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Tectonoelectric Signal Related with the Occurrence of the 1995 Hyogo-ken Nanbu Earthquake (*M* 7.2) and Preliminary Results of Electromagnetic Observation around the Focal Area

Electromagnetic Research Group for the 1995 Hyogo-ken Nanbu Earthquake*

In association with the 1995 Hyogo-ken Nanbu earthquake, we observed changes in the telluric field by about 10 mV/km about 10 s after the origin time with some long-span electrical dipole network located at about 70 km from the epicenter. After the occurrence of the earthquake, electric and magnetic measurements such as DC resistivity, VLF-MT, self-potential, and the geomagnetic total intensity across the Nojima fault were made at several places in Awaji Island. The low resistive zone beneath the western side of the fault was found in the derived resistivity structure of the shallower portion of the fault in Hirabayashi. On the other hand, however, no significant anomaly associated with the fault structure was found from the measurements of total intensity and self-potential. Prior to the occurrence of the main shock, no geomagnetic or electric continuous stations existed near the focal area. Approximately within 1 week after the occurrence of the main shock, we set up 10 continuous observation sites for the geomagnetic total intensity in the focal area in order to detect geomagnetic changes due to stress change caused by the aftershock activity. No changes in the total intensity in association with the individual aftershock activity have been observed so far. However, systematic temporal trends in the geomagnetic differences have been observed, especially at sites in the northern half of the observation area.

1. Introduction

The 1995 Hyogo-ken Nanbu earthquake (*M* 7.2) occurred on January 17, 1995 in southern Hyogo Prefecture, western Japan. The epicenter of the main shock was located in Akashi Strait (34.6N, 135.0E), several kilometers from the northern tip of Awaji Island. Its focal depth and origin time were 17.2 km and 05:46:51.47(JST), respectively. The seismic fault (the Nojima fault), which showed about 1 m right-lateral displacement during the main shock, was found in the northern Awaji Island area (e.g., Nakata, 1995). The fault rupture also extended towards the northeast, beneath Kobe City.

After the occurrence of the earthquake, many witnesses reported various kinds of extraordinary earthquake light accompanying the earthquake in and around the focal area. Some reports could not be denied to be natural phenomena, although some reported sightings can be attributed to the sparkling of damaged electric power lines and so on (e.g., Tsukuda,1995). This might suggest that electromagnetic phenomena in the source region took place accompanying the main shock, and that it would be possible to detect clear changes in the electric and magnetic fields in and around the focal area.

We detected co-seismic changes in the electric field with observation nets of the Network-MT method at distances of about 70 km away from the epicenter.

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*Chief investigator: N. Sumitomo, Disaster Prevention Research Institute, Kyoto University, Uji, 611, Japan. Co-investigator and participants: N. Oshiman, S. Sakanaka, T. Goto, Disaster Prevention Research Institute, Kyoto; H. Utada, Y. Sasai, M. Uyeshima, S. Koyama, R. Ishikawa, Earthquake Research Institute, University of Tokyo; Y. Honkura, H. Tsunakawa, Department of Earth and Planetary Sciences, Tokyo Institute of Technology; S. Yamaguchi, H. Inokuchi, Department of Earth and Planetary Sciences, Kobe University; H. Murakami, Department of Geology, Kochi University; I. Shiozaki, Institute of Earth Science, Tottori University; Y. Tanaka, T. Hashimoto, Aso Volcano Observatory, Kyoto University; T. Mogi, Department of Mining, Kyushu University; T. Uchida, Geological Survey of Japan; A. Jomori, Japan Crust Research Co. Ltd.; K. Suzuki, Central Research Institute of Electrical Power Industry. This manuscript was prepared by N. Oshiman, Disaster Prevention Research Institute, Kyoto University, Uji 611, Japan.

However, since no electric or magnetic observation sites were operated near the focal area at the time of occurrence of the earthquake, we could not detect electromagnetic phenomena with geophysical instruments at sites very near the epicenter.

Investigations on the electromagnetic structure of active faults have been intensively carried out in the past two decades (e.g., Electromagnetic Research Group for the Active Fault, 1982; Honkura *et al.*, 1985; Isikara *et al.*,1985; Handa and Sumitomo, 1985; Ohshiman *et al.*,1987; Tuncer *et al.*, 1991; Nakatsuka, 1995). Through those studies, the existence of 1) low resistive zones related with the existence of the fracture zone and 2) geomagnetic anomaly localized along active faults have been revealed. Several kinds of measurements to investigate the electromagnetic structure of the Nojima fault were made after the earthquake. Preliminary results deduced from the measurements of DC resistivity, VLF-MT, the geomagnetic total intensity and self-potential at some places along the fault are mentioned in this paper.

Changes in the geomagnetic field accompanying an earthquake occurrence have been reported by many researchers. For instance, Sasai and Ishikawa (1980) reported precursory changes in the total intensity observed in association with the occurrence of an earthquake ($M\,5.0$) in the Izu Peninsula. Sumitomo and Noritomi (1986) detected co-seismic changes at a site on the Yamasaki fault. In addition, at several observation sites, Johnston and Mueller (1987) observed co-seismic changes in the total intensity accompanying the North Palm Springs earthquake ($M\,5.9$)

Prior to the occurrence of the 1995 Hyogo-ken Nanbu earthquake, no geomagnetic stations existed near the focal area. In order to detect geomagnetic changes due to stress change caused by the aftershock activity, we set up 10 continuous observation sites for the total intensity in the focal area about a week after the occurrence of the main shock, especially around the Nojima fault in Awaji Island. In this paper, some results obtained from the continuous observations after the main shock in the focal area are described.

2. Changes in the Telluric Field Detected by the Network-MT Observation System

We observed changes in the telluric field associated with the 1995 Hyogo-ken Nanbu earthquake with long-span electrical dipoles of the Network-MT method, which were set up in southwest Japan aiming at the construction of a standard structure model of the resistivity of the earth's interior beneath southwestern Japan. In this section, we mention the observation system of the Network-MT and describe electric field changes simultaneously observed with two independent observation nets in Okayama and Shiga, separated by a distance of about 200 km.

2.1 *The Network-MT observation*

Since 1993, according to the schedule in the 7th 5-year Program on Earthquake Prediction of Japan, we have made magnetotelluric (MT) measurements using the Network-MT method proposed by Uyeshima (1990), in which the earth and telephone cable facilities of NTT (Nippon Telegram and Telephone Corporation) are used for measurements of telluric field. The main purposes for the measurements are making a standard structure model of the resistivity of the earth's interior beneath northeast and southwest Japan, respectively, and clarifying the correlation between the resistivity structure and the spatial distribution of earthquakes.

In the Network-MT method, the telluric fields are measured using the telephone cables of NTT, which makes it possible to obtain the electrical potential differences of very long span ranging from a few kilometers to a few tens of kilometers between two electrodes. As an electrode for measurements of the telluric field, the earth of the branch or central telephone offices, at which the earth is well grounded and the contact resistance is kept to less than 100 Ω, is available as well as our own electrodes installed at places in the target area.

A schematic image of the observation system using the Network-MT method is shown in Fig. 1. In the figure, solid circles denote the earth facilities of NTT, while open circles denote electrodes installed by us. The electrical potential differences between the edges of the solid lines are measured at center sites denoted by larger concentric circles in the figure. Observed data are sent by way of normal telephone line using a modem. The geomagnetic field is observed at one site using a three-component magnetometer as shown in the figure.

We have conducted measurements using the Network-MT method in order to obtain the cross section of the resistivity structure at two areas; one is located in a zone belt passing through Kochi, Tokushima, Okayama, and Tottori Prefectures in southwest Japan, and the other is located in a zone belt passing through Miyagi, Yamagata, and Akita Prefectures in northeast Japan, as shown in Fig. 2. In addition to the measurements above, small area measurements using the Network-MT method with a relatively short length electrode span, namely from a few kilometers to tens of kilometers, were made in Shiga Prefecture. So, observations using the Network-MT method were in operation in Miyagi, Shiga, and Okayama Prefectures when the 1995 Hyogo-ken Nanbu earthquake occurred.

The epicentral distance at each location for the observation nets, Okayama and Shiga, was about 70 km, while that for the Miyagi net was about 800 km. The observation nets of the Network-MT method operated in Okayama and Shiga Prefectures during the occurrence of the earthquake are shown in Fig. 3. In the figure, solid circles denote the positions of electrodes. The epicenter of the 1995 Hyogo-ken Nanbu earthquake is also shown by a concentric circle in Fig. 3.

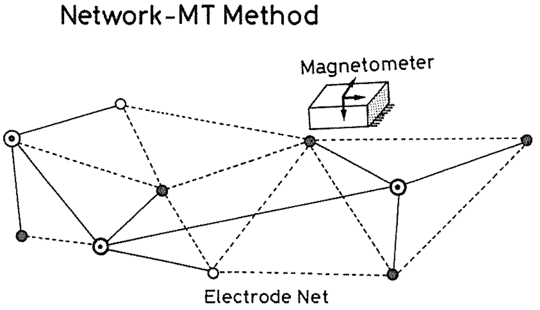


Fig. 1. Schematic net of observation system of the Network-MT method. Solid and concentric circles denote the earth facilities of NTT, while empty circles denote self-installed electrodes. The electrical potential differences between edges of the solid lines are measured at center sites denoted by concentric circles.

2.2 *Observed changes in the telluric field*

The observations using the Network-MT method

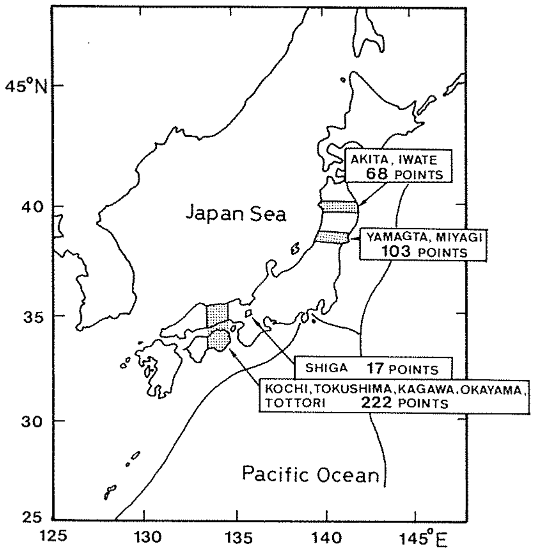


Fig. 2. Target areas of the Network-MT method in Japan.

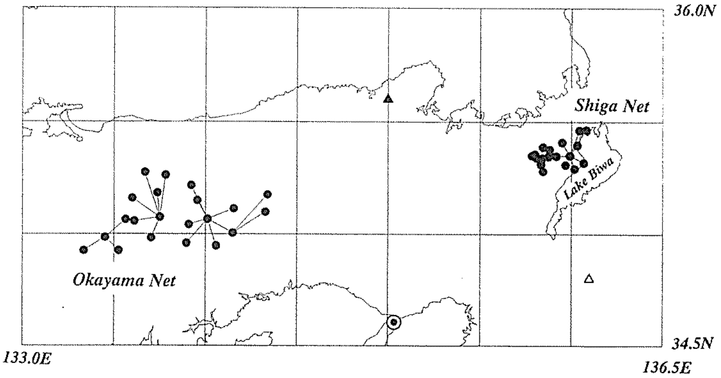


Fig. 3. Localities of observation of the Network-MT method conducted during the occurrence of the 1995 Hyogo-ken Nanbu earthquake. Solid circles connected by solid lines denote two observation nets. A centric circle denotes the epicenter of the main shock, and solid and empty triangles show locations of the stations for the geomagnetic field.

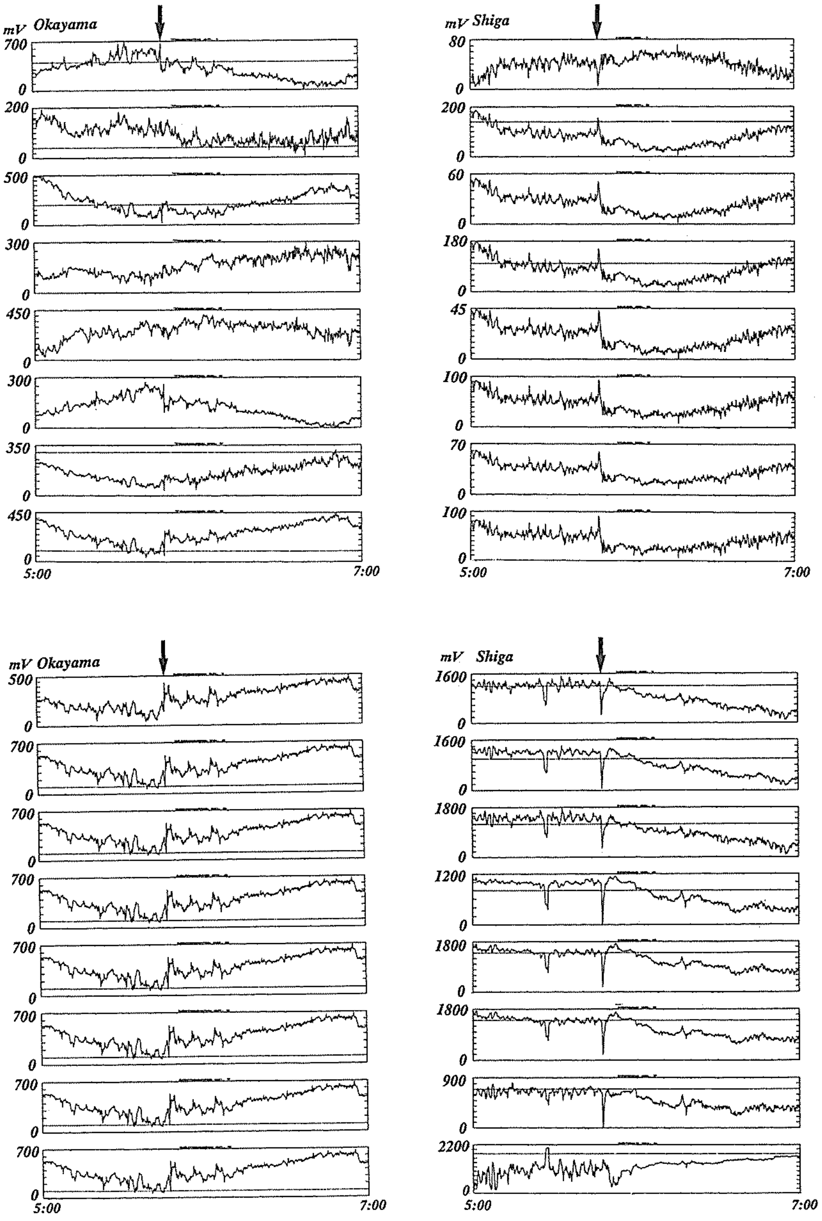


Fig. 4(a). Observed variations in the electric potential difference at each electrode pair in Shiga and Okayama shown in Fig. 3 during the time period from 05:00 to 07:00 on the 17th of January 1995. Arrows show changes related with the occurrence of the 1995 Hyogo-ken Nanbu earthquake.

were started on the 20th and 21st of December 1994 in Okayama and Shiga, respectively. During the period from the beginning of observation to the occurrence of the earthquake, no remarkable precursory changes larger than co-seismic changes in the electric field were observed in the Okayama and Shiga nets.

Telluric changes in association with the occurrence of the earthquake were observed simultaneously in two of the three observation nets described in the previous subsection. Figure 4(a) shows observed variations in the electric potential difference during the time period from 05:00 to 07:00 (JST) on the 17th of January 1995 in the Okayama and Shiga nets. We can easily find very sharp spike-like changes at the time denoted by arrows in the figure. On the other hand, we found no corresponding changes in the telluric field observed in the Miyagi net as shown in Fig. 4(b).

In order to see the details of the changes observed in association with the earthquake, data during the time from 05:45:00 to 05:50:00 (JST) are plotted for several electrode pairs in Fig. 4(c). From the figure, we find that changes in the electric potential appeared from 05:47:00. The 10 s sampling interval mode of the observation system was used for the measurements. When the 10 s interval mode is chosen, a 10 s average is made and only the averaged data are stored in memory. Actual sampling started at 05:46:55 for the 10 s average value at 05:47:00. So, time resolution is not enough to discuss the precise time of the appearance of the changes in the telluric field. We might say, however, that changes started at least 5 s earlier than 05:47:10.

Since we observed changes in the electric potential difference over a relatively large area, we can produce figures of vector field showing the spatial distribution of the electric field change. In Fig. 5, we show changes in the electric field every 10 s with vector arrows whose lengths are scaled for each sub-net of the obsevation system. Numbers shown in the figures represent absolute values of the electric field change for 10 s in units of mV/km. Field changes observed in the Shiga net during the time from 05:46:50 to 05:47:00, from 05:47:00 to 05:47:10, from 05:47:10 to 05:47:20, and from 05:47:20 to 05:47:30 are shown in Fig. 5(a). Field changes observed in the Okayama net are also shown in Fig. 5(b).

The directions of the field change during the time from 05:47:00 to 05:47:10 show headings almost southwest and northwest for the cases of the Shiga and Okayama nets, respectively. Those directions of the field change for the Shiga net almost coincide with the epicentral direction from the site, while those for the Okayama net are in the opposite direction of the epicentral direction.

Two change vectors of the large amplitude in the western part of the Okayama observation net seen in Fig. 5(b) were not changes accompanying the earthquake but variations caused by the electric current leaked from a train running on the Hakubi

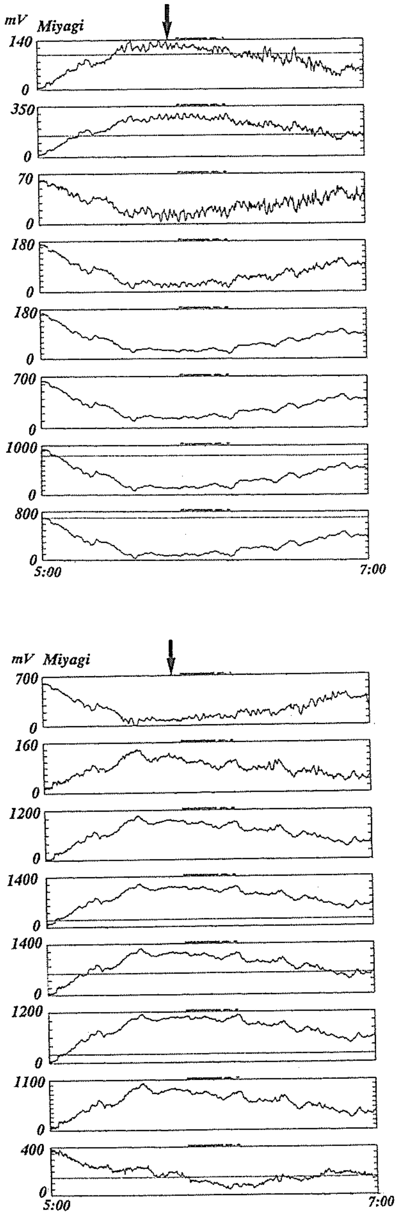


Fig. 4(b). Observed variations in the electric potential difference at each electrode pair in Miyagi during the time period from 05:00 to 07:00 on the 17th of January 1995. Arrows show the occurrence time of the 1995 Hyogo-ken Nanbu earthquake.

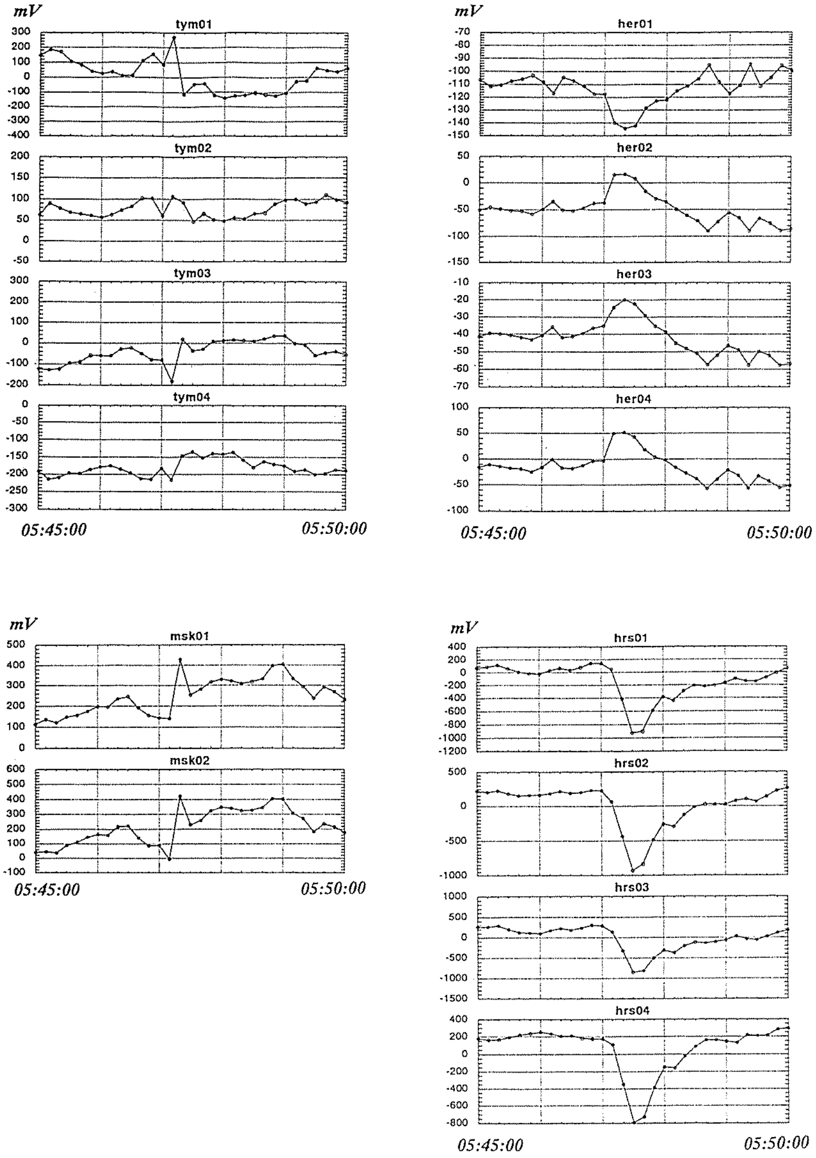


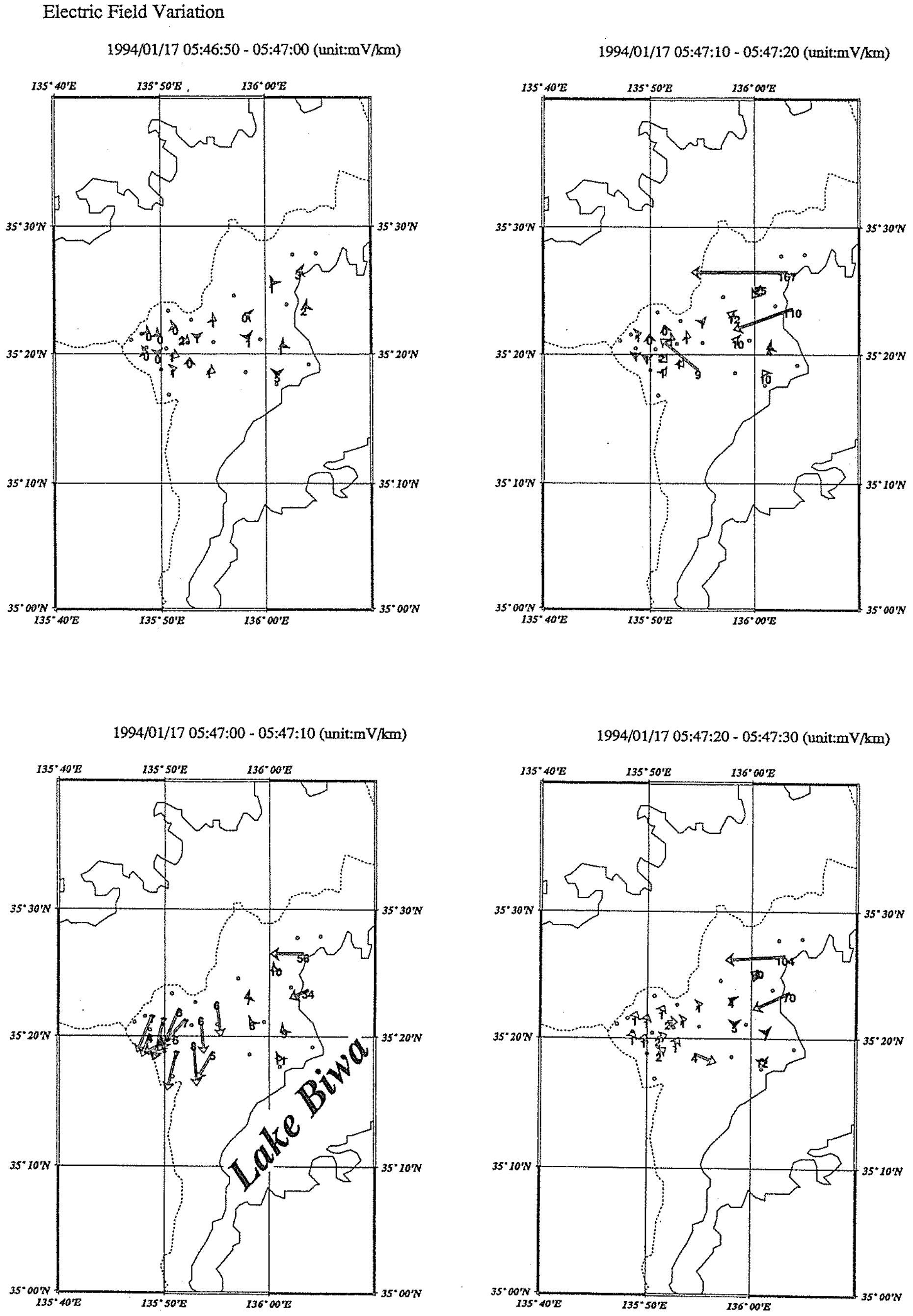
Fig. 4(c). Observed changes related with the earthquake during the time period from 05:45:00 to 05:50:00 on the 17th of January 1995 in Shiga (the right half) and Okayama (the left half). Each dot denotes a value observed at a interval of 10 s.

line of JR (Japan Railway), because such relatively large changes were observed at the same time everyday during the whole observation period in Okayama.

3. Electromagnetic Obsevation after the Occurrence of the Main Shock

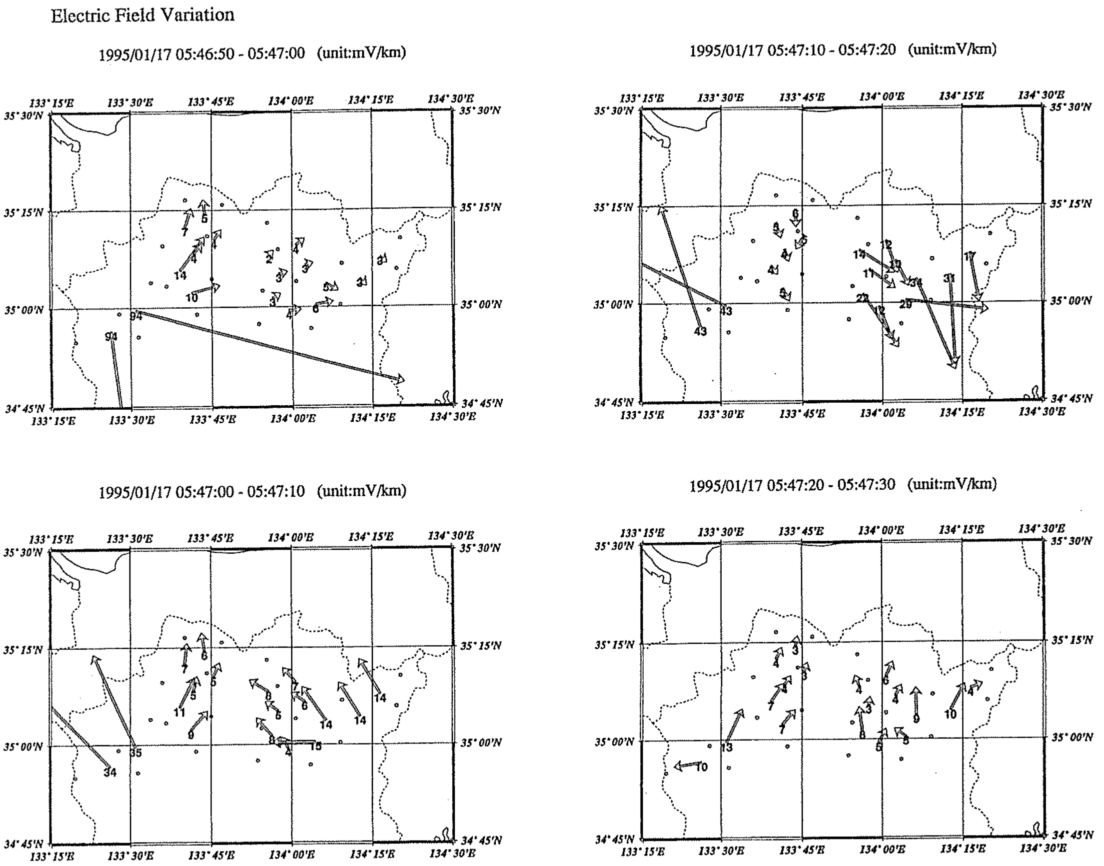
3.1 Electromagnetic structure of the Nojima fault

The Nojima fault, which shows right-lateral strike-slip, is located at the northwestern edge of



(a)

Fig. 5. The arrows show the electric field changes every 10 s from 05:46:50 to 05:47:30 (a) Shiga net, (b) Okayama net.



Electric Field Variation

1995/01/17 05:46:50 - 05:47:00 (unit:mV/km)

1995/01/17 05:47:10 - 05:47:20 (unit:mV/km)

1995/01/17 05:47:00 - 05:47:10 (unit:mV/km)

1995/01/17 05:47:20 - 05:47:30 (unit:mV/km)

Fig. 5(b)

Awaji Island and extends about 10 km in the NE-SW direction (Fig. 6). DC resistivity, VLF-MT, magnetic and self-potential measurements were carried out after the occurrence of the main shock to clarify the structure of the Nojima fault from the electromagnetic viewpoint. In this section, preliminary results along the measurement lines A, B, and C in Fig. 6 will be mentioned.

3.1.1 Resistivity measurements

DC resistivity measurements were conducted 2 months after the occurrence of the earthquake along line A in Hirabayashi, where the largest surface displacement (about 2 m) was found along the Nojima fault in Awaji Island (e.g., Nakata, 1995). The smallest span between electrodes was 5 m. The measurement line has an almost east-west strike across the Nojima fault, which has a strike of N40E there. The surface resistivity structure of the Nojima fault obtained using the 2D inversion method proposed by Uchida (1993) is shown in Fig. 7. In this figure, the Nojima fault is located between the 22nd and 23rd electrodes, whose order is denoted by blue-colored numbers. The right of the figure corresponds to the west, namely the sea side.

A low resistive zone below 100 Ωm was found on the western side of the Nojima fault. It seems that the eastern boundary of the low resistive zone was ruptured to form the displacement of the Nojima fault. The low resistivity zone, whose eastern edge is bounded by the Nojima fault, can also be seen with the VLF-MT measurements along the same line of the DC resistivity measurement as shown in Fig. 8. As is seen in the figure, the existence of a low value zone of the apparent resistivity in the western side of the Nojima fault is clear.

Since the profile length of the VLF-MT and the DC resistivity measurements is only about 200 m, we cannot mention the location of the western boundary of the low resistivity zone, which could be considered to be a fracture zone of the Nojima fault. However, taking account of the recovery of the values of the apparent resistivity at the western edge of the profile and the result obtained from DC resistivity measurements, we may say that the width of the low resistivity zone is about 50 m at least.

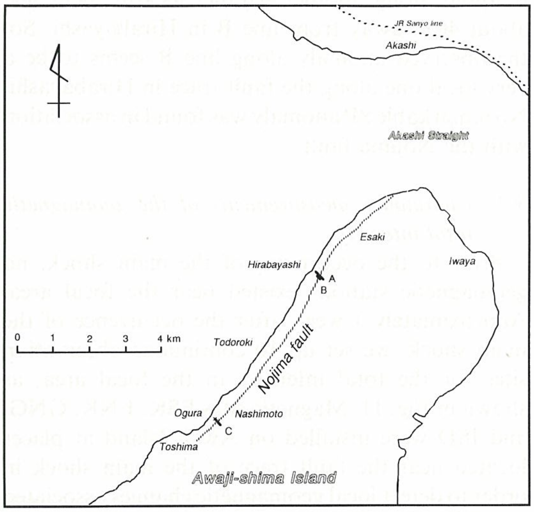


Fig. 6. Locations of measurement lines A, B, and C across the Nojima fault. The length of the solid lines does not always correspond to the real length of each measurement line.

With continuous self-potential measurements initiated immediately after the occurrence of the main shock, and which were located just above the surface rupture of the Nojima fault at Esaki in the northern tip of Awaji Island, Honkura and Tsunakawa (1995) also pointed out the existence of a low resistive zone in the western side of the Nojima fault on the basis of the fact that polarization of the electric field always showed a direction perpendicular to the fault.

3.1.2 Magnetic measurements

Magnetic measurements of the total intensity were made along two profile lines across the Nojima fault in Ogura 2 months after the main shock. The observed total intensity along one of the measurement lines is shown in Fig. 9. However no anomaly in the total intensity was found in association with the fault trace. One magnetic anomaly of an amplitude of about 300 nT is seen in the figure. However, the anomaly seems to be produced by a road.

Difference in the total intensity among continuous observation sites in Awaji Island, which are described in the following section, is about 100 nT at most. Moreover observed magnetic gradients at each observation point of the magnetic survey was very small. The facts mean that there exists no large magnetic anomaly in Awaji Island, at least in our observation area. This fact is also supported by the magnetic property of the bedrock in Awaji Island, where Ryoke granite forms the bedrock. The

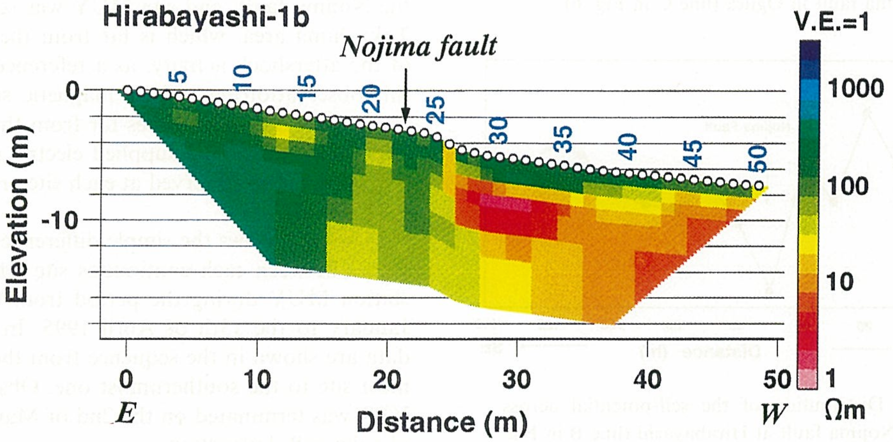


Fig. 7. Two-dimensional model for the surface resistivity structure of the Nojima fault obtained by DC resistivity measurements at Hirabayashi (line A in Fig. 6). The arrow shows the fault location.

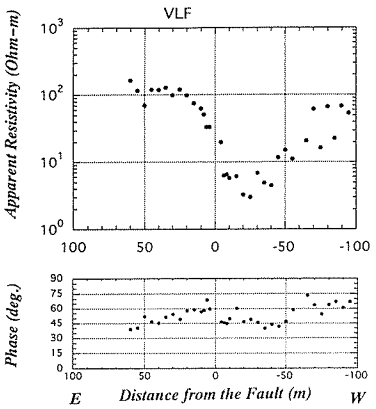


Fig. 8. Distribution of the apparent resistivity (upper) and the phase (lower) for VLF-MT along a measurement line across the Nojima fault at Hirabayashi (line B in Fig. 6).

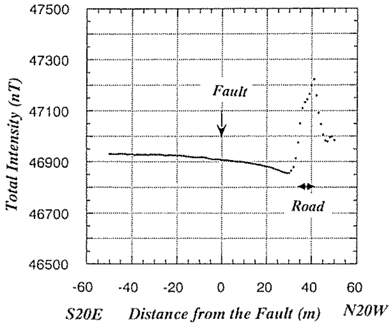


Fig. 9. Distribution of the geomagnetic total intensity along a measurement line across the Nojima fault in Ogura (line C in Fig. 6).

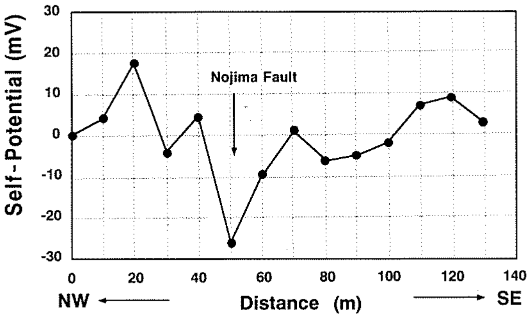


Fig. 10. Distribution of the self-potential across the Nojima fault at Hirabayashi (line B in Fig. 6). The arrow shows the fault location.

intensity of the magnetization of Ryoke granite is quite small, at the order of 10^{-3} A/m (Inokuchi, personal communication, 1995).

3.1.3 *Self-potential measurements*

Self-potential (SP) measurements were carried out along measurement lines perpendicular to the fault trace in Esaki, Hirabayashi, and Todoroki. Figure 10 shows the result along line B in Hirabayashi. Along this line, a negative anomaly exceeding 25 mV at the fault is seen. However, no notable anomaly is found along another parallel measurement line about 40 m away from line B in Hirabayashi. So, the observed anomaly along line B seems to be a very local one along the fault trace in Hirabayashi. No remarkable SP anomaly was found in association with the Nojima fault.

3.2 *Continuous measurements of the geomagnetic total intensity*

Prior to the occurrence of the main shock, no geomagnetic stations existed near the focal area. Approximately 1 week after the occurrence of the main shock, we set up 10 continuous observation sites for the total intensity in the focal area, as shown in Fig. 11. Magnetic sites ESK, FNK, GNG, and ISD were installed on Awaji Island at places located near the fault trace of the main shock in order to detect local geomagnetic changes associated with following aftershock activity. Sites TKG, KSG, and TNJ were installed on the northern side of the Rokko mountain range, far from the focal area in Kobe, in order to avoid artificial noises. Site YZR, on Awaji Island, was installed at a place far from the Nojima fault, and site MUY was set up in the Tokushima area, which is far from the focal area of the aftershock activity, as a reference station of this observation net. These magnetic sites, except KSG, were set up at places far from the source of man-made noises and supplied electric power with solar cells. Data observed at each site are stored on a EP-ROM.

Figure 12 shows the simple differences of all day values between each continuous site and reference station MUY during the period from the 25th of January to the 13th of April 1995. In the figure, data are shown in the sequence from the northernmost site to the southernmost one. Observation at YZR was terminated on the 2nd of March because of solar cell destruction.

As is seen in Fig. 12, data at sites in the northern observation area are more contaminated with

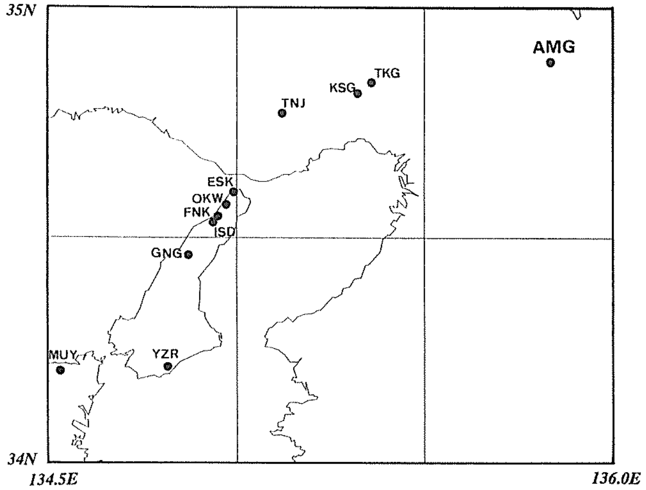


Fig. 11. Localities of continuous sites for observation of the geomagnetic total intensity in the focal region.

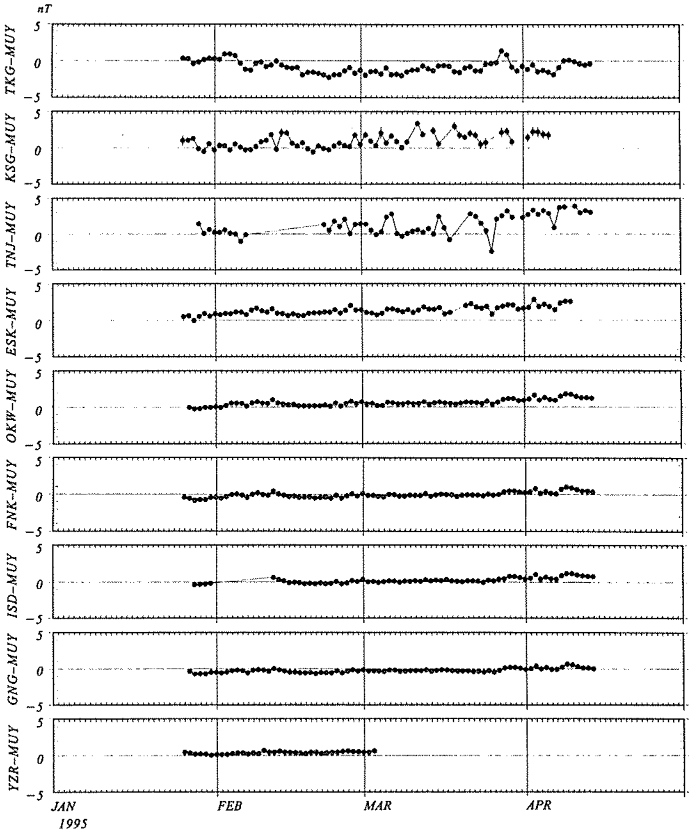


Fig. 12. Daily mean of simple differences of the total intensity between each site and MUY during the period from Jan. to Apr. 1995.

artificial noises than those in the southern area. We can see, however, systematic trends in the differences shown in Fig. 12, although fluctuations are seen at sites especially on the northern side of the Rokko mountain range. Changes at sites located on the southern side of site ISD show almost constant differences, while those at the northern sites from FNK on Awaji Island show increasing trends depending upon the distance from FNK. Namely, going up to the northern site on Awaji Island, a larger rate in the increasing trend is seen. This tendency can be seen up to the site TNJ, where the maximum rate increase is seen. An increasing tendency, however with a rate smaller than that of TNJ, is also seen at KSG, while a decreasing trend is seen at TKG, which is located at the northernmost point. The systematic regional tendency observed is not well understood at this moment.

We could not find geomagnetic changes associated with the aftershock activity. As is mentioned in the previous section, the rock magnetization in this region is weak. So, local geomagnetic changes produced by rock magnetization change due to stress change (e.g., Sasai, 1991) cannot be expected even if the aftershock activity causes reorganization of the stress distribution around Nojima fault.

A non-uniform structure of rock magnetization along a fault can enhance changes in total intensity as compared to the uniform case, as Oshiman *et al.* (1991) showed. However, a non-uniform structure of the distribution in rock magnetization along active faults, as reported by the previous magnetic investigations of active faults (e.g., Isikara *et al.*, 1985), does not exist along the Nojima fault because no remarkable magnetic anomaly was found along the fault. Accordingly, an enhancement effect on the local geomagnetic change due to stress change is not expected along the Nojima fault. This might also explain the fact that no changes were observed in association with the aftershock activity, as well as the small intensity of magnetization itself.

4. Discussion and Concluding Remarks

As mentioned in Sec. 2, we observed remarkable changes in the electric field associated with the occurrence of the 1995 Hyogo-ken Nanbu earthquake at two different nets in Okayama and Shiga. In the mean time, Iyemori *et al.* (1996) detected variations in the geomagnetic field observed with a fluxgate magnetometer having 0.05 nT resolution and 1 Hz sampling in association with the occurrence of the earthquake at two stations about 100 km apart from the focal region. Those two stations are shown in Fig. 3 with solid and empty triangles. The main phase of the variations seems to start to appear prior to the arrival of the P wave at each station, at least by about 10 s; namely about 10 s after the origin time or earlier. Its duration and maximum amplitude were about 30 s and 1 nT, respectively.

Eleman (1966) reported that variations in the geomagnetic total intensity and the telluric field, which coincided with the arrival of the surface waves and showed good correlation with the wave, were observed in association with the 1964 Alaska earthquake. He concluded that the variations could be explained by piezoelectromagnetic effect generated by the surface wave arriving beneath the station. However, geomagnetic variations detected by Iyemori *et al.* (1996) could not be explained by the generation mechanism which Eleman (1966) showed, because the variations started prior to the arrival of the P wave.

The commencement of the variations in the geomagnetic field almost coincides with that of the telluric field observed in Shiga and Okayama by the Network-MT method, although the duration is much shorter than that of the telluric field. As revealed by Kikuchi (1995), the main portion of fracturing on the fault surface was completed in about 10 s after the origin time. At this time, changes in the geomagnetic and the electric fields started. The fact could be a key for a better understanding of the electromagnetic phenomena generated by earthquakes in and around the source region.

However, we cannot exclude a possibility that the observed changes in the geomagnetic and the electric fields were due to an electrical shock generated by the heavy destruction of the electric distribution system in the large city accompanying the strong motion that struck Kobe City about 10 s after the origin time.

Many researchers have reported changes in the electric field preceding earthquakes (e.g., Miyakoshi, 1986; Varotosos and Alexopoulos, 1984a, b). However, no changes in the electric field preceding the earthquake larger than the co-seismic changes were observed with the observation nets.

Meanwhile, research on the electromagnetic structure of the Nojima fault is just the beginning for us to reach our goal of whole understandings. Although information on the electromagnetic structure of the Nojima fault obtained so far is limited to the shallow portion of the earth's crust, it still gives us an important suggestion as to the existence of a low-resistivity zone, namely a fracture zone, along the fault trace, as revealed by previous electromagnetic research for active faults (e.g., Electromagnetic Research Group for the Active Fault, 1982; Ohshiman *et al.*, 1987).

The Awaji area will become a very important target area for multidisciplinary research on active fault as "a very fresh fractured fault." In this sense, it is interesting whether the width and depth of the low-resistivity zone represents the history of activities of the Nojima fault until the 1995 event, and whether resistivity contrast, which might represent the degree of fracture and degree of water content along the fault, near the ruptured surface in the direction of the fault strike is found to associate with the fault displacements along the Nojima fault observed by Nakata (1995). However, further investigation on a deeper portion of the electromagnetic structure of the Nojima fault is indispensable, together with making various kinds of profile measurements at different places along the fault.

We would like to express our cordial thanks to all the staffs of NTT for their extensive assistance for the research using the Network-MT method. We are also indebted to all local people who kindly helped us at each temporal observation site on Awaji Island and around the Rokko mountain range. Parts of this research were financially supported by the Grant-in-Aid for Co-operative Research (A), Nos. 05302022 and 06306022 from the Ministry of Education, Science, Sports and Culture, Japan. Valuable suggestions made by two anonymous referees of this paper are gratefully acknowledged.

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