Deep underground structure and hydrothermal modeling inferred from integrated geophysical surveys

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ABSTRACT

A detailed study of the deep geothermal system in Kuju volcano, central Kyushu, Japan. This study was part of a project funded by the New Energy and Industrial Technology Development Organization (NEDO) to explore supercritical geothermal resources. This study involves the development of a hydrothermal conceptual model that incorporates geophysical, geological, and geochemical data. Geophysical surveys, such as magnetotellurics (MT), seismic, gravity, and fumarole gas analyses, were conducted. The conceptual model indicates that faults in the Hatchobaru area may act as pathways for magmatic fluids, contributing to the high-temperature zone identified on the western side of Mt. Kuroiwa. The model also suggests the existence of an up-flowing path for volcanic fluids. The geological setting of the Kuju volcanic complex is characterized by faults aligned in an east-west direction owing to north-south extensional stress. The study also discusses the resistivity structure, which reveals a low-resistivity zone associated with faults near the Hatchobaru-Otake power plant. Additionally, the model inferred the presence of a magma chamber and identified pathways for magmatic fluid flow. A numerical simulation using the TOUGH2 was conducted to validate the model. The simulation results closely matched the observed temperature and pressure data, although further refinement of the model is recommended for greater accuracy.

1. INTRODUCTION

Kuju volcano is an active area on Kyushu Island, which caused a phreatic eruption in 1995 and contains many fumaroles and hot springs. A conceptual model of the Kuju volcano based on the distribution of the resistivity structure (Aizawa et al., 2022a) was constructed by the project "Potential survey and estimation of power generation of supercritical geothermal resources in East Japan and Kyushu, Japan (FY2018-FY2020)". To determine a drilling target, its successor project "Potential survey and estimation of power generation of supercritical geothermal resources in the Kuju area (FY2021-FY2023)" was conducted. Both projects were funded by the New Energy and Industrial Technology Development Organization (NEDO). This project aims to create a hydrothermal conceptual model based on geophysical, geological, and geochemical characteristics. To obtain these properties, geophysical surveys, such as MT, seismic, gravity, and geochemical analyses of fumarole gas, have been conducted.

We improved a conceptual model of the geothermal system in this area based on the gravity basement, distribution of resistivity (Aizawa et al., 2022b), micro-earthquake hypocenters (Andajani et al., 2023), and the analysis of gas isotopes from vents and hot springs (Ishibashi et al., 2022).

Three-dimensional natural-state geothermal reservoir modeling was also performed based on the updated conceptual model. A model has been estimated that generally explains the temperature and pressure of the deep and shallow reservoirs in the Hatchobaru-Otake area, where geothermal development is taking place, and this paper reports an updated conceptual model and the results of heat-water flow modeling.

2. GEOLOGICAL SETTING

The Kuju volcanic complex is located in the central part of Kyushu Island, where stresses work in the direction of north-south extension (Tada, 1984). For this reason, there are many faults with an east-west strike.

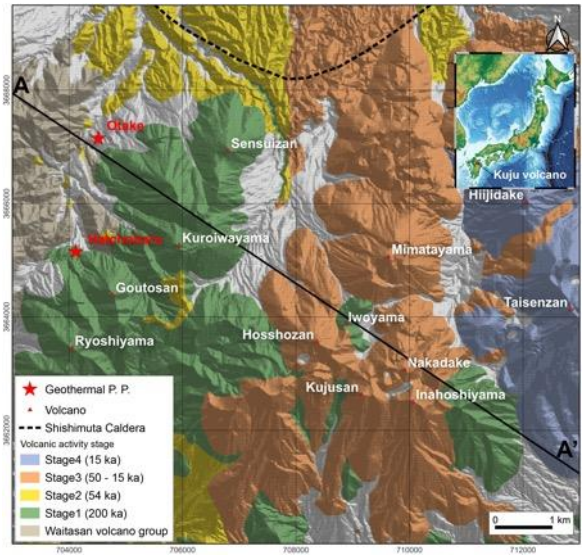

Figure 1: Geological map of the Kuju volcano, modified from Kawanabe et al. (2015). Shaded topography was made a 10m mesh DEM (GSI, 2024).

Kuju volcano is composed of small stratovolcanoes and lava domes of andesite and dacite, respectively. The active period of Kuju volcano can be divided into four periods, from stage 1 to stage 4 (Fig. 1). Stage 1 (200-54 ka) volcanic activity formed Mt Kuroiwa, Mt Gotosan and Mt Ryoshiyama in the west and Mt Kutsukakeyama, Mt Narukoyama and Mt Kuju-Iwoyama in the central part. Stage 2 (54-50 ka) volcanic activity includes the eruption of the Iida pyroclastic flow and the eruption of fallen volcanic ash, fallen pumice, and pyroclastic flows. In Stage 3, the Hoshho, Nakadake, Minamata, and Dainoyama volcanoes formed between 54 ka and 15 ka. Mafic magma began to be active in the eastern part of Kuju volcano from approximately 15 ka (Stage 4) in the late Pleistocene (Kawanabe et al., 2015).

3. GEOPHYSICAL SURVEYS

Fig. 2 shows the Bouger anomaly with an assumed density of 2200 kg/m^3, which was calculated using 3650 gravity data points from previous surveys (Shichi and Yamamoto, 2001; Honda et al., 2012 ; AIST, 2013). For Bouguer and terrain corrections, an assumed density of 2200 kg/m^3 was determined by the G-H relationship (Rikitake et al., 1965) and the F-H relationship (Parasnis, 1952). Terrain corrections were calculated using the 50-m mesh digital elevation map of the Geospatial Information Authority (GSI) of Japan. The complete Bouguer anomaly was interpolated to a 100-m grid using the minimum curvature method (Smith and Wessel, 1990). The Bouguer anomaly is negative, ranging from −35 to −5 m gal, and decreases in the northern regions of the mapped area corresponding to the Shishimuta caldera.

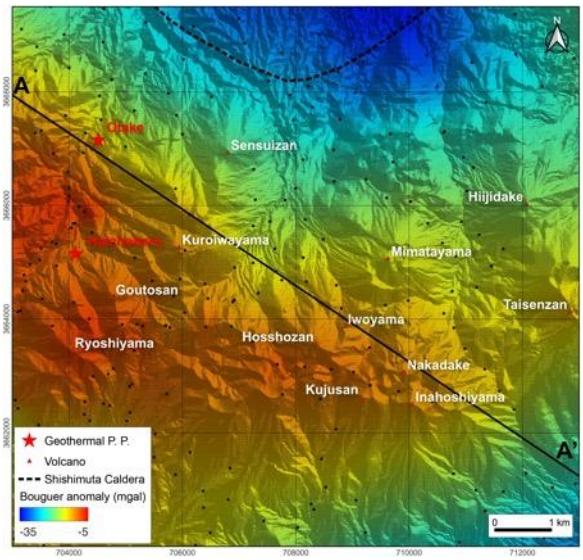

Figure 2: Bouguer anomaly with assumed density of 2200 kg/m^3. The black dots indicate the locations of the gravity stations.

Fig. 3 shows distribution of three-dimensional gravity basement structures is modeled by approximating them to an aggregation of rectangular prisms whose horizontal dimensions are the same as those of the input Bouguer anomaly grid (Nishijima and Fujimitsu, 2015). The thickness of the prisms represented the depth from the surface to the basement, and a constant density contrast of −400 kg/m^3 was assigned to all prisms. The density of the volcanic rocks was set to 2250 kg/m^3, and the density of the basement metamorphic rocks was set to 2650 kg/m^3 (Komazawa and Kamata, 1985). The horizontal size of the prismatic cell is 100 m. Fig. 3 indicates that an obvious depression of the metamorphic basement exists between Mt. Sensui and Mt. Mimatayama. The other volcanic body shows a shallow depth of basement rock.

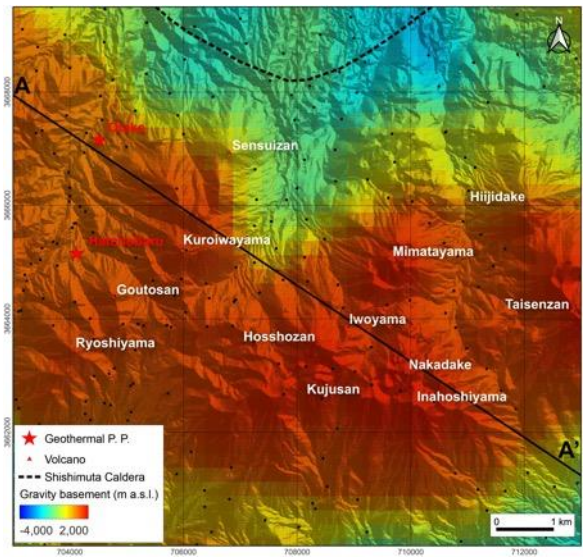

Figure 3: Gravity basement in meters above sea level with density contrast of 400 kg/m^3

Fig. 4 shows the distribution of the resistivity in the Kuju Volcano. The resistivity structure was analyzed with 143 sites using the WSINV3DMT (Siripunvaraporn and Egbert 2009) inversion code (Aizawa et al., 2022b). The low-resistivity zone was separated into shallower (0 to -2 km a.s.l.) and deeper (below -3 km a.s.l.) parts. The shallower low-resistivity zone is elongated in the NW-SE direction, which corresponds to the fault strike near the Hatchobaru-Otake power plant.

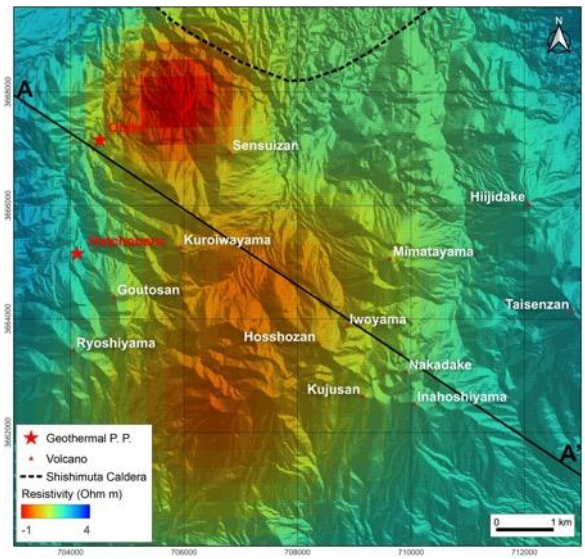

Figure 4: Horizontal depth slices at a depth of -4 km a.s.l. through the 3-D crustal resistivity structure.

Two NW–SE-trending faults are located along the southwestern edge of the shallow low-resistivity zone. The deeper low-resistivity zone was located approximately 1 km

northeastward, relative to the shallower low-resistivity zone (Aizawa et al., 2022b). This low-resistivity zone becomes deeper compared with the previous model (Aizawa et al., 2022a).

Fig.5(a) shows the distribution of hypocenters observed at 47 stations, which were vertical-component seismometers with a sampling frequency of 100 Hz. Most earthquakes are concentrated around the Otake and Hatchobaru power plants and the western part of Mt. Kuroiwa (Andajani et al., 2023). The projected vertical section indicates two clusters with shallower (1–3.5 km) and deeper (4–6 km) parts (Fig. 5(b) and (c)). Deeper clusters are distributed at the edge of the low-resistivity zone compared with the MT result and the temperature distribution (Kitamura et al., 2023). A deeper hypocenter cluster indicates a brittle-ductile boundary.

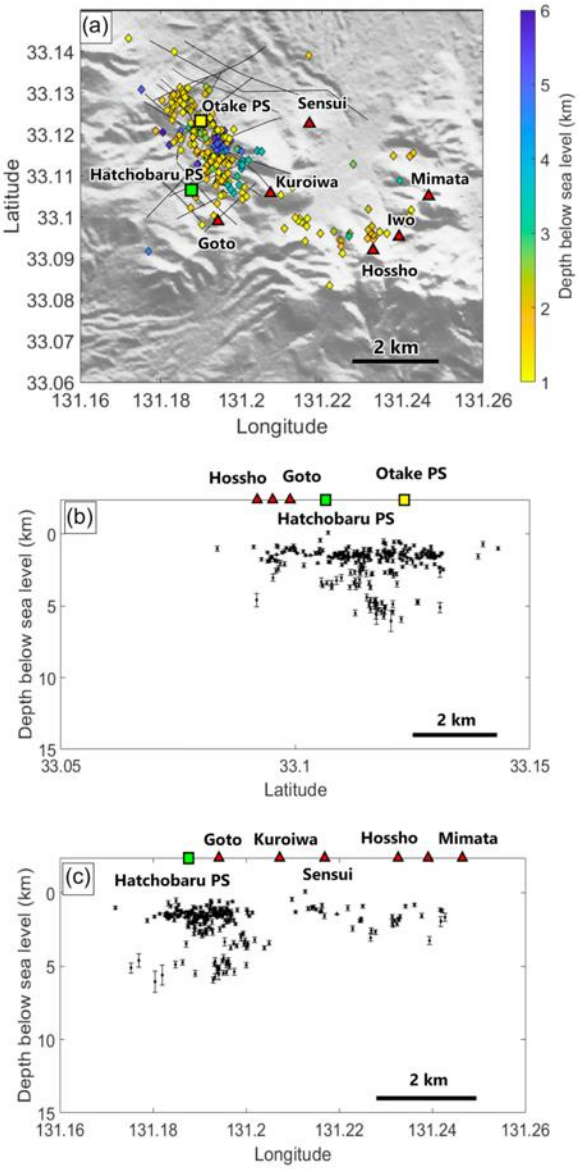

Figure 5: Distribution of hypocenters (Andajani et al. 2023). (a) Plan view with depth represented by color (b) North-South and (c) East-West vertical projected hypocenters.

4. CONCEPTUAL MODEL

A conceptual model was constructed based on gravity, MT, micro-earthquake, and geochemical analysis results (Fig. 6).

The location of the magma chamber is inferred from the deeper low-resistivity zone and deeper cluster of hypocenters of the micro-earthquake. Considering the history of volcanic activity (Kawanabe, 2015), it is highly likely that this magma contributed to the stage 3 activity. The magmatic fluid flowed to the top of the magma chamber at a depth of -4 km a.s.l. through the cracks in the solidified surface of the magma chamber. The cracks distributed at the top of the magma chamber were gradually sealed by silica precipitation, and the permeability of the cracks decreased. A magmatic fluid reservoir was formed between the solidified magma and the basement metamorphic rocks. The temperature of the deep reservoir (450 – 500 °C) was estimated by borehole temperature extrapolation (Kitamura et al., 2023). When the reservoir pressure exceeds the pressure threshold, the faults, which are connected to the western area of Mt. Kuroiwa, Hatchobaru, and Otake geothermal fields, are opened, and magmatic fluid flows to the shallow area with micro-earthquakes. According to isotope analysis of the hot water of the Hatchobaru power plant (Ishibashi et al., 2022), the helium isotope ratio is high, and the isotopes of hydrogen and oxygen ratios are plotted between meteoric water and andesite water. In addition, the results of the Carbon and Sulfur isotopes in the Hatchobaru hot water and gas indicate that some part of the meteoric water infiltrates the deeper part of the basement rock and flows upward with the magmatic fluid to the Hatchobaru geothermal reservoir.

The magma chamber had another flow path of magmatic fluid in Kuju-Iwoyama. The maximum temperature of 508 °C was observed for the fumarole in Kuju-Iwoyama (Mizutani et al., 1986). Moreover, the magmatic fluid flowing upwards to the shallow part beneath Kuju-Iwoyama and forming a hydrothermal reservoir was estimated by numerical simulation (Ehara, 1992). The magmatic fluid flows upward along the intrusive body in the basement rocks and then mixes with meteoric water in the hydrothermal reservoir beneath Kuju-Iwoyama.

5. NATURAL STATE SIMULATION

Based on the conceptual model, a numerical hydrothermal fluid flow model was constructed to identify the potential of deep reservoir zones in the Kuju volcano, in particular, to obtain a model with steady-state conditions using the TOUGH2 code (Pruess et al., 2008).

The discretization comprises 41 blocks in the northwest direction and 37 blocks in the northeast direction. The grid block sizes range from 200 m to 800 m in the NW and NE directions, with the core region having the best resolution and the buffering area having the lowest resolution. The vertical range of the model is from the ground surface to -5000 m ASL with 28 levels. The grid ranged in thickness from 250 to 500 m.

Based on the geological conceptual model, the subsurface strata were split into five layers with various physical properties: Kuju volcanic rocks, Hohi volcanic rocks, Usa formations, basement rock, and intrusive bodies (magma chamber). Permeability was assumed in previous research, except for the deep reservoir permeability. The permeability of the deep reservoir was estimated to be 1×10^{-15} (m^2) from

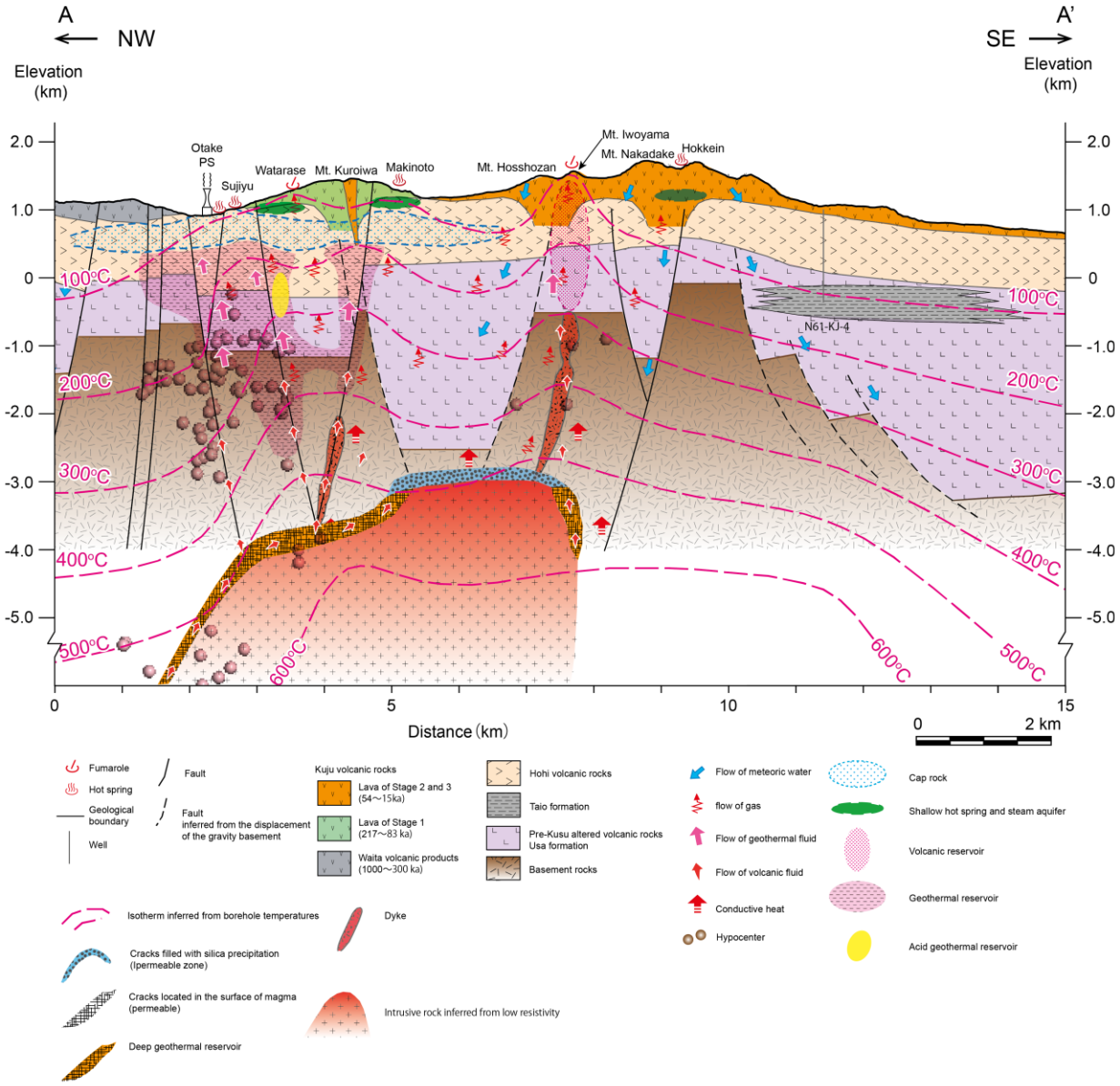

Figure 6: Conceptual model in the Kuju volcano.

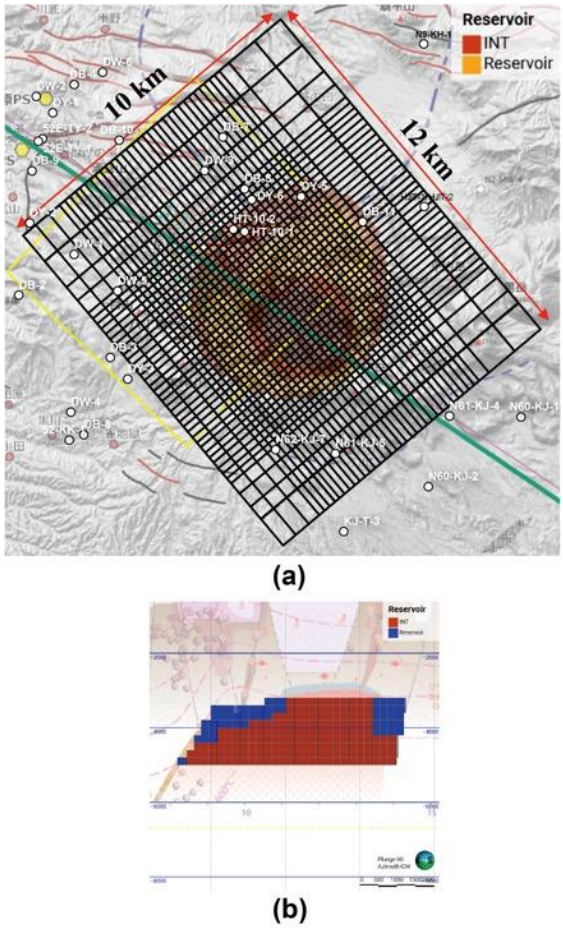

Figure 7: (a)Simulation grid for natural-state hydrothermal simulation. (b) Simulation grid for supercritical reservoir (blue) and magma chamber (red).

at the edge of the magma chamber. The pressure and temperature at the upper bounds of the lithological units to 0.1MPa Pa and 17 °C, respectively. The boundary conditions were set to make the bottom impermeable with a continuous heat flow of 150 mW/m^2. The boundary on each side is a hermetic thermal barrier. Magmatic fluid of 2700 kJ/kg was injected at the bottom of the deep reservoir. The rate of magmatic fluid was 100 – 200 (t/h), which was estimated by geochemical analysis.

Fig. 8 (a) shows the temperature distribution at the cross section of the conceptual model. The deep and shallow temperatures are approximately fitted to the interpolated and extrapolated temperatures (Kitamura, 2023). In addition, the upward flow from the deep reservoir to the shallow reservoir through the faults was explained by this numerical model.

Fig. 8. (b) shows the pressure distribution. The pressure in the deep reservoir was estimated to be 35 MPa. This implies that the pressure in the deep reservoir was almost hydrostatic. The calculated pressure of the shallow reservoir indicates a good fit to the borehole pressure in the Hatchobaru-Otake area.

Fig. 9 shows the match between the observed and calculated temperatures. Almost wells indicates good fit. Based on these matching results, this hydrothermal model is almost valid, although it is not a perfect fit. Therefore, improvement of the conceptual model based on additional data or modified interpretations is required.

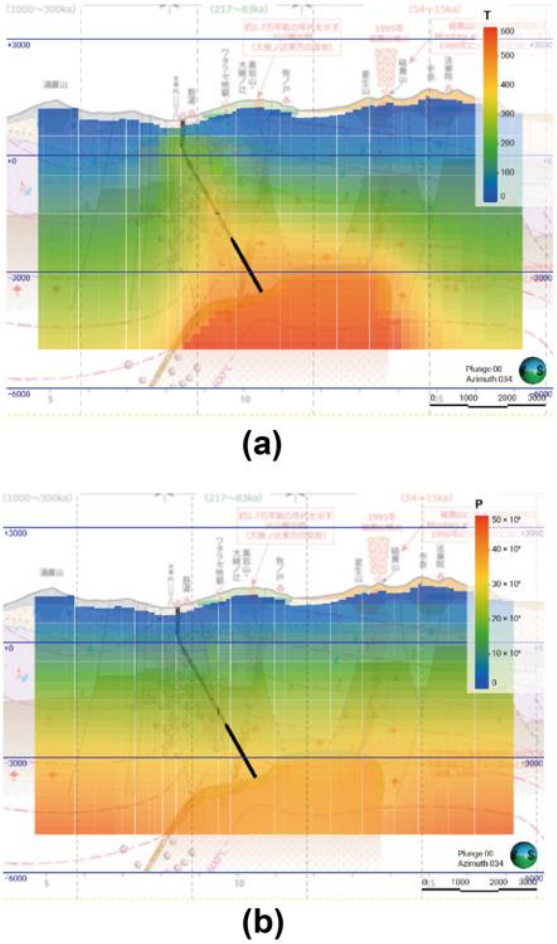

Figure 8: (a) Temperature distribution and (b) pressure distribution.

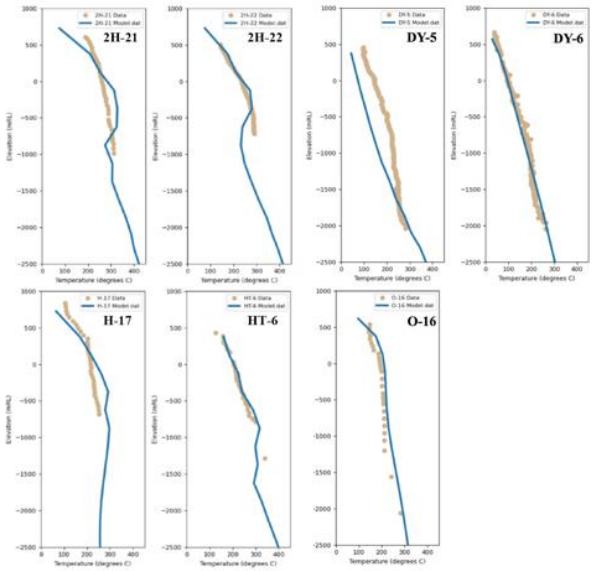

Figure 9: Results of observed and calculated temperature matching.

6. CONCLUSION

In this study, the conceptual model was improved using gravity basement modeling, MT data analysis, and microearthquake hypocenter observations. These analyses enable clarification of the location and shape of the magma chamber, deep geothermal reservoir, and flow path of deep high-temperature geothermal fluids. Based on the improved conceptual model, natural-state deep and shallow numerical reservoir simulations were conducted using the TOUGH2. The simulation results closely matched the observed shallow temperature and pressure data, although further refinement of the model was recommended for greater accuracy.

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