A key process of natural state modeling:
3D Geological model of Jaboi Geothermal field,
Nangro Aceh Darussalam, Indonesia

Nugraha R P and John O'Sullivan
Department of Engineering Science, The University of Auckland, Private Bag 90210,
Auckland, New Zealand
Email: rnug441@aucklanduni.ac.nz

Abstract. This project aims to develop a new natural state model of Jaboi geothermal area to obtain an improved understanding of the subsurface conditions and behavior of the reservoir. This paper describes the progress that has been made in the project so far which includes a new geological model developed in LEAPFROG Geothermal and the reservoir model setup and definition. The new geological model provides a very useful 3D visualization tool and compiles all of the exploration data. Jaboi geothermal field has been explored since the 1970’s until today. However, no research has gone as far as creating a 3D model of the area. The construction process of the new 3D geological model of Weh Island was carried out using a compilation of geoscientific data derived from the Ministry of Energy and Mineral Resources exploration activities within 2005-2006. The 3D geological model assigns the related features such as the geological structures, water level, rock types, and surface manifestations and the model will be used as the basis for developing the new reservoir model. A description of the new reservoir model’s setup and definition is given, and details of the proposed mode calibration are outlined. The simulations will be run using AUTOUGH2.

1. Introduction
Jaboi geothermal area is located on 95°12’00"E - 95°23’00"E and 05°46’00”N - 05°55’00”N, approximately 15 km south of Sabang city, Weh Island, Nangro Aceh Darussalam (Figure 1). Jaboi geothermal field has been explored since the 1970’s until today. The early exploration started through a preliminary survey in 1972 and was followed by the geothermal manifestation and geoelectrical survey in 1983-1984. The advanced surface explorations were conducted by the Directorate of Geothermal, Ministry of Energy and Mineral Resources within 2005-2006 to obtain more specific data about the geology and geophysics of Jaboi geothermal area through geomagnetic, gravity, geochemical and geoelectrical survey [9].

Currently, Indonesia plans to extend the supply of geothermal energy supplied throughout the archipelago to fulfill the power demand, especially in areas lacking electricity with excellent geothermal potential. Sabang city, located in Weh Island, is one of the areas the government plans to build an 80 MW geothermal power plant (PLTP) to fulfill the electricity demand and support the economic development of the maritime industry, particularly on tourism and hospitality within the island.
However, to realize the government plans, this project has to achieve a more advanced stage of exploration. A three-dimensional (3D) geological and reservoir model of Jaboi geothermal can help support the exploration process. It is important to complement the early stages of explorations with a natural state simulation not only to compile and analyze all the exploration data but also to create an attractive and visual model that can help deliver a better understanding about the subsurface condition of the project area. The calibration process for the reservoir model can also help test different conceptual models of the system even when subsurface data is limited. While these types of natural state simulations cannot predict the exact subsurface conditions when data is limited, they can help to rule out certain possibilities. Also, any natural state reservoir models created during the exploration phase of a project can easily be extended once downhole data becomes available thus providing a useful for supporting production drilling and testing.

This paper presents the preliminary study’s progress, which consists of a new 3D geological model developed in LEAPFROG Geothermal and the reservoir model setup and definition. The description of the reservoir model will include the model design and boundary condition. The new 3D geological model and the reservoir model are based on an existing conceptual model of the Jaboi system [1][14]. The Jaboi conceptual modeling phase combined data from the geological, geophysical, geochemical, and drilling of gradient wells to give an overview describing the physical processes that regulate the fluid flow in the Jaboi geothermal system. The next phase created a 3D geological model of Weh Island by assigning the related features of its structures, rock types and surface manifestations and will be used as the preparation of the reservoir model. The proposed mode of calibration for natural state simulation is based on the surface thermal manifestation data and geochemical geothermometers.

2. Geological Setting of Jaboi Geothermal System
Weh Island is located in the northern part of the Great Sumatra Fault system which has an NW-SE lineage. It is a young volcanic island located on the Sunda Orogen volcano alignment from east to west from Nusa Tenggara - Bali - Java - Sumatra to other islands located at the extreme north-west of Sumatra. It is a type C volcano which is a volcanic type with an unknown center of the eruption but shows characteristics of fumarole fields in its past activities [2].

Dirasutisna & Hasan (2005) described the lithology of Weh Island as formed from Tertiary and Quaternary rocks which is divided into 4 main rock groups; the Tertiary (Miocene) sedimentary rock group which is the Weh Island rock, the old volcanic rock group of Weh Island which is aged Quaternary-Tertiary made of lava and pyroclastic flow, young volcanic rock group which is aged
Quaternary made of a series of young volcanic cones that form a volcanic line of northwest-southeast and north-south, and a group of limestone reefs.

![Figure 2. Geological map of the Weh Island [7].](image)

Weh Island has several main faults (Figure 2), mostly consisting of normal faults, which are the geological structures responsible for the geothermal system. Also, there are also secondary faults formed from tectonic processes in this area such as Leumoo Matee fault, Ceunohot, Iboih, Jaboi and Nibung fault [14].

### 3. Geochemical Studies

Geochemical studies are used to classify the type of surface thermal manifestations and to predict the deep reservoir temperature. The classification is also used to determine the upflow and outflow zones of the geothermal system. An uncontaminated hot water spring is needed to determine the reservoir temperature or by conducting gas geothermometer.

![Figure 3. Cl-SO₄-HCO₃ and Na-K-Mg ternary diagram of Jaboi’s hot springs [5].](image)

The thermal manifestation in Jaboi consists of hot springs, fumaroles, steam vents, steaming ground, warm springs and cold springs. The hot springs sampled for analysis using geochemical methods are namely: 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). There are also two fumaroles located in Jaboi area with temperature 98.4°C and 99.4°C taken as samples [1].

3.1. Ternary Diagram Analysis
Based on the ternary diagram of Cl-SO\(_4\)-HCO\(_3\) (Figure 3), Jaboi hot water is a sulfate type which is the hot water vapor area, while Ieseum, Keunekai hot springs, and Seurui are on bicarbonate type, and Batetamon, Lhok Male Lhaot, and Jaboi hot spring are in the chloride type.

The type of sulfate in Jaboi hot spring shows the presence of meteoric water combined with ulcers containing H\(_2\)S. The high temperature (> 95°C) steam is condensed with surface water and forms a soluble sulfate keeping the surrounding rocks oxidized. Iesum hot springs are bicarbonate typed with a dominant HCO\(_3\) content and a relatively high SO\(_4\). This type of bicarbonate is formed from dissolved magmatic CO\(_2\) gas and groundwater forming HCO\(_3\), while the SO\(_4\) content indicates the hot spring is still associated with Jaboi hot spring area. The hot spring that appears near the southeast coast is bicarbonate type Keunekai with high chloride that may result from the influence of seawater.

The results of the analysis of Na-K-Mg ternary diagrams (Figure 3) show that almost all of the hot spring samples that were taken include immature water proving the influence of dominant meteoric water. The hot fluid from the reservoir interacts with the rock and is mixed with groundwater near the surface and possibly also influenced by sea water which indicates the magnitude of Cl content in most hot springs. Only Lho Pria Laot Hot Spring approach the equilibrium condition as it is in the partially equilibrated area.

The estimation of reservoir temperature uses Iesum hot spring because it has a high temperature, is neutral and does not indicate seawater contamination. SiO\(_2\) conductive cooling geothermometer [4] denotes the 187°C as the minimum temperature. While the result of gas geothermometer CO\(_2\)-H\(_2\) [11] from Jaboi fumaroles, obtained a temperature of 327°C as the maximum temperature [14].

4. Geophysical Surveys
Geophysical surveys are used to locate subsurface extent of the geothermal system, heat source and geological structures that control geothermal fluid movement. The conducted surveys are in the form of geomagnetic, geoelectric and gravity that will record the geophysical parameters of the geothermal system.

4.1. Geoelectric
The presence of low anomalies characterizes the AB/2 750m pseudo resistivity map to less than 10 Ohm-m with a closed pattern in the center of the area of the Jaboi fumarole manifestation which could be a potential Cap Rock area (Figure 4). This pattern also has a characteristic that spreads in either direction, i.e., towards the east-southeast coast of Jaboi where several hot springs near the coast are found, and to the southwest which then continues south to Keuneukai Beach where the hot springs are located. Both patterns of the tongue are known to be associated with the outflow pattern of a geothermal system.
4.2. Geomagnetic
The map of the total magnetic anomaly (Figure 5) is characterized by a high anomaly concentric to the Jaboi fumarole manifestation region and is surrounded by the low anomalies. In the area around the magnetic equator, such as the Jaboi region, a low magnetic susceptibility contrast will provide an anomalous response of high magnetic fields on the surface. Therefore, this high anomaly is possibly associated with geothermal rock alteration which has also been demagnetized.

4.3. Gravity
The gravity anomaly map (Figure 6) is characterized by the emergence of regional structures in the northwest-southeast of this region such as lineament in that direction, especially north of Balohan. The fumarole manifestations area coincides with the high-gravity anomaly and is characterized by the many dominant north-southwest oriented majors, but some are almost northwest-southeast. These alignments reflect the number of fracture structures in the Jaboi geothermal area.
5. Temperature Gradient Wells

Temperature gradient well method was conducted to complete the exploration stage (geology, geophysics and geochemistry survey) of the potential geothermal area. The objective of this activity is to find the thermal gradient of the potential field, to identify the subsurface lithology and to determine the limit of the resource area of the potential geothermal site.

Figure 6. Modified Bouguer anomaly map with 2.50 g/cm$^3$ of density correction [10].

Figure 7. Modified temperature profile of JBO-1 & JBO-2 [6].
Two shallow wells, JBO1 and JBO2, were drilled in late 2006 as the follow up of the previous surveys and part of the exploration stage. JBO1 was drilled until 238 m with the thermal gradient ranging from 20.5 – 22°C per 100 m and JBO2 reached 250 m depth with 17°C per 100 m of the thermal gradient (Figure 7). Lithologies of the wells consist of tuff breccia, andesite lava flow, and breccia intercalated by tuff. Several alteration minerals were also encountered from these wells including; kaolinite, smectite, montmorillonite, secondary quartz, iron oxide, halloysite, pyrite, calcite, chlorite, and alunite. All of the above minerals are argillic type of alteration and function as a clay cap of Jaboi geothermal system [6].

6. Conceptual Model of the Jaboi Geothermal Area

Based on the literature review above, a new 3D geological model of Jaboi geothermal area was constructed using LEAPFROG geothermal. The geological model adopted the previous conceptual models from [1] and [14] with additional information from the result of the drilling of gradient wells. The description of this conceptual model is presented below.

The geothermal heat source of this region is thought to originate from the remaining magma of Leumo Mate and Seumeureuguh volcanoes with a depth of > 4 km [12]. This residual magma heats the permeable upper rocks formed by the fracture zone of the main fault structures that develops in this area and becomes a reservoir in the geothermal system. The reservoir layer is thought to be composed of Weh volcanic rocks with estimated densities of 2.62 g/cm$^3$ and permeability 27 millidarcys and sandstones with an estimated density of 2.52 g/cm$^3$ and a permeability of 3 millidarcys. The depth of the reservoir zone peaks based on geophysical modeling is at 550-600 m below the surface around the Jaboi manifestations and deeper for those outside of the area (Figure 8). Above the reservoir layer, there is an impermeable layer with a thickness of 400-500 m indicated by a low resistivity value (<10 ohm-m) that serves as a rock cap. The constituent rock of this layer is estimated to be the product of the Leumo Mate mountain, the Seumeureuguh mountain, the Weh pyroclastic and part of the Weh lava that has been strongly altered in the acidic environment to become argillic alteration rocks. Weh Island has volcanic morphology with an altitude of 300-600 meters which acts as a water trap area and is a depressed area that has a complex fault structure making it an excellent medium for meteoric water to soak into the subsurface and accumulate in the reservoir (recharge water) mixed with deep reservoir fluids. The fluid is then heated by residual magma (pluton) and mixes with magmatic fluids (SO$_2$, CO$_2$, H$_2$S, H$_2$O, HCl, and HF), and through cesarean control appear on the surface as thermal manifestation. The structures constructing the geothermal system in Jaboi are based on geology surface, gravity levation, modeling, and the drilling of gradient wells (Ceunohot and Leumo Mate Fault). Both of these faults are the youngest normal fault with the direction of NW-SE and NE-SW forming the graben valley between Seumeureuguh and Leumo Mate volcanic bodies [14].

Ceunohot Fault serves as a hydrothermal fluid rise medium from the deep reservoir to the surface. This is evident from the drilling mud temperature spike in JBO-1 higher than the temperature in JBO-2 well due to JBO-2's closer distance to the Ceunohot fault than JBO-2. Also, the temperature gradient of JBO 1 is also higher than JBO-2. The position of the distance between the two wells to Ceunohot fault greatly affects the subsurface temperatures in the area. Thus, the Ceunohot fault along with other fault lines intersected in the Weh Island Graben zone can be referred to as a prospect fault in the Jaboi geothermal area and serve as an excellent drilling target for exploration and development well in the future [8].
7. 3D Geological Model Construction
This preliminary study developed a 3D geological model of Weh Island using LEAPFROG Geothermal. All the data used in this study are public data derived from a literature review of the journals or papers discussing Jaboi geothermal area and Weh Island volcano activities. The literature review of Weh Island exploration resulted in the following data in Table 1 below:

Table 1. Summary of data for the 3D geological model.

| Type of Data      | Function                        | Remark                          |
|-------------------|---------------------------------|---------------------------------|
| XYZ Data          | Constructing the topography of the Weh Island | Derived from public satellite data |
| Geological Map    | Determining the Weh Island rock stratigraphy | Derived from the literature review |
| Geological Cross-section Map | Determining the lithology of Weh Island | Derived from the literature review |
| Bathymetry Data   | Determining the depth of the sea around Weh Island | Derived from public bathymetry data |
The diagram shown in Table 2 is the workflow for creating a 3D model of Weh Island.

**Table 2. The work process diagram of Weh Island model.**

| Step               | Actions                                                                 |
|--------------------|-------------------------------------------------------------------------|
| Initiation         | • Collect the public data related to Weh Island or Jaboi area           |
| Topography Setup   | • Import the XYZ data of Weh Island                                      |
|                    | • Import the bathymetry data                                            |
|                    | • Short the "bad" data using python script                              |
| Stratigraphy Setup | • Import the geological map to overlay the topography of the island     |
|                    | • Digitize the geological structure (primary and secondary faults)      |
| Lithology Setup    | • Import the geological cross-section map                               |
|                    | • Determine the lithology sequence based on the age of the rock         |
|                    | • Create "artificial" wells to control the rock distribution           |
| Completion         | • Adjust the rock distribution using polyline                           |
|                    | • Setup the model grids                                                |

As seen above, this project was initiated by collecting the relevant data of Weh Island and Jaboi geothermal area. The data were then sorted into three categories which are topography, stratigraphy and lithology data. The 3D model resulting from the workflow diagram is described below.

### 7.1. Topography Setup

The XYZ data derived from the public satellite data were imported into LEAPFROG to create the topography of the model. The bathymetry data are used to determine the depth of the sea around the Weh Island. Where the bathymetry data was not complete or inconsistent, polylines were constructed around the island following the depth of the sea to create the underwater topography. Some adjustments were made using a python script to sort the “bad” data that was created by the data fitting algorithms, and the remaining data were used to create the topography of the Weh Island and the sea. Figure 9 is the complete topography model of Weh Island. The green polylines represent the coastline of the island.

![Figure 9. The result of the combination of XYZ and bathymetry data of Weh Island.](image-url)
7.2. Stratigraphy Setup

The geological map of Weh Island given in Figure 2 was imported into LEAPFROG to overlay the complete topography of the island. The map was used to define the rock unit distribution within the island and to create the fault models controlling the established geothermal geological structure. The following table is the summary of the Weh Island rock stratigraphy:

| 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    | Qaps         | Quartenary    |
| Flow                      |              |               |
| Leumo Matee Volcanic       | Qvlm         | Quartenary    |
| Leumo Matee Pyroclastic    | Qaplm        | Quartenary    |
| Flow                      |              |               |
| 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 Weh Pyroclastic Flow (QTpw) unit and Weh Lava Flow (QTvw) unit are classified as Mid Quartenary Volcanic and Lower Quartenary Volcanic respectively. It was found that the Weh Pyroclastic Flow unit and Weh Lava Flow unit always appeared on each geological cross-section map of the Weh Island as the first and second to bottom formations respectively. Thus the distribution of both rock units covers the whole island.

The Sedimentary group was set on the top of the Mesozoic Basement formation and comprised of Tuffaceous Sandstone (Tms) unit and Limestone (Qgt) unit. Both rock units were found on the eastern coast of the island. Meanwhile, the Young Volcanic group was only Young Kulam Volcanic (Qvk-2) unit due to its formation on the top of the Pawang Volcanic (Qvp) and Old Kulam Volcanic (Qvk-1). The rest of the rock units were categorized as Upper Quartenary Volcanic group.

The fault blocks were created by digitizing the main faults on the geological map using the polyline function. The dip of the faults referred to the cross-section map with a range of vertical to 75°. The following table is the summary of the main faults that construct the structure of the Weh Island:
Table 4. Summary of the main faults and its trend

| Fault      | Trend   |
|------------|---------|
| Sabang     | NW-SE   |
| Seukeu     | NW-SE   |
| Balohan    | NW-SE   |
| Labu Ba'u  | N-S     |
| Bangga     | NW-SE   |
| Pria Lhaot | N-S     |
| Kulam      | N-S     |
| Leumo      | NW-SE   |
| Matee      | NW-SE   |
| Ceunohot   | NE-SW   |

Figure 10. The fault blocks of the 3D model

Figure 10 indicates the fault blocks from the digitized geological map image. These blocks show the subsurface structure of the Weh Island that control the geothermal reservoir and the emergence of the surface thermal manifestations.

7.3. Lithology Setup

The geological cross-section maps of the Weh Island were used as the subsurface information source to determine the locations of rock formations. The cross-section maps were imported into LEAPFROG and plotted following the topography of the model. Then 135 “artificial” wells were built to control the lithological distribution and set the boundary of the geological model. The wells were 3000 m deep and positioned in each rock unit area of the geological map. Thus the previous six groups of rock formation were utilized as primary input for the geology data of the wells. The result of the process of the lithology setup can be seen in Figure 11.

Once the lithology setup was done, the output volumes of the 3D geological model can be generated. Many adjustments were carried out on the artificial wells lithology to ensure the rock distribution of the model followed the distribution of the rock units on the geological map. The thickness of each rock formations was adjusted based on the cross-section maps. The lateral distribution of the areas with no data was interpreted using the closest cross-section map, and if the results were not in accordance with the geological map, trial and error method was used to adjust the thickness of the rock formation. The
wells positions also played a significant role in affecting the lateral distribution. Two crucial formations that should be geologically realistic are the Sedimentary and Mesozoic Basement because they construct the two bottom layers of the model and the Sedimentary layer is thought to contain the geothermal reservoir. The upper formations distribution geometry could be adjusted using the polyline function.

![Figure 11](image1.png)

**Figure 11.** The distribution of 130 “artificial” wells near the cross-section maps and at the edge of the model.

8. **3D Geological Model**

A complete 3D geological model of Weh Island has been generated using the public data (Figure 12). This 3D model represents the comprehensive geological structure and stratigraphy identified in the geological map of Weh Island and the conceptual model of Jaboi geothermal area. The Weh Island 3D model covers the entire island, an estimated 400 km² area.

There are nine primary faults assigned in the model with the majority being a normal fault. These faults control the fluid flow patterns of the hydrothermal fluids in the Weh Island in general and 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 cross-section maps and the topography of the model, while the Sedimentary thickness was estimated to remain roughly constant at 1000 m. The remaining depth of the model is Mesozoic Basement.

![Figure 12](image2.png)

**Figure 12.** The complete 3D geological model of Weh Island, Nangro Aceh Darussalam.
9. Reservoir Model Grid Setup
The final step in this stage of the project is setting up the AUTOUGH2 grid in LEAPFROG geothermal using the 3D model. The AUTOUGH2 grid is 19.2 km in length and 17.6 km wide with total 21,141 blocks (Figure 13). The blocks are 800m x 800m and range in vertical thickness from 500m in the Mesozoic Basement to 100m near the surface. The grid is more highly refined in the potential area (Jaboi geothermal field) with blocks 400m x 400m used. This grid will be used as the reservoir simulation model to achieve a natural state condition. 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 will automatically transfer those changes into the AUTOUGH2 model it generates.

![Figure 13. The grid layout: (a) side view and (b) top view.](image)

10. Discussion and Path Forward
Two points of interest can be derived from this project as followed:
- The progress of this project so far has succeeded in compiling all exploration data into an attractive and useful 3D geological model of the Weh Island which can help give a better understanding about the subsurface condition of the project area.
- The AUTOUGH2 grid has been generated using the new 3D geological model with a higher resolution focused on the potential geothermal area.

The next step of this project is to assign the rock properties, permeability structure, surface heat flow and mass flow into the model to represent the natural state condition of the geothermal system in this area. The simulation of the model will then be run using AUTOUGH2 for an extended time until the steady state condition is reached. This natural state condition is then calibrated with heat discharge surfacing from the thermal manifestations, temperature profiles obtained from the temperature gradient wells (JBO-1 & JBO-2) and the geothermometer information. The surface thermal manifestation data of 10 hot springs and two fumaroles will be utilized to calculate the surface heat flow. The vertical temperature validation of the model will use the temperature profiles of JBO-1 and JBO-2.

This research project so far only uses publicly available data. The results and usefulness of both the 3D geological model and the reservoir model can be strengthened through the contribution of other stakeholders including the private sector. The more data are retrieved, the more comprehensive and reliable the results of the project will be.

An important strength of the approach used in this project is that as more data become available, they can be absorbed in the 3D geological model replacing assumptions and estimates that have been used so far. LEAPFROG geothermal will then automatically adjust the 3D geological model to be
consistent with the data and will also automatically update the reservoir model setup. The workflow not only dramatically increases the speed at which data can be absorbed and analyzed but also ensures that the 3D geological model and the reservoir model are seamlessly updated allowing them to be regularly used to support decision-making by all the stakeholders.

Acknowledgments

We acknowledge the support of Seequent though their ongoing collaboration and the generous provision of research licenses for LEAPFROG Geothermal.

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