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Characterizing the Two-Phase Geothermal System of the Ulumbu Field Through Updated Data and Numerical Reservoir Modeling to Support Capacity Expansion Planning

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Abstract. The Ulumbu geothermal field in Flores, Indonesia, exhibits a two-phase system characterized by steam-dominated conditions at shallow depths and liquid-dominated conditions at greater depths. An existing facility currently generates 4 × 2.5 MW, with a planned expansion of 2 × 20 MW as outlined in the 2021–2030 RUPTL. However, uncertainties concerning subsurface structure, heterogeneous permeability, and long-term reservoir sustainability necessitate a comprehensive re-evaluation. Earlier studies relied on exploratory conceptual models with limited geoscientific data. The studies introduced the first natural state model using TOUGH2, confirming the presence of a steam cap overlying a liquid-dominated zone.

This study presents an updated and integrated conceptual and numerical model of the Ulumbu geothermal system based on recent geoscientific, geophysical, and well data. Numerical simulation was conducted using the Volsung simulator to improve natural state representation and inform future development. A potential upflow zone is identified beneath the Lungar area, directly connected to the heat source and underlying a steam-supplying two-phase zone. The model achieves calibration with well data, reproducing key reservoir characteristics: a ~600 m thick steam cap (saturation 0.6–0.7, ~260°C), a ~200 m thick boiling zone (~290°C), and a deeper liquid-dominated reservoir (~300°C) below –1000 m asl. While this study successfully reconstructs the natural state of the system, future production simulations are still required to confirm long-term deliverability and the feasibility of 2 × 20 MW expansion.

Keywords: *ulumbu geothermal, reservoir modelling, steam-cap, numerical simulation, geothermal development.*

1 Introduction

The Ulumbu geothermal field, located in Flores, Indonesia is situated approximately 22–26 km south of Ruteng, the capital of Manggarai District, with a travel time of approximately 65 minutes by road explained in Figure 1. Ulumbu is part of an active volcanic complex associated with the Rii caldera and the collapsed Leok Crown volcano. The yellow box indicates the working area of Ulumbu (WKP Ulumbu), while the red box shows the planned detailed survey area. Access to Ulumbu from Jakarta requires approximately 3 hours of flight to Kupang, followed by 65 minutes of flight to Ruteng. The map also shows main access roads, rivers, residential areas, and identified eruption centers based on regional geological mapping.

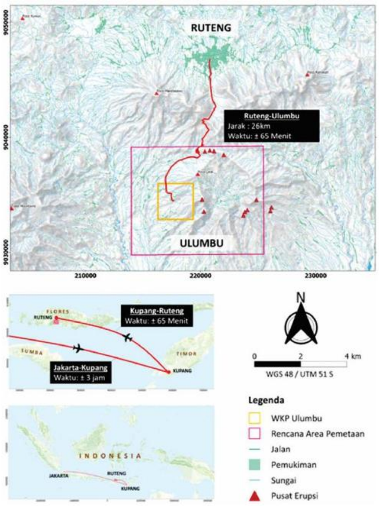

Figure 1 Location of Ulumbu geothermal field (PLN Pusenlis, 2018)

The geothermal system represents a two-phase reservoir system characterized by vapor-dominated conditions at shallow depths and liquid-dominated zones at greater depths. Although a power plant with an installed capacity of 10 MW (4×2.5 MW) has been operational since 2012, the field is currently under consideration for expansion to 2×20 MW, as planned by PT PLN. However, the historical performance of production wells, particularly ULB-2, has shown a declining trend in wellhead pressure and unstable power output, indicating challenges in ensuring long-term production sustainability. Furthermore, the current production zone in the Wewo area is largely associated with a shallow steam cap, which has been interpreted in recent technical evaluations as an unsustainable reservoir zone (WestJEC, 2023). These conditions call for a comprehensive re-evaluation of the subsurface structure, resource distribution, and dynamic behavior of the reservoir system.

Earlier studies have developed initial conceptual and numerical models to describe the characteristics of the Ulumbu geothermal system. The first natural state model, developed and calibrated using the TOUGH2 simulator (Kurniawan et al., 2017), confirmed the existence of a steam cap overlying a liquid-dominated zone and provided initial estimates of the field's sustainable capacity. The model is still built on limited geoscience data, especially in terms of geophysical data. The latest developments in the Ulumbu data geoscience that is regarding conceptual model, the resolution of magnetotelluric (MT) surveys, and gravity data for update numerical modelling.

This study aims to develop an updated and integrated conceptual and numerical model of the Ulumbu geothermal system to support the planned 2×20 MW capacity expansion. By characterizing the location and properties of upflow zones, analyzing permeability and fluid phase distribution within the reservoir, natural state simulations are carried out to support more precise well targeting and to assess the long-term sustainability of the system. Referring to recent modeling approaches developed by Pratama & Saptadji (2016) and Berian et al. (2023), this research emphasizes the importance of utilizing simulation to achieve a natural state condition in order to reduce uncertainties in field development. As a result, this study not only provides an updated reservoir characterization for Ulumbu but also offers a decision-support framework to facilitate sustainable geothermal expansion in the Flores region.Outline of the Ulumbu Geothermal System

1.1 Geological, Geochemical and Geophysical

The Ulumbu geothermal field is hosted within a complex volcanic terrain composed of Quartenary volcanic sequances and tertiary sediments units. Figure 2 explained the geology of western Flores is divided into three primary lithological domains extending from north to south: (1) Tertiary sedimentary rocks, predominantly exposed in the northern region (yellow); (2) Tertiary volcanic and sedimentary sequences composed of interbedded sandstone, limestone, and volcanic products distributed in the central area (orange); and (3) Quaternary volcanic products including andesite, basalt, and dacite, extensively covering the southern part of the island (red), which host the majority of the geothermal prospects.The surface geology is dominated by endesitic lava flows, tuffs, volcanics breccias and sedimentary layers of sandstone and mudstone. The field lies in proximity to several post-caldera volcanic center, including Golo Mompong and Poco Leok, which are considered to be geologically and thermally active likely sources of heat for the geothermal system. Structurally, the geothermal system is controlled by several fault with dominant NE-SW and NNW-SSE orientations, including the Wae Wara and Wae Kokor faults. These structure are belived to facilitate fluid flow and heat transfer from depth, particularly in the Lunggar Area which has been identified as the primary upflow zone.

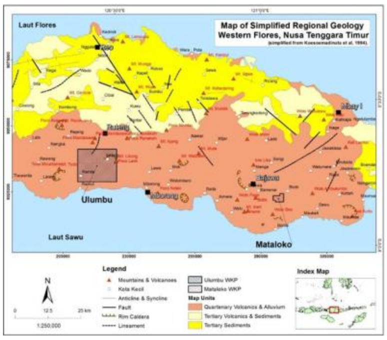

Figure 2 Map of simplified regional geology western flores, NTT (PLN Pusenlis, 2018))

Geochemical analysis using the Na-K-Mg ternary diagram indicates that hot spring fluids from both Wewo and Lungar areas plot near the Mg corner, reflecting immature waters unsuitable for reliable reservoir temperature estimation. In contrast based on Figure 3, well fluid samples provide more meaningful data: ULB-1 fluids (separated water and downhole sample) plot in partial equilibrium, suggesting reservoir temperatures of 260–280°C; ULB-3 fluids (downhole sample) indicate partial equilibrium at approximately 210°C, reflecting mixed two-phase conditions between deep liquid and steam condensate. Fluids from ULB-2 (separated water and surface condensate sample) remain in the immature water zone, and thus are not considered for reliable temperature estimation.

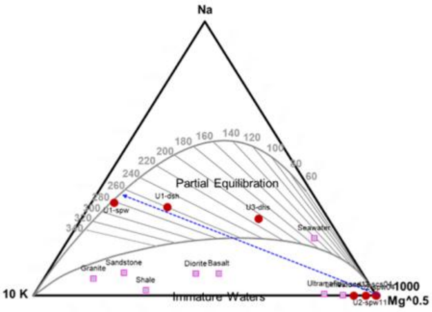

Figure 3 Ternary diagram Na-K-Mg Ulumbu well fluid (PLN Pusenlis,2018)

Geophysical MT surveys delineate a prominent low-resistivity cap (~20 Ω·m) coinciding with the smectite alteration zone and top of the reservoir. This cap is shallower and thinner in Lungar (~500 m) and deeper (~1500 m) in Wewo, indicating a possible upflow center near Leok Crater intersection, and lateral outflow toward Wewo. The density model reveals the presence of a high-density body (>2.8 g/cc) located in the central Lungar area. This body is interpreted as a subsurface intrusion or basement rock associated with the heat source. The resistivity model along the NE-3 section Figure 4, which traverses from the Wewo well site to Lungar, displays an updoming structure—a characteristic feature of high-temperature geothermal systems. This pattern indicates that the clay cap structure is shallower and weaker in the Lungar area, reinforcing the interpretation of Lungar as the upflow zone, while Wewo functions as a lateral outflow zone.

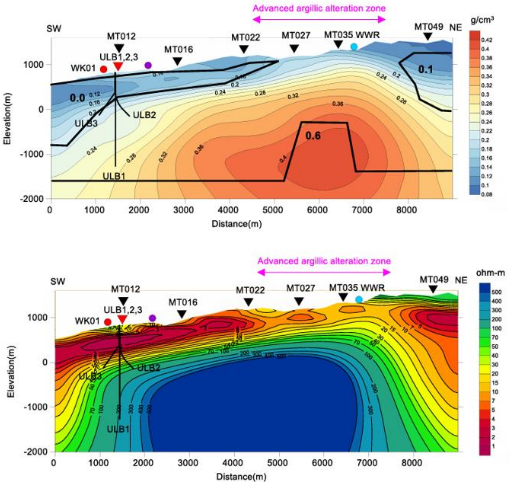

Figure 4 Density model (upper) of profile NE-3 and 3D (bottom) resistivity model of Ulumbu area (WestJEC,2023)

1.2 Well Caharacteristics

Three deep wells—ULB-1, ULB-2, and ULB-3—have been drilled in the Wewo area. ULB-1, the deepest (1887 m), encountered temperature reversals at depths >1300 m, suggesting its location on the outflow flank. Figure 5 present pressure and temperature profiles ULB-1, ULB-2 and ULB-3. These wells were drilled from a single well pad located at an elevation of approximately +623 meters above sea level in the Wewo area. Static pressure and temperature (PT) logs obtained during shut-in conditions indicate conductive thermal gradients in the shallow section of each well (~500–700 m depth), consistent with the presence of a low-permeability clay cap. Shut-in tests conducted in 1996 and 2018 reveal a static water level at approximately 900 m depth (−277 m asl). However, this measurement is influenced by the partial pressure of non-condensable gases (NCGs), which depresses the apparent water level by 300–400 m relative to its natural position. Below the casing, temperature profiles remain linear with no significant convective features, and the maximum static temperature recorded is 232°C in 1996. Notably, a temperature inversion observed below 1250–1300 m suggests that ULB-1 is situated on the lateral margin of the reservoir rather than within the central upflow zone.

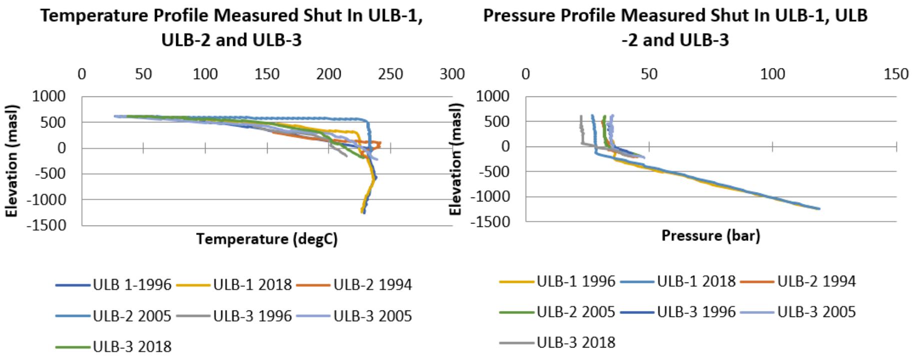

Figure 5 pressure and temperature profiles ULB-1, ULB-2 and ULB-3 (modified from WestJEC, 2023)

ULB-2, completed to a depth of 878.6 m, underwent shut-in testing in 1994 and 2005. The water level under static conditions ranged between 400–900 m. During a bleed test conducted in 2004, the water level was measured at ~640 m, aligning with the main feed zone inferred at 650–700 m depth. A column of steam and NCG is observed above this interface. The maximum reservoir temperature measured is 234°C in 2004.

ULB-3, with a total depth of 945 m, was subjected to shut-in tests in 1996, 2005, and 2018. The static water level was recorded at ~770 m (−77 m asl), with a steam and NCG column extending to ~700 m (−16 m asl), indicating a two-phase zone. The maximum recorded temperature approached 240°C. Spinner log data show the main feed zone to be located at ~880 m (−173 m asl), near the well bottom.

1.3 Conceptual Model and Fluid Flow

The conceptual model of the Ulumbu geothermal system Figure 6 illustrates a two-phase convective geothermal system controlled by complex geological structures and lithological variations. The upflow zone is interpreted to be located beneath the Lungar area, where magmatic heat input from post-caldera volcanic activity provides the primary heat source. Heat is transferred from this source into the reservoir, where fluids ascend and undergo phase separation, generating a vapor-dominated zone in the upper part of the system. Heated meteoric fluids ascend from below -1000 m asl through Tertiary formations, reaching boiling conditions around 0 m asl, thus forming the steam cap. The system then flows laterally toward Wewo and SE, fueling fumaroles and steam-heated features along its path.

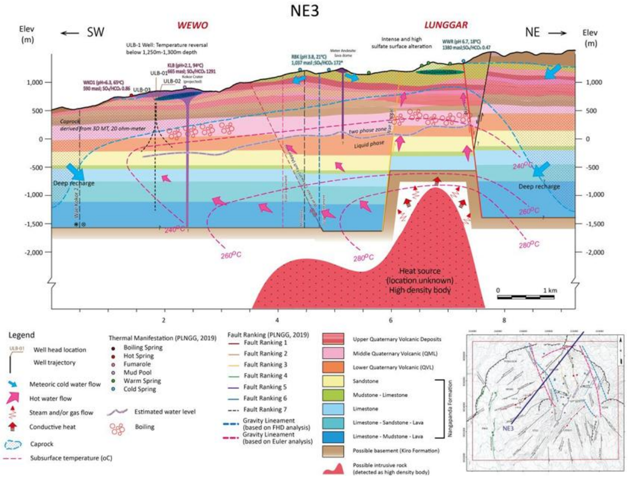

Figure 6 Cross section of the updated conceptual model of Ulumbu geothermal field (WestJEC,2023)

The steam cap is interpreted to be thin and potentially unsustainable under current exploitation, particularly in Wewo. The deeper liquid reservoir, with higher temperatures and lower NCG, offers better long-term development potential. This highlights the necessity for targeted drilling in Lungar to access the upflow and for strategic reinjection to maintain pressure support.

2 Methodology

The methodology of this study is illustrated in Figure 7. The first step involves conducting a literature review, particularly from previous research. This is followed by the interpretation of the updated conceptual model, including 3G data (geological, geophysical, and geochemical) and well data. Using the updated conceptual model, a numerical model is developed, which includes the construction of grids, topography, layers, geometry, and internal boundaries. Once the model is established, initial conditions are defined and input into the simulation. Then run the model to achieve a natural state condition by matching simulated temperature and pressure profiles to well data, following common geothermal simulation practices (Pratama & Saptadji, 2016). The results of this natural state model serve as the basis for scenario studies to identify promising areas for the development of an additional 2×20 MW geothermal capacity.

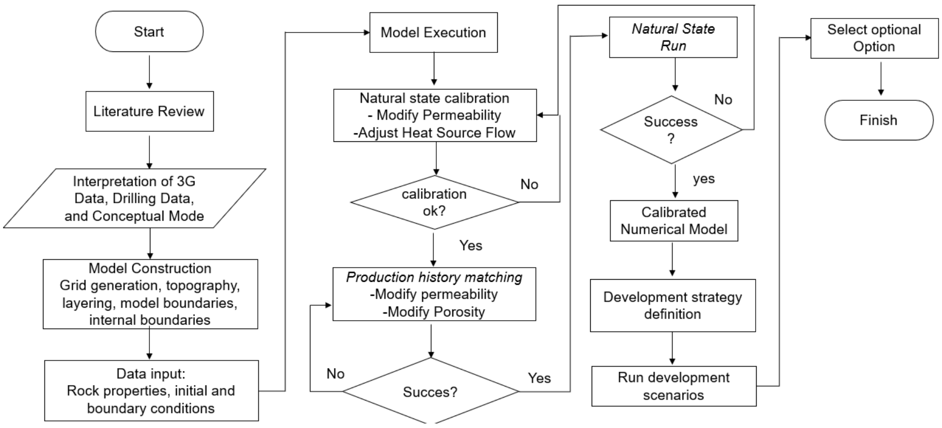

Figure 7 Methodology the research

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2.1 Data integration and conceptual model construction

The conceptual model is built upon recent geoscientific interpretations from the PLN update reports (2023) study. Geological mapping and stratigraphic correlation revealed that the Ulumbu system is hosted in a volcanic sequence composed primarily of: Quaternary andesitic-basaltic lavas, tuffs, and breccias, Overlying Miocene-Pliocene sedimentary rocks (sandstone, mudstone, and limestone), intruded by post-caldera volcanic centers such as Poco Leok and Golo Mompong. Fault mapping identified several major structural controls, including the Wae Wara, and Wae Kokor-1 faults, which serve as key fluid pathways and structural boundaries. The Base of Conductor (BOC) is defined as the base of the clay cap (<20 ohm-m) and is used to infer the top of the geothermal reservoir. BOC elevation maps reveal shallow BOC zones (higher elevation) in the Lungar area and deeper BOC contours extending southwest toward Wewo. A tongue-shaped BOC anomaly trending NE–SW follows major fault alignments (e.g., Meter and Wae Kokor-1 faults), indicating preferential lateral fluid flow pathways. The alignment of the BOC with gravity high zones and surface manifestations reinforces the interpretation of Lungar as the main upflow zone, with Wewo acting as a lateral outflow area.

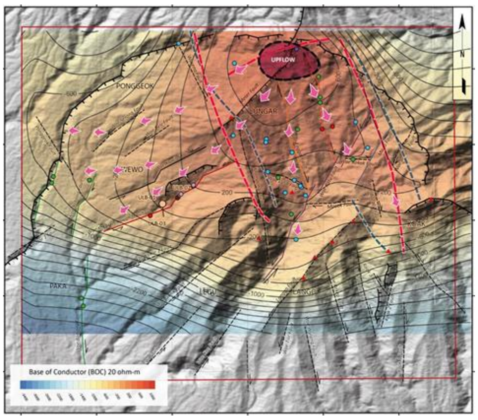


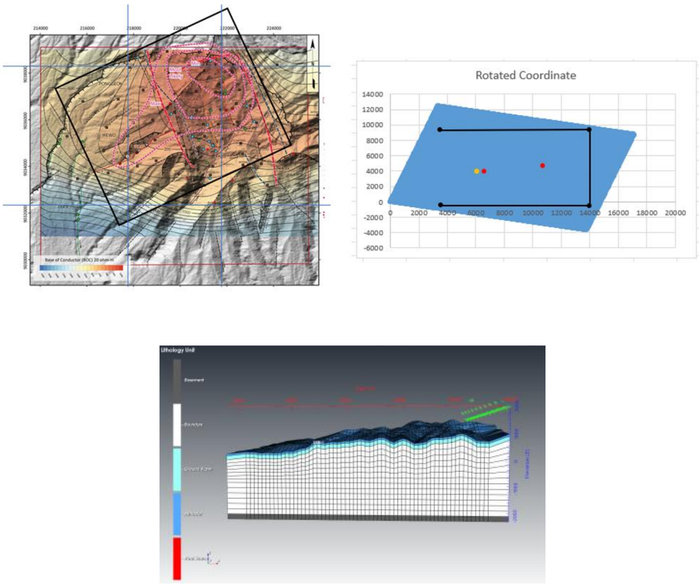
Figure 8 Plan view of the proposed updated conceptual model of Ulumbu geothermal field (WestJEC,2023)

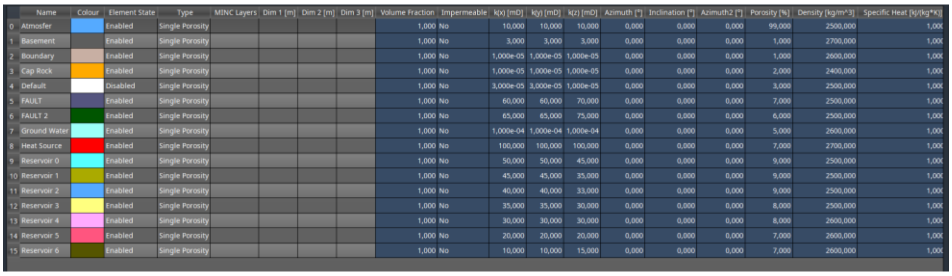
Based on the integration of recent MT resistivity data, geochemical indicators, the presence of an extensive advanced argillic alteration zone at the surface, and the identification of high-permeability zones associated with fault intersections and caldera rim structures Figure 8, a fluid flow model of the Ulumbu geothermal system has been developed. The model suggests that the dominant upflow zone is located near the WWR-5 acid warm spring and the nearby neutral pH WWR cold spring. Isotopic analysis indicates that the recharge source for this system originates from higher elevation terrains surrounding the prospect area, notably the Ranakah Crown.

2.2 Volsung Grid Setup and Numerical Model Construction

A 3D Cartesian grid was generated covering the estimated 8–10 km² reservoir area, refined around Lungar and Wewo sectors. The model grid was vertically divided into 16 layers. Each grid block was assigned material properties including porosity, permeability, rock density, and thermal conductivity, calibrated from well. Reservoir layers were modeled with single-porosity approximations. The area is determined based on interest area the updated conceptual model and geoscientific interpretation of the Ulumbu field, considering the main upflow, outflow zones, and fault structures controlling the reservoir system.

The development of the numerical model for the Ulumbu geothermal system was initiated by defining the simulation domain Figure 9. The area of interest was delineated using a boundary box, which was then spatially rotated to align with the principal fault orientations influencing fluid flow within the system. This rotation ensures that structural controls are properly represented in the numerical grid. The gridding process was performed using the Volsung simulation platform, generating a 3D grid structure. The vertical stratigraphy of the model was divided into 16 layers, each representing different lithological units assigned with distinct rock properties, including porosity and permeability. As shown in Figure 10, the model layering reflects the conceptual stratigraphy of Ulumbu, consisting—sequentially from top to bottom—of an atmospheric layer, shallow groundwater zone, hydrothermally altered caprock, the productive geothermal reservoir rocks, and the underlying heat source.





	Name	Colour	Element State	Type	MINC Layers	Dim 1 [m]	Dim 2 [m]	Dim 3 [m]	Volume Fraction	Impermeable	k(x) [mD]	k(y) [mD]	k(z) [mD]	Azimuth [°]	Inclination [°]	Azimuth2 [°]	Porosity [%]	Density [kg/m^3]	Specific Heat [kJ/(kg*K)]
0	Atmosfer	🟦	Enabled	Single Porosity					1,000	No	10,000	10,000	10,000	0,000	0,000	0,000	99,000	2500,000	1,00
1	Basement	⬛	Enabled	Single Porosity					1,000	No	3,000	3,000	3,000	0,000	0,000	0,000	1,000	2700,000	1,00
2	Boundary	🟫	Enabled	Single Porosity					1,000	No	1,000e-05	1,000e-05	1,000e-05	0,000	0,000	0,000	1,000	2600,000	1,00
3	Cap Rock	🟧	Enabled	Single Porosity					1,000	No	1,000e-05	1,000e-05	1,000e-05	0,000	0,000	0,000	2,000	2400,000	1,00
4	Default	⬜	Disabled	Single Porosity					1,000	No	3,000e-05	3,000e-05	1,000e-05	0,000	0,000	0,000	3,000	2500,000	1,00
5	FAULT	🟪	Enabled	Single Porosity					1,000	No	60,000	60,000	70,000	0,000	0,000	0,000	7,000	2500,000	1,00
6	FAULT 2	🟩	Enabled	Single Porosity					1,000	No	65,000	65,000	75,000	0,000	0,000	0,000	6,000	2500,000	1,00
7	Ground Water	🟦	Enabled	Single Porosity					1,000	No	1,000e-04	1,000e-04	1,000e-04	0,000	0,000	0,000	5,000	2600,000	1,00
8	Heat Source	🟥	Enabled	Single Porosity					1,000	No	100,000	100,000	100,000	0,000	0,000	0,000	7,000	2700,000	1,00
9	Reservoir 0	🟦	Enabled	Single Porosity					1,000	No	50,000	50,000	45,000	0,000	0,000	0,000	9,000	2500,000	1,00
10	Reservoir 1	🟨	Enabled	Single Porosity					1,000	No	45,000	45,000	35,000	0,000	0,000	0,000	9,000	2500,000	1,00
11	Reservoir 2	🟦	Enabled	Single Porosity					1,000	No	40,000	40,000	33,000	0,000	0,000	0,000	9,000	2500,000	1,00
12	Reservoir 3	🟨	Enabled	Single Porosity					1,000	No	35,000	35,000	30,000	0,000	0,000	0,000	8,000	2500,000	1,00
13	Reservoir 4	🟪	Enabled	Single Porosity					1,000	No	30,000	30,000	30,000	0,000	0,000	0,000	8,000	2600,000	1,00
14	Reservoir 5	🟥	Enabled	Single Porosity					1,000	No	20,000	20,000	20,000	0,000	0,000	0,000	7,000	2600,000	1,00
15	Reservoir 6	🟫	Enabled	Single Porosity					1,000	No	10,000	10,000	15,000	0,000	0,000	0,000	7,000	2600,000	1,00

Figure 9 Determining area model, modelling layer and property material

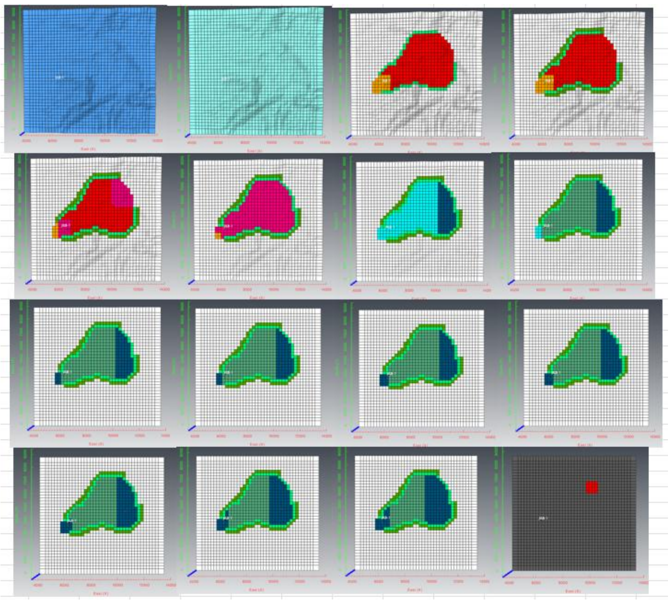


Figure 10 Horizontal slices of the distribution of lithology

2.3 Boundary and Initial Conditions

The initial conditions of pressure and temperature were assigned using hydrostatic and geothermal gradients, calibrated with well data to match field measurements and accelerate natural state convergence. The top boundary was set to atmospheric pressure (1.013 bar) and surface temperature (25°C), while a large volume factor was applied to stabilize conditions at the surface. The lateral boundaries were treated as impermeable no-flow boundaries to isolate the reservoir domain from external recharge or discharge. To ensure solver stability while fully restricting flow across these lateral boundaries, the permeability was assigned a very low value of 1×10^{-22} m² (~1×10^{-7} mD), effectively preventing both mass and heat transfer laterally.

At the bottom boundary, both heat source and deep recharge were represented to better simulate the natural upflow system observed in Ulumbu. The heat source was assigned a constant temperature of 311.5°C and pressure of 142.5 bar, while a deep mass recharge of 0.0025 kg/s/m² with an enthalpy of 1411 kJ/kg was introduced to simulate vertical inflow of hot liquid. An additional background conductive heat flux of 0.08 W/m² was applied to the surrounding basement. This configuration allowed natural convective upflow to develop, ensuring realistic two-phase circulation within the simulated reservoir system.

2.4 Natural State Calibration

The first stage of numerical simulation focused on achieving natural state conditions by iteratively adjusting permeability and porosity distributions. Calibration was performed using Volsung by comparing simulated temperature and pressure profiles against measured newest well shut in data from ULB-01 and ULB-03. The ULB-02 newest shut in data was excluded due to disturbed and not consistent static profiles.

3 Result and Discussion

3.1 Natural State Result

The natural state validation for this model includes several aspect such as pressure and temperature matching, steam cap and heat and mass flows. The pressure and temperature matching use ULB-1. In this study, the result of this model compared to the latest temperature shut in data. Based on the result Figure 11 the model is nearly matched.

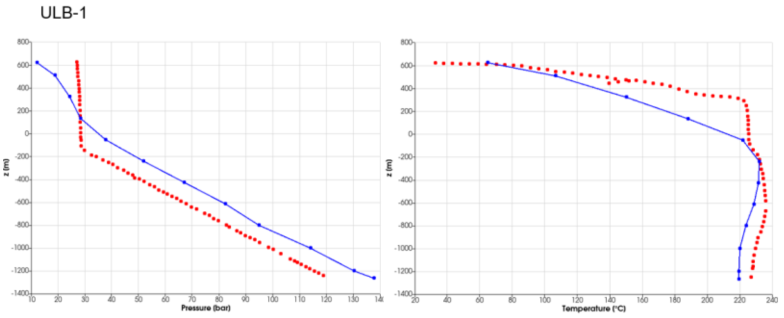


Figure 11 Pressure and Temperature Profiles ULB-1

3.2 Flow and Heat Distribution

The primary challenge in modelling the Ulumbu reservoir lies in identifying and validating the presence of a steam cap formed above the liquid-dominated zone figure 11, separated by a boiling zone. Based on simulation results and the conceptual model interpretation, the boiling zone is estimated to occur near the upflow area beneath the Lungar region, where hot fluid ascends from depth and undergoes phase transformation.

In the initial phase, steam is generated within the deep boiling zone and flows laterally through fractured pathways toward the reservoir before rising toward the caprock. As the steam is constrained by the caprock—which is conductive yet relatively impermeable—part of the steam loses heat and condenses. This condensation process contributes to increased rock permeability due to mineral dissolution by the hot condensate. In the Ulumbu model, the steam cap can be identified through phase distribution and pressure mapping in the natural state simulation, which indicates vapor-dominated conditions at depths of approximately 100–600 meters in the Lunggar area.

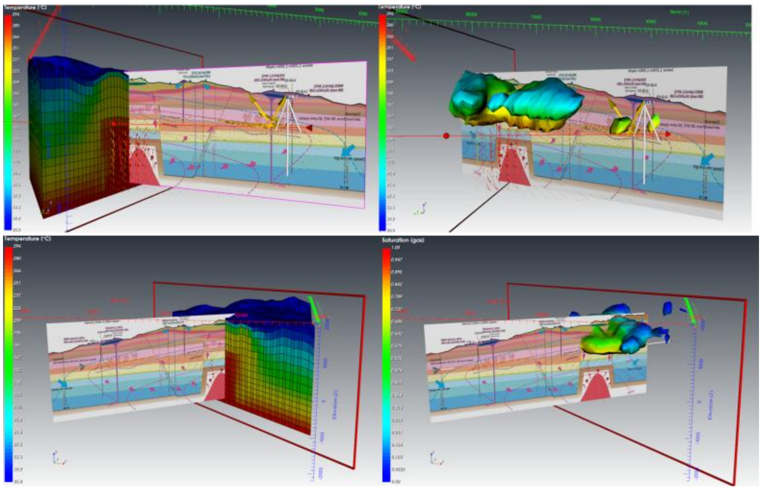


Figure 12 Flow and heat distribution, and vapor zone

The simulation results figure 11 also provide insights into the distribution of the productive zone, particularly the presence of a steam cap that supports dry steam production. Based on the modeling outcomes, the productive zone extends from the Lungar area to Wewo, with the steam cap thickness varying between 300 and 600 meters. This information is critical for determining new drilling targets to support the planned additional 2×20 MW capacity expansion.

In addition, the model identifies the phenomenon of steam condensate flow. Heat loss leads to partial condensation of ascending steam, with the resulting condensate moving downward under the influence of gravity, while fresh steam continues to rise from the heat source. The interaction between upward steam flow and downward condensate movement creates a counter-flow mechanism, which serves as an important indicator for reservoir pressure management and long-term injection planning. This phenomenon reinforces the need for a development strategy that ensures a balance between production and reinjection in the two-phase Ulumbu geothermal system.

3.3 Reservoir Characterization

This section describes the characteristics of the Ulumbu reservoir by comparing actual well measurements with the outputs from the natural state numerical simulation. The goal of this characterization is to evaluate the consistency between the model and the observed subsurface behavior. Key parameters analyzed include temperature, pressure, reservoir zoning, and steam saturation.

Temperature is one of the primary indicators in geothermal system evaluation. Based on measured temperature profiles from ULB-2 and geochemical geothermometry (Na–K and Na–K–Ca), reservoir temperatures in Ulumbu range between 250°C and 280°C. The simulation results show that the reservoir zone (approximately between –1000 m to 0 m asl) maintains a thermal structure consistent with these measurements, especially around the Lungar upflow area.

The vertical structure of the reservoir includes three main zones: a ~600 m thick steam cap (steam-dominated), an underlying ~200 m boiling zone (~290°C), and a deeper liquid-dominated reservoir with temperatures of 310–320°C. This zonation is supported by static pressure–temperature profiles from wells ULB-1, ULB-2, and ULB-3, and correlates well with resistivity and alteration data. A temperature reversal observed in ULB-1 below 1300 m depth further suggests its location on the margin of the main upflow.

The distribution of steam saturation—derived from the simulation output—indicates that the vapor-dominated zone contains gas saturation values ranging between 0.60 and 0.70. These values reflect the thermodynamic state of the modeled system and were calculated from gas saturation outputs, not input parameters. While classical vapor-dominated reservoirs such as The Geysers (USA) or Darajat (Indonesia) typically exhibit steam saturation above 80% to ensure high productivity (O'Sullivan et al., 2001; Zarrouk & McLean, 2019), the 60–70% saturation observed in Ulumbu remains adequate for producing significant volumes of dry steam under the current thermal conditions and system geometry. The extent of the steam cap zone is approximately 5.5 km^2, with lateral continuity from Lungar toward Wewo, confirming this area as the main target for the proposed 2×20 MW expansion.

4 Conclusion

This study presents the development of an updated numerical model of the Ulumbu geothermal field in Flores, Indonesia, with the objective of supporting the planned 2 × 20 MW capacity expansion. Built using the Volsung simulation platform and based on recent geological, geophysical, and geochemical data. Several point can be concluded :

- The natural state model for the two-phase reservoir system in Ulumbu, which includes a steam cap overlying a liquid-dominated zone, has been successfully developed and validated using pressure and temperature data, as well as heat and mass flow information.

- The model achieves calibration with well data, reproducing key reservoir characteristics: a ~600 m thick steam cap (saturation 0.6–0.7, ~260°C), a ~200 m thick boiling zone (~290°C), and a deeper liquid-dominated reservoir (~300°C) below –1000 m asl. While this study successfully reconstructs the natural state of the system, future production simulations are still required to confirm long-term deliverability and the feasibility of 2 × 20 MW expansion..

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