

## Reservoir Rock of Ulubelu Geothermal System, Indonesia

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### ABSTRACT

Ulubelu geothermal field lays in a volcano-tectonic depression produced from combined Sula post-caldera depression and tectonism related to the Great Sumatera Fault at 700 to 900 meter above sea level, Lampung, Indonesia. The field associated with a dormant strato-volcanoe called Mt. Rendingan in the northern part, in which its pyroclastic products fills the graben structure to the southern part. As a sequence of graben filling formation, the lithology distributed evenly inside the Ulubelu graben boundary. Drilling data and well test result show a conformable trend between reservoir feed zone and Ignimbrite (Rhyolitic tuff) layer distribution as a highly permeable zone.

With its unique pattern and characteristic, Ignimbrite layer is proven to be a productive reservoir zone controlled by both lithological facies distribution and rock fracturing. Targeting this layer will improve the success ratio of production well in Ulubelu field. This stratigraphic approach is effectively applied in volcano-tectonic depression setting filled by pyroclastic materials. With the same regional tectonic setting, this lateral permeability concept might be suitable and relevant to be applied on other geothermal fields along the great Sumatran fault.

### 1. INTRODUCTION

Ulubelu geothermal field located about 100 km west of Bandar Lampung, Lampung province, Sumatra Island, Indonesia. Pertamina Geothermal Energy (PGE) conducted the exploration stage in Ulubelu since the late 80's. The three first exploration slim holes were drilled in 1995 with maximum borehole temperature of 225°C and depths averaging 900-1000 meter (Siahaan, 2015).

Ulubelu is a neutral liquid dominated geothermal system with 4x55 MWe installed capacity within 2018. The information about Ulubelu geothermal field is shown in Table 1 and Table 2 below.

**Table 1. Information of Ulubelu geothermal field**

Ulubelu Geothermal Field	1 <sup>st</sup> & 2 <sup>nd</sup> Unit	3 <sup>rd</sup> & 4 <sup>th</sup> Unit
Commission	2012	2015
Energy sales contract	Steam	Electricity

**Table 2. Character of Ulubelu geothermal system**

Reservoir fluid	Water dominated system.
Fluid pH	Neutral.
Reservoir temperature	250 – 280 °C.
Heat source	Mt. Rendingan.
Proven productive structure	Northwest - Southeast trending structures inside the depression.

Ulubelu geothermal field lays as a half graben structures related to tensional stress from Great Sumatran Fault (GSF) inside the post-caldera depression of Mt. Sula. GSF controls geological structures along Sumatran Island trending to northwest - southeast which is perpendicular to subduction zone in the western part of Sumatra. The collapse structure produced from tensional stress controls surface manifestations pathways in Ulubelu. Ulubelu productive structures identification was based on the interpretation from surface structure alignments and also from borehole image data. Two main structures trending northwest - southeast defined as boundary of hydrothermal distribution in the system. Pagar Alam fault restrains reservoir fluid pathways in the western, as well as Talang Marsum fault in the eastern part of the depression (Trianggono, 2015).

The secondary fractures trending NW-SE and NNW-SSE inside the graben boundary is targeted as productive fault for production well. This patterned fractures is proven as a feed zone associated with lateral permeability controlled by reservoir rock formation facies. Targeting these fractures in reservoir rock layers will increase the permeability rate of production well in Ulubelu.



**Figure 1: The figure of Ulubelu geothermal field from surface model and satellite image taken in early 2019 showing the distribution of structures, manifestations, production - injection zone, and power plants location.**

Ulubelu depression flanked by two young volcanoes, namely Mt. Rindingan and Mt. Tanggamus. With the diameters of 4 km, Ulubelu depression mostly filled by young volcanic activity products and occurrence of monogenic volcanoes such as Mt. Duduk and Mt. Tiga. Subsurface stratigraphy of Ulubelu geothermal field composed of lava and pyroclastic products of Mt. Rendingan, mixed volcanoclastics breccia associated with carbonates lenses, ignimbrite as the reservoir facies of the system, and carbonaceous rocks as the deepest layer penetrated by numerous wells at elevation around -1100 masl. The stratigraphy of Ulubelu geothermal system is summarized in the table 3 below.

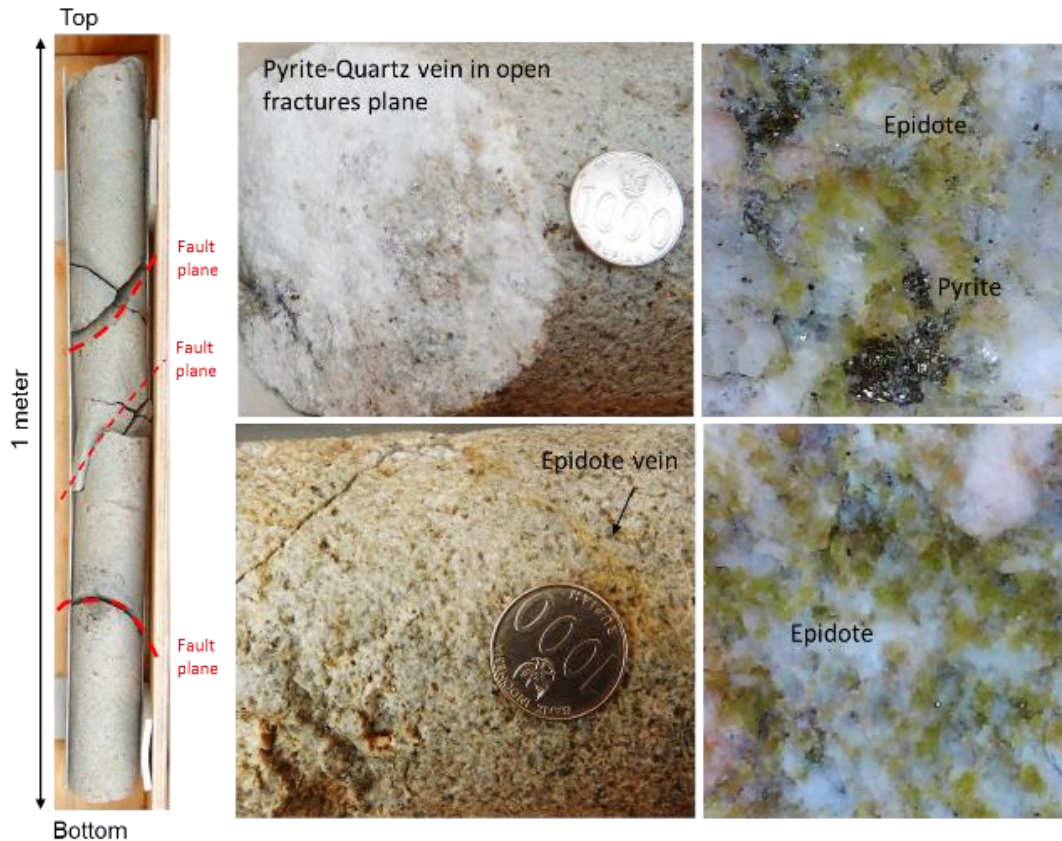
**Table 3. Subsurface stratigraphy of Ulubelu geothermal system obtained from borehole data analysis**

Stratigraphy Facies	Rock Unit	Elevation	Character
Andesite Lava.	Vesicular Andesite lava with sheeting & columnar joint in the surface. Porphyritic texture, strongly oxidized.	Surface to 400 masl. This depth interval is covered by a cemented 20" blind casing.	Shallow loss zone with high mud loss rate, secondary permeability caused by fractured primary rock structures (sheeting & columnar joints).
Pyroclastic breccia. As Claycap zone.	Tuff breccia, tuff lapilli, andesite breccia. Associated with carbonate lenses.	400 to (-500) masl. This formation is thickening to the east.	Typical high clay concentration (15-50%), Washout sticky clay from rock matrix are commonly causes bit balling problems.
Lenses of Epiclasts and Carbonates. As Marker formation.	80% reworked skeletal content (mudstone) fragments in epiclast breccia, matrix consist of tuff and mud.	(-200) to (-500) masl. The depth varies inside the Pyroclastic breccia layer. This interval covered by 13-3/8" blind casing.	Rate of drilling mud loss 2-11 BPM. This formation defined as a marker of transition alteration zone in Ulubelu. Clay concentration gradually decreasing from 50% to 10%.
Ignimbrite. As Reservoir rock.	White colored fragmental tuff with clear quartz, grain supported. Described as "clean tuff" or Rhyolitic tuff facies as well. Washout clays are disappeared.	(-500) to (-1100) masl. The top of reservoir rock zone is found to be tilted deeper to the east. Production interval secured by 10-3/4" liner.	Clay concentration drop significantly to $\leq 10\%$ . Mud loss rate increasing gradually. Stated as proven feed zones from PT-spinner measurement data in several wells.
Carbonaceous slate/rock. As base of reservoir zone.	Dark colored, consist of carbonaceous rich clay (Illite) to sand sized material with micas. Vein filled by wairakite. Shaly structure and foliated, brittle, and unstable.	(-1100) to (-1300) masl. The bottom depth of the formation is undefined due to drilling problem. Shoe of 10-3/4" or contingency 8-7/8" perforated liner is set in this depth as TD well.	Total loss circulation with aerated water circulation,. Collapsed formation in this interval is still unsolved by multiple drilling scenario in total loss condition. It causes high torque and stuck on drill pipe.

As a sequence of graben filling formation inside of a depression system, the formation lateral distribution are spread evenly aligned the basin topography. It is proven by borehole data in every well inside the depression that the dipping of this sequence of lithology is tilted to east near Talang Marsum fault as the boundary.

## 2. RESERVOIR ROCK FACIES

Petrography analysis of core and cutting samples determine the reservoir rock facies in Ulubelu as an altered Rhyolitic tuff facies by its composition, or also called as Ignimbrite. It has fragmental texture, matrix supported, felsic color with vesicular structure filled by secondary mineral. The Ignimbrite from core samples are fractured and jointed by later tectonic deformation.



**Figure 2: Megascopic image of Ignimbrite in Ulubelu which is defined as a reservoir rock facies from core samples showing the permeability features from secondary faults, microfractures, and its primary rock texture (vesicular) associated with Epidote, Secondary Quartz, Pyrite, and Wairakite.**

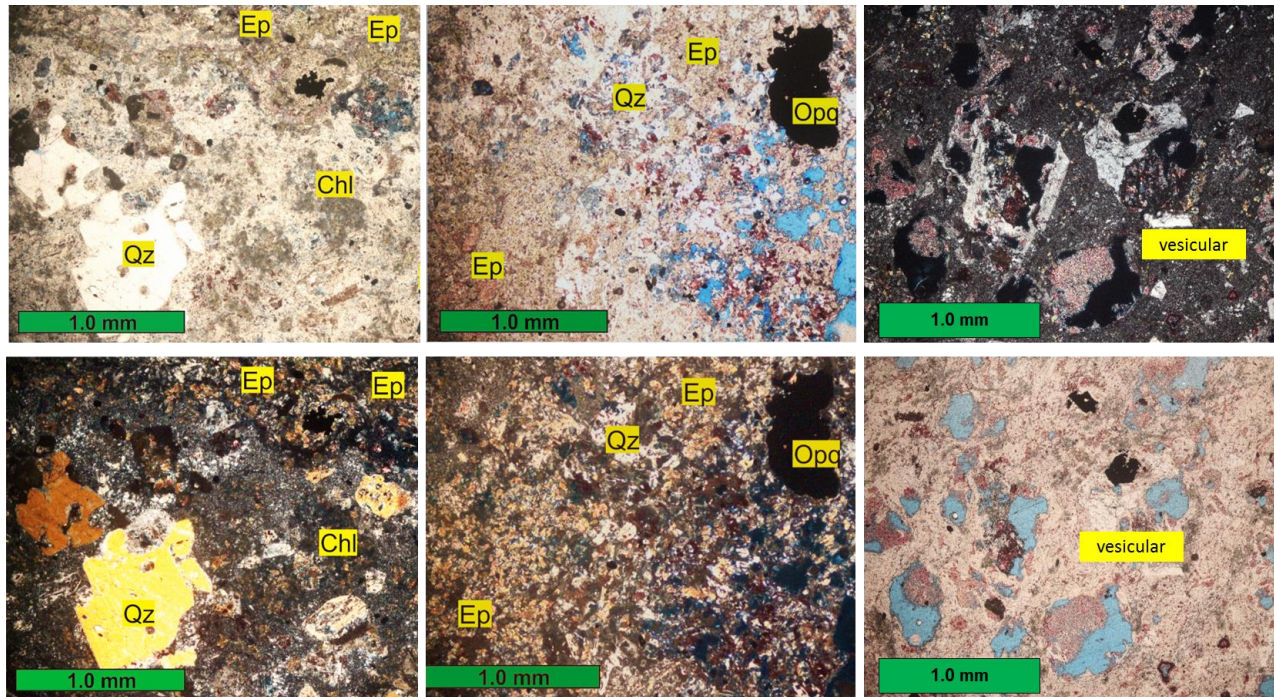
The ignimbrite consists of volcanic glass as ground mass, fine size plagioclase and primary quartz as phenocrist. Some glass shard texture can be found in fully altered condition. Intensity of alteration in this facies is 0.6 IA or very intense. Ignimbrite is strongly altered in groundmass and phenocrist to secondary minerals such as wairakite, illite, chlorite, carbonates, quartz epidote and opaque. These secondary minerals also fill the vein and grain contact in rock body. Primary permeability in this lithology comes from its microfractures, open veins, and vesiculars. Major composition of Ignimbrite in reservoir zone described at Table 4 below.

**Table 4. Mineral composition of Ignimbrite in reservoir zone of Ulubelu geothermal system**

Minerals	Abundance by whole rock percentage	Remarks
Volcanic Glass	20%	As altered groundmass with vesiculars, replaced by Chlorite & Illite.
Plagioclase	5%	Phenocrist. Size 0.3-1 mm. subhedral, replaced by calcite and quartz.
Primary Quartz	5%	Phenocrist. Size 0.1-2 mm, euhedral to anhedral.
Epidote	25%	Sized 0.3-0.5 mm, subhedral-euhedral, replace groundmass, as vein, fills the pore.
Sec. Quartz	12%	Fine grain size, replace the ground mass, as vein associated with epidote.
Calcite	13%	Size 0.3-1 mm, replace the phenocrist, fills the veins and groundmass.
Opaque	7%	Dispersed in groundmass and vein.
Illite	5%	In groundmass, associated with chlorite and opaque.
Chlorite	5%	Replace plagioclase and groundmass.
Wairakite	3%	As veins associated with quartz and Opaque (pyrite).

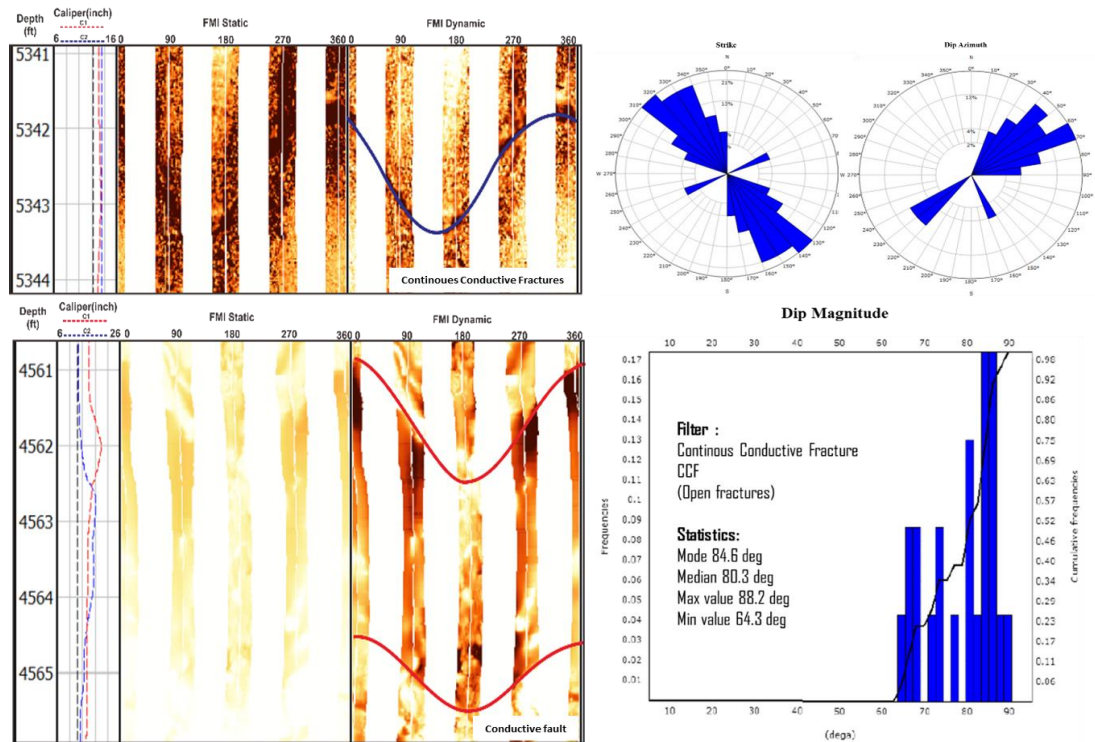


Microscopic image shows formation-hosted permeability such as microfractures, open veins, and vesiculars are abundant in Ignimbrite. These features are natural conduit where the hydrothermal fluid flows within reservoir rock.



**Figure 3:** Microscopic image of Ignimbrite in reservoir zone showing primary permeability in microfractures, open veins, and vesiculars. It is filled by neutral high temperature indicator minerals in some samples or remain as an open space in rocks.

Fracture intensity in Ignimbrite analyzed using resistivity logging image. The concept of resistivity logging image is to identify structural features based on its resistivity contrast. Fractures were further mainly classified as conductive (open) and resistive (filled vein) fractures. Fracture intensity analysis in Ignimbrite shows statistic trend of conductive open fractures and fault dominant to NW-SE with high dip magnitude, which is conformable with Ulubelu regional trend. The result of resistivity log interpretation is shown in Figure 4.



**Figure 4:** Fracture analysis from resistivity data concludes that the major open fracture (CCF) and faults zone in the reservoir formation is trending NW-SE with high dip angle ranges from 80-84°.



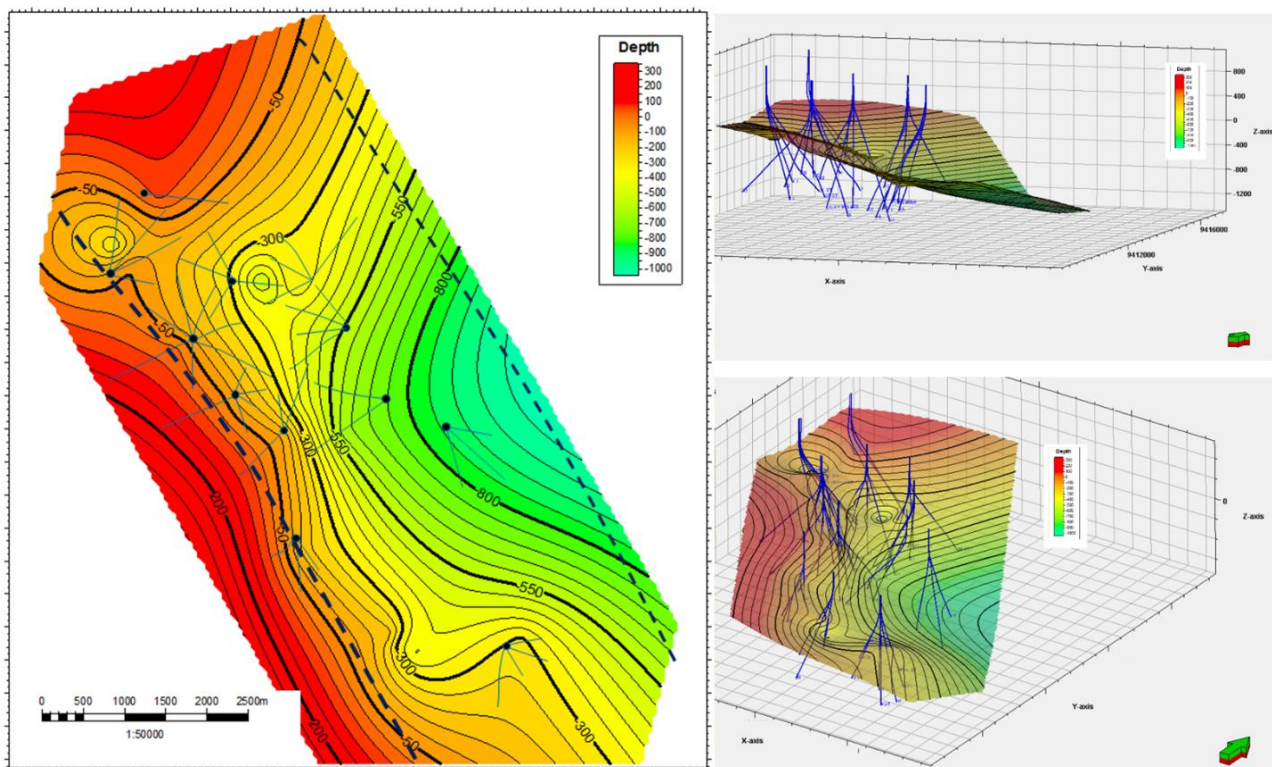
Ignimbrite texture in borehole logging image has relatively extreme high resistivity reading and bright image color in static image log. In significance, Ignimbrite in Ulubelu sweet spot has angular shape and conductive fragments in dynamic image log. The conductive features interpreted as products of intensive alteration from reservoir fluid – rock interaction process and permeability features. This conductive features represent clay altered fragment, and or open fractures which is overflowed by hydrothermal fluids.

Rock properties data will be used as factor value in the future study about numerical reservoir modelling and simulation. Rock properties measurement from several core samples were done in the laboratory. The rock property of Ignimbrite in reservoir zone defined in Table 5.

**Table 5. Rock properties of ignimbrite in reservoir zone of Ulubelu geothermal system.**

Rock Unit	Avg matrix permeability <i>md</i>	Avg matrix porosity/ Helium porosity %	Bulk density (gr/cc)	samples
Ignimbrite	0.25	9.6	2.3	5

Integrated borehole analysis is conducted to identify this unique reservoir formation as Ignimbrite. Ignimbrite are found in all wells. The lateral distribution of Ignimbrite surface layer is relatively tilting to east. It has 10° to 15° of slope inclination and the azimuth around 90° to 115° (east to southeast). Subsurface map and model are built to show the top of Ignimbrite layer distribution.



**Figure 5: Isopach map of ignimbrite in reservoir zone of Ulubelu geothermal system. Top of ignimbrite distribution become deeper in the eastern to southeast part correspond with its claycap thickness in the upper part of Ignimbrite layer.**

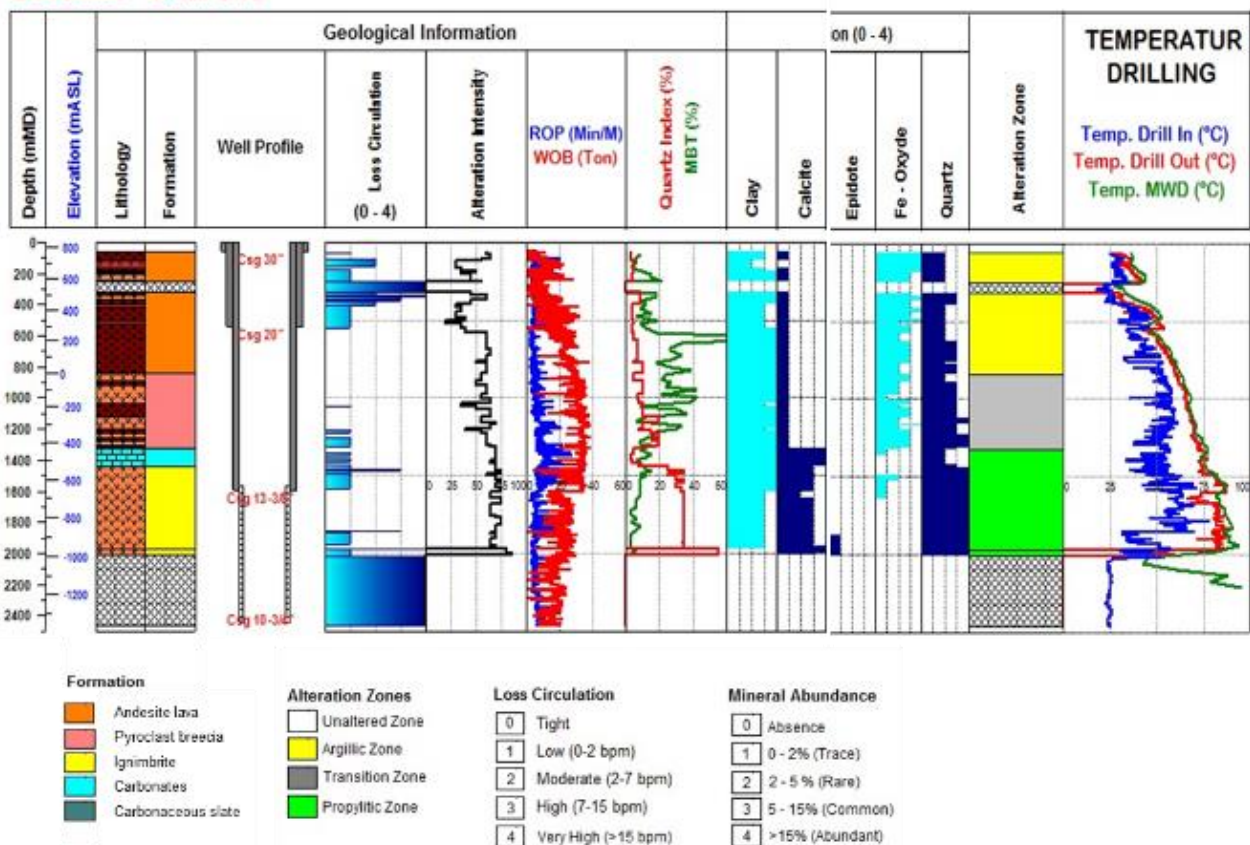
The isopach map of ignimbrite distribution made to delineate top of reservoir rock in Ulubelu where the production casing shoe is set. Drilling data and well test result shows a conformable trend between reservoir feed zones and Ignimbrite distribution as a highly permeable zone. Most of feed zones in Ulubelu geothermal system lays within this ignimbrite body with and/or without fault evidence. Based on that facts, ignimbrite top layer is stated as Top of Reservoir (TOR) in Ulubelu geothermal system where the production casing is set.

Targeting production zone below the ignimbrite layer which is intersected by NW-SE trending faults are highly suggested in Ulubelu drilling program. The productivity rank is higher when production casing is set in top of ignimbrite layer depth. It means that the depth of production casing will be shallower in the west and getting deeper to the east. With the same well configuration, the cost and risk to drill production well in the western part will be lower than in eastern part of the field.

Ignimbrite in reservoir zone of Ulubelu geothermal system has typical character which is reflected in drilling parameter data log. Some drilling parameter trends are similar in many wells when the drilling reach ignimbrite zone. Distinctive trend in drilling parameter data log notifies the onsite wellsite geologist to prepare for setting the production casing. Distinctive characters of ignimbrite in drilling parameter data log are summarized in the table 6 and shown in figure 6.

**Table 6. Drilling parameter of reservoir rock in Ulubelu geothermal system.**

Drilling parameter	Character of ignimbrite in reservoir rock
Circulation loss rate. PLC: Partial loss circulation TLC: Total loss circulation	The upper part of ignimbrite is drilled with KCL polymer mud. PLC rate 0.3-2 BPM consistently appear in the upper depth interval. This depth indicating the depth of production casing point should be set. Some intermittent 3-8 BPM PLC zone are found before TLC. Circulation system switched to fresh water. Rate loss increasing gradually from 7 BPM to $\geq 20$ BPM and remain constant at this rate. Circulation system replaced to aerated fresh water. Blind drill condition.
Cutting composition and secondary/primary minerals.	Alteration mineral in cutting (onsite): Clay 0-35%, Calcite 7-20%, Chlorite 2-20%, Pyrite trace to 1%, Iron Oxide 0-3%, epidote trace to 2%. Strongly altered (SM/TM 60-85%).
Reactive clay concentration	Reactive clay concentration trend increases gradually from the surface to claycap zone. The trend climbs up to 50% in claycap zone then it nosedives significantly to $\leq 10\%$ . Clay percentage below 10% indicating that the drilling progress enters ignimbrite zone in reservoir.
Temperature in / Temperature out.	Before the drilling hit total loss circulation zone in reservoir, the mud temperature in and out measured from the borehole has more than 10 degree Celcius difference ( $\Delta T$ ).
Quartz Index	Quartz index percentage increasing significantly in this formation, ranging from 30-40%. The concentration of quartz is inversely proportional to clay concentration from MBT (Methylene Blue Test).

**ULUBELU - LAMPUNG****Figure 6: Drilling parameter log represents the trend of each borehole parameter in Ulubelu geothermal wells including mineralogy distribution in each subsurface rock formation**

Compatibility between systematic trends and proven by core samples from the reservoir, ignimbrite is believed to be a productive zone at Ulubelu geothermal system. Ignimbrite consist of multiple layers inside their facies that has capability to transmit reservoir fluids in lateral direction. Not only primary structure, its primary rock texture from grain contact, vesiculars and microfractures provide initial high bulk matrix permeability. The permeability rate in this rock will be elevated by the occurrence of secondary

structures like open fractures near existing fault zone. For the next targeting in development well, it is highly recommended to consider the ignimbrite distribution elevation combining with fractures/faults as drilling targets.

### 3. CONCLUSION

Lateral permeability controlled by reservoir rock in volcano – tectonic depression like Ulubelu is proven to be productive. The subsurface distribution of the reservoir rock, in this case identified as ignimbrite lateral layer, should be mapped and modelled from borehole data and taken into consideration to become target of geothermal well drilling.

The strategy of using combined lateral permeability and faults in depression system which is filled by volcanic rocks facies is successfully applied for wells sitting and targeting in Ulubelu. It is elevate the drilling success ratio in the recent drilling campaign from 2016 to 2018.

Preliminary geoscience study should be able to identify the regional tectonic volcano stratigraphy of a field and decide if this semi-sedimentary lateral concept is suitable to be applied in one of the geothermal field in Sumatra depression (pull apart basin) region such as Ulubelu. There is a high possibility that this lateral permeability concept might be suitable and relevant to be applied on other geothermal fields along the great Sumatran fault which is produced by the same regional tensional stress like Ulubelu geothermal system.

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