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3D Model of Bora Pulu Non-Volcanic Geothermal Prospect, Central Sulawesi, Indonesia

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ABSTRACT

Geothermal 3D geological modeling provides an integrated database, detailed visualization, and representation that could improve geothermal prospecting. This approach also facilitates new perspectives related to geothermal system conditions that may not be represented properly through 2D conceptual models. The 3D model development is an important step for geothermal prospecting not only for mature and well-surveyed areas but also for greenfield areas or areas in the exploration phase.

Bora Pulu is a geothermal prospect located in Sigi Regency, Central Sulawesi, Indonesia. It is estimated to hold a potential capacity of 123 MW in possible reserves and is classified as a medium enthalpy system. Bora Pulu is associated with extensional tectonic activities of the NW-SE trending Palu-Koro fault and plutonism instead of the volcanic controlled systems mainly preferred for utilization in Indonesia. Geologically, Bora Pulu is hosted by granitic and metamorphic rocks. These characteristics are also similar to other geothermal potentials formed along the Palu-Koro segment.

This research has objectives to develop a 3D geological model of the Bora Pulu geothermal prospect through several published data related to stratigraphy, structural geology, hydrogeologic condition, and conceptual model. Authors perform 3D geological modeling using Leapfrog geothermal to visualize geological unit boundary, fault geometry and manifestation location in the prospective area. This model would enrich the recent perspective from the prospect to gain a better understanding of the non-volcanic geothermal system in Indonesia.

1. INTRODUCTION

The Island of Sulawesi hosts the largest geothermal potential in Indonesia after Sumatera and Java, comprised of mostly nonconventional geothermal prospects (Fahrurrozie, et al., 2015). Situated in Eastern Indonesia, the tectonism of Sulawesi is complexly formed by the collision of the Sundaland and Austalia continents in Late Oligocene to Early Miocene, with ongoing and continuous deformations to this age (Hall & Wilson, 2000). Thus, the north arm of the island evolved into an active magmatic arc, while the east and southeast arms, characterized by microcontinent and ophiolite fragments, accreted to the west part of the island. In the Central Sulawesi area, the regional Palu-Koro fault separates western Sulawesi from the eastern side (Suryantini & Wibowo, 2010). The Palu-Koro fault shows a predominantly sinistral strike-slip movement and trends NW-SE. The fault is classified as very active, and the fault zone has been known to be the hypocenter of several inland earthquakes in the last few decades (Supartoyo, et al., 2014).

A number of nonconventional geothermal prospects are formed in Central Sulawesi along the segments of the Palu-Koro fault, marked by the occurrence of thermal manifestations. In total, 14 prospects have been identified within the Palu-Koro fault zone and the associated depression morphology of Palu Graben (**Figure 1**). The majority of these geothermal prospects are still under the preliminary survey phase. However, detailed survey has been conducted for the prospects Bora, Pulu and Marana (Idral, 2010). The neighboring Bora and Pulu prospects are located in the Sigi Regency, approximately 20 km from the city of Palu (Risdianto, et al., n.d.). According to EBTKE (2020), Bora-Pulu Geothermal Working Area (GWA) is predicted to have 123 MW of resources and intended for development as a geothermal power plant with 40 MW capacity. Detailed lithology and structural mapping, geochemical water and soil surveys, as well as geophysical surveys of gravity and resistivity have been completed for the two areas (Risdianto, et al., n.d.; Wibowo, et al., n.d.; Bakrun, et al., 2003; Kurniawan, et al., 2017). Meanwhile, magnetotelluric survey and shallow thermal gradient well drilling had only been conducted in the Bora area (Risdianto, et al., n.d.; Zarkasy, et al., n.d.).

The Bora Pulu prospect is known to be hosted by Pre-Tertiary metamorphic rocks consisting of schist basement intruded by granite gneiss unit and overlayed by a vastly distributed phyllite-slate unit. Granite and granodiorite bodies intruded the older metamorphic units in the Tertiary period, followed by Quaternary colluvium and alluvium deposition in the Palu Graben depression. The highly fractured metamorphic schist unit is interpreted to be the reservoir of Bora geothermal system, while sedimentary and phyllite-slate units show signs of argillic alterations which forms the impermeable clay cap (Risdianto, et al., n.d.; Wibowo, et al., n.d.).

Inferred from MT data at Bora, the reservoir in this sector is estimated to be at 600 m depth below Bora and Lompio Hot Springs manifestations, with about 500-600 m thickness, deepening towards the north and southwest (Kholid, et al., n.d.; Zarkasy, et al., n.d.).

The reservoirs for Bora and Pulu are most likely separate, with respective subsurface temperatures of 150-220 °C and 120 –180 °C, however Pulu is predicted to have a similar reservoir depth of approximately 600 m (Risdianto, et al., n.d.). The heat source in Bora Pulu is most likely Quaternary granite plutonic bodies alike the Pleistocene aged intrusive bodies exposed in nearby areas of Limbong and Lompio.

The extensional structures in the Palu Graben acts as the main control to the vertical flow of meteoric water to reach the depths of cooling pluton, the accumulation of hydrothermal fluid in the fracture lithologies and the subsequent thermal manifestations. 2D conceptual models have been generated for both the Bora and Pulu geothermal systems (Wibowo, et al., n.d.; Bakrun, et al., 2003). Using the detailed survey data of Bora Pulu prospect, 3D visualization is generated using Leapfrog Geothermal to refine the current model. Furthermore, due to its extensional tectonic setting, heat source, and heat transfer mechanism, the Bora Pulu prospect has been characterized as a fault-controlled play based on Moeck's (2014) geothermal play types and will be modelled accordingly.

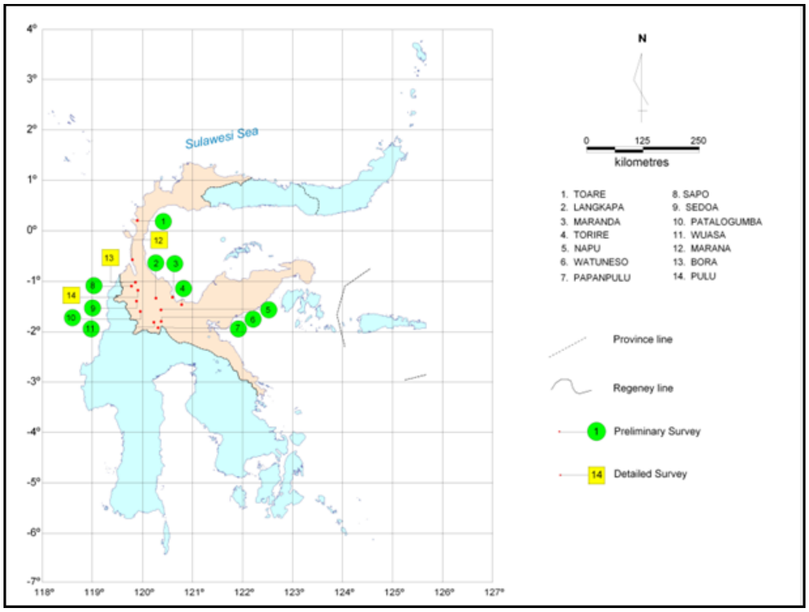

Figure 1: **Map of the 14 geothermal prospects in Central Sulawesi (Idral, 2010)**

2. METHOD AND DATA

The 3D model is built using Leapfrog Geothermal software. Leapfrog geothermal software is a 3D modeling and visualization tool first developed by ARANZ Geo. At the moment, Leapfrog Geothermal is owned and developed by Seequent Ltd. The basis of stratigraphic (lithological contacts) in Leapfrog Geothermal is modeled using RBFs (Radial Basis Functions) scheme (Alcaraz et al., 2011). RBFs are a family of interpolation functions used to obtain a smooth geological surface of interpolation. In contrast with other local technique interpolation methods (polygonal, kriging, IDW), RBFs are a group global interpolation method. Therefore, the interpolant is dependent on all data points, which are suitable for aspects of geological modeling (Cowan et al., 2002).

To build a 3D geological model of the Bora Pulu geothermal prospect, the basic 3G (geology, geochemistry, geophysics) data were incorporated. The data used in this paper are openly sourced data, which is collected from the GIS database and literature review from previous studies. Some of the data, such as geochemistry and temperature gradient measurement report data were provided by the Center for Mineral, Coal, and Geothermal Resources (PSDMBP). **Table 1** is a summary of the availability and quality of data, which are used in this paper.

Table 1: Summary of data input availability and sources

Data	Type of Data	Remarks	Source
Remote sensing	Digital elevation imagery	The spatial resolution is about 0.27 arcseconds or equivalent to 8.1 m.	DEMNAS
Geology	Stratigraphy	Obtained from the previous literature study; compiled from regional and previous geological survey report with minor modification and extrapolation to fit model boundaries.	Sukido, et al., 1993; Risdianto,et al., n.d.; Bakrun, et al., 2003
	Geological structure	Obtained from previous literature study and independent lineament analysis using DEMNAS imagery.	Kurniawan, et al., 2017; DEMNAS

Data	Type of Data	Remarks	Source
Geochemistry	Surface thermal manifestation	Including coordinate plot, surface elevation, and physical characteristics (manifestation temperature, pH, flow rate, and electroconductivity).	PSDMBP
	Solute constituents	Including laboratory analysis data in the ppm and mg/L units.	PSDMBP
	Isotope	Stable isotope the analyses from the previous study. Only available for thermal manifestation of Bora.	Wibowo, et al., n.d.
Geophysics	MT	Available in the form of slicing model only at Bora area.	Zarkasyi et al., n.d.; Bakrun, et al., 2003; Idral & Mansoer, 2015
Conceptual Model	Map and Section	Available for Bora and Pulu conceptual models. Bora conceptual model shows better resolutions.	Wibowo, et al., n.d.; Bakrun, et al., 2003
Temperature gradient	Gradient temperature profile	Gradient temperature graph profiles are available for BRA-1 & BRA-2, including their coordinates.	PSDMBP

2.1 Geological Data

The geological analysis of Bora Pulu area was carried out utilizing remote sensing analysis and several published geological studies. To construct the geological map, at least three geological maps were used. The map was constructed by the combination of Regional Geological Map of Pasangkayu Quadrangle (Sukido, et al., 1993), Bora geological map (Wibowo, et al., n.d.), and Pulu geological map (Bakrun, et al., 2003). Remote sensing analysis using DEM and satellite imagery are also used to better delineate the surface lithology boundary and structural lineaments in this area. The geological map result does not undergo many changes as the purpose of the modification is only to compile the lithological units and to adjust the extent and order of the lithological units. **Figure 2** shows the modified geological map of Bora Pulu.

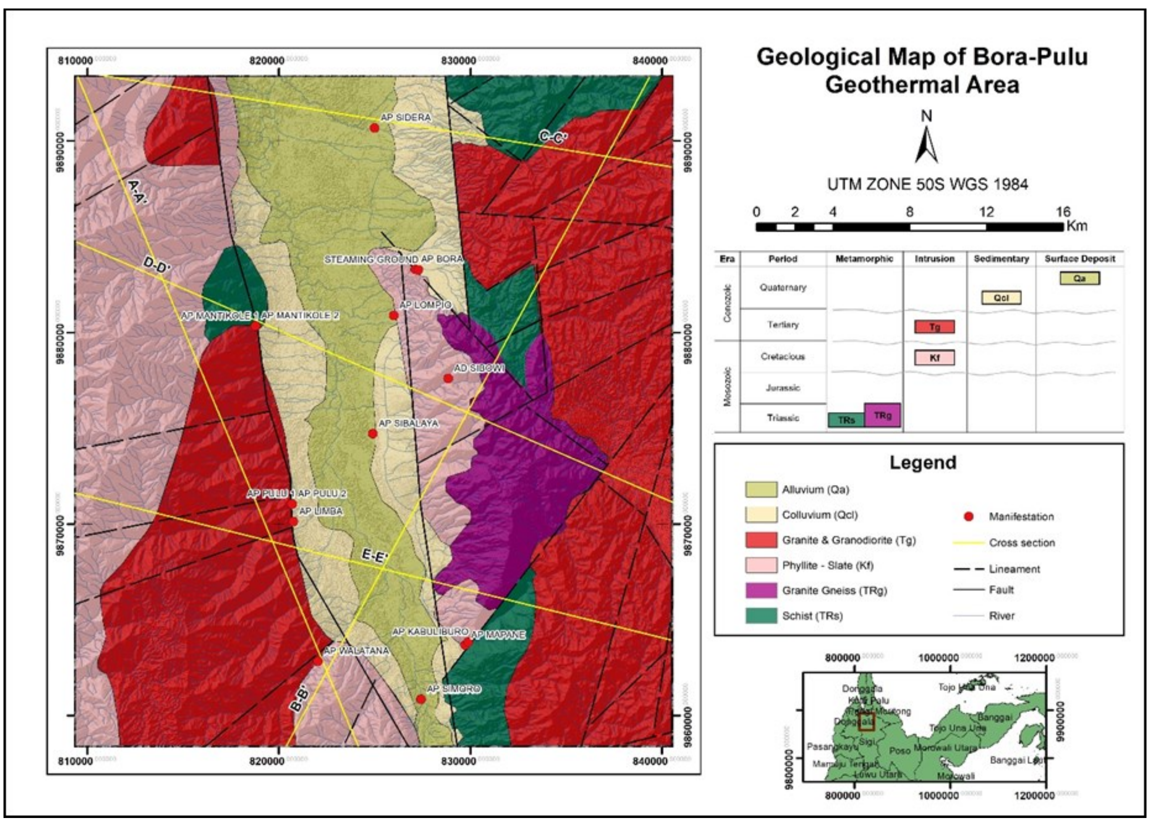

Figure 2: **Modified geological map of Bora Pulu generated by integration of regional geological map of Pasangkayu Quadrangle (Sukido et al., 1993), Bora geological map (Risdianto, et al., n.d.), and Pulu geological map (Bakrun, et al., 2003)**

At least five cross sections were created to accommodate the subsurface condition of the model, especially in the Palu-Koro area. These sections intersect all existing lithologies and main fault of the area, the Palu Koro fault. The subsurface thickness and visualization principally follows the regional cross section and Bora Pulu cross section from the literature with few modifications of the geometry. Two samples of the generated cross sections are displayed on **Figure 3**.

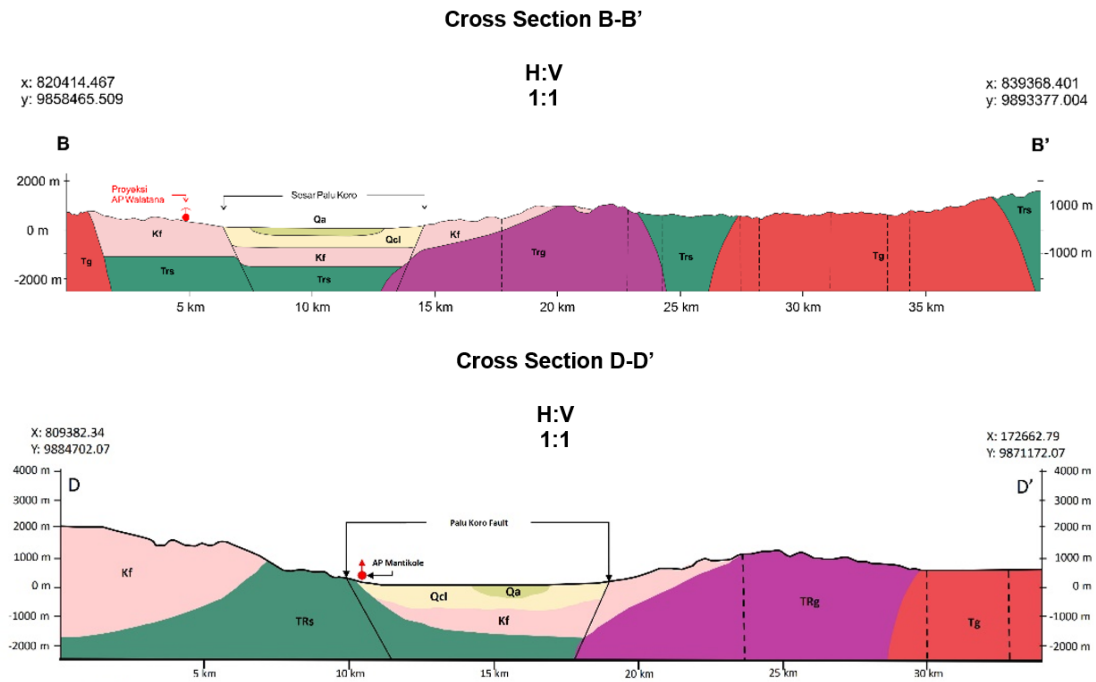

Figure 3: Cross sections which illustrate the subsurface condition of Bora Pulu geothermal area

2.2 Geochemical Data

The geochemical data were provided by the Center for Mineral, Coal, and Geothermal Resources (PSDMBP), collected in exploration activity of Bora and Pulu Geothermal prospect areas. Accurate information about the location of surface thermal manifestation is an important aspect to develop the 3D model. Therefore, the raw data is then converted to point data consisting of local coordinates, elevation, and surface thermal manifestation temperature. The surface thermal manifestations of Bora Pulu geothermal system are divided into Bora Area, consisting of warm and hot springs with temperatures ranging from 40.4°C to 90.1°C and Pulu Area, consisting of warm and hot springs with temperatures ranging from 40°C to 94.8°C. The presence of steaming ground was also reported around Bora hot spring (Wibowo, et al., n.d.). The summary of physical properties of each surface thermal manifestation are given in **Table 2**. Moreover, the chemical solutes data were used to determine the characteristics of thermal fluid beneath the Bora-Pulu geothermal system.

Table 2: Physical properties of thermal waters in Bora area and Pulu area

No.	Sector Area	Location Name	Coordinate (UTM)		Code	Elevation (m)	T (°C)	pH	Flow Rate (L/s)	EC (µS/cm)
			X	Y						
1	Bora area	Bora hot spring	827121	9883283	APBR	131	90.1	7.22	3	3630
2		Sidera warm spring	825004	9890666	APSD	67	37.8	7.61	0.1	404
3		Mantikole 1 warm spring	818816	9880332	APMKL-1	117	44.3	8.70	0.5	330
4		Mantikole 2 warm spring	818782	9880341	APMKL-2	131	40.4	7.71	0.3	272
5		Lompio hot spring	825999	9880889	APLP	59	58.1	8.51	0.5	294
6		Sibowi cold spring	828844	9877593	ADSB	315	27.8	7.11	-	89

No.	Sector Area	Location Name	Coordinate (UTM)		Code	Elevation (m)	T (°C)	pH	Flow Rate (L/s)	EC (µS/cm)
			X	Y						
7	Pulu area	Pulu-1 hot spring	820698	9871046	APP-1	104	75.7	8.6	4	-
8		Pulu-2 hot spring	820698	9871046	APP-2	104	78.9	8.6	1	-
9		Mapane hot spring	829722	9863687	APMP	137	94.2	8.1	0.04	-
10		Kabuliburo hot spring	829888	9863845	APKBL	137	94.8	8.3	-	-
11		Sibalaya warm spring	824910	9874713	APSBL	79	40	6.5	4.9	-
12		Limba hot spring	820756	9870124	APL	99	40.9	7.7	-	-
13		Walatana hot spring	822041	9862839	APWL	193	41.5	7.2	0.2	-
14		Simoro warm spring	827419	9860854	APSMR	126	48.6	7.0	-	-

2.3 Geophysical Data

To predict subsurface conditions, the geophysical data was also incorporated as the basis to construct the 3D model. Unfortunately, there was only MT inversion data consisting of resistivity map and slicing 2D inversion model. Moreover, only the MT data around Bora area has successfully been acquired from previous studies. The horizontal slicing MT model generated lateral distribution of various resistivity consisting of slicing depths of 500m, 1000m, 1500m, and 2000 m (**Figure 4**).

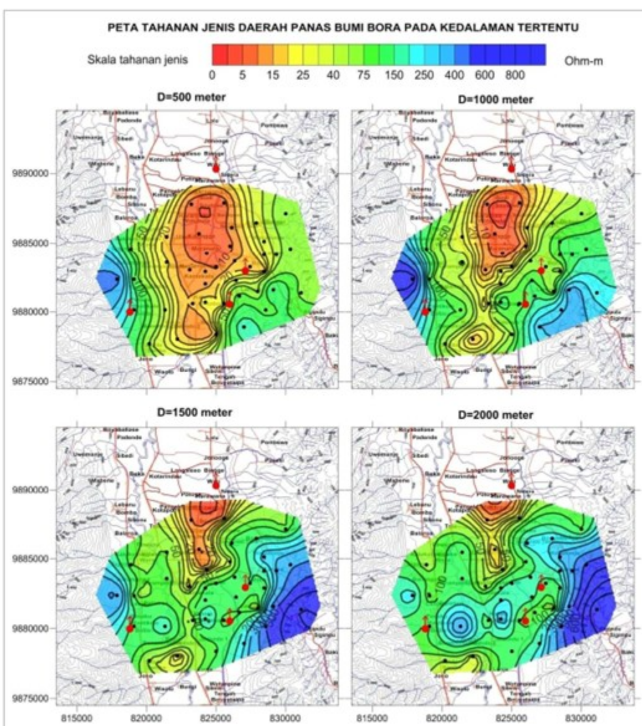

Figure 4: **MT horizontal cross sections (Zarkasyi et al., n.d.)**

The distribution of acquired points was used to input data for 3D modeling using Leapfrog Geothermal. The digitized point data consisted of values of X, Y, Z, and resistivity value per slicing depth. The 3D model was constructed by contouring resistivity value using polyline. Then, the vertical slices shown in **Figure 5** consist of E-W and N-S sections across the Bora hot spring (APBR) were used to help the interpretation of subsurface geometry in the data integration stage.

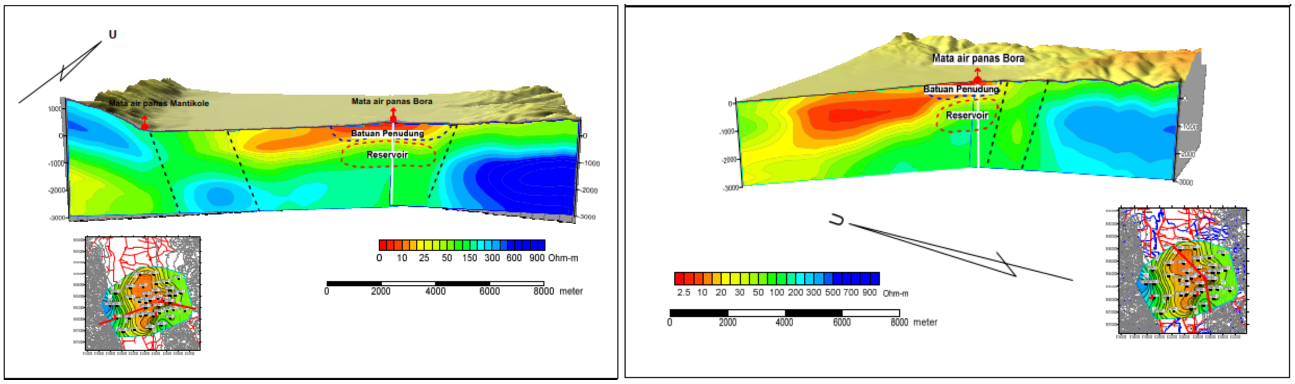

Figure 5: **MT vertical cross section of Bora area and surroundings (Zarkasyi et al., n.d.)**

2.4 Temperature Gradient Wells

There are two temperature gradient wells that have been acquired around the Bora area, namely BRA-1 and BRA-2. Results of temperature-depth profile from gradient temperature well data are considered in the construction of the isothermal line model. BRA-1 reportedly has a bottom hole temperature of 54°C at 160 m depth. Meanwhile, BRA-2 reportedly has slightly higher bottom hole temperature of 73.5°C at 250 m depth. With the assumption of surface temperature about 29°C, it could be calculated that BRA-1 and BRA-2 have temperature gradient of 15.6°C /100 m and 17.8°C/100 m, respectively. Therefore, it could be concluded that the Bora area has a temperature gradient of 5 to 6 times the normal temperature gradient.

2.5 Leapfrog Modelling Workflow

Collecting of the data was done parallel with preliminary study. Geological data was inputted as surface geological map and cross sections to build the 3D geological model. Geophysical data including MT points and MT slices at 500 m, 1000 m, 1500 m, and 2000 m depth were used to construct 3D MT model. The 3D isothermal model on the other hand was built based on geochemical data of the manifestations (temperature and fluid type data) and gradient temperature data. The 3D geological model, MT model, and isothermal model were then visualized simultaneously as an integrated 3D conceptual model later used to update subsurface interpretations. **Figure 6** displays the general workflow used in this study.

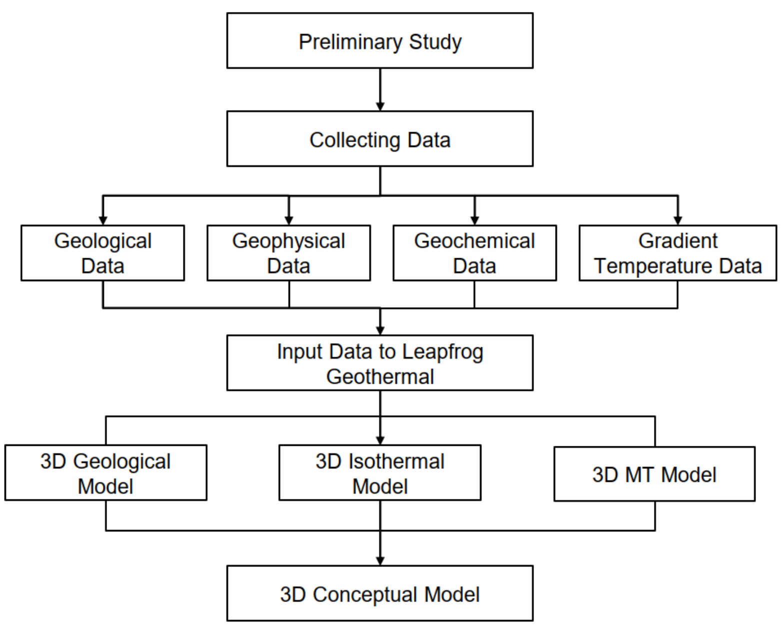

Figure 6: **Workflow for Bora Pulu geothermal area 3D modelling**

3. RESULT AND DISCUSSION

3.1. Geological 3D Model

3.1.1. Stratigraphy

The model, as mentioned in the section 2.1, relies on the availability of surface data expressed in the modified geological map. Before creating the geological model, surface topography was made using Digital Elevation Model National (DEMNAS) with 8 m resolution. The geological model was later built with respect of the topography model. The extent of the geological model follows the topographic model set to 42 km x 50 km, with minimum elevation of -2500 m. The model's resolution is a moderate 50 m. Thus, the model would not be too slow to generate as is prone for high resolution (smoother triangle) or having too low resolution (coarser triangle), which can lead to difficulty in defining the lithology boundary precisely. After the base model is created, the delineation of surface boundary was carried out using GIS line to control the extent of the lithology. The subsurface contact based on five cross sections made earlier was also delineated using polygons to define the subsurface condition of the lithology. The generation of stratigraphy model was done from the youngest lithology to the oldest lithology. The chronological visualization of the stratigraphy order of Bora Pulu area can be seen in **Figure 7**.

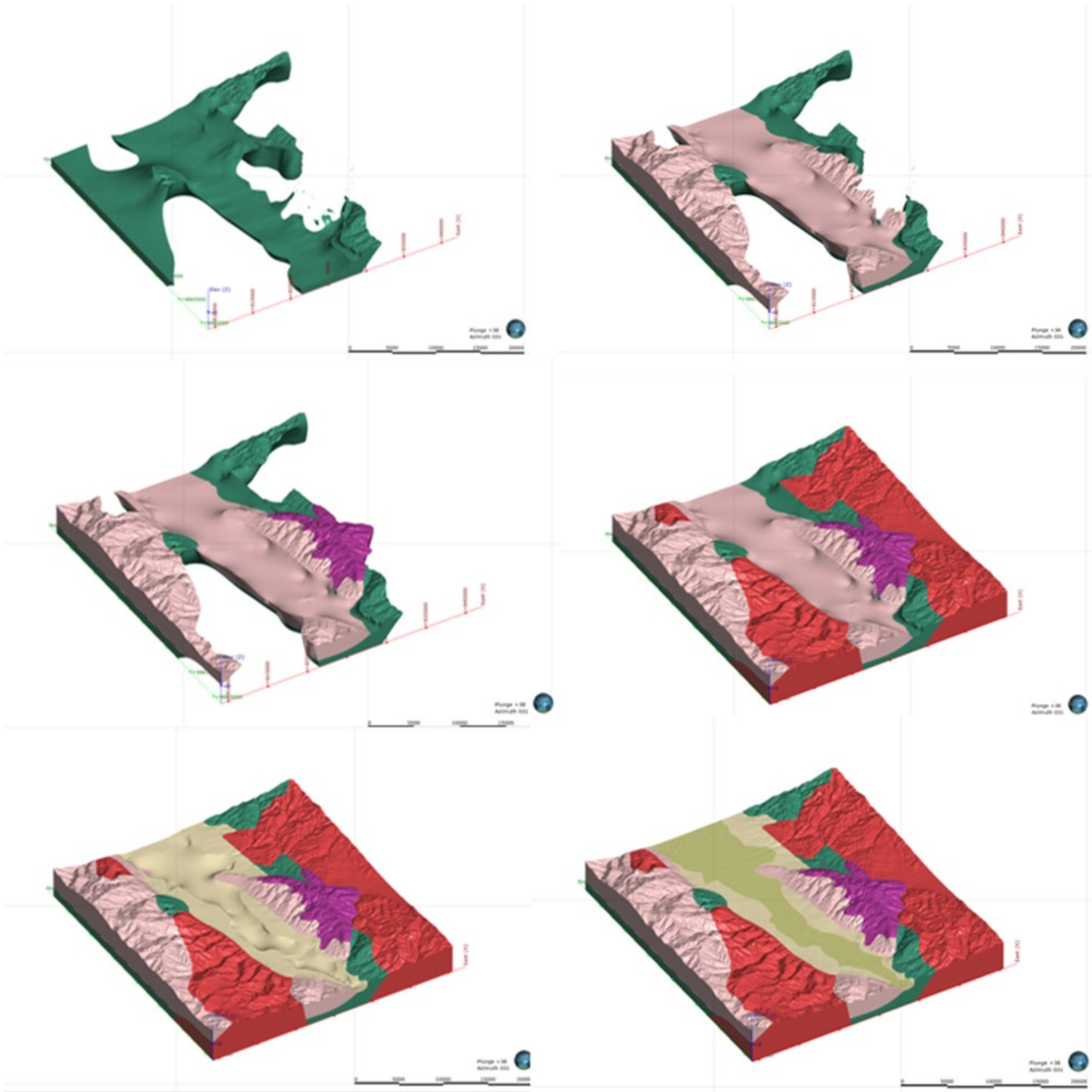

Figure 7: Geologic model in chronological order

As defined in the geological map, the lithology found in the Bora Pulu area varies from sedimentary rocks, plutonic body, to metamorphic rocks. The surface chronology contacts were defined before generating the output volume. The sedimentary rocks comprised of alluvium and colluvium deposits were modelled as lateral deposits eroding the previous deposits using erosional contact. The granite and granodiorite intrusion were modelled as curved bodies that penetrates the older formation of metamorphic rocks using intrusion contact. The metamorphic rocks, however, were modelled considering each formation's protolith and compatible output result later. As phyllite-slate protolith originates from sedimentary formation, the use of erosional or deposit contact is required. The erosional contact is ultimately preferred because of the complex cross cutting relation between the phyllite-slate unit and other units. For the granite-gneiss, the geometry and the genetic suits the intrusion contact better. Schist was modelled as background lithology as it is the basement and the oldest lithology in this area.

3.1.2. Structure

The geothermal system on Bora Pulu area is located overlying with the Palu Koro fault zone. It is known as a major transform fault with sinistral movement (Hamilton 1979; Hall and Wilson 2000; Hinschberger et al. 2005; Hall 2012). Lineament analysis was done using DEM data based on morphological breaks, ridge-hill offset, and regional trends with consideration of previous geological maps as mention on Section 2. Several WSW-ENE, NNW-SSE, NW-SE, and NE-SW structural lineaments were delineated as the result. The Palu Koro, the major regional fault, would crosscut all lineaments intersected with published dip angle of around 60° that develop graben structure based on Kadarusman (2002).

This structural zone corresponds with several geothermal manifestations presence and thought to control the permeability and reservoir geometry of the system, thus indicating fault-controlled system. The correlation between surface manifestation and structural lineaments occurred on Bora Hot Spring, Lompio Hot Spring, Simoro Warm Spring, and Mapane Hot Spring.

In Leapfrog, the lineaments were delineated as surface GIS line and would later build as wall plane with structural orientation accordingly. The crosscutting relationship would follow the fault chronology in the modified geological map (see **Figure 2**). The Palu Koro fault was modelled using the earlier mentioned dip data while other lineaments were constructed with 90° vertical dipping as no literature mentioned the dipping orientation nor field checking has been conducted to confirm all lineaments here. The structural dip information is combined to the plane model using structural disc feature. The structural framework in this area can be seen in **Figure 8**.

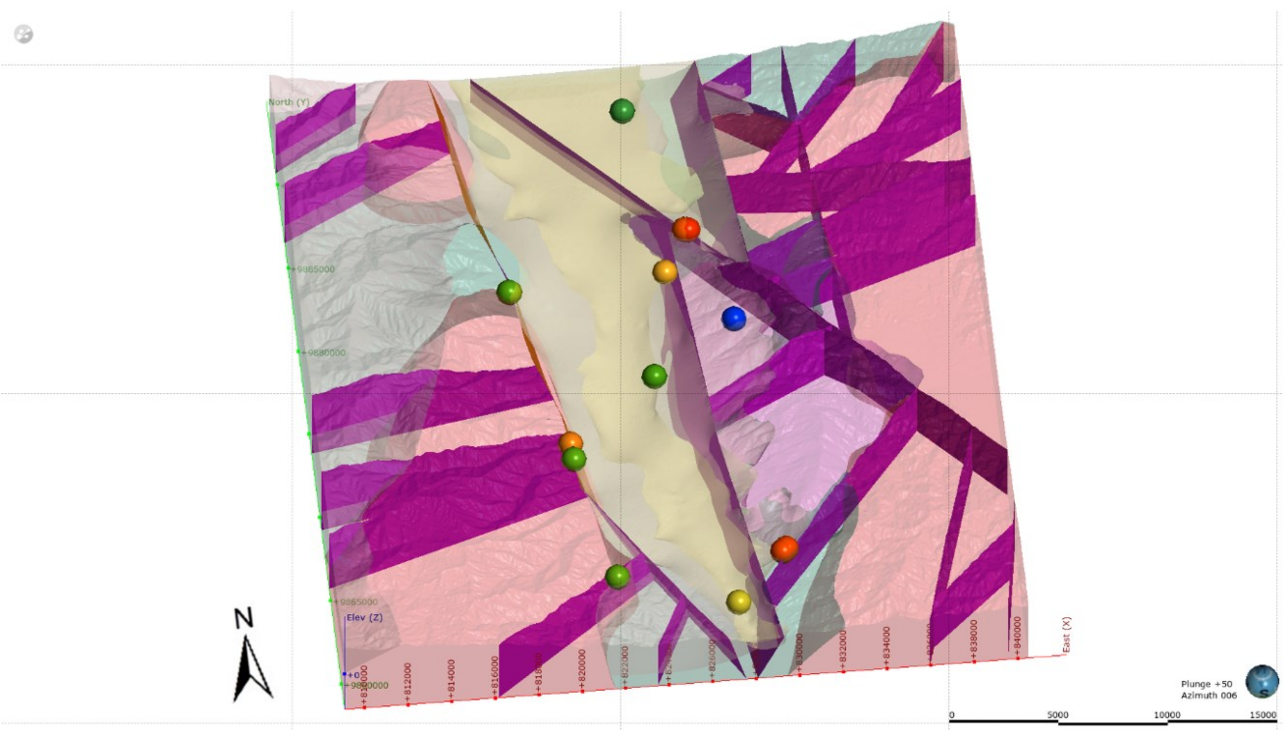

Figure 8: Generated 3D structural framework of the Bora Pulu area

The structural model has limitation related to the high uncertainty of fault presence since no field observation was performed to confirm the structure characteristics. Furthermore, the fault-permeability analysis could not be conducted properly to determine the detail structural control on Bora Polu geothermal prospect since the kinematics and dynamics of fault is still relatively unexplored.

3.2. Geophysical Model

The 3D Model of 2D MT inversion model occupied Bora area's surroundings with 500 masl and -2000 masl maximum and minimum elevations, respectively. Due to the lack of acquired data especially at Pulu area, the model only focused on Bora area. The lateral boundary was limited by the segment of Palu Koro fault on the eastern and western part. Meanwhile, the northern and southern part was bound by Sidera Warm Spring (APSDR) and Sibalaya Warm Spring (APSBL), respectively. Conductive layer distribution was well portrayed in 3D model of 2D MT inversion. MT control points are used in addition to the digitized polylines to form the 3D MT model (**Figure 9**).

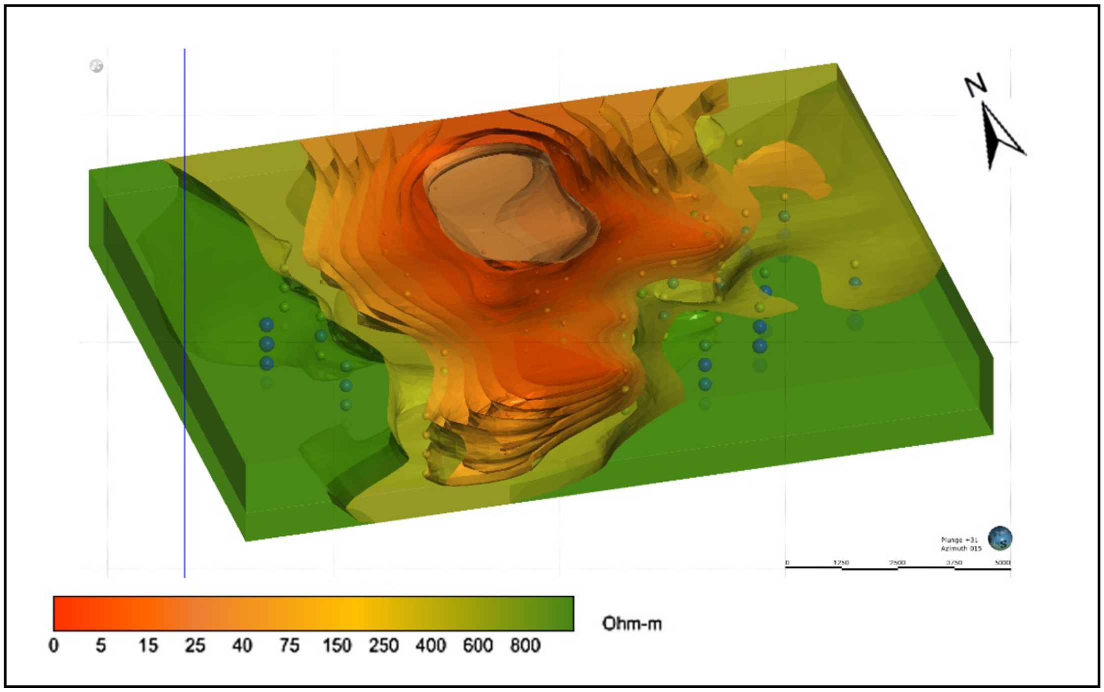

Figure 9: MT points and generated 3D model of Bora Pulu geothermal area

Figure 10 shows the updoming feature could be found beneath Bora Hot Spring (APBR) that also corresponds with Bora steaming ground. The distribution of conductive layer was determined by the mapping of BOC with 10-15 ohm.m resistivity value as the cut off. It could be seen in the **Figure 11** that conductive layer was thickening in northern and southwestern parts following the deepening of BOC. This opposite condition occurs to southward, whereas only thin conductive layer could be found. Although the conductive layer obviously determined, but previous surveyor mentioned that there was possibility that the existing of shallow groundwater aquifer may affect the MT readings.

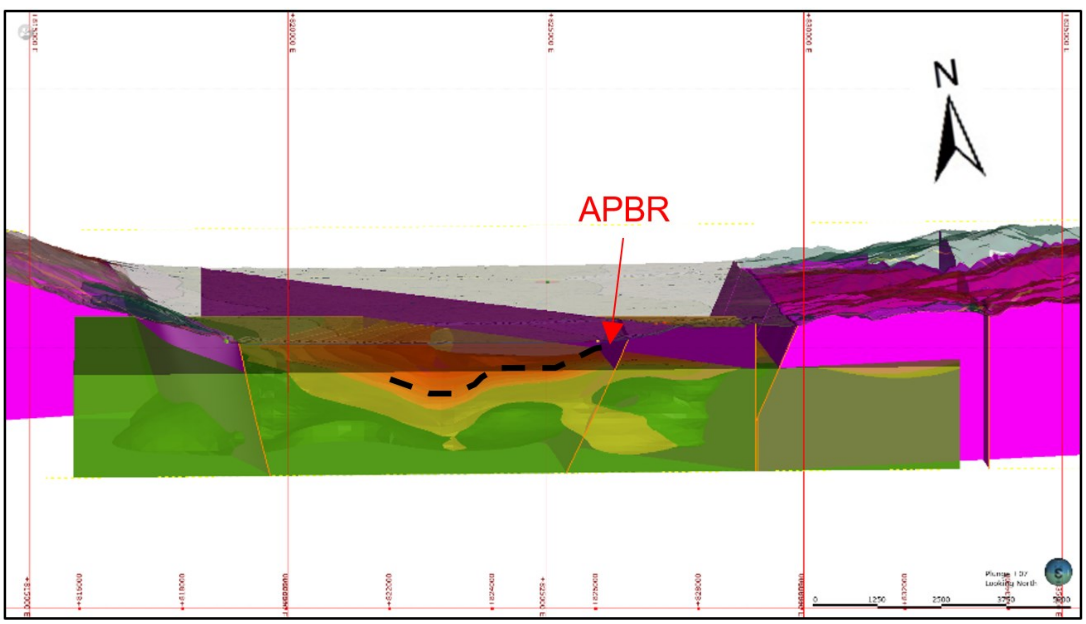

Figure 10: Updoming of conductive layer beneath Bora Hot Spring (APBR) and Bora steaming ground

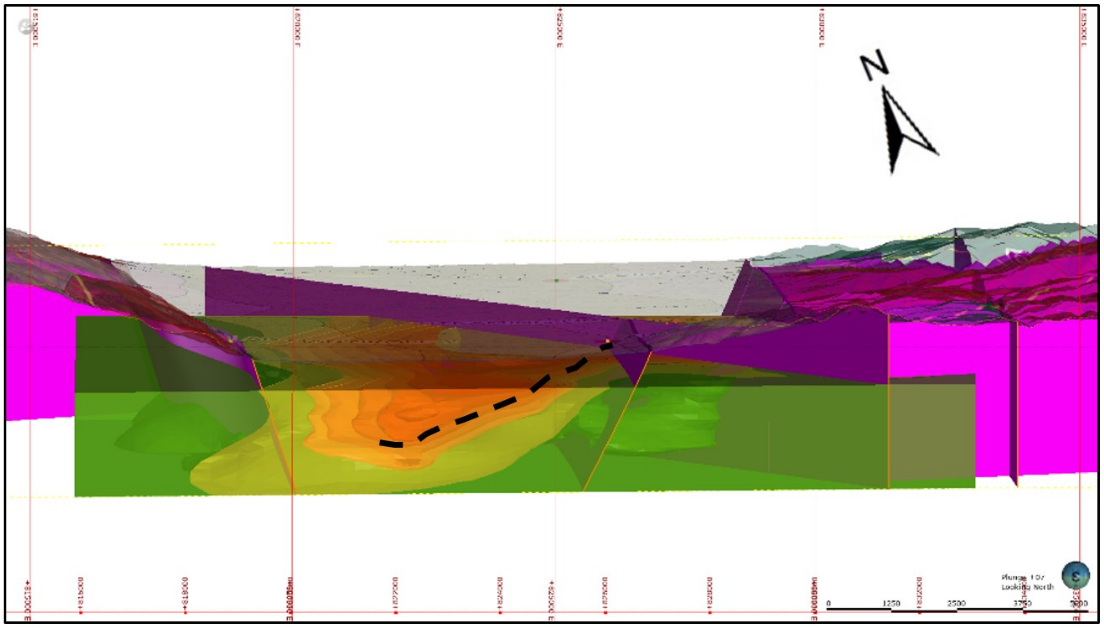

Figure 11: Thickening of conductive layer following BOC deepening in the SW

3.3. Isothermal Model

The isothermal model of Bora-Pulu Geothermal System is constructed by considering the geothermal system type. Based on the topographic condition, Bora-Pulu Geothermal System could be classified as a moderate to flat terrain system. Therefore, the upflow zone beneath the system occurs at low elevations and corresponds with flat terrain regions. As the structural-hosted geothermal system, the fault system within the area has an important role to contribute the fluid path and the occurrence of high-temperature zone. The conduit profile will follow the structural pattern as well as the hydrothermal fluid flowing to the surface.

The upflow zone could be distinguished by the presence of high-temperature surface thermal manifestations. Bora Hot Spring (APBR) has the highest temperature up to 90.1°C in Bora sector area. Meanwhile, in the Pulu sector area the highest temperature could be found at Kabuliburo Hot Spring (APKBL) and Mapane Hot Spring (APMP) with the temperature range of 94.8°C and 94.2°C, respectively. Additionally, high-temperature manifestation in Pulu sector could be found at Pulu-1 (APP-1) and Pulu-2 (APP-2) Hot Springs having temperatures of 75.7°C and 78.9°C, respectively. Therefore, thermal manifestations indicate three upflow sector zone beneath the Bora Pulu Geothermal System.

Fluid geochemistry analyses was used to support the interpretation. Based on the Cl-SO_4-HCO_3 ternary diagram, only Bora Hot Spring (APBR) is classified as a chloride water type (**Figure 12**). Though, according to Na-K-Mg ternary diagram, Bora Hot Spring (APBR) is plotted between partial equilibrium and immature water zone. It indicates that the hydrothermal fluid has encountered re-equilibrium with rock formation in shallower condition prior to emerging to the surface. In comparison, Kabuliburo Hot Spring (APKBL) and Mapane Hot Spring (APMP) are classified as diluted chloride-bicarbonate water based on the Cl-SO_4-HCO_3 ternary diagram and have partially equilibrium in deep reservoir based on Na-K-Mg ternary diagram. It seems that hydrothermal fluids flowed rapidly in this sector and only encountered dilution processes. Those similar conditions also could be found in Pulu-1 (APP-1) and Pulu-2 (APP-2) Hot Springs.

To investigate the similarity source of reservoir, Cl-Li-B ternary diagram analysis was considered. However, the plotting was scattered and did not show a clear separation between the Bora and Pulu systems. Moreover, the relative Cl/B ratio (**Figure 12**) implies there were several compartments of the reservoir. By integrating the spatial distribution of manifestation, range of temperature, fluid type, and Cl-B ratio itself, grouping can be made for the compartments of reservoir. Bora (APBR), Sidera (APSD), and Lompio (APLP) Hot Springs are interpreted to originate from a similar reservoir. It is predicted that fluid from the reservoir uplows within Bora Hot Spring (APBR) before flowing laterally to Sidera (APSD) and Lompio (APLP) Hot Springs. Another compartment seems to be present within Kabuliburo (APKBL), Mapane (APMP), Simoro (APSMR), and Walatana (APWL) Hot Springs belonging to the same group. Moreover, Limba (APL) and Mantikole 1-2 (APMKL-1 & 2) Hot Springs are thought to be influenced by upflowing zone beneath Pulu-1 & Pulu-2 (APP-1 & 2) Hot Springs. This interpretation needs further investigation since there is possibility that Cl and B content within this area has been influenced by subsurface processes such as boiling and/or sub-boiling and mixing.

The isothermal model was generated using the Numeric Model > RBF interpolant option in the Leapfrog project tree. Due to the lack of subsurface data, the isothermal model can only be extended to enclose the Bora MT model with a minimum elevation of -2500 m. The control data for the isothermal interpolation relies mainly on point data of manifestation and gradient well temperature measurements. As these are considered to be directly obtained hard data, it is most suitable to calibrate the model. The manifestations enclosed inside the isothermal model boundary are Bora Hot Spring, Sidera Warm Spring, Mantikole 1 Warm Spring, Mantikole 2 Warm Spring, and Lompio Hot Spring.

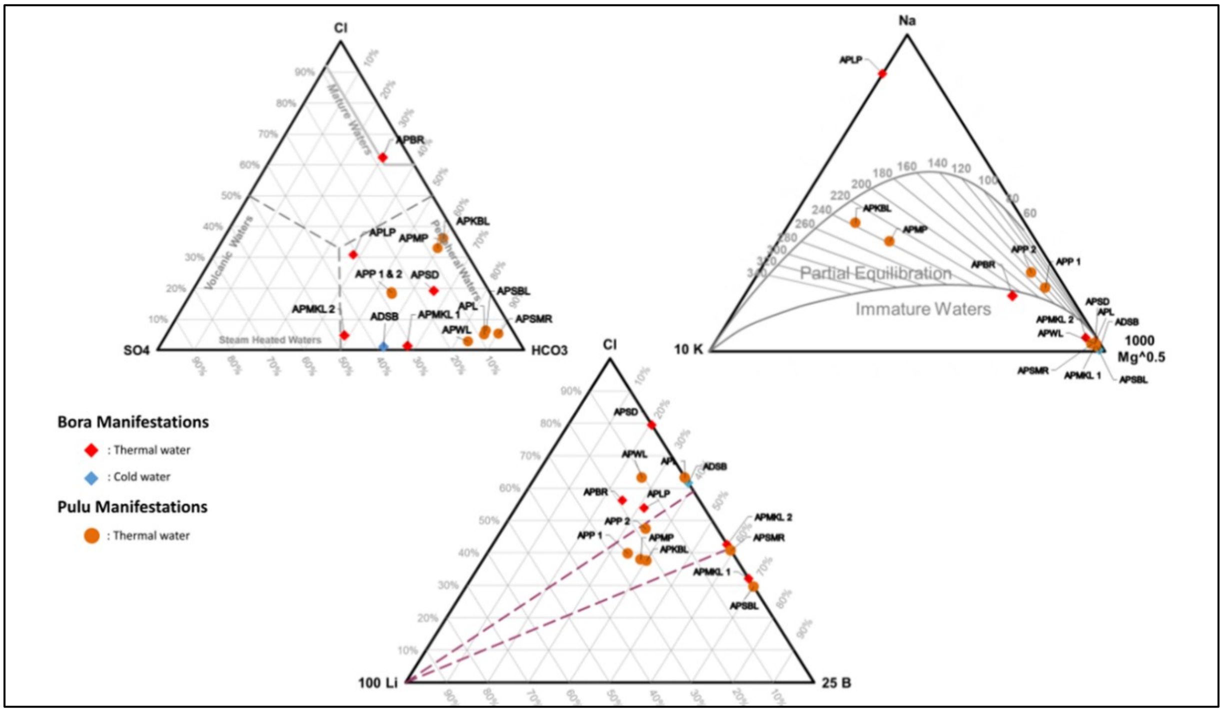

Figure 12: Cl-SO$_4$-HCO$_3$, Na-K-Mg, Cl-Li-B ternary diagram for Bora Pulu manifestations

Aside from point data, the Leapfrog numeric modelling function can be customized to accommodate other types of data as well by manual definition of isosurfaces using polylines. Geothermometer calculations indicated a reservoir temperature of 220°C in the Bora area. Thus, isosurfaces were created for the temperatures. To aid the drawing of the polylines, three vertical isothermal cross sections were added to the Leapfrog environment as subsurface controls. Interpolations are drawn to look as natural as possible by taking the following factors into consideration to model the structurally controlled field of Bora:

1. The presence of conductive (<15 ohm.m) and sub-resistive (20-100 ohm.m) layers in the MT model as indications of clay cap/impermeable layer and possible reservoir zone, respectively (Zarkasy, et al., n.d.). Highly resistive layers (>100 ohm.m), like the one found between the Mantikole and Bora Hot Springs, are drawn as possible barriers of the Pulu and Bora reservoir.

2. Permeable structures and structural damage zones facilitate convective heat flow and cause locally elevated isothermal pattern. The fluid movement and high temperature tend to be constrained to a narrow zone of high permeability. The subsurface temperature will drop significantly outside of this zone unless a permeable lithological layer is available nearby to support a fault leakage mechanism (Wisian, 2000; Moeck, 2014). The main Palu-Koro fault is known to be a conduit for the majority of thermal manifestations, thus heat flow along the fault zone forms steep, vertical patterns. However, the roles of other faults not related to thermal manifestations are very unclear. As they cannot be clearly categorized into conduits or barriers, the isothermal model does not currently recognize these faults as controls to the heat flow.

Figure 12 displays the generated isothermal model alongside the manifestation points below the Bora and Mantikole Hot Springs area. The isothermal pattern shows shallow elevated temperatures reaching 150°C in the upflow zone under Bora Hot Spring at approximately 600-1000 m depth. Temperatures drop in the middle of the Palu Graben following higher values of resistivity, which is interpreted as a possible impermeable barrier zone, before becoming slightly elevated once again under the Mantikole Hot Spring and associated fault strand.

Moving further south, **Figure 14** shows a gradual deepening of the high temperature isotherm under the Lompio Hot Spring. Temperature is predicted to continue to drop gradually following the absence of high temperature manifestations and relatively more resistive MT values towards the southern part of the prospect. In **Figure 15**, the isothermal model is overlayed with the geological model and sliced along the upflow zone. As seen on the model, the reservoir temperature of 150-220 °C expected of the Bora reservoir might actually extend towards Phyllite-Slate unit. Heated hydrothermal fluids might also leak to the nearby more permeable Quaternary deposits of Collovium or groundwater aquifers. However, a fault leakage mechanism cannot be confirmed for certain with a lack of field data regarding the permeability of the units.

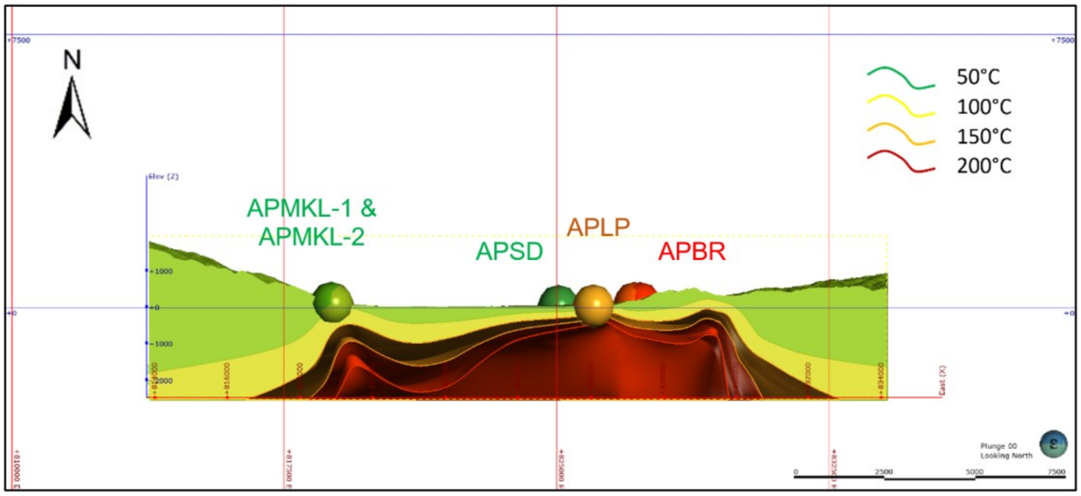

Figure 13: Slice of 3D isothermal model farther south beneath Bora and Mantikole Hot Springs

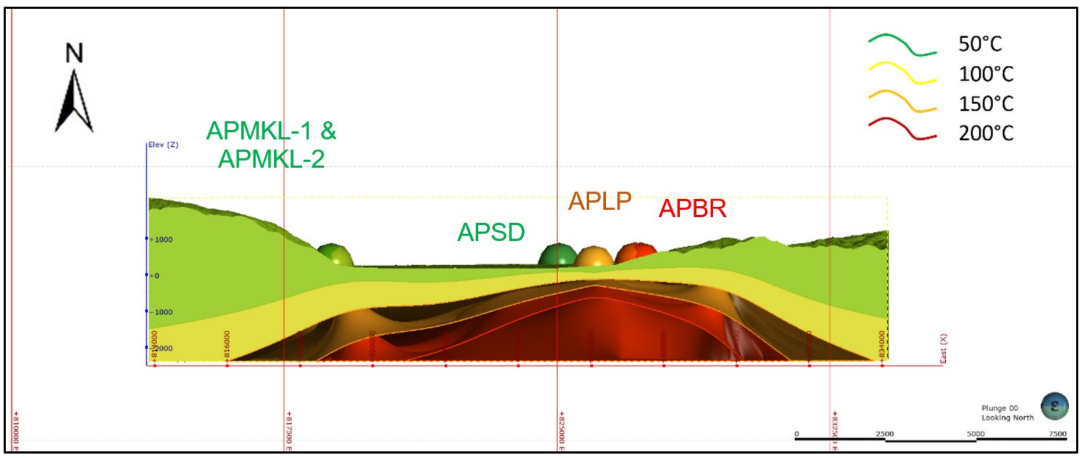

Figure 14: Slice of 3D isothermal model farther south beneath Lompio Hot Spring

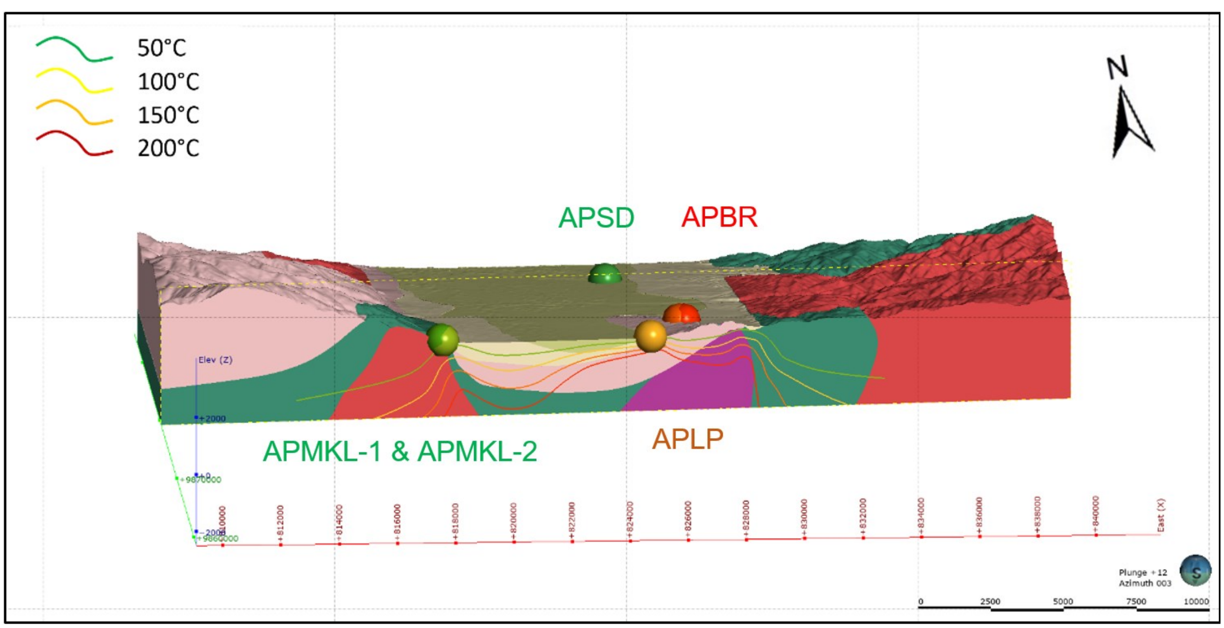

Figure 15: Slice of 3D isothermal and geological model in Bora

4. UPDATES TO THE CONCEPTUAL MODEL

- The new conceptual model has projected the isothermal line according to the interpreted shape of the reservoir. As is common in fault-hosted systems, the reservoir geometry most likely resembles compartments along the Palu-Koro fault zone separated by low permeability barrier rather than a continuous shape typically found in conventional geothermal systems.

- This is also supported by the geochemical plotting, which shows no clear groupings between the manifestations in the Bora and Pulu area. Three upflows had been identified, namely under Bora Hot Spring, Kabuliburo-Mapane Hot Springs, and Pulu 1-Pulu 2 Hot Springs. The Bora manifestation most likely flows out towards the Sidera and Lompio Hot Springs. The Kabuliburo, Mapane, Simoro, Walatana Hot Springs most likely originate from the same compartment, while the Pulu 1-Pulu 2 Hot Springs flows to Limba, Mantikole 1, and Mantikole 2 Hot Springs.

- Updoming of temperature is restricted to the immediate vicinity of the fault zone, particularly in areas of high thermal manifestations. The inferred upflow zone is along the main Palu Koro fault, where temperatures are generally elevated, while minor faults which shows no clear associations to permeability is assumed to be less significant to the convective heat flow pattern. In addition, the outflow zone consists of manifestations with moderate temperature, possibly formed due to shallow lateral flow through permeable layers of colluvium and alluvium or indirect heating mechanism.

- The system most likely terminates northward of the Sidera manifestation, since no other manifestation can be found further north. Meanwhile, the Bora reservoir most likely is bound by the resistive body in the middle of the Palu Graben area in the west and a few kilometers from the Palu-Koro eastern strand depending on the extent of the damage zone. In the south, no conclusive boundary can be defined yet between the Bora and Pulu reservoir. However, the impermeable layer separating the Mantikole manifestation from the other Bora manifestations is predicted to extend further south, separating the Pulu 1, Pulu 2, Limba, Mantikole 1, Mantikole 2 compartment.

- While the previous conceptual model cites the reservoir to be hosted by mostly schist lithology, integrated visualization of the 3D geological model, MT model, and isothermal model might indicate that the sedimentary originated phyllite-slate unit might be the dominant lithology in the reservoir (**Figure 16**).

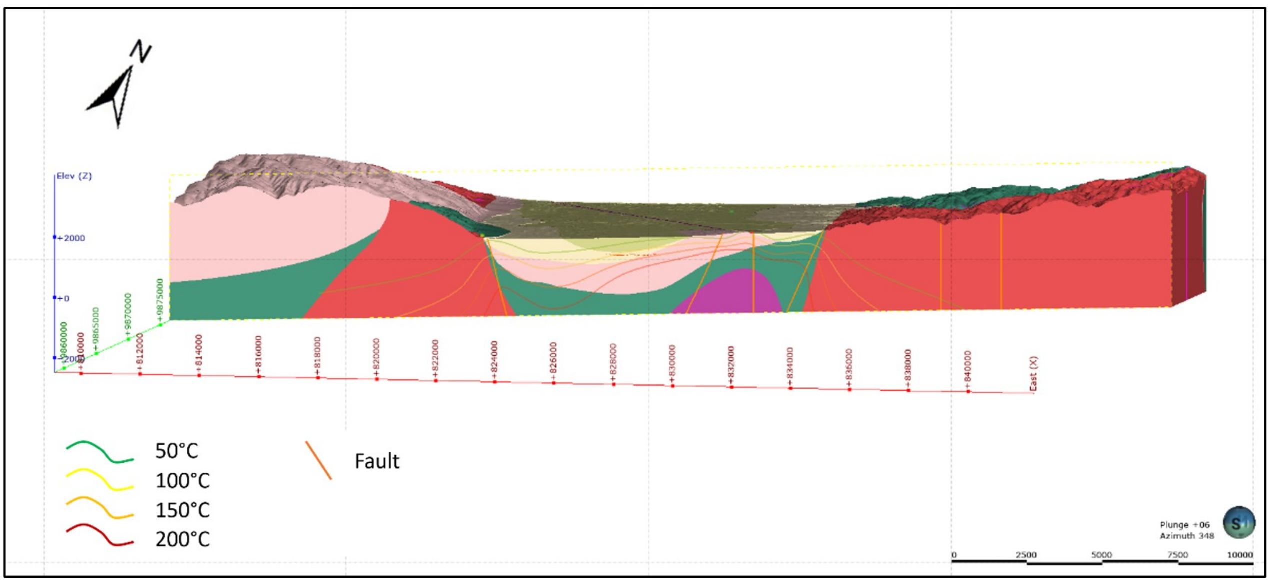

Figure 16: Integrated view of 3D stratigraphy, structural, and isothermal model

To conclude, a 3D geological, MT, and isothermal model had been generated for the field of Bora Pulu in its detailed exploration phase using Leapfrog Geothermal. Though many uncertainties remain in the model in terms of data resolutions and current lack of subsurface measurements, it has proven to be a useful tool to aid visualization and interpretation for this fault controlled field. The model can be updated to accommodate as more data is collected in the future.

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