



# Variations of geoelectric potential differences associated with an anomalous volumetric strain change in the region of expected Tokai Earthquake, Japan

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**Abstract.** For the prediction of the expected Tokai Earthquake (EQ), Japan Meteorological Agency (JMA) has been observing volumetric strain changes to detect its presumed pre-slip phenomena in Tokai and South Kanto regions. In 1998, an anomalous volumetric strain change, lasting for 5 days, which initially attracted much attention as a possible precursor to the Tokai EQ, was observed at Shimizu station in the Tokai area. Eventually, the Tokai EQ did not occur and the causal mechanism of the observed anomaly was unknown. However, we found variations of geoelectric potential differences (GPD) possibly associated with the anomaly by applying Principal Component Analysis (PCA) to the GPD data taken in the same area. From the polarities of the observed GPD changes, we infer that these GPD variations were caused by electrokinetic effects of groundwater motion, which might have been related with the strain changes. These results imply that the GPD observations may assist us in understanding the nature of EQ precursory phenomena.

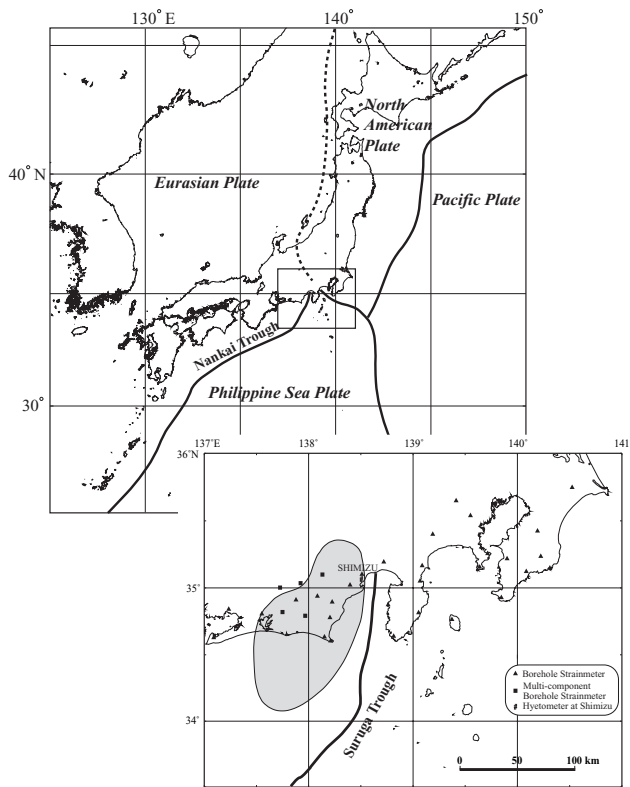
## 1 Introduction

Large EQs recur in the subduction zones along Japanese Islands. For example, EQs in Nankai trough occur every 100–150 yr (Ando, 1975; Thatcher, 1984; Strasser et al., 2009). In Suruga trough, the eastern extension of Nankai trough, large EQ has not occurred since  $M = 8.4$  Ansei-Tokai EQ in 1854. This is where “Tokai EQ” has been forecasted since the late 1970s (Ishibashi, 1981). In Japan, “intensified observation” network has been in operation only in this area with the hope of detecting pre-slip phenomena (Kato and Hirasawa, 1999). The expected focal zone of “Tokai EQ” partially covers the land area (Fig. 1).

For the purpose of its short-term prediction, Japan Meteorological Agency (JMA) and the government of Shizuoka Prefecture operate the “intensified observation” network which is comprised of 36 volumetric strainmeters in Tokai and South Kanto regions (Fig. 1). The volumetric strainmeters can detect volumetric change in the order of  $10^{-12} \sim 10^{-11}$ , which is not detectable by GPS (Yamasato, 1999). When the anomaly exceeds a certain threshold, at more than 3 stations, JMA immediately convenes the Earthquake Assessment Committee to examine whether or not the anomaly is a precursor of the Tokai EQ. This has never happened so far.

An anomalous expansion began to appear on 11 October 1998 on the volumetric strainmeter in Shimizu (35.1016° N, 138.5102° E), which is one of the 36 stations in Tokai region (Yamasato, 1999). This anomaly was observed only at this station. Although similar local anomalies were observed in 1986 and 1992 in Shimizu, not much attention was paid to them. However, this time apparently due to a monitoring policy change, JMA paid special attention to this anomaly. Actually, however, the anomaly almost disappeared on 16 October, without expanding to other stations, and JMA concluded that this anomaly was also an unimportant local one. The causal mechanism was unclear although Yamasato (1999) proposed that the anomaly might be attributed to local groundwater motion.

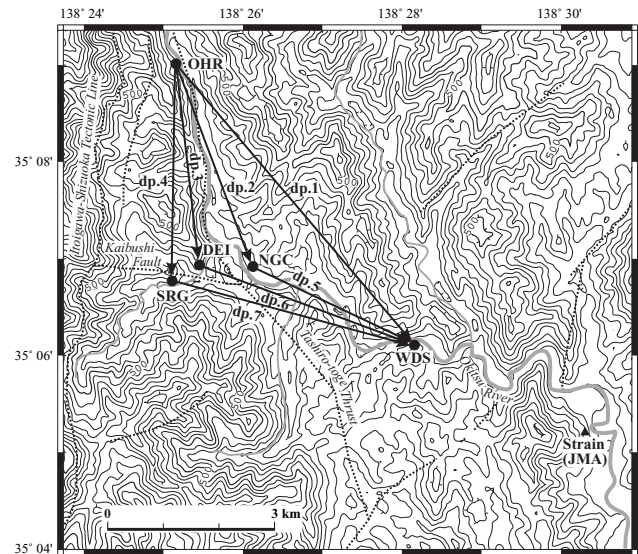
Volumetric strain, in general, is changed mainly by atmospheric pressure variation, solid earth tide, variation of groundwater pressure caused by rainfall (Furuya et al., 1986; Nihei et al., 1987). From the ground-based observations of the atmospheric pressure and the rainfall and the theoretical model of solid earth tide, the variations of volumetric strain because of them can be estimated. In order to ascertain that the observed variations of volumetric strain are due to local groundwater motion, however, its information around the



**Fig. 1.** Locations of strainmeter in Tokai and South Kanto Region. They have been operated by Japan Meteorological Agency (JMA) and the Government of Shizuoka Prefecture. A grey ellipse in the lower figure shows the most up-to-date “expected focal region” of the Tokai Earthquake. (<http://www.seisvol.kishou.go.jp/eq/hantekai/q1/q1.html>).

observation site is required. There are two ways to assess the local groundwater motion: one is to monitor groundwater level in wells, and the other is to monitor geoelectric potential variations, namely the self-potential (SP) measurement. A dense network of well observations is required to monitor horizontal groundwater motion while SP measurement, which is often used to measure hydrothermal groundwater convection in volcanic region, is simpler to carry out (Zablocki, 1976; Ishido et al., 1983).

Geoelectric potential measurement, with only short dipoles, is strongly affected by conditions of electrodes in contact with the soil, which is influenced by rainfall. But, by making the separation of electrodes wider, the relative weight of this type of effect on an individual electrode can be reduced because meaningful signals get stronger with dipole length, hence, a better S/N ratio can be obtained (Mori, 1987). Meanwhile, geoelectric field is also affected by the variation of geomagnetic and tidal induction and artificial noises due to DC driven trains and factories. These effects are not usually reduced by simply widening the electrode separation. In order to discriminate these variations, methods



**Fig. 2.** Configuration of dipoles at Shimizu (SMZ) GPD station and location of the JMA strainmeter. Dotted lines indicate faults (Sugiyama and Shimokawa, 1990).

of signal extraction have been developed: e.g., BAYTAP-G (Ozima et al., 1989), Particle Motion Diagram (Yamaguchi et al., 2000), Principal Component Analysis (Uyeda et al., 2002), and Independent Component Analysis (Koganeyama et al., 2002; Orihara et al., 2009).

We were conducting geoelectric potential difference (GPD) observation at Shimizu (SMZ) station with long dipoles in the area several kilometres northwest of the JMA strainmeter when the anomalous strain expansion was recorded (Fig. 2). In this section, we analyse the GPD data during the three months including the strain anomaly period to investigate their relationship with the strainmeter data using Principal Component Analysis (PCA).

## 2 Observation system

Figure 2 illustrates the locality of the JMA strainmeter and the dipole configuration of Shimizu (SMZ) GPD station, which consists of seven 3 to 7 km long dipoles. Non-polarizing handmade Pb-PbCl<sub>2</sub> electrodes were installed at about a 2-metre depth in the ground at each end of the dipoles. Metal lines of telecommunication facility connected the electrodes. The long-dipole telluric observation system like this is often used in earlier works (Kinoshita et al., 1989; Uyeshima et al., 1989) and the Network-MT survey (Uyeshima, 2007). For data acquisition, we installed SES96 data logger (ADOSYSTEMS Co. Ltd.) at site WDS, equipped with a 2-s low-pass filter and a 20-bit A/D converter. Sampling rate was 10 s. The observation started on 22 August 1997. Geological surroundings of electrodes were deposits of alluvial lowlands and river beds (Sugiyama

and Shimokawa, 1990). Volumetric strainmeter at Shimizu was installed at 125 m depth in mudstone. The observation began on 1 July 1980 for monitoring the Tokai EQ (Furuya et al., 1986; Nihei et al., 1987).

### 3 Comparison between volumetric strain data and geoelectric potential data

Figure 3a shows one-hour averaged volumetric strain and geoelectric field from 1 December 1997 to 30 November 1998. Figure 3b shows magnified three-month records from 1 September to 30 November 1998. The upper seven panels of Fig. 3a and b are GPD data for each dipole in terms of mV per kilometre. It will simply be denoted geoelectric field hereafter, which means the mean geoelectric field strength in the direction of concerned dipole. Note that the term GPD will be used for the actual differences in geoelectric potential at two points. The 8th panel in both Fig. 3a and b show the volumetric strain data after reducing the effect of variation in barometric pressure (Furuya et al., 1986). The lowest panel of Fig. 3a is one-hour rainfall at Shimizu reported by JMA data. The 9th and lowest panel in Fig. 3b are the total magnetic force at JMA Kakioka Observatory (36.23° E, 140.19° N; about 200 km northeast of Shimizu) and one-hour rainfall data at Shimizu. Shaded rectangles in Fig. 3a and b show the period from the beginning of the volumetric strain anomaly at 16:00 LT (Local Time) on 11 October 1998 to the end of it as assigned by JMA (see Yamasato, 1999) for the rainfall at 00:00 LT on 17 October 1998. This was reported as one of the rare cases of anomalous changes unrelated to rainfall during the whole period of the observation.

Daily variations of the geoelectric field clearly seen in Fig. 3b are the induction to diurnal geomagnetic variations. The largest intensity is S1 component, namely 24 h cycle. A few sharp peaks in the geoelectric field data are induced by geomagnetic disturbances. Detailed discussion on the spectrum components recorded at Shimizu (SMZ) was described in Kudo and Nagao (2000). As stated above, in general, GPD induced by geomagnetic field variations is proportional to the dipole length, whereas the rainfall influence on electrodes is independent of the dipole length. Therefore, at SMZ station, where dipoles were long enough, rainfall effect was small compared to the geomagnetic effect. On the other hand, we clearly recognise the effect of rainfall on the volumetric strain. Note that the present time-series of volumetric strain does not show the daily variation because barometric pressure components, including daily variations, were already reduced.

As shown in Fig. 3a and b, variations of all dipoles, i.e., dipoles 1–7, look similar and are mostly caused by geomagnetic daily and other transient variations. Even rainfall influence on GPD is not recognised. Only a slight DC change may be noticed on dipoles 3, 4, 6 and 7, during the

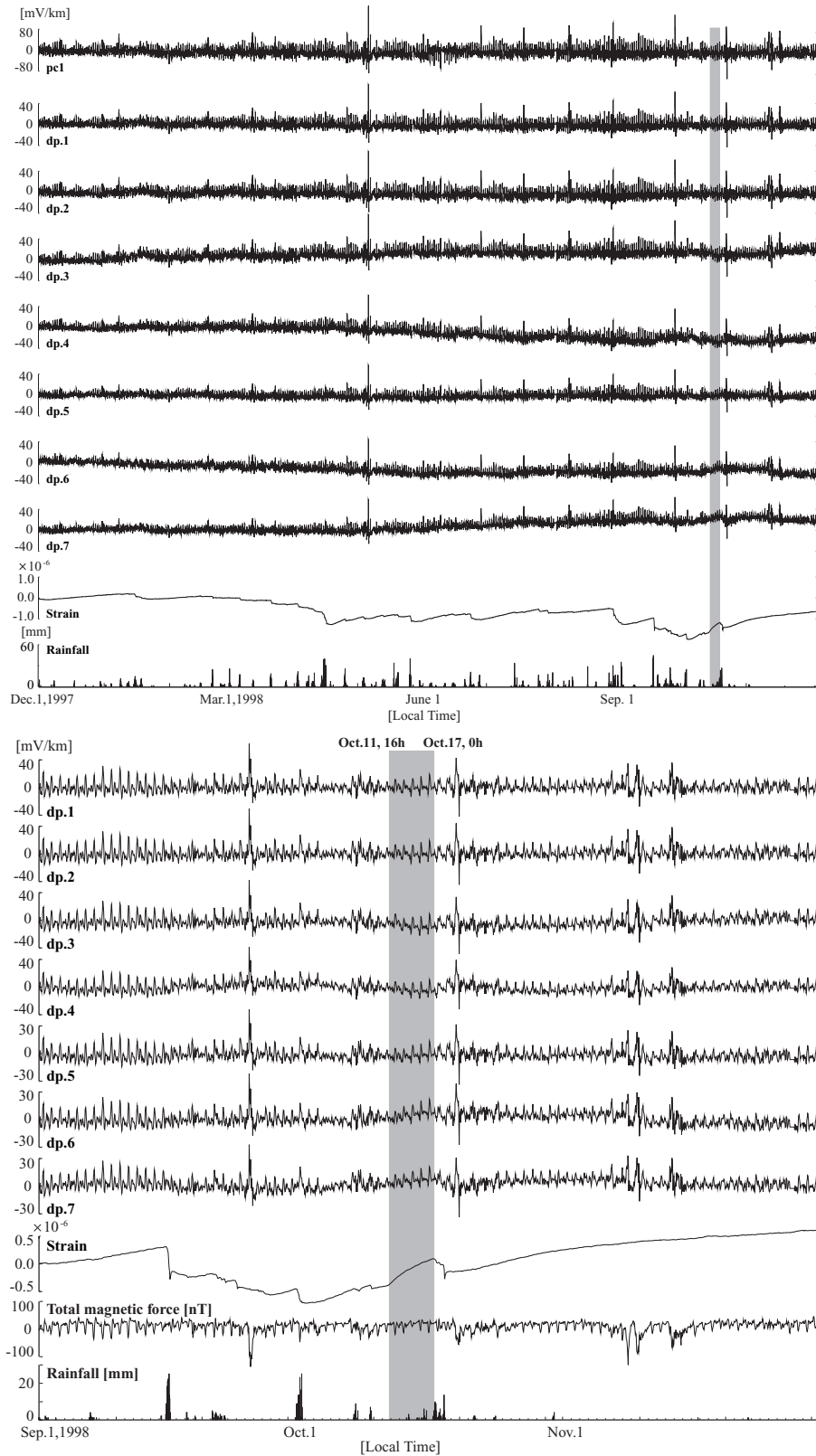
shaded anomalous period of volumetric strain. Such a change is not visible on dipoles 1, 2 and 5. In order to distinguish the predominant geomagnetic induced daily variations and the possible DC change, we applied Principal Component Analysis (PCA) to the geoelectric field data by using all 7 dipoles. When PCA is applied to seven time-series, the first principal component indicates the predominant direction in virtual space of seven dimensions and the second to seventh principal components indicate the direction orthogonal to the others (Jolliffe, 2002). For our time-series of geoelectric field, in which geomagnetic induced variations are predominant, other small variations were expected to be extracted as the other components. Then, we compared the volumetric variation and the geoelectric field data after eliminating the first principal component.

### 4 Results and discussion

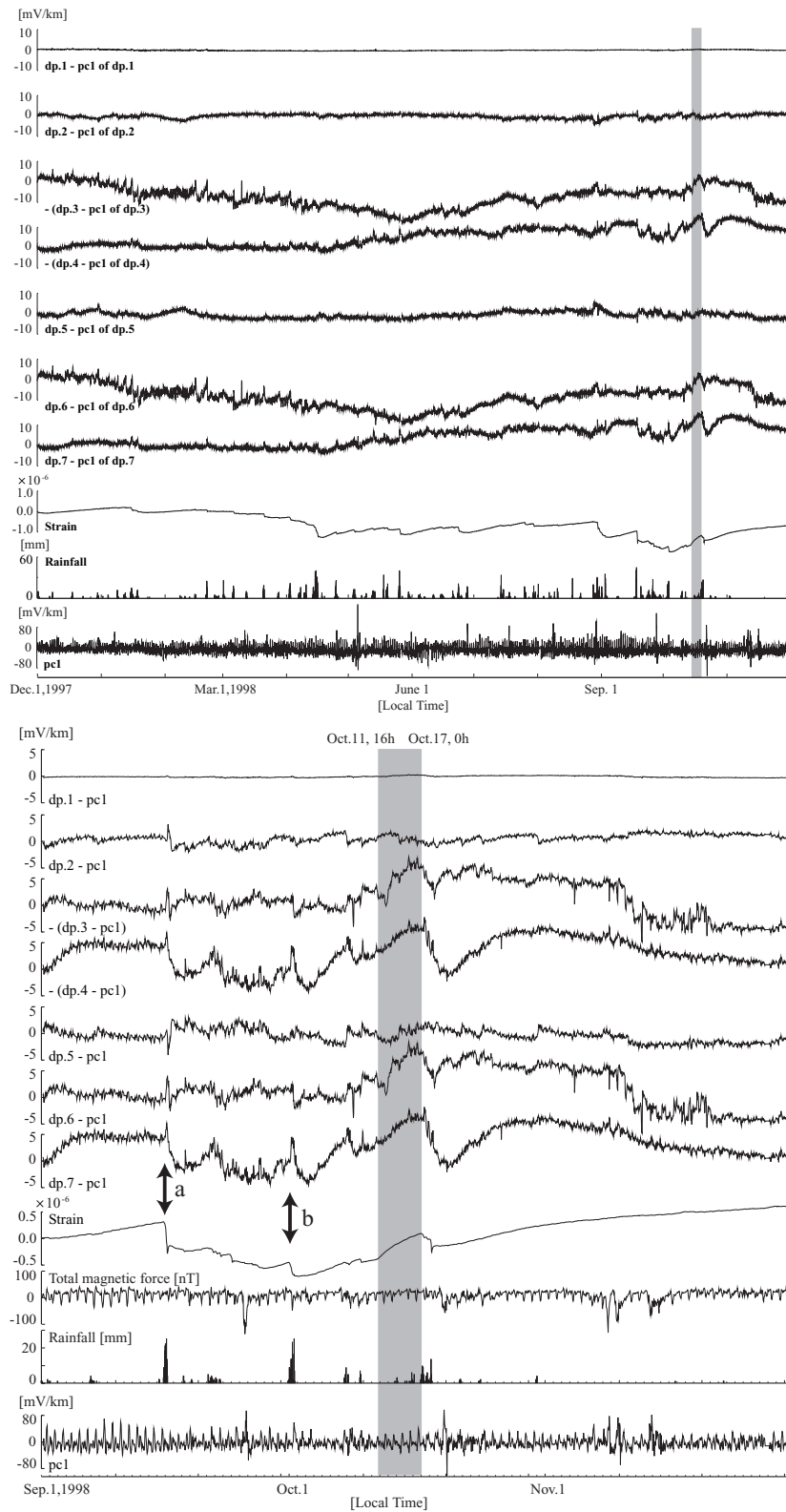
The upper seven panels of Fig. 4a and b show the time-series of the same period as in Fig. 3a and b, after eliminating the first principal component, pc1, shown in the bottom panel. It is remarkable that dp.1 data are almost identical to pc1. It may be because one of the electrodes of dp.1 shares one of the electrodes of the other dipoles and they contain common variations attributed to dp.1. The variations in dipoles 4 and 7 after removing the first principal component seem to correlate with each other during not only the volumetric anomaly period, depicted by shaded vertical rectangle, but also the whole observation period. Less clear, but similar variations during the volumetric anomaly period are also detected for dipoles 3 and 6. On the other hand, the similar variations during the volumetric anomaly period cannot be recognised in dipoles 1, 2 and 5. The effect of rainfall is also clearly recognised in both the strainmeter and GPD data, as pointed by arrows a and b in Fig. 4b. Rainfall effects on the volumetric strain were step-type negative changes, while they were positive changes in GPD. It may be noteworthy that these features became recognisable only after the application of PCA on the raw data shown in Fig. 3b.

The anomalous variation was not detected in dipoles 1, 2 and 5 even after eliminating the first principal component. It implies that the geoelectric potential change occurred only at SRG and DEI (see Fig. 2) when the volumetric strain anomaly took place.

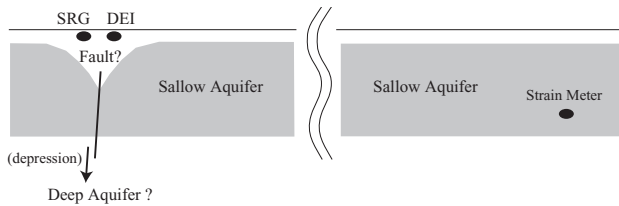
Possible candidates of the cause of the above GPD changes are piezoelectric and electrokinetic effects. However, the transient piezoelectric effect is unlikely in this case, and the quasi-stationary electrokinetic effect is more plausible because the anomaly continued for more than 5 days. Since the anomalous geoelectric field variations observed at SRG (dipoles 4 and 7) and DEI (dipoles 3 and 6) coincided in time with the anomalous strain variations eight kilometres away, the following speculations may arise (see Fig. 5): The anomalous geoelectric potential changes at SRG and DEI



**Fig. 3.** (a) One-year records and (b) three-month records of the geoelectric field, volumetric strain and rainfall at Shimizu. The shaded rectangle indicates the period of the volumetric strain anomaly in question. The panel second from the bottom in (a) shows the total magnetic force at Kakioka.



**Fig. 4.** (a) Upper seven panels are one-year records and (b) magnified three-month records of the geoelectric field after eliminating the first principal component pc1 shown in the bottom panel. The anomalous changes are made visible particularly in (b). Other panels are the same as in Fig. 3a and b. Arrows a and b in (b) indicate heavy rainfall time. A shaded rectangle shows the period of the anomalous strain change.



**Fig. 5.** Schematic diagram of a speculative mechanism of anomalous geoelectric field variations.

(Fig. 4a and b) were generated by the electrokinetic effect due, for instance, to a local depression of groundwater level, similarly with the case of the pumping well experiment of Bogoslovsky and Ogilvy (1973). In other words, the descent of groundwater into Kaibushi Fault (Fig. 5), which we notice passes through the zone (Fig. 2), might have caused the depression of water pressure in the surrounding region and further caused the volumetric expansion at the strainmeter, if the strainmeter is connected to the SRG-DEI zone through shallow aquifer. The GPD of dipole 7 (SRG-WDS), dipole 4 (OHR-SRG), dipole 6 (DEI-WDS), and dipole 3 (OHR-DEI) may have reached approximately 20 mV of total enhancement during the anomaly, because as shown in Fig. 4b,  $5 \text{ mV km}^{-1}$  enhancement of the principal component of electric field variation was measured on these four dipoles which are several kilometres in length. Bogoslovsky and Ogilvy (1973) showed that approximately 20 mV positive geoelectric potential changes could be observed 50 ~ 60 m away from the pumping well where the descent of the groundwater occurred. Hence, if the groundwater depression occurred near SRG and DEI, the above cited positive polarity GPD changes could have occurred. Moreover, Murakami et al. (1984) observed positive GPD enhancement around an active fault, which was explained by electrokinetic effect on the groundwater motion along the fault. In fact, Kaibushi fault goes through between SRG and DEI as shown in Fig. 2. Therefore, the 20 mV enhancement may not be totally unrealistic by the water level depression in Kaibushi fault between SRG and DEI as shown in Fig. 5.

## 5 Conclusions

An anomaly of volumetric strain, which looked like a precursor to the expected Tokai EQ at that point in time, was observed in October 1998 at Shimizu, Japan. Although no EQ followed, leaving its casual mechanism unknown, we could find small geoelectric potential difference (GPD) changes simultaneous with the strain anomaly. The GPD variations could have been generated by electrokinetic effect due to a local depression of groundwater. The simultaneous occurrence suggests that the anomaly of the strain might also have been related to the same groundwater motion. If so, the present work has shown, perhaps for

the first time, that there was a strain change accompanying a GPD change which was probably caused by groundwater motion. Although these changes were not followed by the Tokai EQ, further monitoring of GPD may contribute to the basic study of EQ precursory phenomena, of which our present knowledge is almost nil. It is possible that the real precursor may also be related to minute changes of underground water levels.

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