Preliminary Magnetotelluric Modeling in the Nikko Volcanic Area
—Potential Break of Fluid Trap by Volcanic Intrusion

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We collected magnetotelluric data in the Nikko volcanic area in the period range from
0.01 to 10 sec. Impedance data were decomposed with the regional strike direction N0°E and
were analyzed by two-dimensional inversions including static shifts as model parameters. The
major model features are: (1) southern conductor at 8 km depth which is consistent with the
seismic S-wave reflectors, (2) northern conductor located at 5 km depth, consistent with the
seismic attenuation zones, and (3) a resistive gap in between, consistent with the magnetic
body inferred from aeromagnetic data. The two conductors probably imply trapped free
water at around 400°C. The resistor in between implies the volcanic body, which intruded
the crust and may have broken the regime of trapped free water.

1. Introduction

The Nikko region is located on the volcanic front of the northeastern Japan arc, as shown
in Fig. 1. This area has been a target for intensive seismological studies because of the high
seismic activity. Seismic reflective layers have been found most clearly in the south of Nikko-
Shirane volcano, which is currently active (Mizoue et al., 1982; Horiuchi et al., 1988, Matsumoto
and Hasegawa, 1996). The reflective layer shallows toward the volcano and has been interpreted
as representing a layer containing magmatic melt (see Fig. 1). Horiuchi and Tsumura (1995)
observed seismic wave attenuation and mapped attenuation zones in the upper to mid crust. High
attenuation zones are located consistent with the reflectors detected by Matsumoto and Hasegawa
(1996), and they spread further to the north, shallowing toward Nikko-Shirane volcano.

The objective of our study is to derive information on another independent and important
physical parameter, the electrical resistivity, by use of the magnetotelluric (MT) method. Electric
conduction in crustal rocks is usually controlled by ionic conduction through pore fluid, rather
than the matrix itself. Thus the resistivity of rocks is a function of porosity and fluid resistivity.
The resistivity is also sensitive to the existence of melt.

If there is partially molten magma in the crust and the porous structure containing magma
is well connected, the effective bulk resistivity can be as low as 1 Ω·m, depending on the degree
of partial melting (e.g. Honkura, 1975; Shankland and Waff, 1977). Thus our goal is to examine
whether a conductor representing fluid or melt exists beneath the Nikko area. In this short letter,
we describe the preliminary results.

2. Data Acquisition

We carried out MT measurements at seven sites shown in Fig. 1. This area includes the
inaccessible national nature conservation area, and hence our sites could not be aligned in the
north–south direction. In fact, main five sites are located along a SW–NE line. We selected one
site in the north of Nikko-Shirane volcano, and another at the southern end of the area. These two sites were also utilized as remote reference sites for the main five sites.

The southernmost one of the main five sites is located over the northernmost part of the seismic reflective zone which has been detected so far (Matsumoto and Hasegawa, 1996). We used two sets of V5-MT system manufactured by Phoenix Geophysics Ltd., Canada. The frequency range was from 320 Hz to $5.5 \times 10^{-4}$ Hz (1,820 sec in period). Severe cultural noises turned out to arise, especially from rather remote DC-operated railway systems, and restricted our measurements to the hour range from midnight to early morning. Thus the usable longest period was about 5 sec to 100 sec.

3. Data Processing

After inspecting the time series data, we found a regularly appearing noise of specific waveform, probably from a nearby telephone system or the like. The duration of the noise waveform was approximately 4.5 sec, and it repeatedly appeared every one minute. Since the noise waveform was consistent throughout the night, we could make pseudo time series by subtracting one-minute-shifted time series from the original time series. We reprocessed the pseudo time series with remote reference and found that the quality of impedance estimates was fair in the period range shorter than 10 s.
Fig. 2. (a) Decomposed apparent resistivity at the five sites. The plus and cross signs denote the TM and the TE mode data, respectively. Error bars represent respective one standard deviation. Solid and broken lines represent TM and TE mode model responses including static shifts. (b) Same as (a) except that the model responses do not include static shifts. Differences between (a) and (b) represent the static shifts. (c) Decomposed phases at the five sites. The plus and cross signs denote the TM and the TE mode data, respectively. Error bars represent respective one standard deviation. Solid and broken lines represent TM and TE mode model responses. (d) A model of resistivity structure along the N–S profile. Sites are projected onto the profile (see Fig. 1).
4. Tensor Decomposition

In recent data analyses and modeling, it is often assumed that the structure is approximated by a three-dimensional local anomaly superposed on a regional two-dimensional structure. In this case, first of all, we need to establish a regional strike direction for the dataset. For this we used the extended code of Groom and Bailey (1989) in which the twist and the shear are period-independent and the strike is period- and site-independent (McNeice, 1994).

The regional strike estimated for the period band 0.1 to 10 sec is N90°E. In the magnetotellurics the strike direction determined from the impedance tensor has ambiguities of π/2. Thus N0°E is also a best fitting strike direction. Induction vectors have maximum responses at around 3Hz, and their real part point to the north (Fig. 1). Thus we chose N90°E as a regional strike. Figures 2(a), (b), and (c) include plots of the decomposed apparent resistivity and phase responses. Corresponding to the large induction arrows at around 3 Hz, we found a large phase split between the two principal impedances (Fig. 2(c)). In the following two-dimensional modeling, we project the five sites on a profile as shown in Fig. 2.

5. Two-Dimensional Modeling

The decomposed data are still affected by site gain and anisotropy, that is, by the so-called static shift. We included static shifts as model parameters in addition to the model resistivity (Ogawa and Uchida, 1996). The misfit was minimized under the two constraints; one is the Laplacian model roughness and the other is static shift $L_2$ norm. Tradeoff parameters between the misfit, model roughness and static shift norm were determined so that the Bayesian likelihood of the data is maximized. The initial model was a 1,000 Ω-m uniform earth and the initial static shifts were set to zero. The error floor for the apparent resistivity was assumed as 10% and an equivalent for the phase. After 20 iterations, the model parameters converged with rms = 1.38.

The final model is shown in Fig. 2(d) with the vertical exaggeration as 0.2. Model responses are shown as curves in Figs. 2(a), (b), and (c). They give reasonable fit to the major features of the decomposed apparent resistivity and phase values. It should be noted here that the model responses in Fig. 2(a) include static shifts, whereas those in Fig. 2(b) do not. The differences in the apparent resistivity values between Figs. 2(a) and (b) correspond to the estimated static shifts.

6. Discussion and Conclusion

We conducted a resolution study on the final resistivity model(Fig. 2(d)). Figure 3 shows a simplified model where only well resolved features are drawn.

At the surface, the resistor is almost exposed in the southern sites, whereas 1 km thick conductor($C_1$) is covering the surface in the northern sites, implying Oku-Nikko-Caldera fill (Takakura, 1991).

In the upper to middle crust we have two significant conductors. One is $C_2$ at 8 km depth in the southern part, where seismic S-wave reflectors are found clearly at same depth. This coincidence implies existence of magmatic melt or free water. Although the seismic S-wave reflector shallows toward Nikko-Shirane Volcano, the reflector does not always mean magmatic melt itself, but it can also be a layer of trapped free water. Dehydrated free water is supplied from the deep crust. Hydration reaction and precipitation of minerals take place at around 400°C, leading to creation of layers of trapped free water (Jones, 1987; Hyndman, 1988). This interpretation is supported by the cutoff depth of the earthquakes, under which there are no earthquakes (Fig. 3). The seismicity cutoff depth is interpreted as brittle/ductile boundary, and geotherm (Matsumoto and Hasegawa, 1996). The reflector is dipping parallel to the seismicity
Fig. 3. Simplified resistivity structure and known seismic information: the seismic reflective layers and the lower limit of shallow seismicity beneath which there are no earthquakes (after Matsumoto and Hasegawa, 1996). Crustal conductors are assumed to extend beyond the profile length.

cutoff. Thus the coincident reflector and conductor (C2) can imply layer containing free water. Matsumoto and Hasegawa (1996) analyzed the thickness of the reflector as less than 100 m. On the other hand, C2 is \( \approx \)2 km thick. This discrepancy can be reconciled if we take the equivalence of the model into account. We get an equivalent conductive layer as far as we keep conductance (thickness divided by resistivity) unchanged (Jones, 1987). Thus the conductors can be 100 m thick if the resistivity is one twentieth of the original (\( \approx 50 \) \( \Omega \cdot \text{m} \)), i.e., \( \approx 2.5 \) \( \Omega \cdot \text{m} \).

The other mid crustal conductor is C3 located at 5 km in the northern part. This is consistent with the high attenuation zone of seismic waves (Horiuchi and Tsumura, 1995), which is significant between Nantai and Nikko-Shirane volcanos at the depth of 4 to 6 km. The attenuator has southward extension and is located consistently with the S-wave reflectors further to the south.

Between C2 and C3, there is a resistive gap (R in Fig. 3). The location of the resistor coincides with that of the magnetic body which was inferred from the analysis of aeromagnetic data over the Nikko region (Makino, 1996, personal communication). We interpret the high resistivity/magnetic body as representing a intruded volcanic body itself. Its location also coincides with the northern edge of the known seismic reflectors and the high seismicity region (Fig. 3). This crustal heterogeneity is likely controlling the local seismic activities.

One of the possible interpretations for the above geophysical evidences, (seismicity, seismic reflector, resistivity, and magnetic properties) is the formation of the fluid trap at the mid-crust and its breakage between Nantai and Nikko-Shirane by the intrusion of the Quaternary volcanic body.

Throughout the profile, a deep conductor was inferred below 18 km depth, however its resolution is poor. More MT soundings are underway extending both the profile length and the
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