RESISTIVITY STRUCTURE AND HYDROTHERMAL SYSTEM AROUND THE WAITA VOLCANO IN CENTRAL KYUSHU, JAPAN

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ABSTRACT

Tensor controlled-source audio-frequency magnetotelluric (CSAMT) and self-potential (SP) surveys were carried out on and around the Waita volcano in central Kyushu, southwest Japan. This work is to figure out resistivity structures and hydrothermal system developed in the study area. Two-dimensional (2-D) forward modeling of both data was conducted separately using the finite element method. Final Tensor CSAMT resistivity models show a remarkable shallow low resistive zone, as low as 1-3 ohm-m, beneath Takenoyu-Hagenoyu geothermal field located in the western foot of the Waita volcano. A cap layer of 20-100 ohm-m underlies this zone. The SP profile calculated for the final model shows an excellent match with the observed one. The resultant 2-D model suggests the extent of fluid flow system around the Waita volcano including surface manifestation area on the foot of the volcano. This work concludes that there is an evidence of subsurface horizontal fluid flows starting from the southeastern part of the Waita volcano to its western foot in Takenoyu geothermal field. Moreover, it can also be concluded that a combination of magnetotelluric and self-potential survey is essential tool for geothermal exploration and reservoir monitoring.

1. INTRODUCTION

Resistivity structure and subsurface fluid flow are important information that we often rely on in geothermal field exploration and monitoring, respectively. In the recent years, geothermal exploration-development and reservoir monitoring have been respectively a major objective of the CSAMT and SP works. For the respective methods, it is because the CSAMT is suitable for detailed resistivity structural studies (e.g. Sandberg and Hohmann, 1982; Berktold, 1983). Because of its controlled source, CSAMT enables a greater signal-to-noise ratio and hence higher accuracy than natural source magnetotellurics, although the latter method has potential for greater depth of investigation. While, the SP method may indicate the locations of recharge or discharge zones, as well as their depths. Anomalies in electric potentials are often related to subsurface hydrothermal activities (Ishido, 1989). One of the biggest advantages of SP exploration is its low cost. The tools are simple, and surface SP is easy to measure, compared to downhole measurement.

In this work, related with the above mentioned, tensor CSAMT and SP surveys were carried out on and around the Waita volcano in central Kyushu, southwest Japan. A combination of these geophysical methods is aimed to clarify, in more detail; shallower subsurface resistivity structure and subsurface fluid flow of the hydrothermal system that has been developed around the volcano. This study applied two-dimensional finite element numerical modeling to model and evaluate quantitatively to both of CSAMT and SP data.

2. GEOLOGY AND GEOTHERMAL PROSPECT

Waita volcano is situated in the western part of the Hohi Geothermal Region (HGR) in central Kyushu **(Figure-1)**. The HGR is one of the most striking and enigmatic geothermal features in southwest Japan. The HGR is belonging to the western part of an extensive east-west elongated volcano-tectonic depression, called Beppu-Shimabara Graben, region formed under an extensional stress field after Neogene and Plio-Pleistocene to recent volcanism which took place at loci of eruption center characterizes large extent of volcanic rocks (Kamata, 1989).

From wells data compiled by Tamanyu (1985), the local geologic succession in the study area is summarized as follows. In general, Pliocene-Pleistocene volcanic rocks predominate in this area. The basement is placed by pre-Tertiary rocks, primarily Cretaceous granite and Paleozoic schist. They are absent as outcrops in the surface but occur in drill holes about 2 km below the surface. The basement is underlain by Tertiary and Quaternary volcanics, partly intercalated with lake sediments and their basement rocks. Tertiary rocks are composed of the Miocene and Pliocene strata. Quaternary rocks are composed of the Pleistocene strata and the Holocene fan and talus deposits.

There are rather minor faults in the study area. Most of them are having EW and NW-SE directions. They are commonly as normal faults (Ikeda, 1979). Among them, the Takenoyu fault is a well-known fracture zone and it seems to control white-color alteration zones (solidified or clay zones) seen at the surface, since they are widely distributed in the same direction as the elongation of the Takenoyu fault.

Special attention is paid at around the Waita volcano, particularly at the western foot of the volcano where Takenoyu-Hagenoyu geothermal field is located. A number of steaming grounds and hot-water discharged can be identified in the field. From the data reported by Kawamura (1985); there are at least 21 hot springs having temperature range between 36.5-87.8°C with the total hot-water and heat discharges of 524 l/min. and 323 kcal/sec, respectively.

Another factors make the area around Waita volcano a favorable geothermal prospect: there are several zones of great geothermal significance where the presence of strong conductivity contrasts at depth can be assumed, due to structural or lithological factors and especially to the existence of the remaining magma stills in process of cooling (Ehara, 1989).

3. METHODS

3.1. Survey Design and Data Acquisition

In the tensor CSAMT survey, two grounded bipole source polarizations are required to set-up in the field because, unlike natural source magnetotellurics, the CSAMT source is not omni-directional, but fixed in a specific polarization. The electromagnetic wave was transmitted, independently for each source, at twelve related frequencies from 4.2 to 8700 Hz. A receiver equipment, with four-channel recording system to measure magnitude and phase of orthogonal components of electric and magnetic fields (Ex, Ey, Hx, and Hy), was operated also in the frequency range within 4.2 to 8700 Hz. Widarto et al. (1992) measured at 58 sounding sites at twelve selected frequencies 4.2, 8.5, 17, 34, 68, 136, 272, 545, 1000, 2100, 4300, and 8700 Hz. Most of data are concentrated at the Takenoyu-Hagenoyu geothermal field, at the western foot of Waita volcano that shows intensive geothermal activity, mainly fumarolic activity **(Figure-2)**. The source-receiver separation ranges from 3 to 7 km. They have to be separated as far as possible to alleviate the so-called near-filed phenomena since the resistivity structure is *a priori* unknown to some extent (e.g. Zonge et al., 1986; Yamashita, 1984). In the near-field, the measured impedance has the minor effect of induction. Fortunately, the data that obtained from all measuring sites were free from near-field phenomena.

SP measurement was conducted from the summit of Waita volcano to its western foot where the Takenoyu hot springs area is located. Elevation from the summit of the volcano to the hot springs area differs by 750 m. The total number of the SP measurement points is 420 points with spacing of 50 m along survey lines. The survey region covers an area of about 4 km in the NW-SE and 2.5 km in the NE-SW directions. **Figure-3** shows the location of the SP survey point along Takenoyu to Waita volcano area.

3.2. Two-Dimensional Modeling

In this work, some prospective CSAMT survey lines are modeled in the manner of 2-D resistivity structure. The forward modeling used the finite element method applying the Galerkin weighted residual method as described in Reddy and Rankin (1975). The Galerkin weighted residual equation is written as,

$$L \sum_{e=1}^{m} f(e) - S \approx R \qquad (1)$$

where L is linear operator of Helmholtz equation, f is a field variable as a function of the impedance, S is source function, and R is residual error. By multiplying equation (1) to the weighted function (w_j), we obtain

$$\int_{v} WmRdv = 0 \quad ; m = i, j, k \qquad (2)$$

In this method, weighted function (w_j) is used as a coordinate function f(e). Detailed algorithm and the flow of computational code of the method are described in Widarto and Arsadi (1997). The result of those electrical resistivity models will be taken into account in the geological interpretation stage and as a basic data to generate model mesh in the modeling of SP data. However, in this paper, we present only our 2-D resistivity model of CSAMT line that crosses along the elongation of Takenoyu fault in NW-SE direction as shown in **Figure-4**.

A two-dimensional forward modeling of SP data is performed using a coupled fluid flow and SP simulator code PTSP that was developed by Yasukawa et al. (1993). This combined code calculates an SP anomaly for any two-dimensional mass and heat flow field. It contains two modules that compute a velocity and temperature field at any time and the corresponding SP field. This code can be used to quantitatively interpret SP data in terms of fluid velocities in up-flow zones and their projected depths from the surface. In this paper, a 2-D SP modeling was completed along the NW-SE line that parallel or nearly coincide with the one used for 2-D CSAMT model. **Figure-5** illustrates the SP model that extends in approximately 4.5 km long.

In PTSP, temperature and pressure distributions in a system are calculated based on the energy and mass conservation equations for proper boundary conditions. The distribution of fluid velocity is thus obtained and the current source distribution caused by fluid flow is calculated for a given electro-kinetic cross-coupling conductivity as follows;

$$S = -\nabla \mathbf{L_v} \cdot u - \mathbf{L_v} \nabla \cdot u \qquad (3)$$

where S, Lv and u are electrical current per unit volume (Amp/m^3), velocity cross-coupling conductivity (Amp-sec/m^3) and velocity field (m/sec), respectively. The induced SP distribution is then calculated for a given resistivity structure. Therefore input data of permeability, resistivity and cross-coupling conductivity distribution, in addition to boundary conditions are required for the calculation by PTSP. For more details, see Yasukawa et al. (1993).

Note that the temperature dependence of cross-coupling conductivity is automatically calculated in PTSP. According to Sill (1983), the variation of L_v with temperature T below 300°C is approximately described by;

$$Lv\ (T) = Lvo\ \ (1 + C\Delta T), \quad \Delta T = T - To \qquad (4)$$

where C is a constant and subscript 0 indicates the reference temperature T_o. This equation is introduced in PTSP with the constant C=0.01 (°C^{-1}), which is consistent with the experimental results of Ishido and Ishido and Mizutani (1981), as well as those of Morrison et al. (1978).

4. RESULTS AND DISCUSSION

As shown in **Figure-4**, the 2-D resistivity model shows the existence of a highly anomalous zone at a relatively shallow depths ranging in tens meter beneath the Takenoyu hot springs area. Low-resistive layer of less than 10 ohm-m places this zone, and beneath some sites are extremely low, less than 1 ohm-m. This zone extends from Takenoyu hot springs area to the southeastern foot of Waita volcano and crosses the top of the volcano in NW-SE direction. This anomalous zone is also detected beneath the summit of the volcano but at deeper part of about 300 to 400 meter below the surface. Surface geological mapping suggests that the extension of this anomalous zone corresponds with the direction of geological structure that associated with fault or fracture zones. These facts bring our assumption that there is an evidence of subsurface horizontal fluid flows developed beneath the Waita volcano and it's adjacent.

The principle question to be addressed in interpreting the obtained model is the nature of this extremely low-resistive zone. A high temperature may cause the existence of a low-resistive zone in many volcanoes. The source of high temperature is considered to be magma intrusions or hot hydrothermal fluids. However, there is no evidence of the existence of magma at a shallow depth except during the periods of eruption of Waita volcano. The low-resistive zone in the study area exists at shallow depths. It is well known that, at shallow depths, the resistivity of rocks is mainly a function of porosity, permeability, and pore fluid resistivity, which the latter being dependent upon temperature. The resistivities can also be decreased by melting of rocks, but this phenomenon appears at temperatures over 700°C and under the pressure of 2 or 3 km depth (Wyllie, 1971). The subsurface temperature in the vicinity of Waita volcano is less than 200°C at 2 km depth as estimated from wells data.

To illustrate the effects of temperature and pressure on pore fluids, Hermance (1973) who compiled data from Quist and Marshall (1968) describes the relationship of electrical resistivity to depth and temperature for lithostatic and hydrostatic conditions and for geothermal gradients of 60° and 120°C/km. His result shows that at shallow depths the electrical resistivity decreases with temperature because the pore fluid viscosity is decreasing, but ionic association increases resistivity below depths of about 2 and 5 km for the two gradients.

Rock resistivity variations with temperature depend on the variation of pore water resistivity at up to 370°C. The resistivities of hot spring water discharges near Kuju-Iwoyama area, at the southeast-west of Waita volcano, vary from 5 to 10 ohm-m (Ehara et al., 1981; NEDO, 1989). Unfortunately, the resistivity data measured from the hot water discharge in the vicinity of Waita volcano is not available here.

White-color alteration zones (solidified or clay zones) seen at the surface around Takenoyu area. They are widely distributed in the same direction as the elongation of the Takenoyu fault. Characteristic minerals in the white colored alteration halos are pyrophyllite, alunite, kaolinite, cristobalite, quartz and K-feldspar. Rock resistivities decrease with increasing content of altered minerals such as clays. Mogi et al. (1986) deduced theoretically a formula of expressing the excessive conduction of clay based on the surface conduction theory. They showed that rock resistivity decreases with increasing specific surface area. For a prolate particle with a surface area of 20 m^2/g, the resistivity decreases into 60% of the original value when pores are filled by water whose resistivity is 10 ohm-m and about 30% when the pore water is 1 ohm-m. Mogi (1992) showed that this theory is applicable to volcanic and granitic rocks in Kuju area and its surrounding. Some rock samples of well data DB-1 to DB-5 contain a small amount (less than 1%) of pyrite (Takashima et al., 1985), which should partially contribute to the reduction in resistivity. Mogi and Hamasaki (1990) collected rock samples from a borehole 3 km from the south of Kuju-Iwoyama and measured resistivity value of the samples at room temperature. They showed that, include the 1 ohm-m pore water, the resistivity values of volcanic rocks are within the range of 15-30 ohm-m and porosities are 10-25%. These rocks are weakly altered and their specific surface area from 5 to 16 m^2/g. These resistivities are higher by one order of magnitude that the value of the low resistivity zone. The low resistivity zone must be more porous and more strongly altered. From these discussions, it can be concluded that the extremely low resistive zone exists at shallow depths beneath the fumarous area and is caused by a severely fractured zone having high porosity (>30%), a strong alteration zone accompanied by many clay minerals (high specific surface area of >20m^2/g), and high subsurface temperature (~200°C). Much hydrothermal fluid is flowing up and convecting in this zone.

For the SP data modeling, an idealized fluid flow models were examined with PTSP in order to understand the effects of electrical resistivity, cross-coupling conductivity and temperature distribution on SP profiles. The topographic effects on SP for inhomogeneous cases were also investigated. In the next step, a more realistic flow model beneath the Waita volcano in its natural state was developed to conduct a data matching of observed and calculated SP profiles. Since there is no information about hydraulic conductivity in this area, permeability distribution in the model was supposed and gradually improved by trial and error method while resistivity distribution was fixed based on the obtained resistivity model. The SP profile calculated for the final model shows an excellent match with the observed one. The resultant two-dimensional model suggests the extent of fluid flow system developed around the Waita volcano including surface manifestation area on the foot of the volcano.

Generally, a positive SP anomaly is interpreted as an up-flow zone and/or a discharge zone and negative as down-flow and/or recharge zone. However the exact location of these flow zones are not necessarily corresponding to the highest SP anomaly because of the inhomogeneity of the subsurface structure (Yasukawa et al., 1993). Therefore an analysis of SP data considering the hydrological and electrical structure is invariable for its interpretation (Yasukawa and Mogi, 1998). Around the volcano, SP tends to decrease according to the elevation but high negative anomaly up to 600 mV can be observed at the middle height of the volcano. As mentioned previously, negative peak anomaly of an SP profile has been generally interpreted as an indicator of a recharge zone. However, numerical modeling of the subsurface fluid flow and its corresponding SP shows that a negative peak anomaly at the middle height of a mountain can not be explained by a model with a higher permeability in the middle height nor by a homogeneous permeability model. Further simulation suggests the existence of a higher permeability column underneath the summit of the volcano. The hot water flows up beneath the volcano and flows horizontally toward the geothermal system that has been developed at the foot of the volcano. All of these results well agree with the previous geological and geophysical surveys, as well as the record of drilling data conducted by Tamanyu (1985).

5. CONCLUDING REMARKS

The results of tensor CSAMT and SP studies in around the Waita volcano bring the conclusions as follows.

An extremely low anomalous resistive zone is recognized at shallow depths of tens meter beneath the Takenoyu fumarous area in the western foot of the volcano. This zone seems to extent to the southeastern part of the volcano as the elongation of the so-called Takenoyu fault. The possible causes of this low resistivity value should be explained due to porous and strongly altered rocks with temperature range of 150° to 200°C, the porosity of >30% and specific surface area of >20 m^2/g on the basis of experimental results of Mogi and Hamasaki (1990).

The SP profile calculated for the final model gives an excellent match with the observed one. The resultant two-dimensional model suggests the extent of fluid flow system developed around the Waita volcano including surface manifestation area on the foot of the volcano. Further simulation concludes the existence of a higher permeability column underneath the summit of the volcano. The hot water flows up beneath the volcano and flows horizontally toward the geothermal system that has been developed at the western foot of the volcano in the Takenoyu area.

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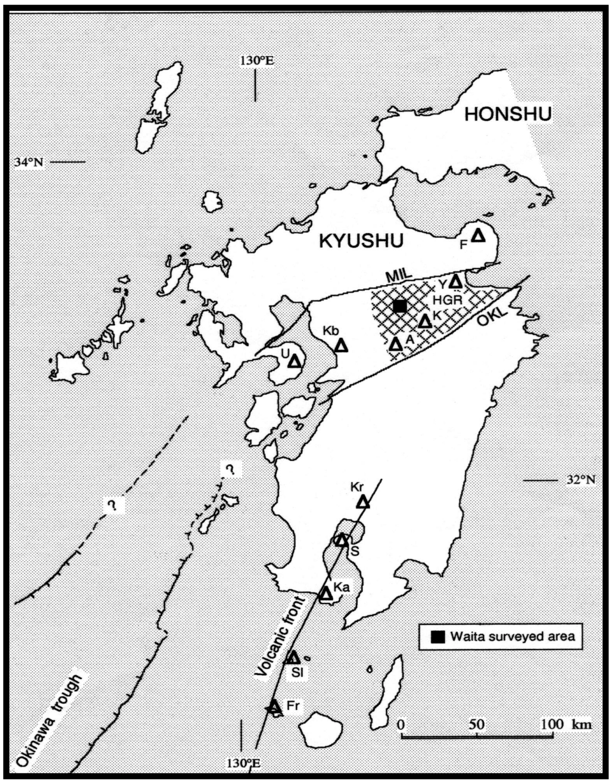

Fig. 1 Major tectonic structure in and around Kyushu. Cross-line marked area is the Hohi Geothermal Region. The Okinawa trough bounded by normal faults is also illustrated. Open triangles are Quaternary volcanoes (U=Unzen, Kb=Kinpou, A=Aso, K=Kuju, Y=Yufu-Tsurumi, F=Futago, Kr=Kirishima, S=Sakurajima, Ka=Kaimondake, SI=Satsuma-Iwojima, Fr=Furudake). MIL= Matsuyama-Imari Tectonic Line, OKL=Oita-Kumamoto Tectonic Line, and HGR is the Hohi Geothermal Region (after Kamata, 1989).

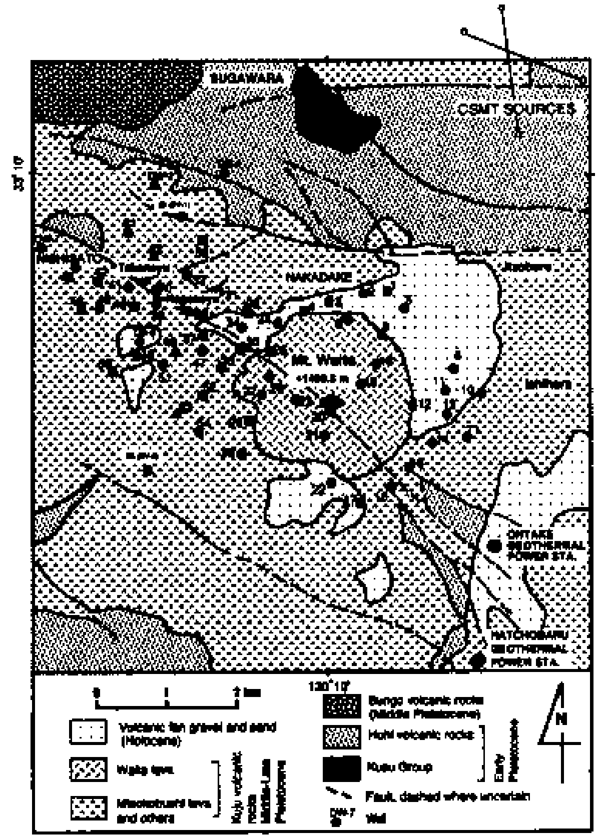

Fig. 2 Surface geological map around the Waita volcano. Crossed Solid lines in the upper part of the map and dashed circles are tensor CSMAT sources and sounding sites respectively.

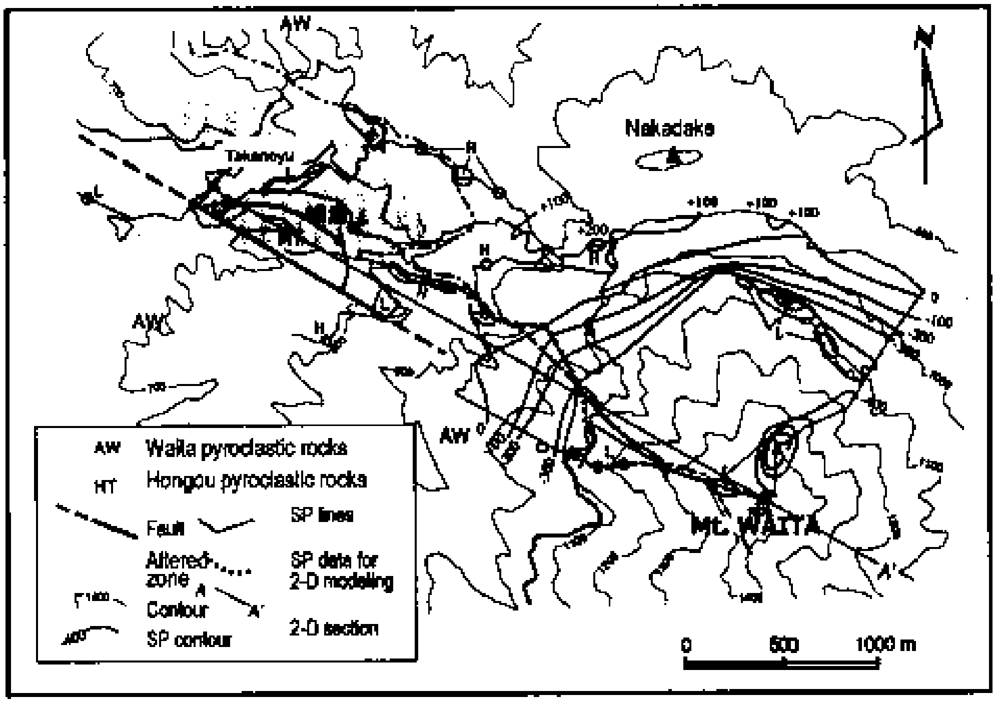

Figure-3
Self-potential survey lines around the Waita volcano

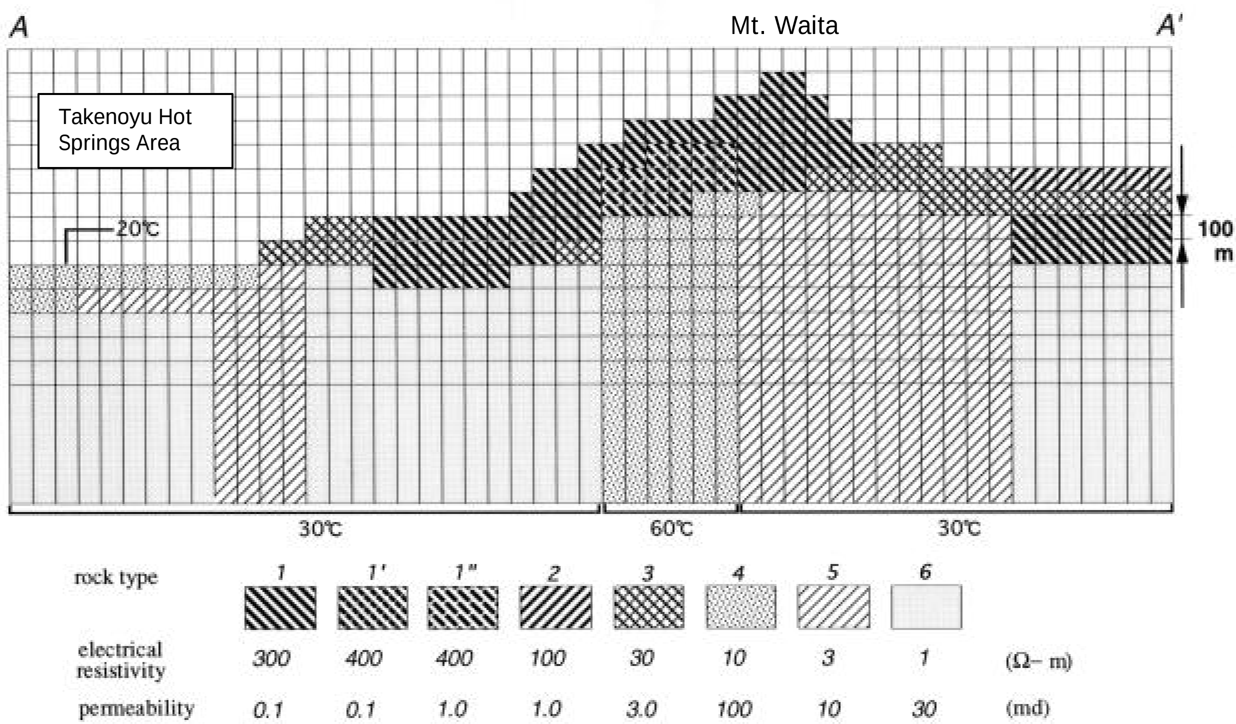

Fig. 4 Resistivity model that obtained from two-dimensional forward modeling of CSAMT data. This model is then being used as input model for PTSP numerical simulator in which parameters such as permeability, tempe-rature and resistivity data are taken into consideration.

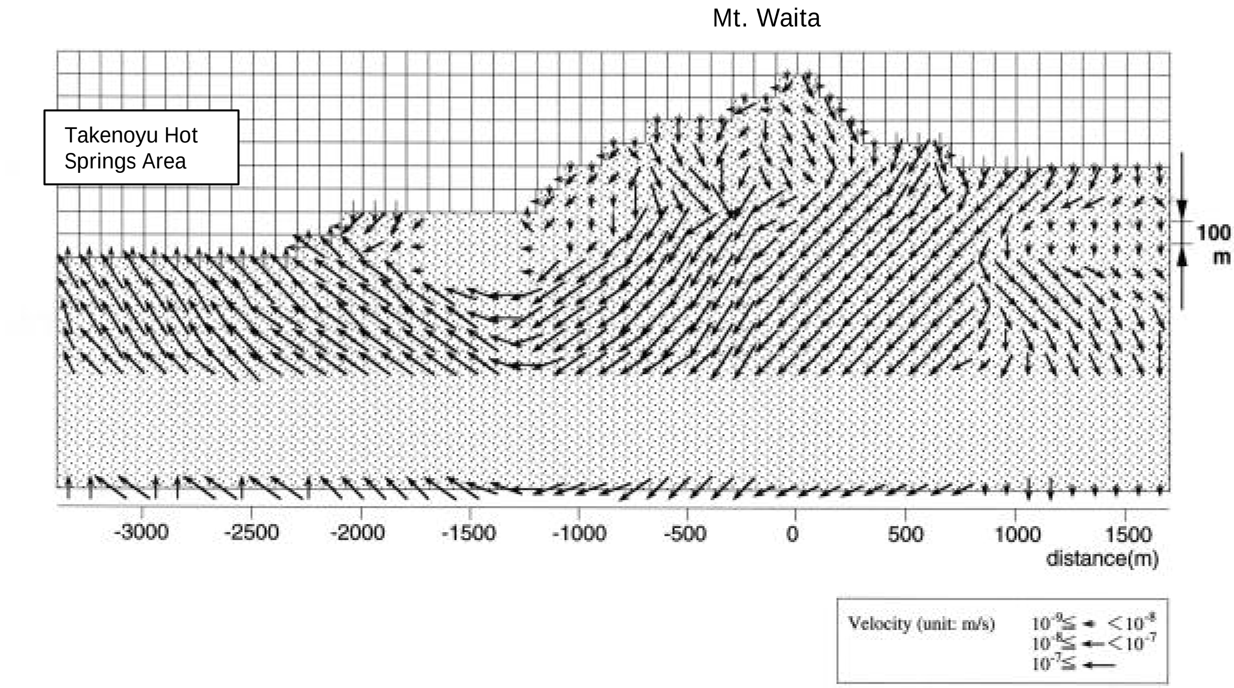

Fig. 5 Fluid velocity distribution as obtained using PTSP numerical simulator of the model with its parameters in Figure 4.