operated by PT Pertamina Geothermal Energy (PGE), is situated in the Province of Lampung, Indonesia. This field is considered a volcanic-high terrain geothermal system controlled by the Sumatra Fault System, which provides a high-enthalpy, water-dominated reservoir. Since 2017, the Ulubelu field has been generating 4x55 MWe of geothermal energy, which accounts for 25% of the electricity supply of the Province of Lampung (Pertamina, 2018).

Radar and Imagery Landsat study by Siahaan et al. (2015) identified that the Ulubelu field lies in the lineaments patterns, fault segments, circular features, and collapse structure, which are strongly influenced by the overlapping NW-SE trends parallel to Sumatera Fault System (Husein at al., 2015). Recent geological mapping was done to clarify the existence of the volcanic structure of the Old Sula Volcano by visiting its caldera wall. In addition, gravity exploration was conducted in 2021 to map the Bouguer anomaly of the system.

The gravity data consists of over 600 stations, covering 20 x 20 km of the study area. Complete Bouguer Anomaly (CBA) was calculated using 2.2 gr/cm^3 of Bouguer density. The CBA anomaly of Ulubelu ranges from 24 mGal to 65 mGal, where the higher anomaly surrounds the lower anomaly in the existing exploitation area. The caldera of the Old Sula Volcano is shown as a circular shape of the high-Bouguer anomaly, which ranges from 54 mGal to 65 mGal and is associated with andesitic-lava formation. The graben structure, situated inside the caldera, is shown by a slightly lower Bouguer anomaly of 45 mGal – 50 mGal, which associates with pyroclastic rocks.

CGG Geoscience performed three-dimensional inverse modeling using a joint inversion scheme with Magnetotelluric data (CGG Geoscience, 2021). The 3D model shows the caldera structure of Old Sula Volcano as a high-density 2.5 gr/cm^3 - 2.6 gr/cm^3 circular feature. Mount Rendingan, which provides the geothermal system's heat source, has a density of 2.6 gr/cm^3, shown as a high-density body that intrudes on its lower-density surrounding rocks, is located at the Northern edge of the old Sula Caldera. The model estimates Sula's depression has a thickness of approximately 2500 m, showing low-density 2.0 gr/cm3 - 2.2 gr/cm3 layers that fill the higher-density caldera. Moreover, these recent investigations of the caldera might significantly influence the field's development, thus potentially hosting another geothermal system aside from Ulubelu's existing geothermal area.

1. INTRODUCTION

The Ulubelu Geothermal field is located in Tanggamus district, 115 km West of Bandar Lampung-Indonesia (Figure 1). Ulubelu is part of the Mount Way Panas geothermal concession area, owned by PT Pertamina Geothermal Energy, with 89,280 Hectares of total area, which comprises two prospects; Ulubelu and Waypanas (KESDM, 2017). 4x55 MWe of clean geothermal energy has been dispatched from this field since 2017, which accounts for 25% of the total electricity supply of the Province of Lampung (Pertamina, 2018).

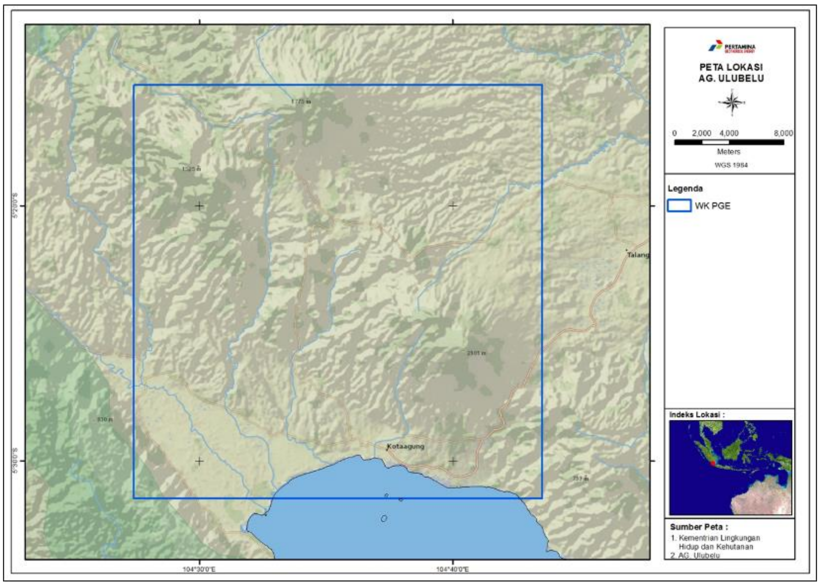

Figure 1. Map of Ulubelu Geothermal Field Concession Area

The early exploration campaign has been carried out since the early ’90s, where three exploration slim holes were drilled in 1995 with a maximum temperature of 225^0C at 1195m depth (Siahaan et al., 2015). Following the slim holes, currently, 30 production wells and 14 reinjection wells have been drilled to support the steam and reinjection requirement of the field.

2. GEOLOGICAL SETTING

Radar and the MSS imagery Landsat study by Siahaan et al. (2015) reveals the Ulubelu field lies in the lineament patterns, fault segments, circular features, and collapse structure, which according to Trianggo et al. (2015) identified as volcano-tectonic depression. The Dextral movement of the NW-SE Sumatra Fault System forms several depressions of pull-apart basins, providing numerous geothermal systems, including Ulubelu (Muraoka et al., 2010).

Several volcanic activities were developed along Ulubelu’s depressions, such as Mount Sula, Rendingan, and Tanggamus. In addition, smaller monogenic volcanisms are linked to the depression: Mount Gunung Tiga, Duduk, Kabawok, and Kukusan. As a result, the Ulubelu field was formed by a series of volcanic products such as Rendingan Lava, Oxidized Lava, Mixed Volcaniclastic Breccia, Rhyolitic Tuff, Metasediment, and Diorite Intrusion, as shown in figure 2.

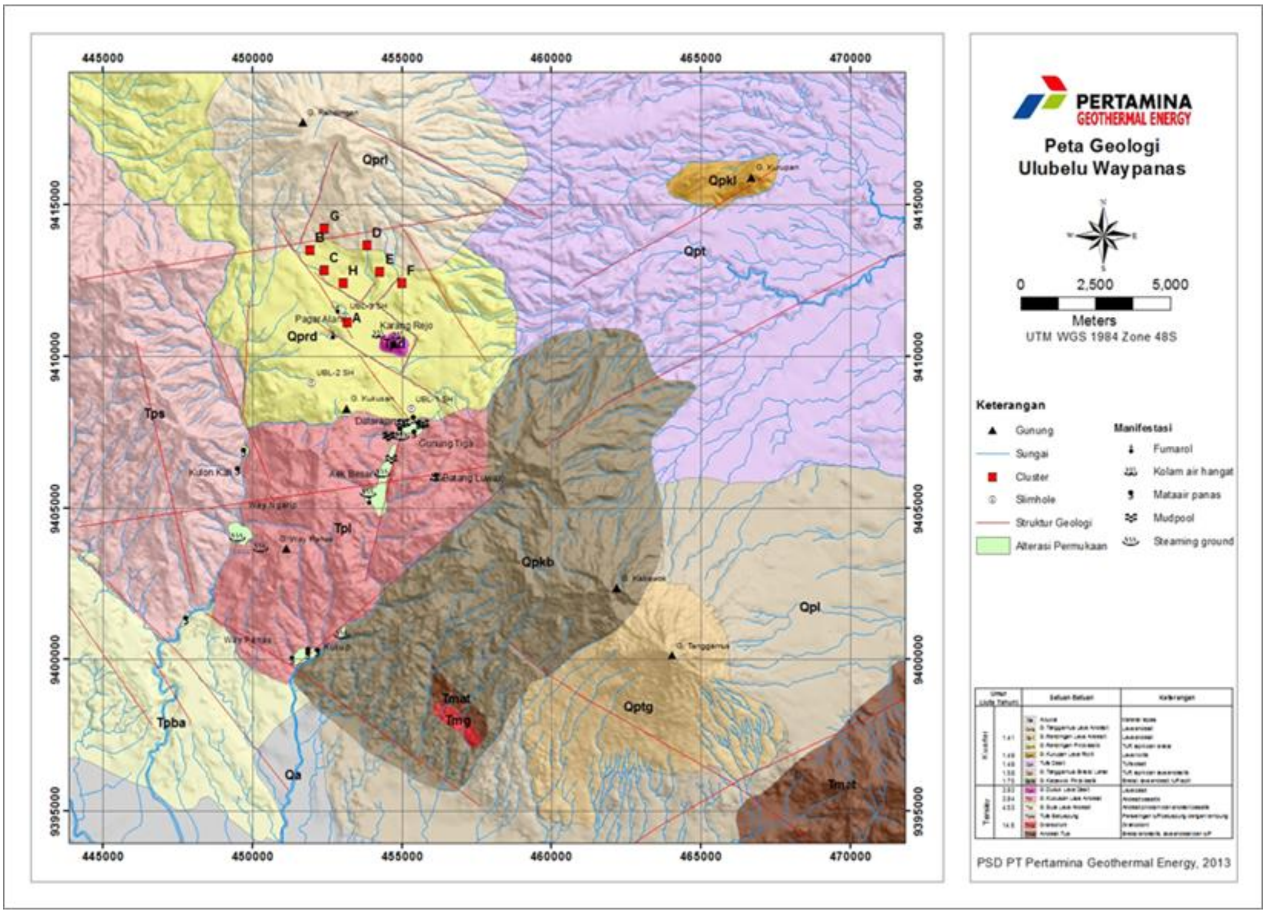

Figure 2. Geological Map of Ulubelu Geothermal Field (Pertamina Geothermal Energy, 2013)

Three NNW-SSE normal faults split the volcanic deposits within Ulubelu’s depression, the synthetic fault of the Great Sumatra Fault, namely the Pagar Alam fault, Karang Rejo, and Talang Marsum fault. Those three faults are the major faults that control the reservoir's permeability and influence the well targetting of the field. (Trianggo, et al., 2015). On the other hand, the ENE-WSW antithetic faults, such as Sula and Kukusan faults, show a less permeable zone, which diverts the geothermal fluid's lateral flow towards the South of Ulubelu. Faults and other geological structures of the field are shown as a structural map of Ulubelu Geothermal Field in Figure 3. In addition to the secondary permeability, the Rhyolitic-Tuff formation provides matrix permeability of the system, hence, hosts the geothermal reservoir.

A recent study by PGE (2021) reveals the caldera structure in the greater area of the field, known as Old Sula Caldera, whose product is the Rhyolitic-Tuff Formation. This massive circular-shaped buried structure was identified as a semi-circular collapse structure at the Southwestern part of Ulubelu. In addition, significant joints and faults are recorded at the surface outcrop, strengthening Old Sula Caldera's evidence. Moreover, this recent investigation of the caldera might influence the development of the field. The Rhyolitic-Tuff (reservoir rock) fills the caldera massively and potentially hosts another geothermal system aside from Ulubelu’s existing area, which will be elaborated more in the following sections.

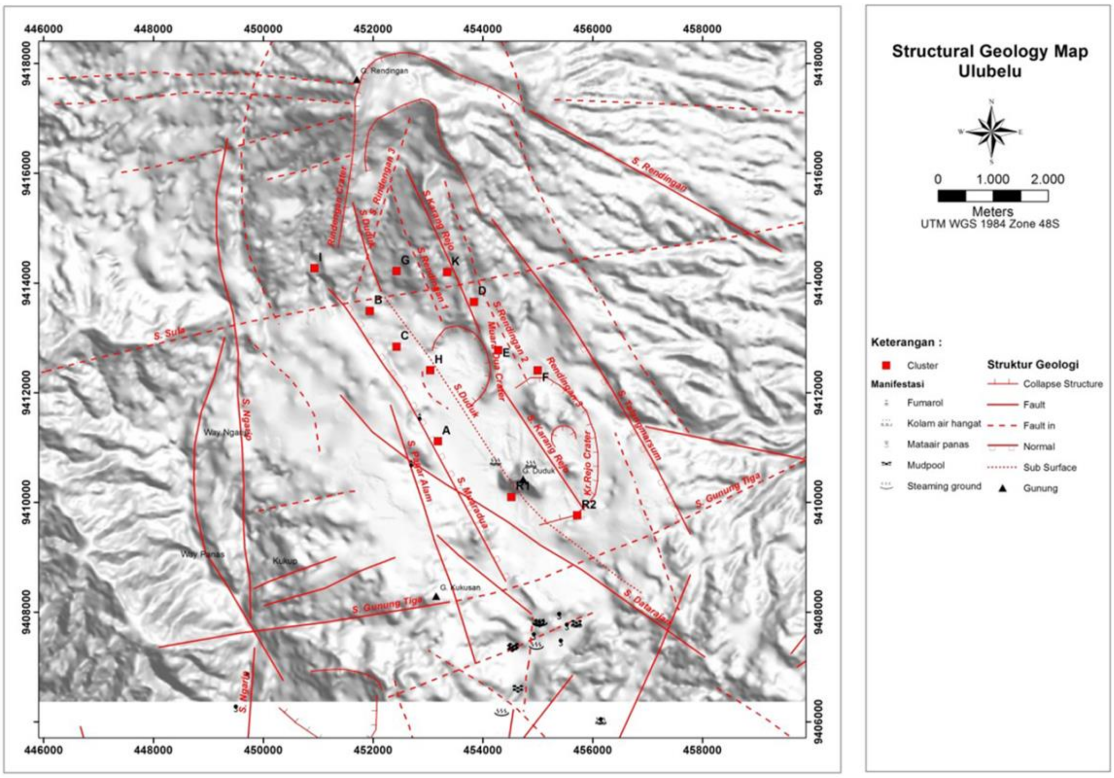

Figure 3. Structural map of the Ulubelu Geothermal Field. The Well pad is shown as red squares (Trianggo et al., 2015).

3. GRAVITY DATA

The gravity survey was conducted in several campaigns in Ulubelu. Thus, over 600 gravity stations have been acquired, which provide very good coverage of the Ulubelu resource. The Complete Bouguer Anomaly (CBA) was calculated using 2.2 gr/cm^3 of Bouguer density, which correlates with the pyroclastic formation that dominates the field's lithology, as shown in Figure 4.

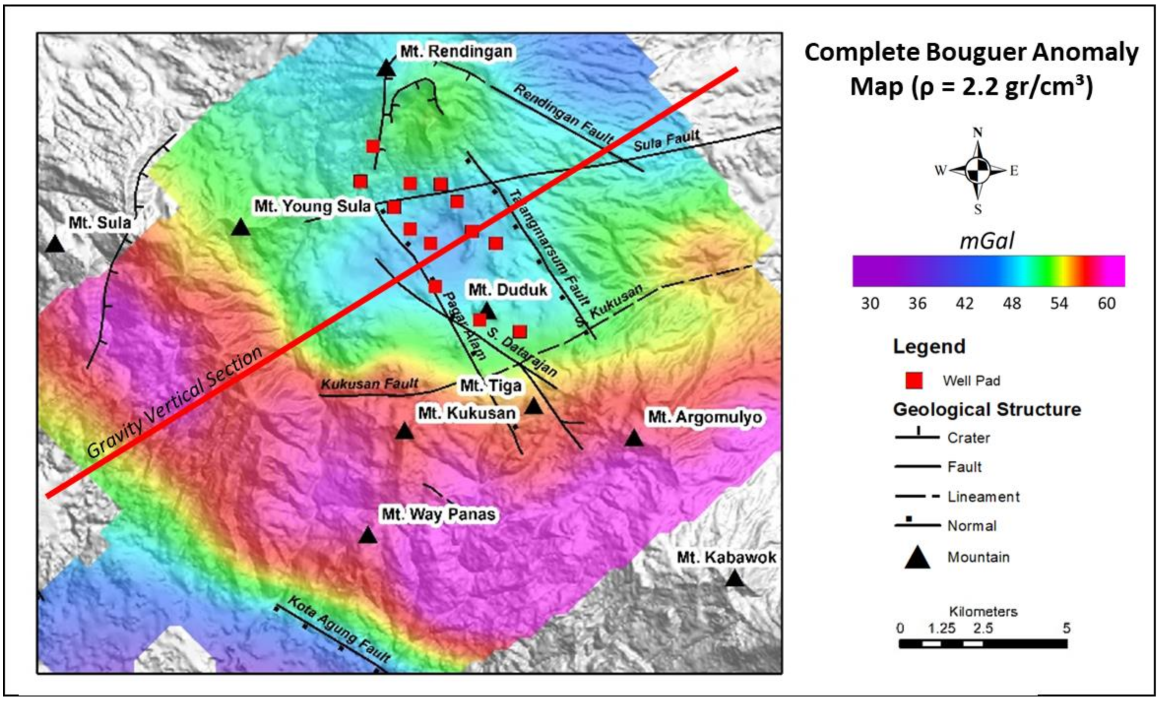

Figure 4. Complete Bouguer Anomaly Map of The Ulubelu Field. The solid red line is the slice plane for the gravity model.

The Bouguer anomaly value of the study area is within the range of 24 mGal to 65 mGal. The CBA's map shows a good correlation between the gravity data and the surface rock lithology. High gravity anomaly (reddish color), which has a Bouguer anomaly value of 54 mGal to 65 mGal, is associated with the Older Tertiary rocks. This semi-circular shape of gravity anomaly is interpreted as the caldera of the Old Sula Volcano. Moreover, smaller monogenic volcanisms are linked to this high gravity anomaly, such as Mount Gunung Tiga, Mount Kukusan, Mount Argomulyo, Mount Sula, Mount Kabawok, and Mount Way Panas.

Younger Quaternary rocks are shown as a low-Bouguer Anomaly (blueish-greenish color), which has a Bouguer anomaly value of 36 mGal to 48 mGal. Mount Rendingan, whose magma is the heat source of the geothermal system, is shown as a slightly higher Bouguer anomaly (50 mGal) than its surrounding area. The existing exploitation area, located in the vicinity of the well pads and the graben structure, is depicted with a low gravity anomaly (blueish color). The Bouguer anomaly exhibits that the reservoir zone has a Bouger anomaly value of 45 mGal to 50 mGal in the Ulubelu field.

4. DISCUSSION

The three-dimensional gravity model was performed by CGG Geoscience (2021) using a joint inversion scheme with Magnetotelluric data to reconstruct the subsurface density structure of the field. Since the model is three-dimension, the subsurface density variation can be displayed as horizontal and vertical sections, as illustrated in Figures 5 and 6.

According to the lateral density variations, the subsurface rock has a density value between 1.8 gr/cm^3 – 2.6 gr/cm^3 (Figure 5). The Density variation corresponds with the bouguer anomaly and the geological map, where less dense rock is associated with a low bouguer anomaly and the pyroclastic rock distribution. On the other hand, it can be seen that denser rock is associated with the high bouguer anomaly and the older tertiary rock, which is mainly lava deposits.

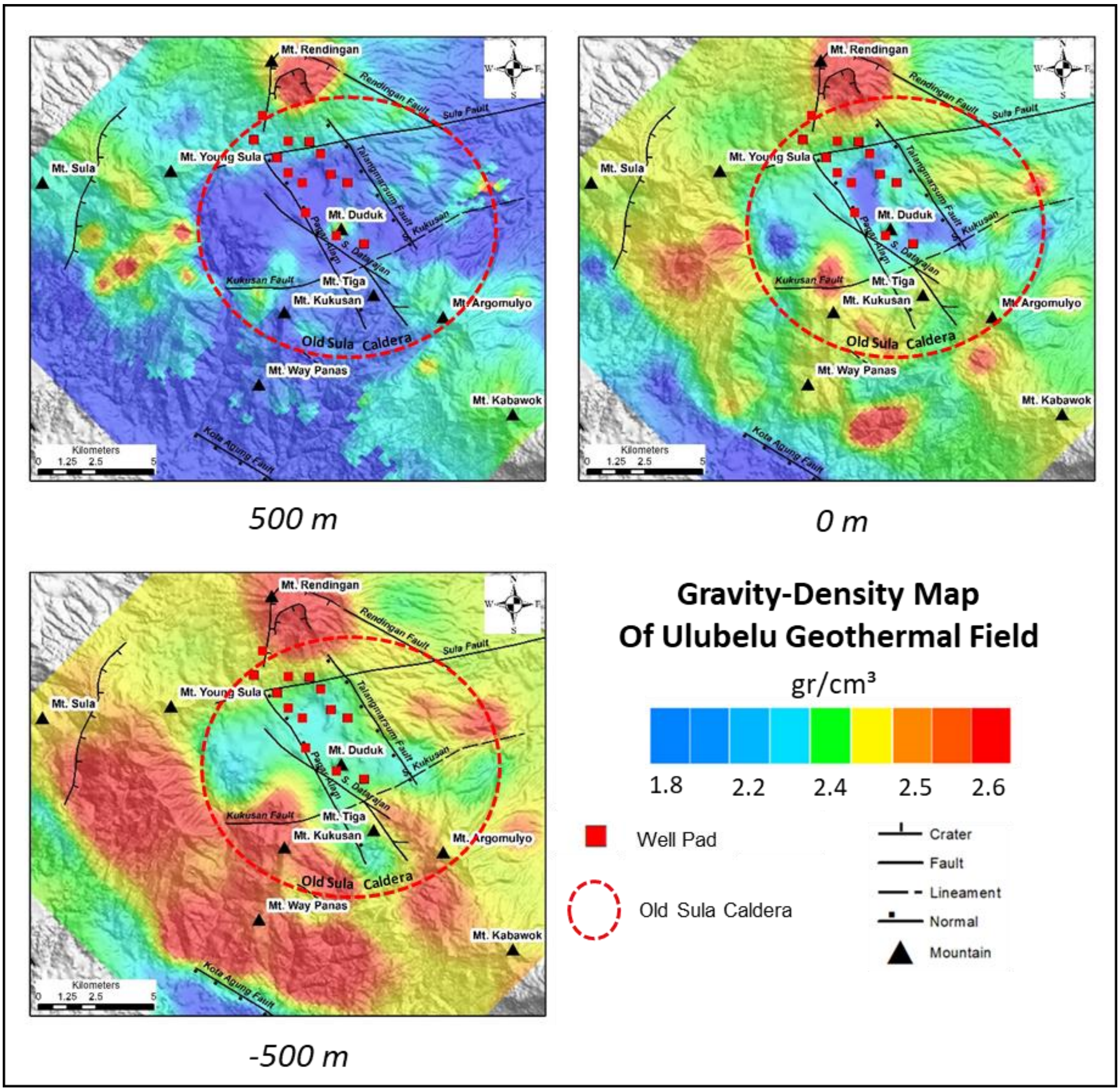

Figure 5. Horizontal slices at various elevations of subsurface density in the Ulubelu field

The caldera structure is illustrated as a semi-circular shape of a high-density body, where its rim is associated with the high to low-density anomaly. Mount Rendingan, which provides the heat source of the geothermal system, has a density of 2.6 gr/cm^3. The high-density anomaly of Mount Rendingan is shown as a high-density body that intrudes on its lower-density surrounding rocks, which are situated at the Northern edge of the Old Sula Caldera. Moreover, smaller monogenic volcanism along the caldera rim, such as Mount Young Sula, Mount Kukusan, Mount Tiga, and Mount Argomulyo, has a density value of 2.4 gr/cm^3 – 2.5 gr/cm^3, which is a relatively higher than their surrounding rocks. The monogenic volcanism and high-density anomaly along the caldera rim indicate the permeability distribution that allows the post-caldera volcanic event to emerge and might host another geothermal system.

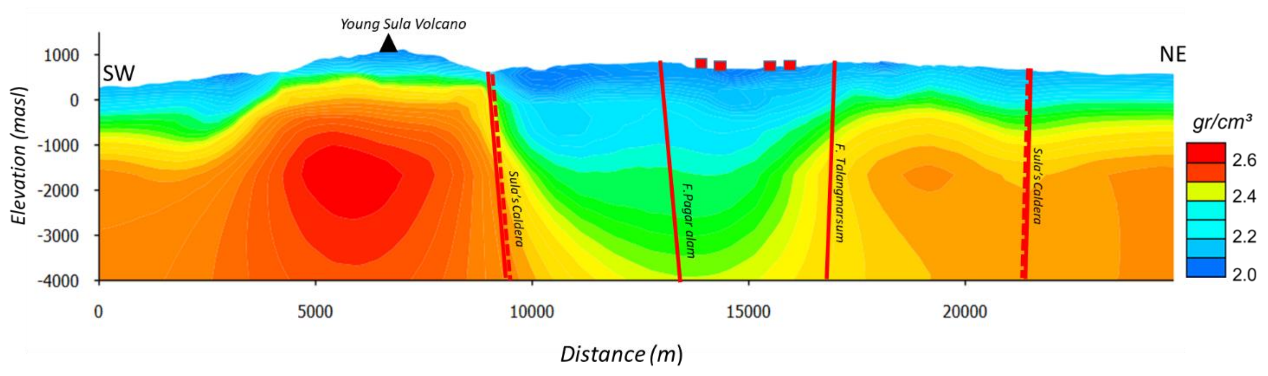

Figure 6. SW-NE Vertical section of the 3D gravity model in Ulubelu field. Well pads are shown as red boxes at the surface.

The existing exploitation area is dominated by the low-density body, which is localized at the graben structure between Pagaralam Fault and Talangmarsum Fault and extends to the West towards the caldera rim. The model estimates Sula's depression has a thickness of approximately 2500 m, which is shown as a low-density 2.0 gr/cm3 - 2.2 gr/cm3 layer that fills the higher-density caldera. Moreover, the model also suggests that the pyroclastic product of the Sula Volcano might fill the caldera up to elevation -4000 masl, which is shown as a low-density 2.0 gr/cm3 - 2.4 gr/cm3.

5. CONCLUSION

Three-dimensional inverse modeling with a joint inversion scheme with MT data can reduce the gravity model's ambiguity, particularly the model's vertical resolution. This method has advantages in modeling geological features, especially those sensitive to density variation. In this study, the gravity method reveals the magmatic intrusions and caldera structure with a satisfactory result. Furthermore, integrated analysis with other geophysical methods, such as magnetotelluric and microearthquake, could lead to a more comprehensive understanding of the field.

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