A 3D GEOLOGICAL MODEL AND NATURAL STATE SIMULATION OF JABOI GEOTHERMAL FIELD, NANGRO ACEH DARUSSALAM, INDONESIA

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ABSTRACT

This project aims to develop a comprehensive numerical model of Jaboi geothermal area which represents the subsurface permeability structure, heat, and fluid inputs of the real reservoir with reasonable accuracy by utilizing the published data. A new 3D geological model developed in LEAPFROG Geothermal and a new natural state model simulated using AUTOUGH2 are presented. Jaboi geothermal field has been explored since the 1970's, however, no previous studies have gone as far as creating a 3D geological model or a numerical model of the area. The construction of the new 3D geological model of Weh Island was carried out using a compilation of geoscientific data derived from exploration activities of the Directorate of Geothermal, Ministry of Energy and Mineral Resources during 2005-2006. The 3D geological model describes the features such as the geological structures, water level, rock types, and surface manifestations. This model is then used as the basis for developing a new reservoir model, whose grid is 19.2 km in length and 17.6 km wide, with a total of 21,141 blocks. The model domain covers the entire island and extends from the surface to depth and uses an air-water equation-of-state. The simulation was run until steady-state conditions were reached and the model was calibrated using the field data. The best-calibrated model shows the upflow area is adjacent to the fumaroles (FJB-1 and FJB-2) and acidic hot springs (APJ-1 and APJ-2). The temperature of the upflow zone in this model also fits with the geothermometer prediction of values ranging from 250-300°C. This match is achieved by assigning a deep upflow of 36 kg/s of hot water at an enthalpy of 1,400 kJ/kg into four blocks of the Bangga fault beneath Mt Leumo Matee.

1. INTRODUCTION

Located at 95°12'00"E - 95°23'00"E and 05°46'00"N - 05°55'00"N in Weh Island, Nangro Aceh Darussalam (Figure 1), Jaboi geothermal field has been explored since the 1970's. Sabang city, located in Weh Island, is an area in which the government plans to build a 10 MW geothermal power plant (PLTP) in 2019. A three-dimensional (3D) geological and numerical model of Jaboi geothermal can help support the exploration process.

This project presents a modelling study of Jaboi reservoir, which consists of developing a new 3D geological model in LEAPFROG Geothermal and setting up and calibrating a natural state numerical model using AUTOUGH2. The description of the reservoir model includes the model design and boundary conditions. The new 3D geological model and the reservoir model are based on an existing Jaboi conceptual model (Akbar, 2009; Zarkasyi, 2011). The conceptual modeling phase involved combining data from geological, geophysical and geochemical investigations and temperature gradient wells to give an overview of the physical processes that regulate fluid flow in the Jaboi geothermal system. The 3D geological model of Weh Island was created by combining the related features of its structures, rock types and surface manifestations. This geological model was used as the preparation for the reservoir model. The calibration of the natural state model is based on the temperature gradient wells, surface thermal manifestation data, and geochemical geothermometers.

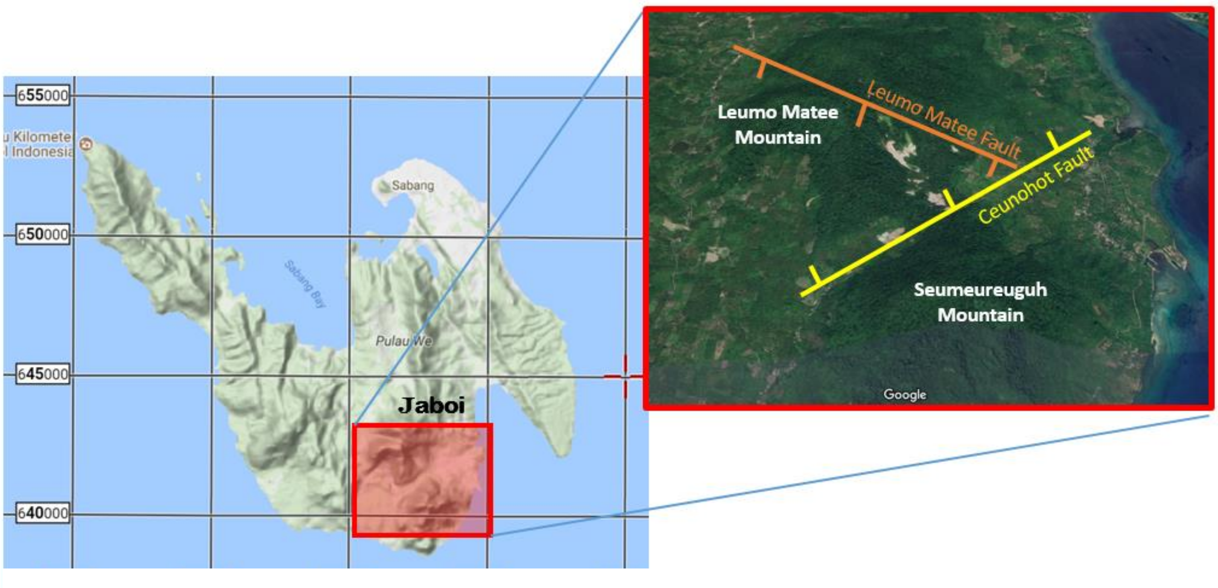

Figure 1: Map of the Jaboi concession area modified from Google Maps (2018)

2. GEOLOGICAL SETTING

Weh Island is a young volcanic island with a type C volcano, a volcanic type with an unknown eruption center and fumerole fields indicating past activity. The island is on the Sunda Orogen volcano lineament which follows a direction of east to west from Nusa Tenggara - Bali - Java - Sumatra to other islands in the extreme north-west of Sumatra. It is also situated in the northern part of the NW-SE Great Sumatra Fault system (De Neve, 1983).

According to Darasutisna & Hasan (2005), Tertiary and Quaternary rocks form the lithology Weh Island. The lithology can be divided into 4 main rock groups: the Tertiary (Miocene) sedimentary rock group which is the main Weh Island rock, the old volcanic rock group of Weh Island which is Quaternary-Tertiary in age and consists of lava and pyroclastic flow, young volcanic rock group which is Quaternary aged from a series of young volcanic cones forming a volcanic lineament in the direction of northwest-southeast and north-south, and a group of limestone reefs.

Figure 2 shows the main faults of Weh Island. The geological structures affecting the geothermal system mainly consists of normal faults. The secondary faults arising from tectonic processes are Leumoo Matee fault, Ceunohot, Iboih, Jaboi and Nibung fault (Zarkasyi, 2011).

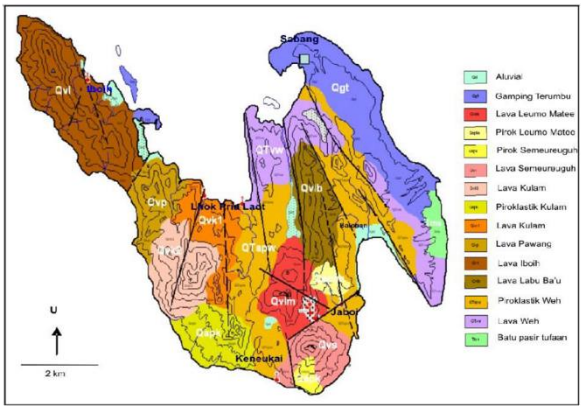

Figure 2: Geological map of the Weh Island (Soetoyo & Widodo, 2010)

3. GEOPHYSICAL SURVEYS

Geophysical surveys can assist in the location of the subsurface extent of the geothermal system, the potential source of heat and geological structures controlling the movement of the geothermal fluid.

3.1 Geoelectric

The analysis of the AB/2 750m pseudo resistivity shows that it is characterized by anomalies of less than 10 Ohm-m, with a closed pattern, in the Jaboi fumarole manifestation central area, indicating a possible potential cap-rock area. This pattern also spreads both towards the southwest and continuing south to Keuneukai Beach where some hot springs are located and also to Jaboi's east-southeast coast where several hot springs near the coast are found. This tongue pattern is known to be associated with the outflow of a geothermal system (Direktorat Panas Bumi, 2017).

3.2 Geomagnetic

The total magnetic anomaly analysis indicates that the Jaboi fumarole manifestation has low anomalies surrounding a high anomaly at its centre. The Jaboi region shows anomalously high magnetic fields on the surface indicates a low magnetic susceptibility contrast. Demagnetized geothermal rock alteration can be linked to the high anomaly (Direktorat Panas Bumi, 2017).

3.3 Gravity

The gravity anomaly coincides with the emergence of regional structures in the northwest-southeast of the research area, such as a lineament in that direction, particularly in the northern area of Balohan. Numerous dominant north-southwest oriented features, along with almost northwest-southeast oriented features characterize the high gravity anomaly coinciding with the fumarole manifestations. These alignments reflect the many fracture structures in the research area (Direktorat Panas Bumi, 2017).

4. GEOCHEMICAL STUDIES

Hot springs, fumaroles, steam vents, steaming ground, warm springs and cold springs are parts of the Jaboi surface manifestations. The hot springs analyzed with geochemical methods are: Jaboi Hot Spring (APJ), Iesum Hot Spring (APS), Batetamon Hot Spring (APBA), Lho Pria Laot Hot Spring (APPL), Seurui Hot Spring (APSE), Keunakai Hot Spring (APKE) and Pasi Jaboi Hot Spring (APPJ). Additionally, two fumaroles in the Jaboi area with temperatures of 98.4°C and 99.4°C were also analyzed (Akbar, 2009).

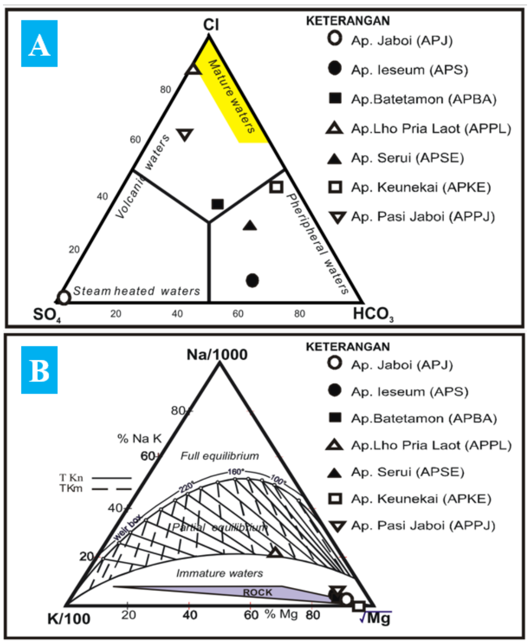

Figure 3: The ternary diagram of Jaboi's hot springs (Kusnadi, Supeno, & Purwoto, 2005): A. Cl-SO_4-HCO_3 and B. Na-K-Mg

4.1 Ternary Diagram Analysis

The ternary diagram of Cl-SO_4-HCO_3 (Figure 3) shows that Batetamon, Lhok Male Lhaot, Ieseum, Keunekai hot springs, and Seurui are of bicarbonate type and Jaboi hot spring are considered in the chloride type, Jaboi hot water is the sulfate type (hot water vapor area).

Meteoric water mixed with vapor containing H_2S characterize Jaboi's hot springs of sulfate type. Surface water and condensed vapor give the > 95°C temperature and a soluble sulfate that keeps the surrounding rocks oxidized. A dominant HCO_3 content and a relatively high level of SO_4 characterize the bicarbonate type of Iesum hot spring. This type of bicarbonate water contains HCO_3 which is formed from dissolved magmatic CO_2 gas and groundwater, while the SO_4 content indicates the hot spring is still linked with the Jaboi hot spring area. Seawater possibly affects the composition of a hot spring near the southeast coast (Keunekai), which is of bicarbonate type but with a high chloride content.

The analysis of Na-K-Mg ternary diagrams (Figure 3) indicates the presence of immature water in all samples from the hot springs, verifying the dominance of the meteoric water. The Cl content in most hot springs indicates possible seawater influence and the interaction of the hot fluid from the reservoir which is then mixed with groundwater near the surface. The only near-equilibrium conditions are found in Lho Pria Laot hot spring, as it is in a partially equilibrated area.

Iesum hot spring is used to estimate the reservoir temperature because of its high temperature, neutrality, and lack of seawater contamination. A minimum temperature of 187°C is indicated by the SiO_2 conductive cooling geothermometer. Meanwhile, 327°C is the maximum temperature of the CO_2-H_2 gas geothermometer obtained from Jaboi fumaroles, giving an average estimated reservoir temperature of around 250°C (Zarkasyi, 2011).

5. TEMPERATURE GRADIENT WELL

At the exploration stage and following up previous surveys the drilling of shallow wells JBO1 and JBO2 was carried out. JBO1 reached 238 m in depth with the thermal gradient ranging from 20.5 – 22°C per 100 m and JBO2 was drilled to 250 m, with 17°C per 100 m for the thermal gradient. Tuff breccia, breccia intercalated by tuff and andesite lava flow characterize the well lithologies. Kaolinite, alunite, pyrite, montmorillonite, smectite, secondary quartz, calcite, iron oxide, halloysite, and chlorite were some of the alteration minerals found in the wells. The alteration minerals listed above are of the argillic type and function as a clay cap for the Jaboi geothermal system (Munandar, Boegis, & Simarmata, 2006).

6. CONCEPTUAL MODEL OF THE JABOI GEOTHERMAL AREA

The conceptual models made by Akbar (2009) and Zarkasyi (2011) were used as the basis for our conceptual model but were adapted based on the present geological model, and also temperature gradient wells results. Leumo Mate and Seumeureuguh Volcanoes at a depth of over 4 km were estimated to be the region's source of the geothermal heat. The residual magma then heats the permeable upper rocks which were formed from the fracture zone of the main fault structure, becoming a reservoir in the geothermal system with the temperature of around 250°C. The reservoir layer is thought to be composed of Weh volcanic rocks with estimated densities of 2620 kg/m^3 and permeability of 27 millidarcys and sandstones with an estimated density of 2520 kg/m^3 and a permeability of 3 millidarcys. The peak depth of the reservoir zone is at 550-600 m below the surface around the Jaboi manifestations.

A low resistivity value (less than 10 ohm-m) indicates a 400-500 m impermeable layer which is present above the reservoir layer. The constituent rock of the impermeable layer is estimated to be products of the Leumo Mate mountain, the Seumeureuguh mountain, the Weh pyroclastic and part of the Weh lava that have been strongly altered in the acidic environment to become argillic alteration rocks.

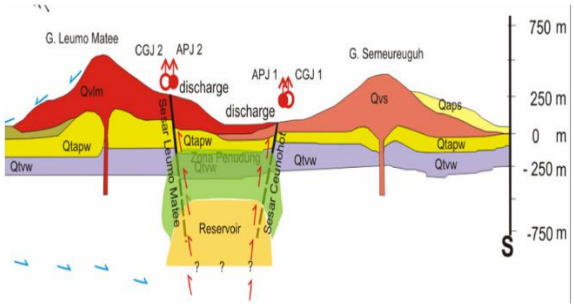

Figure 4: The conceptual model of Jaboi geothermal area (Akbar, 2009)

The high elevation (300-600 m) zone of Weh Island's volcanic morphology acts as a water trap area. This is also a depressed area with complex fault structure and thus provides a good medium for the soaking of meteoric water into the subsurface and its accumulation in the reservoir (recharge water) mixed with deep reservoir fluids. The fluid is then heated by residual magma (pluton) and mixed with magmatic fluids (SO_2, CO_2, H_2S, H_2O, HCl, and HF), and appears at the surface as thermal manifestations.

The geology, drilling of temperature gradient wells and gravity measurements indicate that the main structures forming Jaboi's geothermal system are the Ceunohot, and Leumo Matee Faults. Both faults are the youngest normal faults with a NW-SE and NE-SW direction, forming the graben valley between Seumeureuguh and Leumo Matee volcanic bodies (Zarkasyi, 2011).

7. 3D GEOLOGICAL MODEL CONSTRUCTION

LEAPFROG Geothermal was used to develop a 3D geological model of Weh Island, based on the following data from the literature review: A. XYZ data to construct the topography of Weh Island, B. Geological map to determine the rock stratigraphy, C. Geological cross-section to define the lithology and D. Bathymetry data to construct the sea depth around the island.

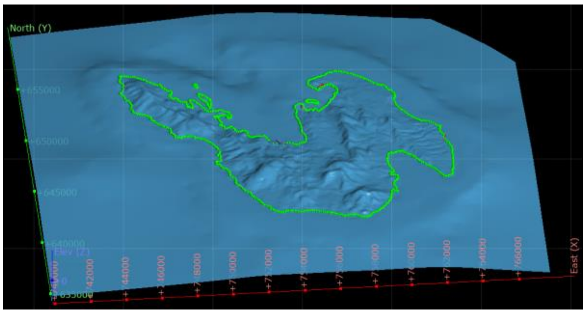

Figure 5: The result of the combination of XYZ and bathymetry data for Weh Island

7.1 Topography Setup

The model topography was created by importing the XYZ data into LEAPFROG. The sea depth around Weh Island used bathymetry data. When the data were inconsistent or incomplete, the bathymetry was made by constructing polylines around the island following the depth of the sea. A python script was used to remove the "bad" data from the data base while the remaining data were used to create the topography of the Weh Island and the sea. Figure 5 shows the complete topography model of Weh Island. The green polylines represent the coastline of the island.

7.2 Stratigraphy Setup

The complete topography of the island was overlaid with the imported LEAPFROG geological map of Weh Island. The map was utilized to create the fault models representing the established geothermal geological structure and to define the rock unit distribution within the island. The following table summarizes the Weh Island rock stratigraphy:

Table 1: Summary of rock stratigraphy in Weh Island

Rock unit	Abbreviation	Geologic age
Tuffaceous Sandstone	Tms	Tertiary
Weh Lava Flow	QTvw	Upper Tertiary
Weh Pyroclastic Flow	QTpw	Upper Tertiary
Labu Ba'u Volcanic	Qvlb	Quartenary
Iboih Volcanic	Qvi	Quartenary
Pawang Volcanic	Qvp	Quartenary
Old Kulam Volcanic	Qvk-1	Quartenary
Kulam Pyroclastic Flow	Qapk	Quartenary
Young Kulam Volcanic	Qvk-2	Quartenary
Semeureuguh Volcanic	Qvs	Quartenary
Semeureuguh Pyroclastic Flow	Qaps	Quartenary
Leumo Matee Volcanic	Qvlm	Quartenary
Leumo Matee Pyroclastic Flow	Qaplm	Quartenary
Limestone	Qgt	Quartenary
Alluvial	Qa	Mixed

Based on the age of the rock unit, the Weh Island rock formation was divided into six groups which are Young Volcanic, Upper Quartenary Volcanic, Mid Quartenary Volcanic, Lower Quartenary Volcanic, Sedimentary and Mesozoic Basement.

The main faults on the geological map were digitized using the polyline function to create the fault blocks. The dip of the faults ranged from vertical to 75º and was based on the cross-section map. Figure 6 shows the subsurface structure of Weh Island likely to be controlling the emergence of the surface thermal manifestations and the geothermal reservoir.

7.3 Lithology Setup

The rock formation locations were determined by using the geological cross-section maps as the subsurface information source of the Weh Island. The cross-section maps were imported into LEAPFROG and plotted together with the topography of the model. The lithological distribution control and the boundary of the geological model were set up with the creation of 135 "artificial" wells. Each well was positioned in a rock unit area of the geological map and were 3000 m deep. The geology data for the wells utilized the six groups of rock formation as primary input. Figure 7 shows the process used for setting up the 3D model lithology.

The 3D geological model output volumes were generated after the lithology setup. Adjustments to the lithology in the artificial wells were made to ensure the rock distribution of the model followed the distribution of the rock units on the geological map. The cross-section maps were used as the

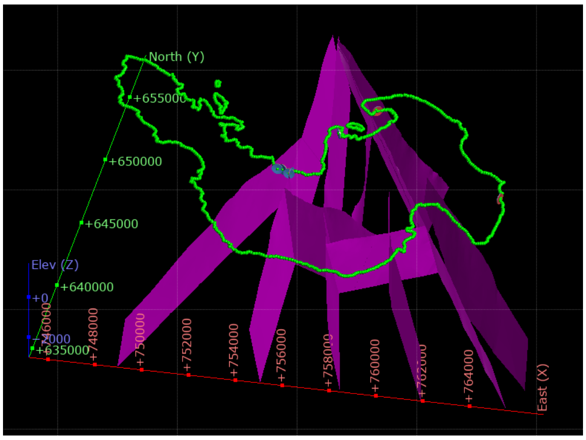

Figure 6: The fault structures of the 3D model

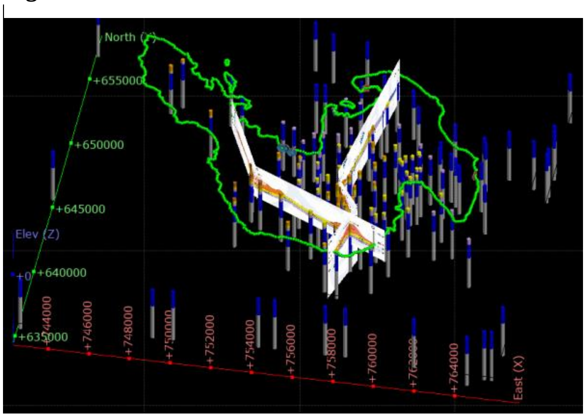

Figure 7: The distribution of 135 "artificial" wells inserted in the cross-section maps and at the edge of the model

basis for adjusting the thickness of each rock formations. The lateral distribution of lithology in the areas with no data was interpreted using the closest cross-section map, and if the results did not suit the geological map, a trial and error method was then applied to adjust the thickness of the rock formation.

8. 3D GEOLOGICAL MODEL

Figure 8 shows the complete 3D geological model of Weh Island. The model covers the entire 400 km^2 area of Weh Island and represents the identified stratigraphy and geological structure in Weh Island's geological map and the conceptual model of Jaboi geothermal area.

Nine primary faults, with the majority being normal faults, are assigned in the model. These faults control the fluid flow patterns of the hydrothermal fluids in the Weh Island in general and the Jaboi geothermal area specifically. The stratigraphy sequence of the model from top to bottom is Young Volcanic, Upper Quartenary Volcanic, Mid Quartenary Volcanic, Lower Quartenary Volcanic, Sedimentary and Mesozoic Basement. The thickness of the Young, Upper, Mid and Lower Quartenary Volcanic follow the topography of the model and the cross-section maps, while the sedimentary thickness was predicted to remain constant at 1000 m. The remaining depth of the model is the Mesozoic Basement.

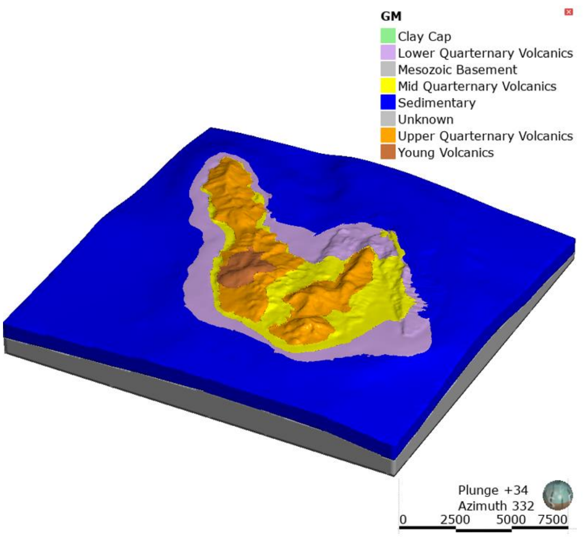

Figure 8: The complete 3D geological model of Weh Island, Nangro Aceh Darussalam

9. NUMERICAL MODEL DEVELOPMENT

9.1 Reservoir Model Grid Setup

The AUTOUGH2 grid is 19.2 km in length and 17.6 km wide with a total of 21,141 blocks (Figure 9). The blocks are 800 m x 800 m and range in vertical thickness from 500 m in the Mesozoic Basement to 100 m near the surface. The grid is more highly refined in the potential production area (Jaboi geothermal field) with blocks set at 400 m x 400 m and 200 m x 200 m.

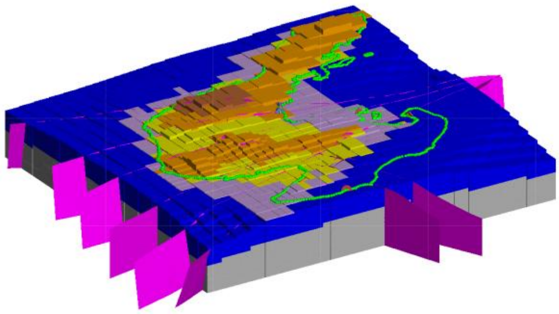

Figure 9: The grid layout side view

This AUTOUGH2 grid was then optimized using a Python script and imported back into Leapfrog geothermal. This makes use of unstructured grid spacings that are not currently available in Leapfrog geothermal and can result in faster more efficient simulations. This optimized grid was then used as the reservoir simulation model to achieve natural state conditions. Once the optimized grid is imported, the rock types are automatically assigned by Leapfrog Geothermal which saves significant amounts of time by avoiding the arduous task of manually assigning geology into the reservoir model. Also, and most importantly, as the geological model is updated, Leapfrog geothermal can automatically transfer those changes into the AUTOUGH2 model that it generates.

9.2 Boundary Condition

Top boundary: At the top of the model, dry atmospheric conditions are assigned at the top surface of the island with the pressure of 1 bar and mean temperature of 30°C. The conditions below sea level follow the hydrostatic pressure and the temperature varies following the universal temperature data of ocean water. The equation of state, EOS3, is used in this model which simulates mixtures of water and air and allows the model to include the vadose zone thus representing the system all the way to the surface. An ideal gas approximation is adopted and the partial pressures for air and vapor in the gas phase are added, $P_g = P_a + P_v$ (Pruess, Oldenburg, & Moridis, 2012). An annual rainfall of 1,943 mm/year (CLIMATE-DATA.ORG, 2018) and an infiltration rate of 10% are used. The top three blocks of this model were set up using a Python script with the rock properties specified in Table 2. This was done to represent the near-surface unconsolidated soil conditions, with substantial permeability that allows the rainwater to infiltrate and flow to lower elevations following the topography.

Table 2: The rock properties of near-surface blocks

Rock Properties	Value
K1	1013.25 mD
K2	1013.25 mD
K3	101.325 mD
Porosity	25%
Density	2500 Kg/m^3
Conductivity	2.5 W/m°K
Specific heat	1000 J/Kg°K

Side boundary: The side boundaries are presumed to be no-flow boundaries, i.e., no heat or mass are entering or exiting the system. The side boundaries are located in the ocean area and far away from the potential geothermal field.

Base boundary: The 80mW/m^2 of heat flux is assigned at the bottom layer of the model (layer 27) as the background heat input for the model. The upflow zone is represented by a hot water flux in the fault zone below Mt Leumo Matee.

10. NATURAL STATE SIMULATION

The natural state model was run for 1x10^{16} seconds of simulated time to achieve steady-state conditions. The hot water was injected in 4 blocks as the upflow zone at layer 27 (Basement) with the dimension of each block being 200 m x 200 m x 500 m. These hot water injection sites were set on the Bangga fault which crosses the Mt Leumo Matee in NW-SE direction and is thought to act as the main fault controlling the geothermal system in Jaboi area. The Leumo Matee and Ceunohot faults are the secondary faults forming the geothermal reservoir in the Jaboi area, as identified by the conceptual model.

The clay cap was set at layers 11, 12, 13, and 14 to reflect the clay cap area obtained from AB/2 750m pseudo resistivity map, with the thickness of 400 m. This clay cap acts as an impermeable layer and constrains the hot water flow to follow the lateral tongue patterns below the clay cap. Directly beneath the Cap Rock area is a reservoir zone with a thickness of 600 m. This reservoir zone consists of Lower Quartenary Volcanic and Tertiary rock formations. Thus, these two rock formations are set to have high permeability compared with the other rock formations to accommodate the flow of hot fluids from the deep formation and to allow recharge of meteoric water.

11. MODEL OUTPUTS AND CALIBRATION

The calibration process for a natural state model involves the adjustment of the upflow zone location, the rock permeabilities (K1, K2, and K3), and the mass rate and enthalpy of the hot fluids. This process was done manually until a good match between the model simulation results and the measured field data was achieved. The only available data are the public exploration data from the Directorate of Geothermal, Indonesian Ministry of Energy and Mineral Resources, and the natural state simulation results were calibrated with the following observed data:

Temperature gradient well data: The temperature data from two shallow gradient wells (JBO-1 and JBO-2) are utilized as a temperature data baseline in adjusting the rock permeabilities and the rate of injection of hot fluids at the bottom layer of the model. The comparison of observed temperature data and model results are shown in Figure 10.

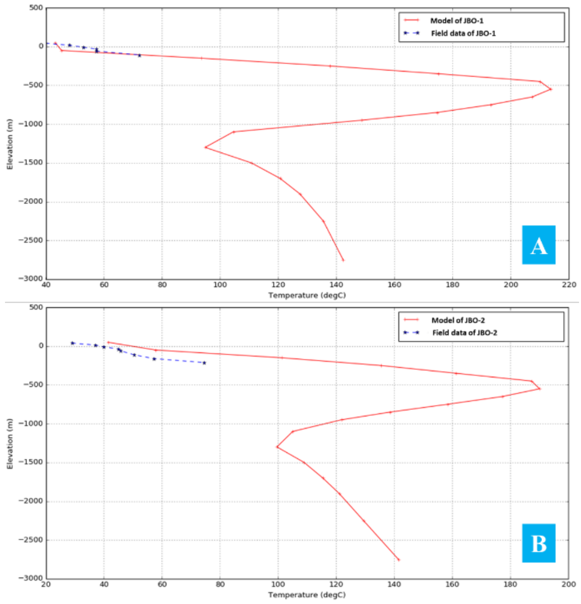

Figure 10: Down-hole temperature match of the shallow wells: A. JBO-1 and B. JBO-2

Surface manifestations: The type and location of surface manifestations data are very useful for calibrating the distribution of the hot fluids in the model because the surface manifestation data are direct data that represent the current condition of the Jaboi geothermal system. Through these data, the location of the upflow and outflow zone can be inferred. Figure 11 shows the location of the surface manifestations around Jaboi area.

The predicted upflow zone area is the area between Mt Leumo Matee and Mt Semeureuguh indicated by the existence of fumaroles (FJB-1 and FJB-2) and acidic hot springs (APJ-1 and APJ-2) with pH ranging from 2.4 - 2.52. The outflow zone is located about 3.5 km to the east of the upflow area and is indicated by the emergence of neutral bicarbonate hot springs (APS-1, APS-2, APS-3, and APBA) and neutral chloride spring (APPJ). The model cross-section is made following the green line in Figure 11 to display the modelled distribution of hot water.

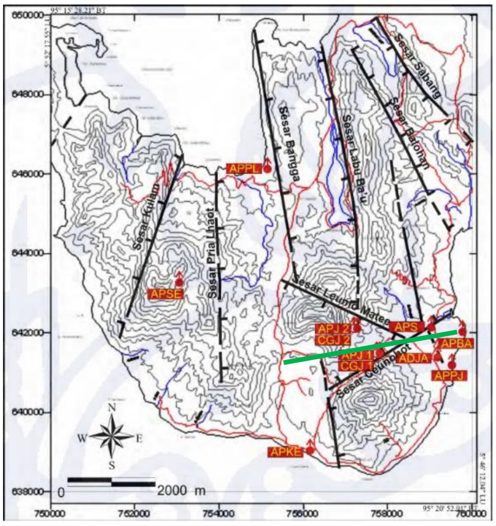

Figure 11: The surface manifestation location map and location of the cross-section of the model (green line) (Akbar, 2009)

Geochemical geothermometer: The estimation of the deep average reservoir temperature using geochemical geothermometer is 250ºC. This number constrains the temperature of the upflow zone in the model which becomes the possible main target for drilling in the next stage of exploration. The natural state simulation results which have been calibrated using the surface manifestation and geothermometer data are shown below in Figure 12.

Leumo Matee fault and Ceunohot fault are effective in controlling the occurrence of Jaboi geothermal system as discussed in the conceptual model. Figure 13 clearly shows this phenomenon where the hot water at the bottom Mt Leumo Matee is flowing upward and fills the reservoir zone through the Leumo Matee fault and Ceunohot fault. This hot fluid then flows to the east following the Cap Rock in the model and becomes an outflow of the system. The cold water mainly flows from northwest to southeast following the direction of the main faults forming Weh Island, and it recharges the geothermal system through layer 21 below the reservoir zone.

As seen in Figure 14 and Figure 15, the simulation results match with the observed locations of fumaroles (FJB-1 and FJB-2) and acidic hot springs (APJ-1 and APJ-2). The upflow area of the geothermal system is indicated by the hot convective plume rising vertically near those manifestations. The temperature of the upflow zone in this model also fits with the geothermometer prediction with the value ranging from 250-300ºC, as the result of the input of 36 kg/s of hot water at the enthalpy of 1,400 kJ/kg assigned into four blocks of the Bangga fault beneath Mt Leumo Matee. This model was simulated using 302 calibrated rock properties.

12. CONCLUSION AND RECOMMENDATION

This project has succeeded in developing an attractive and useful 3D geological model of Weh Island and a new numerical model of Jaboi geothermal area. The complexity

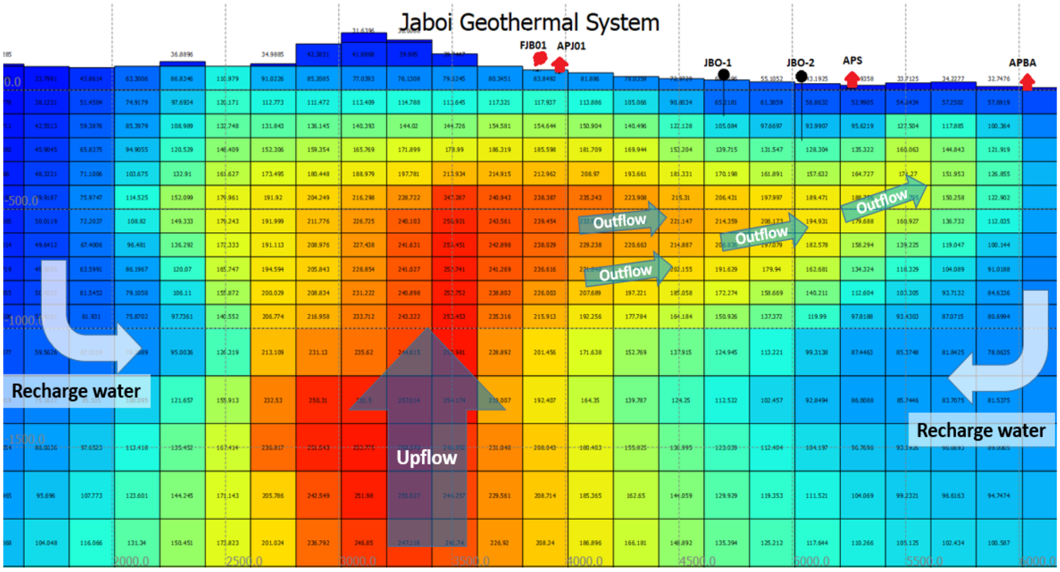

Figure 14: Steady-state temperature distribution for the natural state model simulation

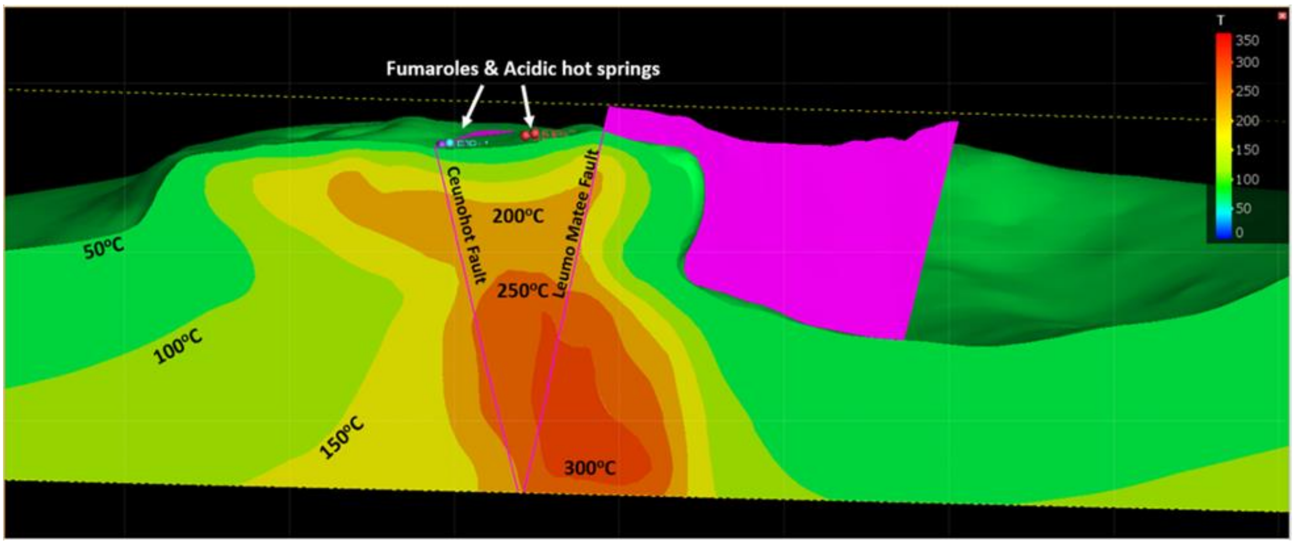

Figure 12: Simulated natural state temperature output volumes of Jaboi geothermal area

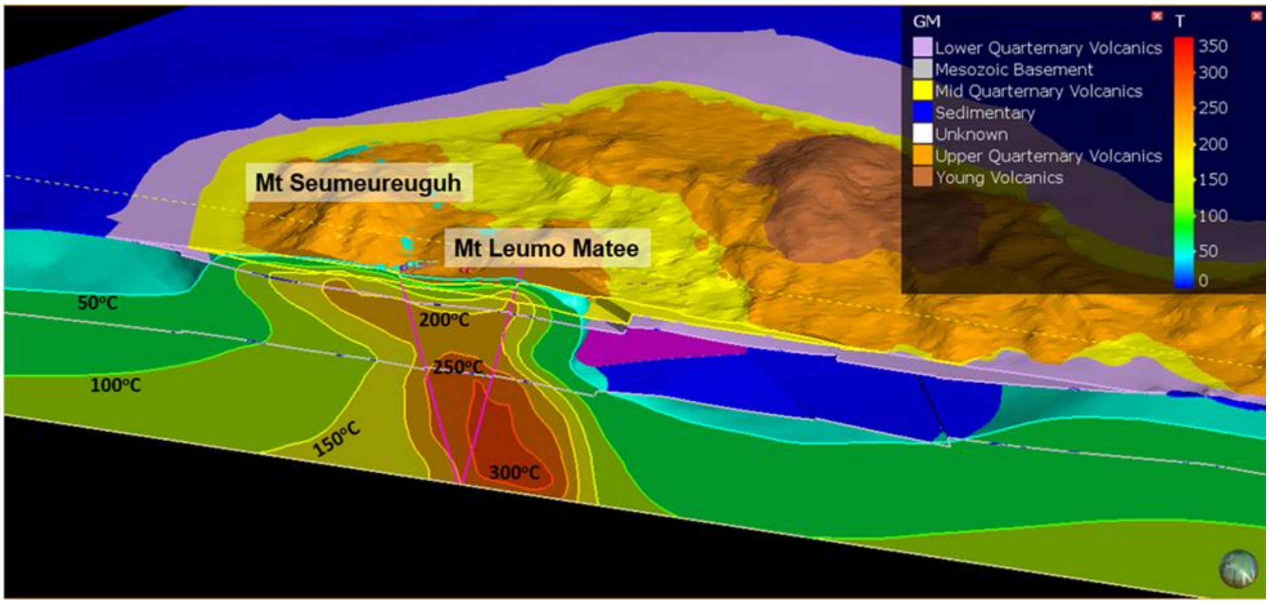

Figure 13: Vertical slice of Weh Island 3D model in NW – SE direction showing the temperature distribution

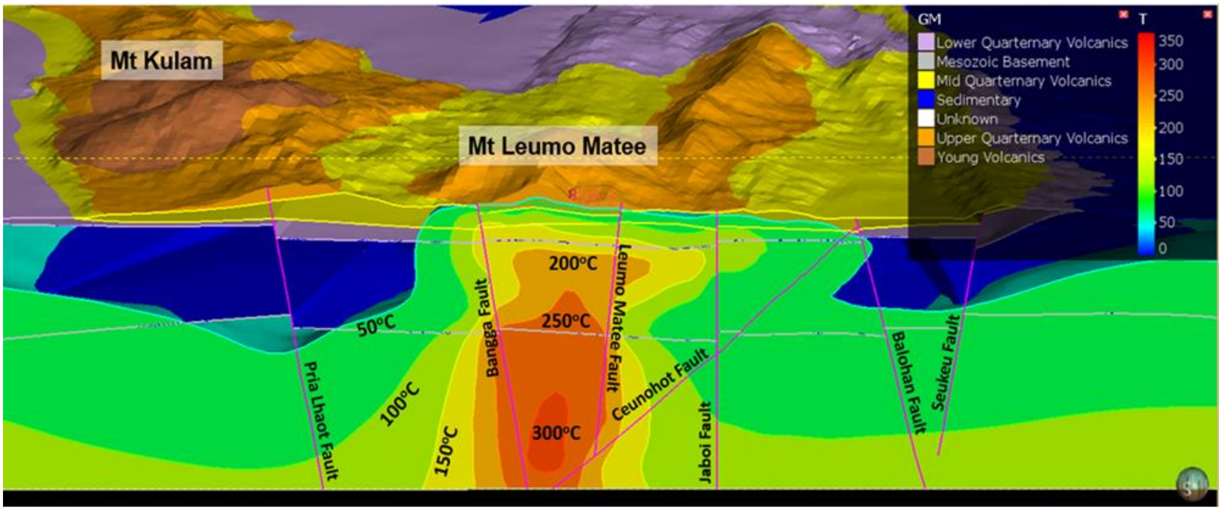

Figure 15: Vertical slice of Weh Island 3D model in SW - NE direction showing the temperature distribution and the geological structures

of the structure and stratigraphy of Weh Island has been included in the 3D model using LEAPFROG geothermal. The calibration process achieved satisfactory agreement between the temperature gradient well data, geothermometry and the model results. This project could provide a novel method in estimating the potential geothermal resource for the early exploration stage. The authors believe this method can help reduce the risks associated with the initial resource estimation because it can be used to exclude potential conceptual models that are inconsistent with the data thereby reducing the uncertainty around the conceptual model. This study only used existing publicly available data. However, an advantage of the approach presented is that the assumptions and estimates used in it can be updated as more data becomes accessible. Leapfrog Geothermal automatically adjusts the existing model to be consistent with the updated data, thus updating the numerical model setup. In this way, the speed of data analysis and uptake can be significantly increased in the workflow allowing both models to be updated seamlessly. This process eases the access and allows the models to be directly used by other stakeholders. The attractive model can help attract investment to the project working area, increasing the economic potential of the geothermal area.

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