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Geoelectric potential difference monitoring in southern Sumatra, Indonesia—Co-seismic change—

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Five geoelectric potential difference (electric field, here after) monitoring stations have been in operation since September 1997 in an area near Liwa town, southern Sumatra, Indonesia, to examine the relationship between electric field changes and earthquakes. Short-term electric field variations were found to correspond mainly to geomagnetic activity, while long-term variation was mostly gradual shift and was clearly correlated neither precipitation nor ground water level variations. Co-seismic electric field changes ranging between 1 and 8 mV were observed for five $mb > 5$ earthquakes at multiple stations during September $\sim$ December 1997. The epicenters of the earthquakes were in the Indian Ocean within about 170 km from the monitoring sites.

1. Introduction

Geoelectric potential difference (electric field, here after) changes possibly associated with earthquake occurrences have been reported in several countries (e.g., Corwin and Morrison, 1977; Varotsos and Alexopoulos, 1984a, 1984b; Varotsos *et al.*, 1993, Nagao *et al.*, 1996). In order to understand the electromagnetic phenomena possibly related to seismogenic processes, the Institute of Physical and Chemical Research (RIKEN) of Japan established the International Frontier Program on Earthquake Research and began monitoring the changes of electric field. The RIKEN Program has installed the monitoring system at about 30 locations in Japan and 5 locations in southern Sumatra, Indonesia. This paper reports some results obtained so far from the stations near the town of Liwa in the Great Sumatra Fault (GSF) zone in western Indonesia, where artificial electromagnetic noise level was expected to be much lower than in countries like Japan.

The Great Sumatra Fault is seismically active and extends to 1650 km along Sumatra Island. The 1994 Ms 7.2 earthquake, that occurred in the Liwa area, caused serious damage (Widiwijayanti *et al.*, 1996). The Research and Development Center for Geotechnology, Indonesian Institute for Sciences (RDCG-LIPI) established the Geo-engineering Implementation Unit (GIU) in Liwa and plans to implement geophysical monitoring systems. Since September 1997, electric field monitoring has been carried out in the Liwa area under a cooperative research program between RDCG-LIPI and RIKEN.

Liwa is the capital of West Lampung District, where there is no public electricity except in the center of the town. The monitoring sites being located outside the town, the electric noise was found to be very low. Since earthquakes occur frequently in the surrounding region, our stations were considered to be ideal for our purpose.

Five $mb > 5$ Earthquakes occurred in the Indian Ocean within the distance of approximately 170 km from the monitoring sites during September $\sim$ December, 1997, and we observed co-seismic electric field changes for all of these earthquakes. The term co-seismic here is used in a broad sense that the signal happened at approximately the same time as the earthquake.

2. Seismicity of the Region

Liwa is located in the southern part of Sumatra Island, through which the GSF and the magmatic belt run parallel to the Sunda trench, from the Andaman Sea back-arc basin to the Sunda Strait extensional fault zone. The GSF is a right lateral strike-slip fault dragged by the obliquely subducting Indian Ocean Plate. The slip rate of the fault was estimated, using satellite images, to be 23 ± 3 mm/yr in the northern part and 6 ± 4mm/yr in the southern part (Bellier and Sebrier, 1994). The epicenter of earthquakes, occurring between September and December 1997, were shown in Fig. 1 and listed parameters in Table 1. The 1994 destructive Ms =

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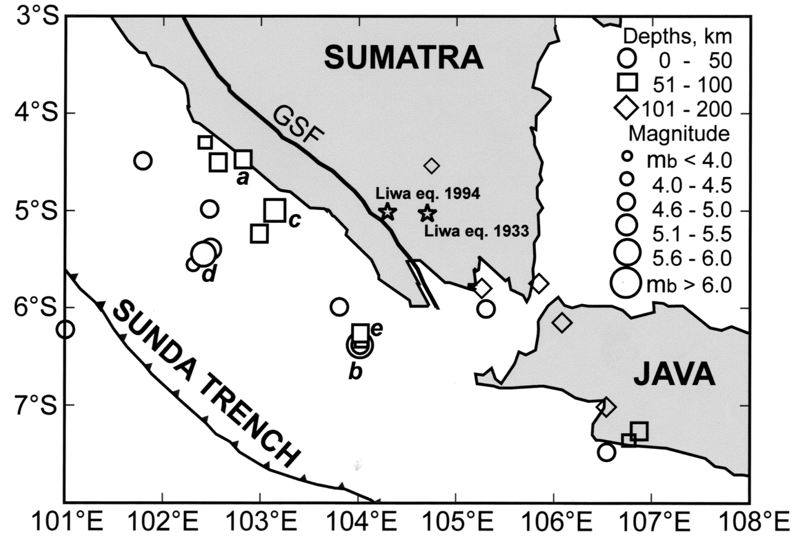

Fig. 1. Seismicity map based on USGE-NEIC database ($mb > 4$), during September ~ December 1997. GSF: Great Sumatra Fault. a, b, c, d, e denote epicenters of earthquakes for which co-seismic electric field change was observed. Parameters of these earthquakes are shown in Table 1.

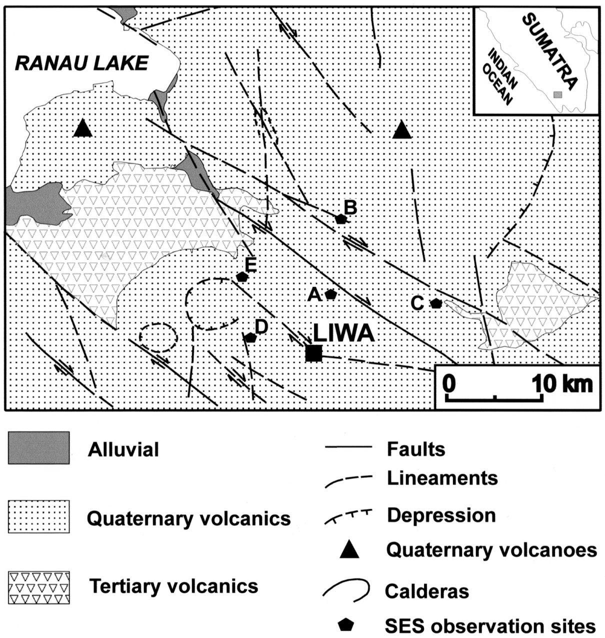

Fig. 2. Geology and structural lineament of the Liwa area. Simplified from Suwijanto *et al.* (1996). Locations of stations are also shown.

7.2 (NEIC-USGS) earthquake which occurred in the Liwa region (Fig. 1, 4.97S, 104.30E, depth 23 km) killed more than 200 people. The heavy damage was confined to a long and narrow zone, coinciding with the strike of the GSF. The 1933 $Ms = 7.5$ earthquake (Fig. 1, 5.09S, 104.70E) affected roughly the same epicentral area as the 1994 event (Katili and Hehuwat, 1967). Earthquakes occur frequently in areas close to the GSF, but the seismicity is much higher in the fore-arc region of Sunda trench off the southwest coast of Sumatra. The high seismicity is probably not only related to the oblique convergent process of the Indian Ocean Plate but also to fore-arc deformation (Widiwijayanti *et al.*, 1996).

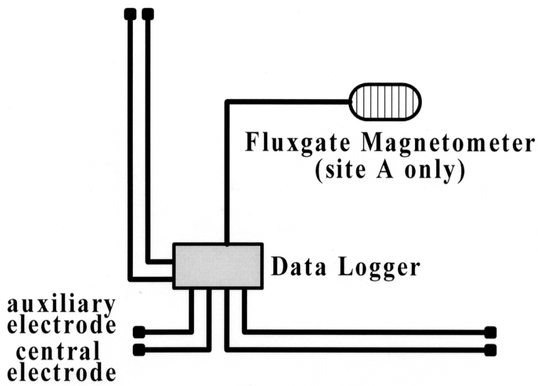

Fig. 3. Field set-up at monitoring sites.

3. Monitoring System

The electric dipoles were deployed at five sites as marked by the points A-E in Fig. 2, in which the geology and structural lineations around the Liwa area, inferred from the Landsat image (Suwijanto *et al.*, 1996), are also shown. The Geoengineering Implementation Unit (GIU) of LIPI is located at about 5 km north of the center of Liwa (Site A in Fig. 2). Electricity and telephone lines had not been installed in the area and the electric power to support our instruments was provided by an electric generator and batteries. The generator was running only at night, was several hundred meters away, and was a small one. Thus, the electric noise was extremely low, as expected.

Site A which measures both electric and magnetic fields was set-up at about 200 m southwest of GIU. Sites B, C, D and E, which only measure the horizontal components of electric field, were set-up at around 10 km distance from GIU. At each site, as shown in Fig. 3, two parallel dipoles of the same length (about 90 m) were installed approximately 1 m apart in both N-S and E-W directions from a central (common) electrode in "L" shape, to identify the noise that

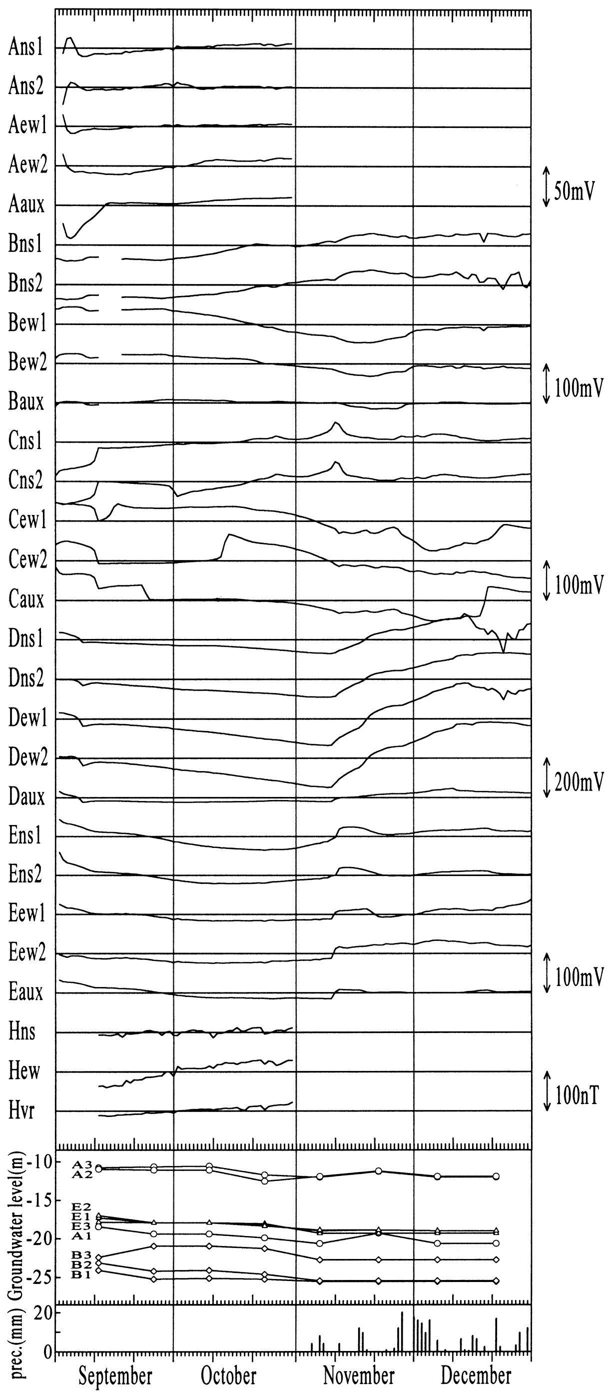

Fig. 4. Top: Records of the daily mean of electric field variations (mV/100 m) during September ∼ December 1997. Measurement interruption: site *A* (October 31 ∼ December 31), site *B* (September 13 ∼ 18), line *Caux* (October 15 ∼ December 16), lines *Dns*1 and *Dew*1 (December 17 ∼ 31). Bottom: Ground water level and precipitation during September ∼ December 1997. Precipitation was observed at GIU and the ground water level was observed at wells close to Sites *A*, *B* and *E*. *A*1, *A*2, *A*3 are wells located close to Site *A*. *B*1, *B*2, *B*3 and *E*1, *E*2, *E*3 are located close to Sites *B* and *E* respectively.

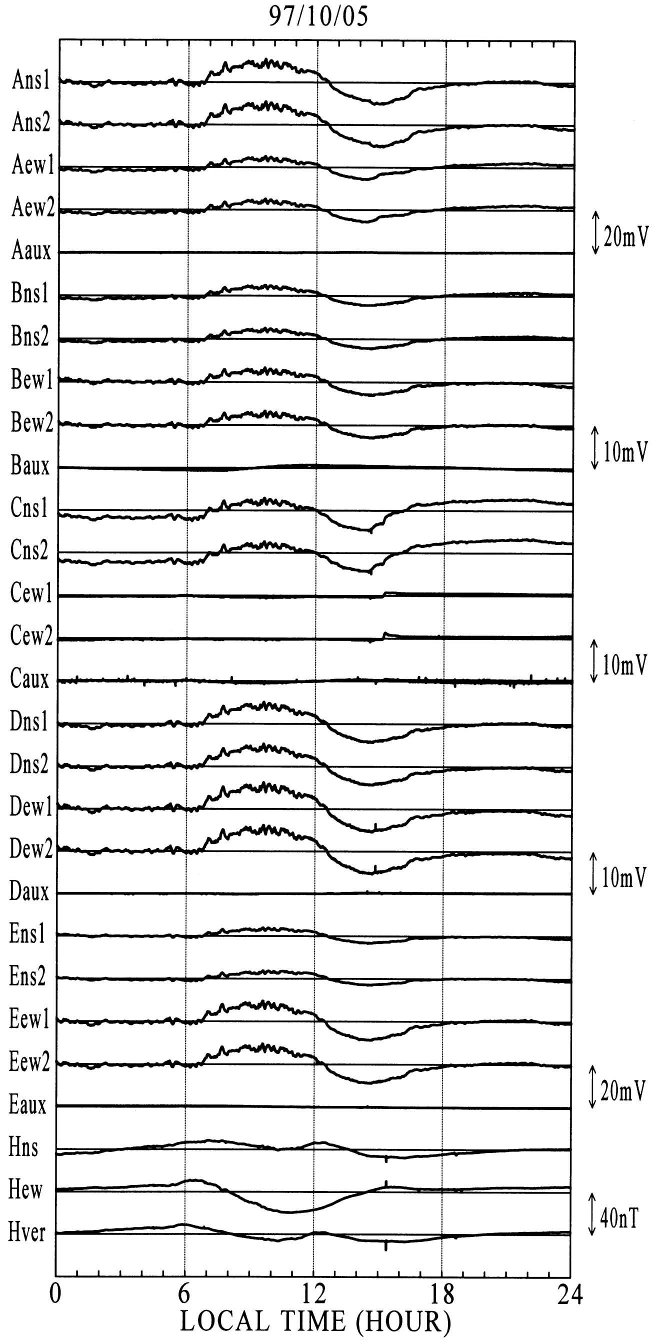

Fig. 5. An example of 24 hour records of electric field variations (mV/100 m) on a magnetic quiet day.

may be generated at individual electrode. The potential difference for a short spacing (about 1 m) was also measured between an auxiliary electrode and the central electrode to check noise generated at the central electrode.

Chloride coated lead tubes buried at 1 m depth were used as electrodes. Chemical material called “Chiko Gel”, which is conductive material and mainly composed of gypsum, was used to cover the electrode and reduce the contact resistance to the earth. The data were sampled at every 10 seconds and stored in a data logger (Hakusan, LS-3300) with 20 MB memory. A fluxgate magnetometer with sensitivity of 25 mV/nT was installed at Site *A*.

The electric field is sometimes affected by precipitation, and the variation in ground water level. To examine these effects, daily precipitation was observed by a rain gauge at GIU and the ground water level was monitored at two week interval in three 10 ∼ 20 m deep wells located close to each

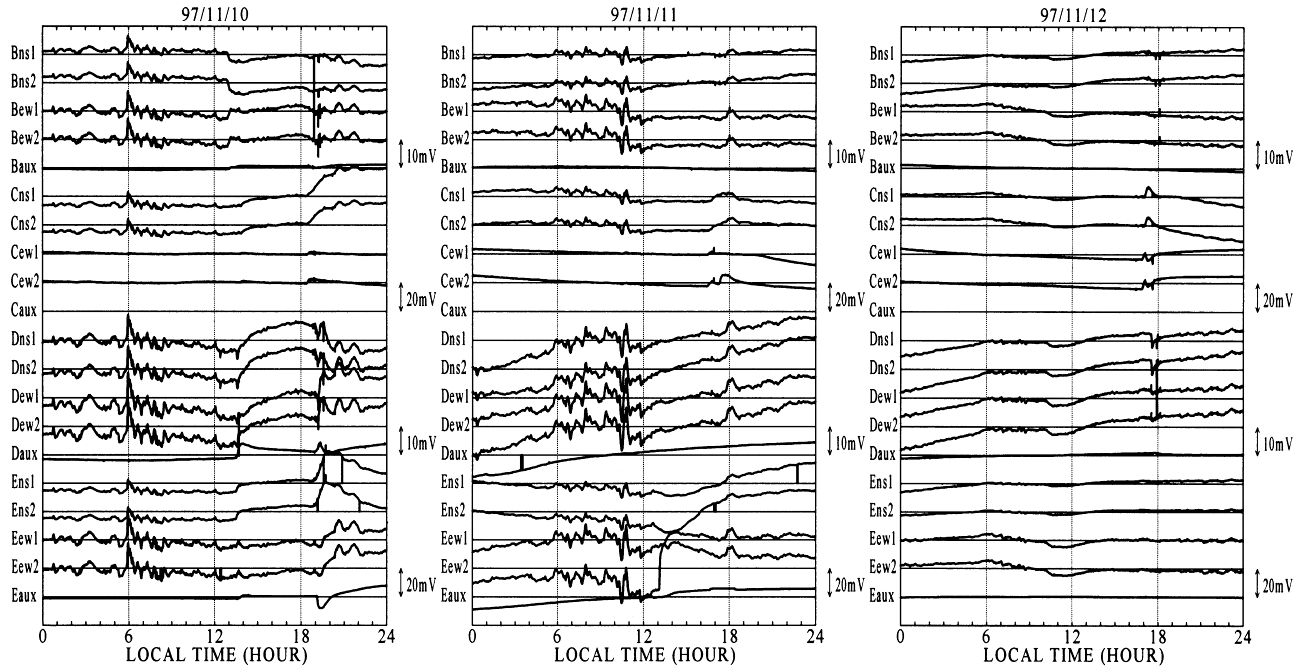

Fig. 6. Twenty-four hour records of electric field variations (mV/100 m) on November 10, 11, 12 when large change was observed at all site. Measurements were interrupted on these days at site *A* and the lines of *Caux*.

Sites *A*, *B* and *E*. The bottom of Fig. 4 shows the ground water level and precipitation during September ∼ December 1997, early part of which was the dry season of the year and no precipitation was observed before November 4. The groundwater levels in the wells, except *B*3, were gradually lowering about 2 m in September and October. The level was nearly constant in November at Sites *B* and *E*. It rose 1 to 2 m at Site *A* in the middle of November and then returned to the lower level in December.

4. Daily Variation

Figure 5 is an example of a 24 hour record showing the typical variation of the electric field (mV/100 m) at all the sites and the magnetic field at Site *A* of a geomagnetically quiet day. In this figure, for example, *Ans*1 means the first pair of NS line at Site *A* and *Aaux* means the record of potential difference between the central electrode and the auxiliary electrode set at 1 m spacing. Deviations from the daily mean value are plotted. The records were found to be virtually noise free and the voltage differences of two parallel dipoles were almost less than 0.3 mV. Major features of the variation were correlated with the daily geomagnetic fluctuation. The amplitude of the field in quiet days was mostly about 10 mV/100 m. Most of shorter variations were identified also as due to geomagnetic fluctuations.

5. Longer Term Variation

The top of Fig. 4 shows the variation of daily mean values of electric field (mV/100 m) at each site in September ∼ December 1997. Some lines were out of operation on the periods shown in the figure caption. There were large variations in the beginning of September. Part of these variations were probably caused by the usual drift of newly installed electrodes, because variations were not always in parallel between two parallel dipoles. Overall variations showed a shift toward the minus side at Sites *D* and *E* in September and October, toward the plus side at *Bns* and *Cns*, and to the minus side at *Bew* and *Cew*. There were some noticeable variations in November and December.

Water levels were lowering from September to the beginning of November, except *B*3, but no clear correlation between the water level variation and the electric field variation was seen in this period. After the beginning of November, entering the rainy season, precipitation was observed intermittently, but no large variation of water level was observed at Site *B* and *E*. The water level at Site *A* rose during the first half of November, and lowered after the mid-November. Apparently there was no clear correlation between water level and electric field variations in this period too.

As mentioned above, no precipitation was recorded before November 4. After November 4, there was intermittent precipitation. Therefore, the large variation in November might have been related to the rain fall. But, although much precipitation was recorded at the beginning of December, no corresponding electric field variation was observed. Thus, the relation between rainfall and electric field variation was obscure.

The general trend of electric field changed on November 10 at all the sites simultaneously. The large change toward the plus side was observed at Sites *B*, *D* and *E* until November 12. Figure 6 shows the records between November 10 and 12. Some peculiar large changes were recorded at around 12:00 ∼ 14:00 and 19:00 ∼ 22:00 in November 10 at all the sites. This means that the changes were not caused by local noise but by some changes in the "geoelectrical state" in the observation area. Rainfall was not observed on that day at GIU. The spike like noise seen during 19:00 ∼ 22:00 might have arisen from lightning. Rainfall was recorded

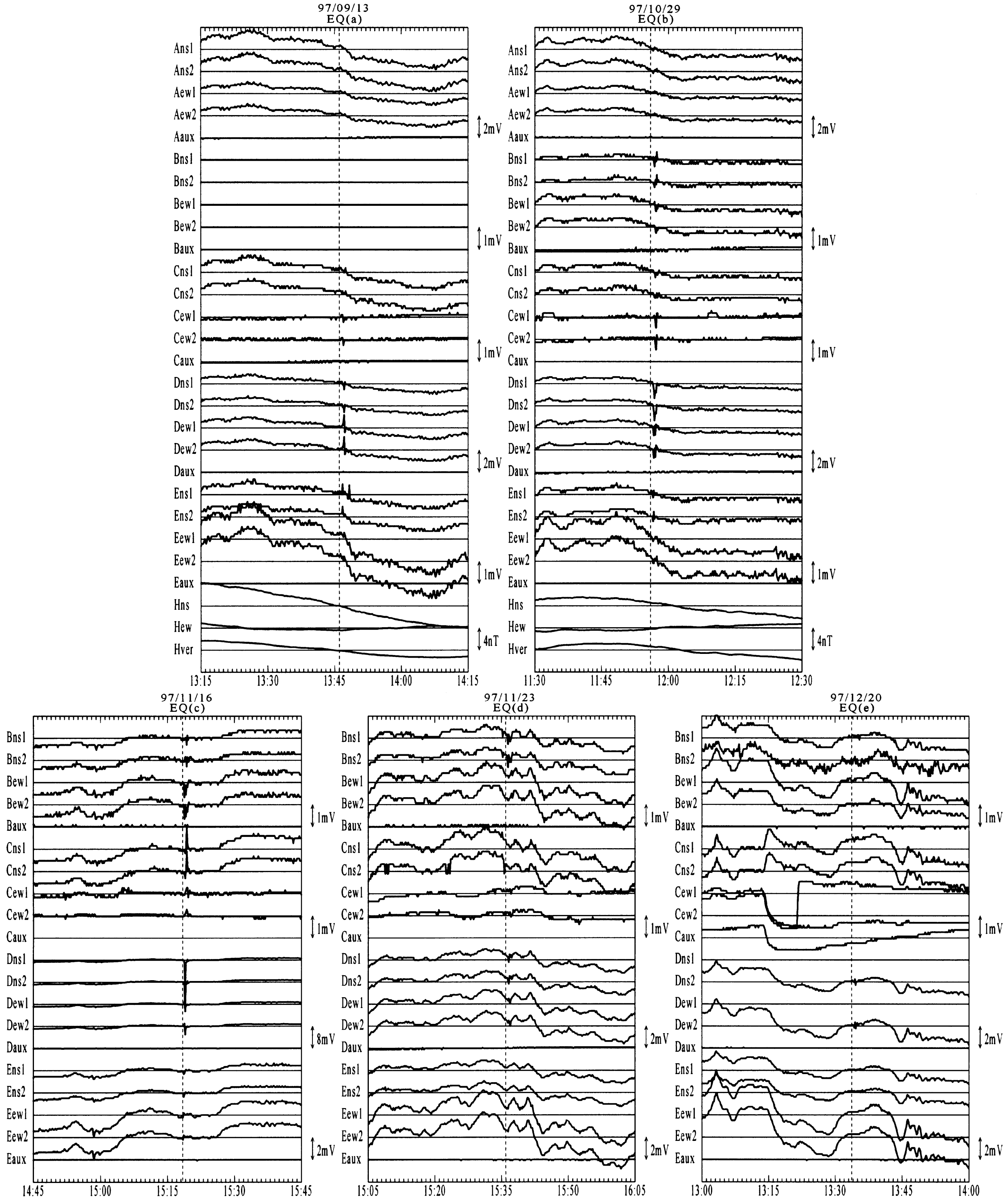

Fig. 7. Electric field changes (mV/100 m) at each site for 1/2 hour before and after the five $mb > 5$ earthquakes listed in Table 1. Measurement interruption: site *B* (97/09/13), line of *Caux* (97/10/29), site *A* and line *Caux* (97/11/16 and 97/11/23), site *A* and the lines of *Caux*, *Dns*1 and *Dew*1 (97/12/20).

intermittently after November 4, but such peculiar change was not seen on the other days. Observed electric field data were not directly affected by rainfall.

Several records show some inconsistency between parallel dipoles on November 11 and 12. Records *Eew*1 and *Eew*2 (Fig. 6) between 13:00 on November 11 and 6:00 on November 12 do not resemble each other despite the electrodes of these 90 m long dipoles are only 1 m apart. Similar discrepancies can be seen *Cew*1-*Cew*2, *Ens*1-*Ens*2, and *Cns*1-*Cns*2 during this same time period (Fig. 6). The prox-

Table 1. All $mb > 4$ earthquakes during September ∼ December 1997, which were plotted in Fig. 1. Five earthquakes observed co-seismic electric field change were annotated symbol a, b, c, d and e in the first column (atter USGS-NEIC).

Symbol	Origin time (local time) M/D H:M:S	Epicenter	Distance (km)	Depth (km)	mb	Remark
	09/03 03:26:15	6.36S, 104.09E	149	100	4.3	
a	09/13 13:46:03	4.45S, 102.84E	142	97	5.2	Mw
	09/15 13:27:37	4.61S, 102.65E	155	53	4.6	
	09/16 12:07:44	4.96S, 102.51E	165	38	4.7	
	10/03 23:22:51	5.23S, 102.99E	114	52	4.6	
	10/11 10:03:07	5.71S, 105.87E	221	131	4.9	
b	10/29 11:55:59	6.38S, 104.01E	152	45	5.6	Mw
	11/04 06:38:39	6.33S, 104.08E	147	50	4.9	
	11/05 21:29:55	4.58S, 104.76E	96	168	4.3	
	11/12 00:42:38	6.09S, 105.38E	194	33	4.9	
	11/13 09:55:39	7.38S, 106.80E	406	80	4.5	
	11/15 06:29:12	7.27S, 106.88E	404	74	4.6	
	11/15 21:56:33	4.35S, 102.43E	188	66	4.5	
c	11/16 15:18:16	4.96S, 103.19E	89	58	5.5	
	11/23 14:54:32	5.57S, 102.35E	193	33	4.3	
d	11/23 15:35:48	5.41S, 102.52E	169	33	5.1	
	11/25 08:44:28	5.78S, 105.28E	165	148	4.8	
	11/27 07:20:29	4.54S, 101.83E	245	33	5.0	
	12/07 12:53:25	5.94S, 103.81E	106	33	4.6	
	12/12 01:47:10	6.20S, 101.01E	356	33	5.1	
e	12/20 13:33:43	6.33S, 104.08E	146	71	5.0	
	12/26 05:30:52	7.53S, 106.60E	400	50	4.9	
	12/27 11:51:57	7.08S, 106.55E	362	108	4.5	
	12/31 23:10:48	6.19S, 106.18E	274	150	4.2	

imity of the electrodes on parallel dipoles eliminates all but a very localized change around one electrode as a possible explanation for these inconsistencies.

Unfortunately we have no geomagnetic data at the sites in this period, but according to Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University, the short period changes seen from 5:00 to 9:00 in November 10 and from 6:00 to 11:00 in November 11 were due to geomagnetic activity.

6. Electric Field Changes Possibly Associated with Earthquakes

Five $mb > 5$ earthquakes occurred within around 170 km from the monitoring sites during September ∼ December, 1997 (Fig. 1). Some parameters of these earthquakes, after the USGS-NEIC catalog, are summarized in Table 1. Epicenters were in the Indian Ocean northwest to south of the stations. Figure 7 shows the electric field changes (mV/100 m) at each site for 1/2 hour before and after the listed five earthquakes.

The electric field changes, approximately 1 mV/100 m in amplitude, were observed only in Site D at the earthquake a and e. But, the changes were observed at Sites B, C, D and E for the earthquake b and c. Similar changes were observed at Sites B and D for the earthquake d. The amplitude of the field changes reached 8 mV/100 m at Site D for the earthquake c. The amount of field changes is different from site to site when the changes were observed at several sites simultaneously, Site D being the most sensitive. As shown in Fig. 7, the parallel dipoles at each site showed the same changes. Similar change was not observed in the record of the electric potential difference between the auxiliary electrode and the center electrode. This means that the change was not caused by the change related to the electrode contact, because if each electrode was moved independently due to ground motion, the field change ought to be different from electrode by electrode.

Another two $mb > 5$ earthquakes occurred at 251 km and 361 km distance in this period, but, no electric field changes were seen. The earthquake of $mb = 4.6$ (October 3) and $mb =$

4.3 (November 5) occurred at relatively closer place (114 km and 96 km distance respectively) in this period. But, no electric field change were observed. Thus the electric field changes were not observed at $mb < 5$ earthquakes that occurred even within about 100 km distance. In fact, no changes comparable to those mentioned here were observed during the observation period. Thus, co-seismic changes seem to be detectable for $mb > 5$ earthquakes occurring within 170 km distance in the Liwa area.

Figure 8 shows the enlarged records for 3 minutes before and after the occurrence of earthquakes *b* and *c*. The beginning of the changes was observed at 36 (Site *D*) to 43 (Site *B*) seconds after the origin time of earthquake *b* and 21 (Site *E*) to 34 (Site *C*) seconds after that of earthquake *c*. The changes continued for 30 to 60 seconds at each site. Since our sampling rate was 10 seconds, neither the onset time nor the waveform of changes could be accurately identified. Since there was no seismometer working in the area, the precise time sequence of arrivals of seismic waves and the electric changes is also hard to determine. Assuming the reasonable velocity of seismic waves such as 3.5 km/s, it may be inferred that the field changes began approximately at the arrival time of seismic waves. Masturyono *et al.* (1997) estimated *P* velocity of crust in north Sumatra by seismic tomography as 4.5 to 6.5 km/s at a depth up to 40 km. Based on this, the velocity we have obtained was probably *S* wave or a surface wave.

The electric field changes accompanying seismic waves have long been known as "electroseismic effect" (Thompson, 1939; Martner and Sparks, 1959). The effect has been observed for nearby explosions. The generating mechanism of the effect is considered as the resistivity change of the ground induced by the elastic deformation associated with earthquakes (Thompson, 1939; Long and Rivers, 1975) and/or the streaming potential generated by the displacement of the ionic pore water against the wall of rock particles (Long and Rivers, 1975; Pride, 1994; Haartsen and Pride, 1997).

In our observation, there were time lags of 30 to 60 seconds between the origin time of earthquakes and the onset time of electric field changes. This means that the generation of the co-seismic changes was not at the time of seismic fracture. The fact that the amount of changes was different from site to site in a small area may mean that the phenomena strongly depend on the local resistivitiy structure of each site, if the ground motion was more or less similar with each site. We need further observation and resistivity survey to confirm these points.

The large electric field change observed on November 10 recorded at around 12:00 ∼ 14:00 and 19:00 ∼ 22:00 might have been a precursor of the earthquake *c* (November 16). But similar change has not been found for other earthquakes. We need further and detailed observation to identify precursory changes.

7. Concluding Remarks

Five monitoring stations have been in operation near the town of Liwa to detect electric field changes that may be related to the occurrence of earthquakes. Co-seismic electric field changes ranging between 1 ∼ 8 mV/100 m were detected at several tens of seconds after the origin time of five $mb > 5$ earthquakes within 170 km from the stations during September ∼ December 1997. Most of the changes were detected at more than one monitoring site.

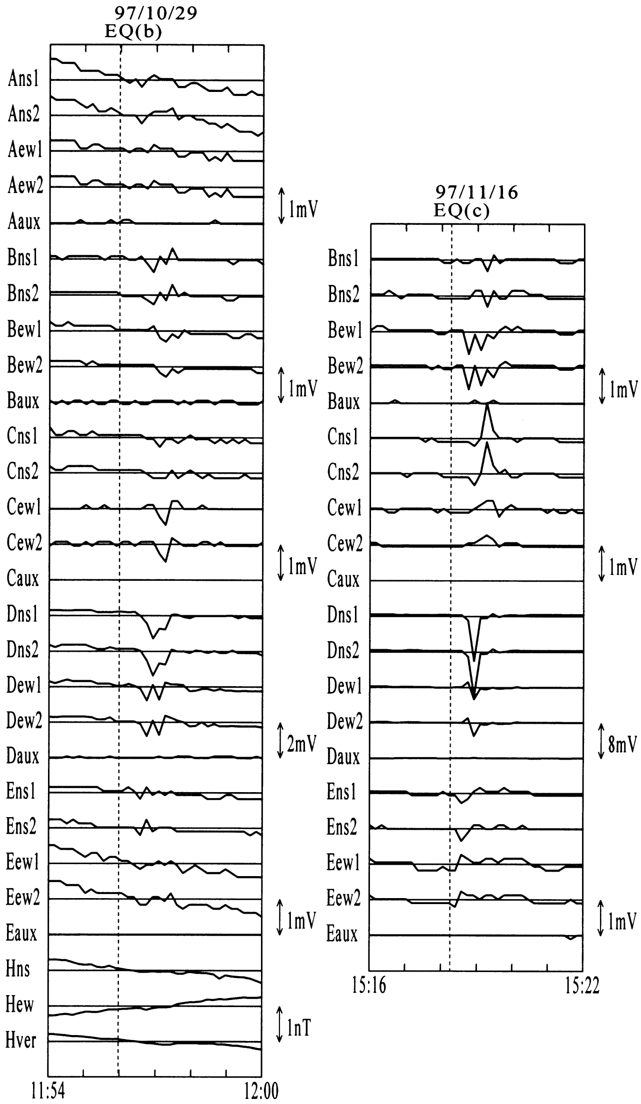

Fig. 8. Electric field changes (mV/100 m) at each site for 3 minutes before and after the co-seismic change associated with *b* and *c* earthquakes (see Table 1). Measurement interruption: line of *Caux* (97/10/29), site *A* and line *Caux* (97/11/16).

Similar observations related with natural earthquakes were reported earlier for Okinawa, Japan by Kinoshita *et al.* (1989) and the same data have been re-examined lately by Takahashi *et al.* (1999). Recently, Takeuchi *et al.* (1997) have observed a number of clear-cut electroseismic signals for almost all of felt earthquakes and some unfelt earthquakes in Sendai city, northeast Japan. Moreover, more examples have been found at Kitafuji station, central Japan for nearby March 6, 1996 M5.3 earthquake and at Iwate Yama station for also nearby September 3, 1998 M6.0 earthquake (to be reported elsewhere). Similar observations have been made also in Greece (P. Varotsos, private communication). With high sampling rates, like 50 Hz, changes were reported to be similar to seismogram records. All these changes could have been caused by the so-called electroseismic effect. However, for the present case in Sumatra, neither the onset time nor the wave form were precisely determined since the sampling rate was 10 seconds. Further studies seem to help understanding the real nature of electromagnetic phenomena related to earthquakes.

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