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Updated Geological Framework of Wayang Windu Geothermal Field, Indonesia

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ABSTRACT

The Wayang Windu geothermal field is one of the most prominent geothermal fields in Indonesia and has been producing since 2000 with a total installed capacity of 227 MWe. The published Wayang Windu geological model was evaluated in 2006 and focused on facies units and regional structures setting from the analysis of LANDSAT data.

During 2006 to 2021, additional data has been sufficiently gathered, including subsurface lithology data from make-up wells which drilled in several drilling campaigns between 2006-2021, gravity data from gravity survey obtained in 2008 and high-resolution Digital Elevation Model (DEM) data from Light Detection and Ranging (LiDAR) survey in 2019.

In 2021-2022, the geological model is updated with the main objectives is to have a better understanding of the geological framework at the Wayang Windu geothermal field and providing a more robust data feeding for advanced analysis (i.e., static model and numerical reservoir model). Several initiatives were executed during the geological model update. The DEM data analysis was performed, aimed at refining the interpretation of volcanic features, surface formation boundary and surface structure lineaments. The subsurface lithology data from the well have been regrouped into specific petrophysics groups where the group will be related to the formation in Wayang Windu. Paleosol identification and XRD analysis were conducted to have a better understanding of paleosol characteristics and its distribution in Wayang Windu. The paleosol is used as a marker for subsurface formation distribution. Gravity inversion model is constructed to give a better picture of the intrusion shape in Wayang Windu.

The DEM data shows several conspicuous volcanic centers in Wayang Windu. The surface formation boundary suggests nine formations unit related to the identified volcanic centers. The combination of surface formation boundary and subsurface lithology distribution, enhanced with paleosol analysis as a marker, has helped refine the formation distribution and allowed the definition of eleven formations unit in Wayang Windu. The surface structures lineament analysis from DEM, combined with gravity data and subsurface lithology distribution suggests several structure lineaments, which dissected the field into several zones that have a different formation distribution. A gravity inversion modeling has allowed the interpretation of the intrusion body, which is distributed in the South and North of Wayang Windu, completing the updated geological framework of Wayang Windu.

1. INTRODUCTION

The Wayang Windu Field, located in Pangalengan district, West Java Province, about 150 km southeast of Jakarta (capital city of Indonesia), lies on the southern slopes of a large andesitic stratovolcano called Mt. Malabar, and on a string of smaller volcanoes trending towards the south, which includes Mt. Wayang and Mt. Windu. This field is surrounded by several high-terrain geothermal systems such as the Darajat, Kamojang, and Patuha fields (Figure 1). The initial exploration stage, undertaken by PERTAMINA, drilled the discovery well of the Wayang Windu field in 1991, confirming the transitional liquid-vapor type geothermal system (Bogie et al., 2008). The development began in 1996 by MNL (Magma Nusantara Ltd.), and the production has been commenced in 2000 with a total installed capacity of 227 Mwe to date.

Figure 1: The location map shows the location of Wayang Windu geographically and the surrounding geothermal fields.

The published Wayang Windu geological model was focused on facies units as result of volcanic facies model and regional structures setting from LANDSAT data analysis. The use of LANDSAT and volcanic facies analysis is quite challenging due to the presence of multiple volcanic centers at Wayang Windu field that make it more difficult to attribute the volcanic rocks to which vent or volcano. The first geological model of the Wayang Windu field defined five formations with formational boundaries represented by sharp changes in volcanic facies and/or where an angular unconformity is found (Bogie and McKenzie, 1998). The five formations, from the oldest to the youngest, are Loka formation, Waringin formation, Pangalengan formation, Malabar formation, and Wayang Windu formation. The development in the northern area of the Wayang Windu field suggests the re-classification of formations where the Dogdog formation was distinguished and interpreted as having a similar age and interfingering relationship with the Pangalengan formation (Ramadhan et al., 2012).

Additional subsurface lithology data since the first geological model published are gathered from cutting and core during drilling campaigns. Five make-up well drilling campaigns were performed from 2006 until 2021. Total of nine wells were drilled from 2006 to 2007, followed by 12 wells in 2011-2012 drilling campaign. Five make-up wells were drilled from 2015 to 2016 before drilling other four wells in 2018- 2019 campaign. Recently, total of six make-up wells were drilled in the last drilling campaign that was held from 2020 to 2021. Currently, Wayang Windu field has a total of 65 wells including five slim holes. Some essential information also has been collected through several key surveys during this period, such as gravity and LiDAR surveys. Gravity survey was conducted in 2008, followed by gravity inversion modeling which will be incorporated in this paper. Whereas, a LiDAR survey was conducted by the end of 2019, resulting in a DEM with high resolution.

Referred to the additional data gathered after the first geological model published, this paper will discuss the updated geological model, results of stratigraphy and structure analysis of Wayang Windu field using the 2019 LiDAR data, subsurface lithology information from wells drilled during 2006-2021 make-up well drilling campaigns, gravity data and gravity inversion model.

2. STRATIGRAPHY ANALYSIS

Situated in an area with multiple volcanic centers, the stratigraphic sequence of Wayang Windu is quite challenging to determine. Mt. Wayang Windu has dacitic-andesitic volcanism, Mt. Papandayan in the southeastern has basaltic-andesitic volcanism, while in the northern area andesite lava of Mt. Malabar is found. It is difficult to determine the stratigraphic sequence of these three volcanisms, but from the three different rock properties, it is suspected that there was a magma differentiation from intermediate-felsic-mafic which forms a Northwest-Southeast volcanism trend (Masdjuk, 1991).

Based on the published geological model of Wayang Windu, six formation units are identified, consisting of Loka formation, Waringin formation, Pangalengan formation, Malabar formation, Wayang Windu formation, and Dogdog formation. The Loka formation, possibly having Pliocene age, consists of crystal tuffs, lapilli tuffs, and subordinate lavas and hence is medial facies. The Waringin formation consists of andesitic pyroclastic and lavas which possibly having Mid-Pleistocene age. The Pangalengan formation has a basal conglomerate overlain by interbedded sandstones, siltstones, and minor lignite beds, which in turn are overlain by intercalated lahars and fine-grained tuffs. The age of this formation possibly is Mid-Pleistocene age and suggests distal facies that grades toward medial facies upwards. The Malabar formation consists of interbedded lavas, breccia, and lahars of basaltic andesite to dacite in composition, and has K-Ar dates of 0.23 Ma ± 0.03. The Wayang Windu formation consists of quartz andesite overlying quartz andesite crystal tuff and is exposed at the surface as an approximately north-south trending ridge of small volcanic centers. The main eruptive centers of Mt. Bedil, Mt. Wayang, and Mt. Windu have K-Ar dates of 0.18, 0.49, and 0.10 Ma respectively. It is interpreted that Mt. Wayang has undergone sector collapse; hence it is likely that the dated sample from that eruptive center was taken from a much older part of the volcanic pile (Bogie et al., 2008). The last formation identified is Dogdog formation. The Dogdog formation was distinguished by its medium to coarse-grained pyroclastic, compared to the lava-rich Malabar formation. The Dogdog formation was interpreted to have a similar age and interfingering relationship with the Pangalengan formation (Ramadhan et al., 2012).

Three initiatives conducted to update the stratigraphy in Wayang Windu: 1). LiDAR DEM analysis to define volcanic center and surface formation boundary, 2). Formation profiling, including paleosol XRD analysis, to define subsurface lithology distribution and, 3). Gravity inversion model to define the shape of the intrusion body. The formation unit is chosen to be the grouping method of several lithology sequences rather than facies units. Stratigraphy is referred to the volcanic center that is interpreted as the source of material deposition. The distribution of formation units will combine the surface formation boundary and subsurface lithology distribution.

2.1. LiDAR DEM Analysis

The LiDAR DEM analysis is intended for defining the volcanic center and surface formation distribution related to the volcanic center. The analysis suggests that the prominent volcanic center in Wayang Windu at least consists of five major volcanic centers inside the DEM coverage area; Puncak Besar, Gambung A, Gambung B, Wayang and Windu. The additional volcanic center which might contribute to the volcanic product deposition in Wayang Windu is the older volcanic center surrounding Wayang Windu (Kencana in the South, Malabar in the North, and Dogdog-Kamojang-Darajat-Papandayan in the East-Southeast) (Figure 2).

The analysis of DEM shows nine distinct surface formation boundaries. Correlating the boundary and the formation description from the previous researchers suggest nine formation units (Figure 2), from old to young, as follows:

- Waringin formation *(War)*. This formation is the oldest formation in Wayang Windu which outcropped on the surface (Boogie & McKenzie, 1998). The Waringin formation lies at the southernmost of DEM coverage area which is characterized by low terrain-rough surface area.
- Pangalengan formation *(Pgl)*. This formation is observed majorly in East and West of DEM coverage area, in the low terrain-relatively smooth surface area, separated by the high terrain of Mt. Wayang and Mt. Windu.
- Old Wayang formation *(O-Wyg)*. This formation is lies in the center of DEM coverage area and distinctly identified as it is represented by the volcanic edifice of Mt. Wayang. The Old Wayang term is mostly derived from the age dating result from

Boogie & McKenzie (1998), where in Mt. Wayang there are two different age dating results, 0.49 and 0.18 Ma respectively. The very wide age differences allow interpretation of Old Wayang and Young Wayang formation. The Old Wayang forming the high terrain volcanic edifice of Mt. Wayang, where the surfaces roughness of the Mt. Wayang is smoother compared to the Mt. Windu, with less radial drainage pattern. This parameter indicating Mt. Wayang is older compared to Mt. Windu. Major collapse structures are clearly observed in this formation with the collapse direction to the West and East from the approximation of its volcanic center.

- Malabar formation *(Mlb)*. This formation is the widespread, observed from the northernmost of DEM coverage area to the Mt. Wayang area, bordering with Pangalengan formation. Regionally, this formation is situated in the southern slope of Mt. Malabar volcanic edifice. Major collapse structures are also identified in this formation with the collapse direction to the North and Northwest. Minor collapse structure observed with the collapse direction to the to the Southwest. However, the approximation of its volcanic center is not clearly defined within the DEM coverage area.
- Puncak Besar formation *(Pb)*. This formation is situated on the slope of Mt. Malabar volcanic edifice with characterized by the volcanic pile above the older volcanic product (Malabar formation). To the Southeast, this formation seems to be overlaid by younger volcanic product (Gambung-A formation). Minor collapse structure is clearly observed in this formation with the collapse direction to the Southwest from the approximation of its volcanic center.
- Gambung-B formation *(Gmb-B)*. This formation is situated on the Southeast of Puncak Besar formation, on the slope of Mt. Malabar volcanic edifice. This formation is overlaid by the younger volcanic product (Gambung-A formation). Collapse structure is clearly identified in this formation with the collapse direction to the Southwest from the approximation of its volcanic center.
- Gambung-A formation *(Gmb-A)*. This formation is located in between Puncak Besar and Gambung-B formation, on the slope of Mt. Malabar volcanic edifice. This formation overlay Puncak Besar and Gambung-B formation. Major collapse structure is clearly observed in this formation with the collapse direction to the South, Southeast and Northeast from the approximation of its volcanic center.
- Young Wayang formation *(Y-Wyg)*. The Young Wayang shows volcanic deposition from reactivation of the eruption center, in the West and the East of Mt. Wayang. This formation is differentiated from Old Wayang formation based on the origin of the deposition from DEM analysis. The volcanic material clearly shows deposition above the older volcanic product (Old Wayang formation). Collapse structures as the source of volcanic material deposition of this formation is clearly identified with the collapse direction to the West and East from the approximation of its volcanic center.
- Windu formation *(Wnd)*. This formation can be distinctly identified as it is represented by the southernmost volcanic edifice in DEM coverage area (Mt. Windu). Several collapse structures are identified with major collapse direction to the West while another collapse direction to the South, Southeast, East and North from the approximation of its volcanic center.

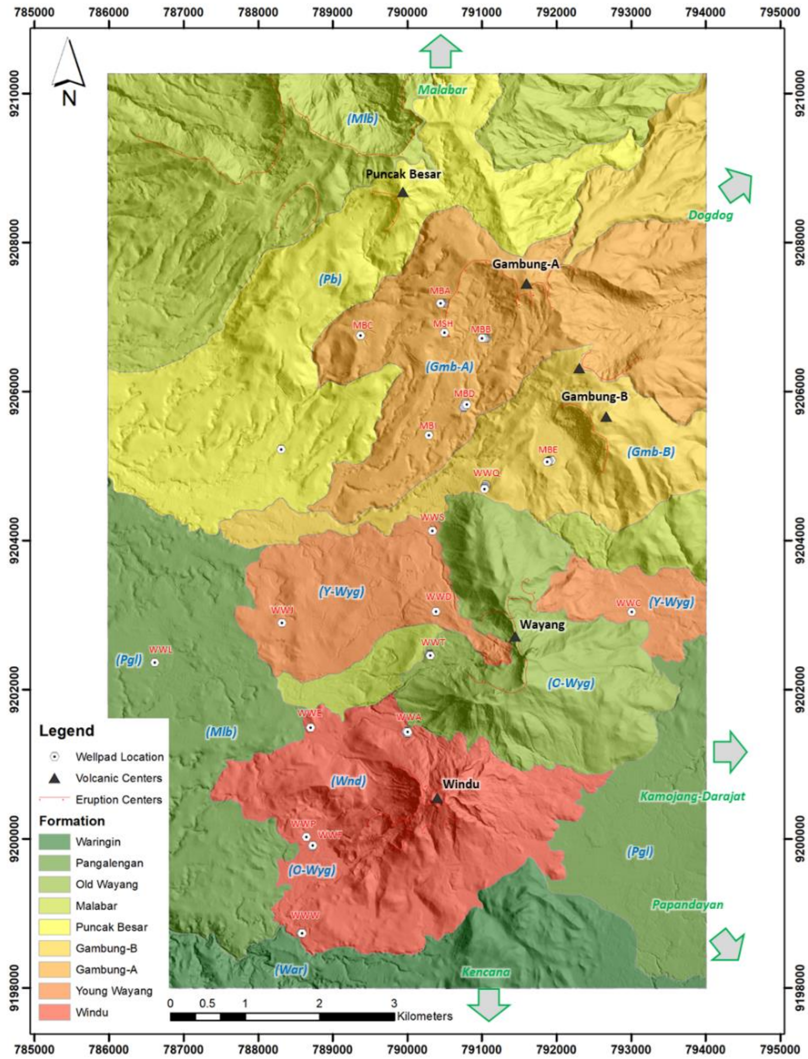


Figure 2: The volcanic center location and formation unit distribution on the surface based on DEM analysis and information from previous researchers. The potential volcanic center which contributes to the depositional process in Wayang Windu is also displayed (green text), next to the arrow showing proximity of the location. The formation name is abbreviated (blue text), following the abbreviation mentioned in the main paragraph.

2.2. Formation Profiling

Having 65 wells drilled throughout the field since the 90's, different types of subsurface lithology were described from the drilling cutting samples and core samples, which were also validated by petrographic analysis. Wayang Windu has identified various types of lava, from basaltic andesite, andesite, to dacite lava, which was distinguished from their color, having dark to lighter colors, respectively. Mineralogy composition is the main factor in naming the lithology, from basaltic andesite to dacite, increasing amount of quartz crystals observed, respectively, and from Ca-plagioclase to Na-plagioclase. An intrusion was also interpreted from the rock sample as microdiorite. As for typical stratovolcano, aside from lava, pyroclastic rocks were also identified, from breccia to tuff. The breccia, was very common to have the lava fragments, therefore resulting in naming andesitic breccia, dacitic breccia, or simply stated as coarse pyroclastic, by having large-sized fragments. As for the medium-sized fragments or grains, the rock samples were identified as lapilli or lithic tuff, the specific names are andesitic lithic tuff, dacitic tuff. For the fine-grained pyroclastic rocks, various types of tuffs were identified simply as tuff or crystal tuff, vitric tuff.

With numerous types of subsurface lithology observed from the wells, grouping became a necessity. Differing the lava composition, three groups of lava is selected: basaltic andesite lava, andesite lava and dacite lava. The various types of breccia are simply grouped as coarse pyroclastic. Different types of lapilli and lithic tuff are grouped as lithic tuff. The many types of tuffs are grouped as tuff. As final grouping, the subsurface lithology in Wayang Windu is categorized into six Petrophysic Group (PG); Basaltic Andesite Lava, Andesite Lava, Dacite Lava, Coarse Pyroclastic, Lithic Tuff and Tuff. Two additional PG which are not related to volcanic activity in Wayang Windu is observed: Conglomerate and Paleosol. Paleosol which was observed in Wayang Windu as reddish brown-grey, dominantly by fine-grained tuff, consisted of smectite and/or mixed layer with illite. Generally, it can be divided into sticky and non-sticky (brittle). The sticky has a characteristic of high methylene blue and smectite, and mostly occurs above the reservoir section. This type of paleosol tends to swell when in contact with drilling fluid and has poor mechanical strength. The non-sticky paleosol has low methylene blue and smectite, and mostly occurs in the reservoir section. In most cases, the number of paleosol encountered in the reservoir section is greater than the above reservoir, where it is absent toward the northern part of Wayang Windu.

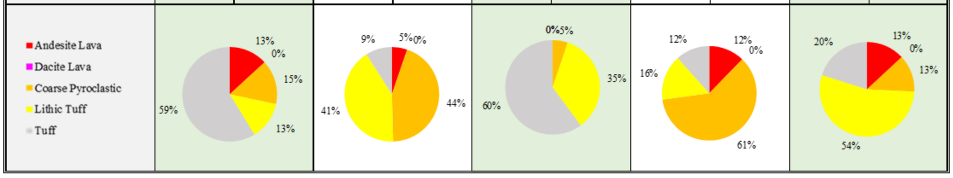
Formation profiling in Wayang Windu is based on the grouping of PG in the well by composition (in %). PG distribution which associated with volcanic activity in Wayang Windu unfortunately does not shows any possibility existence of a key marker to be the bold line of correlation guidance across the field. Hence, to define the formation profile in Wayang Windu, the rule of thumb used as formation profile definition is a group of PG which has distinct differences of PG composition (in %), compared to the above or below PG's group. Some formation profiles have a marker that is easy to be distinguished, however, some formation profiles do not.

To enhance the formation profile definition, the paleosol layer which present in between formation profiles, will act as a formation depositional break marker (paleosol will be developed when the volcanic depositional process is stopped and taken over by the weathering-erosion process). To support this argument, an XRD analysis is conducted for several paleosol samples. The objective of XRD analysis is to define the characteristic of illite in the paleosol, which can be used to conclude the major process that created the paleosol. Two major processes of illitization in paleosol can be identified: the pedogenic and diagenetic processes. The pedogenic is illitization process associated with the forming of soil on the earth's surface, while the diagenetic is illitization process associated with compaction after deposition, even though there are other factors involved; water-rock reaction and microbial activity. Hence, the paleosol containing illite from pedogenic illitization represents paleosol as a depositional break marker (soil formed during a volcanic depositional break on the earth's surface). The pedogenic illitization is characterized by randomly ordered, mixed layer illite-smectite (Eberl et al, 1986; Hower et al, 1976; McIntosh, 2018). This type of mixed layer in XRD will show the peak 2:1 phyllosilicate mineral (i.e., smectite group, vermiculite group, illite) in X-Ray Diffraction Spectrum at ± 5° 2ϴ (McIntosh, 2018). Another characteristic of this mixed layer clay in XRD is observed from the percentage of the illite in the illite/smectite ratio. The pedogenic mixed layer clay will have illite < 60% (Hower et al., 1976; Moore and Reynolds, 1997; McIntosh, 2018).

Ten formation profiles can be deducted from the subsurface lithology in Wayang Windu: Waringin, Pangalengan, Old Wayang, Young Wayang, Gambung -B, Gambung-A, Puncak Besar, Malabar, Dogdog and Old Dacitic (Figure 3). Only one formation that cannot be profiled (Windu formation), due to there isn't any well drilled into Windu formation. Pangalengan formation has a unique marker; conglomerate and basaltic andesite lava which is in line with the definition of Pangalengan formation by Boogie and McKenzie (1986). The existence of basaltic andesite lava also shows that this formation is older than recent volcanism (andesite and dacite lava). The source of the basaltic lava might be derived from Papandayan volcanic complex, in the Southeast of Wayang Windu, which is quite far and in line with the existence of conglomerate (distal facies). The formation profile also indicates that Old Wayang and Young Wayang can be divided clearly by the existence of dacite lava in the Young Wayang. The dacite lava also can be used as a marker for Gambung-A formation, compared to Gambung-B. Gambung-B formation has dacite lava up to 6%, hence Gambung A only has andesite lava. However, the existence of dacite lava in Gambung-B which showing that the Gambung-B is younger compared to Gambung-A, needs to be confirmed in 3D modelling process, as based on the formation distribution from surface data indicating that the Gambung-B is older compared to Gambung-A. Two formations which are not exposed at the surface also can be profiled. The formations are Dogdog formation and Old Dacitic formation. Dogdog formation dominantly consists of tuff which is in line with Dogdog formation definition by Ramadhan et al. (2012). The Old Dacitic dominantly consist of tuff with dacite lava up to 6%. The term Old Dacitic based on the formation is located below Puncak Besar and Malabar formation. The existence of dacite lava below both formation is questionable as dacite lava should located in the younger formation unit. Additional work will be conducted to investigate this phenomenon.

Three paleosol samples were examined using XRD analysis; TS-1, TS-2 and TS-3 respectively. The consideration of the sample selection is based on the amount of paleosol in the cutting and core, which must fulfill minimum weight. The paleosol layer is also must separating two formation profiles which have distinct profile and ages. The first sample, TS-1 is taken from the well in wellpad MBC which separates two formations: Gambung-A and Puncak Besar. The second sample, TS-2 is taken from the well in wellpad WWA which separates Young Wayang and Old Wayang formation. The third sample, TS-3 is taken from the well in wellpad WWC which separates Young Wayang and Pangalengan (Figure 4). The XRD shows that the TS-1, TS-2, and TS-3 have illite less than 60% in the illite/smectite ratio. The TS-1 has the highest illite (~30%) compared to TS-2 and TS-3 (< ~5%). The peak 2:1 phyllosilicate mineral in X-Ray Diffraction Spectrum at TS-1 is located near ± 9° 2ϴ, while the TS-2 and TS-3 is located near ± 5° 2ϴ. Referring to the pedogenic characteristic, it is concluded that TS-1 does not fully meet the pedogenic characteristic, comparing to TS-2 and TS-3. This condition might be represented by the formation age gap separated by TS-1. The Gambung-A and Puncak Besar are grouped as Malabar formation (Boogie & McKenzie, 1998) which nearly have the same age (0,23 ± 0.03 Ma and 0,23 ± 0.01). Hence the TS-1 might represent a short formation deposition break, therefore diagenetic process might be dominant in this sample. The TS-2 and TS-3 represent a wide age gap, TS-2 separating Young Wayang and Old Wayang (0.19 ± 0.01 Ma and 0.49 ± 0.01 Ma) while TS-3 separating Young Wayang and Pangalengan (0.19 ± 0.01 Ma and Mid Pleistocene). The pedogenic process might dominated the origin of TS-2 and TS-3.

Petrophysic Group	Waringin		Pangalengan		Dogdog		Old Wayang		Malabar	
	Thick (m)	%	Thick (m)	%	Thick (m)	%	Thick (m)	%	Thick (m)	%
Andesite Lava	1,027	13%	187	5%	-	0%	1,168	12%	2,816	13%
Dacite Lava	-	0%	-	0%	-	0%	-	0%	-	0%
Coarse Pyroclastic	1,182	15%	1,581	44%	77	5%	5,781	61%	2,734	13%
Lithic Tuff	1,007	13%	1,478	41%	514	35%	1,483	16%	11,656	54%
Tuff	4,580	59%	320	9%	892	60%	1,107	12%	4,325	20%
	7,795	100%	3,566	100%	1,484	100%	9,539	100%	21,531	100%
Coglomerate			211							
Basaltic Andsite Lava			5							



	Old Dacitic		Puncak Besar		Gambung-A		Gambung-B		Young Wayang	
	Thick (m)	%	Thick (m)	%	Thick (m)	%	Thick (m)	%	Thick (m)	%
Andesite Lava	-	0%	1,231	20%	5,233	24%	434	11%	721	5%
Dacite Lava	20	3%	-	0%	-	0%	258	6%	1,794	13%
Coarse Pyroclastic	176	30%	3,433	55%	5,452	25%	1,174	29%	3,908	29%
Lithic Tuff	12	2%	1,152	19%	8,888	41%	1,872	47%	3,121	23%
Tuff	386	65%	369	6%	2,351	11%	255	6%	3,832	29%
	594	100%	6,185	100%	21,923	100%	3,993	100%	13,376	100%
Coglomerate										
Basaltic Andsite Lava										

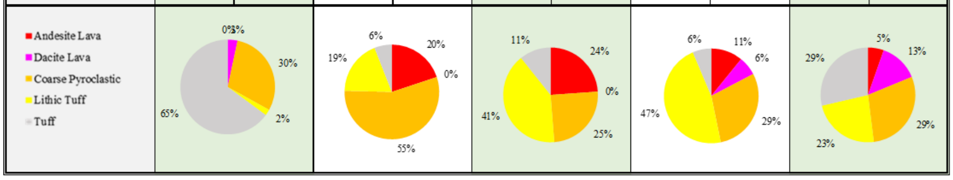


Figure 3: The formation profile from Wayang Windu based on PG grouping. The formation profiles in this picture are based on total thickness from all wells which show the same profile. For each well, there are some variations. However, the variations are still acceptable.

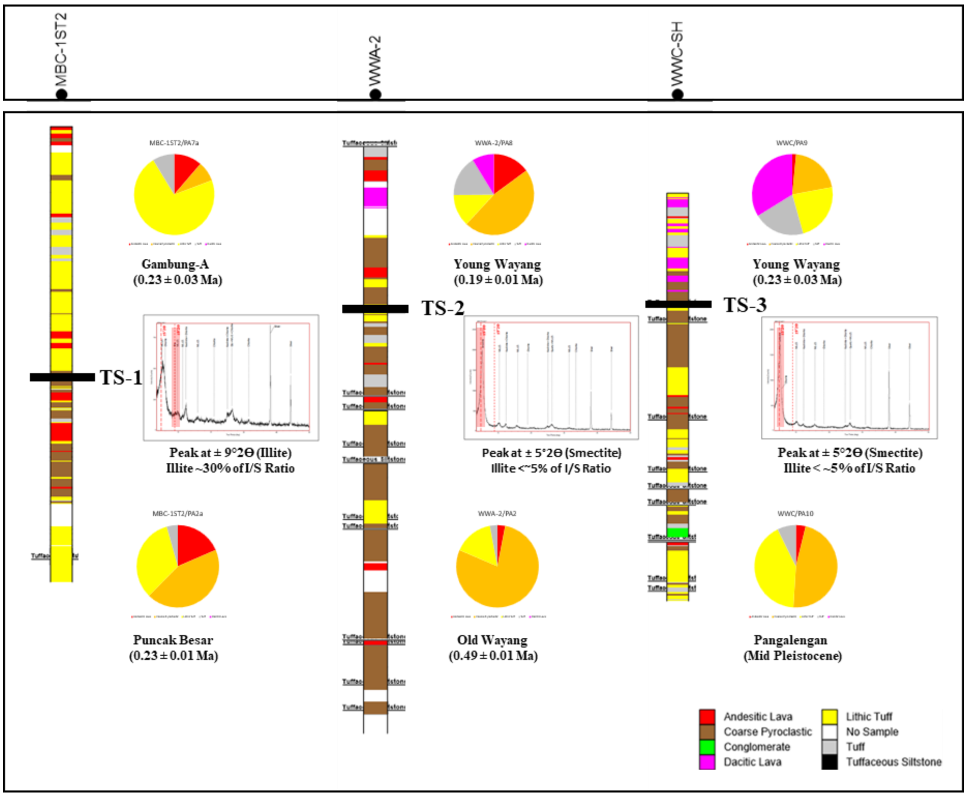
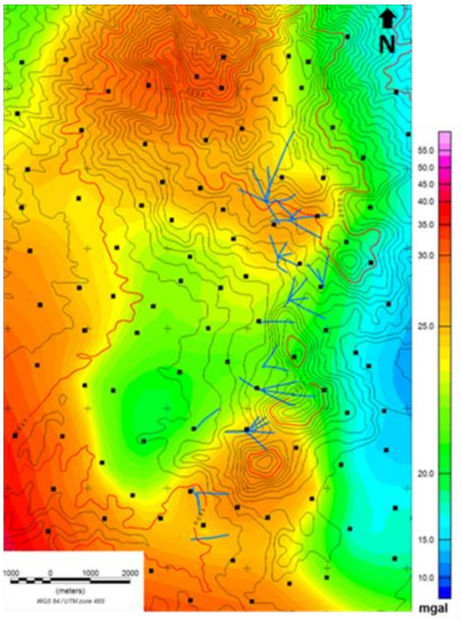
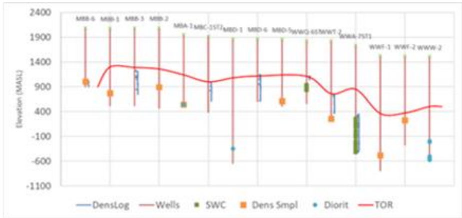


Figure 4: The application of paleosol layers as the marker for the formation depositional break in Wayang Windu. The paleosol TS-1 layer separating Gambung-A and Puncak Besar formations does not clearly show pedogenic origin, which might not indicate a wide depositional age gap. As for paleosol TS-2 and TS-3, both show pedogenic origin, as they have a wide gap in depositional age, separating Young Wayang and Old Wayang, and Young Wayang and Pangalengan respectively.

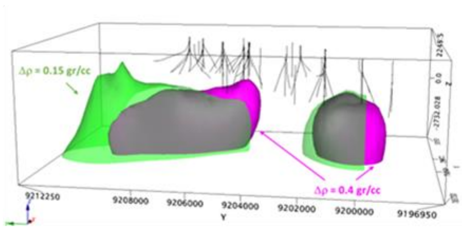
2.3. Gravity Inversion Model

As part of stratigraphy analysis, 3D intrusion model is conducted using result of gravity inversion model. There are 139 well-scattered gravity measurement points distributed within the concession area with an interval distance between 1 to 2 km and getting wider as it is going further from the field. The inversion model was developed from the Complete Bouguer Anomaly (CBA), with a background density of 2.4 gr/cc, constrained by well data i.e., laboratories rock density measurement (cores), and density logging data (Figure 5). The well data is distributed evenly from the northernmost production pad, MBB, to the southernmost production pad, WWA. Microdiorite as intrusion rock was found in the cuttings and cores, honored as one of the input data for the inversion. It is assumed to have density of microdiorite about 2.8 gr/cc (Telford, 1978). The Bouguer anomaly map indicates the high-density body below the WWA pad in the south and below the MBD, MBA and MBB pad in the north. The constrained 3D inversion model shows high density body (dome pattern) in the southern part of the field and one in the north, with the empty space in between. The contrast density of 0.4 gr/cc or equal to the density of 2.8 gr/cc interpreted to be the intrusion body (interpreted heat source) of the geothermal system. The top of 2.8 gr/cc body in the north goes deeper northwards (Figure 5). This interpreted intrusion body will be used as the guidance for the 3D intrusion model for Wayang Windu.





b. Well data distribution used to constraint inversion model.

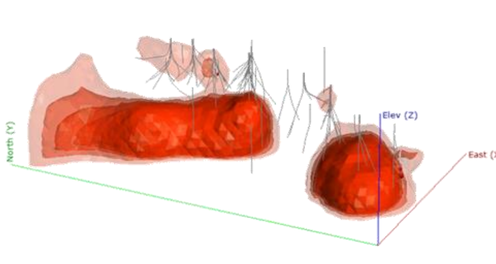


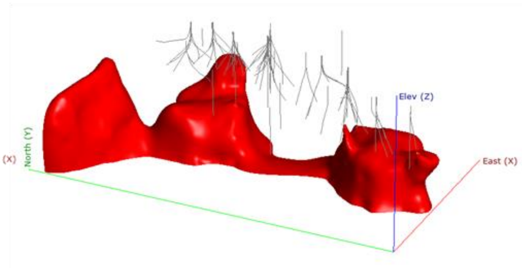
a. Complete Bouguer Anomaly (CBA) map overlaid by elevation contour

c. Iso-surface of contrast density value of 0.15 gr/ss (green) and 2.4 gr/cc (purple).

Figure 5: (a) Complete Bouguer Anomaly (CBA) map overlaid by elevation contour, black boxes (■) are gravity stations. (b) Well data distribution used to constraint inversion model consist of cutting, cores samples, and density log. (c) The iso-surface model which consists of contrast density values of 0.15 gr/ss (green) and 2.4 gr/cc (purple) will be used as the basis for the 3D intrusion model.

Refer to the nature shape of the interpreted intrusion body from the result of gravity inversion model (Figure 5), intrusion is modeled in form of a big intrusion body with a small dike to the shallowest part. The 3D intrusion model (Figure 6) created from 2.8 gr/cc body of the gravity inversion model (Figure 5) which imported to Leapfrog.





a. Iso-surface of contrast density body which has been transferred into Leapfrog as basis of 3D intrusion model

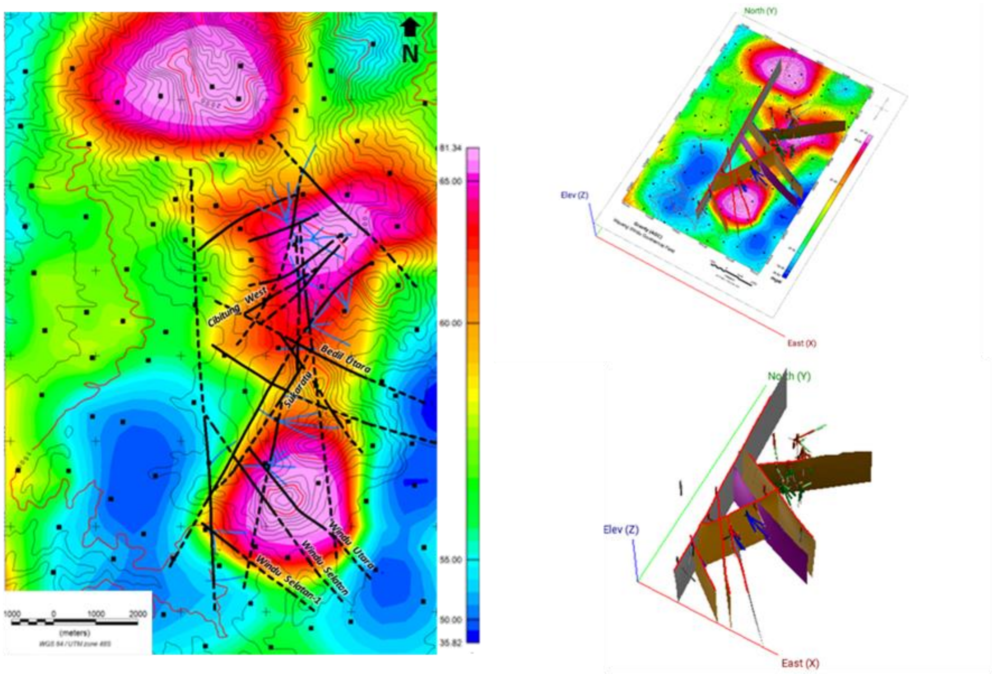
b. 3D intrusion model created in the Leapfrog, considering iso-surface body and other data (lithology data, gravity data)

Figure 6: (a) Iso-surface of contrast density body which has been transferred into Leapfrog then used as basic for intrusion model. (b) 3D intrusion model created in the Leapfrog, considering iso-surface body and other data (lithology data, gravity data).

3. STRUCTURE ANALYSIS

Another purpose of DEM analysis is to define surface structure lineament, which will be related to gravity data, to have more robust structure lineament data. Surface structure lineament deducted from LiDAR DEM is the result of a combination of drainage pattern lineament, ridge pattern lineament, and extracted lineament using automatic lineament generation. The surface structure lineament is overlaid with the enhanced CBA gravity map, known as Automatic Gain Correction (AGC) map, which sharpens the distinction of gravity objects in the subsurface. This map is showing a better resolution of gross structure in Wayang Windu. The structure lineament which combined with AGC map consists of azimuth directions relatively North – South (4), Northeast – Southwest (2), East-Northeast – West-Southwest (5), North-Northeast – South-Southwest (5), Northwest – Southeast (3), West-Northwest – East-Southeast (4), North-Northwest – South-Southeast (1) (Figure 7).

It is necessary to have 3D fault planes in order to incorporate the structure lineament in the geological framework. At this stage, the structure lineament is combined with the formation distribution from formation profile to create an approximation of the fault plane's dip angle. Mostly the 3D fault plane has relatively high-degree dip angle (> 70°) (Figure 7), be in accordance with regional tectonic setting in Wayang Windu which is dominated by a combination of strike-slip and normal regime.



a. Automatic Gain Correction (AGC) Map overlaid by surface lineament

b. 3D fault plane overlie AGC and subsurface lithology (above) and final 3D fault plane for (below)

Figure 7: (a) Gravity AGC Map overlaid by surface structure lineament and incorporated with formation profile from well to define the 3D fault plane. (b) The 3D fault plane considering the regional setting (strike-slip and normal regime) which mostly has relatively high-degree dip angle (> 70°).

4. UPDATED GEOLOGICAL FRAMEWORK

The updated geological framework is conducted using 3D modeling software (Leapfrog). The workflow in the Leapfrog permits utilization of 3D fault plane as the boundary of several smaller 3D blocks for modeling, hence the 3D fault plane contribution in updated geological framework (i.e., formation boundary) can be identified during modeling. The 3D fault plane which has been constructed is applied for the first input in the 3D model. The 3D intrusion model is applied as the last input.

The formation profile, which has been defined for each well, is correlated using guidance of surface formation boundary and known sequence of volcanic deposition in Wayang Windu. The 3D geological framework shows the distribution of the Waringin formation, as the oldest formation in Wayang Windu, relatively shallow in the South and deeper to the North, reaching Mt. Wayang area in the deeper part (Figure 8). The Pangalengan formation is deposited above Waringin formation, distributed relatively shallow in the Southwest and deeper toward Mt. Wayang area. The Pangalengan formation then replaced by Dogdog formation, in the deeper part, where Dogdog is interfingering with Pangalengan formation (Ramadhan et al., 2012). Dogdog formation distributed localized, only observed between Mt. Wayang and Gambung Complex area (Figure 8). Old Wayang formation distribution is also localized, centered in the collapse of Mt. Wayang, and spread to Mt. Windu area (Figure 8). The most widespread formation in Wayang Windu is Malabar formation, where it is distributed from the slope of Mt. Malabar in the North to the slope of Mt. Windu, at the deeper part, in the South. The Malabar formation is deposited above Waringin, Pangalengan and Dogdog formation. The Malabar formation is deeper toward Northwest and overlaid by Puncak Besar formation (Figure 8). Conceptually, Malabar formation is exposed in the Northwest of Wayang Windu. However, there is no well data in that area. The Malabar formation to the Northeast is overlaid by Gambung-B and Gambung-A formation. The Gambung-B formation is localized and only taken the East of Gambung Complex. The Gambung-B distributed above Malabar formation only (Figure 8). The deposition process of Gambung-B, based on 3D model, is clearly showing that it is older than Gambung-A. Hence, the 3D model supporting the interpretation of formation distribution from DEM analysis. The Gambung-A is more widespread compared to Gambung-B. Despite it is deposited above Malabar formation, it is also deposited above Puncak Besar formation in the North of Wayang Windu (Figure 8). The youngest formation in Wayang Windu, Young Wayang and Windu formation, abruptly overlaid the older formation in the Mt. Wayang and Mt. Windu area.

Several 3D fault planes are identified as formation boundary. For example, Windu Utara fault plane (F. Windu U.) separating Waringin and Old Wayang formation at the deeper part in the southern area. Bedil Utara fault plane (F. Bedil U.) is also separating Waringin and Dogdog formation at the deeper part, in between Mt. Wayang an Gambung Complex. Cibitung West fault plane (F. Cibitung W.) showing offset of Gambung-A and Puncak Besar at the shallow part in the Gambung Complex area (Figure 8). The intrusion body is located below Mt. Windu in the South. While in the North, intrusion is located below Gambung Complex and Mt. Malabar (Figure 8).

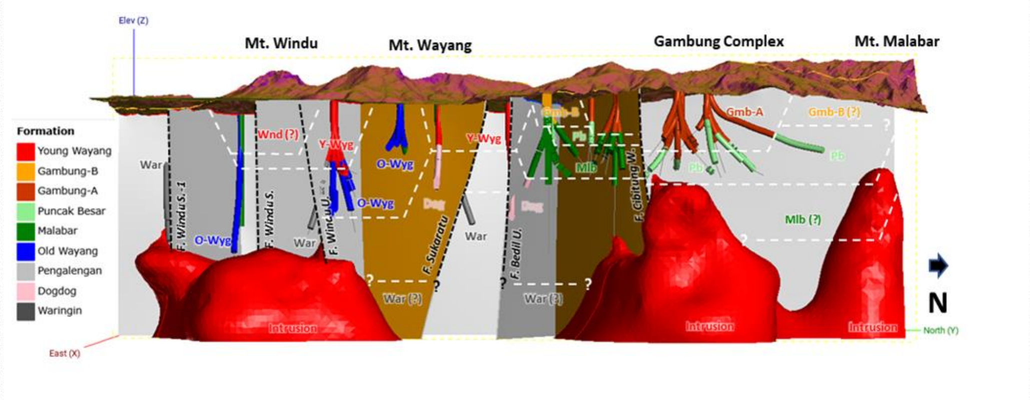


Figure 8: North-South cross section of 3D geological network consists of 3D fault plane and 3D intrusion model in Wayang Windu. The dashed white line is showing proximity of Wayang Windu formations distribution. Several 3D fault planes are identified as formation boundary in Wayang Windu.

CONCLUSION

LiDAR DEM analysis suggests nine surface formation unit identified in Wayang Windu, based on formation boundary and location volcanic center. The formation unit, from old to young, are: Waringin, Pangalengan, Old Wayang, Malabar, Puncak Besar, Gambung-B, Gambung-A, Young Wayang and Windu.

The formation profiling based on subsurface lithology data in Wayang Windu demonstrates ten formation units, eight formation units explained the surface formation unit and two formation units are formation units which are not exposed in the surface (Dogdog and Old Dacitic formation). Only one surface formation unit cannot be profiled (Windu formation) due to there isn't any well drilled into this formation. XRD analysis of paleosol layer, which is suspected as marker of volcanic depositional brake, supporting the deduction, where the paleosol layer separating wide age gap of formation unit is forming by pedogenic process. While in opposite, the paleosol layer which separates slight age gap of formation unit, might represent short volcanic depositional brake (dominantly by diagenetic process). Result of gravity inversion model, in form of density body (dome pattern) with contrast density of 0.4 gr/cc or equal to the density of 2.8 gr/cc, used as the basis of intrusion shape in Wayang Windu. The dome pattern of density body is located in the southern part of the field and one in the northern part, with the empty space in between. Intrusion body in Wayang Windu modelled in form of a big intrusion body with a small dike to the shallowest part.

Surface structure lineament from LiDAR DEM analysis is combined with AGC map to define a series of robust structure lineament with azimuth directions North – South, Northeast – Southwest, East-Northeast – West-Southwest, North-Northeast – South-Southwest, Northwest – Southeast, West-Northwest – East-Southeast, North-Northwest – South-Southeast. 3D fault plane is created by incorporated the formation unit distribution in the well, where the dip angle of the fault plane maximum ~70 ° as representing control of regional tectonic worked in Wayang Windu (strike-slip and normal tectonic regime).

3D geological framework suggests distribution of Waringin formation reach Mt. Wayang area, in the deeper part. Pangalengan formation is not found under Mt. Wayang and Mt. Windu area, replaced by Dogdog formation. Dogdog formation is deposited above Waringin formation between Mt. Wayang and Gambung Complex. The Old Wayang is localized and deposited in the Mt. Wayang and Mt. Windu area. The Malabar formation is overlaid by the younger formation (Puncak Besar, Gambung-B and Gambung-A) in the northern area. The youngest formation (Young Wayang and Windu) deposited above the older formation in the southern area. Several 3D fault planes identified as formation boundary: Windu Utara in the South, Bedil Utara in between Mt. Wayang and Gambung Complex and Cibitung West in the North area. The big intrusion body in Wayang Windu is located in the South below Mt. Windu and in the North below Gambung Complex and Mt. Malabar.

In addition, there are two observation which need to be followed up: the existence of dacite lava in the Gambung-B formation and the existence of Old Dacitic formation. The dacite lava founded in Gambung-B formation is contradictive, as based on model, the Gambung-B is older compared to Gambung-A. Gambung-A only consist of andesite lava. This phenomenon might be indicating reactivation of Gambung-B volcanic center, where the only collapse structure observed in this formation is quite fresh, compared to collapse structures in Gambung-A. The percentage of the dacite lava in Gambung-B, where only 6%, might also indicating that the dacite lava is mixed with the predominant andesite lava. However, this phenomenon will be followed up further. The existence of Old Dacitic formation below Puncak Besar and Malabar also needs to be followed up further as it shows a unique fact, contrary with the known and updated geological framework in Wayang Windu.

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