3D Modelling using 2D data of Sokoria Geothermal Field, Ende, Flores, Indonesia

Triwening Larasati[1], Jessica Ivana[1], Prasellia Djie Novila[2], Ferdino R Fadhillah[1], Muhammad Ghassan Jazmi Shalihin[1], Vicky Rai Chandra[2], and Clare Baxter[3]

[1]PT Geoenergi Solusi Indonesia, Cibis Nine Building 11th Floor, Jakarta Selatan 12560, Indonesia

[2] PT Enerka Bhumi Pratama, Cibis Nine Building 11th Floor, Jakarta Selatan 12560, Indonesia

[3]Seequent Limited, Christchurch 8011, New Zealand

larasatitriwening@gmail.com

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ABSTRACT

The Sokoria geothermal system is volcano-hosted and its reservoir is liquid-dominated. The thermal manifestations are distributed on the flank of the Kelimutu volcano characterized by acidic lakes, fumaroles, and hot springs. Several 3G studies and surveys have been conducted in this geothermal area, including five deep wells drilling.

Geoscientific data (geology, geochemistry, geophysics) in the geothermal resource development needs an integrated interpretation of the geoscience data sets that may not be sufficiently understood using only two-dimensional (2D) models, thus three-dimensional (3D) models have been increasingly used to solve this issue. One of the tools used to generate a 3D model is the Leapfrog Geothermal software. Leapfrog Geothermal is specifically designed for the geothermal industry and also provides for the integration of geothermal datasets.

This study aims to create a 3D conceptual model to visualize the geological and geothermal systems of the field and to better understand the nature of the geothermal framework in Sokoria. In this study, secondary data such as geological, geophysical, geochemistry, well data, and raster data from open-sourced platforms were utilized, with additional analysis applied to better characterize the outcome of the model. Despite the lack of subsurface data available to be freely accessed, application of the modelling method is fruitful and hopefully could be utilized for any future consideration in developing the field.

1. INTRODUCTION

The Sokoria geothermal field is a liquid-dominated field located in Ende regency, East Nusa Tenggara Province. Several studies and surveys had been conducted to identify geothermal resources in this area, including integrated geology, geochemistry, and geophysics studies. Also gradient holes (SK-1 and SK-2), a slim hole (SR-1), five wells (both standard and big holes) in well Pad-A, and well Pad-C have been drilled (Boegis et al., 2005; Munandar et al., 2007; Sarmiento et al., 2019; Hinz et al., 2021; Siagian et al., 2022). FEDCO in Hinz et al. (2021) suggests that the field consists of two sectors, namely Mutubusa and Kelimutu. The former is associated with the older volcanism in the southwestern side characterized by the Mutubusa fumarole and more neutral fluid, and the latter is associated with acid core of active volcanism in the northeastern side. Lowongopolo fault, as a major structure with NE-SW trends, was interpred as a boundary of both reservoirs. Currently, the exploration and development activity is focusing on the Mutubusa sector (Hinz et al., 2021).

Several two-dimensional (2D) models have been generated from previous studies. In order to gain more perspective on the surface and subsurface conditions, a three-dimensional (3D) model that visualizes the whole geometry of the geological and geothermal system of the field is required. Leapfrog Geothermal software is used to visualize the stratigraphy, geological structure, magnetotelluric (MT), and temperatures of Sokoria geothermal field. The model was built using secondary data from open-sourced platform.

2. METHOD AND DATA

2.1 Method

Leapfrog Geothermal is a 3D modelling and visualization software developed by ARANZ Geo in cooperation with GNS Science (Alcaraz et al., 2011). As of today, Leapfrog Geothermal is owned by Seequent. This software has an integrated interface that provides several tools to address specific geothermal industry needs, from general geological modelling to advanced numerical modelling.

3D modelling is used since it is better for interpreting and visualizing the subsurface condition compared to the traditional 2D model. The data can also be interpolated and extrapolated in all directions to better visualize geothermal features. Fast and continuous interpolation is used in Leapfrog Geothermal to cover all data points in the model (Alcaraz et al., 2015). In this paper, the 3D geological model, MT model, and temperature model were built with the integration of geological, geophysical, geochemical, and borehole data. Interpolation is obviously used in the model and extrapolation is used to accommodate the larger extent of the models.

2.2 Data Availability

The data used for this modelling are derived from open-source databases, such as papers/journals, maps, and/or GIS data. Figure 1 shows the list of data used for the model creation.

2.2.1 Geological data

The knowledge of surface geology of the Sokoria field is obtained based on remote sensing analyses and the results of several previous studies to build a geological map for the modelling purposes of this study (Figure 3). Several cross sections were later created to reconstruct the subsurface geological conditions in the research area (Figure 4). The geological information was obtained from:

- DEM and satellite imagery analyses to better understand the surface geologic condition, also to infer lineaments that could associate with geological structures other than the Lowongopolo fault;

- Geological maps of PLN (1995) in Boegis et al. (2005) and Sarmiento et al. (2019) are used to identify lithologic units in Mutubusa;
- Regional geological map of Ende (Suwarna et al., 1989) are used to determine the larger extent of the lithologic distribution;
- Well stratigraphy from well Pad-A borehole data in Sarmiento et al. (2019).

Geological Model	MT Model	Isothermal Model
Surface Geology Geological map[1,2,4] Lineament map[1,2,4]	Cross Section MT vertical section[4] MT horizontal section[4]	Borehole Data Profile PT shut-in[4,5]
Remote Sensing Data DEM[6] BATNAS[6]		Geochemical Data Manifestation temperature[3]
Cross Section 2D geological section		
Borehole Data Lithology and rock formation profile[2,4,5]		

1) Suwarna et al., 1989)
2) PLN (1995) in Boegis et al. (2005)
3) Harvey et al. (1998)
4) Sarmiento et al. (2019)
5) Hinz et al. (2021)
6) Geospatial Information Agency (BIG)

Figure 1: List of used data for 3D geological, MT and temperature models.

2.2.2 Geochemical data

The geochemical data is taken from Harvey et al. (1998). It consists of the distribution of 18 surface manifestations (Figure 3), fluid type, and temperature. The surface manifestations consist of an acidic lake, fumaroles, and thermal springs, varying from acidic to chloride and sulphate waters. The fluid type is used to interpret the flow pattern and temperature data are used to build a temperature model as a control on the isosurfaces.

2.2.3 Geophysical data

Magnetotelluric (MT) data are collected from MT-3D inversion model vertical and horizontal cross sections (750 masl) in Sarmiento et al. (2019). The data was digitized and imported into Leapfrog Geothermal software to create isosurfaces of contact value as a constituent of 3D MT model construction. Additionally, gravity data obtained from Hinz et al. (2021) was used as a basis of interpretation, though the data was not modelled on itself.

2.2.4 Borehole data

The borehole data used in this study consist of the location of the well, lithology and formation, clay alteration, epidote occurrence, pressure, temperature, and feedzones. The data are taken from five wells trajectory coming from well Pad-A. Well trajectory was plotted using the azimuth and depth data, while the remaining well data were digitized from Sarmiento et al. (2019) and Hinz et al. (2021) as csv points or intervals.

2.3 Modelling Workflow

The workflow is shown in Figure 2. All data from Section 2.2 Data Availability is entered into Leapfrog Geothermal to build three different but integrated 3D model.

3. RESULT AND DISCUSSION

3.1 3D Geological Model

The extent of the geological model was set to 17 km x 17 km with a minimum elevation of -1500 masl. The surface topography was created using the Digital Elevation Model National (DEMNAS) with 8 m spatial resolution. Since the southern part of the area borders with the Sawu Sea, Bathymetry National (BATNAS) with a surface resolution of 6 arc-second (approx. 180 m) was also used to model the sea floor. Once the base geometry of the model was set, all geological units were input into the lithologies section of the project tree.

2D models and profiles were then added to the Leapfrog Geothermal project tree and used to build the geometries of the geological units in three-dimensional. In total, five cross sections were utilized to define the subsurface geological conditions of the Sokoria field. GIS lines were used to bind the model with the surface topography, while bottom contact polylines were drawn manually for each cross section to define the subsurface contact. The generation of the lithologic model generally was done sequentially from the youngest to the oldest.

In general, the subsurface lithology in the Sokoria is composed of various volcanic products (e.g., lava flow, undifferentiated volcanic units, pyroclastic, and lahar) overlaid by a recent alluvium deposit. Each lithology is modelled differently from the other. Lava flows and undifferentiated volcanic units were modelled as curved geometries that penetrate through older formations using the intrusion surface type. Meanwhile, the erosion surface type was deemed most effective in mimicking the lateral distribution and cross-cutting of older lithologies for modelling pyroclastic, lahars, and alluvium units. The sea is later defined using intrusion surface type as the youngest unit. Once the surface chronology had been clearly defined, the output volume of each unit was generated. The chronological order of the stratigraphy can be seen in Figure 5.

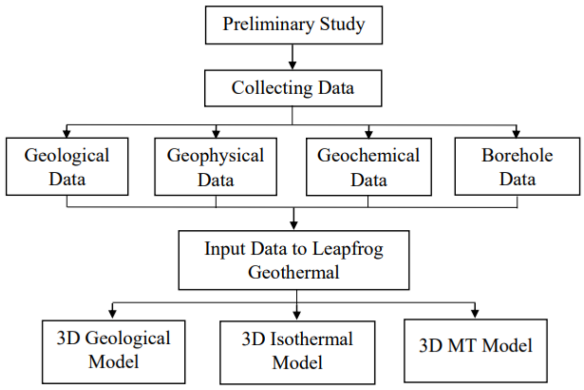

Figure 2: Workflow chart of the modelling.

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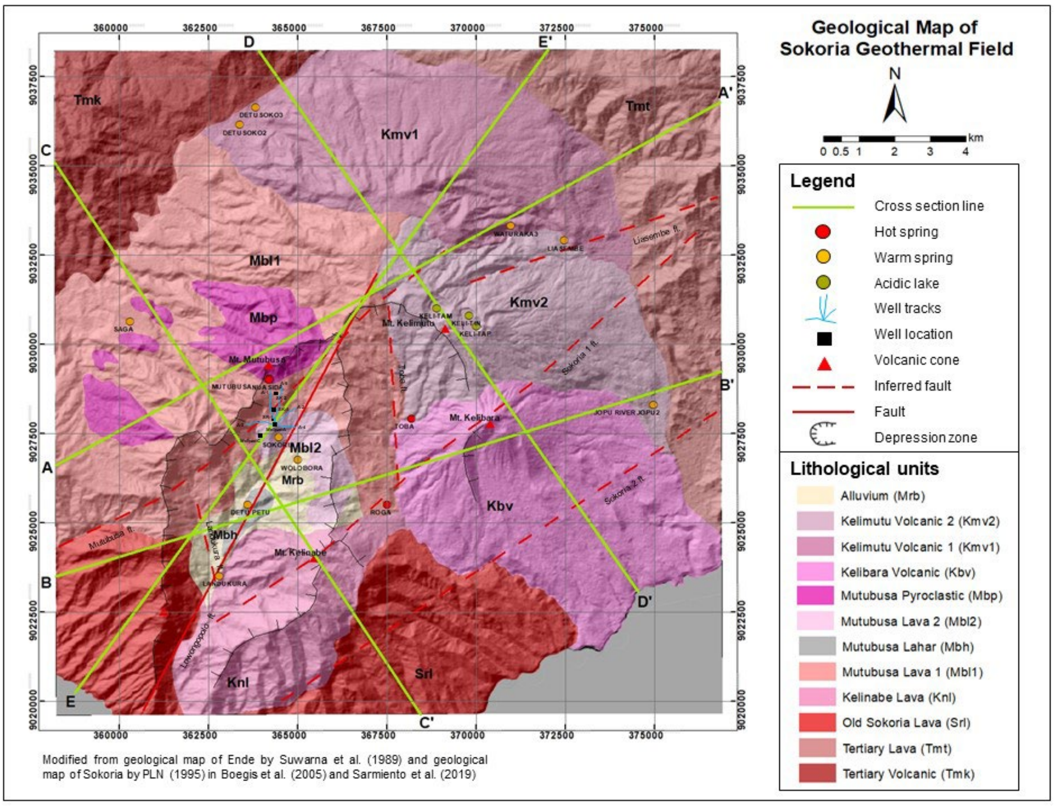

Figure 3: Modified geological map and manifestation distribution of Sokoria geothermal field from Suwarna et al., (1989), PLN (1995) in Boegis et al. (2005), and Sarmiento et al (2019).

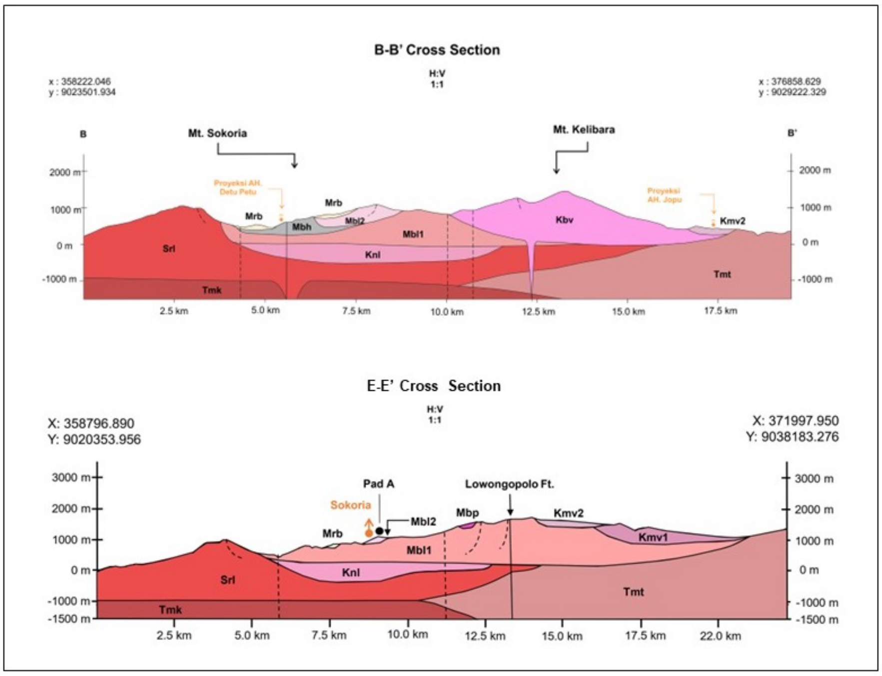

Figure 4: Example of stratigraphical cross sections used for geological model construction.

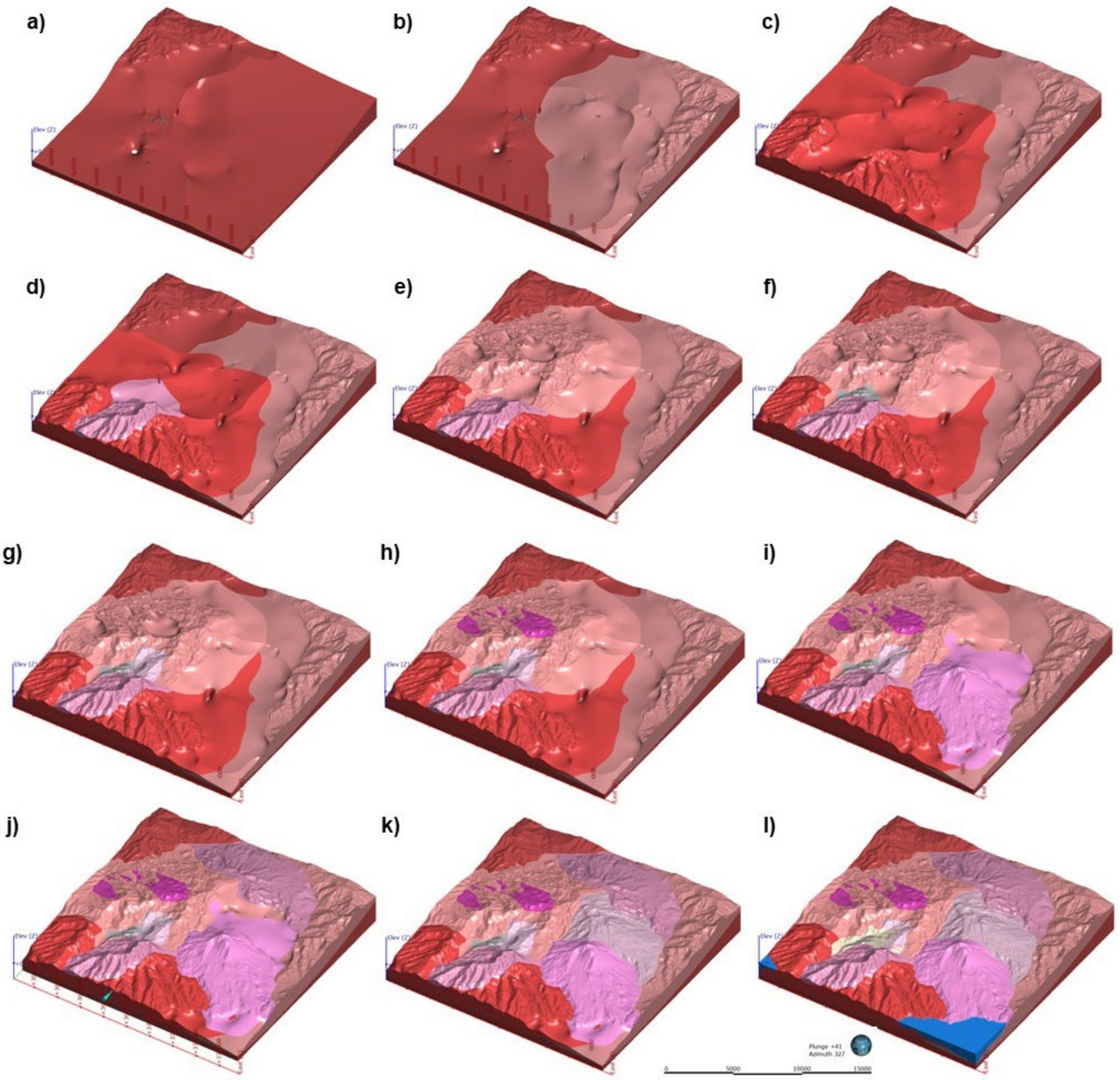

Figure 5: Stratigraphic model of Sokoria field from geological map and cross sections. Older to younger lithological units order can be seen from a) to l) in chronological order. Blue colored unit shows Sawu sea.

The structural model of Sokoria was developed based on the combined interpreted structural lineaments from DEM analysis and the available geological map. The lineaments were delineated as GIS lines in Leapfrog and act as a reference for the structural orientation to build 3D structural framework. The preliminary framework displays the structure as the wall plane with extension along the 3D model area. In addition, the structural disc features enable the framework to display the structural dip. This feature is also able to provide various dip angle fault condition (e.g., listric fault). Leapfrog Geothermal also allows the modeller to determine the cross-cutting relationship of the faults based on the fault chronology to generate a proper 3D structural framework.

The structural framework of Sokoria shows six possible faults and one confirmed fault with main orientation of NE-SW. All lineaments were identified from remote sensing analysis, except Lowongopolo fault in which the presence has already been confirmed by ground truthing as it was visible by the topography of the valley which later supported by the MT data (see section 3.2 3D MT Model) and the presence of minor feedzones in one of the well in wellpad-C which also have a conductive temperature gradient (Siagian et al., 2022). Unfortunately, the wellpad-C data is not open for public. No ground truthing result mentioned in open-sourced documents for the kinematic of Lowongopolo fault. All of these faults are only displayed as wall planes since the dip angle and azimuth data are not publicly available, and thus a vertical dip was used. The cross-cutting relationship shown by the fault scrapes in DEM analysis indicates that the Lowongpolo fault is the main fault, with a NE-SW orientation, and other faults terminate against the Lowongpolo fauls. Figure 6 shows the 3D structural framework of Sokoria.

The geological model adequately represents all surface and subsurface condition of the field. As indicated by the drilling results, variations can still be found for the larger lithological units. The geological model has not taken mineral alterations into consideration. Furthermore, detailed kinematic analysis of the faults had not been done as no field evidence and direct structural measurements are available, possibly buried by the younger formation as it happens in the western side of Lowongopolo fault confirmed by the drilling results. The permeability condition of the fault zones is mostly unknown.

The available well data and analysis only indicating the tight or less permeable condition of Lowongopolo fault and the presence of more permeable condition in the western side of the fault as it was interpreted as damage zone (Siagian et al., 2022). The other faults outside of Mutubusa area could also exists in the same condition. Several structures in the geological model i.e., Toba fault, Liasembe fault, and Sokoria 1 fault could probably serve as permeability zone for the nearby manifestations. The interconnection needs to be assessed in order to get a bigger picture of how the system works in this area. Thus, further survey and analysis especially ground truthing is needed to clarify the structure. Despite the data limitations, particularly its low subsurface lateral resolution, this geological model should still be a useful tool when updating the conceptual model, conducting well prognosis, well targeting, and other activities.

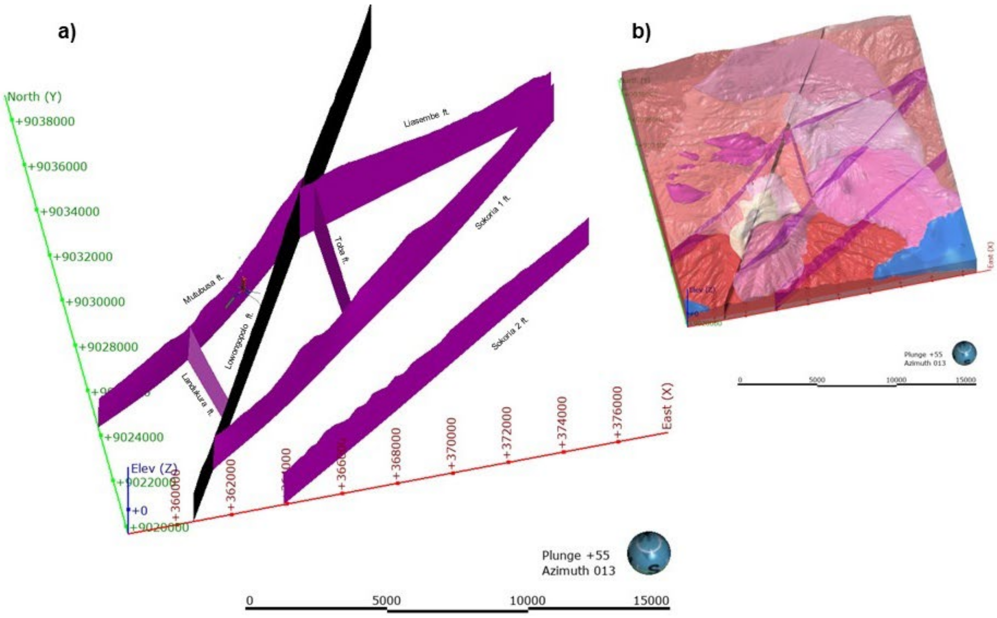

Figure 6: Modelled structural framework of Sokoria field. A) shows the illustrated fault and the cross cutting relationship. Structural framework visualized with lithology can be seen in b).

3.2 3D MT Model

The MT model coverage concentrates on the Mutubusa sector with an area of about 5.5 km x 5.5 km and minimum elevation at -1600 masl. Its extent is smaller than the geological model due to the limitation of the data coverage and to avoid excessive extrapolation that would result in higher model uncertainty. The MT model was developed by digitizing the MT values from vertical cross section in Sarmiento et al. (2019) to obtain X, Y, Z, and resistivity values in CSV format. The input was processed using RBF interpolant into a numerical model. Additional isosurface polylines of resistivity values were contoured from vertical and horizontal cross sections to provide a better resistivity distribution.

The MT model of Sokoria on 750 masl shows a conductive layer distribution on the NW and SE part separated by NE-SW resistivity gaps in between. This conductive body discontinuity correlates well with the NE-SW trending Lowongpolo fault which is expected to act as a boundary. Figure 7a shows the comparison between the slice at 750 masl and the 3D model, while Figure 7b shows the comparison between an MT cross section and the 3D MT model result from the Leapfrog Geothermal. Even though the comparison shows similar result for both the section and the 3D model, this model does not really represent the resistivity profile far from the section locations due to the extrapolation process. Additional cross sections or MT data should aid the clarification of the model in the future. However, the current digitized MT model should give better representation to the geometry and insights to the system when overlayed with the 3D geological model and isothermal model.

3.3 3D Temperature Model

The temperature model was built using temperature data of T-shut in from well Pad-A in Mutubusa area. The data were incorporated as temperature profiles in the well data section. The temperature of manifestations in Mutubusa sector and Kelimutu sector, derived from Harvey et al. (1998), were also used and were incorporated in the points section.

Although the existing well data are only from one wellpad in Mutubusa, the temperature model was extended to the Kelimutu area to accommodate both systems. Thus, the isothermal profile on Hinz et al. (2021) was digitized and modified to accommodate well data and interpretation of possible barrier to build the temperature model. Since there were not adequate data in the Kelimutu area, the uncertainty remains very high, and the model displayed is only aimed to illustrate what could possibly exist in the subsurface, with consideration of the active volcano activity within the area.

Based on the integration of the well data and surface manifestations data, we were able to develop the temperature model as shown in Figure 8. The latest shut-in measurements were the most considered well data since they could be the real conditions of the reservoir. Temperatures of the manifestations were used as reference for the near-surface temperature model. In addition, isosurface polylines were created to better to align with the modeller's interpretation of the system.

An updoming feature exists beneath Mutubusa fumarole as indicated by the existence of a near 100°C fumarole and hot spring manifestations at the surface. It was also supported by the existence of near 250°C temperatures at depth based on well temperature data around 500 m away from the Mutubusa fumarole. The updoming feature also exists beneath Kelimutu lake considering the active status of the volcano. The isothermal profile draws down with a steep gradient along the Lowongopolo fault since the fault is considered as the boundary of the Mutubusa sector and Kelimutu sector. The 200°C isotherm shows matching patterns with the bottom of the conductive layer defined in Hinz et al. (2021) in association with Mutubusa Lava 1.

The temperature model is assumed to be valid because it uses data coming directly from the wells. For the larger extent, the model is controlled by the extrapolation methodology available in the Leapfrog software and the modeller's interpretation about the geological and geothermal system of the Sokoria field. Hence the model still has high uncertainty. The model, however, could serve as a visual guide of the temperature distribution of Sokoria geothermal system and can be further used for development studies, such as drilling campaign well targeting or any other.

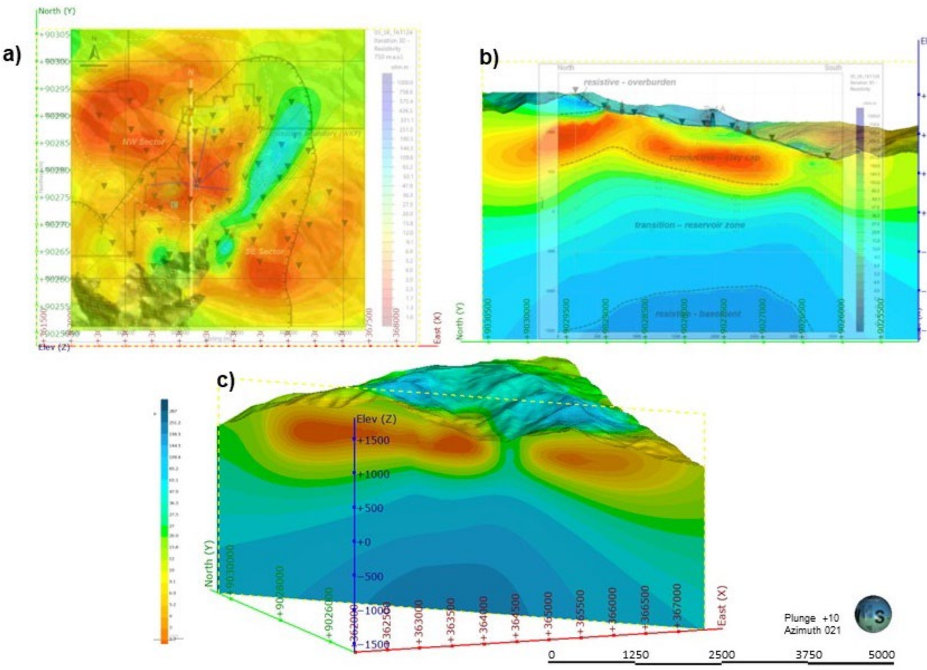

Figure 7: MT model developed from depth slice 750 masl and vertical cross sections. Both a) and b) shows matching visualization between the sections and the model. NW-SE sliced model seen in c) also displays high degree of similarity with the sections.

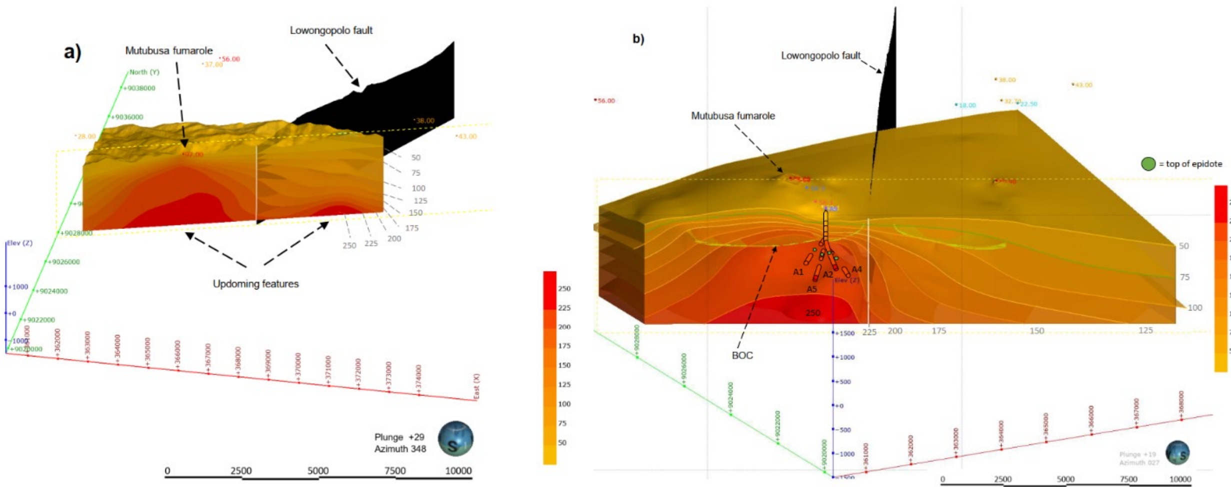

Figure 8: Isothermal model result of the Sokoria field. Updoming feature in Mutubusa area and Kelimutu area can be seen in a) together with dropping profile along Lowongopolo fault. BOC in line with 200°C temperature while borehole temperatures align with each isothermal line as seen in b).

4. CONCLUSION

3D geology, MT, and temperature models of Sokoria geothermal field from combined surface data and limited well data were successfully made to improve on the lack of visualization from the 2D model. The modelling method is proven to be applicable even when the available data are not abundant and when it mostly comes from surface data. The current 3D models use a lot of extrapolation to compensate for the limited data available for public access and the making of this paper, consequently causing high uncertainty in the model. The 3D model, however, could be refined with the increased availability of data in the future. For the current state, these models could be beneficial in preliminary analysis of the field until more data becomes available for updating the current conceptual models.

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