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The Resistivity Structure around the Hypocentral Area of the Ebino Earthquake Swarm in Kyushu District, Japan

Tadanori GOTO, Naoto OSHIMAN, and Norihiko SUMITOMO

Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji City, Kyoto Prefecture 611, Japan

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Wide band and dense MT soundings on the hypocentral area of the Ebino earthquake swarm, which occurred in 1968, in southern Kyushu were performed to examine the existence of fluid in the hypocentral area, which possibly caused the earthquake swarm. The regional strike and the induction arrow were calculated first. Then a two-dimensional resistivity structure beneath the surveyed area is calculated by using an inversion technique. The best fitted model shows that the hypocentral area is relatively more resistive than the surrounding area. We conclude that a large mass of fluid is not likely to exist in the hypocentral area.

1. Introduction

Recently, much interest has been focused on fluid from the deep interior of Earth's crust as one of the causes of earthquake swarms. It has been argued in seismogenic models that fluid plays important roles to trigger earthquakes (Byerlee, 1990; Rice, 1992; Blanpied *et al.*, 1992). For example, Sibson *et al.* (1988) suggested that overpressured fluid below the seismogenic zone is periodically expelled upward through the fault zone during the process of earthquake rupture. Some field observations also suggest importance of existence of fluid for earthquake swarms. During the Matsushiro earthquake swarm, which occurred in 1965–1967 in central Japan, a gush of a significant amount of water was found. The total amount was estimated at 10^7 m^3 (Wakita *et al.*, 1978) and the change of flow rate was correlated with the seismic activity (Ohtake, 1976). Wakita *et al.* (1978) found an anomalous high ^{3}He to ^{4}He ratio in upwelled water. They concluded that the origin of helium is the upper mantle and suggested that the water was upwelled from a deeper part than the earthquake swarm zone. The time variation of the geomagnetic total field which was observed during the Matsushiro earthquake swarm is also considered to be caused by a large mass of water which had come from the lower crust (Sasai, 1994). In addition, Ohtake and Hamada (1975) found the seismic activity of the Matsushiro earthquake swarm showing a tendency to move upward with the progression. In other earthquake swarms, similar spatial variations of hypocentral areas are found (Tanaka, 1990). It is well-known that the resistivity of crustal material is controlled largely by the existence of fluid so that studying resistivity structure is in one sense finding the fluid in the crust. However, detailed structure of resistivity around a hypocentral area of an earthquake swarm has not been well-understood and such fluid has not been identified except for the Matsushiro earthquake swarm.

The Ebino earthquake swarm occurred during 1968–1969 in Ebino, near the Kirishima volcanoes in the southern Kyushu district of Japan (Minakami *et al.*, 1969, 1970). The Kirishima volcanoes are Quaternary composite volcanoes including Mt. Karakuni-dake (see Fig. 1). Basement rocks of the Kirishima volcanoes are Cretaceous to Paleogene sedimentary rocks (Shimanto group) and early to middle Pleistocene volcanic rocks (Imura, 1994) and the surface consists of lava flows, tuff, andesite and other volcanic rocks (Aramaki, 1968). The Ebino earthquake swarm occurred near the center of the Kakuto caldera in the northwestern foot of the Kirishima volcanoes. Locations of epicenters during the Ebino earthquake swarm are shown in Fig. 1. The

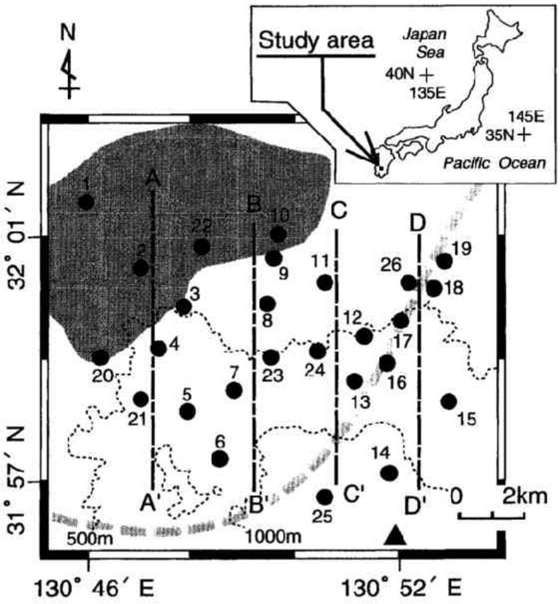

Fig. 1. Location of the study area and magnetotelluric stations(circles). Four profiles are discussed in this paper (AA′, BB′, CC′ and DD′; dashed-dot lines). Circles with numbers denote locations of the sites used for the modeling of the two-dimensional resistivity structure. The epicentral area of the Ebino earthquake swarm (Minakami *et al.*, 1970) is indicated by the hatched area. The location of Mt. Karakuni-dake, one of the Kirishima volcanoes, is also shown (triangle). Dashed lines indicate the topography. A gray broken line indicates the southeast rim of the Kakuto caldera after Tajima and Aramaki (1980).

magnitude of the largest earthquake was 6.1 on the Richter scale, which occurred near the center of the hypocentral zone. Minakami *et al.* (1970) reported that the hypocenters of the Ebino earthquake swarm were distributed in depth from 3 to 9 km and in horizontal extent from 5 to 10 km. Five earthquake swarms have been observed in the Kakuto caldera since 1913 (Miyazaki *et al.*, 1976), with the 1968–1969 Ebino earthquake swarm being the largest. Four of them occurred near the center of the caldera except for a small earthquake swarm which occurred in 1975 in the east area of the caldera (Miyazaki *et al.*, 1976). However, the recent seismicity under the Kakuto caldera is low (Kagiyama, 1992).

In this paper, we are going to present a hypothesis and examine the validity of it. The hypothesis is that the major cause of the 1968–1969 Ebino earthquake swarm was a large amount of fluid or magma intruding from deep interior of the Earth. The reasons which leads to the hypothesis are the following: One is that, according to Minakami *et al.* (1970), the activity of the Kirishima volcanoes occasionally followed earthquake swarms in the Kakuto caldera and the 1968–1969 Ebino earthquake swarm was related to the magma supply system of the Kirishima volcanoes. We consider that not only magma but also fluid released from magma possibly triggers or gives some influence to the Ebino earthquake swarm. Another is a correlation between the frequency of seismic P waves of the Ebino earthquake swarm and the location of its hypocenters (Watanabe, 1970). Watanabe (1970) pointed out that the seismic waves show the lower frequency near the center of the focal area than in the periphery of the focal area. The attenuation of the seismic wave increases with crack density if the cracks are saturated by fluid (O'Connell and Budiansky, 1977). Those observations imply that fluid may have caused the Ebino earthquake swarm. There have been no reports about this earthquake swarm to demonstrate overflows of fluid from underground or eruptions of vapor on the earth's surface such as those observed at the Matsushiro earthquake. Therefore, there is a possibility that fluid remains in the subsurface, maintaining a low resistivity around the hypocentral area if the Ebino earthquake swarm followed a large amount of upwelled fluid such as the Matsushiro earthquake. The purpose of the present study is to investigate the resistivity structure around the hypocentral area of the Ebino earthquake swarm and to discuss the possibility of existence of fluid in the hypocentral area.

2. Data Acquisition and Analyses

Research group for Crustal Resistivity Structure in Japan (referred to as RGCRS) carried out magnetotelluric(MT) soundings and geomagnetic depth soundings (GDS) at 26 sites around the Kakuto caldera in 1994 (Sasai *et al.*, 1995). The locations of the sites are shown in Fig. 1. These sites are located between Mt. Karakuni-dake and the epicentral area of the Ebino earthquake swarm. The locations were selected in order to examine if fluid or magma, which may be related to both volcanic and seismic activities, exists in the area. RGCRS used the MT measuring system manufactured by Phoenix Geophysics Ltd. Magnetic sensors of this system are induction coils. Electrodes are of the Pb-$PbCl_2$ type and are usually separated about 50m for measurement of electric fields. RGCRS observed the natural fluctuations of the magnetic and electric fields for about three days at each site. After that, the impedance tensor, apparent resistivity, impedance phase, induction arrow and other electromagnetic responses are calculated in the broad band of almost continuous frequencies between 0.00055 Hz to 384 Hz. These response functions are calculated according to the remote reference method (Gamble *et al.*, 1979). In this survey, four sites were set simultaneously. As the reference site, we chose the site with the best quality data from the simultaneous four sites.

It is necessary at first to determine the strike direction at each site to confirm whether the resistivity structure beneath the studied area is two or three dimensional. To estimate the direction of the strike at each site, the method by Chakridi *et al.*(1992) is applied. This method avoids the effect of surficial galvanic distortion (Groom and Bailey, 1989). If a rotation angle of an impedance tensor corresponds with the regional strike, following equations

$$\arctan\frac{imag(Z_{xx}/Z_{yx})}{real(Z_{xx}/Z_{yx})}=0 \tag{1}$$

and

$$\arctan\frac{imag(Z_{xy}/Z_{yy})}{real(Z_{xy}/Z_{yy})}=0 \tag{2}$$

are satisfied where Z_{xx}, Z_{xy}, Z_{yx} and Z_{yy} are elements of a rotated impedance tensor. However, it was not able to obtain stable directions for every frequency at some of the sites probably because the Chakridi's method is not effective in the case of no distortions. In such cases, another method by Jones and Groom (1993, Eq. (10) and (11)) is also applied. When the difference between a rotation angle and the strike is 45^o, following equations

$$\arctan\frac{imag[(Z_{xx}+Z_{xy})/(Z_{yx}+Z_{yy})]}{real[(Z_{xx}+Z_{xy})/(Z_{yx}+Z_{yy})]}=0 \tag{3}$$

and

$$\arctan\frac{imag[(Z_{xx}-Z_{xy})/(Z_{yx}-Z_{yy})]}{real[(Z_{xx}-Z_{xy})/(Z_{yx}-Z_{yy})]}=0 \tag{4}$$

are satisfied. Jones and Groom's method is similar to the Chakridi's but is more robust in the case of no distortions.

The regional strike was calculated by using both Chakridi's and Jones and Groom's method such that the least standard deviation for the observed frequencies is obtained. The estimated directions of the regional strike are shown in Fig. 2 with the Rose diagrams. At frequencies lower than 0.1 Hz, we can recognize that the strikes point to approximately N-S or E-W directions. Though average value of strikes at frequencies higher than 0.1 Hz also shows N10°-20°E or N70°-80°W, they are unstable, especially with frequencies 10–0.1 Hz. In addition, induction arrows at all sites are also calculated and shown in Fig. 3. Note that these induction arrows are unreversed, that is, point to conductors. It is found that the induction arrows tend to point to the south at 0.035 Hz and 0.093 Hz, although those at 0.093 Hz point to SSE near Mt. Karakuni-dake. The average skin depth at 0.1 Hz is about 10 km. We conclude by considering the distribution of strikes and induction arrows that the resistivity structure below the depth of about 10 km

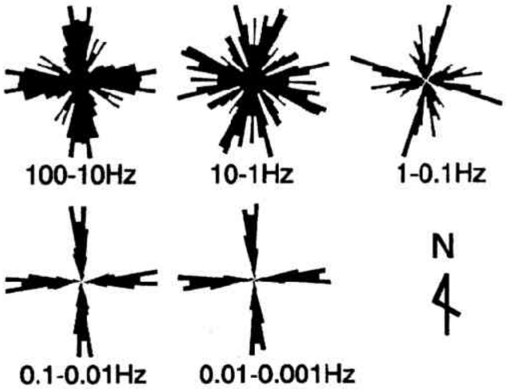

Fig. 2. Histograms of the strike, combined for all the sites, for respective frequency bands.

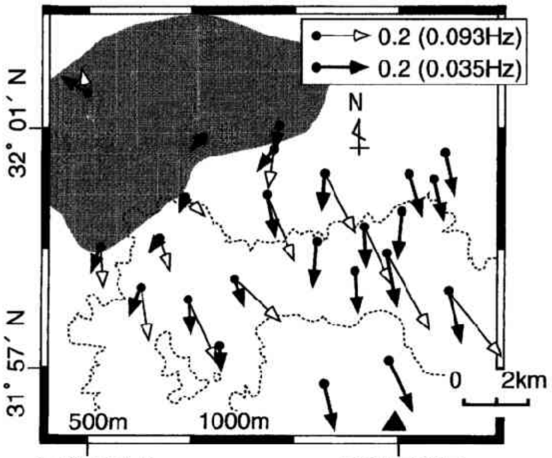

Fig. 3. Distribution of the induction arrows at 0.093 Hz and 0.035 Hz (real part). The GDS stations are located at the base of arrows. The epicentral area is indicated as the hatched area.

is approximately two-dimensional with the strike of the E-W direction, however the shallower part is not clearly two-dimensional and is possibly three dimensional because of the complicated surface geology.

The apparent resistivities and impedance phases roughly show similar tendencies at all sites. Typical curves of apparent resistivity and phase at representative sites are shown in Fig. 4. It is recognized that apparent resistivity values have a minimum commonly around 10–1 Hz and gradually increase as the frequency decreases below 1 Hz. Phases also show a similar feature that the values at 100 Hz are higher than 45 degrees, gradually have a minimum around 1–0.1 Hz and increase as the frequency decrease below 0.1 Hz.

In a frequency range lower than 0.1 Hz, there are separations between two apparent resistivity curves obtained from N-S and E-W components of the electric field at all sites. The induction arrows approximately point to the south in the low frequency. Therefore, we infer that the separations are due to a low resistivity zone in the south of the studied area. Such low resistivity zone can explain that apparent resistivities obtained from the N-S electric field (TM mode) are lower than those from the E-W electric field (TE mode) as shown in Fig. 4.

In addition, the apparent resistivities and phases obtained in the epicentral area of the Ebino

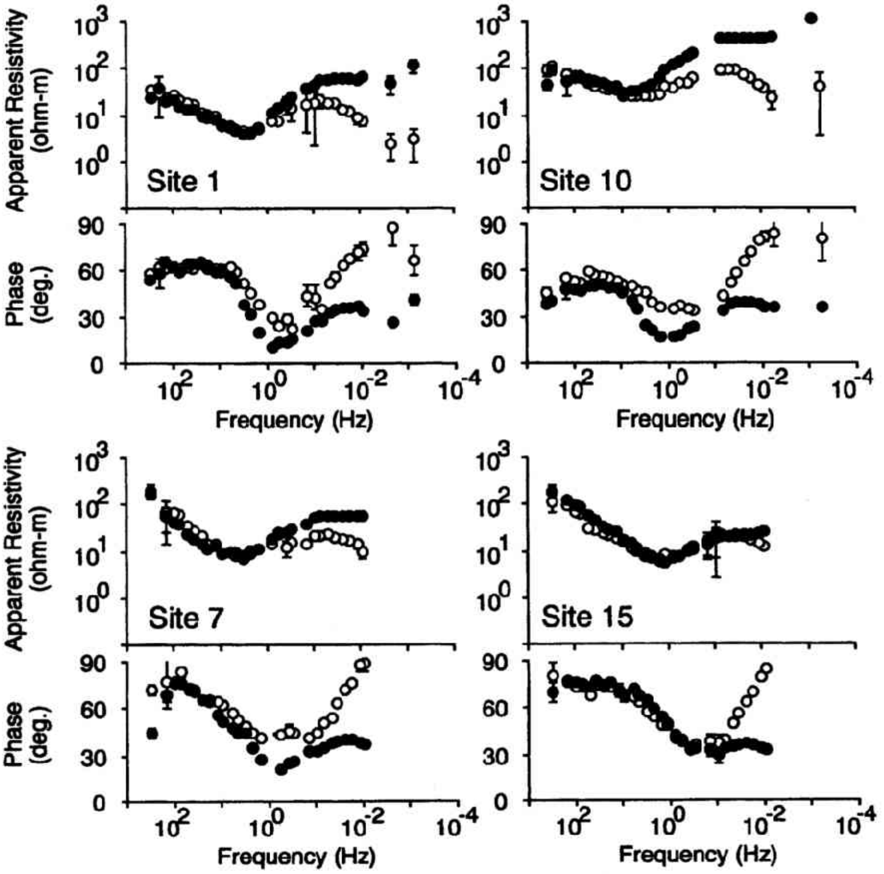

Fig. 4. Curves of the apparent resistivity and phase at the representative sites with the 68 per cent standard error. Open and solid circles are obtained from the N-S (TM) and E-W (TE) components of the electric field, respectively.

earthquake swarm have different features from those in the surrounding region of the epicentral area. At all sites, in general, the apparent resistivity increases as the frequency decreases below 1 Hz as mentioned above. However, above the hypocentral area, the gradient with frequency is very large and the apparent resistivity value at the frequency around 0.1 Hz is almost the same or rather higher than that at the frequency around 300 Hz (see Fig. 4., site 1 and site 10). On the other hand, in the surrounding region of the epicentral area, the apparent resistivity around 0.1 Hz is lower than that around 300 Hz (see Fig. 4, site 7 and site 15). Phase value also shows different feature between in and around the epicentral area. The phase values around epicentral area (at sites 1 and 10, especially at site 1) become a minimum around 1 Hz, which is lower than those in the surrounding area (at sites 7 and 15). These features are important to consider the resistivity structure around the studied area. We will discuss this point later.

3. Modeling

In the studied area, the resistivity structure is clearly two-dimensional in the deeper part, but two dimensionality is unlikely to hold in the shallower part. It is required to construct a three-dimensional model to explain the observed data. However, it takes very long time to compute the MT responses for a three-dimensional model with enough accuracy. Also, inversion methods for three-dimensional modeling are still under development. Moreover, the MT responses show roughly similar features in the studied area (Fig. 4). In this paper, a two-dimensional modeling

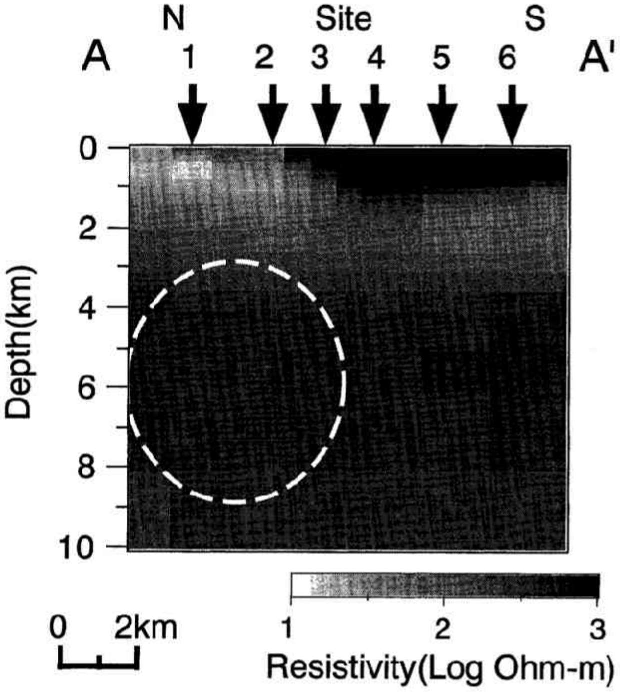

Fig. 5. The most suitable 2-D model of the resistivity structure along profile AA′. Resistivities are expressed as logarithmic values. Locations of MT sites are indicated by arrows with the site number. The outline of the hypocentral area of the Ebino earthquake swarm based on Minakami *et al.* (1970) is also indicated (the broken curve).

is employed as a preliminary result.

An two-dimensional inversion is carried out using the observed apparent resistivities and phases of TM mode only because the TM mode gives a good approximation for a three-dimensional resistivity structure (Ting and Hohmann, 1981). The direction of the strike is assumed to be E-W because the strikes and induction arrows at frequencies lower than 0.1 Hz and averages of those at 100–0.1 Hz indicate the E-W strike direction roughly. Four profiles are made in the studied area for the analyses as shown in Fig. 1. We used sites 1–6 for the analysis along the profile AA′, sites 6–10 for the profile BB′, sites 10–14 for the profile CC′ and sites 14–19 for the profile DD′, respectively. The observed data at sites 20 and 21 were not used for an inversion because the data quality are lower than those at sites 4 and 5 whose locations on the profile AA′ is close to those of sites 20 and 21, respectively. The data at site 22 was not used because site 22 is located just in the middle between the profiles AA′ and BB′. Also, sites 23–26 were not used for the modeling because of poor data quality. The two-dimensional least squares inversion with the smoothness constraint developed by Uchida and Ogawa (1993) is applied to analyze the data of each profile to construct the most suitable resistivity model. The initial model for the inversion is a half space of uniform resistivity of 1000 Ωm.

Static effects, which are detected as DC-shifts in the logarithm of apparent resistivity (Jones, 1988) yield an erroneous resistivity structure and should be removed. In our inversion procedure, we selected weights for the smoothness calculation to be small at the surface layer comparing with the other part of the model. This weight setting allows that a spatial variation of resistivity is smooth except for the surface layer. Such model will be able to include static effects as shallow localized anomalies. The effectiveness of the method to decrease the static effects is

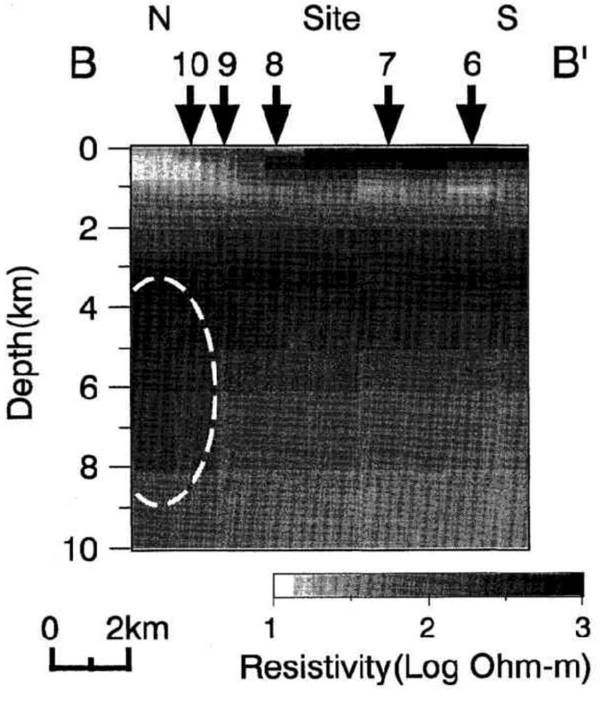

Fig. 6. The most suitable 2-D model of the resistivity structure along profile BB′. The outline of the hypocentral area of the Ebino earthquake swarm is shown as a broken line with the similar manner in Fig. 5.

confirmed by an inversion using synthetic data from a simple layered resistivity model with surface heterogeneities.

The most suitable model of the two-dimensional resistivity structure along each profile well explained the observed electromagnetic responses. In Fig. 5, the most suitable resistivity model along the profile AA′ is shown, which goes just across the area of the epicenters of the Ebino earthquake swarm. The outline of the hypocentral area drawn in Fig. 5 is based on the results by Minakami *et al.* (1970). The observed and calculated response from the model along the profile AA′ are shown in Fig. 9 together with those along other profiles. In our model, a conductive layer (less than 50 Ωm) at depth of about 0.5–2 km is identified. Similar conductive layers are recognized in the best fit models along the profiles BB′, CC′ and DD′, shown in Figs. 6, 7 and 8, respectively. The conductive layers shown in all profiles are responsible for the low apparent resistivity at 10–1 Hz and the high phase value at 100 Hz observed at all sites.

It is also recognized in the resistivity models that the hypocentral area of the Ebino earthquake swarm is more resistive than the surrounding area. The models along the profiles AA′ and BB′ (Figs. 5 and 6), which go across the hypocentral area, show high resistivity values (higher than 500 Ωm) in the hypocentral area. However, along the profiles CC′ and DD′ (Figs. 7 and 8), the resistivities in depth of 3–9 km are about 100–200 Ωm and less resistive than those along AA′ and BB′. The calculated responses from the models for the profiles AA′ and BB′ well fit the large increase of the apparent resistivity and the low phase value around 1 Hz (see Fig. 9) observed above the hypocentral area. Note that the southern area along the profile AA′ (beneath sites 4–6), which is out of the hypocentral area, shows high resistivity value at depth of 4–8 km.

The resistivity model along the profile of DD′, which is located at the northern foot of Mt.

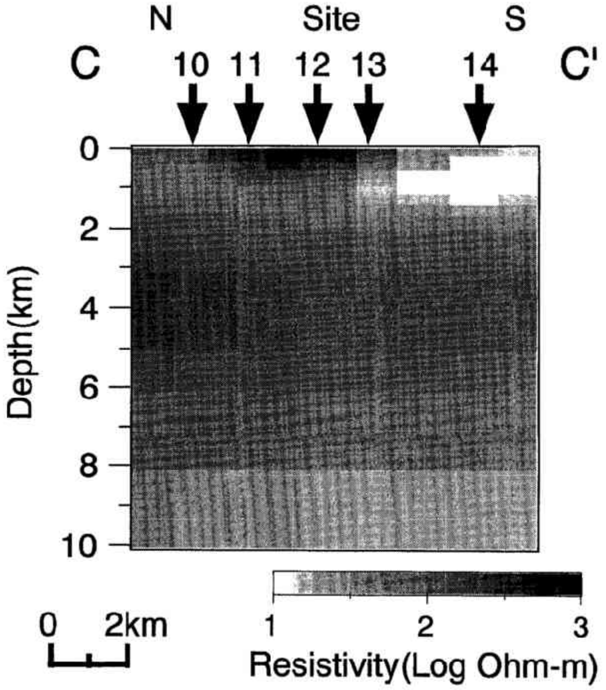

Fig. 7. The most suitable 2-D model of the resistivity structure along profile CC′.

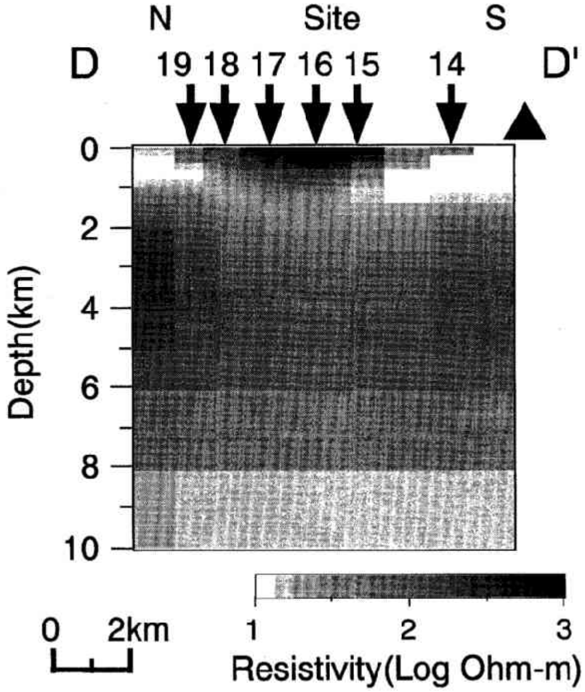

Fig. 8. The most suitable 2-D model of the resistivity structure along profile DD′. The location of Mt. Karakuni-dake is shown as a triangle.

Karakuni-dake, shows a conductive zone (lower than 20 Ωm) at a depth deeper than about 8 km (see Fig. 8). This deep conductive zone is also recognized in the southern part of the model along the profiles CC′ and BB′. The resistivity of the deep conductive zone decreases toward the south, that is, toward the Kirishima volcanoes. The spatial variation of resistivity is harmony with the induction arrows pointing to the south and the separation of the apparent resistivity curves.

4. Discussion and Conclusion

It was revealed by the MT sounding that the resistivity of the hypocentral area of the Ebino earthquake swarm is higher than that of the surrounding area. The resistivity value beneath the southern area along the profile AA′, which belongs to the surrounding area, is as high as in the hypocentral area. However, two other earthquake swarms had occur in the southern area along AA′ in 1915 and 1961. Therefore, we conclude in the studied area that the hypocentral areas of earthquake swarms are relatively more resistive than the surrounding area. In this area, the seismic velocity structure is reported by Yamamoto and Ida (1994) using a three dimensional tomography method. The spatial resolution of their model around the hypocentral area is lower than ours, but they reported that the seismic P wave velocity in the hypocentral area is approximately equal to those of the surrounding area. Both the resistivity structure and the seismic velocity structure imply that a large volume of fluid and the partial melting does not exist in the hypocentral area.

It is difficult to discuss whether fluid caused the Ebino earthquake swarm or not on the basis of the conclusion that the hypocentral area is more resistive than the surrounding area. If

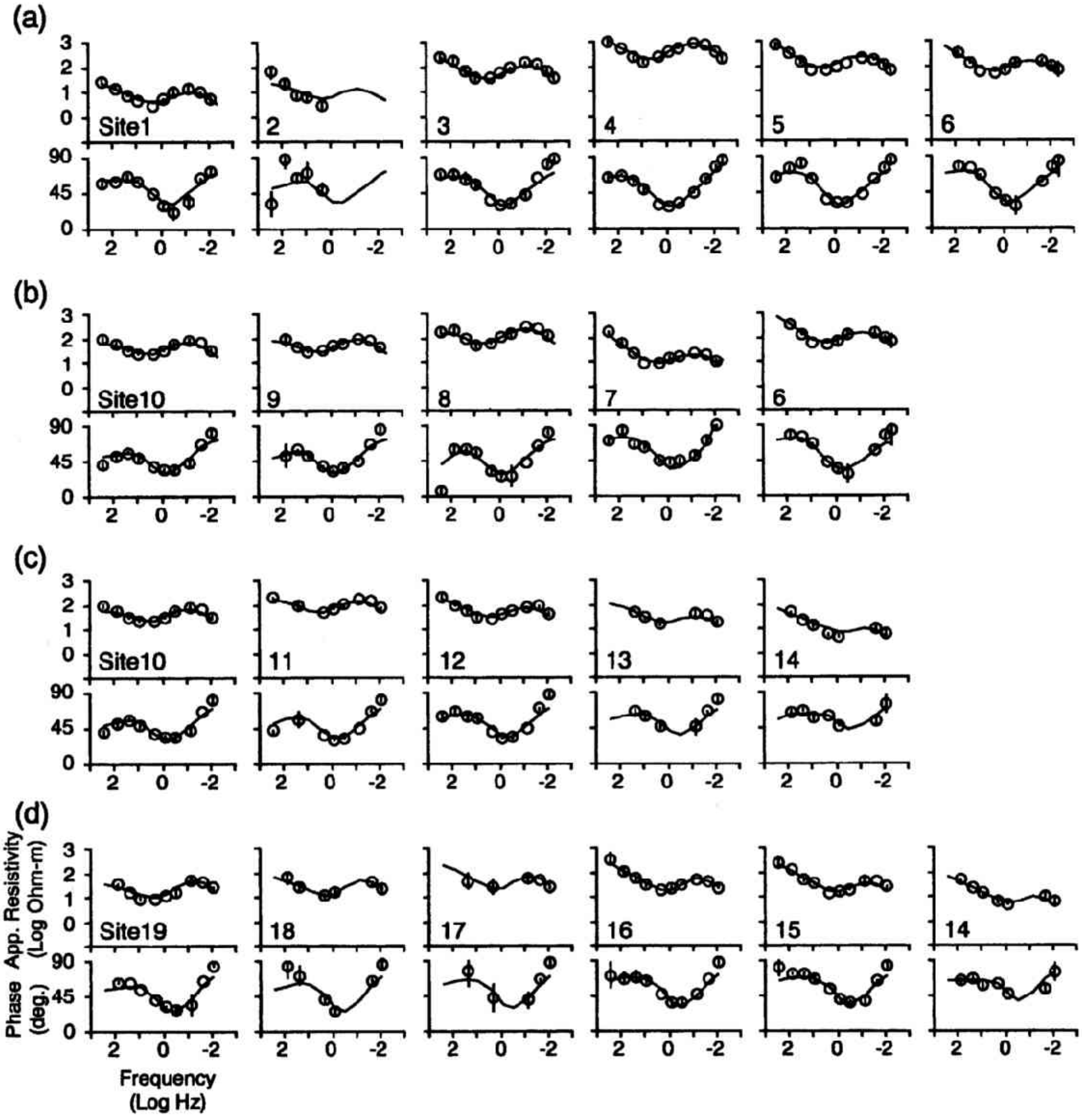

Fig. 9. Observed apparent resistivities and phases (open circles) and calculated ones from the two dimensional model along (a) the profile AA′, (b) BB′, (c) CC′ and (d) DD′, shown in Figs. 5–8, respectively. Apparent resistivity and frequency are shown in a logarithmic scale.

the hypocentral area would have been already resistive before the earthquake swarm, fluid might be not related to the occurrence of the earthquake swarm. In this case, the heterogeneity on strength of the upper crust may strongly affect the occurrence of the earthquake swarm. However there is a possibility that a large mass of fluid might exist in the hypocentral area during the earthquake swarm and might have diffused after the earthquake swarm. In such case, fluid should be expelled from the hypocentral area after the earthquake swarm because the hypocentral area is more resistive than the surrounding area now. Such mechanisms can not be confirmed in this study. It may be a candidate of mechanisms expelling fluid that deposits such as $CaCO_3$, which dissolved in fluid at first, was created and filled in pores and cracks within the hypocentral area after the earthquake swarm. Such deposits are suggested to explain the uplifted surface associated with the Matsushiro earthquake swarm and remaining now (Ohtake, 1976).

On the other hand, it is pointed out that earthquake swarms have been generated in rocks with low density of cracks, where vertical flows of fluid might be trapped. Nakamura *et al.* (1996) studied the Inagawa earthquake swarm which has occurred in Kinki district of west Japan since 1995. They found that the layer of high seismicity indicates low seismic anisotropy, while the low seismicity layer beneath this high seismicity layer indicates relatively high anisotropy. Nakamura *et al.* (1996) concluded that fluid, which is upwelled from the layer of high crack density, might be trapped in the layer of low crack density, and the trapped fluid increases the pore pressure. Such fluid decreases the effective stress and causes rocks to slip (Nur and Byerlee, 1971). In the case of the Ebino earthquake swarm, there is a possibility that a small amount of the upwelled fluid might be trapped in the region of high resistivity, that is, low porosity and connectivity, and might cause the earthquake swarm. However, there remains a question whether the hypocentral area was resistive during the earthquake swarm or became resistive after the swarm.

Although thermal structure of the crust affects seismic activity (Sibson, 1984), it may not be a major cause of the Ebino earthquake swarm. Ito (1993) concluded that the seismic activity around the Kirishima volcanoes is related to the thermal structure because the cutoff depth of the micro-earthquakes decreases toward craters located in the center of the Kirishima volcanoes. However, the cutoff depth of seismicity is about 12 km beneath the east and central part of the Kakuto caldera (Ida *et al.*, 1986). The result from Ida *et al.* implies that the spatial difference of thermal structure is small between the hypocentral area of the Ebino earthquake swarm and the surrounding area. We conclude that the thermal structure is approximately equal in and around the hypocentral area and is not a major cause of the Ebino earthquake swarm, although it is related to activities of earthquakes.

The conductive layer spreading beneath the surveyed area at the depth of about 0.5–2 km and the conductive zone beneath the Kirishima volcanoes deeper than 8 km are also observed by MT surveys on the Kirishima volcanoes (Utada *et al.*, 1994). Utada *et al.* (1994) found that there exists a conductive layer at a depth of a few hundred meters. On the basis of the geological and logging data in the Kakuto caldera, Aramaki (1968) found that the shallow layer consists of thick lava flows and that hydrothermaly altered tuff and andesitic lava with clay minerals underlie at depth of about 370–430 m. Referring to his investigation, we conclude that the existence of the conductive layer widely spreading around the Kirishima volcanoes is probably due to the shallow hydrothermal activity. On the other hand, Utada *et al.* (1994) also found that a deep conductor exists at about 10 km depth below the surface of the surveyed area and the depth tends to become shallower toward the Kirishima volcanoes. The deep conductive zone beneath 8 km depth near Mt. Karakuni-dake found in our study is similar to the conductor found by Utada *et al.* (1994). The deep conductive zone corresponds with a low seismic velocity zone found by Yamamoto and Ida (1994) beneath Mt. Karakuni-dake at depth of 8.5–13.5 km. In addition, the seismic attenuation zone is found by Oikawa *et al.* (1994) at depth of about 4–5 km beneath Mt. Karakuni-dake. We therefore conclude that the deep conductor at the depth of about 8 km may be due to partial melting or released fluid from magma which are related to the magma supply system to the Kirishima volcanoes.

There remain many problems to be solved in roles of fluid to occurrence of earthquake swarms. However, since the hypocentral area is more resistive than the surrounding area, we conclude that a large mass of fluid does not exist in the hypocentral area of the Ebino earthquake swarm. It is difficult to discuss the cause of the Ebino earthquake swarm in this study. Three possibilities about the cause of the earthquake swarm are suggested as followings.

1. Fluid did not cause the earthquake swarm.

2. A large mass of fluid caused the earthquake swarm and have been expelled from the hypocentral area.
3. A small amount of fluid trapped in the low porosity area caused the earthquake swarm.

In this study, we treated the resistivity structure as two-dimensional. This treatment provides insufficient structure to confirm accurate boundary of the resistive block because the resistivity structure beneath the studied area seems to be three-dimensional. We will construct a three-dimensional resistivity model around the studied area in near future to make the relationship between the resistivity structure around the hypocentral area and the Ebino earthquake swarm clearer.

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REFERENCES

Aramaki, S., Geology of the Kakuto basin, southern Kyushu, and the earthquake swarm from February, 1968, *Bull. Earthq. Res. Inst.*, **46**, 1325–1343, 1968 (in Japanese with English abstract).

Blanpied, M. L., D. A. Lockner, and J. D. Byerlee, An earthquake mechanism based on rapid sealing of faults, *Nature*, **358**, 574–576, 1992.

Byerlee, J., Friction, overpressure and fault normal compression, *Geophys. Res. Lett.*, **17**, 2109–2112, 1990.

Chakridi, R., M. Chouteau, and M. Mareschal, A simple technique for analyzing and partly removing galvanic distortion from the magnetotelluric impedance tensor: application to Abitibi and Kapuskasing data (Canada), *Geophys. J. Int.*, **108**, 917–929, 1992.

Gamble, T. D., W. M. Goubau, and J. Clarke, Magnetotellurics with a remote magnetic reference, *Geophys.*, **44**, 53–68, 1979.

Groom, R. W. and R. C. Bailey, Decomposition of magnetotelluric impedance tensor in the presence of local three-dimensional galvanic distortion, *J. Geophys. Res.*, **94**, 1913–1925, 1989.

Ida, Y., M. Yamaguchi, and F. Masutani, Recent seismicity in Kirishima volcano and Kakuto caldera, *Zishin (J. Seismol. Soc. Jpn.)*, **39**, 595–605, 1986 (in Japanese with English abstract).

Imura, R., Geology of Kirishima Volcano, *Bull. Earthq. Res. Inst.*, **69**, 189–209, 1994 (in Japanese with English abstract).

Ito, K., Cutoff depth of seismicity and large earthquakes near active volcanoes in Japan, *Tectonophysics*, **217**, 11–21, 1993.

Jones, A. G., Static shift of magnetotelluric data and its removal in a sedimentary basin environment, *Geophys.*, **53**, 967–978, 1988.

Jones, A. G. and R. W. Groom, Strike-angle determination from the magnetotelluric impedance tensor in the presence of noise and local distortion: rotate at your peril!, *Geophys. J. Int.*, **113**, 524–534, 1993.

Kagiyama, T., Geophysical background of Kirishima volcanoes, *Rep. Geol. Surv. Japan*, **279**, 89–92, 1992.

Minakami, T., S. Utibori, M. Yamaguchi, N. Gyoda, T. Utsunomiya, M. Hagiwara, and K. Hirai, The Ebino earthquake swarm and the seismic activity in the Kirishima volcanoes, in 1968–1969, Part 1.—Hypocentral distribution of the 1968 Ebino earthquakes inside the Kakuto caldera, *Bull. Earthq. Res. Inst.*, **47**, 721–743, 1969.

Minakami, T., M. Hagiwara, M. Yamaguchi, E. Koyama, and K. Hirai, The Ebino earthquake swarm and the seismic activity in the Kirishima volcanoes, in 1968–1969, Part 4.—Shift of seismic activity from the Kakuto caldera to Simmoe-dake, Naka-dake and Takatiho-mine, *Bull. Earthq. Res. Inst.*, **48**, 205–233, 1970.

Miyazaki, T., M. Yamagichi, F. Masutani, and H. Terao, The earthquake swarms in the northern area of the Kirishima volcanoes, 1975–1976, *Bull. Earthq. Res. Inst.*, **51**, 115–149, 1976 (in Japanese with English abstract).

Nakamura, M., M. Ando, K. Kusunose, and T. Sato, Depth-dependent crustal anisotropy at mid western Honshu, Japan, *Geophys. Res. Lett.*, **23**, 3417–3420, 1996.

Nur, A. and J. D. Byerlee, An exact effective stress law for elastic deformation of rock with fluids, *J. Geophys. Res.*, **76**, 6414–6419, 1971.

O'Connell, R. J. and B. Budiansky, Viscoelastic properties of fluid-saturated cracked solids, *J. Geophys. Res.*, **82**, 5719–5735, 1977.

Oikawa, J., K. Yamamoto, and Y. Ida, High attenuation region of seismic waves beneath Kirishima volcanoes, *Bull. Earthq. Res. Inst.*, **69**, 291–307, 1994 (in Japanese with English abstract).

Ohtake, M., One decade since the Matsushiro earthquake†, *Kagaku*, **46**, 306–313, 1976 (in Japanese).

Ohtake, M. and K. Hamada, Depth distribution of the Matsushiro earthquake swarm as inferred from a tripartite observation, hypocenter migration, and permeability of the crust, *Zishin (J. Seismol. Soc. Jpn.)*, **28**, 321–329, 1975 (in Japanese with English abstract).

Rice, J. R., Fault stress states, pore pressure distributions, and the weakness of the San Andreas Fault, in *Fault Mechanics and Transport Properties of Rocks*, edited by B. Evans and T.-F. Wong, pp. 475–503, Academic, San Diego, Calif., 1992.

Sasai, Y., A mechanism of the generation of the Matsushiro earthquake swarm—the natural and large fracturing by upwelled fluid†, *Proc. 1994 Conductivity Anomaly Symp.*, 181–195, 1994 (in Japanese).

Sasai, Y., H. Utada, and N. Sumitomo, Geoelectric and geomagnetic surveys in southern Kyushu†, *Proc. 1995 Conductivity Anomaly Symp.*, 1–3, 1995 (in Japanese).

Sibson, R. H., Roughness at the base of the seismogenic zone : contributing factors, *J. Geophys. Res.*, **89**, 5791–5799, 1984.

Sibson, R. H., F. Robert, and K. H. Poulsen, High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits, *Geology*, **16**, 551–555, 1988.

Tajima, K. and S. Aramaki, Bouguer gravity anomaly around Kirishima volcanoes, Kyushu, *Bull. Earthq. Res. Inst.*, **55**, 241–257, 1980 (in Japanese with English abstract).

Tanaka, K., Spreading and growth of the hypocentral area of earthquake swarms†, *Chikyu Monthly*, **132**, 331–335, 1990 (in Japanese).

Ting, S. C. and G. W. Hohmann, Integral equation modeling of three dimensional magnetotelluric response, *Geophys.*, **46**, 192–197, 1981.

Uchida, T. and Y. Ogawa, Development of FORTRAN code for two-dimensional magnetotelluric inversion with smoothness constraint, *Open-File Report, Geological Survey of Japan*, No. 205, pp. 115, 1993.

Utada, H., T. Kagiyama, and EM Research Group for Kirishima Volcano, Deep resistivity structure of Kirishima volcano (I), *Bull. Earthq. Res. Inst.*, **69**, 241–255, 1994 (in Japanese with English abstract).

Wakita, H., N. Fujii, S. Matsuo, K. Notsu, K. Nagao, and N. Takaoka, "Helium Spots": caused by a diapiric magma from the upper mantle, *Science*, **200**, 430–432, 1978.

Watanabe, K., Some investigations about Ebino earthquake swarm, *Zishin (J. Seismol. Soc. Jpn.)*, **23**, 32–40, 1970 (in Japanese with English abstract).

Yamamoto, K. and Y. Ida, Three-dimensional P-wave velocity structure of Kirishima volcanoes using regional seismic events, *Bull. Earthq. Res. Inst.*, **69**, 267–289, 1994 (in Japanese with English abstract).

†: These titles are translated by the author T.G.