Time Changes in Geomagnetic Transfer Functions at Lunping before and after the 1986 Hualian Earthquake [Ms = 7.6]

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A strong earthquake of magnitude 7.6 occurred on November 15, 1986 near Hualian. The Lunping geomagnetic observatory in the Taiwan region is situated 110 km from the epicentre of the strong earthquake. In this study, the geomagnetic data of the Lunping observatory from 1970 to 1988 are utilized for computing the geomagnetic transfer functions. Our results show that the remarkable time changes in \( A_u \), the real part of the transfer function \( A \), appear to be related to the occurrence of the 1986 earthquake. The magnitudes of \( A_u \) for the periods of 31, 25, 21 and 14 min decreased gradually from 1970 to 1985 and partially recovered in 1986 before the earthquake occurrence. After the earthquake occurrence the magnitudes of \( A_u \) decreased again. No significant variation was detected in the time changes of \( A_v, B_u \) and \( B_v \) within the error levels. In other words, the real Parkinson arrow rotated clockwise towards the earthquake region in the interval of 1970 to 1985. We consider that the variation of the real Parkinson arrow might be ascribed to the elevation of the top level of a conductivity anomaly, which is deeply buried at the south-east side of the Lunping observatory. We propose that this elevation might be related to the preparation process of strong earthquake. Besides, it is worth pointing out that the noticeable annual change rate in \( A_u \) is up to 0.01 before the 1986 Hualian earthquake; such a change rate is comparable to that detected at Kakioka before the 1923 Kanto earthquake.

1. Introduction

The conductivity of rocks is one important physical property which can be measured in the Earth. The temporal variation of the conductivity underground has been related to earthquake occurrence in some earthquake prediction theories. One well-known model of earthquake mechanism is called the 'dilatancy' model, which proposes that the volume increased in stressed rock produces a large increase in porosity and mechanical permeability (SCHOLTZ et al., 1973; SCHOLTZ and KRANZ, 1974). When electrolytic water permeates the pores and cracks, the conductivity of rock can increase significantly. Apart from the 'dilatancy' model, there are other reasons, such as a rise in temperature, may also lead to noticeable increasing of the conductivity within the rock in an earthquake preparation zone (OLHOEFT, 1981).

In earthquake prediction practice, detecting the time change of the geomagnetic transfer functions is available for monitoring the possible conductivity change in the crust or upper mantle. The first two reports on this subject were published by YANAGIHARA (1972) and MIYAKOSHI (1975). Yanagihara and Miyakoshi studied respectively the time changes in geomagnetic transfer functions which are considered to be associated with the 1923 Kanto earthquake with magnitude of 7.8 and the Tashkent earthquake with magnitude of 5. After that, similar or more precise works concerned with other earthquake occurrences can be found in the literature of YANAGIHARA and NAGANO (1976), RIKITAKE (1979), HONKURA (1979), SANO (1980), SHIRAKI (1980), CHEN (1981), GONG (1986) and FUJITA (1990). We would like to emphasize that Yanagihara's results
indicated that quite a remarkable secular change in transfer function $A$ at Kakioka magnetic observatory decreased to a minimum prior to the earthquake occurrence and recovered steeply in time after the minimum.

The geomagnetic data of 1972–1976 for the Lunping observatory in the Taiwan region have been analysed using a simple method (Chen, 1981). This method is to measure directly the maximum amplitudes of $\Delta H$, $\Delta D$ and $\Delta Z$ for each individual disturbance event, while $\Delta H$, $\Delta D$ and $\Delta Z$ are respectively the variations of the horizontal, the declination and the vertical components. Moreover, the spectral analysis method was employed for determining the complex transfer functions for the Lunping data of 1970–1986. The results have been briefly reported at the ‘International Symposium on Geomagnetism’ held in Shanghai, China (Chen and Fung, 1990). In the present paper, we extend our analysis to contain data for the period of 1987–1988, so that the temporal variations in complex transfer functions before and after the strong Hualian earthquake occurred in 1986 are included.

2. Analysis of the Geomagnetic Data together with the Selected Earthquake Data

A strong earthquake of magnitude 7.6 occurred on November 15, 1986 near Hualian (see Fig. 1). The depth of focus is 38 km. The Lunping Geomagnetic Observatory (121°10'E, 25°00'N) is situated 110 km from the epicentre of the great earthquake. The geomagnetic data digitized from the magnetograms recorded by the analog Ruska magnetometer for 1970–1988 at the Lunping observatory are utilized for computing the complex transfer functions. The geomagnetic disturbance events analyzed in the present study are selected with a duration of either 2 hours or 3 hours. After linear detrending and passing through the Hanning window, Fast Fourier transforms of three magnetic components are calculated for each event, and the transfer functions of four periods (31, 25, 21 and 14 min) are obtained according to the formula introduced by Everett and Hyndman (1967) based on the least square method

$$A = \left[ \sum H_x^* H_x \sum H_y^* H_y - \sum H_x^* H_y \sum H_y^* H_x \right] D^{-1},$$

$$B = \left[ \sum H_x^* H_x \sum H_z^* H_z - \sum H_x^* H_z \sum H_z^* H_x \right] D^{-1},$$

where

$$D = \sum H_x^* H_x \sum H_y^* H_y - \sum H_x^* H_y \sum H_y^* H_x,$$

while $H_x$, $H_y$ and $H_z$ are the three components of the geomagnetic field, and * indicates the complex conjugates. In order to determine one set of complex transfer functions, the selection of ten to fifteen disturbance events is needed. The standard errors of the transfer functions are estimated by the method introduced in Hildebrand (1974).

Because too many earthquakes occurred in the whole Taiwan region and its vicinity during the period in this study, how to select the earthquakes for searching the correlation of the time changes in transfer functions and the earthquake occurrences is a difficult problem. Most of the earthquakes are distributed in the region of the Tai-Dung seismic belt, which runs parallel with the east coast of the Taiwan Island. The formation of the Tai-Dung seismic belt can be primarily attributed to the collision between the Eurasian and Philippine Sea Plates. Figure 2 shows a picture of earthquake distribution in the Taiwan area during the period of 1974–1976, we see that the epicentres are mainly concentrated at the northern segment of the Tai-Dung seismic belt (after B1q (1981)). In Fig. 2 the earthquakes are hypocentred between 30 and 70 km, but the magnitudes of these earthquakes were not clearly indicated. Those magnitudes may be greater than 3.0 in reference to other sources (e.g. Tsai et al., 1981). As a matter of fact, the stated northern segment lies under and in parallel with the 121.5°E meridian between 24.0°N
and 25.0°N. Such a region represents the western edge of the northward subducted Philippine Sea plate which is revealed by the presence of a Benioff seismic zone dipping north at about 45°. However, the central and southern segments mark a transform-fault type boundary (Tsai et al., 1981). In this study, we choose those strong earthquakes with Ms ≥ 6.3 occurred in the region of the northern segment and whose epicentral distances from the Lunping observatory being less than 150 km. According to these criteria, the selected earthquakes and their parameters are listed in Table 1. The distribution of these earthquakes are shown in Fig. 1.

<table>
<thead>
<tr>
<th>Earthquake No.</th>
<th>Date</th>
<th>Ms</th>
<th>Depth of focus (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-9-1978</td>
<td>6.8 (mb)</td>
<td>115</td>
</tr>
<tr>
<td>2</td>
<td>29-1-1981</td>
<td>6.4</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>23-1-1982</td>
<td>6.5</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>22-9-1983</td>
<td>6.4</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>13-6-1985</td>
<td>6.3</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>16-1-1986</td>
<td>6.4</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>20-5-1986</td>
<td>6.9</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>15-11-1986</td>
<td>7.6</td>
<td>38</td>
</tr>
</tbody>
</table>

3. Time Changes in Transfer Functions

Figure 3(a) shows the remarkable time changes of $A_u$, the real part of the transfer function $A$, for the periods of 31, 25, 21 and 14 min. We can see that during the period of 1970 to 1985, $A_u$ for the period of 31 min changed gradually from −0.17 to 0.0, and partially recovered in 1986 before the occurrence of the $M7.6$ earthquake. After the occurrence, $A_u$ increased again. The
Fig. 3. Time changes in (a) $A_u$, (b) $A_v$, (c) $B_u$, and (d) $B_v$ for the Luning observatory in the interval of 1970–1988. The error bars are ±2 sd. The arrow represents the earthquake occurrence ($M_s = 7.6$).

time changes of $A_u$ for other three periods, 25 min, 21 min and 14 min, have similar features as that for 31 min. Figures 3(b)–3(d) show respectively the time changes of $A_u$, $B_u$ and $B_v$ for the four periods mentioned above. $A_u$ denotes the imaginary part of the transfer function $A$. $B_u$ and $B_v$ denote respectively the real part and imaginary part of the transfer function $B$. No significant variation was detected in the $A_u$, $B_u$ and $B_v$ curves in view of the error estimates. The error bars in Figs. 3(a)–3(d) denote two standard deviations. The time change in transfer function $A_u$ appears to be closely related to the occurrence of the 1986 Hualian earthquake with $M_s = 7.6$. Before the strong earthquake occurrence the values of $|A_u|$ for all the four periods decrease gradually with an annual change rate of about 0.01.

The feature of the time variations in transfer functions can also be seen in the frequency response curves for different years. In Fig. 4, the frequency response curve of $A_u$ for 1986 changes significantly in comparison with the curve of $A_u$ for 1972. However, the frequency response curves
Fig. 4. Frequency responses of transfer functions for different years.

Fig. 5. The rotation of the real Parkinson arrow for $T = 31$ min during the period of 1970 to 1985. The contours are the bathymetric lines in meters.
of $A_u$ for different years, as well as that of $B_u$ and $B_v$, are almost unchanged.

Furthermore, the real Parkinson arrow, which is constructed from $-A_u$ and $-B_u$, turned gradually towards the earthquake region during the period of 1970 to 1985 (see Fig. 5). However, the imaginary Parkinson arrow did not change significantly during the same interval of 1970–1985.

4. Discussion and Conclusion

(a) FUJITA (1990) found that the time variations in the monthly means of transfer functions are generally correlated among several observatories located separately (such as Memambetsu, Kakioka and Kanoya), hence he concluded that the transfer function is not adequate for the short-term earthquake prediction. However, Fujita pointed out that the annual change rates of the transfer functions might be meaningful for monitoring earthquake occurrence.

In this study, the measured $A_u$ values at Lunping changed remarkably at least from 1970 to 1985. We consider that this variation occurs locally and may be related to the 1986 earthquake occurrence. For comparison, we introduce the time changes in transfer functions observed at the Zose observatory (i.e. the Shanghai observatory, 121°11'11"E, 31°05'48"N) analyzed by ZENG et al. (1992). Figure 6 shows the month-to-month variations of $|A|$ in the interval of 1977–1984 for Zose. It is redrawn from Fig. 3 of their paper. $|A|$ is the modulus of the complex transfer function $A$. We can see the time changes of $|A|$ at the Zose observatory is not large in the whole interval except for the first year (1977–1978). The variation of $|A|$ in the period of 1977 to July, 1979 was regarded as the precursor phenomena of the Liyang earthquake ($Ms = 6.0$) by Zeng et al. The Liyang earthquake occurred on July 9, 1979, and its epicenter is located at the west of Zose, the station-epicentral distance is about 190 km. Another earthquake indicated in Fig. 6 is the Huanghai earthquake ($Ms = 6.2$) occurred on May 21, 1984, located at the north of Zose, and the station-epicentral distance is found to be about 150 km.

![Fig. 6. Time changes in $|A|$ for the Zose observatory in the interval of 1977–1984. This figure is redrawn after ZENG et al. (1992).](image)

Although the study interval (1977–1984) shown in Fig. 6 did not covered the whole interval of 1970–1988 concerned in this paper, we can still make a comparison in the common time interval of 1978–1984. In this study, the 31-minute-period $A_u$ observed at Lunping changed from $-0.09$ (in 1978) to $-0.03$ (in 1984); but in the same six-year interval the 26-minute-period $|A|$ at Zose increased only about 0.01. Comparatively speaking, the average annual change rate of $|A|$ at Zose for the 26-minute-period appears to be larger than those for other periodicity (see Fig. 6).

Besides, a similar comparison have been reported in CHEN (1981), the annual change rate of $A$ at the Hong Kong observatory ($114°13'15"E, 22°21'36"N$) is very small in the interval of
1972–1976. In contrast, the annual change rate of $A$ for Lunping is comparatively large in the same interval.

(b) It is difficult to give an accurate quantitative explanation to the different characteristics between the real and the imaginary Parkinson arrows at the present stage, especially in the case that we have only the result obtained from one observatory. Roughly speaking, the magnitude and the direction of the Parkinson arrow at Lunping may be dependent on the presence of sea water surrounding the Taiwan Island and the temporal variation of a possibly existed conductivity anomaly, which is deeply buried and associated with the earthquake preparation zone. We consider that the conductivity of sea water should be unchanged in time during the studied period. The fact that the real Parkinson arrow rotated gradually towards the earthquake region before the earthquake occurrence and the imaginary arrow remained unchanged can be qualitatively explained by the elevation of the top level of the conductivity anomaly in the south-east region of the Lunping observatory, i.e. in the northern segment of the Tai-Dung seismic belt. This region is just at the upper boundary of the subducting Philippine Sea plate. Since the temperature structure near the upper boundary is usually very complicated, we assume that the vertical gradient of temperature there might change in accordance with the movement of subducting plate. Hence, the volume variation of highly conductive anomaly, due to the elevation or subsidence of isogeothersm, might be related to the seismic activity.

We shall proceed to present two 2-D models for a qualitative explanation to the different characteristics of the real and the imaginary arrows observed in this study. The characteristics of the two models are indicated in Fig. 7 which also shows the $A_u-x$ and the $A_v-x$ curves for the two models when the inducing period is taken to be 30 min, where $x$ denotes the distance in the north direction measured from the centre of the conductivity anomaly in units of km. The first model is constructed by a deeply isolated buried anomaly, whose top is assumed to be at the level of 50 km. In the second model, the buried depth of the anomaly is assumed to be 20 km. We observe from Fig. 7 that, if the observation point is located near or outside the vertical edge of the anomaly, the transfer function $A_u$ in model 1 differs significantly from that in model 2, but the transfer functions $A_v$ for the two models appear to be different only slightly from each other. Such a calculated feature is expected in the case when the inducing period (i.e. the observation periodicity) is close to the characteristic period $T_c$ of an isolated conductivity anomaly model, while the phase difference $\Delta \phi$ between the vertical magnetic component and the horizontal magnetic component is nearly equal to zero (CHEN and FUNG, 1985, 1986). In other words,

\[ A_u = \left| \frac{H_z}{H_x} \right| \cos(\Delta \phi) \approx \left| \frac{H_z}{H_x} \right|, \quad (4) \]
\[ A_v = \left| \frac{H_z}{H_x} \right| \sin(\Delta \phi) \approx 0. \quad (5) \]

Moreover, if the difference between the $T_c$ for model 1 and the $T_c$ for model 2 is not very large, the behaviour of the $A_u-x$ curve and the $A_v-x$ curve shown in Fig. 7 is plausible. Therefore, we anticipate that the contribution in real transfer functions due to the elevation of the conductivity anomaly, in combination with the ocean effect, causes the clockwise rotation of the real Parkinson arrow before the earthquake occurrence (shown in Fig. 5) as is observed. The imaginary arrow is almost entirely controlled by the ocean effect, and hence remains unchanged during the whole time interval of analysis.

(c) The average annual change rate in transfer functions seems to be closely related to the preparation process of strong earthquake. Before the 1923 Kanto earthquake the annual change rate of $A$ for the period $T$ greater than 6 min for the Kakioka observatory is about 0.01

* A 3-D model is much involved and is beyond the scope of this investigation.
Fig. 7. The $A_u - x$ and $A_v - x$ curves for $T = 30$ min for two models, which configurations are shown at the right hand side of this figure.

(YANAGIHARA, 1972; YANAGIHARA and NAGANO, 1976). Besides, FUJITA (1990) reveals that the annual change rates of the 10-min-period $A_u$'s for the Matsuzaki and the Omaezaki observatories are decreasing remarkably (up to 0.02) during the time interval of 1981 to 1986. Since a large earthquake has been predicted to occur in the near future in the Tokai area, the change rates in transfer functions for these two observatories are regarded as primarily important phenomenon.

In this study, the annual change rate of $A_u$ (for the periods of 14, 21, 25 and 31 min) observed at the Lunping observatory is about 0.01 during the interval of 1970 to 1985. This annual change rate is comparable to that of Kakioka before the Kanto earthquake. Since these large annual change rates are all observed near the subduction zone, we propose to treat them as precursors of large earthquakes which occur within subduction zones.

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REFERENCES


