Seismomagnetic models for earthquakes in the eastern part of Izu Peninsula, Central Japan

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Abstract
Seismomagnetic changes accompanied by four damaging earthquakes are explained by the piezomagnetic effect observed in the eastern part of Izu Peninsula, Central Japan. Most of the data were obtained by repeat surveys. Although these data suffered electric railway noise, significant magnetic changes were detected at points close to earthquake faults. Coseismic changes can be well interpreted by piezomagnetic models in the case of the 1978 Near Izu-Oshima (*M* 7.0) and the 1980 East Off Izu Peninsula (*M* 6.7) earthquakes. A large total intensity change up to 5 nT was observed at a survey point almost above the epicenter of the 1976 Kawazu (*M* 5.4) earthquake. This change is not explained by a single fault model; a 2-segment fault is suggested. Remarkable precursory and coseismic changes in the total force intensity were observed at KWZ station along with the 1978 Higashi-Izu (*M* 4.9) earthquake. KWZ station is located very close to a buried subsidiary fault of the *M* 7.0 Near Izu-Oshima earthquake, which moved aseismically at the time of the *M* 7.0 quake. The precursory magnetic change to the *M* 4.9 quake is ascribed to aseismic faulting of this buried fault, while the coseismic rebound to enlargement of the slipping surface at the time of *M* 4.9 quake. This implies that we observed the formation process of the earthquake nucleation zone via the magnetic field.

Key words *seismomagnetic effect – piezomagnetic effect – Izu Peninsula – magnetic precursor to earthquake – preseismic slip*

1. Introduction

Izu Peninsula is situated in the central part of the Japanese Islands, which is the junction area of the four plates, *i.e.* the Eurasia, the North America (or Okhotsuk), the Pacific and the Philippine Sea plates. Since the Off-Izu-Peninsula earthquake of *M* 6.9 in 1974 which took place at the southern tip of the peninsula, unusually high tectonic activity has been underway there, including several damaging earthquakes, earthquake swarm, anomalous crustal uplift and volcanic eruption on the sea floor.

A similar active period lasted from 1930 to 1934. From February to May in 1930, a remarkable earthquake swarm took place near Ito city in the northeastern part of the peninsula. On November 26, 1930, the North Izu earthquake of *M* 7.3 happened in the north central part of the peninsula, which killed 272 persons. Along the northeastern coastline in Ito city, crustal uplift continued during and after the earthquake swarm, amounting to 35 cm. The seismic activity ceased around 1934. For the past 40 years since then, Izu Peninsula had been tectonically very quiescent.

The activity since 1974 is much more dominant in its intensity and duration than the previous one. The 1930's activity can be regarded

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as an after-effect of the 1923 Great Kanto earthquake of *M* 7.9, which took place adjacent to the Izu Peninsula on its northeastern side. On the other hand, the present activity may be one of the precursory events to the coming «Tokai Earthquake» of *M* 8 or so, which is expected to occur in Suruga Bay, on the western side of the peninsula (*e.g.*, Mogi, 1985).

The tectonic activity in the Izu Peninsula has another nature: this region belongs to the volcanic belt stretching north-south along the Izu-Bonin Arc. During the present activity for decades, two big volcanic eruptions happened in the adjacent area, *i.e.* 1983 Miyakejima (100 km south) and 1986 Izu-Oshima (20 km east) volcano eruptions.

These tectonic events, including the forthcoming Tokai earthquake, should closely interact with the on-going crustal activity in the Izu Peninsula. Observations in the Izu Peninsula provide us with a rare opportunity to prove the usefulness of electromagnetic methods for monitoring the crustal activity as well as to obtain some essential information on its generating mechanisms.

We started our observations of geomagnetic total force intensity in May, 1976 (Sasai and Ishikawa, 1977). Figure 1 shows a location map of observation points. We began continuous measurement of total intensity at station SGH near the center of crustal uplift, while we established 18 repeat survey points. In the southeastern part of the peninsula, disastrous earthquakes happened in succession, *i.e.* Kawazu earthquake of *M* 5.4 in August of 1976, Near Izu-Oshima earthquake of *M* 7.0 in January of 1978 and Higashi-Izu earthquake of *M* 4.9 in November of 1978. Concurrently, crustal uplift continued around the northeastern part of the peninsula at an almost constant speed of 2 cm/yr since 1975. Only 16 h after the Higashi-Izu earthquake, swarm earthquakes started off the northeastern coast near Ito city. The swarm earthquakes have sporadically occurred once or a few times a year since then. In the same swarm area the East Off Izu Peninsula earthquake of *M* 6.7 occurred in June of 1980.

After intermittent swarm earthquakes and continuous crustal uplift for the next 11 years, a large swarm activity including a *M* 5.5 earthquake took place in July of 1989, which was followed by a small-scale sea-floor eruption of Teishi Knoll, a few kilometers away from the shoreline near Ito city, on July 13, 1989. These tectonic events are located in the area of Eastern Izu monogenetic volcanos (Aramaki and Hamuro, 1977): the activity is essentially of volcanic nature.

The results of magnetic observations for the 10-year period from 1980 to 1989 were summarized by Sasai and Ishikawa (1991), with special attention to the preparatory stage of the 1989 eruption of Teishi Knoll. The magnetic changes were considered mainly of thermal origin. On the other hand, the period from 1974 to 1978 can be regarded as that of tectonic earthquakes, which took place in the southeastern part of the peninsula. We have reported so far total intensity changes associated with these earthquakes (Sasai and Ishikawa, 1977, 1978, 1980a,b). However, modeling of coseismic magnetic changes was insufficient and partly erroneous.

Interpretation of coseismic magnetic changes in terms of piezomagnetism was first introduced by Stacey (1964). Modeling of seismomagnetic effects using the elasticity theory of dislocations has achieved by numerical volume integral (Shamsi and Stacey, 1969; Johnston, 1978) and by analytical Green function method (Bonafede and Sabadini, 1980; Sasai, 1980). Both the methods should give the same result except for possible rounding errors. However, a large discrepancy exists between the numerical and analytical results even for a simple 2-dimensional model by Shamsi and Stacey (1969) and Sasai (1980) (*cf.*, Banks *et al.*, 1991; Sasai, 1994a). The cause of the discrepancy turned out to be due to inappropriate treatment of improper integrals in constructing Green functions (Sasai, 1991, 1994b). Sasai (1991) presented the corrected version of previous Green functions for piezomagnetic potential produced by dislocation sources.

The new Green functions were first applied to compute the piezomagnetic field associated with the 1992 Landers, California, earthquake of M_w 7.3, which successfully explained coseismic magnetic changes by a complicated

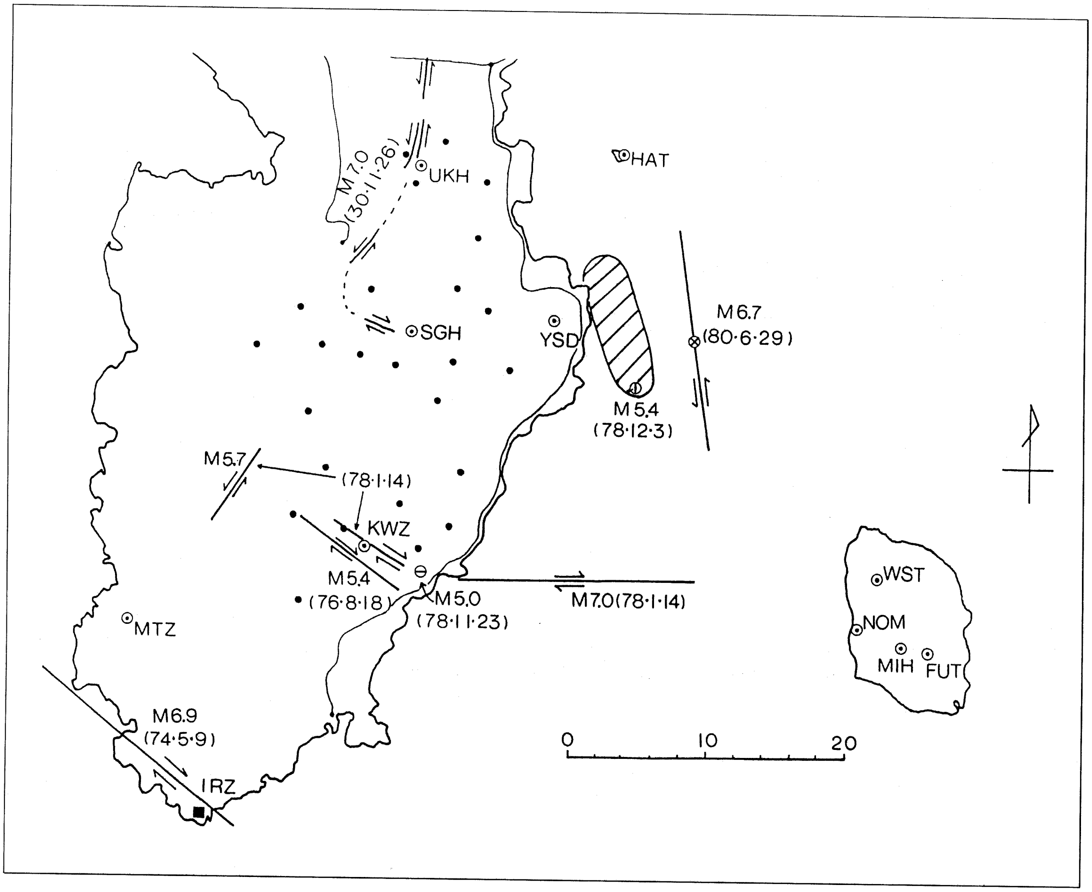


Fig. 1. Map showing the location of earthquake faults in and around Izu Peninsula. The hatched area indicates earthquake swarm which occurred in 1978. Double circles with station codes are continuously recording proton magnetometer stations, while solid circles are repeat survey points. IRZ is the volumetric strainmeter by JMA. Thin lines along the eastern coast and in the northern part are DC electric railways.

fault system with 11 segments (Johnston *et al.*, 1994). Piezomagnetic changes were also calculated for the 1989 seismovolcanic activity in Izu Peninsula, in which an earthquake fault of *M* 5.5 together with an intrusive dyke played the major role (Sasai, 1994b). In this paper we try to model coseismic magnetic changes associated with three damaging earthquakes (*M* 5.4, *M* 7.0 and *M* 6.7) as well as pre- and coseismic changes accompanied by a *M* 4.9 earthquake. All of them were observed in the early stage of our observations (1976-1980).

In particular, the magnetic precursor to the *M* 4.9 quake was one of the most remarkable examples, which we call the Kawazu (KWZ) tectonomagnetic event. We have already attempted to interpret this event (Sasai and Ishikawa, 1980a). However, it was based on the former erroneous Green functions by Sasai (1980). The basic idea on the cause of the precursory magnetic change is the same as before, *i.e.* aseismic slip prior to the *M* 4.9 earthquake. Now we will present a simple and reasonable model of the preseismic fault slip.

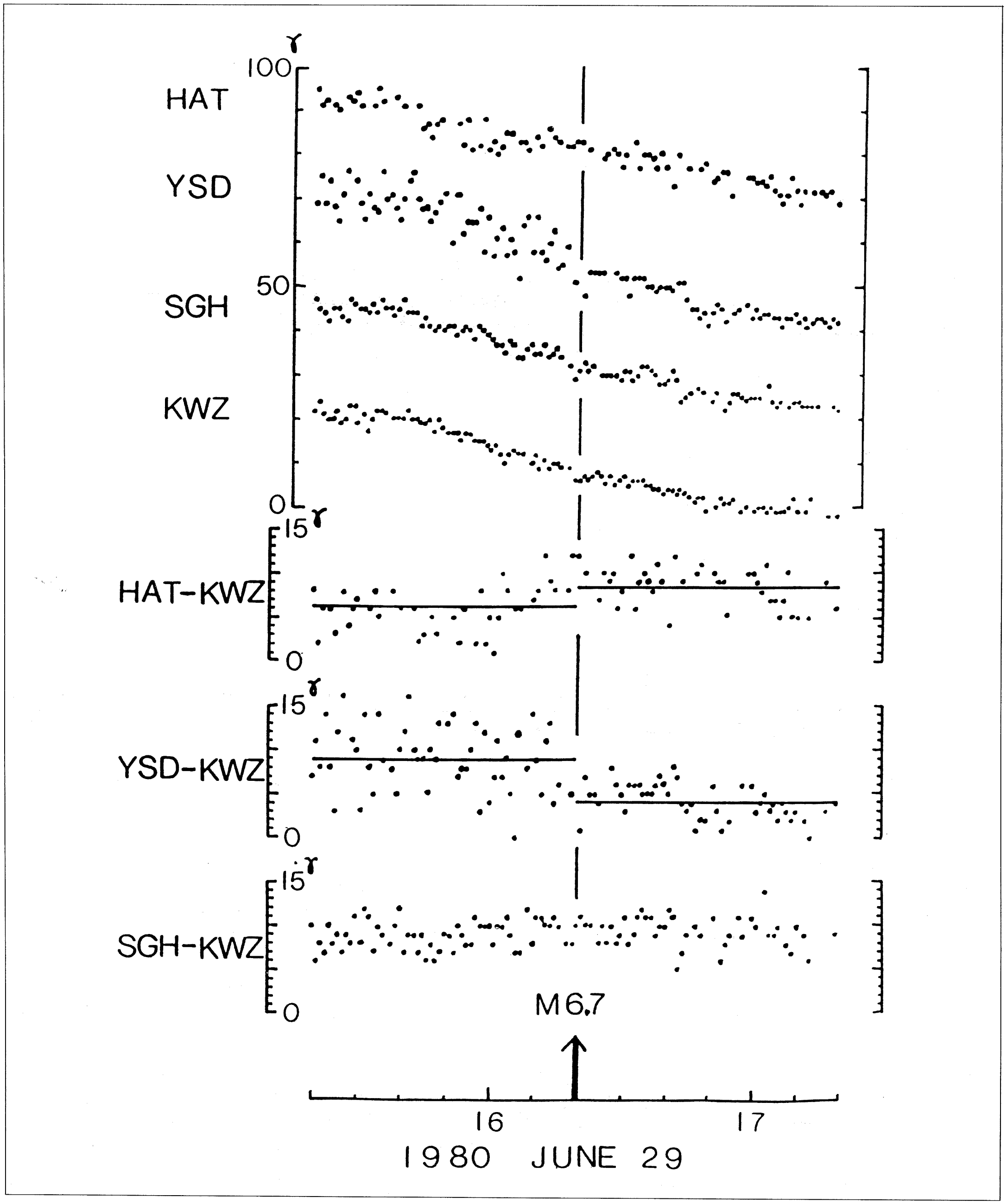


Fig. 2. Plots of total intensity variations at the eastern Izu line of stations. HAT and YSD data are severely contaminated by stray electric current noise. Step-like changes at HAT and YSD relative to KWZ are artificial ones caused by power failure on the electric railway at the time of the M 6.7 earthquake.

2. Observations and quality of data

In 1976, we started our magnetic observations with two proton precession magnetometers, one a continuously recording and the other a portable type (manual operation). As shown in fig. 1, our observation area is surrounded by DC electric railways; most of the repeat survey points suffer serious railway noise. In the early stage of our observations, we made measurements during the night from 23:30 to 04:30 LT when electric trains stopped. This required so much labor that we later introduced automatic recording magnetometers driven by batteries. However, due to a lack of sufficient number of instruments, we were sometimes obliged to make measurement even during the time when the electric trains were in motion. This turned out to have caused serious errors in the repeat survey results.

The errors originated from an unforeseen behavior of DC electric railway noise. Here is a typical example. The East Off Izu Peninsula earthquake of M 6.7 happened on June 29, 1980. At the time of this quake, four proton magnetometers were in operation at SGH, HAT, YSD and KWZ (see fig. 1). Figure 2 shows minute plots of simple differences of total force intensity between each station and the reference point KWZ. KWZ station is far enough from the focal region that it is supposed to be little affected by the earthquake. In spite of scattering due to railway noise, we can clearly see a step-like offset both at YSD and HAT stations. No such variation is seen in the difference SGH-KWZ.

However, these coseismic steps were not the natural ones; they turned out to be apparent changes of artificial origin due to failure of power supply to railways. Figure 3 shows a

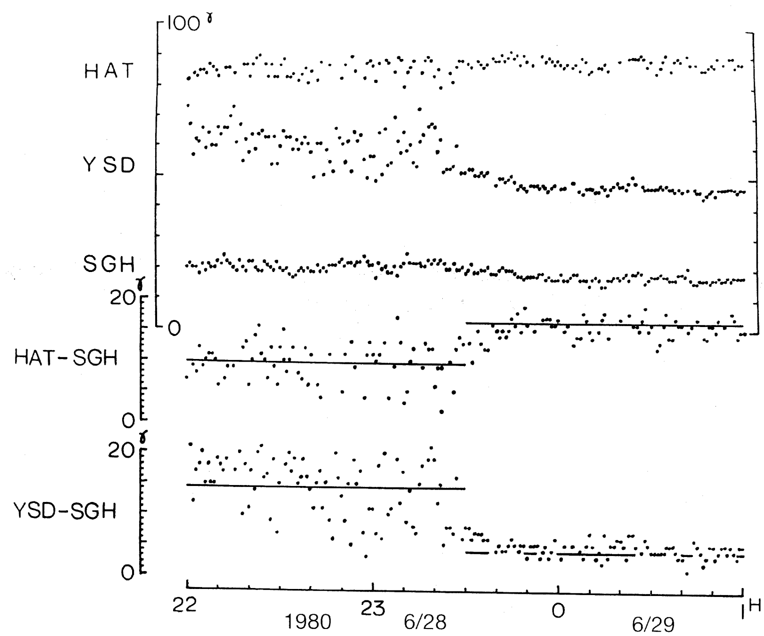


Fig. 3. A demonstration of the direct current bias noise caused by the electric railway which runs very close to HAT and YSD stations. The electric current cut-off to the railway every night produces a step-like recovery to the quiescent state.

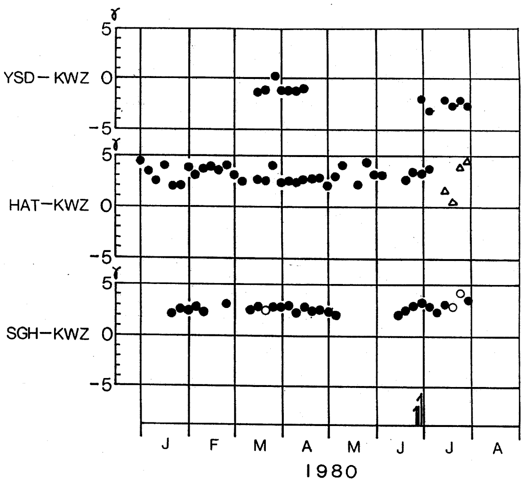


Fig. 4. Total intensity variations before and after the East Off Izu Peninsula earthquake and the accompanied swarm earthquakes (arrows at the bottom) at the eastern Izu line of stations as referred to KWZ. Five-day means of night-time differenced data are plotted. The HAT data scatter sometimes due to artificial disturbances (hollow triangles).

minute plot of total intensity around midnight at HAT and YSD relative to SGH one day before the earthquake occurrence. We can see that quite a similar phenomenon occurs when the trains stop around 23:30 LT; the signs of offset associated with the stoppage of trains are also the same as the «coseismic» changes in fig. 2. Thus DC railway current makes scattering magnetic noise not with zero mean but with some biased offset. As shown in fig. 4, we find no gaps in the 5-day mean plots of simple differences of night-time values (0 h 00 m-4 h 59 m LT) at HAT and YSD.

The northern half of our survey area is surrounded by DC electric railways. Actually, we observed large changes in the total force intensity around the northern area, far from the focal zones at the time of the Near Izu-Oshima earthquake of M 7.0 (Sasai and Ishikawa, 1978) and KWZ tectonomagnetic event (Sasai and Ishikawa, 1980a). We concluded that such magnetic changes in the northern part were not real. The amount of magnetic change during two repeat surveys is estimated as the simple difference between the two data sets (*i.e.*, the average of total intensity values at the survey point relative to the reference station). Large apparent magnetic changes were obtained only for the case when one data set was measured during the night while the other during the time period of trains in operation.

Taking this effect into account, we conducted repeat surveys in a good situation: in both the surveys measurement in the noisy area was made during the night with automatic recording. Figure 5 shows total intensity changes during the period from March to July, 1980 between the East Off Izu Peninsula earthquakes. Estimated magnetic changes are very small. Except for three survey points which suffered artificial disturbances, we find a local

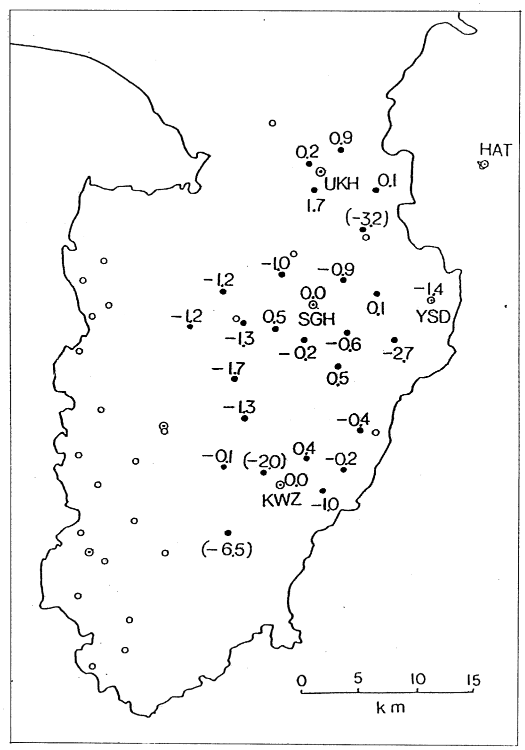


Fig. 5. Changes in the F component relative to KWZ during the period from March to July, 1980. Unit in nT. Values in the parentheses suffered some artificial disturbances.

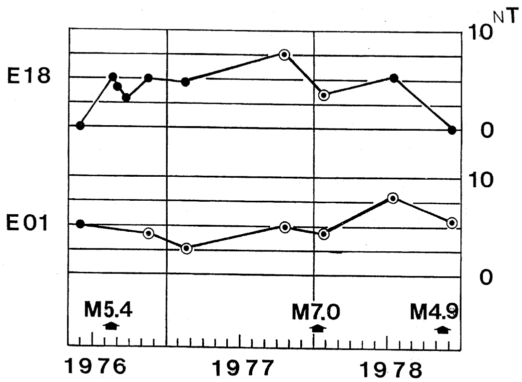


Fig. 6. Changes in the total force intensity at E18 and E01 as detected by repeat surveys. The reference station is KNZ, about 100 km ENE from the survey points. Occurrences of three damaging earthquakes during 1976 to 1978 are shown by arrows at the bottom. Double circles indicate data obtained during the night (0 h 00 m-04 h 59 m LT), while solid circles those observed for at least 30 min or more in the evening.

decrease of 2 nT near the eastern coast and another local decrease of 1 nT in the central part of the peninsula. The latter negative change is probably due to local difference of daily variations. Now we conclude that we can detect a total intensity change of 2 nT by repeat surveys in which DC railway noise and the effect of daily variation are carefully avoided.

From 1976 to 1978, three damaging earthquakes are concentrated near the southern periphery of our survey area. On these days, the serious influence of railway noise had not yet been recognized. Fortunately, however, the railway noise is rather small in the southern part according to the later investigations. In the southern area, the railway runs close to the coastline; the stray electric current is suggested to flow mostly into the sea. We detected significant total intensity changes associated with three consecutive earthquakes (*M* 5.4, *M* 7.0 and *M* 4.9) at two survey points which are located close to the earthquake faults.

Figure 6 shows total intensity changes at the two survey points E18 and E01 for the period from 1976 to 1978. Since the point E18 is not affected by railway noise, we usually make measurements there after sunset. The point E01 slightly suffers the railway noise, and hence we use data during the night. In addition to the two repeat survey points, we started continuous measurement at KWZ station at the end of January, 1978. We will examine if the total intensity changes at these stations close to earthquake faults can be explained by the piezomagnetic effect.

3. Seismomagnetic effects of three earthquakes

In the following, we will compute piezomagnetic changes associated with several earthquake fault models. We employ fault models well-determined by seismological and geodetic data. They are more or less slightly inclined from the vertical; the fault movements include some normal faulting component. However, we have still not completed analytic solutions for piezomagnetic changes of an inclined fault. We regard to these earthquake faults as purely vertical strike-slip ones, and will apply Sasai's (1991) formula. This is because the contribution from normal faulting is negligibly small for a nearly vertical fault (Sasai, 1991).

Secondly, we regard the Earth as a homogeneous and isotropic elastic half-space with a uniformly magnetized top layer. Let us examine the validity of the uniform magnetization assumption. Figure 7 shows a magnetic anomaly map in the area from Eastern Izu Peninsula to Izu-Oshima Island, which gives the residuals of the total force intensity at a height of 2500 feet above sea level from IGRF 1980 (NEDO, 1984). The earthquake faults concerned (*cf.* fig. 1) are distributed around the left-bottom corner of the map, where magnetic anomalies exist but only at most 100 nT. The assumption of uniform magnetization almost holds good.

The intensity of the seismomagnetic effect in a homogeneous earth model is proportional to the product of medium parameters $\beta J_0 \mu$. β is the stress sensitivity, J_0 the magnetization and μ the rigidity. β and μ are the most unknown parameters. Hence we fix the values of

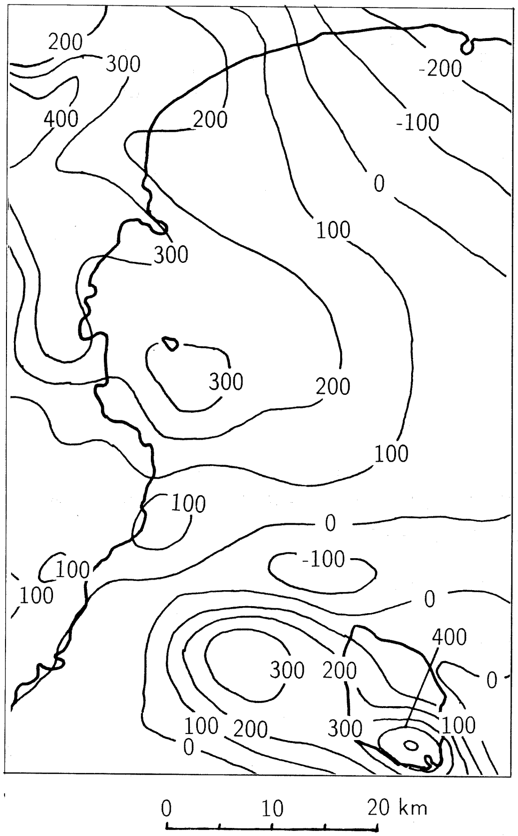


Fig. 7. Magnetic anomaly map in the area from Eastern Izu Peninsula to Izu-Oshima Island. Reproduced from NEDO (1984), which is the residual of the total intensity at a height of 2500 feet above sea level from IGRF 1980. Units in nT.

β and μ as 1.0×10^{-3} MPa^{-1} and 3.5×10^{4} MPa, respectively. The range of J_0 is rather constrained by airborne magnetic data. Adjustment of the computed results with the observations is made by changing the magnetization value J_0 within a range from 1 to 5 A/m.

3.1. *Kawazu earthquake of M 5.4 (August 18, 1976)*

Figure 8 presents the focal region of the Kawazu earthquake of M 5.4, in which the epicenter (by JMA), aftershocks (by ERI) and the trace of the fault model by Abe (1978) are given. The survey point E18 is located very close to the epicenter. As has been shown in fig. 6, we detected an increase in the total force intensity by 5 nT at the point E18 after this earthquake. This is the first example of the seismomagnetic effect observed in Izu Peninsula.

The coseismic piezomagnetic changes are calculated for a fault model by Abe (1978). The computed result is, however, too small compared with the observation, *i.e.* 5 nT (O) *vs.* -0.07 nT (C). The main reasons are that the fault top lies rather deep at a depth of 2.5 km, and that the dislocation is as small as 0.2 m. Since the data were obtained only at E18 which was almost above the epicenter, the observed magnetic change might not be of piezomagnetic origin. However, no local site effects were confirmed, such as due to land slide and/or collapsed houses.

A possibility is that E18 is located near the boundary of a large magnetic mass. Piezomagnetic signals are much enhanced near local magnetic inhomogeneity (Oshiman, 1990). However, such an explanation has a difficulty. At the survey point E18 we observed significant magnetic changes at the time of Near Izu-Oshima earthquake of M 7.0 and Higashi-Izu earthquake of M 4.9 (see fig. 6). Later, these magnetic changes will be well interpreted by fault models in a uniformly magnetized crust. It is a contradiction to introduce magnetic inhomogeneity only for the case of the Kawazu earthquake.

Another possibility is to consider a more complicated fault model. The epicenter of the main shock is located near the center of aftershock distribution; the fault movement was suggested to have propagated bi-laterally toward NW and SE directions (Abe, 1978). If the two fault segments made some bent angle around the focus, strong magnetic lines of force should leak out from the junction. According to Johnston *et al.* (1994), large positive and negative changes are concentrated at connecting edges of fault segments in their piezomagnetic model for the 1992 Landers earthquake of M_w 7.3.

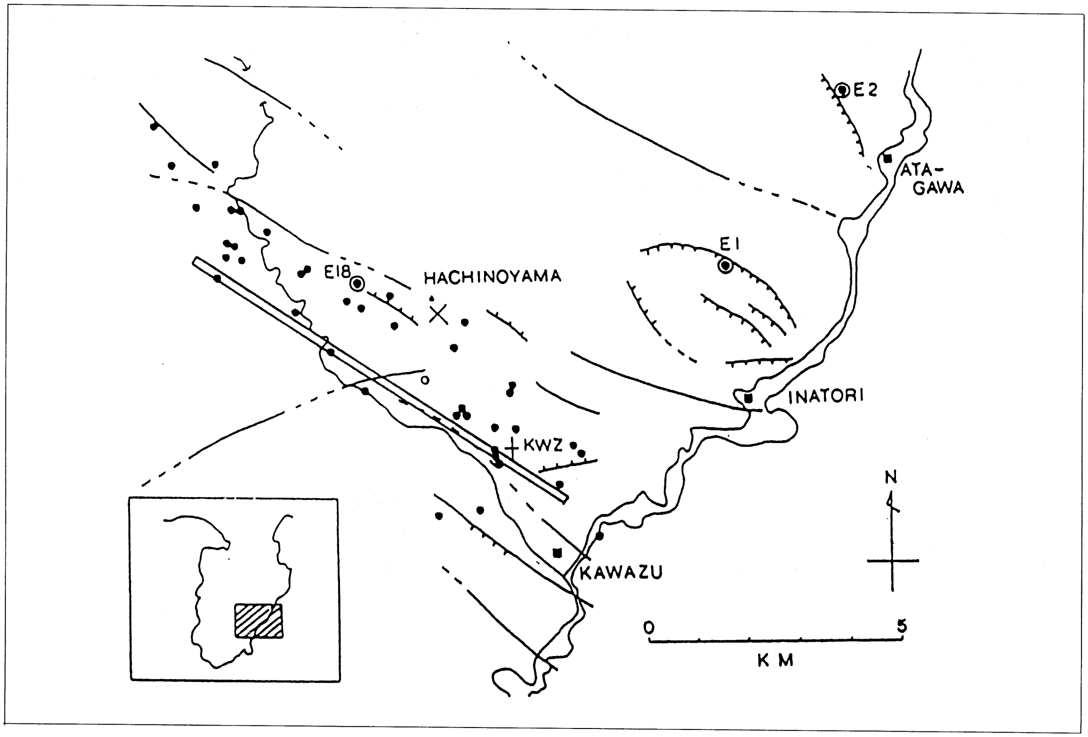


Fig. 8. Map showing the epicentral area of the Kawazu earthquake of *M* 5.4. Epicenters of the main shock (the St. Andrew's cross) and aftershocks (solid circles) are shown. A hollow belt indicates the surface trace of the top of the fault model by Abe (1978). Thick lines are active faults.

Abe's (1978) model successfully explained the overall features of seismic as well as leveling data. Recent analyses of strong motion seismograms provide us with more detailed information on fault segments even for earthquakes of magnitude 5 or so (*e.g.*, Takeo, 1992). However, no sufficient seismic and geodetic data were available at that time for the purpose. We abandoned the search for seismomagnetic models with too much ambiguity only to explain the survey result at E18.

3.2. *Near Izu-Oshima earthquake of M 7.0 (January 14, 1978)*

Repeat magnetic surveys were conducted in October 1977 and January 1978. We detected total intensity changes by −4.3 nT at E18 and by −0.6 nT at E01 (see fig. 6). We will examine if these magnetic changes can be explained by coseismic piezomagnetic field. The fault movements of this earthquake were investigated in detail by Shimazaki and Somerville (1979).

The earthquake fault consists of two separate segments: *i.e.*, the main fault which runs E-W below the sea between Izu-Oshima Island and Izu Peninsula, and the subsidiary fault which runs WNW-ESE on land in Izu Peninsula. On the day after the *M* 7.0 quake, the largest aftershock of *M* 5.7 occurred about 10 km northwest from the subsidiary fault. This aftershock can be regarded as an induced one by the main-subsidiary faults system. It took place far from the survey area and rather deep (5-10 km); we can ignore its effect on the survey points E18 and E01.

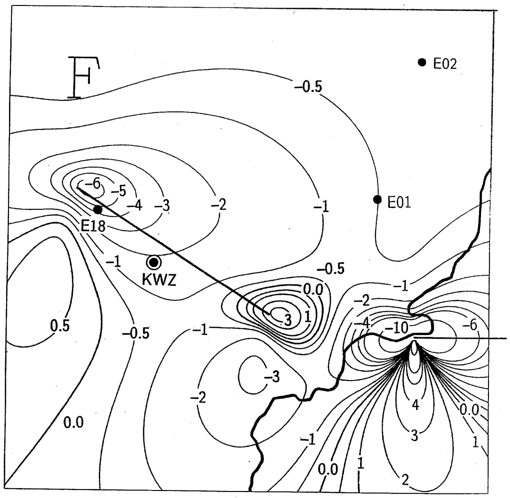


Fig. 9. The computed total intensity change for the fault model of the Near Izu-Oshima earthquake of *M* 7.0. Units in nT. The thick line is a part of the coastline of Izu Peninsula.

Figure 9 shows contours of computed total intensity change based on the model parameters in table I. We assumed the medium parameters as $\beta = 1.0\times10^{-3}$ MPa^{-1}, $J_0 = 1.5$ A/m, $\mu = 3.5\times10^4$ MPa. This model well explains the observations: -4.3 nT (observed) *vs.* -4.5 nT (computed) at E18, and -0.6 nT (O) *vs.* -0.5 nT (C) at E01.

Since January 1978 after the *M* 7.0 earthquake, we have undertaken continuous observation of total force intensity at KWZ station, which is situated around the center of aftershock distribution. We observed remarkable precursory and coseismic changes associated with the Higashi-Izu earthquake of *M* 4.9 on November 23, 1978. We will investigate this tectonomagnetic event in section 4.

3.3. *East Off Izu Peninsula earthquake of M 6.7 (June 29, 1980)*

As has been described in section 2, we could not identify the true coseismic steps in the raw magnetic data associated with this earthquake because of electric railway noise. On the other hand, the night-time averages of differenced data show a decrease by 1 nT or so (fig. 4). Well-conditioned repeat surveys also detected a decrease of up to -2 nT around the east coast closest to the earthquake source region (fig. 5).

Sasai and Ishikawa (1980b) computed coseismic piezomagnetic changes due to a fault model of this earthquake. The calculation was based on an incorrect solution, and we will revise it here. Table II gives fault model parameters. This model is consistent with Takeo's (1988) rupture process model. Figure 10 depicts contours of computed coseismic magnetic changes. We adopt here the medium parameters of $\beta = 1.0\times10^{-3}$ MPa^{-1}, $J_0 = 1.0$ A/m and $\mu = 3.5\times10^4$ MPa. Since the magnetization may vary from 1 to 5 A/m in this volcanic area, we can easily estimate the computed magnetic changes by multiplying the factor. For $J_0 = 2$ or 3 A/m, we can expect a decrease in the total intensity by 1 nT or so around YSD station, which is almost consistent with the observations.

Table I. Model parameters for Near Izu-Oshima earthquake fault.

	Main fault	Subsidiary fault
Fault orientation	N90°E	N58°W
Fault length	17.0 km	6.0 km
Fault width	10.0 km	6.5 km
Depth of burial	0.0 km	0.5 km
Dislocation	−1.83 m (right lateral)	−1.20 m (right lateral)

Table II. Model parameters for East Off Izu Peninsula earthquake fault.

Fault orientation	N7°W
Fault length	16.0 km
Fault width	7.0 km
Depth of burial	0.1 km
Dislocation	1.5 m (left lateral)

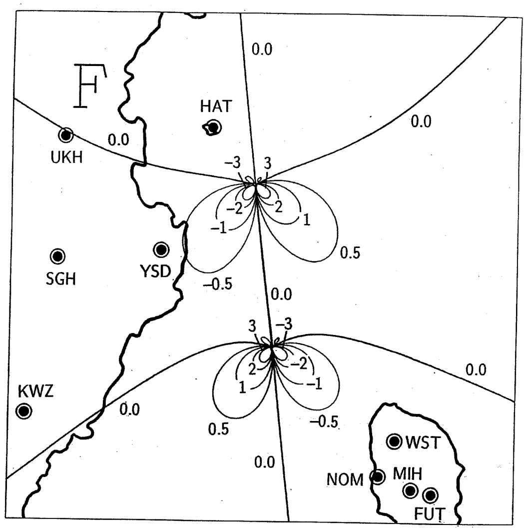


Fig. 10. The computed seismomagnetic effect (total force intensity) associated with the East Off Izu Peninsula earthquake of M 6.7. Units in nT.

It should be mentioned that in the northern half of our observation area, especially near the coastline, the detection capability of tectonomagnetic signals is low; we require more advanced treatment of data, for example Wiener filter method by Davis *et al.* (1981).

4. Kawazu tectonomagnetic event

Figure 11 shows changes in the total force intensity at SGH and KWZ stations for the period from January 1978 to March 1979. The reference station KNZ is located about 100 km east of KWZ. They are plots of 5-day means of night-time differenced data. At KWZ station the total force began to decrease since the beginning of September, reached −7 nT, and jumped coseismically by 5 nT at the time of Higashi-Izu earthquake of M 4.9 on November 23. The Higashi-Izu earthquake itself is regarded as one of the large aftershocks of the M 7.0 earthquake. The immediate aftershocks of the M 4.9 quake are distributed around the subsidiary fault area in fig. 9; hence the subsidiary fault was suggested to have moved again.

The subsidiary fault showed unusual behavior during the Near Izu-Oshima earthquake (Shimazaki and Somerville, 1979). Along the surface trace of this buried fault, land slides took place here and there, which caused the major damage of the M 7.0 earthquake. However, no strong seismic waves were generated from this fault segment, which should have been recorded by a few strong motion seismographs suitably distributed in the peninsula (Shimazaki and Somerville, 1979). Aftershocks

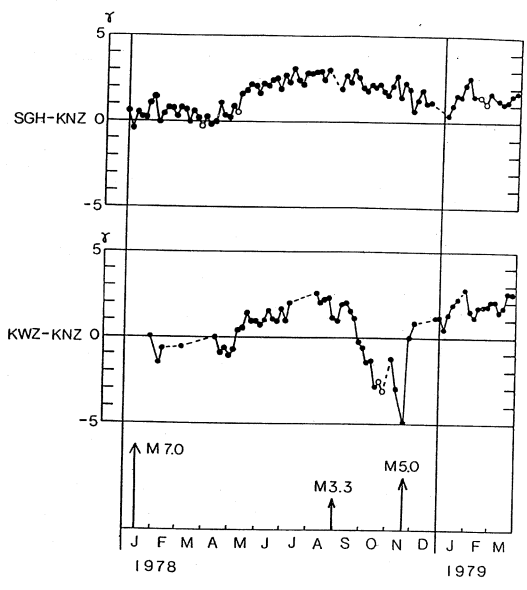


Fig. 11. Changes in the total force intensity at SGH and KWZ relative to KNZ, during the period from January 1978 to March 1979. Five-day means of night-time differenced data are plotted. Arrows indicate the occurrences of major earthquakes along the subsidiary fault.

with small magnitudes made a zonal distribution in WNW-ESE direction, but had no clear linear alignment as the ordinary aftershock patterns; these aftershocks were regarded as an induced seismicity. On the other hand, geodetic data (leveling and triangulation) indicated large ground deformation, which was well approximated by a single fault model. In other words, the subsidiary fault was suggested to have moved aseismically (Sacks *et al.*, 1980; Shimazaki and Somerville, 1979).

Sasai and Ishikawa (1980a) presumed that the buried subsidiary fault might have moved aseismically again before the Higashi-Izu earthquake of M 4.9. We re-examine this idea on the basis of a corrected version of seismomagnetic models (Sasai, 1991). Let us reproduce the coseismic magnetic change of the M 7.0 quake, but only the contribution from the subsidiary fault (fig. 12). We find that the pattern of magnetic changes almost explains the observed feature after the M 4.9 quake: at KWZ station a small magnetic change remained owing to the coseismic recovery, while at E18 there was a decrease in the total intensity up to several nT. The aftershock distribution strongly supports that the entire portion of the buried subsidiary fault slipped at the time of the M 4.9 earthquake. Therefore we can explain the permanent magnetic changes due to the M 4.9 quake by slightly modifying the model in fig. 12.

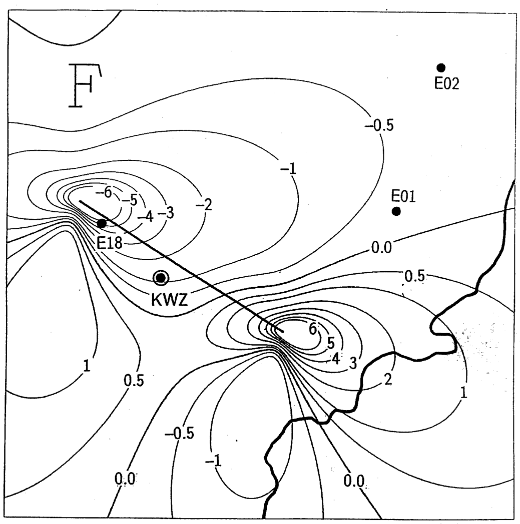


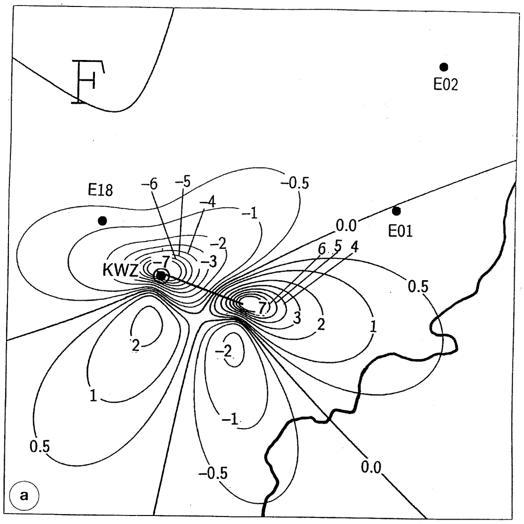
Fig. 12. The computed seismomagnetic change in the total force intensity due to the subsidiary fault. Units in nT.

The problem is how to interpret the pre- and coseismic changes. In the previous model, we assumed that the whole fault surface moved aseismically. This was because the old formula gave large negative changes in the total intensity above the entire fault trace. Then the coseismic rebound in the total intensity at KWZ station was interpreted as due to an additional fault accompanied by the M 4.9 quake, the northwestern end of which reached close to KWZ station. The previous model was essentially a two-fault model.

According to fig. 12, however, we can hardly expect large negative changes in the precursory stage if the entire fault was moving. We notice a strong negative area around the northwestern end of the fault. We can naturally presume: in the precursory period, the southeastern portion of the buried fault around KWZ station slipped aseismically, and then, at the time of the M 4.9 earthquake, the seismic break-down started from the SE end, which extended northwestward across the barrier near KWZ station. This is a single-fault model in which the sliding portion of a fault enlarged aseismically and/or seismically.

Figure 13a shows the pattern of total intensity changes just prior to the M 4.9 earthquake produced by aseismic slip of a buried fault. Only the central one third portion of the fault is assumed to have slipped slowly. KWZ station is included in the area of negative changes near the NW end of the stably-sliding portion. Figure 13b shows the contours of total intensity changes associated with the seismic slip of the entire buried fault. KWZ station belongs to the area of null magnetic change around the center of the fault. This is the mechanism of the coseismic recovery of the magnetic field.

It should be noted that the position of the model fault is different from the Shimazaki and Somerville model. The model fault passes the epicenter of the M 4.9 Higashi-Izu earthquake, stretching northwestward parallel to the



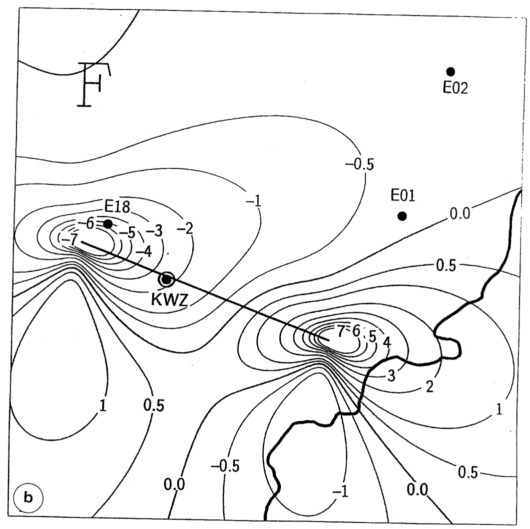


Fig. 13a,b. a) The computed piezomagnetic field change in the total force intensity just prior to the *M* 4.9 earthquake produced by aseismic faulting of a portion of a buried fault. Units in nT. b) The computed total intensity change associated with the seismic/aseismic faulting of a buried fault at the time of the *M* 4.9 earthquake. Units in nT.

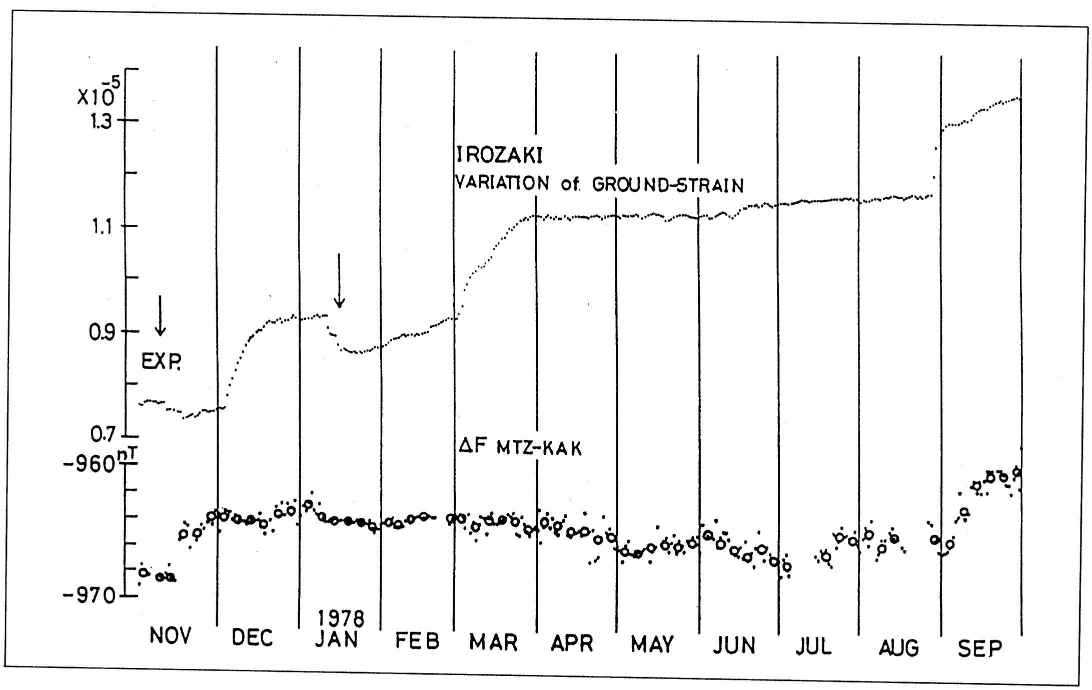


Fig. 14. The daily mean variations of ground volumetric strain at Irozaki (IRZ) and the total force intensity at Matsuzaki (MTZ; see fig. 1) (after Ohchi *et al.*, 1979). The arrow indicates the occurrence of the Near Izu-Oshima earthquake of *M* 7.0. Hollow circles in the total intensity curves are 5-day means.

trend of the immediate aftershock distribution. The fault length and width are the same, but the depth of burial is as shallow as 0.3 km. Dislocation along the fault is $-1.2\ \mu$ (right-lateral). Because of scanty data, our model has a large ambiguity.

Finally, we will introduce another interesting example of tectonomagnetic signals observed by JMA. Figure 14 reproduces the daily mean variation of volumetric strain at Irozaki (IRZ) and the total intensity change at Matsuzaki (MTZ) (Ohchi *et al.*, 1979). Although IRZ and MTZ are 16 km apart (see fig. 1), we recognize some close correlations between the two different kinds of data: *i.e.*, the November-December change before the *M* 7.0 earthquake and the August-September change prior to the KWZ tectonomagnetic event. Both the strain and magnetic changes in November and December can be regarded as precursors to the Near Izu-Oshima earthquake of *M* 7.0.

The August-September change is also noticeable. It should be emphasized that this anomalous change took place along with the beginning of the KWZ tectonomagnetic event. Sasai and Ishikawa (1980a) argued that this strain-magnetic change might be indicative of an abrupt stress increase in the southern part of Izu Peninsula. Such stress may have caused the aseismic slip of the buried fault, which resulted in the KWZ tectonomagnetic event. As for MTZ, however, it is still not clear what mechanism can produce such tectonomagnetic signals. A possibility is that the MTZ station is located near the boundary of local magnetic inhomogeneity to undergo some enhancement effect (Oshiman, 1990).

5. Conclusions

We have attempted to explain total intensity changes associated with earthquakes, which were observed in the eastern part of Izu Peninsula. Most data were obtained by means of repeat surveys, whose quality is not good enough. We can interpret these seismomagnetic effects almost consistently in terms of piezomagnetism due to stresses by faulting. For the medium parameter in piezomagnetic modeling, the value of $\beta J_0 \mu = 5.25$ A/m is appropriate in the southeastern part of Izu Peninsula. For traditional values of $\beta = 1.0 \times 10^{-3}$ MPa^{-1} and $\mu = 3.5 \times 10^4$ MPa, the average magnetization J_0 becomes 1.5 A/m. However, analysis of airborn magnetic data determines a strong average magnetization of 4.1-5.5 A/m (Nakatsuka, 1995). This suggests that the rigidity μ should be much less because we dealt with very shallow earthquakes.

Coseismic magnetic changes can be well explained by the piezomagnetic effect for the 1978 Near Izu-Oshima (*M* 7.0) and the East Off Izu Peninsula (*M* 6.7) earthquakes. The seismomagnetic change detected almost above the epicenter of the 1976 Kawazu (*M* 5.4) earthquake cannot be explained by a single-segment fault: a two-segment fault with different orientations is surmised. Magnetic observations at the very near field may contribute to the search for more realistic model of earthquakes.

Tectonomagnetic events observed at MTZ and KWZ in 1977 and 1978 are the only two examples of significant magnetic precursors to earthquakes observed so far in Izu Peninsula. We introduced a mechanical model of aseismic faulting to interpret the KWZ tectonomagnetic event. Recent progress in the study of the earthquake generating process presents an important concept: prior to an earthquake, the so-called earthquake nucleation zone is inevitably formed, where local aseismic slip develops to unstable rupture propagation (Ohnaka, 1992). Our interpretation of the KWZ event implies that we happened to observe the formation process of the earthquake nucleation zone via the magnetic field. For earthquake prediction in general, we will have to make many efforts to improve the detection capability of tectonomagnetic signals, such as bore-hole magnetometers at depth near active faults (Sasai, 1994c).

In Izu Peninsula the seismomagnetic effect is observable mostly near the earthquake faults, which is now rather common in other tectonically active regions (*e.g.*, Johnston, 1989). An exception is the MTZ tectonomagnetic event, whose mechanism has not yet been clarified. Some examples of seismomagnetic signals were reported in Uzbekistan, which are sensitive to distant earthquakes (Shapiro *et al.*, 1994). They suggested some telluric current origins. However, the quick response to strain change in the MTZ tectonomagnetic event seems favorable to the piezomagnetic effect. In any case, an effort should be made to look for such points as sensitive to regional stress changes.

We discarded the electrokinetic-magnetic effect as a possible source for the KWZ tectonomagnetic event (Mizutani and Ishido, 1976; Fitterman, 1979) because no remarkable variation followed the coseismic jump in the total intensity. Such an abrupt stoppage is unlikely to occur in the ground water flow. But we cannot exclude this effect, especially in the explanation of (at least, a portion of) precursory magnetic changes. Combined electric and magnetic measurements should be emphasized.

On the basis of experiences in 1970's described in this paper, we have developed an EM observation system in Izu Peninsula, including an array network of more than 20 proton magnetometers, continuous SP and resistivity measurements and so on. Recent development should be referred to elsewhere (*e.g.*, Sasai and Ishikawa, 1991; Oshiman *et al.*, 1991; Oshiman *et al.*, 1997).

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