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Coupled integrated Multiphysics approach to quantify Volcanics and Geothermal processes

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INTRODUCTION

Magnetotellurics (MT) methods measures the subsurface electrical conductivity which indirectly reflects rock and fluid properties at a given time. Heat and Mass Flow simulators are used to characterize the pathways for fluids, formation permeabilities and heat sources driving geothermal processes. Tight coupling methodology from a conceptual model to a reservoir model enables to capture geological and alteration heterogeneities in a geothermal system (O'Sullivan et al. 2023).

Within volcanoes and geothermal systems, the interactions between heat, water, and magmatic fluids can result in numerous modifications of fluids, fluid pathways, and physical properties of rocks that can cause increased volcanic activity and modify geophysical signals (Browne and Lawless, 2001). For example, hydrothermal alteration processes such as the reduction of host-rock permeability through mineralisation, can enable the formation of a pressurised gas-dominated region (Fournier 2007). Reliably interpreting geophysical signals that directly image hydrothermal fluids or their pathways has potential to improve eruption forecasting and understanding subsurface geothermal processes.

This study aims at constraining quantitatively the subsurface properties of Aso Caldera by combining an electrical resistivity model with a geothermal flow simulator using an inverse fluid flow modeling approach.

1 METHODS

We used the Aso caldera to investigate coupling electrical resistivity and reservoir modelling. The Aso Caldera is located in the south west of Japan, on Kyushu Island. Figure 1 shows its most active feature, the Nakadake Crater, which produces cyclic phreatomagmatic eruptions (e.g., 2015, 2016, 2019, 2021). Ongoing research aims at monitoring this volcano to improve understanding of its activity and enhance public safety. We used the MT surveys to estimate the subsurface fluid and rock properties.

Figure 2 shows the initial parameters applied to an axisymmetric grid based on the Nakadake crater. Based on a conceptual model of Nakadake Volcano, an initial heat and mass flow axisymmetric simulation was created to match the overall electrical resistivity structure. Atmospheric conditions are set at the topographical surface, with rain infiltrating at 33 % of 1 m /year at around 15°C. A magmatic driven upflow of hot water with a salt concentration of 1500 ppm is set at the vertical of the crater with a high permeability vertical conduit of $10^{-12}m^2$. A basal boundary conditions of 100 mW/m^2 is set. The target area is the zone in the MT extent where we aim at inversing the permeabilities of the heat and mass flow model based on the resistivity data. The model is run using TOUGH3 and the EOS7 equation of state, for air, water and brine.

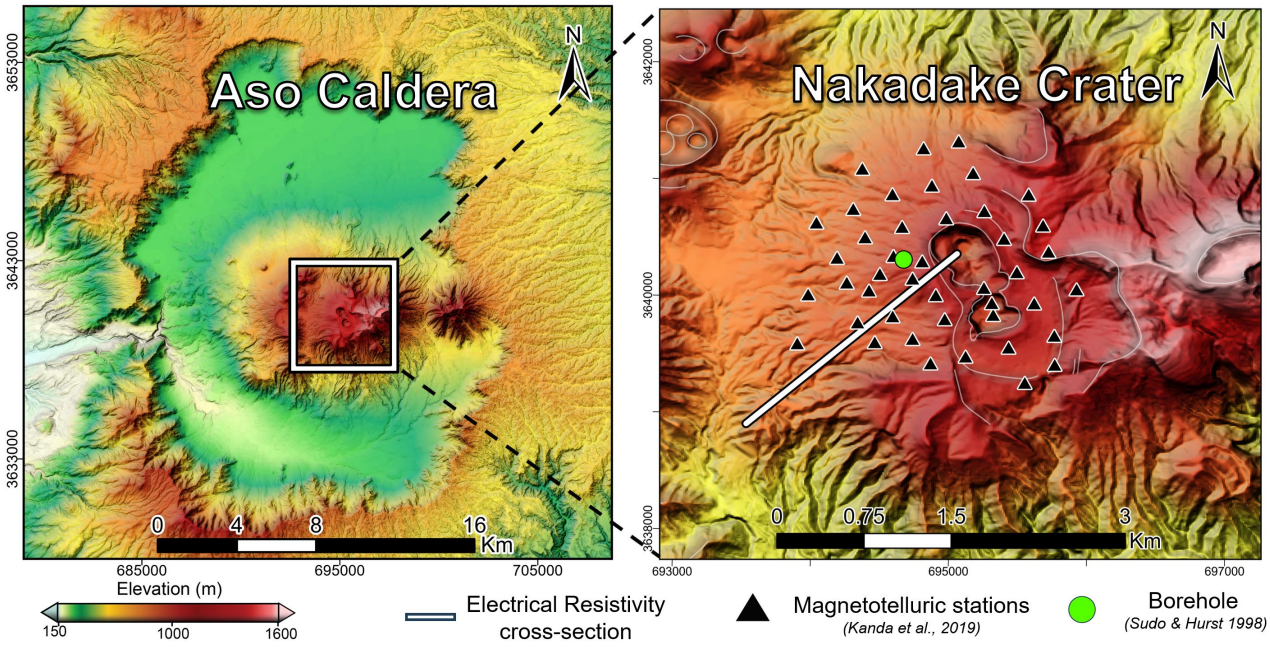


Figure 1: Aso Caldera location and Nakadake Crater with the Magnetotelluric stations.

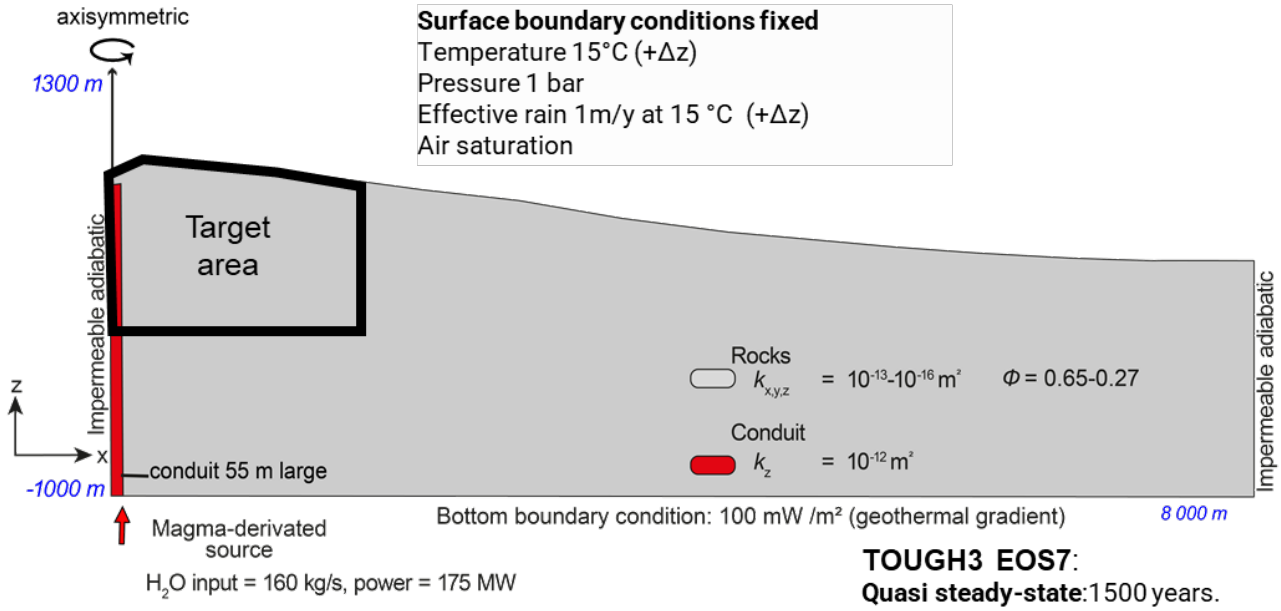


Figure 2: Conceptual model of the Reservoir model used with its parameters.

Using modified Archie's law (Revil et al. 2017 , Gresse et al. 2021) , we obtain the calculated electrical resistivity using the TOUGH3 results for the rock and fluid parameters (e.g., porosity, permeability, temperature, and salt mass fraction). We then compared the calculated resistivity to the observed electrical resistivity from a 3-D MT model (Kanda et al., 2019).

Initially, the TOUGH3 model is set with a porosity and permeability distribution as a function of depth, as shown in Figure 3 g for the vertical permeability. We used PEST (Doherty and Hunt 2010), an inverse modelling tool for model independent parameters estimation to match the MT data only available in the target area. Before the inversion, the target area is initialized with values of 1e-10^{-14}m^2. In the resulting TOUGH3 input file, heterogeneous horizontal and vertical permeabilities are considered in the inverse modelling calculation.

2 RESULTS

Figure 3 shows the Initial model (a,c,e,g) and the inverse modelling results (b,d,f,h). Initially, the heat and fluid flow simulator showed a RMS value of 93 when comparing to the observed resistivity values. The results of the

inversion shows an improved RMS value to 19 after 8 iterations. The numerical model is calibrated through automated inversion, significantly improving the fit to observed electrical resistivity data—by a factor of 3 to 4.

At the end, the main differences between the calculated and observed resistivity remain at the border of the inversed domain. Overall, constraining the numerical model with the electrical resistivity data shows a shallow temperature plume, reducing the cold infiltration to reach depth around -300, -500 m. Thus, the resulting permeability structure obtained at the end of the inversion shows a low permeability barrier, comparable to an alteration clay cap. Hot fluid flows are circulating through the volcanics layers, and permeability changes are likely to occur through mineralisation and alteration processes. Our method provides an automated methodology to image the subsurface structure and dynamics using the magnetotellurics data.

3 CONCLUSION

Magnetotellurics data and resistivity measures are widely performed in geothermal exploration and in volcanic monitoring programs. We used the non-intrusive geophysical data to calibrate a heat and fluid flow model using inverse modelling techniques. An improved fit to the resistivity data has been obtained by a factor 3-4. The permeability structure around the Nakadake crater is likely to host low permeability barrier at shallow depth (0-1 km) .

This approach better constrains the physical properties of rocks in complex volcanic settings and may offers a promising new tool for assessing subsurface structures near active volcanoes. More data could be used to provide a more robust inversion of the heat and fluid flow results. The methodology provides a novel integrated framework applicable to volcanics and geothermal contexts for quantitatively constraining fluid flow and thermal processes by geophysical measurements.

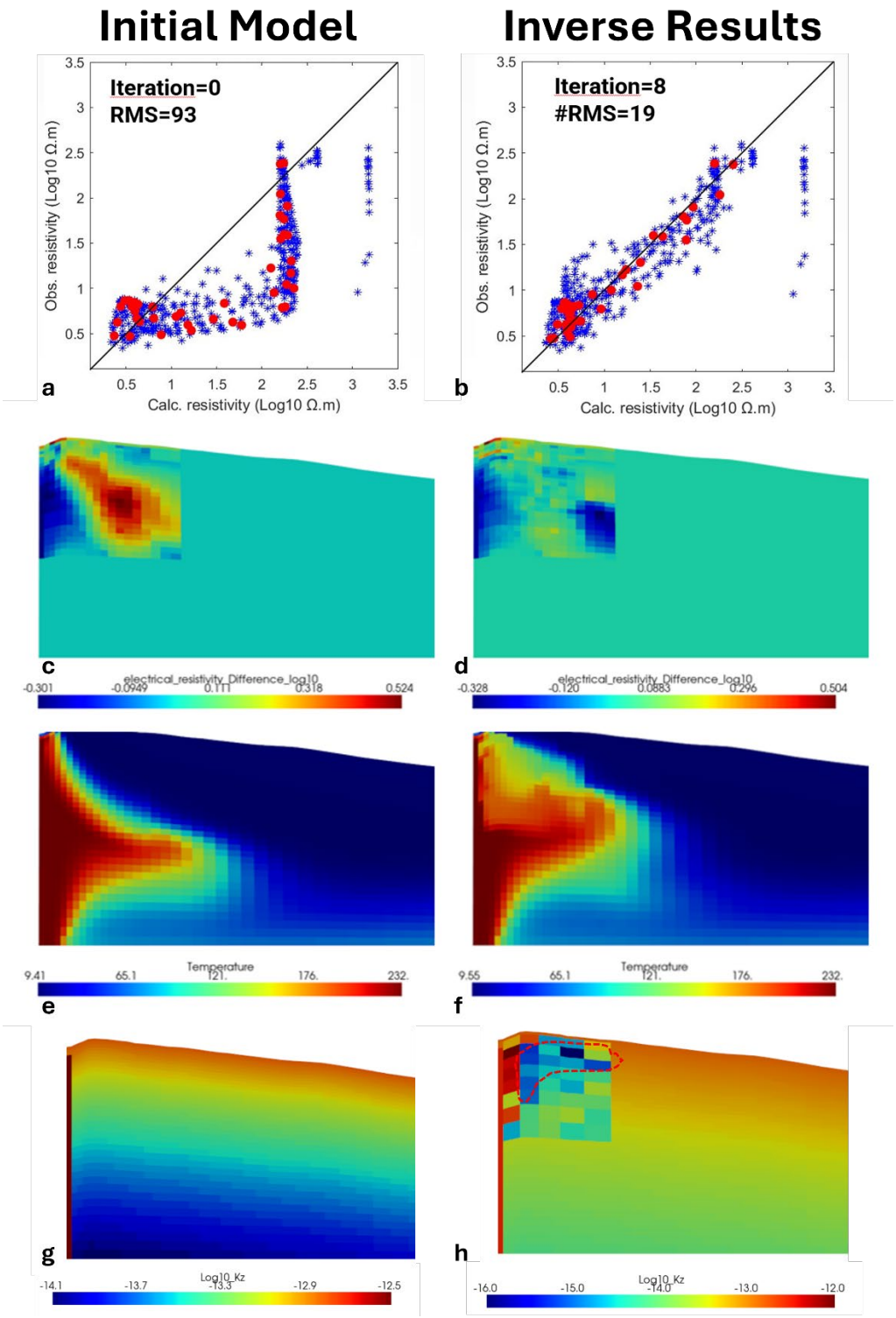


Figure 3: Initial model results (a, c, e, g) and the inverse model results (b, d, e, h). a, b) RMS fit for the observed resistivity versus the calculated resistivity; The red dots are the results in the Target area and blue stars are in the exterior domain. c, d) Electrical Resistivity Difference between the calculated resistivity from the TOUGH3 simulation and the observed resistivity (Kanda et al., 2019) in the Target area. e, f) Temperature results at the end of the TOUGH3 simulation. g, h) Vertical permeability distribution in the initial and best fit of the inversed model. A low permeability zone is identified in the vicinity of the surface by the red dashed line.

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