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PRELIMINARY REPORT OF ELECTROMAGNETIC SOUNDINGS ON EAST ONGUL ISLAND, ANTARCTICA

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Abstract: Observations of the telluric field were carried out at Syowa Station (69° S, 39°35′E) in Lützow Holm Bay, East Antarctica from May 22, 1995 to January 31, 1996. Telluric fields at Syowa Station have strong anisotropy which varies with frequency. Major axis of electrical variations at high frequency (0.1 Hz-0.5 Hz) trend almost N60°E and those at low frequency (1 mHz-10 mHz) have a N135°E trending major axis. These results suggest that electrical anisotropy exists beneath Syowa Station and the trend changes from N60°E to N135°E with depth.

key words: telluric field, geomagnetic field, electrical anisotropy, electromagnetic sounding

1. Introduction

Electromagnetic (EM) sounding techniques, such as the MT (Magneto-Telluric) method, give geophysical information with respect to structures, which are obtained independently from other geophysical observations, such as seismic and geodetic methods. Electrical conductivities obtained from the EM methods are sensitive to the geothermal structure, fluids and so on. However, there is no clear agreement to apply the MT method at high latitude because of the basic plane wave assumption of the MT method. Because of large effects due to inhomogeneous source fields at high latitude and equator, there is no sufficient method to extract information about the earth from the EM data contaminated by source effects (VILJANEN *et al.*, 1993).

Syowa Station is located at 69°S, 39°35′E on East Ongul Island in Lützow Holm Bay, East Antarctica. The first observation of telluric fields at Syowa Station was carried out by the 3rd Japanese Antarctic Research Expedition (JARE-3) using an analog recording system (OGUTI, 1961). No other telluric observations have been conducted at Syowa Station since 1959. IWABUCHI *et al.* (1980) suggested that the orientation of the polarization axis of geomagnetic pulsations at Syowa Station is anomalous. The anomaly is caused by a local effect due to inhomogeneous telluric currents induced underground (KATO, 1996).

In 1995, a new telluric field observation was carried out to obtain the electrical conductivity structures around Syowa Station. To our knowledge, this was the first time that the EM sounding technique has been applied in East Antarctica. However, we still have the problem of whether the plane wave assumption can be applied at high latitude. Therefore, we report here on preliminary results focused on the behavior of the telluric fields at respective frequencies using the EM data obtained at Syowa Station.

2. Telluric Field Measurement

Figure 1 shows the telluric field measurement site at Syowa Station. The site was located on a bedrock (graniticgneiss) area. The measurement was carried out by using four survey lines of which orientations were either along or across geomagnetic north; lengths of lines were either 50 m or 100 m (NSS, NSL, EWS and EWL in Fig. 1).

Figure 2 illustrates the configuration of the measurement system. The lead chloride pipes were used as the survey line electrodes. The pipes were installed in a hole 3 cm in diameter and 30 cm in depth. The gap in the hole was filled with gel (Chi-koh Gel) which reduced the grounding resistance. A pair of pipes was used in one electrode to reduce the grounding resistance.

Three components of geomagnetic data and four components of electrical data were recorded at one second interval using a multiplex digital data recorder without an amplifier which was installed in the Earth Science Laboratory (ESL). These data were

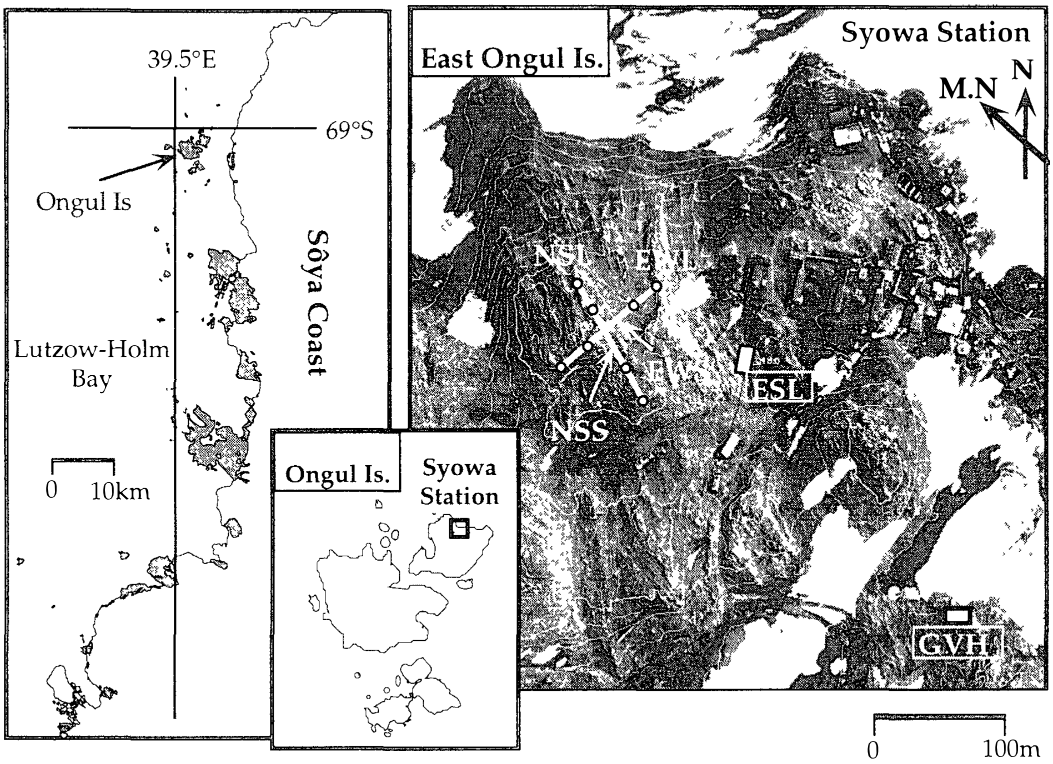


Fig. 1. Location of geophysical facilities and observation site at Syowa Station. ESL: Earth Science Laboratory, GVH: Geomagnetic Variometer Hut. White lines and circles show the survey lines and the telluric electrodes. NSL: 100 m line along geomagnetic north-south, NSS: 50 m line along geomagnetic north-south, EWL: 100 m line along geomagnetic east-west, EWS: 50 m line along geomagnetic east-west.

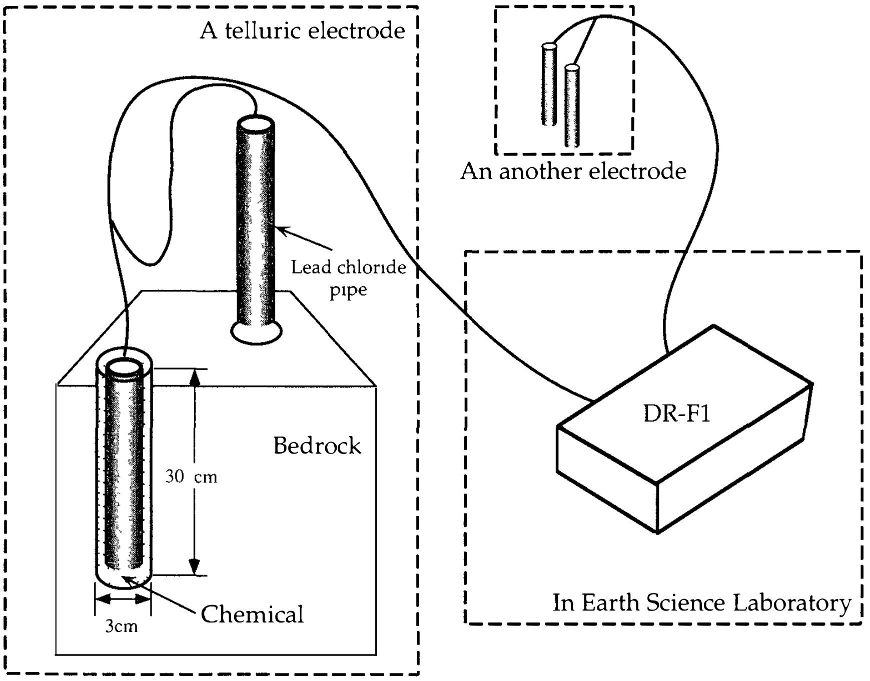


Fig. 2. The telluric fields measurement system. A pair of pipes was used in one telluric electrode. A survey line had two electrodes. Potential differences of the line were observed. The data were recorded using a digital data recorder (DR-F1) in ESL (Fig. 1).

stored on floppy disks. The geomagnetic observations were carried out currently at the Geomagnetic Variometer Hut (GVH) using flux-gate type three component magnetometers.

The observations started on May 22, 1995, and continued until January 31, 1996. Clear signals of currents induced by geomagnetic variations were recorded, although the electrical data included some noises, such as artificial noise, meteorological source noise, etc. We analyze the data obtained only in June (about 30 days) in this paper, because of the low artificial noise and calm weather condition in this month.

3. Data and Analysis

For the data analysis, we took the x-axis to be toward geomagnetic north, the y-axis toward geomagnetic east and the z-axis vertically downward. If the primary inducing field is laterally uniform, a relation between the geomagnetic field and an electrical field (E_x, E_y) is given as follows:

$$E_x = -\sqrt{\frac{i\omega\mu}{\sigma}}\,D, \qquad E_y = \sqrt{\frac{i\omega\mu}{\sigma}}\,H, \tag{1}$$

where E_x and E_y are electrical fields, H and D are geomagnetic horizontal components along the x-axis and y-axis, respectively, and μ, σ and ω denote permeability, conductivity and angular velocity (EGGERS, 1982). The telluric field signals of NSL and EWL are projected onto the x and y-axes by geometric rotation. Hereafter these signals are called E_x and E_y, respectively. NSS and EWS are not used, because signal-to-noise ratios of NSS and EWS are lower than those of NSL and EWL. Additionally, E_x and E_y are expressed by a normalized unit mV/km. In the MT method, apparent resistivity as a function of frequency, in $\Omega \cdot$m, is defined as follows:

$$\rho_a = \frac{1}{\sigma} = \frac{1}{\omega\mu} |Z|^2,$$

where Z is the observed EM wave impedance at the earth's surface (*e.g.*, EGGERS, 1982). In general, the impedance is expressed by a tensor, and the horizontal field components are related by the MT impedance tensor:

$$\begin{bmatrix} E_x(f) \\ E_y(f) \end{bmatrix} = \begin{bmatrix} Z_{xx}(f) & Z_{xy}(f) \\ Z_{yx}(f) & Z_{yy}(f) \end{bmatrix} \begin{bmatrix} H_x(f) \\ H_y(f) \end{bmatrix}, \tag{2}$$

where f is frequency (JONES, 1992).

When the EM wave penetrates into the earth, the skin depth signifies the depth where the intensity of the wave is attenuated by 1/e (about 37%). The skin depth, $D(T)$, of the EM fields is given by JONES (1992) as follows:

$$D(T) \approx 503\,[\rho_a T]^{1/2}, \tag{3}$$

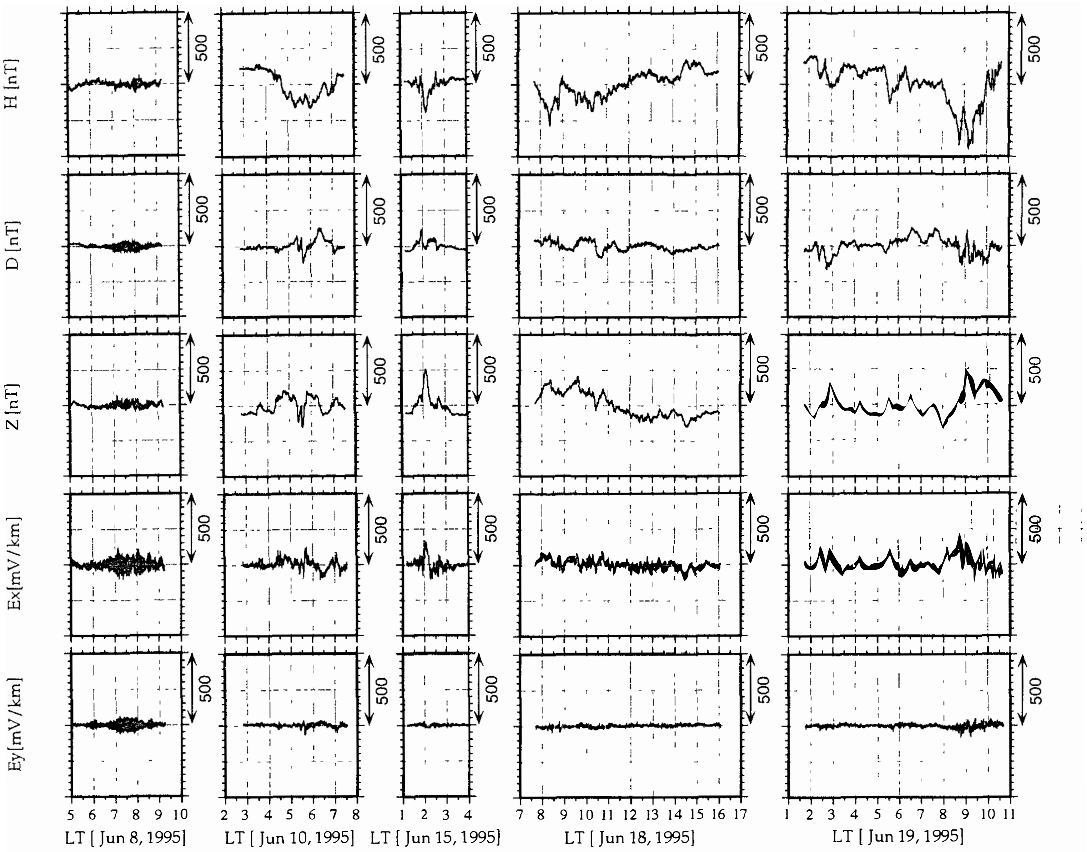
where $D(T)$ is in meters, and T is the period of the EM variations in seconds. The apparent resistivities from surface to deep layers are estimated using natural EM fields which have various periods in the MT method.

We analyzed the data in four different EM situation periods.

1) The geomagnetism and the telluric field variations were active.
2) Both signals were quiet.
3) During blizzards. The geomagnetic signal was quiet, but the telluric variations were active.
4) The electrical data included unknown signals that did not correspond with the geomagnetic variations.

The above periods were named 1) "active", 2) "quiet", 3) "blizzard", and 4) "noise", respectively. The "blizzard" and "noise" periods are not treated in this analysis. Figures 3a and b show time series of the three components of geomagnetic data and the horizontal components of telluric data in "active" (Fig. 3a) and "quiet" (Fig. 3b) periods. It is clearly observed that telluric variations accompany geomagnetic variations. The EM data in "quiet" periods are shown to check the noise level of the measurement system.

A particle motion diagram (PMD) is illustrated to show the telluric variations. The PMD shows a trajectory of the time varying patterns of the observed EM data in the horizontal plane. If we assume that the electrical conductivity structure is one dimensional (1-*D*), the conductivity should vary with depth alone and the MT impedance tensor in eq. (2) becomes:



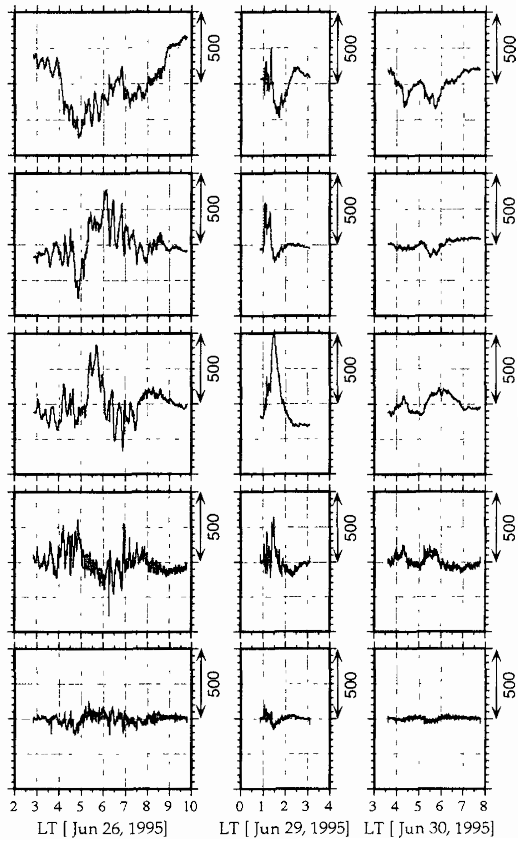


Fig. 3a–b. Observed electromagnetic records. Time series of geomagnetic variations are shown for H (top panel), D (2nd panel) and Z (3rd panel) components, respectively, and time series of electrical filed variations are shown for E_x (4th panel) and E_y (bottom panel). (a) "Active" period.

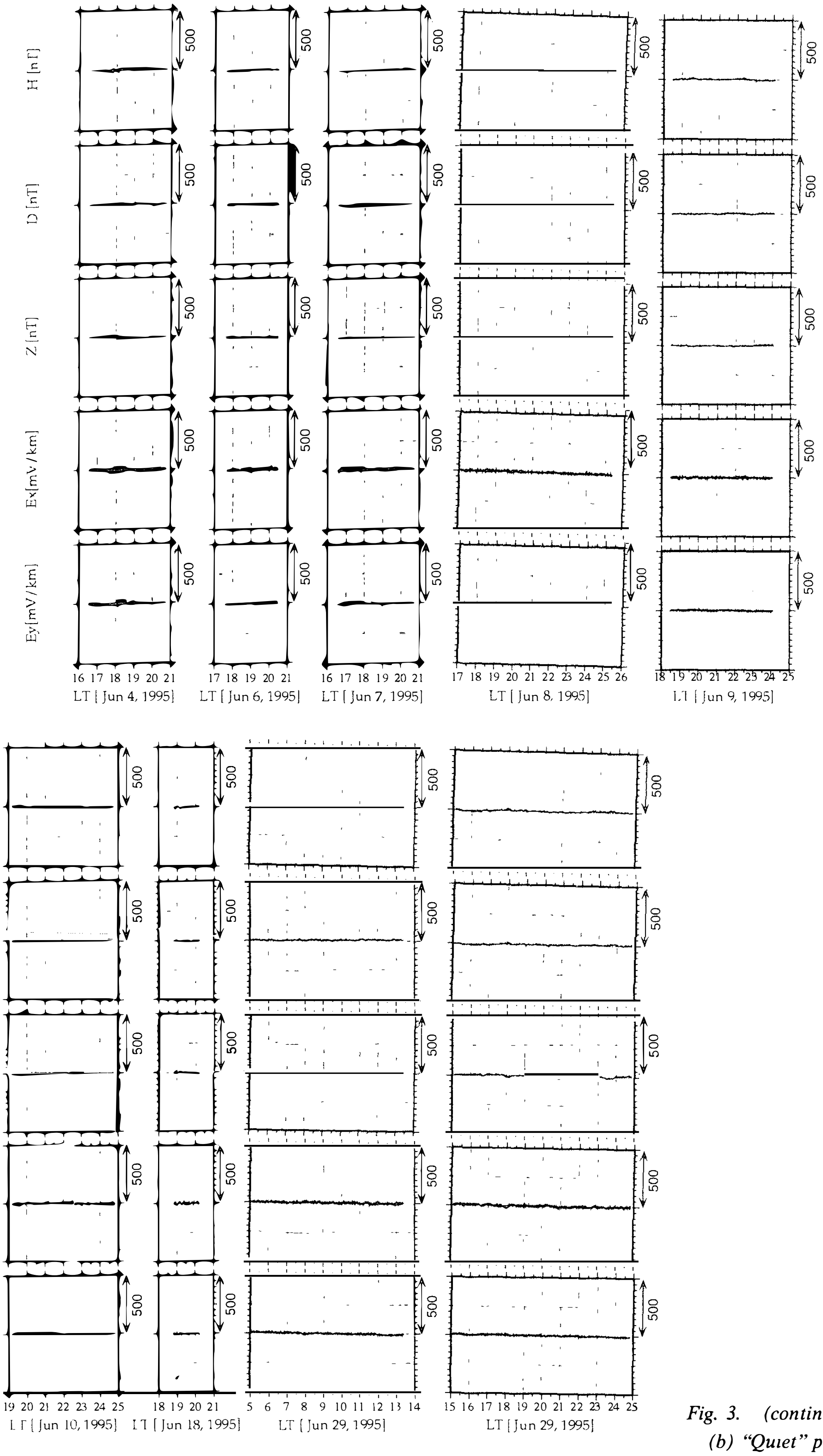


Fig. 3. (continued).
(b) "Quiet" period.

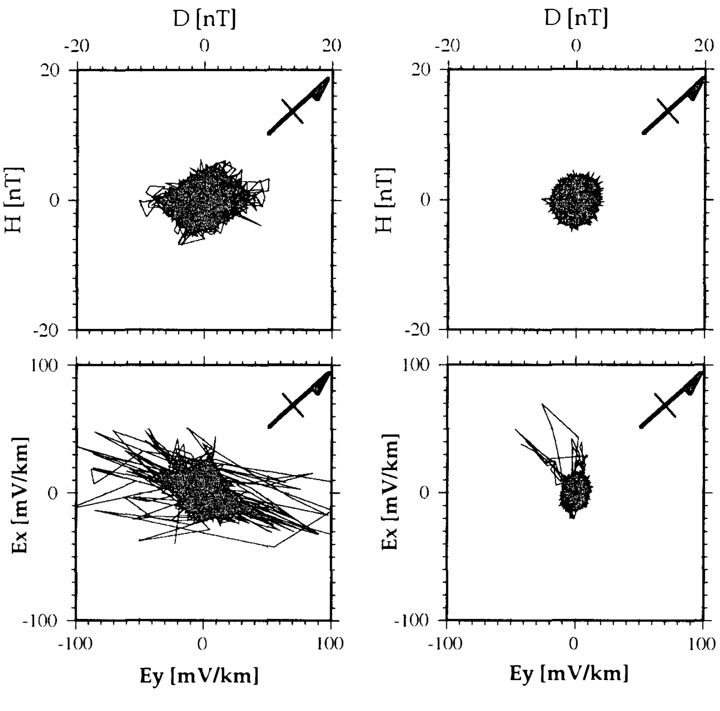
$$Z_{1D}(f)=\begin{bmatrix} 0 & Z_{xy} \\ -Z_{xy} & 0 \end{bmatrix}.$$

Then the pattern of the electrical PMD should be normal to that of the geomagnetic PMD. An inhomogeneous conductivity structure is suggested, if PMD patterns in the H-D plane are nearly circular and those in the E_x-E_y plane are elliptical. In case of a two dimensional (2-D) conductivity structure, when a strike of the conductivity boundary runs along the x-axis, the MT impedance tensor in eq. (2) is written as:

$$Z_{2D}(f)=\begin{bmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{bmatrix}.$$

Then an anisotropic telluric field is induced by an isotropic geomagnetic field. As has been noted, the pattern of electrical PMD may reflect characteristics of the conductivity structure.

We illustrate PMDs in the four frequency ranges 0–1 mHz, 1 m–10 mHz, 10 m–0.1

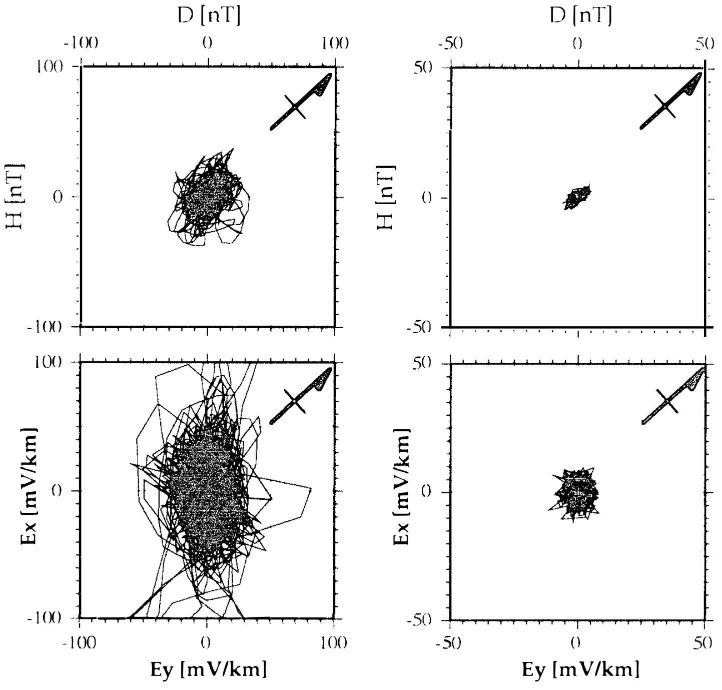


"Active" PMD in 0.1-0.5Hz

"Quiet" PMD in 0.1-0.5Hz

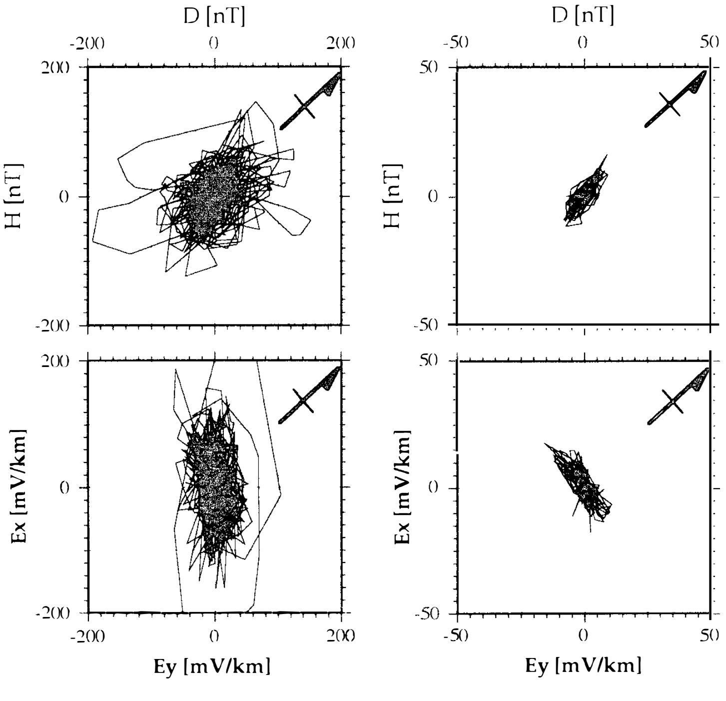
(a) 0.1–0.5 Hz band.

Fig. 4. Particle motion diagrams (PMD) of four frequency bands. The PMDs show the trajectory of the time varying patterns of the electromagnetic data in the horizontal plane. The vertical and horizontal axes are oriented along and across geomagnetic north, respectively. The arrow shows the direction of geographic north around Syowa Station. The trajectories are shown for "active" geomagnetic variations (left top), "active" electrical variations (left bottom), "quiet" geomagnetic variations (right top) and "quiet" electrical variations (right bottom), respectively.



"Active" PMD in 10m-0.1Hz "Quiet" PMD in 10m-0.1Hz

Fig. 4 (continued). (b) 10 m–0.1 Hz band.



"Active" PMD in 1m-10mHz "Quiet" PMD in 1m-10mHz

Fig. 4 (continued). (c) 1 m–10 mHz band.

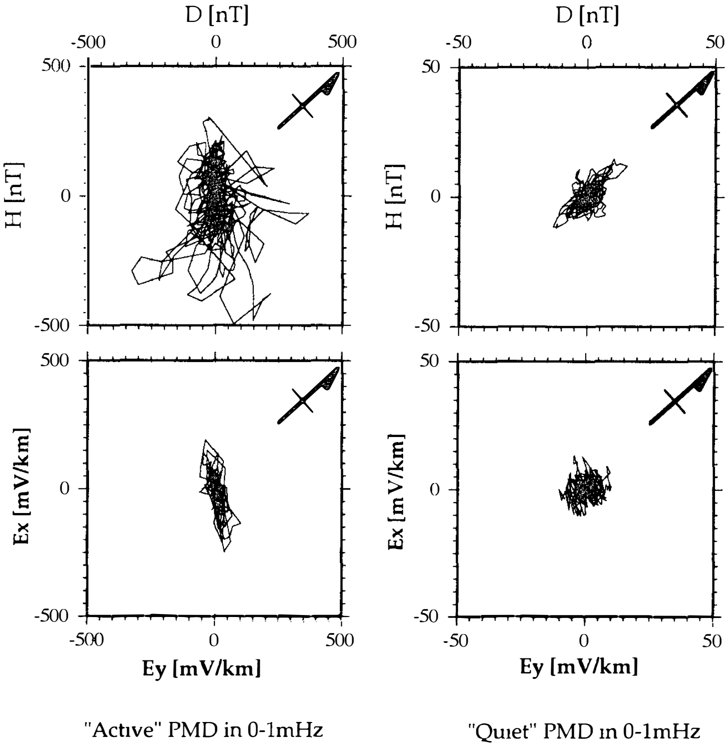


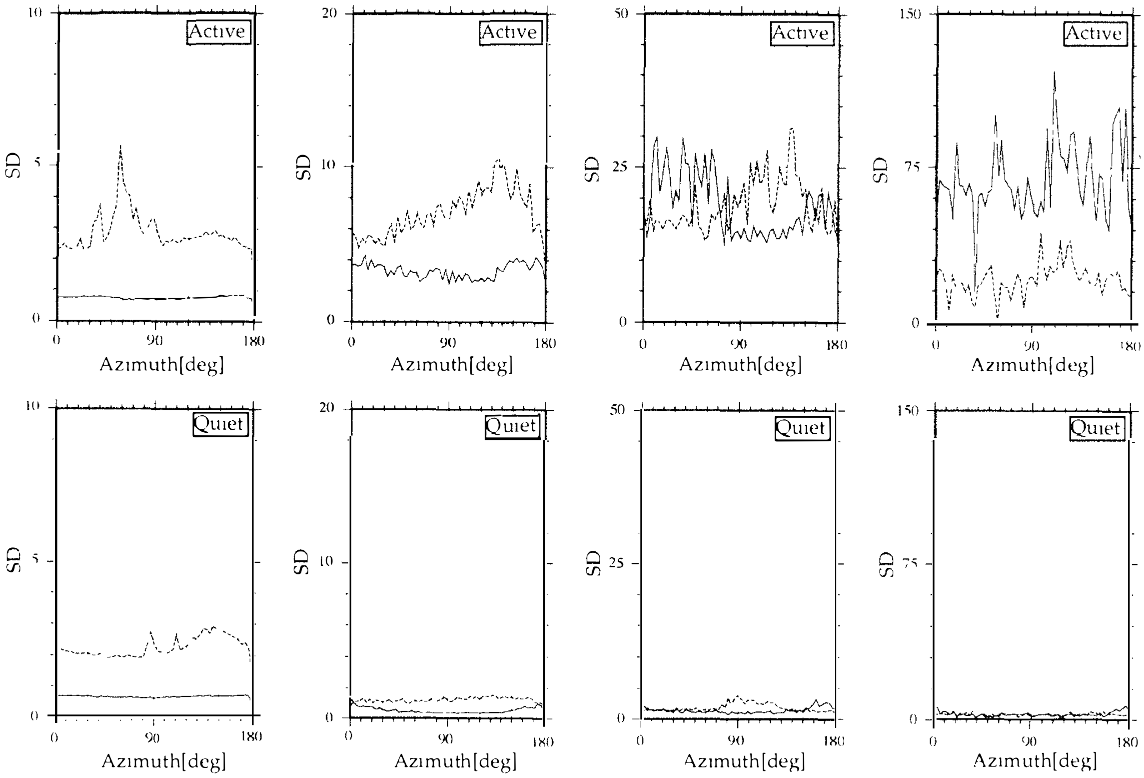
Fig. 4 (continued). (d) 0–1 mHz band.

Hz and 0.1–0.5 Hz in Fig. 4. Four digital band-pass filters have been applied to the data. Furthermore, the averaged deviation (AD) from mean amplitude of EM variations at each azimuth is calculated to detect the dominant azimuth of the EM variations. First, the mean amplitude of EM variations is calculated in each band. Second, the deviations of the amplitude from the mean amplitude are obtained from all sampling points in each band. Finally, the averaged deviation (AD) is calculated by averaging the deviations from all sampling points at each azimuth. If the EM variation is homogeneous, the AD should be uniform over all azimuths. ADs are used to detect the predominant azimuth of the EM variations. ADs in the four bands are shown in Fig. 5.

4. Results

Figures 4a, b, c and d show the PMD patterns in "active" and "quiet" periods in 0.1–0.5 Hz, 10 m–0.1 Hz, 1 m–10 mHz and 0–1 mHz band.

Though the geomagnetic PMD patterns in 0.1–0.5 Hz are nearly small circles, the electrical PMD patterns are ellipses that have the major axis along about N70° W as shown in Fig. 4a. In addition, the ADs of geomagnetic variations are flat over all azimuths, but a significant peak appears in the telluric variations as shown in Fig. 5. These peaks in ADs of telluric variations can also be seen in the other three bands of the "active" period as shown in Fig. 5. The major axes of PMD patterns with respect to "active" in the E_x-E_y plane are N60° E in 0.1–0.5 Hz, N135° E in 10 m–0.1 Hz, N135° E in 1 m–10 mHz and N115° E in 0–1 mHz. These results indicate that the telluric fields



a) 0.1-0.5Hz

b) 10m-0.1Hz

c) 1-10mHz

d) 0-1mHz

Fig. 5. The averaged deviations (AD) of the electromagnetic variations along the azimuth. A solid line represents the AD of the geomagnetic variations and a dashed line that of the telluric variations. (a) 0.1–0.5 Hz band. (b) 10 m–0.1 Hz band. (c) 1–10 mHz band. (d) 0–1 mHz band.

around Syowa Station have strong anisotropy.

No significant anisotropy of the telluric fields is identified in the "quiet" PMDs except for the 1–10 mHz band (Figs. 4a, 4b and 4d). The "quiet" electrical PMD in the 1–10 mHz band (Fig. 4c) seems to have an anisotropy trending almost E-W. However, the amplitude of telluric changes is much smaller than that of telluric variations in the "active" PMDs, and no significant peak in SD of telluric variations is shown in "quiet" 1–10 mHz band (Fig. 5). So this anisotropy in the "quiet" PMD is negligible.

5. Discussion

The major axes of the "active" electrical PMD are N60°E in 0.1–0.5 Hz, N135°E in 10 m–0.1 Hz, N135°E in 1 m–10 mHz and N115°E in 0–1 mHz. Kato (1996) inferred that the origin of the anomalous polarization axis of Pc5 pulsations at Syowa Station was caused by the local effect due to the inhomogeneous telluric currents, which induced the geomagnetic variation along magnetic N-S (N48°W). He interpreted this to mean that inhomogeneous telluric currents were caused by the coast-line effect of the Antarctic Continent (Sôya Coast in Fig. 1). The major axes of "active" electrical PMDs, however, are not parallel to the magnetic E-W direction. So an other interpretation can be necessary for the electrical anisotropy in "active" PMDs.

The presence of the major axes of the telluric variations suggests that the inhomogeneous conductivity structure around Syowa Station can be estimated, if the source field effects are ignored. The "active" EM PMDs show that the anisotropy directions vary from N60°E at high frequency to N135°E at low frequency. In general, high frequency of the EM wave reflects shallower conductivity structures and low frequency deeper conductivity structures. Based on eq. (3), using $\rho_a = 10^3\,\Omega\cdot\mathrm{m}$ in the upper crust, the skin depth is estimated to be about 22 km in 0.5 Hz and about 500 km in 1 mHz. For $\rho_a = 0.1\,\Omega\cdot\mathrm{m}$ as a saline fluid, the skin depth is about 700 m at 0.5 Hz and 16 km at 1 mHz. These imply that the anisotropy direction obtained from EM data varies with depth, although the EM wave is attenuated in shallower depth for the low resistivity structure. Therefore our results suggest that the anisotropy direction at shallow depth trends along N60°E and that at greater depth trends N135°E.

For seismic anisotropy beneath Syowa Station, KUBO and KANAO (1997) showed that the fast polarized direction of crustal shear wave splitting was oriented along N50°W and the fast polarized direction in the upper mantle was oriented along N49°E. The telluric anisotropy tendency is similar to the consequence of seismic anisotropy in the crust and upper mantle beneath Syowa Station. JI *et al.* (1996) showed the consistent obliquity between the polarization direction of the fast split shear wave and the most electrically conductive direction in the upper mantle beneath the Archean Superior Province of the Canadian shield. Since heat flow at Syowa Station is lower than in other regions (KAMINUMA and NAGAO, 1983), it is unlikely that the anisotropy of the electrical conductivities reflects a geothermal structure. The correspondence of seismic and electrical anisotropies observed at Syowa Station may imply that the conductivity structure is similar to the seismic structure which produces an anisotropy.

There is no adequate method yet to estimate the source field effects only from the EM data obtained from a single site, because it is impossible to know the spatial distribution of the nonuniform source fields from a single observation. It is necessary to consider a method to estimate the source field effects from the single observation in order to calculate the impedance tensor and determine conductivity structures.

6. Conclusion

The telluric fields around Syowa Station have strong anisotropy. The anisotropy direction varies with frequency. The major axis of the electrical variations trends from N60°E at high frequency to N135°E at low frequency. These results suggest that the electrical anisotropy direction around Syowa Station changes from N60°E to N135°E with depth.

In conclusion, the EM measurements may provide useful information about crustal and upper mantle structures. However, an array observation of EM soundings is required to determine the detailed conductivity structure and the spatial distribution of nonuniform source fields. The source field effects should be estimated and an impedance analysis performed on the EM data observed at Syowa Station, East Antarctica in the future.

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