Productive Structural Geology in Volcanogenic System: A case study of Lumut Balai Geothermal Field, Indonesia

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Abstract. Lumut Balai is geothermal field that occurs in the caldera system, named Lumut Tua Caldera, approximately 9 km in diameter. Located in Penindaian Village, Muara Enim Regency, South Sumatra Province. Lumut Balai is one of the fields operated by Pertamina Geothermal Energy. The volcanism in Lumut Balai is closely related to the Sumatra Fault System activity. Surface data such as outcrops provide information regarding lithology, alteration type, and geological structures, while manifestations provide fluid geochemistry data. Subsurface data are acquired from rock cuttings and core samples (which are then further analyzed through petrographic analysis and XRD analysis), drilling parameters, and borehole image logging. These provide information and interpretation of subsurface geological conditions such as lithology distribution, alteration distribution, reservoir zone, heat source, and permeability. The methods above result in an interpretation of the Lumut Balai geological model. Lumut Balai is a geothermal system located within the Lumut Balai caldera, composed of andesite, andesite breccia, basaltic andesite, basalt, limestone, meta-sediment, tuff, and tuff breccia which are all altered to certain extents. There are five stratigraphic units, starting from the oldest to youngest are Tertiary Basement Unit, Pre-Old Lumut Unit, Pre-Caldera Unit, Caldera Unit, and Post-Caldera Unit. Alteration zones in Lumut Balai could be classified into smectite+chlorite zone, silica+chlorite zone, and chlorite+epidote zone. Productive faults in Lumut Balai are Air Ringkih Fault with NE-SW trend, Air Udangan Fault trending NE-SW, Lumut Tua Caldera and Gemurah Besar which trends N-S. This study aims to confirm the productive geological structure in Lumut Balai and gives better understanding for future field development, such as well targeting for makeup wells and reservoir simulation.

1. Introduction
Lumut Balai is located approximately 292 km southwest of Palembang, around 8 hours of driving from the Palembang airport. Regionally, Lumut Balai lies 60 km east of the Komering Segment, the eastern side of Sumatra fault (Figure 1).

Lumut Balai is easily recognized by the existence of the NE-SW structures and some of manifestations which are presents within caldera. The geothermal field has been the object of geoscientific investigations since the year 1993, when Pertamina conducted geological, geochemical and geophysical surveys over the whole area of potential interest [1]. Deep exploratory drilling started in 2008, currently there are 20 production wells and 9 injection wells has been drilled. First powerplant
Unit 1 with 1 x 55 MW capacity has begun operating and is planning to expand additional unit 2 for 1x55 MW.

The objective of this paper is to discuss the result of geology, geochemistry and geophysical data analysis in relation to permeability and the appearance of geothermal system in Lumut Balai. Permeability is one of the main components of a geothermal system. In volcanic settings, permeability is mostly controlled by geological structures such as faults and fracture zones. It could also be controlled by lithological contact and the host rock characteristics.

Understanding the permeability distribution of a geothermal field is an essential key to successful exploration. By comprehending the permeability distribution, well targeting process could be more efficient by planning well trajectory and predicting total loss circulation zones more accurately.

2. Data and Method
This study combines surface and subsurface data for interpreting the geology Lumut Balai. We interpret the geology Lumut Balai. The data analysis was conducted using several softwares such as Leapfrog, Logplot, ArcGIS, and Petrel.
2.1. Surface Data
The surface data obtained by LiDAR and IFSAR image analysis, and geological mapping. Geological mapping was also conducted to get a better understanding about the surface geology of Lumut Balai. This covers outcrop observation and measurements from the Lumut Balai field. The data from geological mapping are compiled into a Lumut Balai Composite Log and any joint or slicken line trend measurement are plotted onto the Lumut Balai structure map [3]. The hand specimens are collected to be further analysed by using XRD and petrography analysis. The orientation of slicken line, joint and fracture are then plotted to the geological map to determine the structural geology trend in the area.

2.2. Subsurface Data
Subsurface data used in this research are acquired from cuttings, cores, drilling parameters such as loss circulation zones, and borehole image logging. XRD and petrography analyses of cuttings and cores from Lumut Balai drilling campaign enables a better understanding of the subsurface lithologies and alteration zones [4]. Geophysical measurements, such as magnetotelluric and gravity measurement, have been carried out to comprehend the physical properties in prospect zone. Drilling parameter in the form of loss circulation zones and borehole image logs from each well could confirm the presence of faults and lineaments inferred from surface data. Loss circulation zones provide ample information regarding the permeable zones created by major faults or fracture zones in the subsurface. At the same time, borehole image logs could give information concerning the conductive fracture zones in the well, which gives information regarding the strike-dip trends of subsurface faults and fractures. These strike-dip trends are then plotted on the Lumut Balai structure map, correlated with the faults and fractures found on the surface. The surface and subsurface data are then compiled and inputted to 3D modelling software to construct Lumut Balai’s 3D geological model.

3. Result and Discussion
Lumut Tua Caldera extends approximately ±9 km in diameter., Lumut Balai is an example of a geothermal field that occurs within a caldera. According to [5, 6] volcanic occurrences in Sumatera are closely related to activity of the Sumatran Fault System (SFS). This could be proven by the distribution of Neogen until Quaternary around Sumatra Fault and expanding from southeast to northwest of Sumatera. Volcanic eruption center in Lumut Balai (Pandan Hill – Penindaian Hill – Ringgit Hill – Lumut Hill) forms a north-south lineage pattern. This north-south trend is thought to be the product of Pre-Tertiary N-S faults reactivation by the Quarternary-Recent stress system [2].

3.1. Remote Sensing
LiDAR and IFSAR image analysis inferred that the geological structures in Lumut Balai show an old volcanic complex that has collapsed, forming a giant caldera, which is then referred to as Lumut Tua Caldera. This volcanic complex was built by the series of eruption centers, which are Bt. Pandan, Bt. Ringgit, Bt. Lumut, dan Bt. Balai. On the margin of the caldera’s rim, a new eruption center could be seen, on the southeastern flank of the caldera is Bt. Pandan and on the northwestern side is Bt. Balai. All across the western flank of the Lumut Tua Caldera, a relatively N-S trending fault could be found, this fault is also considered as the western side of the Lumut Balai geothermal prospect’s boundary. The two lineament patterns in the center of Lumut Tua Caldera are interpreted as NE-SW and NW-SE faults. Some major faults are associated with the occurrence of geothermal manifestations such as Air Ringkhi Fault, Gemurah Besar Fault, Patahan Fault, Udangan Fault, Ogan Kanan Fault, and Tanjung Tiga Fault. Meanwhile, on the eastern side, the geothermal prospect boundary is limited by Lumut Tua Caldera (Figure 2).
Figure 2. Slope analysis of Lumut Balai topography. Aspect analysis of Lumut Balai topography. A circular caldera could be identified; it is inferred as Lumut Tua Caldera.

The presence of Lumut Tua Caldera and several other lineaments could be distinguished on hill shaded IFSAR and LiDAR images. Figure 2 and Figure 3 shows the several main geological structures could be identified through hill-shade analysis, such as Lumut Tua Caldera, Gemurah Besar Fault trending N-S, Air Ringkikh Fault with NE-SW trend, Udangan Fault trending NE-SW, Fault Patahan trends NW-SE, Ogan Kanan Fault trending NE-SW, and Tanjung Tiga Fault trending NW-SE.

Figure 3. Hill-shade analysis of Lumut Balai’s IFSAR and LiDAR images shows the N-S, NE-SW, NNE-SSW faults shown in red, and the circular Lumut Tua Caldera in yellow.
3.2. Stratigraphy

The Lumut Balai surface lithologies is composed of andesite, andesite breccia, basaltic andesite, basalt, limestone, metasediment, tuff, and tuff breccia which are all altered to certain extents Lumut Balai is at least divided into thirteen rock units. These thirteen units are determined by surface mapping obtained from around the Lumut Balai geothermal field, outside of and within the Lumut Tua Caldera, with elevation starting from 870 masl to 1880 masl. In addition, morphological characteristics are also obtained from LiDAR imagery enabling a more accurate rock unit determination.

The petrographic analysis shows that the Lumut Tua Caldera is dominated by extrusive rocks such as andesite, pyroxene andesite, andesite lava, breccia, tuff, altered tuff, and conglomerate. There are no intrusive rocks found. Most of the samples found on the surface have been hydrothermally altered and intensively weathered.

From the analyses result and surface data plotting, the lithological distribution pattern could be concluded, which is heavily influenced by the succession of the eruption center. It is then inferred that Lumut Balai has undergone at least two destructive phases [7].

This is evident in the lithological distribution related to the morphology and elevation, see Figure 4. The rock deposits product of the destruction process shows the conformity, which is the higher elevation shows younger lithologies, conversely older lithologies are found on lower elevation [8] and [9], this is evidenced in multiple stopsite on various locations throughout Lumut Balai. Based on the geological data, it is deduced that the oldest lithology in Lumut Balai is the Tertiary Basement, consists of metasediment in the form of meta-shale and metasandstone, which could be found in the northeastern part of Lumut Balai around Bunbun Hill. The youngest lithology is the quaternary Pyroxene Andesite which is a part of Young Lumut formation.

A wholesome Lumut Balai composite log in Figure 4, was constructed from surface mapping data, which includes information concerning lithologies, joints, faults, and alteration distribution. Trends and rosette diagrams from the fault and joints measurements are also plotted onto Lumut Balai Structure Map.

![Figure 4. Lumut Balai Surface Composite Log PGE [10].](image-url)
3.3. Geological Structure
A detailed measurement data confirms the occurrence of seven main geological structures in Lumut Balai, which is pictured in figure 6, namely Lumut Tua Caldera, Gemurah Besar Fault, Air Ringkigh Fault (SAR), Udangan Fault (SUD), Fault Patahan (SPT), Ogan Kanan Fault (SOK), Tanjung Tiga Fault (STT). This geological structure is based on the assessment activities which is conducted in 2018 [10].

3.3.1. Lumut Tua Caldera (KLT). The occurrence of this caldera is determined by observing the scarp morphologies on the east, north, and southern part with the southwest section buried by the Bt. Lumut Muda eruption products and was cut through by Gemurah Besar Fault.

3.3.2. Gemurah Besar Fault (SGB). This fault has N-S orientation and crosscuts two eruption centers which are Bt. Asahan and Bt. Lumut. By observing the morphology of steep scarp, valleys, the occurrence of manifestation, and field measurement data N300°E/85° on the northern part of the field, it is inferred that this fault is dipping to the west. The occurrence of geothermal manifestation to the west of the fault concludes that Gemurah Besar Fault is a normal dip-slip fault with its western block as the hanging wall. Minor faults prominent lineaments trending NW-SE and could also be seen near this fault.

This fault is proven by morphology data in the form of steep scarps facing NW with NE-SW trend, also by the occurrence of Air Ringkigh and Bunbun geothermal manifestation. Air Ringkigh Fault is a normal fault with its NW block as its hanging wall. Several offsets could be found through the Air Ringkigh Fault line as it was also crossed by Patahan Fault trending NE-SW.

3.3.3. Udangan Fault (SUD). This fault is inferred by scarp lineament facing west trending NE-SW, and geothermal manifestation occurrences on the eastern side of the scarps. Based on this data, it could be concluded that Udangan Fault is also normal with its western block as its hanging wall.

3.3.4. Patahan Fault (SPT). Patahan Fault trends NW-SE and crosses over Air Ringkigh Fault. Several geothermal manifestations could be found on the surface of Patahan Fault’s fault line.

3.3.5. Ogan Kanan Fault (SOK). Ogan Kanan Fault trending NE-SW is proven by scarp lineaments and Ogan Kanan 1 and Ogan Kanan 2 geothermal manifestations. It has concurred that this fault is a normal fault with its NW block as its hanging wall.

3.3.6. Tanjung Tiga Fault (STT). Tanjung Tiga Fault is located outside of Lumut Tua Caldera, on the southern part of the Lumut Balai geothermal prospect. Its occurrence is marked by NW-SE lineaments and Tanjung Tiga geothermal manifestation with its massive dimension.

Based on the trend and type, the faults in Lumut Balai could be divided into two main groups, which are: faults that are non-tectonic and faults that are associated with the regional stress. The first group is more closely related to the Lumut Balai Caldera’s formation and radial faults found on the Lumut Tua Volcano’s body. The second group is related to the regional stress pattern with faults trending N-S, NE-SW, NW-SE, and W-E (Figure 5).
According to the regional tectonic pattern, faults trending N-S and NE-SW are first faults to develop and is thought to be the main fault lane in Lumut Balai. This fault lane is the center of Lumut Balai’s Quaternary volcanic activity. These faults have likely been reactivated by younger regional stress, proven by the geothermal manifestation occurring along the faults near Bt. Lumut - Panindayan and Bt. Bunbun-Sepanas Hilir. Fault systems trending NW-SE are the latest to develop and reactivated by the Sumatran Fault such as Patahan Fault and Tanjung Tiga Fault.

In the figure 6 shows the main fault system trending N-S and NE-SW that crosses over Lumut Balai Caldera rim are the main manifestation control at the surface that are spread concurringly as the faults’ trend. In other words, N-S and NE-SW fault controls the permeability of the prospect area, so that the fluids could flow to the surface and forms geothermal manifestations, such as Gemurah Besar Fault (N-S) and Air Ringkih Fault (NE-SW).

**Figure 5.** (a) Rose diagram of radial fault. (b) Rose diagram of regional stress fault trending patterns.
3.4. Subsurface Data

3.4.1. Lumut Balai Subsurface Geology. From cutting and core data, Lumut Balai rock unit could be divided into five stratigraphic units, starting from the oldest to youngest are Tertiary Basement Unit, Pre-Old Lumut Unit, Pre-Caldera Unit, Caldera Unit, and Post-Caldera Unit depicted (Figure 7).
The Tertiary Basement Unit is composed mainly of metasediment lithology (Figure 8), while this unit was not found on the wells within the Lumut Tua Caldera, Tertiary Basement Unit is found more commonly in the wells outside of Lumut Tua Caldera, such as in the reinjection clusters, starting from elevation ±500 masl. Based on the analysis conducted, it is known that this metasediment lithology does not have good permeability in the Lumut Balai geothermal system.

Pre-Old Lumut Unit consists of tuff breccia with foraminifera fossil content (see figure 9). Inside the caldera rim, Pre-Caldera Unit could be found from 500 masl to -1000 masl, while outside of the Lumut Tua Caldera, it could be found on elevation as shallow as 1000 masl to 500 masl. In the productive zone in the southern part of the prospect area, this lithology which is penetrated by drilling, showing that this lithology contributes to lateral permeability.
Pre-Caldera Unit is composed of tuff breccia with lithic andesite fragments, crystal tuff, and andesite lava (Figure 10). Within the caldera, this unit could be found at 1000 masl to 0 masl, and around 1200 masl to 1000 masl outside of the caldera rim. In contrast with the alteration which develops evenly within the caldera, the lithological distribution in Lumut Balai exhibits the occurrence of multiple destructive phases. In some well, such as in the production zone, this lithology is also included as a permeable lithology formation, although less contribution.

Figure 9. Foraminifera fossil fragments in Pre-Old Lumut Unit. (Left: 45°-Nicol, right: X-Nicol)

Figure 10. Andesite fragments within the tuff in Pre-Caldera Unit. (Left: 45°-Nicol, right: X-Nicol)

Figure 11. Pumice in thin section from Caldera Unit. (Left: 45°-Nicol, right: X-Nicol)
Caldera Unit consists of tuff breccia with lithic fragments, crystal tuff, and pumice (Figure 11). This unit could be found at 1200 masl to 500 masl inside the caldera, and approximately 1500 masl to 1200 masl outside of Lumut Tua Caldera. The distribution of this lithology commonly found on the surface, so that it does not have much impact on permeability in the Lumut Balai geothermal system.

Post-Caldera Unit is constructed by intercalation of tuff breccia and andesite lava (Figure 12). This unit could be found to the southwest of the field with 500 – 1000 meters thick. The spread of these rocks shows that the volcanism activities in Lumut Balai are multiple, this is one of the causes distributions of radial geological structures considerable.

Figure 12. Andesite from Post-Caldera Unit. (Left: //Nicol, right: X-Nicol)

3.4.2. Geophysical Data. Geophysical measurements, such as magnetotelluric and gravity measurement, has been carried out before Lumut Balai’s drilling campaign begun [11]. Magnetotelluric measurement is utilized to differentiate the subsurface resistive and conductive zones (Figure 13). By setting the resistive and conductive zones apart, permeable zones could be inferred by identifying openings in the conductive layers or often interpreted as the clay cap. Openings in the clay cap could indicate the presence of major faults.

Figure 13. An example of of Lumut Balai MT section. Openings in conductive layers shown in yellow to red indicates the presence of faults or permeable zones, resulting in surface manifestations.
Gravity measurements could give an overview of the density distribution of the subsurface lithologies (Figure 14). The more solid, heavy and, compact the rocks, the denser it is. Less dense areas could mean porous or permeable lithologies or the presence of fracture or fault zones. From the density map below, anomaly lineaments could be determined by defining high anomaly zones and low anomaly zones. These anomaly lineaments trends NE-SW and NW-SW similar with the trends in Lumut Balai productive geological structures.

The red line depicted in (Figure 14), based on the density anomaly seen. After the line is drawn, it will then be correlated with geological structure data obtained from the results of geological mapping and borehole data. For example, the fault line of the Gemuha Besar Fault, the structure is depicted from a high anomaly in the eastern part with a low anomaly in the west, with the result that fault line can be drawn with N-S direction. Moreover, Lumut Tua Caldera, Air Udangan Fault and Air Ringkhi Fault also be illustrated from the density anomaly.

![Lumut Balai density map](image)

**Figure 14.** Lumut Balai density map. Areas in red are denser than the green and blue areas

3.5. *Lumut Balai Subsurface Faults and Fractures*

The inferred faults have already been established from surface data, namely the Lumut Tua Caldera, Gemuah Besar Fault trending N-S, Air Ringkhi Fault with NE-SW trend, Udangan Fault trending NW-SE, Fault Patahan trends NE-SW, Ogan Kanan Fault trending NE-SW, and Tanjung Tiga Fault trending NW-SE.

These inferred faults could be confirmed or proven by the subsurface data, such as borehole image logging and the presence of total loss circulation zones in each well (Figure 15), which gives information regarding subsurface faults zones and fracture zones.
Borehole image logs (Figure 16) also provides ample information regarding the trends of the subsurface faults and fractures, enabling a correlation between the subsurface faults and fractures with the inferred faults and lineaments on the surface (Figure 17).

![Image of borehole image logs]

**Figure 15.** Correlation of total loss circulation zones in Lumut Balai’s wells

A correlation of total loss circulation zones could provide information regarding the elevation distribution of total loss circulation zones. As seen in figure 15, the shallowest loss circulation zone could be found inside the Lumut Tua Caldera in cluster production with elevation around 750 meters above sea level (mASL), while the deepest loss circulation zone are found in wells outside of Lumut Tua Caldera, particularly in the injection clusters with elevation approximately -1000 masl.

During Lumut Balai drilling campaign, borehole image logging (Figure 16) was carried out in some of Lumut Balai’s wells to determine the subsurface fracture zones and distinguish its major trends.
Figure 16. (a) Borehole image data shows fault zone in volcanic breccia lithology in production well, the fault appeared black meaning the fault is conductive (b) Borehole image data shows permeability is controlled by a rock matrix

By picking out the conductive fractures seen through the borehole image log, a rosette diagram which represents the distribution of the fractures strike and dip could be constructed. Furthermore, by correlating the conductive fracture zones from each well, a 3D fracture zone model could be constructed as depicted on (Figure 17).
Figure 17. Rosette diagram of fractures inferred through borehole image logging overlain on top of Lumut Balai structure map.

Table 1 shows an integration of surface and subsurface data results in Lumut Balai Fault Assessment. From the fault assessment, it could be concluded that the productive faults in Lumut Balai are Air Ringkih Fault, Air Udangan Fault, Lumut Tua Caldera, and Air Gemurah Besar. Air Ringkih Fault is proven through field observation, drilling activities in the form of drilling break and borehole image logging, while from geochemical aspect Air Ringkih Fault provides a conduit for Air Ringkih and Bunbun manifestations and is proven in geophysics’ gravity measurements. Meanwhile, Air Udangan Fault is determined by field measurements and lithological offsets, gravity measurements, also by drilling parameters in cluster production inside the caldera. Air Udangan Fault is the main permeability path for Air Patahan and Air Udangan manifestations. Lumut Tua Caldera is proven by drilling activities in cluster reinjection, gravity data, and lithological offsets found in the field. Lastly, Gemurah Besar fault is proven by field measurements, lithological offsets, loss circulation zones in cluster production, gravity data, and by the presence of Gemurah Besar and Air Abang manifestations.
From the field assessment, it could be concluded that the productive faults in Lumut Balai are Air Ringkih, Air Udangan, Lumut Tua Caldera, and Gemurah Besar. They are proven by geological, geochemical, and geophysical data. Geologically, Air Ringkih Fault is proven through field observation, drilling activities in the form of drilling break and borehole image logging. While from geochemical aspect, Air Ringkih Fault provides a conduit for Air Ringkih and Bunbun manifestations, and is proven in geophysics’ gravity measurements. Meanwhile, Air Udangan Fault is proven by field measurements and lithological offsets, gravity measurements, also by drilling parameters in cluster A wells. Air Udangan Fault is the main permeability path for Air Patahan and Air Udangan manifestations. Lumut Tua Caldera is proven by total loss circulations in reinjection cluster, gravity data, and lithological offsets found in the field. Lastly, Gemurah Besar Fault is proven by field measurements, lithological offsets, loss circulation zones in cluster A, gravity data, and by the presence of Gemuha Besar and Air Abang manifestations.

These faults are also proven through borehole images carried out in several wells in Lumut Balai. The borehole image logging can indicate bed boundaries, fractures, faults, and lithofacies. Seen in figure 18, the dark areas indicates the presence of a fault zone.

The conductive faults and fractures from borehole images are then summarized in a rosette diagram to understand their strike (azimuth) trend. From the correlation done by overlaying the rosette diagrams and the surface fault trend on a comprehensive Lumut Balai structure map, it is found that the subsurface trends and the surface trends are similar. This evidence further confirms the surface trends as productive faults found in well boreholes.
As seen in (Figure 18) the permeable zone is the thickest inside the caldera, especially in southwestern part. The peak of the permeable zone forms a NE-SW lineament, parallel with the NE-SW fault just to the south of the clusters. To the northwest, outside of the caldera, no loss circulation zones have been found. Therefore the permeability model looks quite similar to a dome structure where the peak of the dome is in the center of Lumut Tua Caldera and starting to thin out to the perimeter of the caldera’s rim. If a figure has parts these should be labelled as (a), (b), (c) etc on the actual figure. Parts should not have separate captions.

4. Conclusions
Lumut Balai geothermal field is one of the examples of the geothermal field located within a caldera. Lumut Balai caldera, composed of andesite, andesite breccia, basaltic andesite, basalt, limestone, metasediment, tuff, and tuff breccia which are all altered to certain extents. This study concludes stratigraphic units, starting from the oldest to youngest are Tertiary Basement Unit, Pre-Old Lumut Unit, Pre-Caldera Unit, Caldera Unit, and Post-Caldera Unit. Good permeability is found within the caldera with little to no permeability found outside of the Lumut Tua Caldera. Productive faults in Lumut Balai are Air Ringkik Fault with NE-SW trend, Air Udangan Fault trending NE-SW, Lumut Tua Caldera, and Air Gemurah Besar which trends N-S.

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