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Numerical modeling for the steady-state condition of the geothermal system in Way Ratai

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Steady-state model of geothermal system in Way Ratai for exploration activities was numerically modelled by using the HYDROTHERM INTERACTIVE software based on the Newton-Raphson algorithm. In the present numerical modelling, cross-sectional area was determined by around 18 km in length of northwest-southeast (NW-SE) direction and 5 km in vertical direction from a mean sea level (msl) using grids width of 100 m, 200 m, and 500 m. Numerical simulation was run for 100,000 years using an interval 1000 years along with manifestation data as reference current conditions. Significant results of simulation were obtained at a 25,000 iteration years, identifying as steady-state condition for the Way Ratai geothermal system. The numerical results show that geothermal reservoirs potentially has a length range of approximately 9 km, with a thickness of 0.5-1.5 km with a temperature ranging from 250 - 350°C. The reservoir's depth is ranging from 600-1200 m beneath thick caprocks and strengthens previous AMT research results. The distribution of steam trapped in the southeastern part of the Way Ratai peak becomes an important target for exploration drilling. Furthermore, according to large area, thickness, and high reservoir temperature from numerical models, the Way Ratai geothermal system is potential to being explored because the geothermal reservoirs contain a high enthalpy mass of steam.

Keywords: geothermal, Way Ratai numerical model, reservoir temperature, steady-state

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1. Introduction

The Way Ratai mountain in a district of Pesawaran, Province of Lampung-Indonesia has potential reserves of geothermal energy [1]. Nandi et al. [2] reported that, previous geothermal studies at Way Ratai using geoelectricity have successfully imaged two interconnected hot springs manifestation sources. This manifestation was identified as part of a northwest-southeast trending structure through the Bambu Kuning and Margodadi hot springs [2]. This structure affects results of a thermal conductivity measurement at Way Ratai [1–3].

The inversion of audio magnetotelluric (AMT) data in Way Ratai can be used to describes conceptually a geothermal model with a cap rock at a depth ranging from 100-750 m, a reservoir at a depth ranging from 300-1600 m, and a basement at a depth ranging from 700-3000 m [4]. The geochemical analysis using Quart-max steam loss geothermometer showed that reservoir temperatures in the Way Ratai geothermal field around 131.8°C including in a category of liquid-dominated system [5]. In a recent years, a numerical model is widely used as an indispensable tool for investigating magmatic-hydrothermal systems [6], but it has never been done in Way Ratai.

Numerical models can be used to improve the previous conceptual and numerical geothermal model [7–9], to verify the heat transport system of the geothermal [10], and even simulate the productivity of geothermal reservoirs [11–13]. Numerical simulation of results can be used to describe the hydrothermal fluid flow mechanism and to calculate geothermal fluids' mass and enthalpy [14]. In addition, simulation results can predict heat flow, background temperature distribution, and mass flux patterns in geothermal reservoirs for the next few years [15].

Therefore, we used a numerical method to simulate geothermal activities condition at Way Ratai field and additionally to improve the conceptual model in our previous study [4]. Both hydrothermal fluid flow model and heat energy transfer model in the Way Ratai geothermal system are modeled by combining previous research data and primary measurement data in the field to obtain geothermal system. In the absence of exploration well data in Way Ratai geothermal field, the steady-state condition was approached by using the surface manifestation conditions data at the Margodadi [16].

HYDROTHERM software is widely used as geothermal modeling code, and computationally performed by using structured grids based on a finite difference approach due to an easy-to-use interface and model workflow. In addition, simulation results can describe multiphase groundwater flow conditions and thermal energy/heat transport with supercritical conditions of steam temperatures up to 1200°C and pressures up to 1000 MP$_a$ [6, 9, 17–19]. This software uses the Newton-Raphson algorithm for non-linear differential systems and Slice Successive Over Relaxation (SSOR) and Generalized Minimum Residual (GMRES) for linear systems.

Another features of HYDROTHERM enable to combine interactively a graphical user interface (GUI) known as the HYDROTHERM INTERACTIVE (HTI). HYDROTHERM is open source based software on Fortran90 to employ a dynamic allocation of arrays [20]. Therefore, we use HYDROTHERM INTERACTIVE to model the steady-state condition of the geothermal system in Way Ratai and provide estimation values of the Way Ratai geothermal energy reserves for improvement thermal exploration and science status. In addition, the right rock parameters and numerical models, simulating hydrothermal fluid flow and heat energy transfer close to the Way Ratai geothermal field's actual conditions were investigated.

2. Geological Condition of Way Ratai

The geological map of the research area, shown in Fig. 1, rocks are dominated by-production of young volcanoes (Qh$_y$) consisting of lava (andesite-basalt), breccias, and tuff; there is also alluvium (Q$_a$) which a typical rock of contains gravel and sand. Holocene age of clay and peat are the Hulusimpang (Tomh) formation consisting of basalt andesite lava, tuff, and altered volcanic breccias with limestone dating Oligocene - Early Miocene.

The Sabu Formation (T$_{pos}$) consisting of conglomerate breccias with sandstones of the Paleocene - Oligocene age, meanwhile, the Kantur Formation (T$_{mpk}$) consisting of tuffit and claystone with a mixture of the carbonate and sandstones of the Late Miocene - Pliocene age. The oldest formation is Menanga Formation (Km) consisting of shale and claystone with basalt, chert, and limestone inserts at the early Cretaceous period [16] as shown in Fig. 1.

The fault structure in the Way Ratai geothermal field and its surroundings are dominated by fault structures trending northwest-southeast and northeast-southwest and strongly suspected to be normal faults and part of the Sumatra fault system [16, 21]. In addition, typical two normal fault structures mentioned above (Fig. 1) in the investigation area can be identified by using main northeast-southwest and northwest-southeast trending lineaments. The normal fault formation mechanism was generated from a tensile force (extension) and tends to create a reasonable wide-open space.

Therefore, its presence is necessary to support high permeability of rocks in the Way Ratai geothermal reservoir zone. Therefore, the formation of fault structure become an important discussion, especially for normal fault structures trending northeast-southwest, normal faults trending northwest-southeast, and lineages estimated which significantly affect the geothermal prospect zone in Way Ratai, as shown in Fig. 1.

3. Materials and Methods

HYDROTHERM software uses two mathematic equations for simulation the flow and transfer processes of fluid. Equation 1 was used for the determination of the groundwater flow based on water mass conservation in volume elements and Darcy's law for multiphase flows in the porous medium [13, 20].

$$\frac{\partial}{\partial t}\left[\phi\left(\rho_w S_w+\rho_s S_s\right)\right]-\nabla\cdot\frac{\mathbf{k}k_{rw}\rho_w}{\mu_w}\left[\nabla p+\rho_w g\hat{\mathbf{e}}_z\right] \\ -\nabla\cdot\frac{\mathbf{k}k_{rs}\rho_s}{\mu_s}\left[\nabla p_g+\rho_s g\hat{\mathbf{e}}_z\right]-q_{sf}=0 \quad (1)$$

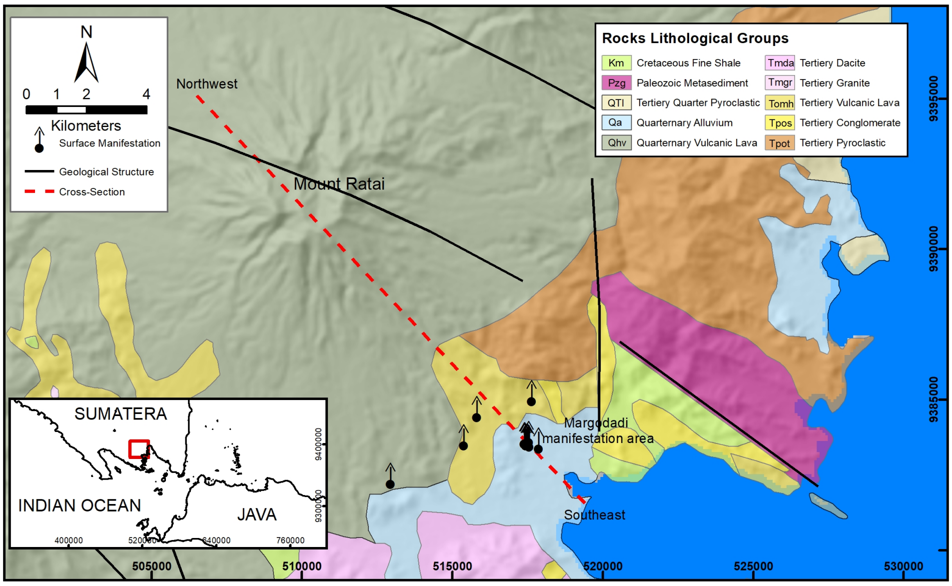

Fig. 1. Map of the regional geological conditions of Way Ratai and the location of surface manifestations. Dashed red-lines are showing a cross-section of simulation model used from modification of the regional geological map of Tanjung Karang [16]

where t is the time (s). ϕ is the porosity. ρ_w and ρ_s are the fluid density (kg/m3), and S_w, S_w are water saturation (subscript of w and s are phase of water and phase of steam, respectively). $\mathbf{k}$, $\hat{\mathbf{e}}_z$, g, ∇ and q_{sf} are the porous-medium permeability tensor (m^2), unit vector in the z-coordinate direction, gravitational constant (m/^{2}), spatial gradient (m^{-1}), and flow-rate intensity of a fluid-mass source (kg/s-m^3), respectively. Furthermore, k_{rw}, k_{rs} and μ_w,μ_s are the relative permeability and viscosity (Pa-s) in the phase of water (w) and steam (s), respectively. Meanwhile, p is the fluid pressure in the liquid phase (P_a), and p_g is the fluid pressure in the gas phase (P_a).

The pore velocity is determined from Darcy's law for the water component given in the equation 2.

$$\mathbf{v}_p = \frac{\mathbf{k}k_{rp}}{\phi s_p \mu_p}\left[\nabla p + \rho_p g \hat{\mathbf{e}}_z\right] \tag{2}$$

Where $\mathbf{v}_p$ is the interstitial or pore velocity vector for water in phase p of water (w) and steam (s) (m/s). Furthermore, the heat transfer equation is based on the enthalpy's conservation in both phases, the liquid phase, and the solid phase. The enthalpy value is generated as the derivative of the internal energy and flow energy using equation 3 [20].

$$\frac{\partial}{\partial t}\left[\phi\left(\rho_w h_w S_w + \rho_s h_s S_s\right) + (1-\phi)\rho_r h_r\right] - \nabla \cdot K_a \mathrm{I} \nabla T \\ + \nabla \cdot \phi\left(S_w \rho_w h_w \mathbf{v}_w + S_s \rho_s h_s \mathbf{v}_s\right) - q_{sh} = 0 \tag{3}$$

where h, h_r, ρ_r, and K_a are the specific enthalpy of fluid phase (J/kg), specific enthalpy and density of the porous-matrix solid phase (J/kg and kg/m^3), and effective thermal conductivity of the bulk porous medium (W/m°C) respectively. Moreover, $\mathbf{I}$, T and q_{sh} are the identity matrix of rank 3, temperature (°C) and the flow rate intensity of an enthalpy source (W/m^3), respectively. All phase is subscript by (w) for water (liquid phase) and (s) for steam phase (gas phase, vapour phase) [20].

3.1. Grid domain and boundary conditions

In order to determine rock parameters as input data in HYDROTHERM INTERACTIVE software, the first step was done to create an incision profile/cross-section. The cross-section was created by using northwest-southeast and crosses the peak of Mount Ratai (see in Fig. 1). This path passed through the geothermal manifestations in the Margodadi area.

We chose this cross-section because the hot water manifestation position was used as reference data to release hot fluid or the outflow zone from the geothermal system in Way Ratai. The cross-section length is 18 km, starting from the northwest to the southeast of Mount Ratai. This cross-section is then used to create a domain area in the HYDROTHERM INTERACTIVE software with a depth of up to 5 km. The initial model was built for numerical simulation using confined groundwater flow, weighting using the upstream formula (threshold value 2 x 10^{-4}), and fluid source using enthalpy.

The relative permeability function used a linear type with a residual saturation of water of 0.3 and steam is 0. The initial pressure condition uses normal surface atmospheric pressure (1.013 × 106 P_a). In contrast, the initial temperature was determined by trial and error by consideration heat source temperature of 1000°C, and the maximum surface temperature was 30°C. For mass balance and energy balance convergence parameters from the Newton-Raphson technique, respectively use the values of 1 × 10^{-12} g / s.cm^3 and 0.01 erg / s.cm^3. The solver technique only used the direct band linear equation.

The boundary conditions used in the simulation model are shown in Fig. 2. The surface area is limited by the same temperature and pressure conditions as the value of the initial condition (ICV) symbolized by the blue line, except in the Margodadi manifestation area. There are no limiting conditions given in the Margodadi manifestation area (symbolized by a line marked in gray) so that the fluid flow rate can flow into this area. This setting is following the conditions in the field where the hot fluid appears on the surface as a manifestation of hot springs as a field reference. For the lower layer of the initial model, a basal heat flux value is 100 mW/m^2 and is symbolized by a yellow line. The initial value condition is determined by using combination from literature data [7, 8, 12, 17].

The entire cross-section profile for modeling using a data grid with width of 0.1 km, 0.2 km, and 0.5 km is displayed in Fig. 2. The dense grid is focused on the heat source and the peak of Mount Ratai, and the Way Ratai geothermal manifestation area. The tightest grid, especially on the surface, is intended to get a sharper and more detailed simulation data resolution. This grid is related to the geothermal system's characteristics, and the main targets are geothermal reservoir and clay cap. Besides, the development of exploration wells before exploitation focus on near-surface hot fluids. It is important to know the groundwater movement as a recharge system for the geothermal reservoir's fluid area.

3.2. Input parameters of Hydrotherm Interactive

Both secondary data from literature [7, 8, 12, 17] and the results of primary field measurements as, the input parameters for numerical simulations are presented in Table 1.

All parameters are inputted into the system by consideration of the geological profile from field observations and regional geological maps which the results simulation of geological profile model is shown in Fig 3.

In the geological model's cross-section, as shown in Fig. 3, the Quaternary volcanic lava (Qhv) is the youngest rocks as the top layer and symbolized by a pinkish color. This rock is volcanic products resulted from the latest eruption of the young caldera of Mount Ratai. Meanwhile, the yellow layer is Tertiary volcanic lava (Tomh) formed beneath the layer of Qhv and spreading to the southeast of Mount Ratai which later those layers can be identified. This layer is known as a product of old volcanism originating from the Gebang caldera or the old caldera of Mount Ratai.

Bedrock formed at basement, according to the distribution of this rock on the regional geological map, it is spread from northwest to southeast of Mount Ratai. This bedrock is a metamorphic rock in a Paleozoic metasediment (Pzg) such as schist, as part of the Mount Kasih Complex rocks formation, as shown in Fig. 3. Furthermore, the heat source (volcanic conduit) estimated under Mount Ratai, show maximum temperature around 1000°C.

The flowchart for numerical method steps in the present study is displayed in Fig 4. The final model was determined by reflecting the Way Ratai geothermal system's steady-state conditions. At simulation stages, an analysis of the original manifestations' suitability is carried out by combination with field characteristics from previous studies as a reference [5, 16]. The simulation process was done by creating the domain and boundary conditions and by fixing the input parameters to produce a model that matches the reference data (Fig 4).

4. Results and Discussions

The numerical simulation process, which was run until reaching time of 100,000 years for describing a hydrothermal fluid flow pattern and heat transfer close to the actual known state, namely geothermal manifestations as a reference for current conditions. A 100,000-year iterations were result of trial and error in the simulation stage. In order to obtain flow patterns, simulation models were determined by using an interval time in year unit: 1,000, 5,000, 10,000, 25,000, 50,000 and 100,000 years as shown in Fig. 5.

The numerical simulation results on the mass flow rate of fluid show the Way Ratai geothermal reservoir's potential location around the slopes of Mount Ratai to the southeast. The heat distribution model analysis and the fluid's mass flow rate were carried out to determine the reservoir potential, namely the characteristics of the fluid's mass rate and the moving fluid mass temperature.

Fig. 5 displays the simulation results of the fluid mass flow model of heat transfer in the Way Ratai geothermal field at an interval time ranging from 1000 to 5,000 iterations (Fig. 5). Meanwhile, in the iteration period from

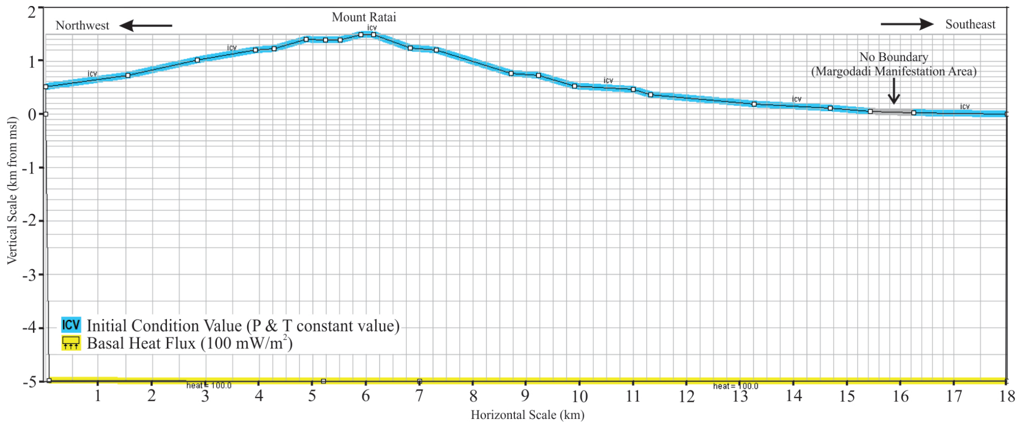

Fig. 2. The grid domain and boundary conditions of the Way Ratai from a numerical simulation model.

Table 1. Characteristic's rock data as input parameters for numerically predicting heat fluid transfer in Way Ratai geothermal field.

Rock Unit	Porosity	Horizontal Permeability (m^2)	Vertical Permeability (m^2)	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)	Density (g/cm^3)
Quaternary Volcanic (Ratai Andesite Qhv)	0.12	1×10^{-16}	1×10^{-16}	2	1083	2.633
Tertiary Volcanic (Gebang AndesiteTomh)	0.12	1×10^{-15}	1×10^{-15}	2	1083	2.6
Basement (Schist Pzg)	0.01	1×10^{-17}	1×10^{-17}	3.5	1000	3
Heat Source	0.01	1×10^{-22}	1×10^{-22}	4	2000	2.65

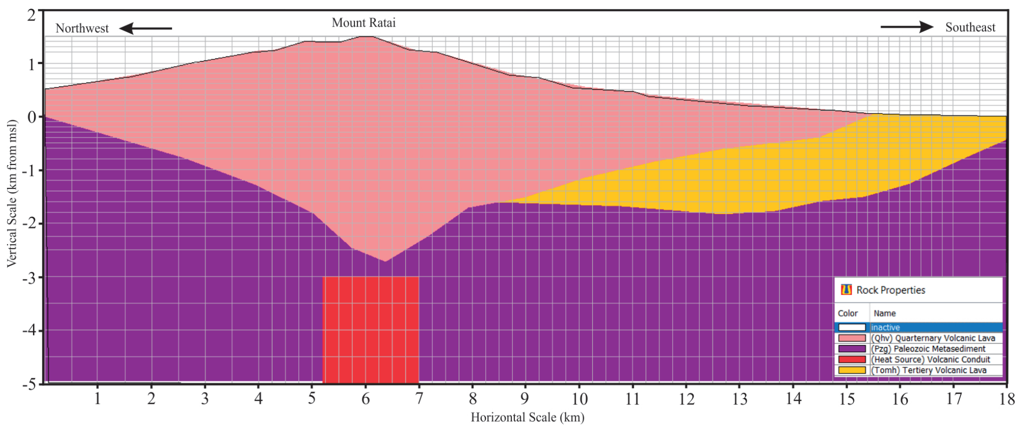

Fig. 3. Geological profile model simplified in Way Ratai from numerical simulation.

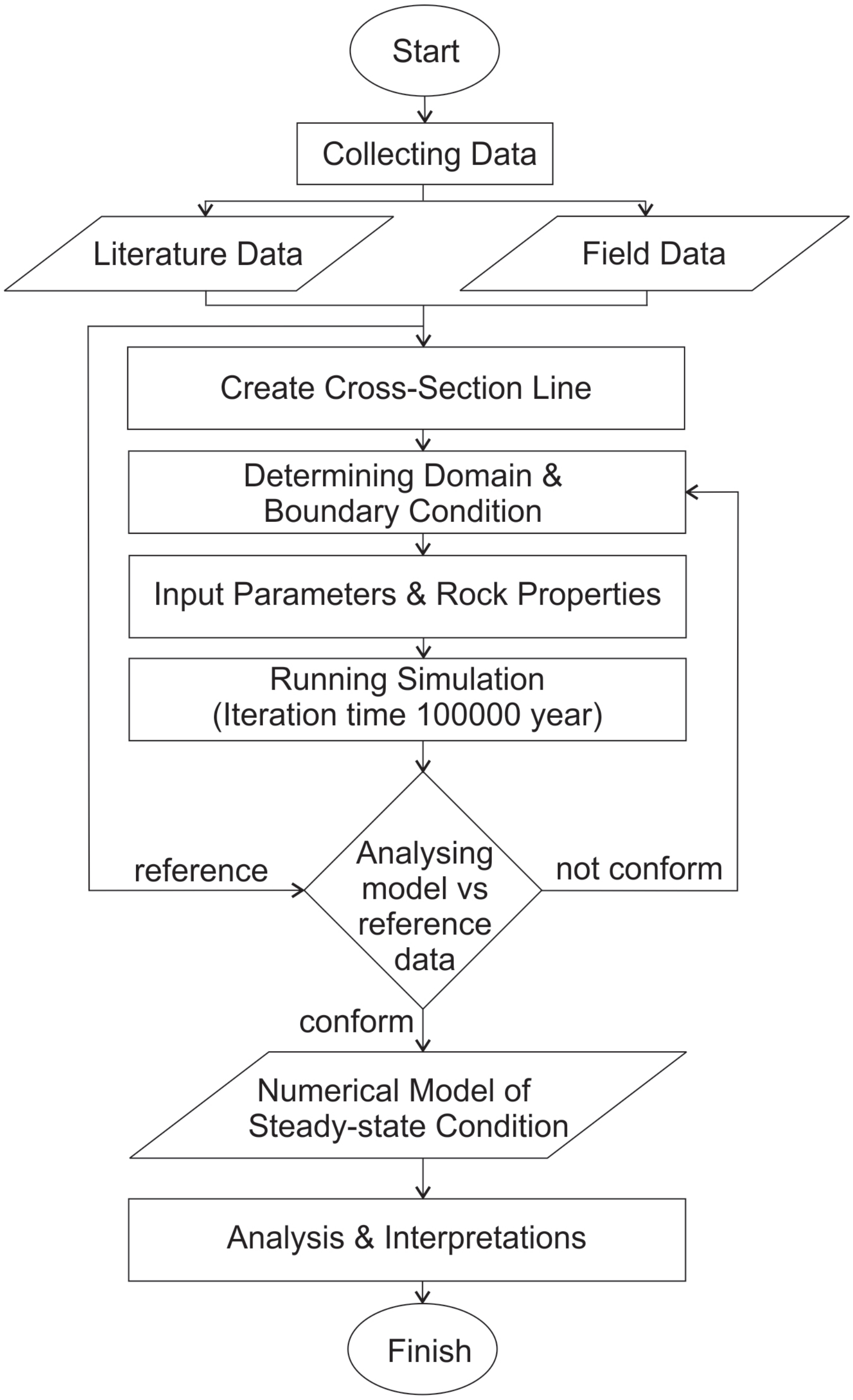

Fig. 4. Flowchart showing step of processing activities and numerical simulation.

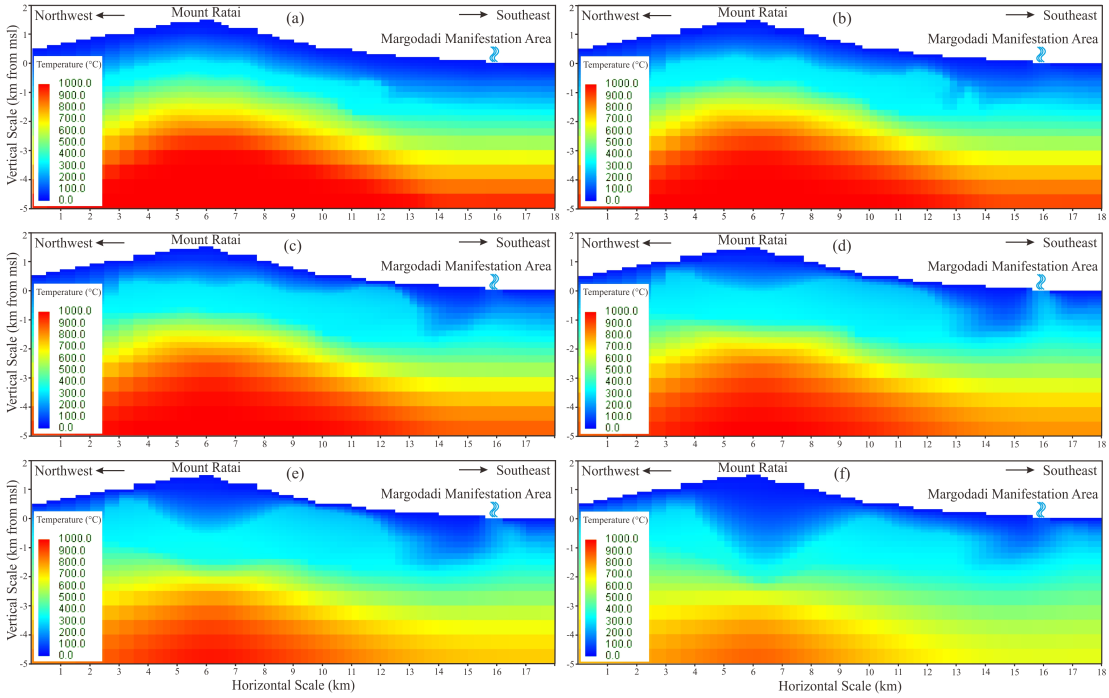

Fig. 5. (a-f) the simulation results showing the numerical model of Way Ratai temperature reservoir using 1,000 to 100,000-year iterations.

50,000 to 100,000 years, the geothermal reservoir is slowly cooling. In the same condition, without the heat source's reactivation (magmatism), it is estimated that the temperature decrease when the heat source reaches at 200°C in this model. This condition can causes a reduction in reservoir volume due to cooling due to recharge from meteoric water coming from the summit of Mount Ratai.

The simulation results for 25,000 iterations displayed in Fig. 6 show a fascinating design. The hydrothermal fluid velocity movement model has similarities to the field conditions, especially about the existing surface manifestation conditions in the Margodadi manifestation area.

The mass flow rate model of water fluid at a temperature of 100°C appears in the manifestation areas of Margodadi and the surrounding. Meanwhile, the field measurement temperatures was ranging from 85 – 98°C [16]. This temperature distribution pattern and mass flow rate are very likely to be interpreted as a current condition or a steady-state in a current Way Ratai geothermal field, as shown in Fig. 6.

The model produced from a 25,000 iterations shows the consistency of the mass distribution of the fluid vapor that does not reach the manifestation area or penetrate other surfaces, which are a consistent result to the actual field conditions in Way Ratai at the steady-state condition from this present study. According to simulation results in Fig. 6, the geothermal reservoir potential has a length range of approximately 9 km, stretches horizontally from a point 3 km to a point 12 km in cross-section., with a thickness between 0.5 - 1.5 km.

The reservoir position is under Mount Ratai, which spreads to the northwest and southeast with a thicker spread in the southeast. The reservoir's depth from the surface ranges from 600 - 1200 meters with a reasonably thick cap rock. This reservoir potential modeling results are consistent with and reinforce with previous investigation using Audio Magnetotelluric (AMT) [4].

Based on the model shown in Fig. 6, the reservoir fluid temperature range is between 250 - 350°C. The type of fluid filling the reservoir is estimated in the model to be the dominant of water in the two-phase zone. This result is significantly different from previous geochemical studies, which estimate reservoir temperatures around 131.8°C [5]. The difference in reservoir temperature values cannot be ascertained whether it is related to weaknesses in the numerical model or the geothermal calculation of geochemical data.

Without exploration well data, the certainty of reservoir temperature cannot be confirmed. However, this study's numerical model is quite certain about the alignment of the reservoir dimensions with AMT data and the alignment with surface manifestations. The confidence in this model

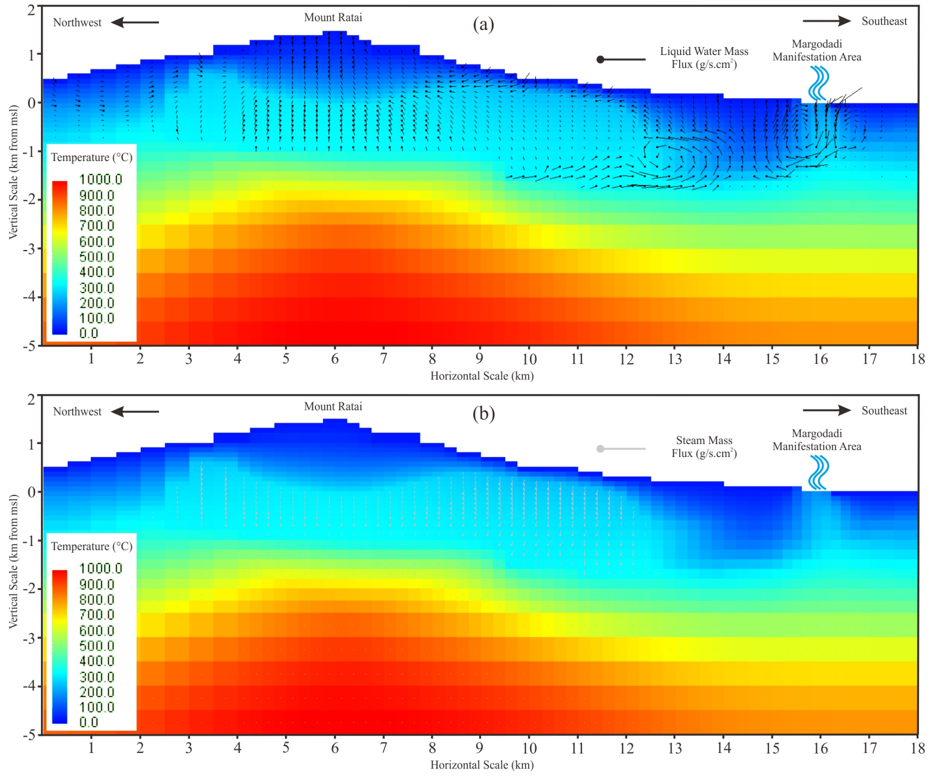

Fig. 6. Model of liquid water mass flux (a) and steam mass flux (b) of heat transfer (in°C) the Way Ratai geothermal field in the 25,000th-year iteration.

is also based on the similarity of the reservoir fluid type dominated by water in the reservoir.

Based on this simulation's numerical model in Fig. 6, the dominant geothermal reservoir is in Quaternary volcanic rock, the Mount Ratai volcanism product. Meanwhile, the prevailing fluid flow rate of hot water that appears in the Margodadi manifestation area is estimated to be in Tertiary volcanic rock, which is the volcanic product of Mount Gebang. The existing rock structures cause the appearance of hot springs around this area. This structure's existence was confirmed by the results of previous studies using the Radon method [2].

The Radon method shows a structured pattern with a northwest-southeast trending and one that cuts a northeast-southwest direction. Although not explicitly seen in the model, the pattern of the existence of structures in previous studies was strengthened in this study's results. This strengthening is evident in the fluid flow pattern that appears vertically under the Margodadi manifestation area. The same pattern can also be seen from the 2D cross-section of the previous research AMT data.

The fluid mass flow movement also shows the dominance of the direction of action from the top and slopes of Mount Ratai as a meteoric water recharge source, as shown in Fig. 6. Still, there is also a southeast movement, namely Ratai Bay, a water fluid source. The movement of water fluid or liquid water mass flux as shown in Fig. 6 appears clearly from the top of Mount Ratai as a recharge zone or a dominant meteoric water source moving to the southeast towards the location of hot water manifestations in the Margodadi and surrounding areas.

This movement is in line with the appearance of various types of representations, especially those in the outflow zone, such as hot springs with neutral pH. The mass movement model of the fluid vapor mass, the result of numerical simulation, shows the distribution pattern under the peak of Mount Ratai and the dominant spread to the southeast. This finding is significant to focus on planning for future exploration wells in Way Ratai.

5. Conclusions

This study's results using numerical modeling significantly shows a stable condition pattern at one cross-section in the Way Ratai geothermal field. The geological model approach, which is simplified into four primary lithologies, can produce up to 100,000 years of fluid motion models.

The resulting mass flow rate model of water fluid also shows similarities to previous studies and conditions in the field, such as fluid at temperatures of 100°C appearing in the manifestation area of Margodadi and surrounding. These results significantly indicate that the iteration period of 25,000 - 50,000 years is ideal for the Way Ratai geothermal system based on numerical simulations. In this period, it is possible to carry out the Way Ratai geothermal energy extraction process.

With a large enough area and thickness and a reasonably high reservoir temperature, the Way Ratai geothermal potential can be categorized as a high enthalpy system. However, the vapor fluid's mass distribution does not reach below the area near the coast or the current surface manifestations. This condition is in line with the Way Ratai geothermal field's actual requirements, which has not found any representations in the form of fumaroles or solfatara.

This model is quite an attractive model because the absence of fumarole and solfatara manifestations has made the study of the upflow zone of the Way Ratai geothermal system uncertain. A possible interpretation that can be conveyed is the presence of a cover layer or a very thick rock cap that causes the vapor fluid to be unable to penetrate to the surface. Therefore, the focus of the recommendation area for exploration drilling is to the southeast of the Ratai peak and above the Margodadi manifestation area.

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