LEAPFROG 3D TEMPERATURE DISTRIBUTION BASED ON TOUGH2 NUMERICAL MODELLING: A NEW APPROACH

Marchel Christian Supijo[1], Heru Berian Pratama[1] and Sutopo[1]

[1]Geothermal Master Program, Institute Technology of Bandung, Jln. Ganesha No.6, Bandung 40132, Indonesia

marchelbinsus@gmail.com

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ABSTRACT

Atadei geothermal prospect area is located in Lembata Regency, East Nusa Tenggara, Indonesia. The estimated reservoir temperature based on ammonia geothermometer is about 221^{o}C, with the upflow zone in three separate locations, namely: Watuwawer, Lewo Kebingin, and Lewokeba. The earlier exploration stage produced minimal subsurface data. Nevertheless, an interpretation of subsurface conditions and the lateral extent of the geothermal area was developed by previous researchers. This includes an interpretation of reservoir geometry; the fluid contained (i.e., steam caps formation), fluids flow pattern, and some structural geology that may control permeability and reservoir depth. Based on these published data, we have created a TOUGH2 numerical model of Atadei geothermal field to add substantial information regarding the reservoir characterization and to avoid inaccurate interpretation during the early exploration stage. This paper aims to explore a new approach regarding integration between TOUGH2 and Leapfrog Geothermal. Reservoir simulation results using TOUGH2 numerical modeling are then integrated into the Leapfrog Geothermal in order to get a more robust 3D model of the temperature distribution of the Atadei geothermal field.

1. INTRODUCTION

Nowadays, it is necessary to build a 3D model of geothermal systems in order to make a reliable interpretation of the subsurface condition. Models that can be used to explain and predict the behavior of geothermal systems have become essential tools in the geothermal industry. The two most commonly used models are a conceptual model and reservoir numerical model using TOUGH2 (Popineau et al., 2018).

The TOUGH2 simulator is commonly used in modelling geothermal reservoirs, as well as other subsurface fluid and heat flow problems (Croucher, 2015). Geothermal reservoir simulation is used to test the conceptual models of systems, investigate system sensitivity, and predict the system response to production scenarios (Newson et al., 2012).

Another 3D modeling interface that has been well acknowledged in the geothermal industry is Leapfrog Geothermal. Different from TOUGH2, Leapfrog Geothermal model is a static conditions model, which means the model cannot be used for forecasts like a dynamic model based on TOUGH2. However, TOUGH2 model can be integrated into Leapfrog Geothermal to interpret the temperature distribution and fluid conditions in the reservoir and combined with the geological model that has already been built in Leapfrog Geothermal. The current approach of integrating the TOUGH2 model into Leapfrog Geothermal, using PyTOUGH, was implemented by Newson et al. in 2012 and Popineau et al. in 2018. PyTOUGH has the flexibility to process variants of models for TOUGH2; however, it still requires familiarity with object-oriented programming and the Python syntax (Newson et al., 2012). This workflow seems quite complex initially as the modeler needs to understand Python syntax first.

This study aimed to propose a new approach for the integration of a TOUGH2 model created outside of Leapfrog into Leapfrog Geothermal. This approach seems more efficient compared with PyTOUGH approach from the perspective of the authors. Based on this point of view, the author tried to 'adapt and improvise' to the resources, one of which is the graphical user interface for the TOUGH2 and Leapfrog Geothermal. After that, the authors tried to 'overcome' in order to create a more robust interpretation. The case study for this research is the Atadei geothermal field which is located in East Nusa Tenggara, Indonesia. Figure 1 shows the workflow in this study.

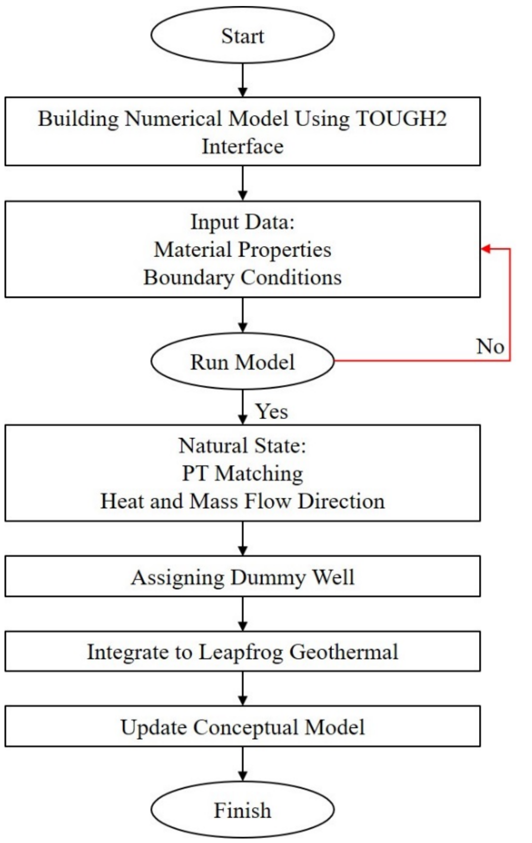

Figure 1: Workflow for a new approach in integrating the TOUGH2 model into Leapfrog Geothermal.

2. CASE STUDY: ATADEI GEOTHERMAL FIELD

Atadei geothermal field is located in Lembata Regency, East Nusa Tenggara, Indonesia. The location of Atadei geothermal field is shown in Figure 2. To reach Atadei from

Jakarta takes around two days, and this is counted as one of the challenges to be faced in developing this field. PT. PLN (a state-owned company), since April 2017 has been the concession owner of this field based on SK-permits No. 1894 K/30/MEM/2017.

Figure 2: The location of Atadei Geothermal field (Supijo et al., 2018).

2.1 Geology Review

During May 2000, explorations that covered around 100 km^2 in the vicinity of Atadei geothermal field produced a geological map that represents the study area, as shown in Figure 3.

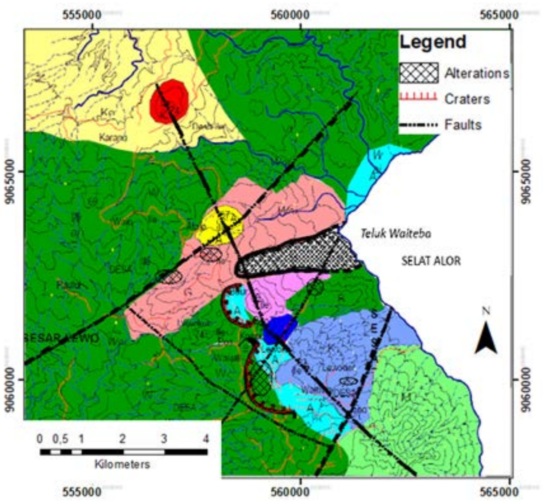

Figure 3: Geological Map of Atadei (after-PSDMBP, 2017)

Based on volcano-stratigraphy, in general, the volcanic products and deposits in Atadei area are divided into two groups. The old volcanics outcrop in the northern and southwest part of the study area, while the young volcanic products are found in the eastern part of the study area. Aswin *et al*. (2001), mentioned the cones of young volcanoes were formed along the main lineament whose direction is almost N-S. The cones consist mostly of andesite pyroxene lava, and pyroclastic (flow and fall) with two NE-SW (Lewo Kebingin and Mauraja) faults controlling the geothermal surface manifestations in this study area.

2.2 Geochemistry Review

According to the previous geochemistry survey and analysis conducted by Nanlohy, Kusnadi, and Sundhoro (2003), most of surface thermal features are found in the vicinity of the three SW-NE main faults in Atadei geothermal prospect. Those main faults are: (i) Watuwawer Fault which controls the typical upflow features such as fumaroles and acid hot springs in Watuwawer and Lewokeba, (ii) Lewo Kebingin Fault which rules the typical mixture manifestations where fumaroles, acid sulfate and bicarbonate springs were found in close proximity to the Lewo Kebingin, Wae Mata, and (iii) Wae Kowan Mauraja Fault solely controlling the outflow type of manifestation (bicarbonate waters or dilute chloride-bicarbonate water) in Wai Keti and Wai Tupat. The ternary plot of water types “Cl-SO_4-HCO3” and ternary plot of ion alkali geothermometer “Na-K-Mg” proposed by Giggenbach (1988) are shown in Figure 4 and Figure 5.

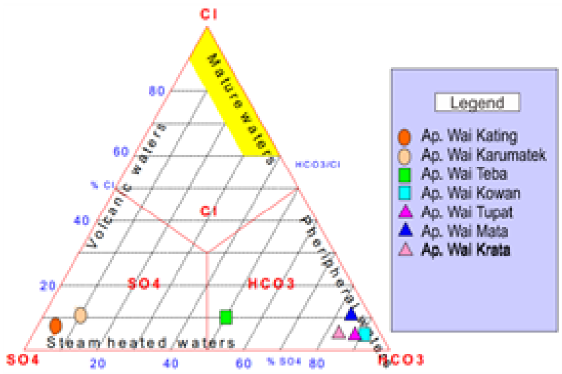

Figure 4: The ternary plot of water types “Cl-SO4-HCO3” (Nanlohy et al., 2003)

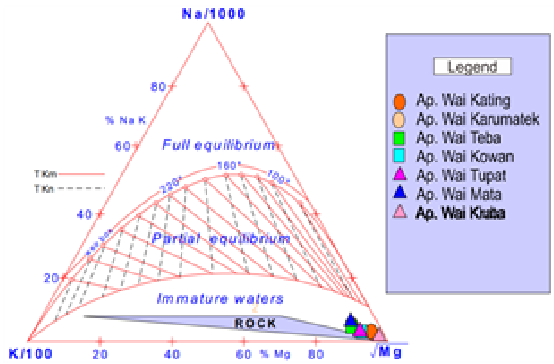

Figure 5: The ternary plot of ion alkali geothermometer “Na-K-Mg” (Nanlohy et al., 2003).

Since there are no springs classified as being in partial equilibrium this means the geothermometer “Na-K-Mg” is not applicable. Thus, the reservoir temperature is estimated using geothermal-gases. Based on an ammonia geothermometer calculation, the reservoir temperature is 221°C.

2.3 Geophysics Review

The magnetotelluric survey has notably indicated a low resistivity layer beneath the Watuwawer manifestation at a near-surface depth of about 200 meters, and it extends to the greater depth of around 400 meters to the East and the West of Atadei geothermal prospect area. At below 1400 m depth or -800 masl, a contrast of higher resistivity occurs and thickens which is later suggested to be a reservoir rock. The exception applies for Watuwawer doming which is shown by the contrast resistivity at a relatively shallow depth around

1200 m depth or around -700 masl. This is consistent with the estimated depth of the top of the reservoir obtained using the method proposed by Saputra et,.al (2016) in the earlier exploration stage. Therefore, the authors have confidence in setting the depth of the top of the reservoir at 1400 m depth and 1200 m depth only for doming/upflow area in the numerical model. The result of 3D MT inversion by PSDMBP (2017) is shown in Figure 6, which illustrate the NW-SE cross-section of Atadei.

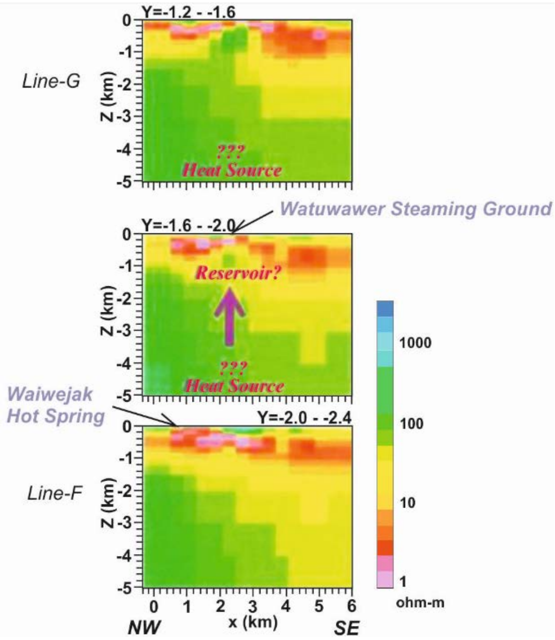

Figure 6: NW-SE cross-section of 3D MT Inversion of Atadei Geothermal Prospect Area

The resistivity data shows that the low resistivity zone beneath the Watu-wawer caldera occurs at a shallower depth than in any others locations. Being consistent with the presence of fumaroles in the Watuwawer caldera, it strongly suggests that small steam cap has developed naturally in that particular area.

The sounding resistivity also indicates the presence of another small dooming of steam caps at Lewo Kebingin and Lewokeba.

2.4 Well Data Review

Two gradient temperature wells, namely: ATD-1 and ATD-2, were drilled to reach a depth of 250 meters. These wells were drilled to get a better understanding of the temperature gradient, especially in the upflow zone, and to delineate the extent of the reservoir at the boundary of the Atadei geothermal field. ATD-1 is situated in the Watuwawer caldera representing the temperature gradient in the upflow area. Meanwhile, ATD-2 is situated in Mauraja, nearly intersecting the Mauraja Fault, thus representing the temperature distribution in the boundary or outflow area (Soetoyo, 2008).

Two years later in 2004, two exploration wells were drilled around the prospect areas of Watuwawer caldera and Bauraja crater, namely AT-1 and AT-2. They were aimed at providing a better understanding of the temperature distribution, particularly in the upflow zone. AT-1 was drilled to the depth of 830.5 m, and AT-2 was drilled to the depth of 750 m.

The result of well testing shows AT-1 had a wellhead pressure of 7 kscg and AT-2 had wellhead pressure of 0 kscg. However, the temperature of both wells at the wellhead is similar to the environment temperature. Thus the pressure measured at AT-1 wellhead does not come from the geothermal fluid. Temperature logging was applied to AT-1 to the depth of 450 m and found that the temperature there was 96.5°C (Sitorus et al., 2005). The temperature profile from AT-1 well is shown in Figure 7.

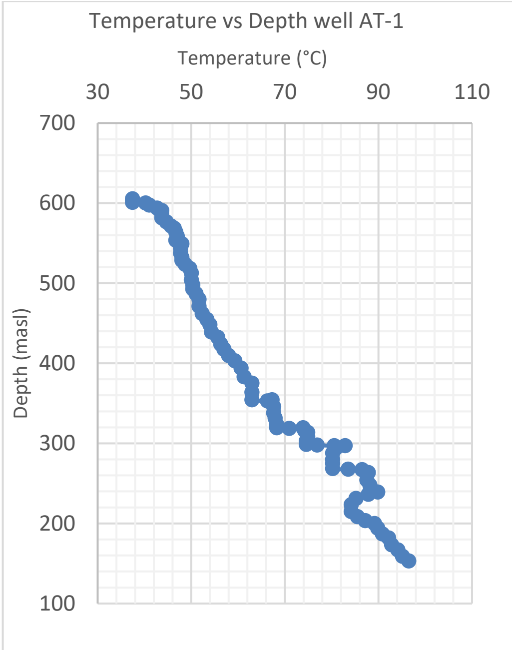

Figure 7: The temperature profile of well AT-1 (Sitorus & Munandar, 2005).

2.5 Atadei Conceptual Model

The conceptual model as updated by (Supijo et al., 2018) is shown in Figure 8. The conceptual model designed was based on comprehensive geoscience reviews and the numerical model approach. It appears that hot geothermal fluid is upwelling from the deep part of the Watuwawer caldera. The deep leakage, through fracture permeability from Watuwawer Fault and Lewo-Kebingin Fault, controls the flow of hot fluids ascending through the given vertical permeability and with some fluids flowing laterally to the Southeast before rising to the surface through the Mauraja Fault as outflow. In contrast to the initial model, there is a change in the estimated depth of the top reservoir, as the updated model has followed the interpretation of Magnetotelluric data rather than DC-Resistivity data which Nanlohy et. al (2003) had followed. In general the top of reservoir of Atadei geothermal area appears to be situated around a depth of -800 masl. The only exception applies for the Watuwawer area iwhere the reservoir reaches a depth of -700 masl.

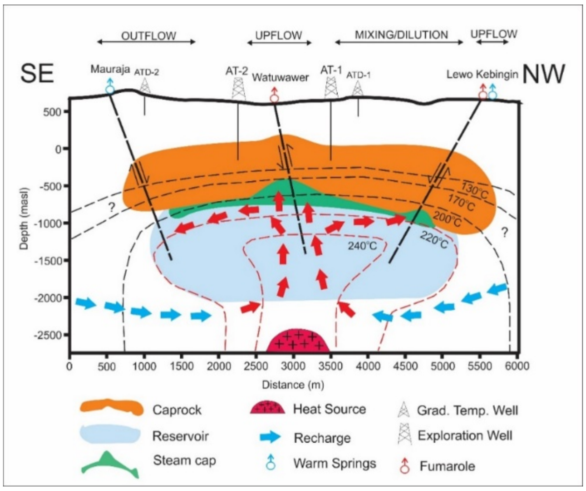

Figure 8: Conceptual model of Atadei geothermal system (Modified from Supijo et al., 2018).

3. ATADEI NUMERICAL MODEL

Based on the conceptual model of Figure 8, a numerical model of the Atadei geothermal system was developed. The modeling process was carried out by using a pre- and post-processor of TOUGH2. The grid of the model is rotated at 127^o to the East to accommodate material assignment aligning with the conceptual model. It covers a total area of 6.4 km x 5 km, or equal to 32 km^2, and has a total thickness of 3.45 km (i.e., from 950 masl to -2500 masl). The horizontal dimension of grid blocks varies from the smallest of 100 m x 100 m to the largest of 500 m x 500 m, and the smallest grid blocks are used near the reservoir area, wells, and faults to increase the modeling accuracy in those areas. The model is divided into 13 layers with some of the top layers following the actual topography. The total number of grid blocks is 22,560, based on a rectangular grid type. The initial conditions needed as input are the initial temperature and pressure for each grid-block in the model. For the initial conditions, the normal gradient is used for both temperature and pressure. Meanwhile, the top layer is set at constant atmospheric conditions with the pressure at 1E+05 Pa and the temperature at 25^{O}C.

Table 1: Material properties

Material	K_{xy} (mD)	K_z (mD)	Color
ATM	10	10	
GW	0.002	0.002	
CAPR	0.00001	0.00001	
BOUND	0.00005	0.00001	
HEAT	100	100	
RES1	60	30	
RES2	40	30	
RES3	20	20	
RES4	10	10	
RES5	70	70	
RESMT	60	30	
FAULT	30	30	
BASE	3	3	
FAUL1	30	20	
TRNS	0.001	0.001	

During the numerical modeling, determining the permeability structure is the essential step. It is iteratively adjusted until the natural state condition are achieved. The iterative process is done by trial and error. The permeability structure used in the final modeling is shown in Table 1 and its distribution to the grid model, also shown in Figure 9. Figure 10 indicates the temperature match for AT-1. It shows a very good match between the actual and the modeled temperature.

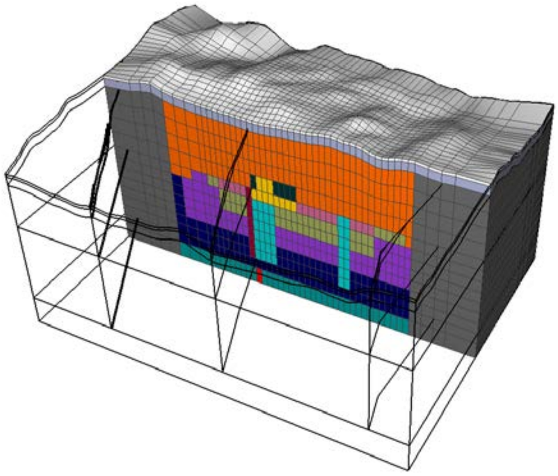

Figure 9: Material assignment to the model

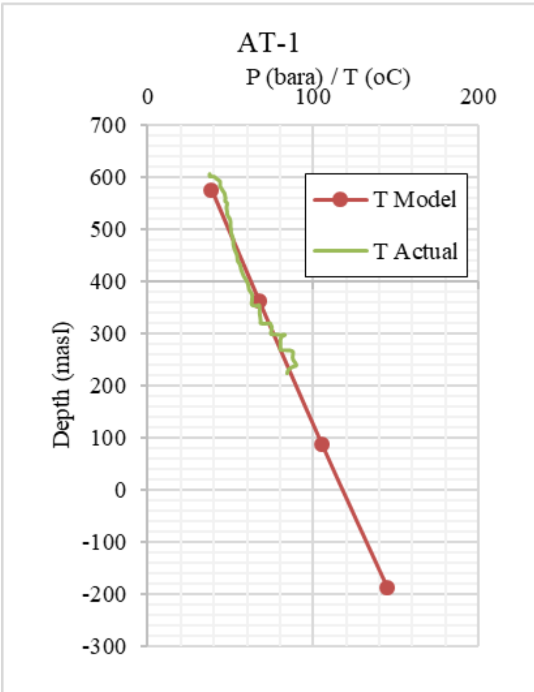

Figure 10: AT-1 temperature matching.

One of the crucial driver outcomes of the reservoir numerical modeling is the simulation of heat and mass flow within the system, as illustrated in Figure 11. It concludes the whole fluid flow process from the upwelling geothermal heat flow beneath the Watuwawer caldera in which the hot fluids ascend directly through the given vertical fracture permeability and later emerge as upflow manifestation in Watuwawer, Lewo Keba and Lewo Kebingin. The residual fluids circulate within permeable zones, as the hot fluid with lighter in density ascends until it reaches the impermeable layers where heat losses occur resulting in some cooler fluids descending back to the reservoir and some fluid flows laterally until it emerges as outflow manifestations at the surface in Mauraja and Lewo Kebingin.

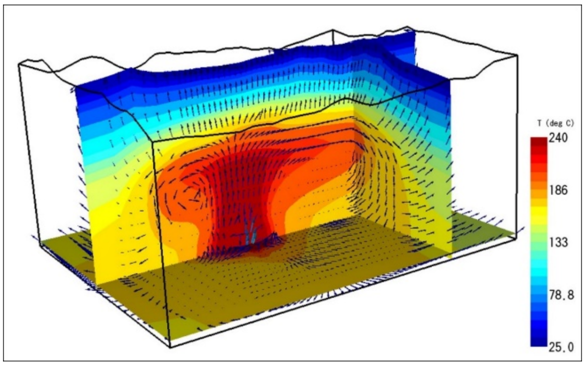

Figure 11: Heat and mass transfer in a vertical and horizontal slice of the numerical model

4. INTEGRATED TOUGH2 MODEL INTO LEAPFROG GEOTHERMAL

Leapfrog Geothermal modeling software has been developed to model and visualizes geothermal systems in three dimensions. The models are based on mathematical interpolation functions, and this provides a grid-free representation of the geological structure and numerical quantities such as temperature and pressure (Newson et al., 2012). In this approach, the initial step in integrating numerical model results into Leapfrog Geothermal is to assign a dummy well in order to obtain the whole temperature distribution for each dummy well. Figure 12 shows dummy wells placed in the Atadei reservoir numerical model.

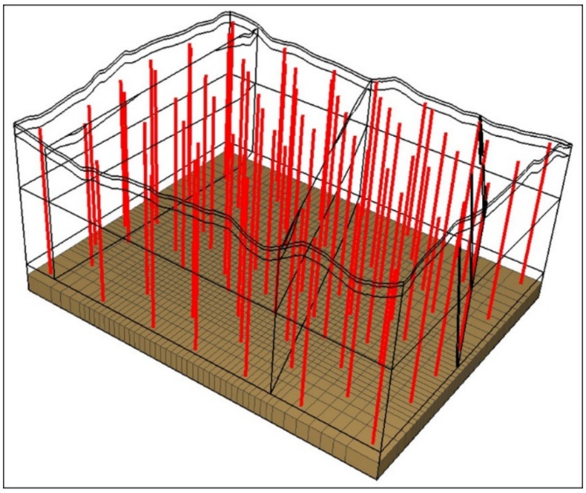

Figure 12: The location of dummy wells in the numerical model that will be integrated into Leapfrog Geothermal

The wells assigned from the surface following the topographical conditions down to the basement of the model at an elevation of -2500 meters above sea level (masl). All dummy wells are vertical. The dummy wells are then integrated into Leapfrog Geothermal along with the topography condition in Atadei Geothermal field. Figure 13 shows the integration results of the dummy wells from the TOUGH2 interface model into Leapfrog Geothermal. The color variation in the topography shows the elevation, where the red color indicated high elevation, while the blue color indicated relatively low elevation.

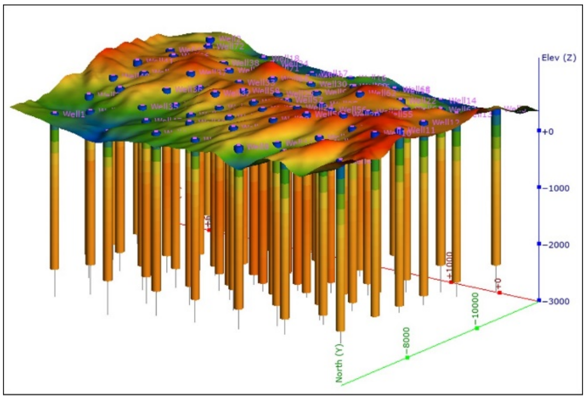

Figure 13: Dummy wells that have been integrated into Leapfrog Geothermal based on TOUGH2 results

After the dummy wells have been integrated into Leapfrog Geothermal, then the software combines the temperature for each well and forms an overall temperature distribution within the modelo. In theory, the mathematical functions underpinning the models are computed using radial basis function interpolation (Newson et al., 2012). Figure 14 shows the integration of results from the TOUGH2 model into the Leapfrog Geothermal.

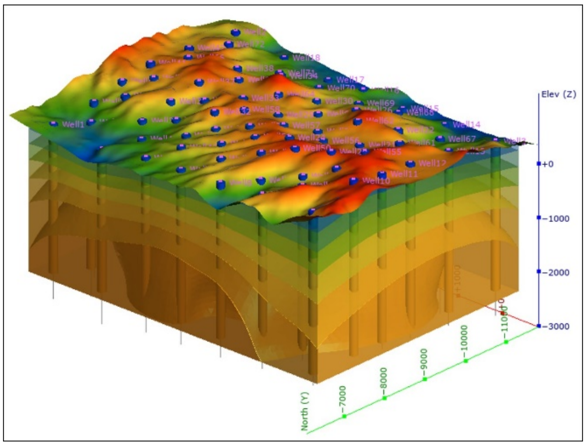

Figure 14: Integration results from the TOUGH2 model into the Leapfrog Geothermal

The Leapfrog Geothermal model that has been created based TOUGH2 numerical model of Atadei geothermal field can assist in comprehensive analysis of the subsurface temperature distribution. Leapfrog Geothermal makes it possible to do slicing from various directions to get information below the surface. In addition to slicing from various directions, this application also makes it possible to interpret one temperature value, and it is made accessible for analyzing reservoir characteristics. Furthermore, the integration results also can be used to update the conceptual model. Ponggohong et al. (2019) using Leapfrog Geothermal model to visualize the geological condition. In Leapfrog, the 3D temperature distribution and 3D geological model can be combined to create a 3D conceptual model under static conditions. This advantage is the main reason for integrating the TOUGH2 results that are created outside of Leapfrog into

Leapfrog rather than using other plotting programs such as Tecplot, Paraview, etc.

After that, we explore the comparison between the TOUGH2 interface and Leapfrog Geothermal temperature distribution results. Figure 15 shows the Leapfrog Geothermal model with a temperature distribution of more than 200°C in the reservoir. The Leapfrog Geothermal model shows a very detailed temperature distribution resolution that can be seen from the cones. The temperature distribution shows the three locations fumarole manifestations occur, namely: Watuwawer, Lewo Keba, and Lewo Kebingin, shown by a doming pattern at the top of the reservoir. It can be concluded that these three locations are possibly the upflow areas of the Atadei geothermal system.

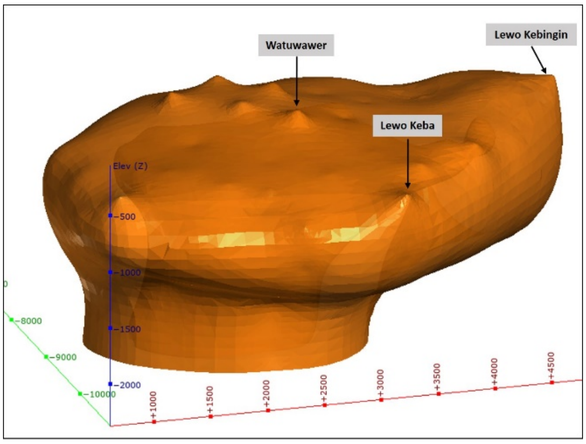

Figure 15: Leapfrog Geothermal model with a temperature distribution more than 200°C in the reservoir

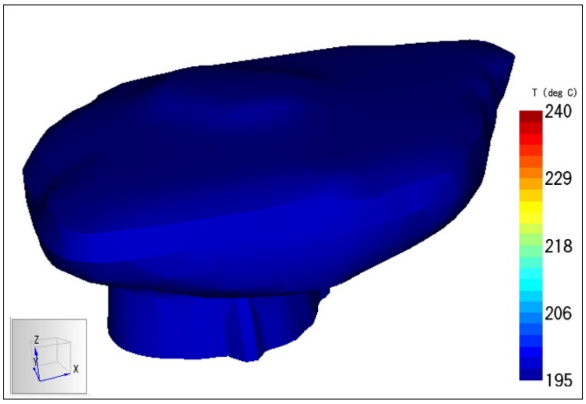

Figure 16: TOUGH2 model using one of the graphical user interface for TOUGH2 with a temperature distribution more than 200°C in the reservoir

The detailed temperature distribution available from Leapfrog Geothermal is an advantage, while with the TOUGH2 interface, the temperature distribution tends not to be able to describe specific conditions. Figure 16 shows a visualization of the TOUGH2 model results, using one of the graphical user interfaces for TOUGH2, with a temperature distribution of more than 200°C in the reservoir. The temperature distribution produced by the TOUGH2 interface is quite different from that produced by Leapfrog Geothermal in modeling the specific conditions.

5. CONCLUSION

1. A new approach of integrating the TOUGH2 results into Leapfrog Geothermal has been successfully developed.
2. The 3D interpretation of the temperature distribution using Leapfrog Geothermal shows more robust results rather than the TOUGH2 interface results. It can be seen from the Leapfrog 3D temperature distribution provides a more detailed resolution compared with 3D temperature distribution obtained using one of the graphical user interfaces for TOUGH2.

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