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21. *Observations of Short-Period Geomagnetic Variations at Nakaizu (2): Changes in Transfer Functions Associated with the Izu-Oshima-Kinkai Earthquake of 1978.*

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Abstract

As an application of CA (Conductivity Anomaly) studies, observations of short-period geomagnetic variations have been carried out at Nakaizu in the Izu Peninsula since July, 1976, in order to examine whether or not the electrical conductivity of the crust changes in association with earthquakes. In view of precursory changes in the amplitudes of horizontal components, that appeared in association with the 1978 Izu-Oshima-Kinkai earthquake of magnitude 7.0, time-dependence of transfer functions is examined.

Transfer functions Au and Bu (the in-phase parts of A and B) seem to have been enhanced prior to the Izu-Oshima-Kinkai earthquake, although the changes are not very significant because of large noises. The observed changes can qualitatively be interpreted as indicating the appearance of a conducting area in the focal region before the earthquake occurrence. Such an increase in electrical conductivity is likely to be a result of underground water flow into the focal region as claimed in the dilatancy-diffusion hypothesis.

1. Introduction

As one of the possible means of detecting a change in electrical conductivity of the crust associated with an earthquake, observations of short-period geomagnetic variations have been carried out since July, 1976, at the Nakaizu station as indicated by NKZ in Fig. 1 (HONKURA and KOYAMA, 1978). The main purpose of the observations is to search for changes in the amplitude of short-period horizontal variations at the Nakaizu station relative to that at a remote reference station. As described in the previous paper (HONKURA and KOYAMA, 1978) and shown in Fig. 2, slight changes seem to have been observed in association with earthquakes of magnitude 5.4 and 7.0, respectively.

In addition to amplitudes of the H and D components, the electric

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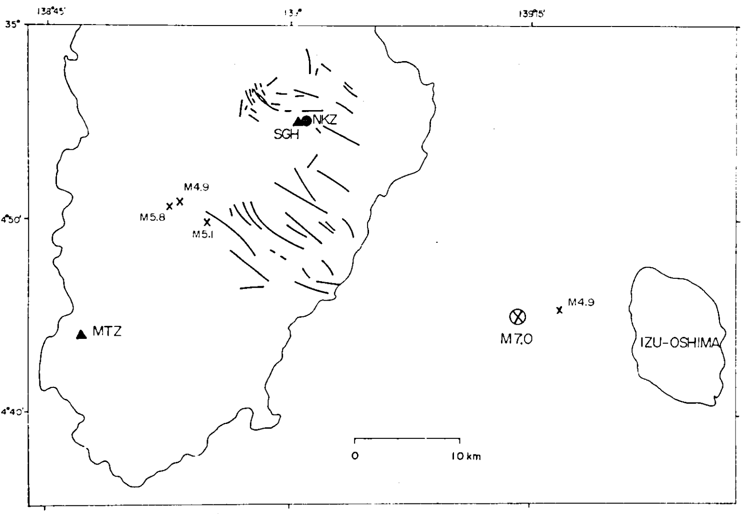

Fig. 1. Location of the Nakaizu station (NKZ). A circle with a cross indicates the epicenter of the main shock of the 1978 Izu-Oshima-Kinkai earthquake of magnitude 7.0. Crosses indicate a foreshock (*M* 4.9) and aftershocks (*M* 5.8, 5.1, 4.9). Solid lines denote active faults in the eastern part of Izu Peninsula.

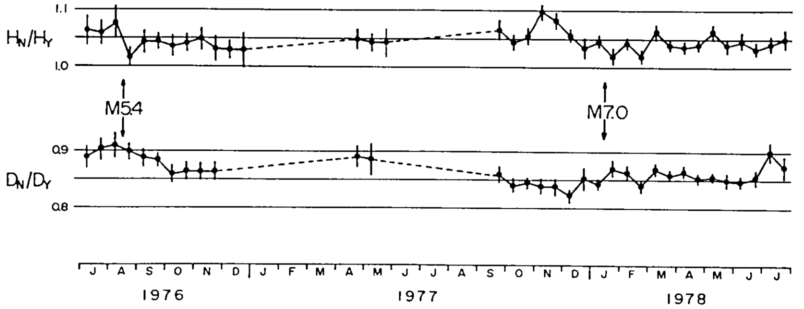

Fig. 2. Changes in the amplitude ratios of the *H* component at NKZ to that at YAT (Yatsugatake Magnetic Observatory) and of the *D* component at NKZ to that at YAT. Error bars denote the 95% confidence intervals of the respective means. Arrows indicate earthquakes of magnitude 5.4 and 7.0, respectively.

self-potential observed at NKZ and the difference of geomagnetic total intensity between SGH and MTZ shown in Fig. 1 also underwent precursory changes before the Izu-Oshima-Kinkai earthquake of 1978. Taking into account other anomalous phenomena concerning underground water, such as water level, water temperature, radon content, and so on, the changes were interpreted as reflecting the flow of underground water into the focal region through fracture zones of active faults (HONKURA, 1978).

It has sometimes been reported that transfer functions characterizing an anomaly of short-period geomagnetic variations underwent remarkable changes in association with earthquakes that occurred at a distance of some tens of kilometers or more (YANAGIHARA, 1972; MIYAKOSHI, 1975; YANAGIHARA and NAGANO, 1976; RIKITAKE, 1979). The main shock of the Izu-Oshima-Kinkai earthquake occurred about 30 km southeast of the Nakaizu station as shown in Fig. 1 and the nearest aftershock area was within a distance of 20 km from the station. Therefore, it is reasonably expected that transfer functions at the Nakaizu station might have changed in association with the earthquake.

This paper aims at investigating time-dependence of transfer functions determined from the data obtained at Nakaizu during a six month period before and after the Izu-Oshima-Kinkai earthquake of 1978 in order to examine whether any changes could be observed or not.

2. Data analyses

An anomaly of short-period geomagnetic variations is usually characterized by an anomalous vertical field (ΔZ) which can be empirically expressed in terms of horizontal fields as

$$\Delta Z = A\Delta H + B\Delta D \tag{1}$$

where ΔH and ΔD indicate the northward and eastward components, respectively. A and B are called the transfer functions and usually they are complex functions of frequency.

Another set of tranfer functions can be obtained by combining the data at a station under consideration with those at another station. If another station is located far from an anomalous region, it can be regarded as a reference station. From the viewpoint of time-dependence of transfer functions, particularly in association with earthquakes, it is preferable that a reference station be located in a seismically quiet area. In this case, the three components of short-period geomagnetic variations at a station under consideration can be expressed by making use of the H and D components at a reference station as

$$\begin{pmatrix} \Delta H \\ \Delta D \\ \Delta Z \end{pmatrix} = \begin{pmatrix} h_H & h_D \\ d_H & d_D \\ z_H & z_D \end{pmatrix} \begin{pmatrix} \Delta H_r \\ \Delta D_r \end{pmatrix} \tag{2}$$

where ΔH_r and ΔD_r denote the H and D components at the reference station, respectively. Usually, ΔH and ΔD should represent anomalous parts of the observed fields and, therefore, should be replaced by $\Delta H - \Delta H_r$ and $\Delta D - \Delta D_r$. However, the difference appears only as addition of a constant to transfer functions h_H and d_D. In this paper, the above expression is used as it is. In the present analysis, the Yatsugatake Magnetic Observatory was chosen as the reference station, because it is located in a seismically quiet area at a distance of 140 km from the station.

About five records suitable for analysis were selected every half a month during an investigated period of October, 1977 to March, 1978. Unfortunately the station NKZ is situated relatively close to the electric railways and considerable noises due to their leakage currents appear particularly in the *Z* component. However, electric trains are not operated from the midnight to about 5 o'clock in the morning and noises during this period are greatly reduced. Therefore, records from 23:30 p.m. to 5:30 a.m. were selected for estimating transfer functions. The auto- and cross-power spectra were calculated and transfer functions were determined by making use of the method as

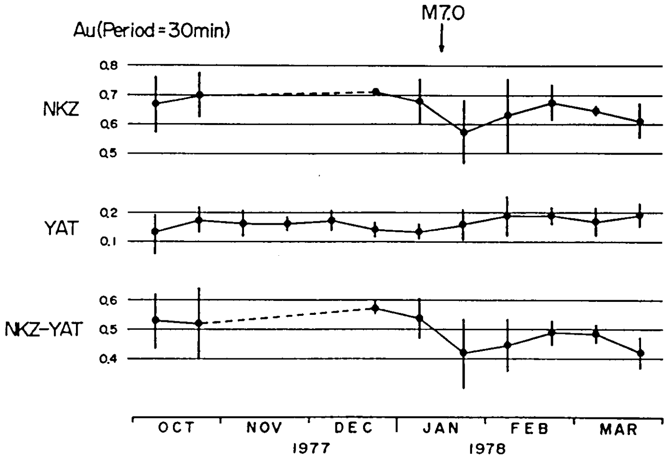

Fig. 3 (a)

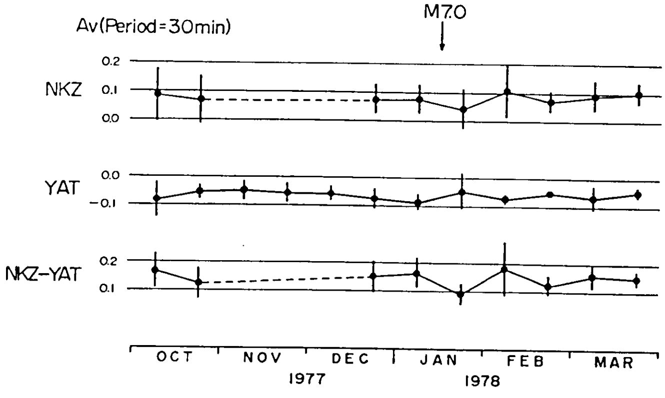

Fig. 3 (b)

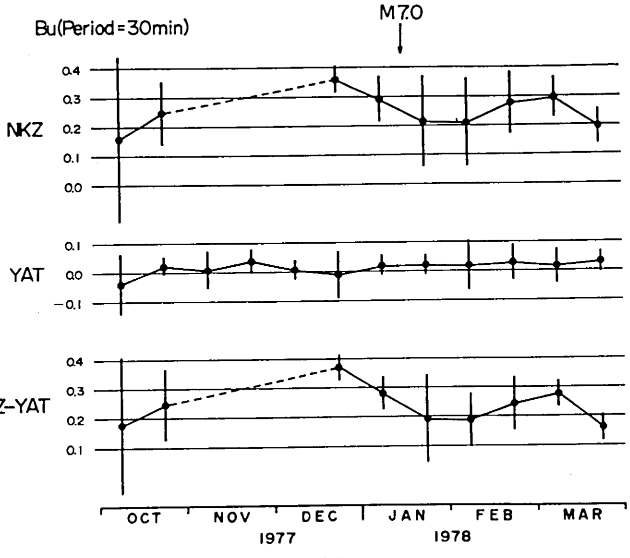

Fig. 3(c)

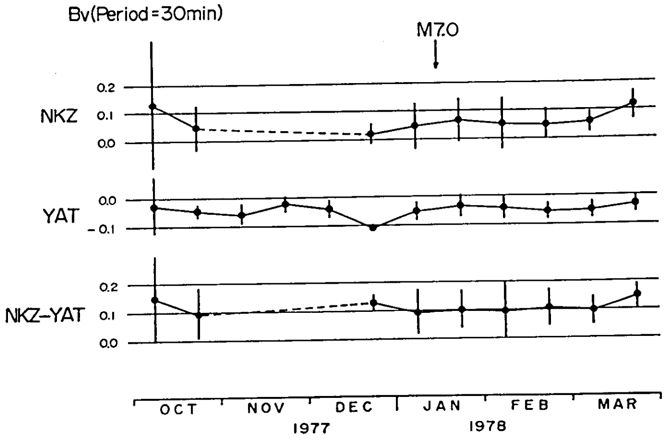

Fig. 3(d)

Fig. 3. Time-dependence of transfer functions at a period of 30 min: (a) *Au*, (b) *Av*, (c) *Bu*, (d) *Bv*, respectively. Error bars denote the standard deviations. An arrow indicates the 1978 Izu-Oshima-Kinkai earthquake of magnitude 7.0.

put forward by EVERETT and HYNDMAN (1967).

3. Results

Time-dependence of *Au* (in-phase part of *A*) at a period of 30 min is shown in Fig. 3(a). Circles and error bars indicate the means and standard deviations, respectively. Large scatter is partly due to noises arising through stray currents from the electric railways and partly due to limited length of records used for analysis (only six-hour duration). Nevertheless, *Au* values seem to be slightly enhanced before the earthquake occurrence, although large errors reduce significance. Transfer functions at the reference station YAT were also determined from simultaneous data and *Au* values there are shown in Fig. 3(a). The difference between *Au* values at NKZ and YAT as shown in the same figure is unlikely to be influenced by the external source-field effect, since its spatial extent would be much larger than the station separation. The tendency as seen in *Au* values at NKZ is more clearly recognized in *Au* value differences, which suggests that *Au* values at NKZ changed prior to the earthquake occurrence. The result for *Av* (out-of-phase part of *A*) is shown in Fig. 3(b). No significant change can be seen in *Av* values at NKZ and also in *Av* value differences between NKZ and YAT.

Figure 3(c) shows time-dependence of *Bu*. As is the case for that of *Au*, *Bu* values seem to be enhanced before the earthquake occurrence, although such a change is not very significant because of large noises. The same tendency can be recognized in the difference between *Bu* values at NKZ and YAT, indicating that the change observed at NKZ should be of local origin. As for *Bv* values, no significant change was observed as shown in Fig. 3(d).

The result for another type of transfer functions is shown in Fig.

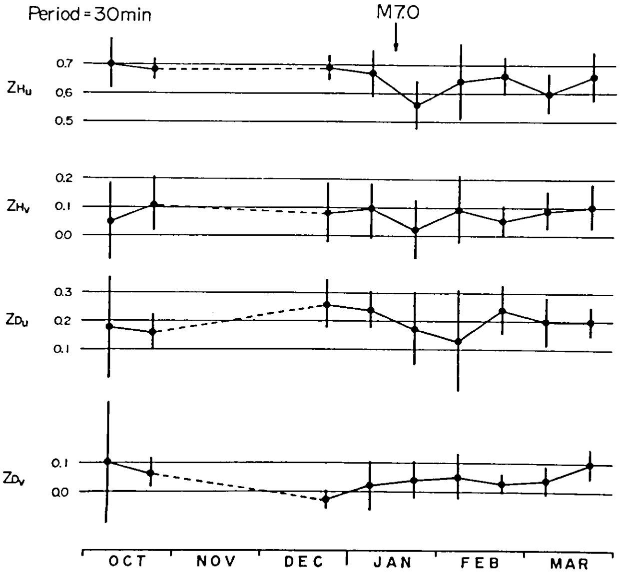

Fig. 4(a)

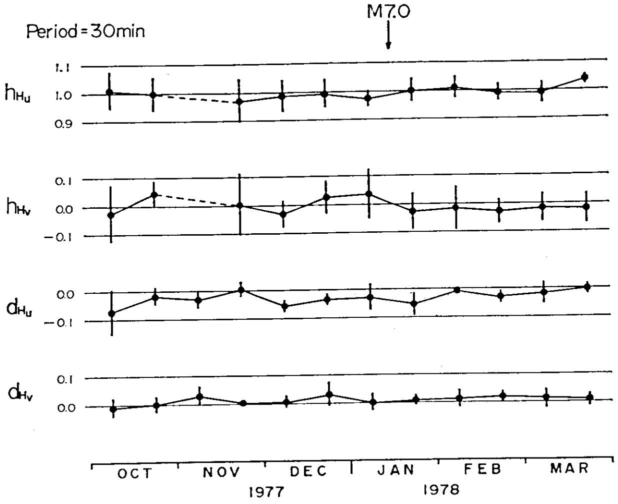

Fig. 4(b)

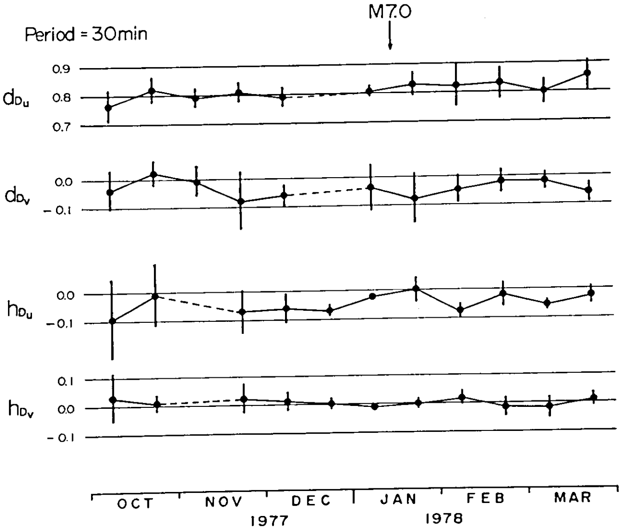

Fig. 4(c)

Fig. 4. Time-dependence of another set of transfer functions at a period of 30 min.: (a) z_H and z_D, (b) h_H and d_H, and (c) d_D and h_D, respectively. Error bars denote the standard deviations. An arrow indicates the 1978 Izu-Oshima-Kinkai earthquake.

4(a) for z_H and z_D, Fig. 4(b) for h_H and d_H, and Fig. 4(c) for d_D and h_D, respectively. Time-dependencies of z_H and z_D are very similar to those of A and B, respectively, as expected from the fact that the H and D components at NKZ are very similar to the respective ones at YAT, as shown by only slight changes in the amplitude ratios. Changes are also seen in d_{Hu}, d_{Du}, and d_{Dv}, although they are not very significant.

The changes in d_{Hu} and d_{Du} suggest the distortion of induced electric currents by a resistivity anomaly appearing in the crust. However, the pattern of these changes is not in good harmony with that of changes in *Au* and *Bu*.

4. Effects of a conductivity change on the amplitude of short-period geomagnetic variations

Theoretical calculations have been made for some models of an electrical conductivity change in order to estimate its effect on transfer functions or induced electric currents (RIKITAKE, 1976; HONKURA, 1976). It is not unlikely that the electrical conductivity increases in association with crustal dilatancy prior to an earthquake as a result of water diffusion into a dilatant focal region (SCHOLZ *et al.*, 1973). In this section, a thin-sheet approximation is used for estimating changes in the amplitude of short-period geomagnetic variations expected for a conductivity change.

We shall suppose that the conductivity changes within a circular column lying at a depth range from the earth's surface to 20 km down. A 20 km thick crustal layer is represented, as an approximation, by a thin-sheet conductor. Then, the problem to be solved is reduced to the perturbation by a circular disk, having a higher conductivity, embedded in a uniform conductor sheet. The distortion of induced currents flowing below 20 km depth is neglected in this approximation. Its effect is unlikely to be large, compared to the horizontal distortion, and the result of calculation would not be remarkably altered. The integrated intensity of currents flowing within the 20 km thick layer is required for the thin-sheet approximation. It is necessary for such a treatment that the intensity and phase of the induced electric field be approximately uniform within the layer. Therefore, the intensity and phase are examined in the following.

For a semi-infinite uniform conductor having a plane surface, the electric and magnetic fields are given in SI units by

$$Ey=-C\sqrt{\frac{i\omega}{\sigma\mu}}\exp\left(-\sqrt{i\omega\sigma\mu}\,z\right) \tag{3}$$

$$Bx=C\exp\left(-\sqrt{i\omega\sigma\mu}\,z\right) \tag{4}$$

where σ, μ, and ω denote the electrical conductivity, the magnetic permeability, and the angular frequency, respectively. C is an arbitrary constant. From (3), the skin depth (d) is given in kilometers as

$$d=\sqrt{\frac{5}{\pi\sigma\omega}} \tag{5}$$

For $\sigma=0.01\,\mathrm{S/m}$ and $\omega=0.01$ (a period of about 10 min) d becomes about 126 km. Therefore, the electric field intensity can reasonably be treated as being uniform within the top 20 km layer. The phase of the electric field is given by

$$\phi=\frac{\pi}{4}-\sqrt{\frac{\omega\sigma\mu}{5}}z \tag{6}$$

The phase difference between $\phi(z=0\,\mathrm{km})$ and $\phi(z=20\,\mathrm{km})$ is only 9° for $\sigma=0.01\,\mathrm{S/m}$ and $\omega=0.01$. Therefore, the phase can also be treated as being uniform within the top 20 km layer.

The integrated current intensity $|Iy|$ can be obtained by using a relation

$$i_y=\sigma Ey \tag{7}$$

as follows:

$$\begin{aligned}|Iy|&=|C|\sqrt{\frac{\sigma\omega}{\mu}}\left|\int_0^D \exp\left(-\sqrt{\frac{\omega\sigma\mu}{2}}z\right)dz\right|\\&=|C|\frac{\sqrt{2}}{\mu}\left[1-\exp\left(-\sqrt{\frac{\omega\sigma\mu}{2}}D\right)\right]\end{aligned} \tag{8}$$

Using (4), we obtain

$$|C|=|Bx(z=0)| \tag{9}$$

From (8) and (9), the integrated current intensity is given as

$$|Iy|=\frac{\sqrt{2}}{\mu}\left[1-\exp\left(-\sqrt{\frac{\omega\sigma\mu}{2}}D\right)\right]Bx_0 \tag{10}$$

where Bx_0 denotes Bx at the earth's surface. Therefore, the integrated current intensity for a unit magnetic field at the surface is given by

$$|Iy|=\frac{\sqrt{2}}{\mu}\left[1-\exp\left(-\sqrt{\frac{\omega\sigma\mu}{2}}D\right)\right] \tag{11}$$

where $D=20\,\mathrm{km}$. For $\sigma=0.01\,\mathrm{S/m}$ and $\omega=0.01$,

$$\mu|Iy|\approx 0.207 \tag{12}$$

According to ASHOUR and CHAPMAN (1965), a disturbing current flow due to a circular disk having a conductivity σ' substituted for an equal part of the sheet having a conductivity σ can be expressed in terms of a current function ψ as

$$\psi=\begin{cases}-K|Iy|r\sin\phi & 0\leqq r\leqq a\\ -K|Iy|(a^2/r)\sin\phi & r\geqq a\end{cases} \tag{13}$$

where a and $|Iy|$ denote the radius of the circular disk and the undisturbed current intensity, respectively. K is given as

$$K=\frac{\sigma-\sigma'}{\sigma+\sigma'} \tag{14}$$

It is possible to obtain the magnetic field over the plane sheet due to such a current flow (ASHOUR and CHAPMAN, 1965). The three components of the magnetic field can be expressed as

$$\begin{cases} Bz=\mu|Iy|\,a\sin\phi\, I(1,\,1;\,0;\,r,\,z) \\ Br=\mu|Iy|\,a\sin\phi\{I(1,\,0;\,0;r,\,z)-(1/r)I(1,\,1;\,-1;\,r,\,z)\} \\ B\phi=\mu|Iy|\,(a/r)\cos\phi\, I(1,\,1;\,-1;\,r,\,z) \end{cases} \tag{15}$$

where

$$I(\mu,\,\nu;\,p;\,r,\,z)=\int_0^\infty \lambda^p J_\mu(\lambda a)J_\nu(\lambda r)\exp(-\lambda|z|)d\lambda$$
$$(\mu+\nu+p>-1,\ a>0,\ r>0) \tag{16}$$

$J_m(x)$ denotes the Bessel function of order m in x. From (11) and (15), the magnetic field over the sheet due to the current distortion can be obtained for the unperturbed magnetic field of unit intensity at the surface.

Figure 5 shows the calculated magnetic field over the disk and its vicinity. In the calculation the sheet is treated as lying at a depth of 8 km, taking into account the effectiveness of the portion close to the surface. The values of parameters used for the calculation are as follows:

$$\begin{cases} \omega=0.01 \\ \sigma=0.01\,\mathrm{S/m} \\ \sigma'=0.1\,\mathrm{S/m} \end{cases} \tag{17}$$

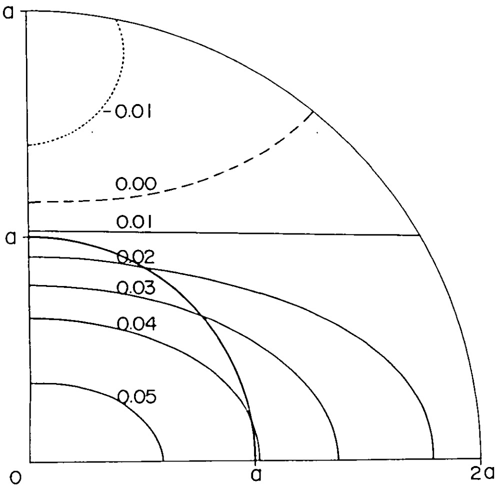

Fig. 5(a)

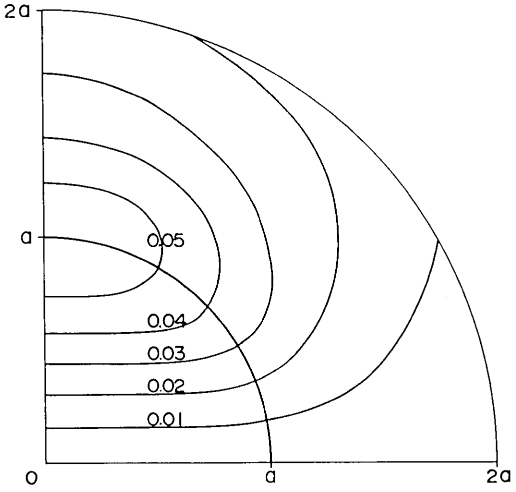

Fig. 5(b)

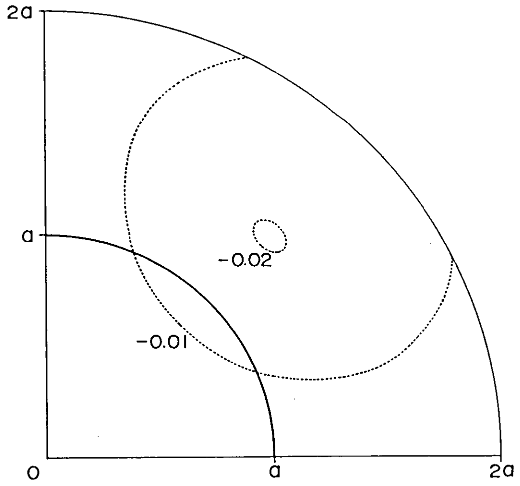

Fig. 5(c)

Fig. 5. Changes in the three components of short-period geomagnetic variations calculated for a northward magnetic field of unit amplitude: (a) the northward magnetic field, (b) the vertical one, and (c) the eastward one, respectively. The unperturbed current flows towards the west. The anomalous area is represented by a circle with radius a. The results are shown for the first quadrant only. Details are given in the text.

The horizontal component perpendicular to the unperturbed current flow increases by about 5% over the central part of the anomalous area having a conductivity one order of magnitude higher than the surrounding region, as shown in Fig. 5(a). It should be noticed that there also exists an area where the amplitude is depressed because of decrease in current intensity arising from the distortion of currents. In the case of the vertical component shown in Fig. 5(b), the maximum of about 0.05 is observed around the edge of the anomalous area. Therefore, a change of 0.05 or so in transfer function can be expected. The horizontal component parallel to the direction of the undisturbed current also appears as a result of the distortion of currents. However, this effect is not very remarkable as shown in Fig. 5(c).

5. Discussion and concluding remarks

It was shown in Section 3 that *Au* and *Bu* values had increased before the Izu-Oshima-Kinkai earthquake, although the amount of increase is not clear because of large errors. According to the result of model calculation as shown in Section 4, a change of 0.05 or so in transfer function is quite possible if the crustal conductivity actually changes by an order of magnitude. Such a change in conductivity is not unlikely to occur in association with the crustal dilatancy before an earthquake occurrence as was clearly demonstrated in the experimental results obtained by BRACE and ORANGE (1968).

Compared to the calculated change in transfer function, 0.05 say, the reported changes amount to 0.1 or more. This discrepancy may indicate that the conductivity changes more remarkably prior to an earthquake occurrence or that there exist additional effects such as the enhancement of undistorted electric currents due to regional current channeling. The latter may be the case, if one takes into account a complex surface structure such as a complicated distribution of highly conducting sea-water and sediments.

The result obtained in Section 4 cannot directly be compared with the observed results shown in Section 3, because of the complicated nature of surface structure in the Izu Peninsula area. However, a qualitative discussion is possible. The enhancement of *Au* and *Bu* values corresponds to appearance of a conducting area in the direction of southeast from the station. Here it should be emphasized that the epicenter of the main shock is located in this direction. Therefore, it is speculated that the electrical conductivity in the focal region may have increased before the earthquake occurrence, although no definitive conclusion cannot be obtained at the present stage. Such an increase in conductivity would be closely related to water-diffusion as presumed by HONKURA (1978).

The amplitude ratio of the *H* component at NKZ to that at YAT was estimated from the power spectral analysis carried out for magnetically disturbed data. The same procedure was also made for the *D* component. Figure 6 shows the result obtained at a period of 30 min.

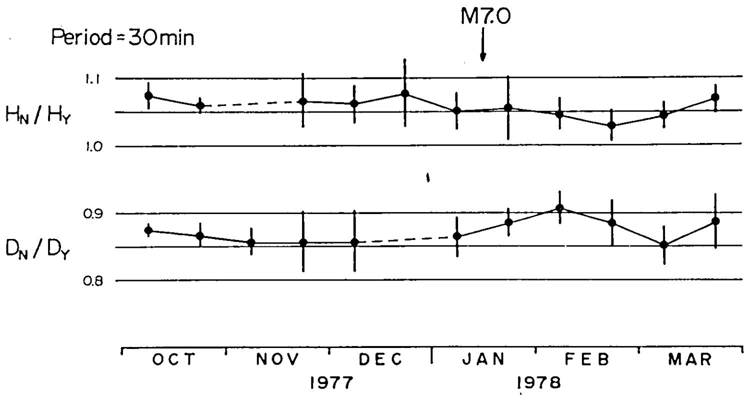

Fig. 6. Time-dependence of the amplitude ratios at a period of 30 min for the *H* and *D* components, respectively, determined from the power spectral analysis. Error bars denote the standard deviations. An arrow indicates the 1978 Izu-Oshima-Kinkai earthquake.

Error bars denote the standard deviations. Compared to the amplitude ratios determined for isolated events by simply reading their maximum amplitudes, error bars are fairly large, probably because of the limited amount of data used for the spectral analysis. Such large error obscures changes in amplitude ratio as shown in Fig. 2, although time-dependence of the *D* component before the earthquake is in good harmony with the result for the *D* component shown in Fig. 2. The amplitude ratio based on the power spectral analysis applied to a large amount of data will be more reliable and suitable when one tries to significantly detect slight changes associated with earthquakes.

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21. 中伊豆における地磁気短周期変化観測 (2): 1978 年伊豆大島近海地震に関連する変換関数変化

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地震に関連して地殻の電気伝導度が変化するかどうかを調べるため，CA 研究の手法に基づいて，地磁気短周期変化の観測を伊豆半島の中伊豆において，1976 年 7 月以来実施している．マグニチュード 7.0 の 1978 年伊豆大島近海地震に関連して，水平成分の振幅に前兆的と思えるような変化が観測されたので，ここでは変換関数の時間的変化を調べることにした．

ノイズが大きいためにあまりはっきりとはしないが，変換関数 Au, Bu (A, B の位相 0° 成分) が伊豆大島近海地震の前に増大していたようである．地震発生前に震源域に高電気伝導度域が出現したとすれば，観測された変化は定性的には解釈可能である．ダイラタンシー拡散説において主張されているように，震源域に地下水が流れ込んだ結果，震源域の電気伝導度が増加したのではないかと考えられる．