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Magnetotelluric resistivity modeling for 3D characterization of geothermal reservoirs in the Western side of Mt. Aso, SW Japan

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Abstract

Geothermal reservoirs are usually located at a depth range of 2 to 5 km, so to efficiently utilize such resources an advanced prospecting method is needed to detect these deep geologic structures. This study aimed to three-dimensionally characterize geothermal reservoirs by a combination of Magnetotelluric (MT) survey, inversion analysis of apparent resistivity, and interpolation of the resistivity data obtained. The western side of Mt. Aso crater, southwest Japan, was chosen as the case study area. Three hot springs exist there and a fault is assumed to go in the direction connecting them. A MT survey was carried out at 26 sites and the data processed by a remote reference method to reduce artificial noises. Based on skewness and Mohr circle analyses of the impedance tensor, the local geologic structure at each site could be approximated as horizontally layered and therefore, a one-dimensional inversion analysis was applied to the MT raw data. The resultant resistivity column data were then interpolated by the three-dimensional optimization principle method. The resistivity distributions obtained clarified continuous conductors with especially low resistivity (less than 10 $\Omega \cdot$m) at the hot springs along the fault. Because the resistivity decreases largely with an abundance of clay minerals, the conductors could be considered to correspond with the cap rocks. Thus, two geothermal reservoirs, whose shapes were estimated to be pillar, were detected under the cap rocks in an elevation range of -1000 to -3000 m. By comparing the resistivity distributions with the temperature distributions based on fluid-flow calculations at a steady state using FEM, the validity of the location and dimension of the estimated reservoirs were confirmed.

Keywords: MT survey; Resistivity; Geothermal reservoir; 3D characterization; Mt. Aso, SW Japan

1. Introduction

Geothermal energy is a clean and sustainable natural resource because it has a small load on the earth's environment, and is especially important in

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Japan where there are many active volcanoes. During the two Sunshine Projects of Japan carried out in 1974 and 1993 to develop energy alternatives to oil, much importance was placed on geothermal sources. Most geothermal energy is obtained in areas where there are surface manifestations such as fumaroles and hot springs, which originate from geothermal reservoirs usually located at a depth range of 2 to 5 km. Geothermal reservoirs are generally composed of porous rocks covered by impermeable layers (cap rocks). Fractures in the reservoirs have important roles as paths and storage places for hydrothermal fluids. Investigative methods that can detect at great depths are indispensable to characterize the locations, dimensions, and shapes of geothermal reservoirs. Sophisticated detection methods can contribute to the efficient development of geothermal energy. Geophysical prospecting methods applicable to reservoir characterizations are restricted to seismic and MT (magnetotelluric) surveys. MT survey is seen as more effective because the electrical properties of rocks are related in part to geothermal and fluid conditions.

Thus, MT surveys have been used widely in geothermal research (e.g., Lagios et al., 1998; Patricia et al., 2002). Three-dimensional modeling of resistivity is the most challenging topic in this field and is essential to accurately characterize reservoirs. However, it is difficult to obtain reasonable results because such modeling and inversion are valid only under a lattice arrangement where sites are measured with small spacings (e.g., Monteiro Santos et al., 2002; Pous et al., 2002). This condition is usually not satisfied due to the topographic restrictions of study areas. To overcome this problem, a methodology based on a combination of inversion and three-dimensional interpolation for MT data obtained at irregularly spaced sites in a mountainous geothermal area has been proposed and applied in research. The western side of the Mt. Aso crater, southwest Japan, was chosen as our case study area to test this combination method. Mt. Aso has the largest caldera in Japan, formed about 90,000 years ago, and the volcanisms which took place after the formation have created the present topography. According to a drilling investigation by the New Energy and Industrial Technology Development Organization NEDO (1994), the main lithologies of the study area from the surface to 1700-m depth are lava, volcanic rocks, lake sediments, and pyroclastic flow deposits. Clay minerals such as sericite and chlorite are rich partly due to the hydrothermal alternations.

By comparing the resistivity model with temperature logging data and temperature distributions based on a fluid-flow calculation at a steady state using FEM, the validity of the location and dimension of the reservoirs estimated from resistivity distributions are discussed and a conclusion is drawn.

2. MT survey method

The MT survey was carried out from Oct. 24 to Nov. 26, 2001. There are three hot springs in the study area, Yunotani, Yoshioka, and Jigoku, with active blowing off of vapors. The resistivity structures around a fault assumed to connect these hot springs are studied. Fig. 1 shows the arrangement of the 26 measurement sites, which were set apart from artificial noise sources and steep topography. Due to these restrictions, the sites could not be regularly spaced.

MTU-5 and MTU-2E of Phoenix Geophysics, Ltd. are used in the survey. MTU-5 measures two orthogonal components of an electric field, (E_x, E_y), and three components of a magnetic field, (H_x, H_y, H_z), whereas MTU-2E is an instrument for electric fields only. The x-, y-, and z-axis are defined along the N–S, E–W, and vertical directions. These electric and magnetic field components are connected by an impedance tensor, $\mathbf{Z}$, as follows:

$$\left.\begin{aligned} \begin{pmatrix} E_x \\ E_y \end{pmatrix} &= \mathbf{Z}\begin{pmatrix} H_x \\ H_y \end{pmatrix} \\ \mathbf{Z} &= \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \end{aligned}\right\} \quad (1)$$

Following Vozoff (1986), skewness, S, and tipper magnitude, T, are defined respectively by

$$\left.\begin{aligned} S &= \left|\frac{Z_{xx}+Z_{yy}}{Z_{xy}-Z_{yx}}\right| \\ T &= \sqrt{\left(\frac{H_z}{H_x}\right)^2+\left(\frac{H_z}{H_y}\right)^2} \end{aligned}\right\} \quad (2)$$