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Geomagnetic changes correlated with crustal movement in the north-eastern part of the Izu Peninsula, Japan

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Abstract
After the 1989 sea-floor eruption off the east coast of Ito city, no remarkable activities of earthquake swarms were observed in the eastern part of the Izu Peninsula, Central Japan during the period from 1990 to 1992. However, a small swarm activity was again observed in January, 1993 and a remarkable one took place again in May-June 1993. Several months after the subsidence of the swarm activity, abrupt changes in the crustal movement in the inland of the peninsula were observed during the period from September 1993 to February 1994. At some continuous observation sites, well correlated changes in the geomagnetic total intensity were observed almost during the same period when the anomalous changes in the crustal movement were seen in the eastern part of the peninsula. The spatial patterns of negative changes of the total intensity in the northern half and positive ones in the south were seen in the north-eastern edge of the domed distribution of the upheaval. The changes in crustal movement and the geomagnetic field terminated when a small swarm activity occurred at the end of February 1994.

Key words *geomagnetic field – piezomagnetic effect – crustal movement – tectonomagnetism*

1. Introduction

Temperature and/or stress changes in the Earth's crust can be possible causes of local changes in the total geomagnetic field at the Earth's surface. So, local changes in the geomagnetic field can be regarded as an indicator representing the crustal condition.

Johnston (1986), who analyzed long period data sets of the geomagnetic total intensity, gravity, strain, and uplift observed near the San Andreas fault, found strong correlations among them including the total intensity, and obtained an empirical relation between the total intensity and the others. For instance, according to his results, a 1nT change in the total intensity corresponds to a strain change of 1.02×10^{-6}.

Changes in the total intensity associated with the earthquake swarm occurred in Matsushiro, Central Japan during the period from 1965 to 1966 were observed by Rikitake (1968) using a proton magnetometer array observation which was the start of such a continuous observation system set up in a narrow active area. At the northern site, the total intensity decreased by about 5 nT, while it increased by about 5 nT at the southern site in association with changes in crustal movements in the same period.

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Many researchers have tried to explain various changes observed in the Matsushiro area. For instance, Stuart and Johnston (1975) tried to explain them in terms of magma intrusion, and Mizutani and Ishido (1976) proposed a model based on the streaming potential theory. However they failed to obtain a full understanding of the phenomenon governing the Matsushiro earthquake swarm. Recently, however, Sasai (1995) succeeded in describing the whole image for the Matsushiro earthquake swarm on the basis of the analytical piezomagnetic modeling method accomplished by Sasai (1991a). This means that tectonomagnetic observations can play a very important role in clarifying the generating mechanism of an earthquake swarm.

In the north-eastern part of the Izu Peninsula, Japan, anomalous crustal uplift accompanying earthquake swarm activity once took place in 1930 and the Kita-Izu earthquake (*M* 7.3) occurred in November 1930 to produce a displacement along the Tanna fault.

Seismic activities in the Izu region have became high since the Izu-Hanto-Oki earthquake (*M* 6.9) which occurred at the southern tip of the Izu Peninsula in May 1974. Since then remarkable crustal activities, namely the anomalous crustal uplift and earthquake swarms, have continued for about 20 years in the north-eastern part of the Izu Peninsula, Japan.

In this study, tectonomagnetic changes observed in the eastern part of the Izu Peninsula during the period from January 1993 to May 1994 are described and their possible generating mechanism is discussed on the basis of the piezomagnetic effect.

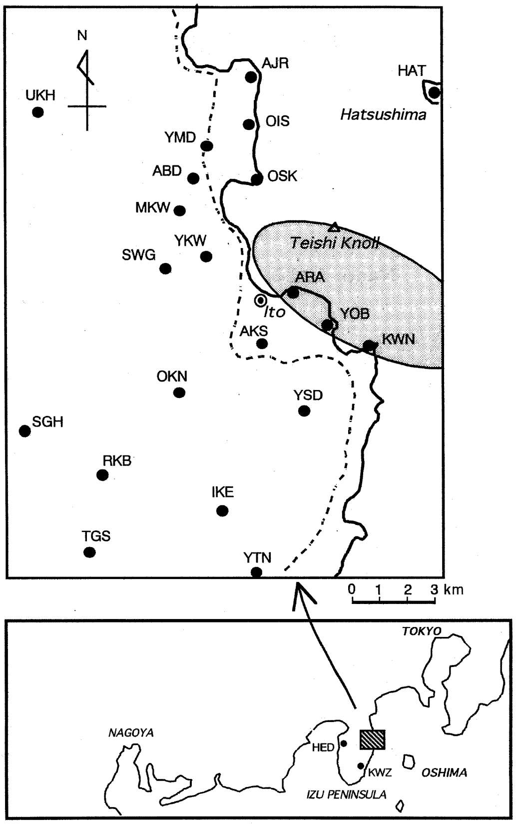


Fig. 1. Distribution of continuous observation sites of the geomagnetic total intensity in the Izu Peninsula after the 1989 sea-floor eruption which formed the Teishi Knoll. The hatched area indicates the activity zone of the earthquake swarms over the past 10 years.

2. Outline of the magnetic observation

The Izu Peninsula is located in Central Japan facing the Pacific Ocean, and about 100 km away from Tokyo as shown at the bottom of fig. 1. Geomagnetic observation was initiated in 1976 in the Izu region, where it became one of the most active regions in Japan. Since then, intensive geomagnetic observations have been carried out (*e.g.*, Rikitake *et al.*, 1980; Sasai and Ishikawa, 1977, 1978, 1980a,b, 1982, 1985). In particular, since 1989 when the Teishi knoll sea-floor eruption occurred off the east coast of Ito city in the peninsula, geomagnetic observations have been intensified with a dense network system of the observation using up to 23 proton precession magnetometers in the north-east coast of the peninsula (Oshiman *et al.*, 1991).

The activities in the north-eastern part of the peninsula are characterized by two types of crustal activities. One is the unusual crustal uplift persisting for about 20 years as revealed by a leveling survey and sea-level measurements at Ito tidal station conducted by GSI, Geographical Survey Institute, Japan (*e.g.*, GSI, 1995) and the other is the earthquake swarm intermittently occurring there since 1978. The main region of earthquake swarm activity in the past 10 years is shown in fig. 1 with the hatched area.

Figure 1 also shows localities of continuous observation sites of the geomagnetic total intensity. Since the sites, KWZ and HED, shown in the map at the bottom of fig. 1 are located at places far from the area concerning the crustal uplift and earthquake swarms, they are used as reference sites for obtaining the differences in the total intensity to separate local changes in the geomagnetic field. Since observed data are not telemetered from observation sites, we visit most sites every 45 days to pick up observed data written on EP-ROM and to make a site inspection of magnetic circumstances.

In this region, geomagnetic circumstances are not so good for observation because an electric railway runs along the coast line and so many houses are there. However, some clear changes in the geomagnetic field were observed in association with the crustal activities there. For instance, paired changes of decreasing and increasing which were well explained by the thermal demagnetization of rocks were observed before the 1989 sea-floor eruption as reported by Sasai (1989) and Sasai and Ishikawa (1991).

In this paper, we describe remarkable changes in the geomagnetic total intensity observed from July 1993 to March 1994, in association with abrupt changes in the crustal uplift which took place in the north-eastern part of the peninsula.

3. Seismicity and crustal movement in the Izu region

Seismic activities in the Izu region have became high since the Izu-Hanto-Oki earthquake which occurred at the southern tip of the Izu Peninsula in May 1974. More than ten moderately large earthquakes ($M \geq 5$) occurred in the Izu region during the period from 1974 to 1981. Rikitake (1982) pointed out a tendency for these epicenters to migrate towards the north since the Izu-Hanto-Oki earthquake.

An earthquake swarm began to occur east off the Kawanazaki Promontory (the continuous observation site, KWN, established in 1989 is located at the promontory), Ito city, at the end of November 1978. Since then, the swarm activities have occurred intermittently for the past 17 years in the eastern part of the Izu Peninsula. Reports on seismicity in the Izu region until 1980 can be seen in, for instance, Tsumura *et al.* (1977, 1978), Tsumura (1980) and Karakama *et al.* (1980). Another feature of the tectonic activity is a crustal uplift in the north-eastern part of the Izu Peninsula with an almost constant rate of upheaval revealed by the Geographical Survey Institute (*e.g.*, GSI, 1995) using differences in the sea-level between Ito and a reference tidal station far from the Izu region.

Figure 2 shows the frequency of the occurrences of earthquakes observed at Ito by the Japan Meteorological Agency (JMA, 1995) since the end of 1976. Seismic activities except ones denoted by asterisks are earthquake swarms which occurred at east off Ito. During the period from 1989, when the Teishi knoll sea-floor eruption occurred, up to 1992 no remarkable activities of earthquake swarm in the north-eastern Izu region were observed except two small swarm activities which took place in August 1990 and December 1991. It seems, however, that the crustal condition in this region has become re-activated again since the end of 1992, so that a swarm activity was observed in January 1993 and a remarkable one took place again in May-June 1993. During the activities, tilt changes amounting to 10 μ rad. (E down) in the EW component were observed by NIED (1994a) at Ito station which is located at a place close to our magnetic observation site, KWN. They interpreted the tilt changes using the same type of tensile fault as Okada and Yamamoto (1991) used for interpretation of a tilt change, amounting to 20 μ rad. observed in association with the 1989 seismo-volcanic activity. After subsidence of this swarm, an abrupt crustal uplift was observed, especially in the inland of the peninsula.

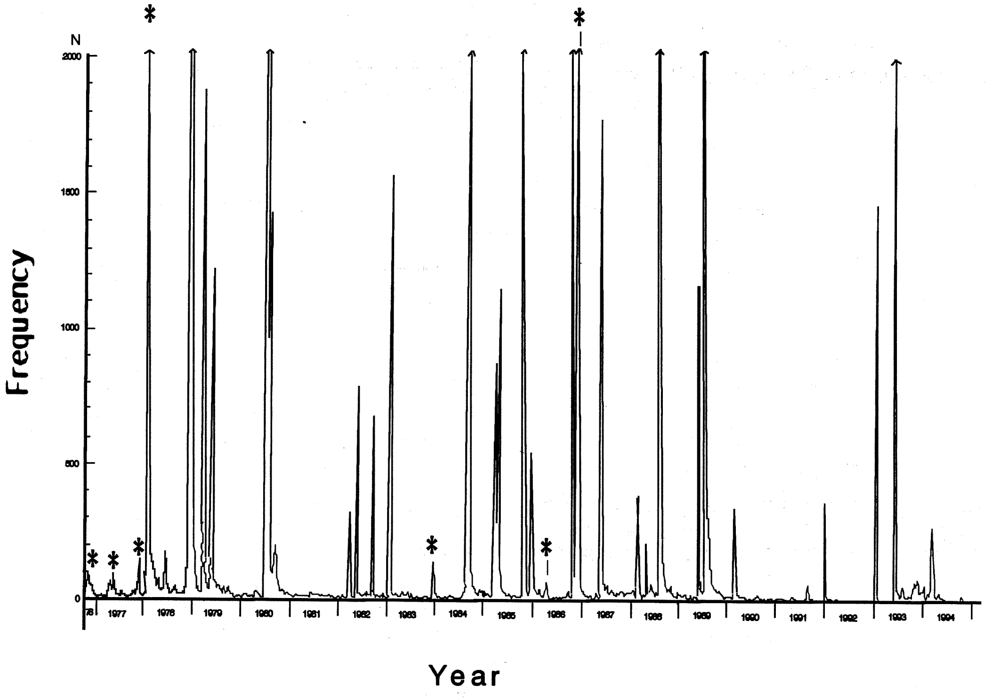


Fig. 2. Earthquake frequency for every ten days observed in Ito city (after JMA, 1995). Seismic activities denoted by asterisks are not the swarm activities which occurred east off Ito city.

Changes in the distance between Ito and Hatsushima and between Komuro and Usami observed by GSI (1995) during the period from September 1990 to July 1994 are reproduced in fig. 3. The offsets seen in June 1993 are observed during the largest earthquake swarm in 1993. From September 1993, an abrupt change is seen in each distance shown in the figure. The distance between Komuro and Usami, which is measured with EDM, increased by about 6 cm until the end of February 1994, while the distance between Hatsushima and Ito, which is measured by GPS, showed a decrease of 2 cm during the period from September 1993 to the end of November 1993. Changes in the tilt are also observed at Ito station by NIED (1994b) resulting in a total amount of about 8 μ rad. (E down) in EW component and about 3 μ rad. (N up) in NS component during the period. JMA (1994) also observed tilt change amounting to 5.3 μ rad. (N down) in the NS component at the tilt observation station which is located at a place very close to our site OSK in Osaki, during the same period. Observed geomagnetic changes have a good correlation with such crustal changes, although the changes started about 2 months later than the crustal change, as is described in the following section.

Spatial distribution of the vertical movement is also revealed by GSI (1995) with the level survey during the period from June-August 1993 to June 1994 as shown in fig. 4. In the central region of the north-eastern part of the peninsula, uplift of more than 5 cm is observed. The spatial distribution of the uplift seems to be a dome-like shape. The center of the uplift can be put somewhere around the place denoted by C in the figure. The contours of 40 and 50 mm shown in fig. 4 are drawn by the authors.

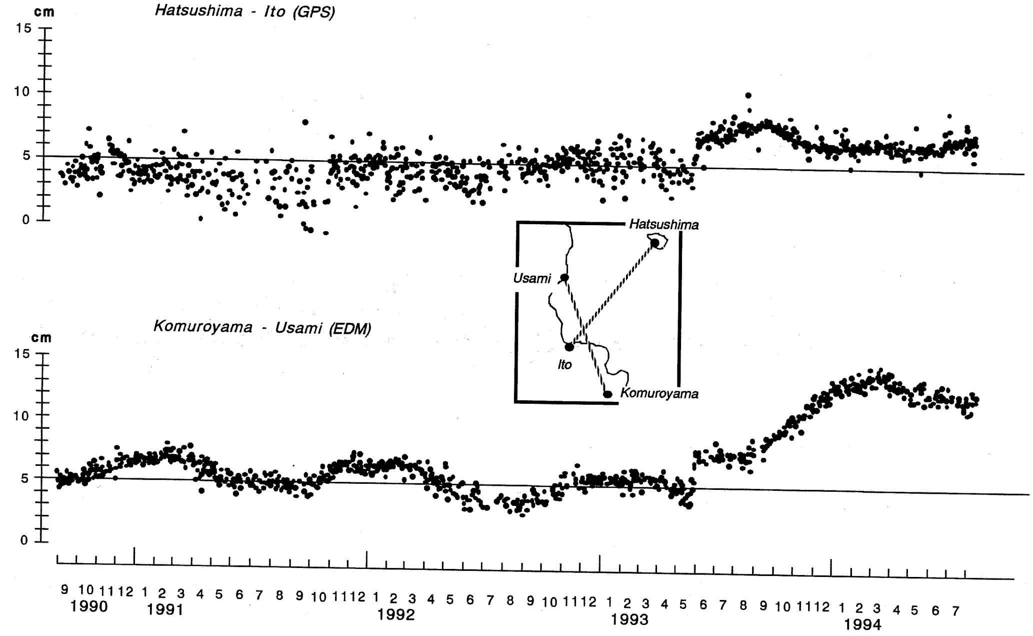


Fig. 3. Changes in the distance observed by GSI (1995). The distance between Hatsushima and Ito is measured with GPS, while the distance between Usami and Komuroyama is measured with EDM. Vertical axes in the figure show relative scales of length.

On the other hand, ERI (1995) revealed a spatial pattern of gravity changes in the eastern part of the peninsula by repeated surveys. They reported that gravity changes associated with the abrupt uplift reached the same amount or more (about $-40\ \mu$ gal) than they observed in association with the 1989 seismo-volcanic activity, and that the area where changes appeared is four times wider than that of the 1989 activity. It seems that changes in the tilts and the distances mentioned above terminated when a small activity occurred at the end

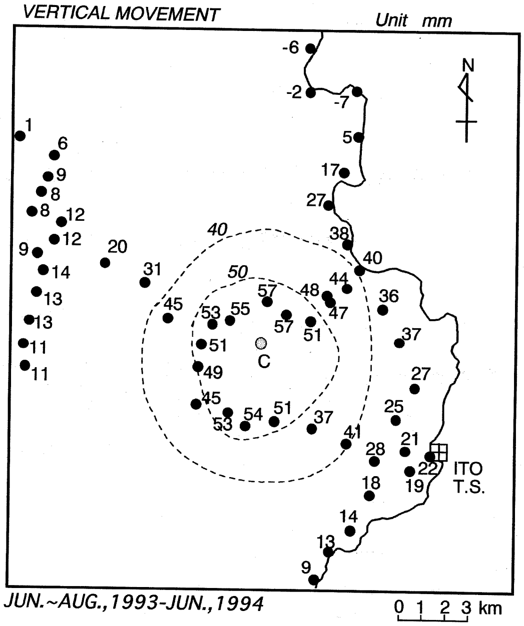


Fig. 4. Vertical measurements in the north-eastern part of the Izu Peninsula during the period from June-August 1993 to June 1994 (GSI, 1995). Units in mm. Contour lines of 40 and 50 mm are drawn by the authors. The location of the Ito Tidal Station (ITS) is also shown.

of February 1994, whose region was located about 6 km south from the eastern portion of the hatched area shown in fig. 1.

4. Geomagnetic changes from June 1993 to May 1994

Remarkable geomagnetic changes well correlated with each other at several observation sites were observed during the period from September 1993 to May 1994. As is mentioned above, during the period the abrupt changes in the crustal movements took place after the 1993 earthquake swarm were also observed by GSI (1995) in the north-eastern part of the Izu Peninsula.

Figure 5 shows 5-day means of simple differences referred to KWZ during the period from January 1993 to May 1994 using night-time data in order to avoid the noise contamination due to the electric railway, especially running along the east coast of the peninsula.

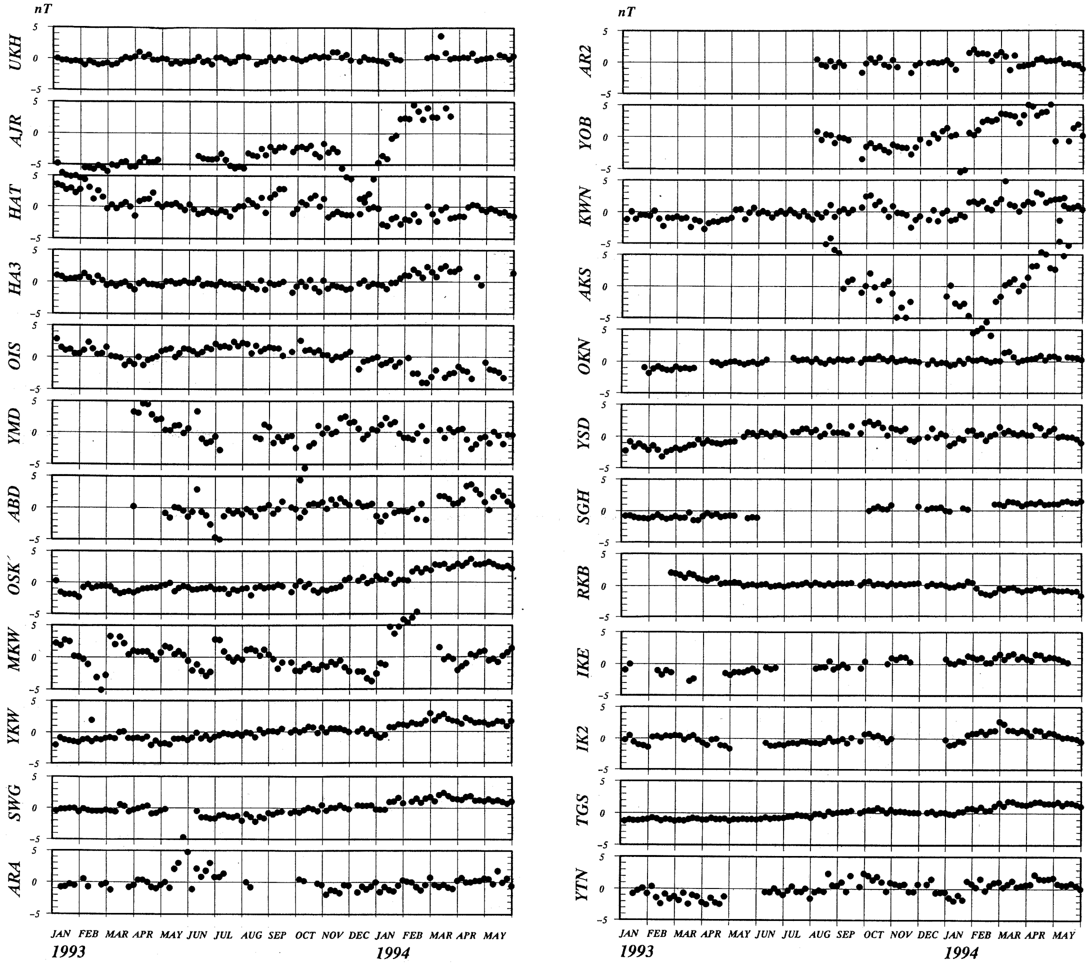


Fig. 5. Changes in the geomagnetic differences during the period from January 1993 to May 1994 in the north-eastern part of the Izu Peninsula. Five day means of night-time (0:00-4:00 LT) differences are shown.

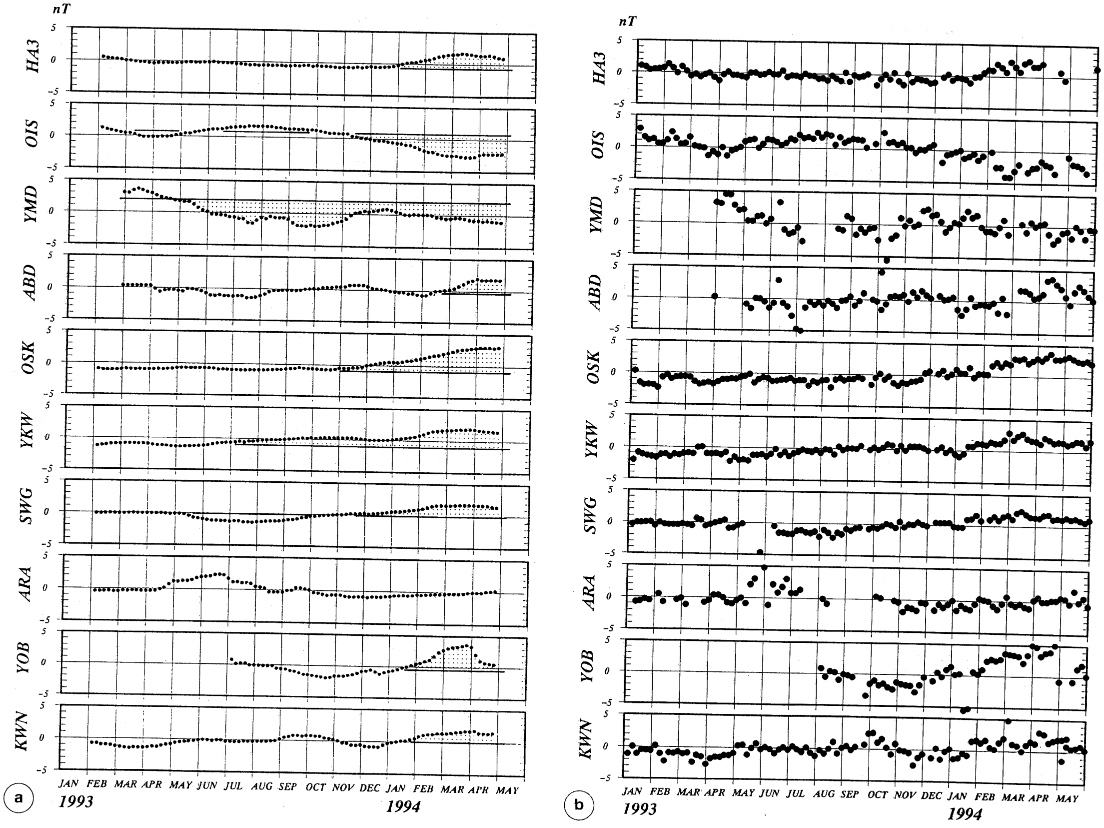


Fig. 6a,b. Fourteen point moving averages (a) applied to the data set of the 5-day means plotted in (b).

Several sites are still affected by artificial influences such as house construction near a site. For instance, the remarkable change observed at AJR since the end of November 1993 seems to be due to an artificial origin, and changes seen at AKS can be also attributed to the influence of the artificial noises. Changes seen at MKW during January-February 1993 and at ARA during May-July 1993 are apparent changes due to artificial origin, too. The remarkable changes correlated with the crustal changes are clearly seen at OIS, OSK, YKW and SWG. At sites OSK, YKW and SWG, increasing changes of the total intensity were observed, especially during the period from November 1993 to March 1994, while at OIS a decrease was observed during the same period. On the other hand, no change was observed at UKH, and the differences at SGH, OKN, ARA and YTN were almost constant during the period. YMD is located just above the tunnel of the electric railway. So data are processed by a special filtering technique (Oshiman *et al.*, 1997) not described in this paper.

Figure 6b shows 5-day means of simple differences using night-time data at sites showing well correlated changes and not affected by artificial disturbances in this period especially in the Ito area, the northern half of this observation area. At most of all sites, except OIS and YMD, differences increase after November 1993. Fourteen point moving averages applied to the data set plotted in fig. 6b are shown in fig. 6a.

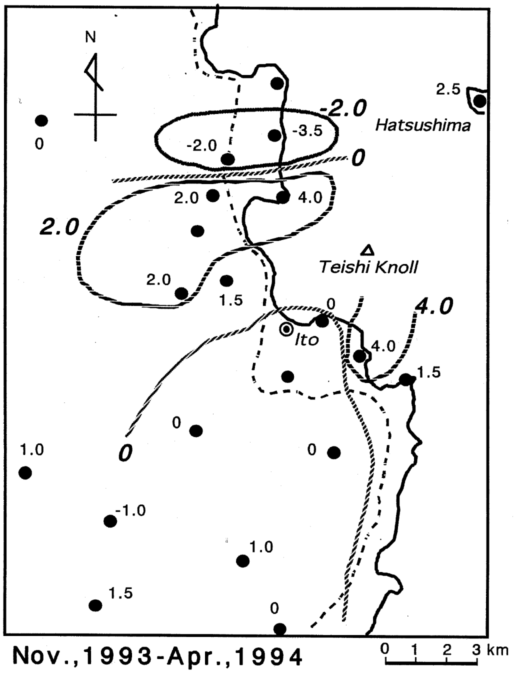


Fig. 7. Spatial distribution of geomagnetic changes revealed by fourteen point moving averages during the period from November 1993 to April 1994.

Figure 7 shows the spatial distribution of geomagnetic changes during the period from November 1993 to May 1994. A negative region is seen in the northern area, and a corresponding positive region is seen in the neighbouring region of the southern side of the negative region. No remarkable geomagnetic changes (fig. 7) are seen in the central area where the uplift is observed (fig. 4), although observation sites are not dense in the area. A center of the paired region of the positive and negative changes seems to be located at somewhere around the northern observation area shown in fig. 7. So, the two centers of the geomagnetic change and the crustal uplift do not coincide with each other. This discrepancy of the location of the two centers makes it very hard to clarify the source mechanism of the observed changes in the geomagnetic total intensity.

5. Magnetic changes produced by a dilatation sphere

Sasai and Ishikawa (1991) discussed the generating mechanism of the total intensity changes observed in the eastern part of the Izu Peninsula during the period from 1976 to 1989 on the basis of both piezomagnetic and thermal demagnetization effects. It does not seem, however, that the observed spatial pattern described in the previous section can be explained in terms of the thermal demagnetization model. Because the thermal demagnetization of the same portion of the crustal magnetization produces a spatial pattern of positive on the north side and negative on the south of the total intensity changes.

Taking account of the observed dome-like distribution of the crustal deformation, one of the simplest elastic models is the Mogi model (Mogi, 1958). The piezomagnetic version of the Mogi model was introduced into the research field of tectonomagnetism by Davis (1976) on the basis of a numerical approach aimed at explaining the volcanomagnetic effect due to the Kilauea volcano in Hawaii. Meanwhile, Sasai (1979) initiated an analytical approach for piezomagnetic modeling. And Sasai (1991a,b) obtained final version of the analytical solution of the piezomagnetic Mogi model. A schematic view of the Mogi model is shown in fig. 8a.

According to the previous studies on the piezomagnetic model, when the depth of the Curie point isotherm, H_0, is deeper than that of the dilating sphere, D, we expect the positive distribution of the total intensity changes around the Earth's surface immediately above the sphere center and negative area in the northern neighbourhood of the positive area. This spatial distribution of geomagnetic changes could explain the observed changes shown in fig. 7.

To explain the observed crustal uplift first, we roughly determine some basic parameters of the Mogi model, such as the radius, a, of the pressurized sphere, the depth, D, pressure change, Δp, shown in fig. 7. The moment of pressure source of the Mogi model is characterized

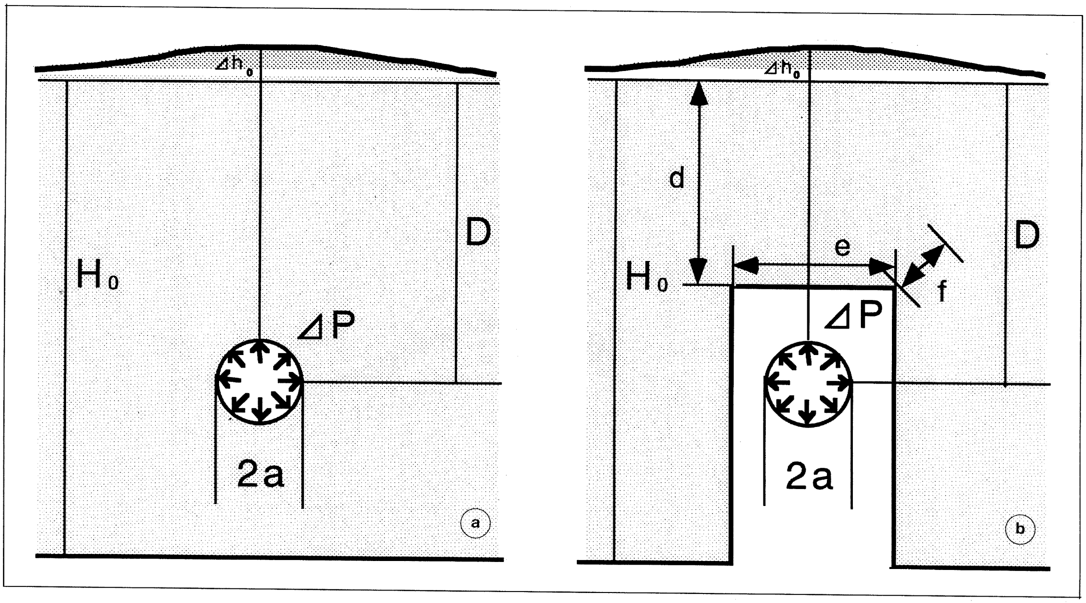


Fig. 8a,b. A schematic view of the Mogi model. a) Uniform case of distribution of the rock magnetization in the crust; b) non-uniform case of distribution of the rock magnetization.

by a following parameter C_0 (Sasai, 1991b);

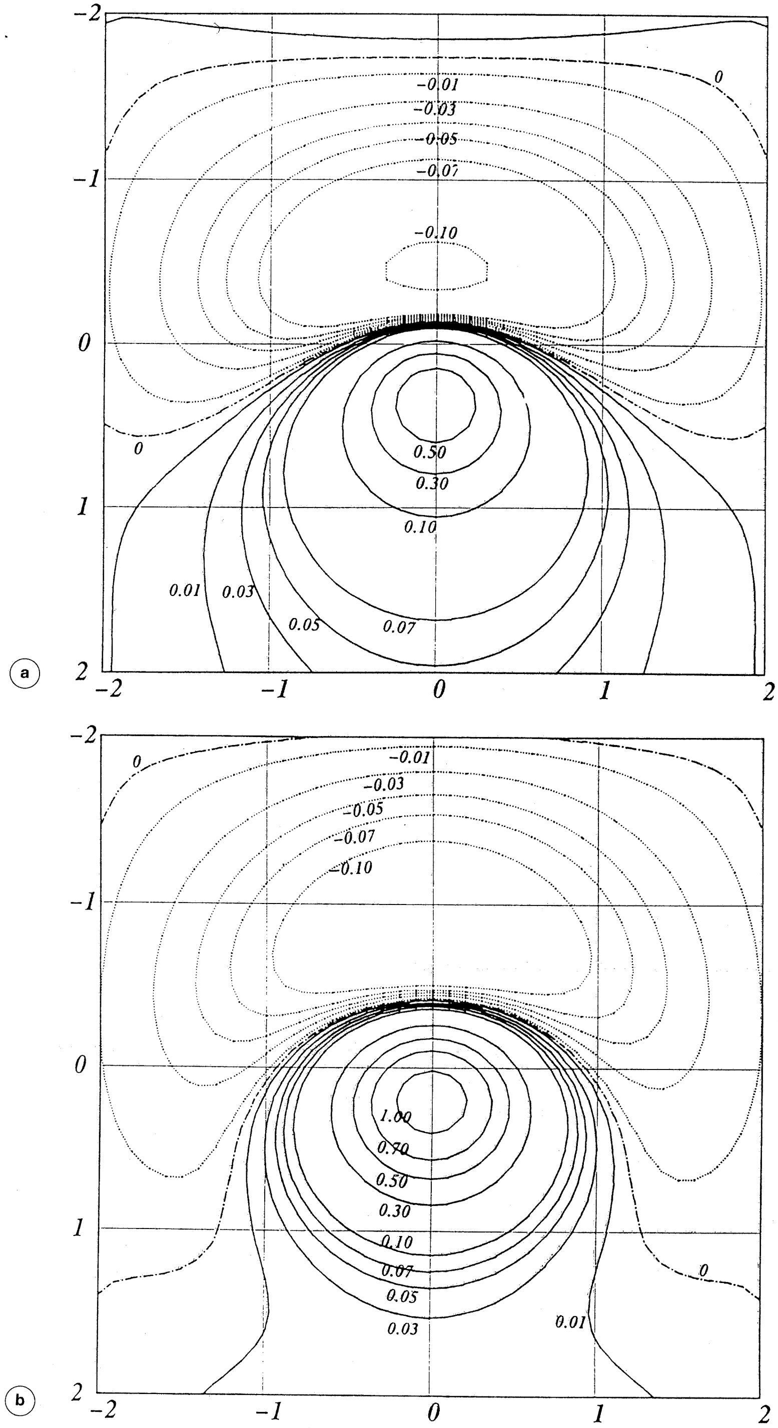
$$C_0 = \frac{\lambda + \mu}{\lambda + 2\mu} \mu D^2 \Delta h_0$$

where λ and μ are Lame's constants, D the depth of an underground dilating sphere, Δh_0 the vertical movement at the surface immediately above its center. So, we do not need values for the radius, a, and pressure change, Δp, explicitly for the point source solution.

The uplift Δh_0 is given to be about 6 cm at most at C from observation shown in fig. 4. The depth, D, can be also estimated at about 7.7 km from the observation results shown in fig. 4 based on a simple method which Hagiwara (1977) proposed to determine D. Using those two parameters thus obtained, we calculate changes in the total intensity due to pressurized center using the calculation code developed in Suzuki and Oshiman (1990). Other model parameters used in the calculation of this study are as follows: $\lambda = \mu = 3.5 \times 10^{11}$ cgs, $I = 45°$, $J = 4.3$ A/m, $\beta = 2.0 \times 10^{-4}$ 1/bar, $a = 2.0$ km, and $\Delta p = 205$ bar.

Figure 9a-c shows calculated spatial distribution of the total intensity changes at the Earth's surface. The direction of the north coincides with the upward direction of the vertical axis. The numeric value on each axis is a value normalized by a unit length of 10 km. The center of dilating source is located beneath the origin. The results shown in fig. 9a-c correspond to the cases of H_0 = 30, 8, and 5 km, respectively.

As already mentioned above, the positive change area of the total intensity appears above the southern half of the upheaval area included just above the center of the dilating source, while negative changes are seen in the northern side, for the case of H_0 = 30 km in fig. 9a. In the case that the dilating sphere is not included in the magnetized region, namely H_0 = 5 km, however, the negative change area is dominant above the upheaval area. This means the parameter, H_0, plays a very important role in identifying the piezomagnetic model for explaining the observed changes in the total intensity in the north-eastern part of the peninsula.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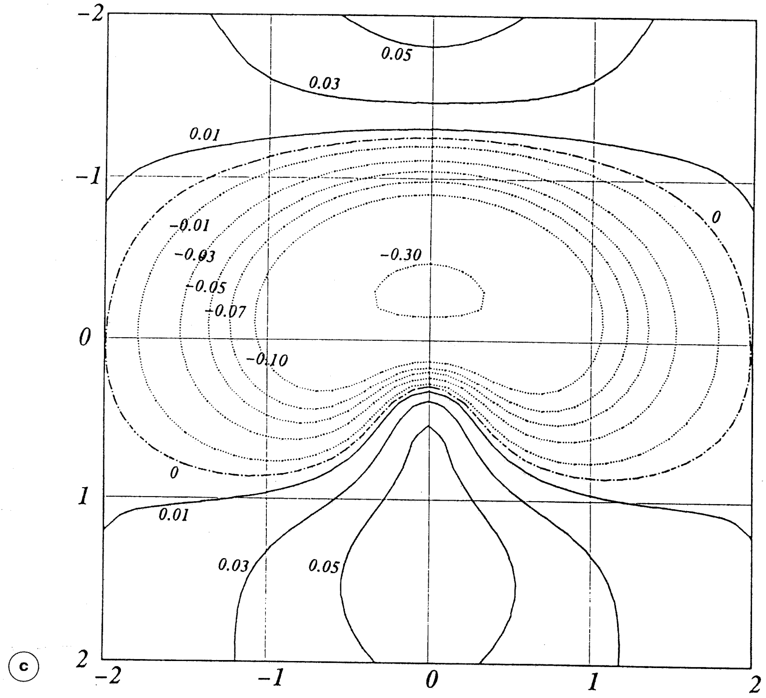
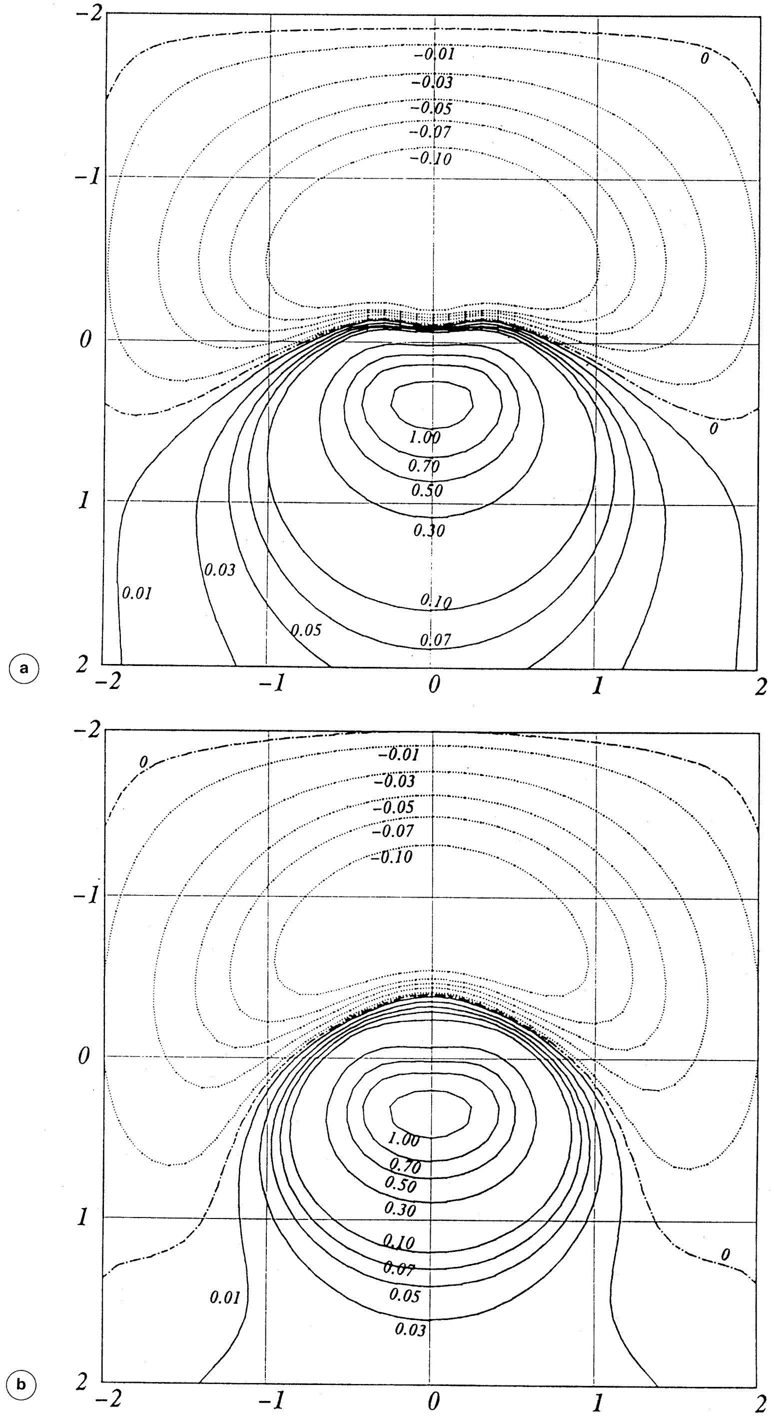


Fig. 9a-c. Total intensity changes due to the Mogi model for the uniform distribution of the rock magnetization shown in fig. 8a. a) Changes due to the Mogi model, when the Curie point isotherm is located at a depth of 30 km; b) changes due to the Mogi model, when the Curie point isotherm is located at a depth of 8 km; c) changes due to the Mogi model, when the Curie point isotherm is located at a depth of 5 km.

Okubo (1984) analyzed air-borne magnetic data sets to obtain a model of the distribution of crustal magnetization beneath Japan, which is regarded, as a first order approximation, to be uniform to a depth of the Curie point isotherm, and inferred that the depth of the Curie point isotherm beneath the eastern part of the Izu Peninsula is very shallow and about 8 km.

On the other hand, Oshiman *et al.* (1983) observed very local secular changes associated with the uplift in the eastern part of the Izu Peninsula during the period from December 1978 to March 1982, and interpreted the observed spatial distribution of the secular changes based on a piezomagnetic Mogi model proposed by Sasai (1979). Negative changes on the northern side are dominant in the observed spatial pattern along the N-S repeated survey line. They used the piezomagnetic Mogi model in the case that the Curie depth was much deeper than that of a dilating source in their interpretation.

The analytic model proposed by Sasai (1979), however, was revised by Sasai (1991b). So we should apply a model of the case that the source is not included in the magnetized region, when we use the piezomagnetic Mogi model in order to interpret the spatial distribution of secular changes observed by Oshiman *et al.* (1983), because negative is dominant in the observed changes. The depth of the source used in Oshiman *et al.* (1983) is 3 km, although it cannot be determined uniquely. So, the Curie depth beneath the eastern part of the peninsula might be much shal-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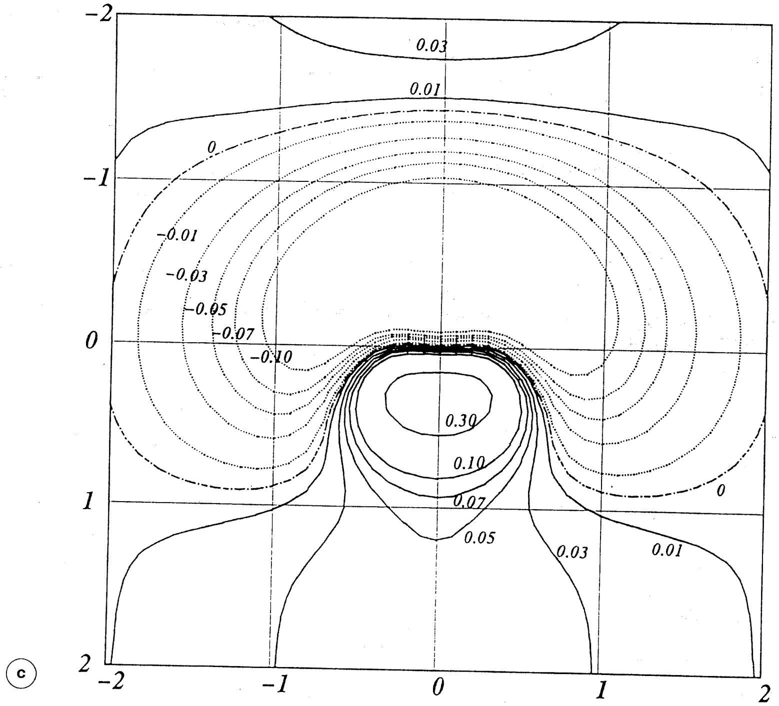

Fig. 10a-c. Total intensity changes due to the Mogi model for the non-uniform distribution of the rock magnetization shown in fig. 8b. a) Changes due to the Mogi model, when the Curie point isotherm is located at a depth of 30 km; b) changes due to the Mogi model, when the Curie point isotherm is located at a depth of 8 km; c) changes due to the Mogi model, when the Curie point isotherm is located at a depth of 5 km.

lower than 8 km. In that case, as is shown in fig. 9c, the negative area becomes so dominant above the upheaval area that we cannot explain the paired positive-negative distribution pattern shown in fig. 7 by using a piezomagnetic Mogi model, because the positive area in fig. 9c is not widely distributed and not so strong in its intensity.

Now we introduce, here, a non-uniform distribution of crustal magnetization for the piezomagnetic Mogi model. The schematic view is shown in fig. 8b. Inside the rectangular solid of a volume of $e \times f \times (H_0 - d)$ surrounding the source sphere, the intensity of crustal magnetization is assumed to be zero.

Figure 10a-c shows the total intensity changes at the Earth's surface for the same basic parameters of the piezomagnetic Mogi model as those in fig. 9a-c, assuming $e = 7.0$ km, $f = 7.0$ km, and $d = 3.2$ km for the size of the non-magnetic rectangular solid. The calculated distribution of changes shown in fig. 10a-c corresponds to the cases of $H_0 = 30$ km, 8 km and 5 km, respectively. As shown in fig. 10c, the spatial distribution pattern of the total intensity changes for the case of the non-uniform model is quite different from that of the uniform case when $H_0 = 5$ km. So, it may be possible to produce a change distribution pattern of negative in the northern half and positive in the southern half when crustal magnetization is not uniform to the Curie depth, even if the depth of the source is much shallower than the Curie depth.

6. Discussion

We observed geomagnetic changes in association with the abrupt ground deformation which occurred after the subsidence of the 1993 swarm activity. Although we have not yet reached the final goal for describing the generation mechanism of the observed geomagnetic changes, we may explain the observed distribution pattern of the total intensity changes with a piezomagnetic Mogi model. Location of the source, however, is different from that inferred from the domed distribution of the crustal deformation. Namely, the source for the piezomagnetic Mogi model should be located at a place about 6 km north from the center, *C*, of the uplift shown in fig. 4, even from the viewpoint of the non-uniform model proposed in the previous section.

Meanwhile, Nakatsuka (1995; personal communication) analyzed air-borne magnetic data around the north-eastern part of the Izu Peninsula using the method proposed by Nakatsuka (1994), and obtained a clear distribution of negative intensity (*i.e.*, reverse magnetization) of crustal magnetization from the Earth's surface to a depth of about 500 m around our observation site, OIS. This kind distribution of reversal magnetization could explain the reason why the center of the paired change distribution of the total intensity does not coincide with the location of the source of the Mogi model for the crustal uplift. As is shown by Oshiman (1990), a paired spatial pattern of negative and positive changes can also be expected on a boundary between different blocks in the direction of crustal magnetization.

We need a more detailed distribution of magnetization to a deeper portion of the Earth's crust in and around our observation area to understand the observed magnetic changes well correlated with the crustal movement.

We have not taken information obtained from the spatial pattern of gravity changes revealed by ERI (1994) into consideration yet for constructing a piezomagnetic model to explain the observed changes. The spatial pattern is elongated in the NE-SW direction in the eastern part of the peninsula. This means that the Mogi model is too simple to explain the observed changes in the total intensity, and that we should use another type of piezomagnetic model, such as a tensile fault model having a length of about 6 km and a width of about 6 km and dipping at a very low angle at a depth. Magma may be supplied to the almost vertical tensile faults revealed by Okada and Yamamoto (1991) during the swarm activities off the east coast of the Izu Peninsula, through such a buried root tensile fault.

Another possible explanation of the observed changes is that based on electrokinetic effects. For instance, Zlotnicki and Mouel (1998) suggested electrokinetic effects as a generating mechanism of geomagnetic changes observed on Piton de la Fournaise Volcano. On the other hand, Hashimoto and Tanaka (1995) found very large changes in the self-potential in association with extrusion of a lava dome on Unzen Volcano, and Hashimoto (1997) claimed that electrokinetic potential associated with subsurface hydrothermal convection seemed to be the most reasonable mechanism. Therefore, we could not exclude the possibility that the observed changes in the north-eastern part of the Izu Peninsula might be generated by electrokinetic effects because changes in subsurface hydrothermal convection in this area would be possible. However, we have no observations such as the self-potential and/or water temperature changes suggesting variations in subsurface fluid flow. So we did not take such effects into consideration in this manuscript.

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