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Modelling Application to Estimate the Thermal Output of Weh Island, Nangro Aceh Darussalam, Indonesia

Rony P. Nugraha and John O'Sullivan

Department of Engineering Science, The University of Auckland, Private Bag 90210, Auckland, New Zealand

rnug441@aucklanduni.ac.nz

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ABSTRACT

Weh Island is located in the westernmost part of Indonesia. It has a geothermal field in the south part and a high intensity of submarine volcanic activities in its middle coastal area due to the existence of the active Sumatran Fault and current volcanism, producing hydrothermal mineralisation in the fault zone. Submarine volcanic activities controlled by normal faults and a graben are observed in Sabang Bay, located near the centre of Weh Island. These submarine volcanic activities are indicated by the many appearances of submarine fumaroles (white smokers) in the seafloor vicinities of Serui and Pria Laot and other bodies of water in Weh Island. There are also surface thermal features that appear in the coastal area in the forms of hot springs, fumaroles, solfataras, hot ground, and hot mud pools. Furthermore, the geothermal system emerging at the south part of the island is also indicated by the appearance of surface manifestations like hot spring, fumaroles, and hot ground at Jaboi.

This project develops a new reservoir model of Weh Island and an uncertainty quantification framework for estimating the total thermal output as a result of the island's volcanic activities. The new model presented consists of the 3D geological model developed in Leapfrog Geothermal combined with the natural state reservoir model simulated using the new geothermal simulator Waiwera. The uncertainty quantification framework adjusts the model parameters affecting both geothermal and volcanic-hydrothermal upflows and constrains them using information regarding Weh Island's submarine volcanic activities and the surface thermal manifestations. The air-water equation of state is used in the model to enable the model to include the vadose zone, thus a comprehensive representation of the system up to the surface can be made.

1. INTRODUCTION

Two types of model exist as the essential tools in the geothermal industry; conceptual model and numerical reservoir model. A conceptual model accumulates and synthesize the available data to coherently represent the system and its behaviour (O'Sullivan & O'Sullivan, 2016), whereas the numerical reservoir model is utilized to simulate the system's natural conditions for use in the beginning stages of the project development and predict the behaviour of the geothermal system in the future, with data processed from the exploration activities (3G surveys and exploration drilling) (O'Sullivan et al., 2017). Although they may be different, these two models are complementary to one another as a good reservoir model is based on the conceptual model, and the results from the reservoir model can often be used to improve the conceptual model (O'Sullivan et al., 2017).

This project develops a framework for predicting the total thermal output of Weh Island's volcanic-hydrothermal and geothermal system using a new numerical reservoir model and uncertainty quantification methods. The first step was to set up and calibrate the natural state numerical model. This process was simplified because the authors have previously generated a new 3D geological model of Weh Island in Leapfrog Geothermal (Nugraha et al., 2018) and used it to calibrate a numerical reservoir model of Jaboi geothermal field in the south of the island. Thus, the Weh Island 3D geological model was extended with the inclusion of some additional geological structures, and it formed the basis of the new reservoir model of the whole island. Furthermore, the rock permeability of the model was taken from the calibrated version of the previous Jaboi reservoir model as the initial guess for the new reservoir model.

The characteristics of the calibrated reservoir model were then parameterised utilising Python scripts, and a framework was developed for quantifying the uncertainty in the upflow parameters using the new geothermal simulator Waiwera (Croucher et al., 2017) and PEST (Doherty, 2016).

2. GEOTHERMAL AND VOLCANIC-HYDROTHERMAL SYSTEM IN WEH ISLAND

Weh Island is a small island located in the northwestern part of the Indonesian archipelago and is famous for its Zero Kilometer point as the initial border marker of the Indonesian state. The only city on Weh Island is Sabang City, with an area of 122.13 km^2 and an average altitude of 28 masl (BPS Kota Sabang, 2018).

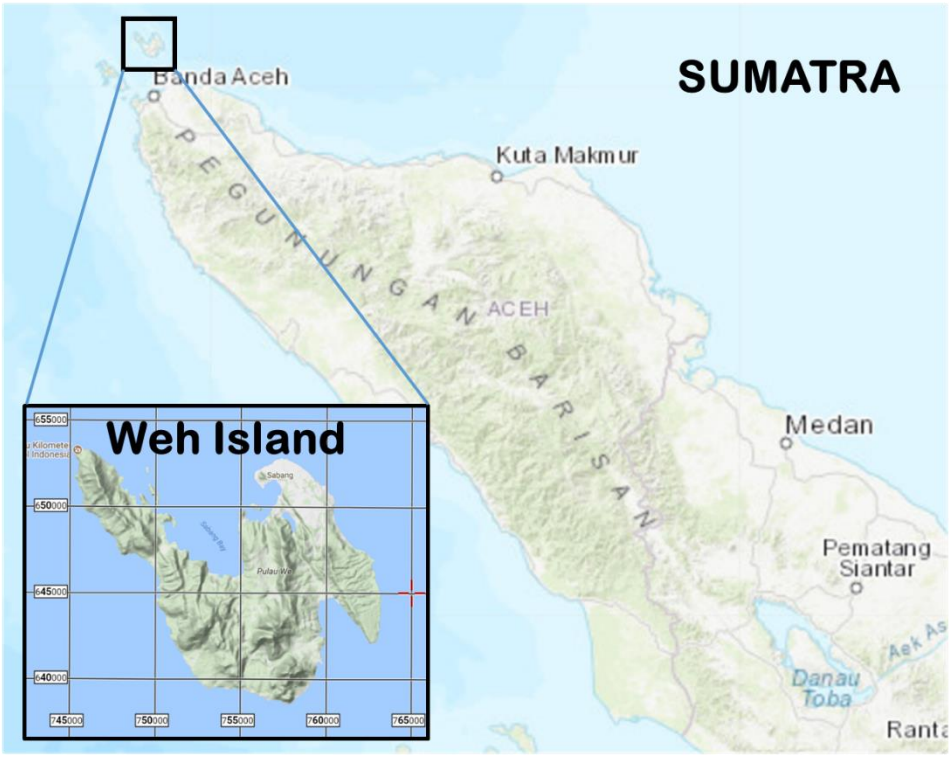


Figure 1: Location of Weh Island at the tip of Sumatra Island modified from Google Maps (2019)

Based on the research by De Neve (1983), Weh Island is included as a young volcanic island with a type C Volcano; this means that the volcano has never erupted and is only a solfatara/fumarole field. Weh Island is on the Sunda Orogen volcano lineament, following east to west direction from Nusa Tenggara - Bali - Java - Sumatra to other islands north-west of Sumatra. The island is also located on the northern part of the NW-SE Great Sumatra Fault system.

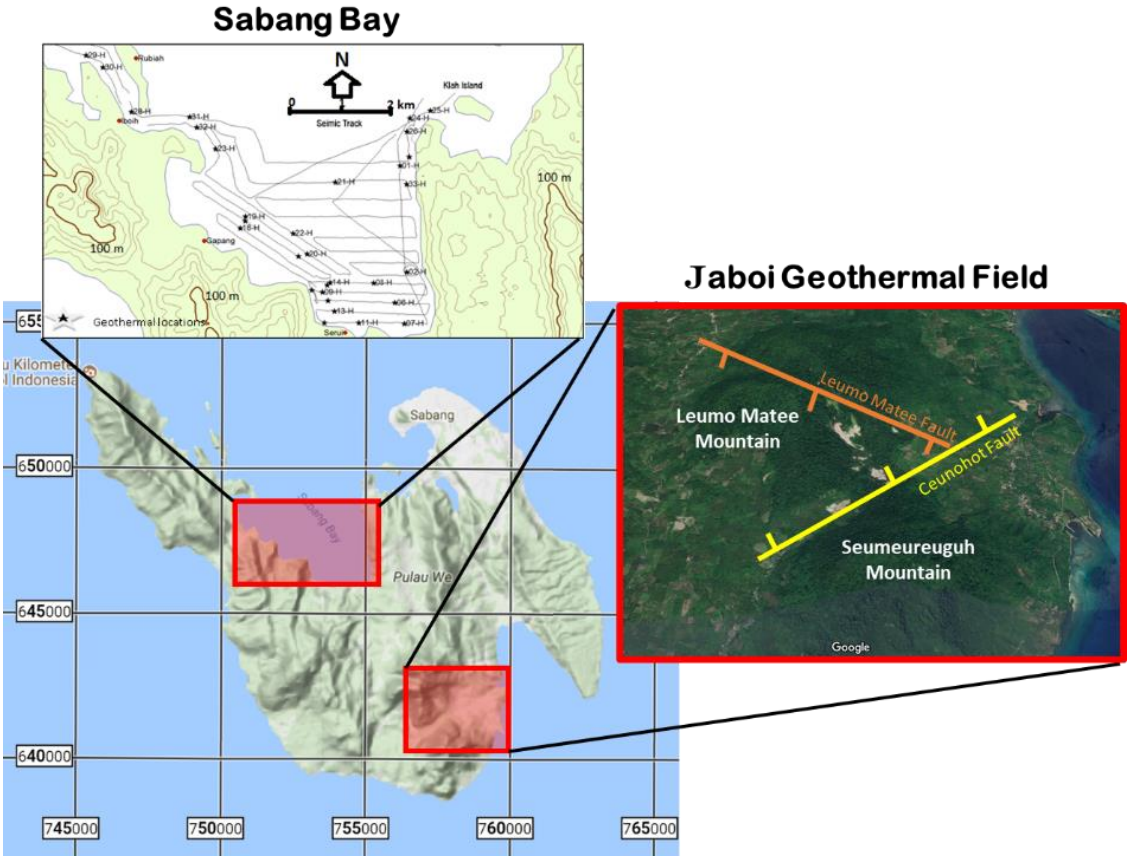


Figure 2: Map of the Sabang Bay and Jaboi geothermal area modified from Google Maps (2018)

Weh Island's location in the active Sumatran faults and current volcanism creates an extreme intensity of volcanic activities, which produces hydrothermal mineralisation in the fault zone (Kurnio et al.,2015 & 2016). Figure 2 shows the location of the submarine volcanic activities controlled by the normal faults, and a graben in Serui and Pria Lot which are close to the middle of the island, also known as Sabang Bay. The submarine volcanic activities are marked with the occurrences of submarine fumaroles (white smokers) in Serui and Pria Laot's seabed. Surface thermal features are also present in the coastal regions, mostly in the forms of hot springs, fumaroles, solfataras, hot ground, and hot mud pools. Balohan Bay in the southeast area of Weh Island is also recognised to hold many high-intensity submarine volcano activities. Although there are only three active fumaroles in the area, the seismically recorded mineral deposits, rock sampling and chimneys from the seabed sediment indicate a submarine volcano of reduced magmatic activities. These two bays (Figure 3): Balohan and Sabang, are thought to have similarities to the caldera collapse model from Lagmay et al. (2000). The collapse was affected by the Sumatra transform fault, and the collapse model has manifested the caldera formation in the northwest and southeast regions of the island, in conjunction with the fault movements. The caldera collapse function as the channel for the hot fluids to resurface, making it a crucial component of the volcanic-hydrothermal system.

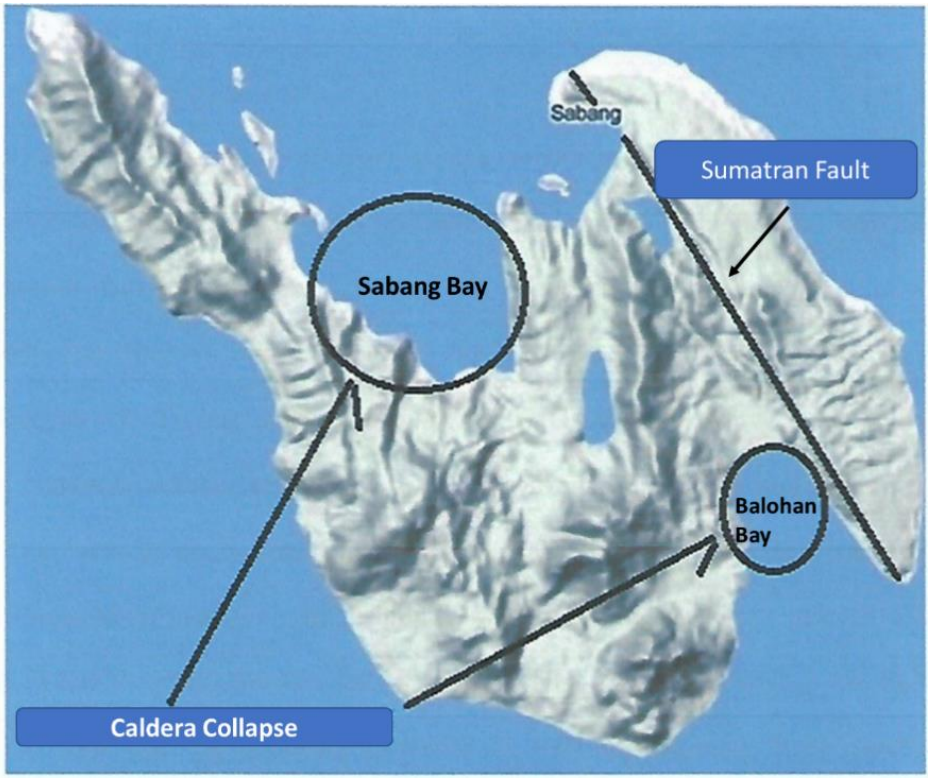


Figure 3: Two caldera collapse in Weh Island which recognised as Sabang Bay and Balohan Bay (Kurnio et al., 2016)

Figure 2 also shows the Jaboi geothermal field located in the eastern direction of Mount Leumo Matee in the south part of Weh Island. The Jaboi geothermal field is characterized with fumaroles, acidic hot springs, and hot ground, correlated as the upflow zone at Jaboi region and the outflow zone as identified by the existence of neutral bicarbonate hot spring and neutral chloride hot spring at the southeast part of the Jaboi field (Kusnadi et al., 2005). This field has been researched since the 1970s, with the most current situation that the Indonesian government is planning to construct a 10 MW geothermal power plant (PLTP) in this region.

3. CONCEPTUAL MODEL

The literature review suggests two types of hydrothermal systems in Weh Island; volcanic-hydrothermal system and geothermal system, with the differences shown in Figure 4. The volcanic-hydrothermal system is characterised by the existence of submarine volcano activities in the form of fumaroles (white smoker) at a depth less than 50 m and mud volcanoes at the hotspots near the seafloor or coastal zone. The intensity of submarine hydrothermal activities located in Sabang Bay is represented in the 32 fumarole locations on the normal faults with an orientation of north-south (Kurnio et al., 2015). Inactive fumaroles make the form of a chimney morphology with a height of about 5 meters. Water vapour makes up 90% of the composition of the gas released from the fumaroles. The pH value of seawater around the fumaroles ranges from 6 to 7.2, getting lower as it approaches the seabed with the seabed PH of 5.59. The pH condition shows that the fluid released out of the submarine fumaroles and solfataras is acidic (Kurnio H., 2016).

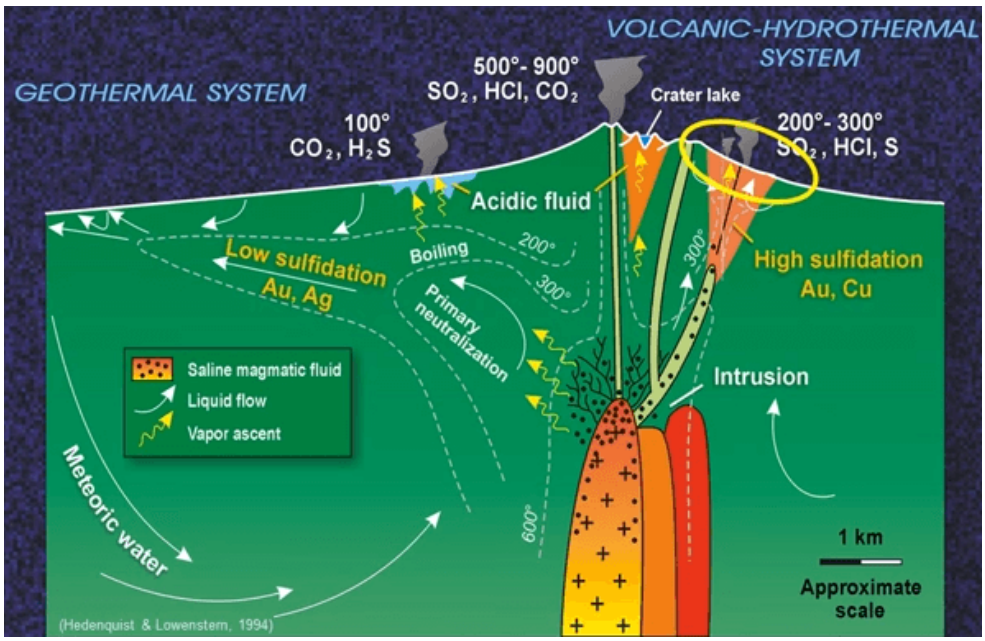


Figure 4: General conceptual model of the geothermal and volcanic-hydrothermal system (Hedenquist & Lowenstern, 1994)

Lowell et al. (1995) summarised the vent flow characteristics from several seafloor hydrothermal systems (black smokers) in the world with the maximum temperature ranging from 280º – 400ºC and the flow rate varying from 0.1 – 3.0 m/s. On the other hand, Leidig and Barth (2009) found that the seafloor temperature from three different submarine fumarole area on the island of Panarea, Italy, was in the range between 32º – 94ºC while Bauer et al. (2009) measured the flow rate of the fumaroles with the range of 150 – 400 L/min. These numbers are further utilised in this research as the base parameter for the submarine fumaroles in the model calibration stage.

The conceptual model of the Jaboi geothermal area made by Akbar (2009) and Zarkasyi (2011) stated that Leumo Matee 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 formed from the fracture zone of the main fault structure, becoming a reservoir in the geothermal system with a temperature of approximately 250ºC. 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 Matee 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. 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 an NW-SE and NE-SW direction, forming the graben valley between Seumeureuguh and Leumo Matee volcanic bodies.

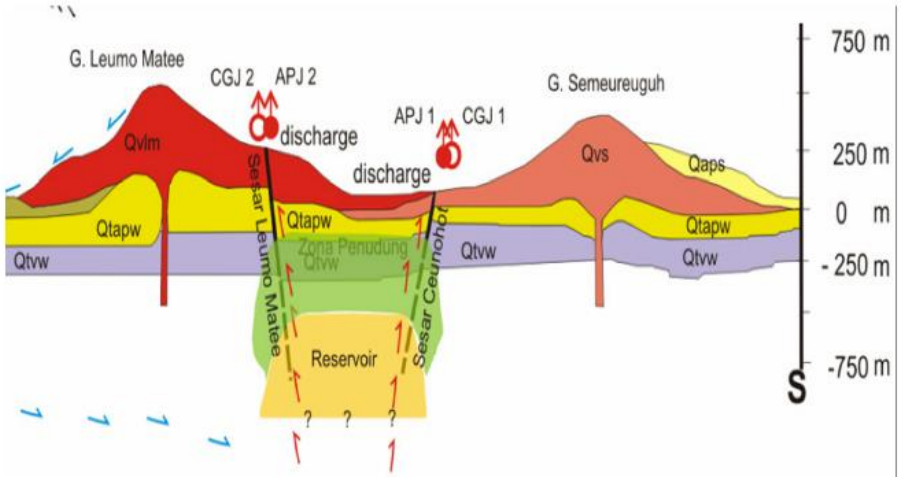


Figure 5: Conceptual model of Jaboi geothermal field (Akbar, 2009)

Nugraha et al. (2018) have succeeded in creating a 3D conceptual model of Jaboi geothermal area (Figure 6). This was the result of a natural state simulation using AUTOUGH2, then transferred into Leapfrog geothermal to incorporate with the 3D geological model of Weh Island. The simulation shows the upward direction of hot water at the bottom Mount Leumo Matee flowing into the reservoir zone through the Leumo Matee Fault and Ceunohot Fault. Then, the hot fluid goes east in the direction of the caprock in the model and becomes the system outflow. After this process, cold water primarily flows in the northwest to the southeast direction, in the

same direction as the main faults of the island, recharging the geothermal system from the formation below the reservoir zone. The upflow area of the geothermal system is characterised by hot convective plumes rising rapidly vertically in the vicinity of the fumaroles (FJB-1 and FJB-2) and acidic hot springs (APJ-1 and APJ-2). The temperature value of the upflow zone ranges from 250-300°C.

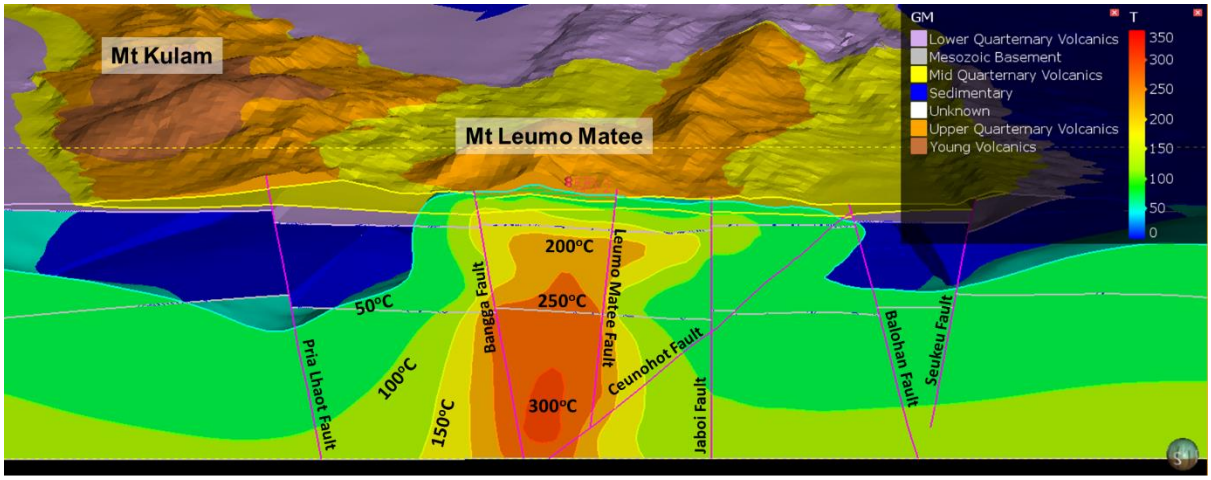


Figure 6: Vertical slice of Weh Island 3D model in SW - NE direction showing the temperature distribution and the geological structures (Nugraha et al., 2018)

4. 3D GEOLOGICAL MODEL OF WEH ISLAND

In this project, the authors utilised the 3D geological model of Weh Island from a previous project. The model was developed with Leapfrog Geothermal with data taken from the literature review: the island's topography was processed from XYZ data, rock stratigraphy was determined from the geological map, lithology was defined from the geological cross-section, and Weh Island's surrounding sea depth was constructed from the bathymetry data. New structures were included in the current 3D model following the conceptual model of Weh Island's volcanic-hydrothermal system. The complete process of the 3D geological model setup will not be further elaborated in this paper. The reader can refer to the previous project of the authors to see the detailed process of the 3D geological model setup (Nugraha et al., 2018).

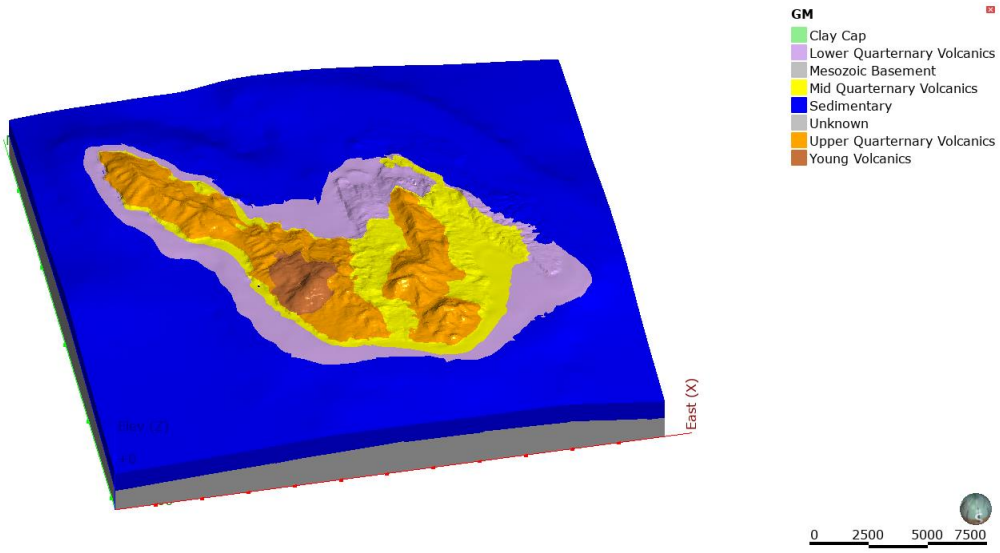


Figure 7: The 3D geological model of Weh Island

Figure 7 shows the complete 3D geological model of Weh Island. The model presents the island's whole area of 542 km^2 and depicts the identified stratigraphy and geological structure in Weh Island's geological map and conceptual model. The model assigns 17 faults, consisting of primary and secondary, with the majority being normal faults. The island's hydrothermal fluid's flow patterns and recharge water are controlled by the faults. 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 are based on the model's topography and 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.

5. NUMERICAL MODEL DEVELOPMENT

5.1. TOUGH2 Model Grid Setup

The numerical model of Weh Island was derived from the 3D model and was set up as a TOUGH2 grid in Leapfrog Geothermal. The TOUGH2 grid is 23.7 km in length and 22.9 km in width (Figure 8). The grid size is 800 m x 800 m and is more highly refined in the area where the submarine fumaroles emerge with blocks set at 800 m x 400 m and 400 m x 400 m.

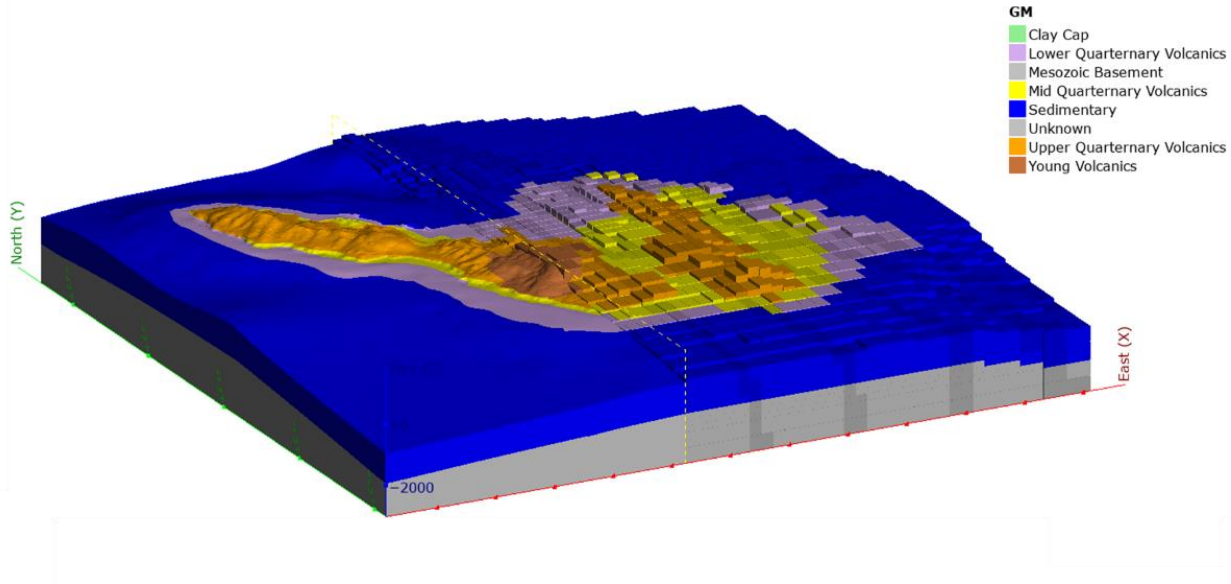


Figure 8: Leapfrog 3D model (left) with generated TOUGH2 model (right)

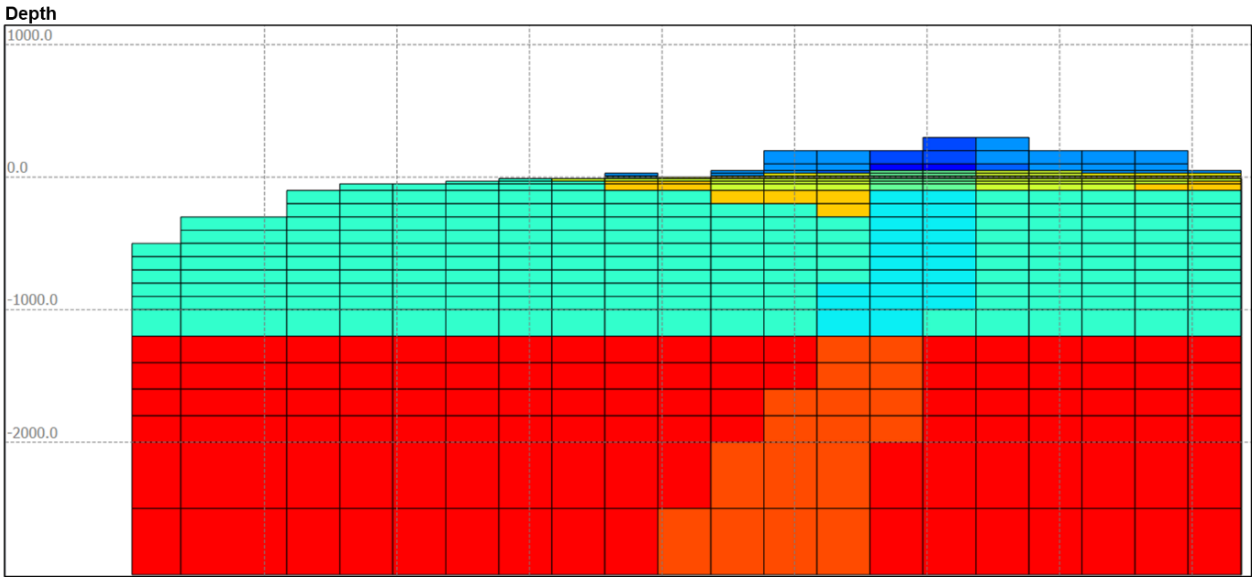


Figure 9: Vertical layer of the TOUGH2 model shows the grid thickness variation for each depth

The range in vertical thickness is varied from the bottom layers to the surface layers, as shown in Table 1. A distinct step in this setup is the highly refined thickness for the layers at depth -50 to 50 mRL, as seen in Figure 9. This was done to obtain a more precise seafloor temperature distribution near the submarine fumaroles and the thermal manifestations at the coastal area. The resulting temperature from the simulation process represents the temperature at the centre of each block; thus, the thinner the grid thickness, the more accurate the result. On the other hand, this will increase the total amount of the grid blocks and slow down the simulation process. Thus, it is essential to determine the size of each grid block to achieve the optimum number of reservoir grid blocks.

Table 1: Layer thickness of Weh Island's TOUGH2 model

Layer	Thickness (m)	Depth (mRL)	Layer	Thickness (m)	Depth (mRL)
0	50	atmosphere	19	100	-200 to -300
5	100	600 to 500	20	100	-300 to -400
6	100	500 to 400	21	100	-400 to -500
7	100	400 to 300	22	100	-500 to -600
8	100	300 to 200	23	100	-600 to -700
9	100	200 to 100	24	100	-700 to -800
10	50	100 to 50	25	100	-800 to -900
11	20	50 to 30	26	100	-900 to -1000
12	20	30 to 10	27	200	-1000 to -1200
13	10	10 to 0	28	200	-1200 to -1400
14	10	0 to -10	29	200	-1400 to -1600
15	20	-10 to -30	30	200	-1600 to -1800
16	20	-30 to -50	31	200	-1800 to -2000
17	50	-50 to -100	32	500	-2000 to -2500
18	100	-100 to -200	33	500	-2500 to -3000

Leapfrog Geothermal assigns the rock types, saving time from preventing the authors from having to assign the geology into the geological model manually. Also, when the geological model is updated during drilling, Leapfrog Geothermal can then automatically transfer the changes into the generated TOUGH2 model. The rock properties can then be assigned to the faulted blocks through PyTOUGH scripts, allowing significant heterogeneity in the TOUGH2 model due to the ability of faulted blocks in the same geological model to have distinct properties (O'Sullivan et al., 2017).

PyTOUGH scripts also assist in setting Jaboi's clay cap zone and its properties in the TOUGH2 model following the conceptual model. The submarine fumarole area does not have a clay cap zone due to its association with the volcanic-hydrothermal system. The clay cap functions as a low permeability layer and inhibits the flow of the hot water to the surface. Directly below the caprock area is the reservoir zone, consisting of Lower Quartenary Volcanic and Tertiary rock formations. Both these rock formations have high permeability in comparison with other rock formations allowing the hot fluid flow from the deep formation convect and allowing meteoric water recharge.

5.2. Boundary Condition

Top boundary: The top part of the model follows the topography and bathymetry with the island assigned with dry atmospheric conditions; the pressure of 1 bar and mean temperature of 30°C. The below sea level conditions followed the hydrostatic pressure with temperature varying according to the global temperature data of ocean water. The air-water equation-of-state was utilised, enabling the simulation of water and air mixture and allowing the model to encompass the vadose zone. This enabled modelling the entire system from its roots up to the surface.

Side boundary: The side boundaries are presumed to be no-flow boundaries, i.e., no heat or mass is entering or exiting the system. The side boundaries were positioned in the sea area, far from the hydrothermal system area.

Base boundary: The model's background heat input was assigned through the 80mW/m^2 of heat flux in the bottom layer of the model (layer 33). The upflow zone was represented by a hot water flux in the fault zones.

6. NATURAL STATE SIMULATION

The natural state model of Weh Island was first run using AUTOUGH2, and then the model was converted to Waiwera (Croucher et al., 2017) using python scripts. The simulations were run for 1x10^{16} seconds of simulated time to achieve good steady-state conditions. For the Jaboi geothermal Field, the hot water was injected in 4 blocks as the upflow zone at layer 33 (Basement) with the dimension of each block being 400m x 800m. These hot water injection sites were set on the Bangga Fault which crosses the Mt Leumo Matee in N-S direction and is thought to act as the main fault controlling the geothermal system in the 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 similar approach was used for the volcanic-hydrothermal area around Weh Island. Selected faulted grid blocks at layer 33 were assigned as the upflow of hot water. The dimension of each block varied from 400m x 400m to 800m x 400m depending on the location of thermal manifestation. The volcanic-hydrothermal system is quite different from the geothermal system because it does not have caprock, and the temperature of the system is higher. Thus, the hot fluids of the volcanic-hydrothermal system flowed directly to the surface and manifested as submarine fumaroles/solfataras and mud volcanoes. These particular characteristics helped determine the calibration process for this model.

7. MODEL CALIBRATION

The objective of calibration is to achieve a good match between the model simulation results and the measured field data. The model parameters resulting from calibration can be used as the basis for the parameter uncertainty analysis. The calibration process can either be carried out manually by using inverse modelling. To date, only manual calibration has been carried out, but the parameter uncertainty framework described below could be used to carry out inverse modelling to further improve the calibration in the future. In manual calibration, the natural state simulation results were calibrated with the following observed data:

Surface manifestations: The type and location of surface manifestations data are critical information for calibrating the distribution of the hot fluids in the model because they are directly measured data that represents the current condition of the whole hydrothermal system in Weh Island. Through this data, the location of the upflow and outflow zone can be inferred. Figure 10 summarises the locations of the surface thermal manifestations around Weh Island. Onshore fumaroles are presented in red and located at Mt Leumo Matee, while offshore fumaroles/solfataras (white smoker) are presented in black colour and spread around the Island. The blue colour indicated the location of all type of hot springs in Weh Island.

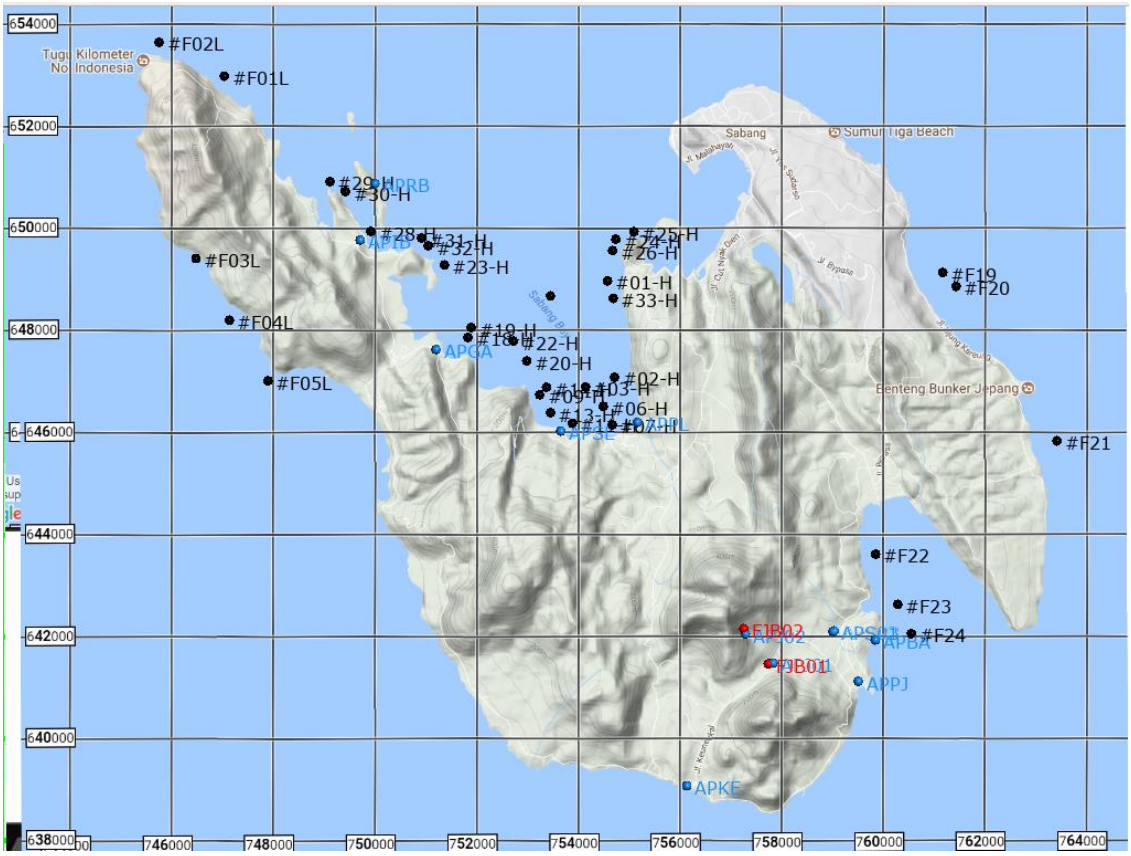


Figure 10: The summarised of all location of surface thermal manifestations around Weh Island

Temperature gradient well data: The temperature data from two shallow gradient wells (JBO-1 and JBO-2) located in Jaboi geothermal field are utilised 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 for the Jaboi area.

Geochemical geothermometer: The estimation of the deep average reservoir temperature in Jaboi field using geochemical geothermometer was 250ºC. This number constrains the temperature of the upflow zone in the geothermal system in the model, which becomes the possible main target for drilling in the next stage of development.

Seafloor temperature: Based on the conceptual model of submarine volcanic activities, the median temperature of the seafloor near the fumarole/solfatara was estimated to be ~60^{O} to 70^{O}C with the mass rate ranging from 2.4 to 10 kg/s. These two ranges constrain the temperature of the model surface in the locations of submarine fumaroles/solfataras.

8. MODEL CALIBRATED OUTPUTS

The results of the final the natural state simulation of Weh Island run using the new geothermal simulator Waiwera are presented in this section. The simulation results achieved a good match with the observed data of two shallow wells, as seen in Figure 11.

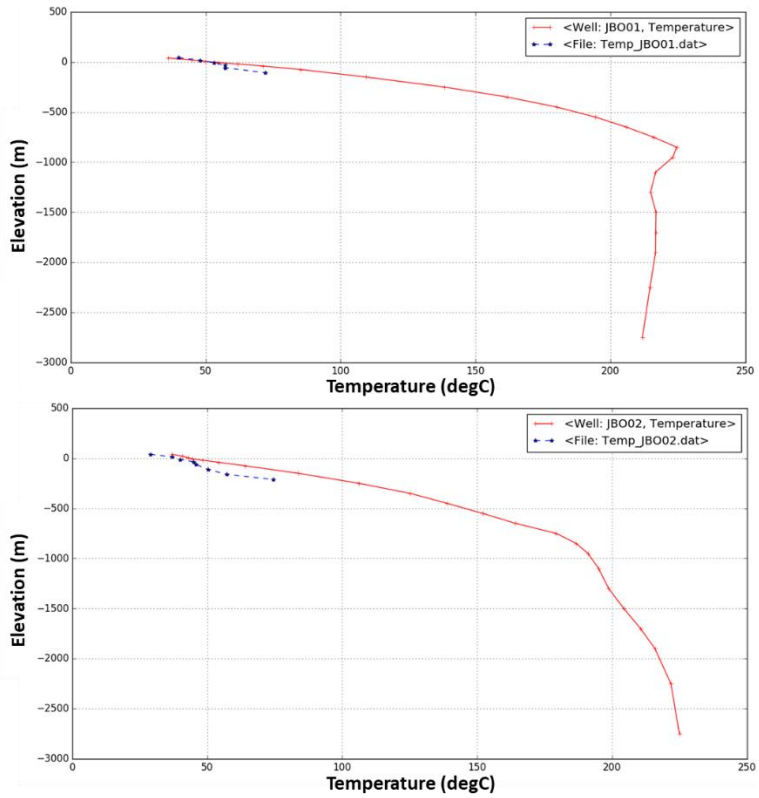


Figure 11: Downhole temperature match of the shallow wells: JBO-1 (top) and JBO-2 (bottom)

Figure 12 shows that the temperature distribution at the top surface the Weh Island reservoir model fits the measured location of surface manifestations. The green colour, indicating a warmer temperature, is only present at blocks around the surface manifestation. The match was achieved with a total input of 28 kg/s of hot water at enthalpy of 1,250 kJ/kg for Jaboi geothermal system and 32 kg/s of hot water at enthalpy of 1,400 kJ/kg for the volcanic-hydrothermal system. Thus the calibrated model estimates that the total thermal output produced by Weh Island's volcanic activities is 72 MWth. The results of this simulation were then transferred to the Leapfrog geothermal to incorporate the current 3D model as seen on the figures below.

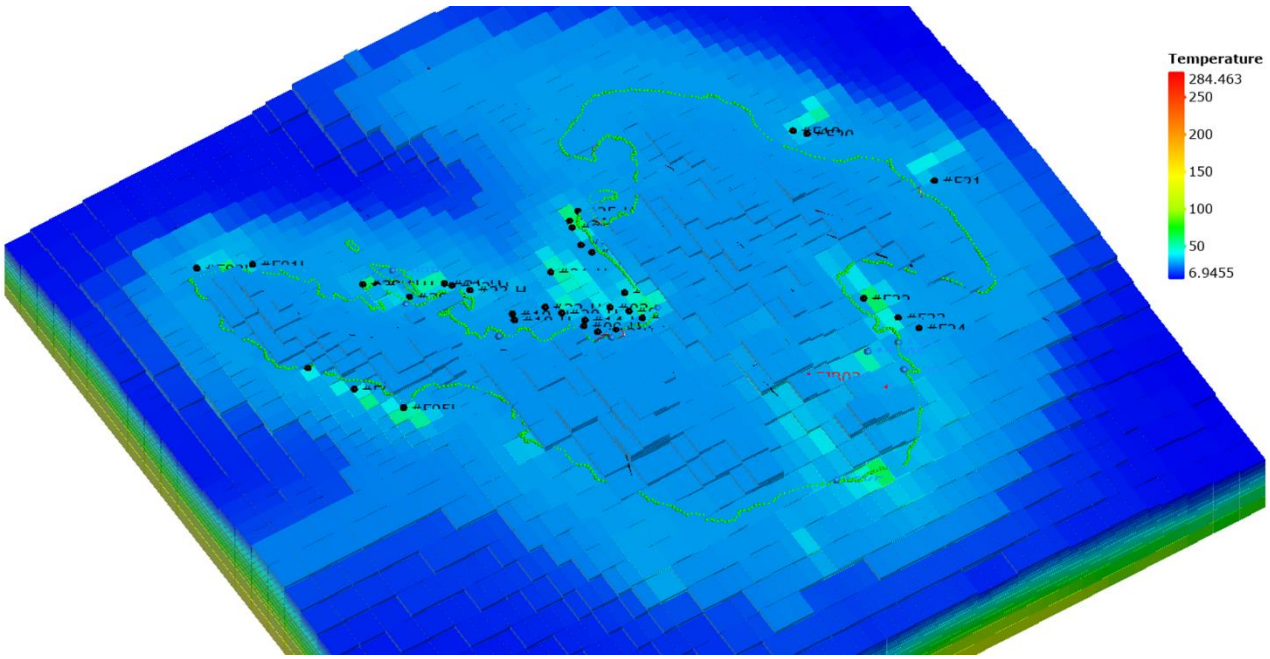


Figure 12: The top surface temperature result of Weh Island's numerical model. The green line indicates the coastline.

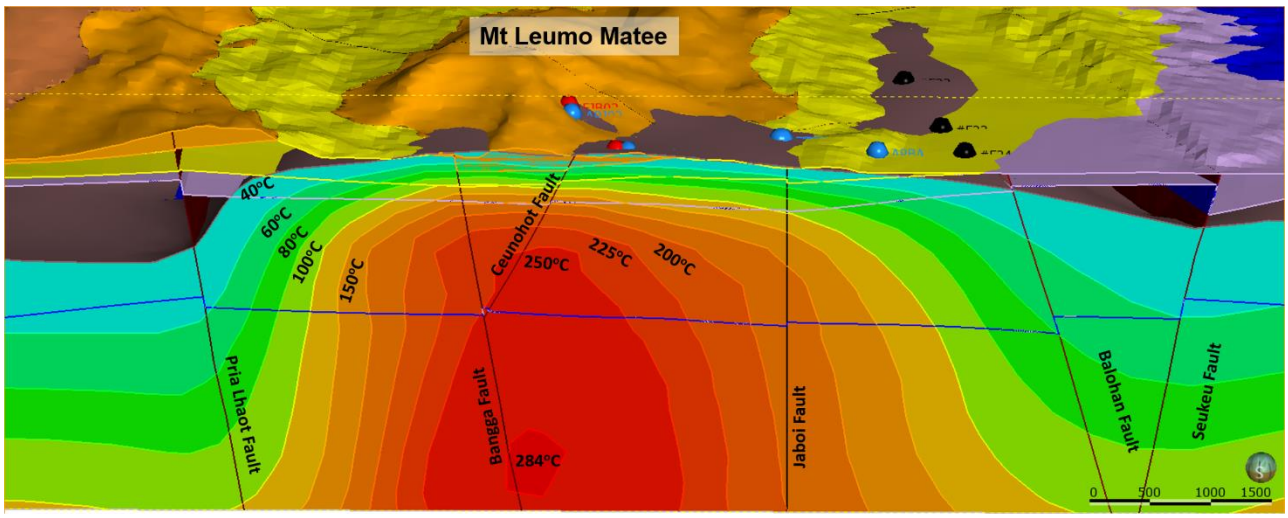


Figure 13: Vertical slice of the geothermal system in the 3D model of Weh Island

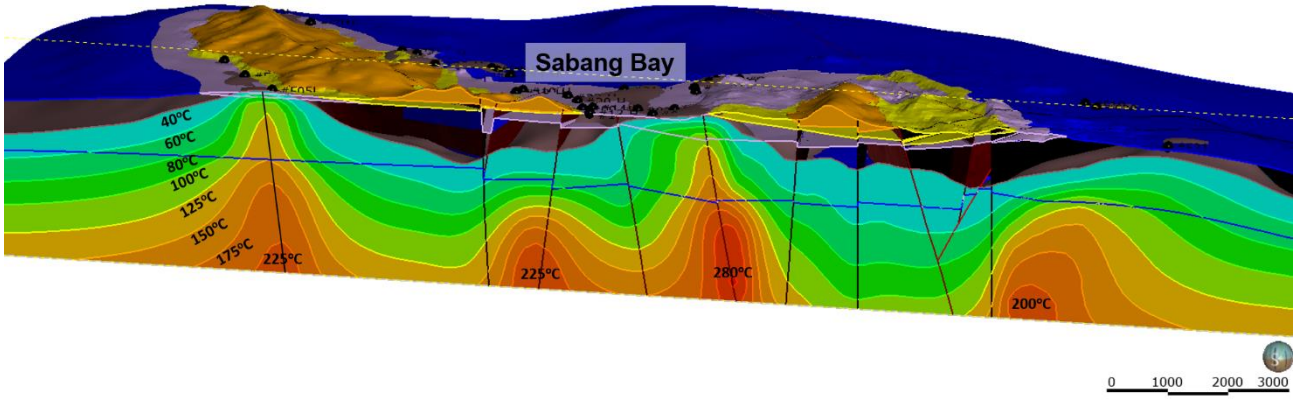


Figure 14: Vertical slice of the volcanic-hydrothermal system in the 3D model of Weh Island

Figure 13 shows the temperature distribution and geological structures of Jaboi field, the geothermal system in Weh Island. The Bangga Fault acts as the main structure and upflow zone for the Jaboi geothermal system where the hot water flows upward from the bottom of Mt Leumo Matee and fills the reservoir zone created by the of Ceunohot and Leumo Matee Faults. The caprock holds the hot fluid inside the reservoir, though some hot fluid escapes to the east and becomes an outflow zone, as indicated by the appearance of several bicarbonate hot springs. Meanwhile, Figure 14 presents the temperature distribution of the volcanic-hydrothermal system in Weh Island. The temperature distribution has a concentrated upflow pattern due to the absence of caprock in this system. Thus, the acid hot water flows directly to the surface following the controlling structures. The bottom temperature of the volcanic-hydrothermal upflow zone ranges from 200-280^{O}C. This temperature also indicates the intensity of the volcanic-hydrothermal system. As seen in Figure 14, the Sabang Bay area is the area with the highest number of submarine fumarole appearances, matching the upflow zone observed in this area, which has a high temperature that reaches 280^{O}C.

9. PARAMETER UNCERTAINTY FRAMEWORK

Parameter uncertainty can be estimated using the parameter estimation software PEST (Doherty, 2016). The framework for carrying out the parameter uncertainty estimate is set up as follows. First, an objective function must be defined. This is a quantitative metric of how well a model fits the measured data (observations). For the Weh island model, the objective function has been constructed using the data for the surface manifestations for both the geothermal system and the volcanic-hydrothermal systems, as shown in Table 2.

Next, the important parameters that control the behaviour of the model need to be selected, and the ranges of values that are to be explored are specified. Ideally, all the parameters that control the behaviour of the model are selected, but in reality, this is still too computationally expensive, and so a subset is selected. As described in the following section, we are making advances in reservoir modelling technology that will allow a much broader set of parameters to have their uncertainty quantified efficiently. The parameters that were selected in this project and their ranges are listing in Table 3.

PEST then runs the model once for each of the parameters using a small increment in the specified parameter value and evaluates the objective function for each. By comparing the objective function calculated each time to the objective function for the calibrated

model, PEST can calculate the effect of each parameter. Using the PEST utilities a linear analysis can then be carried out quantifying the parameter uncertainty following the theory described by Doherty (2016). Finally, the uncertainty in the upflow parameters alone can be combined to give an estimate of the range of total thermal output as a result of the island's volcanic activities.

Table 2: Surface manifestation data for calculating the objective function

No	Manifestation Name	Block Name	Rocktype	Temperature (°C)		MassFlow (kg/s)	
				Min	Max	Min	Max
Geothermal Surface Observations							
1	FJB01 and APJ01	rx 9	UD000	34	38	1	3
2	FJB02 and APJ02	rw 8	U0000	34	38	1	3
3	APS01,APS02, and APS03	sa12	MAK00	40	45	18	20
4	APBA	sc12	M0000	32	34	1	3
5	APPJ	qd13	M0000	32	34	1	3
6	APKE	lw10	M0000	32	34	1	3
7	#F22	wb15	MAC03	40	45	4	8
8	#F23	ud15	MA003	40	45	4	8
9	#F24	se15	M0001	40	45	4	8
Volcanic-hydrothermal Observations							
1	APRB	bao12	S0000	32	34	1	3
2	APIB	auq11	U0000	32	34	1	3
3	APGA	aky15	MN002	32	34	1	3
4	APSE	adh12	U0000	32	34	1	3
5	APPL	adl11	MB000	34	37	2	5
6	#F01L	bkb14	M0000	45	55	6	10
7	#F02L	bnw15	SQ001	45	55	6	10
8	#F03L	asj15	LR001	40	55	3	6
9	#F04L	amo15	LR001	40	55	3	6
10	#F05L	agt15	LR001	40	55	3	6
11	#F19	ats15	SK001	40	50	2	4
12	#F20	art15	SK001	40	50	2	4
13	#F21	aef15	SL001	40	50	2	4
14	#29-H and #30-H	bam15	LM001	55	65	5	15
15	#28-H	awq13	S0000	40	50	2	4
16	#31-H and #32-H	aus14	UN000	50	60	5	10
17	#23-H	asu15	SN002	35	45	2	4
18	#19-H	amy15	UF001	40	50	2	4
19	#18-H	amx15	MN002	35	45	2	4
20	#22-H	alb16	L0001	40	50	2	4
21	#20-H	ajc15	L0001	40	50	2	4
22	#14-H and #09-H	ahe15	UH001	55	65	5	15
24	#13-H	aff15	UH001	40	50	2	4
25	#11-H	afh15	LI001	40	50	2	4
26	#07-H	adk15	L0001	40	50	2	4
27	#06-H	afi15	L0001	40	50	2	4
28	#03-H	ahg15	LI001	40	50	2	4
29	#02-H	ajh15	L0001	40	50	2	4
30	#21-H	ara16	SHI01	40	50	2	4
31	#33-H	ape15	LB001	40	50	2	4
32	#01-H	arc15	L0001	40	50	2	4
33	#26-H and #24-H	avb14	LB000	55	65	5	15
35	#25-H	axa16	LB001	50	60	4	10

Table 3: Parameter ranges estimated from the manual calibration

No	Parameter	Bounds
Geothermal Parameter		
1	Basement Permeability 1	0.5 - 3.5 mD
2	Basement Permeability 2	0.5 - 3.5 mD
3	Basement Permeability 3	0.2 - 2 mD
4	Claycap Permeability 1	0.01 - 0.3 mD
5	Claycap Permeability 2	0.01 - 0.3 mD
6	Claycap Permeability 3	0.01 - 0.1 mD
7	Rock Permeability 1	5 - 35 mD
8	Rock Permeability 2	5 - 35 mD
9	Rock Permeability 3	2 - 20 mD
10	Mass Rate of Hot water	5 - 9 kg/s
11	Enthalpy	1100 - 1400 kJ/kg
Volcanic-hydrothermal Parameter		
12	Basement Permeability 1	0.5 - 7 mD
13	Basement Permeability 2	0.5 - 7 mD
14	Basement Permeability 3	0.2 - 2 mD
15	Rock Permeability 1	5 - 70 mD
16	Rock Permeability 2	5 - 70 mD
17	Rock Permeability 3	2 - 20 mD
18	Mass Rate of Hot water	1 - 2 kg/s
19	Enthalpy	1400 - 1500 kJ/kg

10. CONCLUSION AND RECOMMENDATION

A new numerical model of Weh Island had been generated following the updated 3D geological model in Leapfrog Geothermal. Leapfrog enables new data to be easily inputted into the existing geology model and then directly integrated into a numerical model. This automation saves the researcher time during the initial model set up and also for any model updates.

The differentiation in layer thickness helps in optimising the simulation time and its accuracy, particularly for the refined grid thickness at a depth of -50m to 50m. This can be seen from the simulation results for the seafloor temperature, which has succeeded in matching the data on the conceptual model of the volcanic-hydrothermal system in Weh Island. In addition, the simulation results also obtained a good match with the temperature gradient well and geothermometry data for geothermal systems in the Jaboi field.

The calculation results estimate that Weh Island has a total thermal output of ~ 72 MWth. Although this does not represent the actual amount of geothermal power that can be produced, nonetheless this shows that the geothermal potential on Weh Island is high. It may also be possible to find new geothermal reservoir zones around Weh Island by conducting further detailed and advanced exploration.

A framework for carrying out parameter uncertainty quantification of the Weh Island reservoir model has been developed. It will be used to generate a range of estimates to give more confidence in the total thermal output produced by the hydrothermal system on Weh Island. Adjoint methods are being developed (Bjarkason et al., 2016) to speed up this process and include a large number of model parameters in the framework.

It is essential to make a 3D geological model that can summarise all subsurface data at the beginning of the exploration stages, as the authors have created in this study. Thus, consistent 3D visualisation can be generated to enable all stakeholders to understand the subsurface condition of Weh Island. Also, by including visualisation of the results of the reservoir model, the forecast conditions of the field to be usefully represented. Finally, new model versions can easily incorporate more updated data, to ensure the resulting model is reliable and helpful in making a robust decision for stakeholders.

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