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Crustal Movements Related to the Earthquake on March 18, 1987 in Hyuganada

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Abstract

Crustal deformations associated with the earthquake of magnitude 6.6 on March 18, 1987, in Hyuganada east of Kyushu in Japan are investigated. Of nine extensometers at three observatories around Hyuganada, only one extensometer at Miyazaki, where the epicentral distance is 62 km, recorded an irregular strain change just before the earthquake hidden in the data behind the disturbance due to rainfall. Co-seismic strain steps observed are compared with calculated strains by a dislocation theory. Observed strain steps in five components at two stations agree well with theoretical ones. Post-seismic aftereffects were observed at all observatories. They cannot be attributed to the source property, but probably due to the viscoelasticity around the observatories, as well as to more local or instrumental effects.

1. Introduction

The sea of Hyuganada, east of Kyushu, adjoins the Nankai trough to the east and the northward extension of the Ryukyu trough to the south, and a part of the seismically active zone along the island arc of Japan. In this region, 4 earthquakes whose magnitude were greater than 7 have occurred in recent 30 years.1),2) Earthquakes of this region are of interest for their frequent occurrence, and recently their mechanisms have been investigated with focus on the relation to the subduction of the Philippine Sea plate.3)-6) The focal mechanisms of the major earthquakes of this region have been characterized by a low-angled thrust faulting type. The investigators have further explained the mechanism as being a result of elastic rebound of the continental block.

For the purpose of researching the possibility of predicting major earthquakes in this region, the Miyazaki Crustal Movement Observatory commenced observations in 1976 at the west margin of Hyuganada.7)-9) The observation network of crustal activities in and around this region was started in 1985 and finished in April, 1987. There are 7 observatories in this network, 6 in Kyushu and 1 in Shikoku, northward of Hyuganada, and the observations of crustal movements and earthquakes are carried out at each observatory.10),11) The distances between observatories of this network range from 50 km to 140 km. All observation data collected at these observatories are transmitted by wired telemeter system to the Miyazaki observatory. This network detects the change of strain fields around the focal region of the earthquakes in Hyuganada in real time.

It is thought that one of the most efficient ways to predict the occurrence of an earthquake is to detect its precursory strain changes, if any. Therefore a continuous monitoring of strain fields is very important, but precursory strain changes are probably so small that they might be hidden under noises from both known and unknown sources. As to the strain data observed at the Miyazaki observatory we investigated the influence of rainfall which is the most remarkable noise on the strain data.[12] In a short time range in which only a series of continuous rainy days is included, the deviating strain changes due to rainfall at the Miyazaki observatory can be simulated precisely from the data of water discharge in the observation vault. Concerning precursors of the earthquake occurrence in relation to rainfall, it has been reported by Yamauchi et al. that the response to rainfall in the extensometric records changes their mode temporarily at the Mikawa observatory.[13] More general relations between the effects of rainfalls on strain changes and earthquake occurences at the Yamazaki fault were reported by Oike et al..[14]

The spatial distribution of strains observed in the network may be used to construct or verify a fault model of earthquakes occuring mainly in the Hyuganada or to find out other strain patterns. The strain fields on the surface of a semi-infinite elastic or viscoelastic medium due to a fault of various types within the medium have been derived in analytical expressions,[15]-[17] which can be used to compare with and interpret observed strain.

In this paper, the strain changes associated with the earthquake of magnitude 6.6 occurring on March 18, 1987, at the center of Hyuganada[18] are analyzed into three categories of pre-seismic, co-seismic and post-seismic changes. This earthquake is the first and most major one that had occurred in the sensitive region of this network since the network started its operation.[19] The hypocenter and origin time of this earthquake are given as 31 58.2(±0.7)'N, 132 03.8(±1.0)'E, 48(±4) km in depth and 12h36m29s JST, respectively, by the JMA.[20] The data on the pre-seismic strain changes, earth tides and effects of rainfall were removed from the original data and the existence of precursory strain change was examined. Observed co-seismic strain steps were compared with theoretically expected values based on the dislocation theory. We also estimated the time constants and duration times of post-seismic aftereffects and discussed viscosity in relation to them.

2. Observed data

When this earthquake occurred, in March 1987, extensometers were in operation at three crustal movement observatories in the observation network, Miyazaki and Makimine in Kyushu and Sukumo in Shikoku. In each observatory three extensometers have been installed, each of which are set in three different directions. The data observed by the nine extensometers at these three observatories were used in the analyses of this paper. The positions of these observatories and the epicenter of the earthquake are shown in **Fig. 1** with insertions of the layouts of the observation vaults of each observatory. Epicentral distances from each station were 62 km from Miyazaki, 92 km from Makimine and 130 km from Sukumo. All extensometers are the super-invar bar type and their sensors are differential transducers in all components. At the Miyazaki and Makimine observatories, the super-invar bars are suspended by wire and supported by a roller

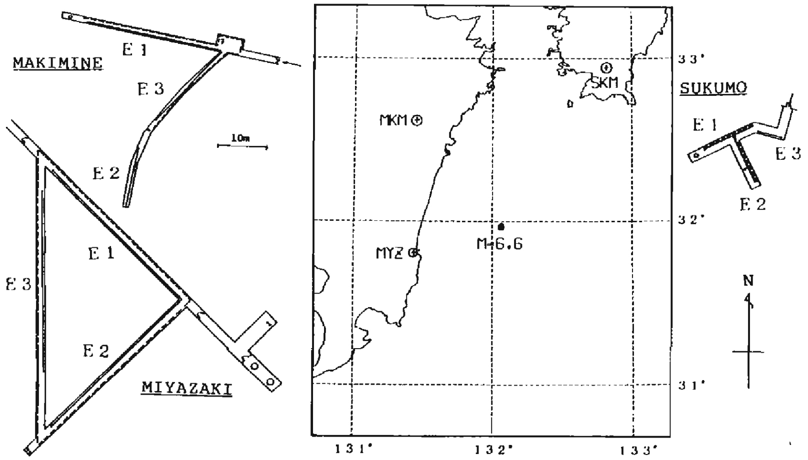


Fig. 1. Locations of the observatories and epicenter of the earthquake on March 18, 1987 in Hyuganada. Insertions are layouts of the observation vaults of each observatory.

at the mid point of each suspending wire. At the Sukumo observatory, only wire suspension is adopted. The ground-strain data of the nine extensometers from seven days before to three days after the earthquake are shown in **Fig. 2.** Notations of each component should be referred to in **Fig. 1.** The lack of records on March 13 is due to the failure of the data acquisition system at the Miyazaki observatory where all data from the network were recorded. The graphs were plotted using hourly data. The rapid changes on March 13 at Miyazaki, March 14 at Makimine and Sukumo, and March 17 at Miyazaki are due to rainfall.

The E-1 component of the Makimine observatory went out of the scale toward extension at the time of the earthquake. Other components at Makimine also recorded larger strain steps than those expected from the magnitude of the earthquake and their epicentral distances. Accordingly, the amounts of the strain steps on E-2 and E-3 components are plotted arbitrarily in **Fig. 2.**

The Sukumo observatory commenced operations in April, 1986 and the data telemetering to the Miyazaki observatory started in June, 1986. Therefore, the initial drifts occurring after the installation of instruments may have not completely ceased. In addition, the seasonal variation in strain changes had not yet been determined. Therefore, the sensitivity of the instruments at the Sukumo observatory were kept lower than that of the others.

It seems that there exists no irregular strain change that exceeds the amplitude of earth tides just before the occurrence of the earthquake on the records of the Makimine and Sukumo observatory in **Fig. 2.** To make matters difficult, strain changes due to rainfall disturb each record of the Miyazaki observatory from 20-30 hours before the occurrence of the earthquake. Accordingly, some parts of the strain owing

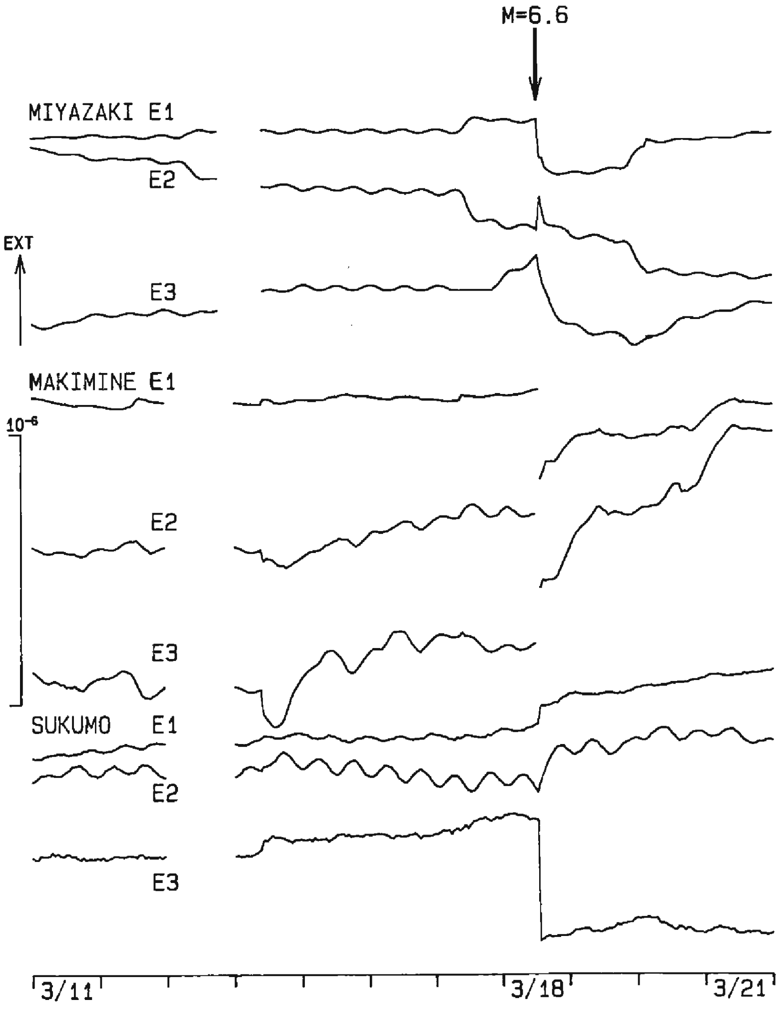


Fig. 2. Variations of ground-strains observed at the Miyazaki, Makimine and Sukumo observatory before and after the earthquake on March 18, 1987, indicated by arrow. Notations are the same as in **Fig. 1.**

to known sources had to be removed in order to detect the small strains related to the earthquake.

3. Removal of earth tides and pre-seismic strain states

The earth tides on each record were analysed by the least squares method on an assumption of 13 tidal constituents. The data used in the calculations are from January

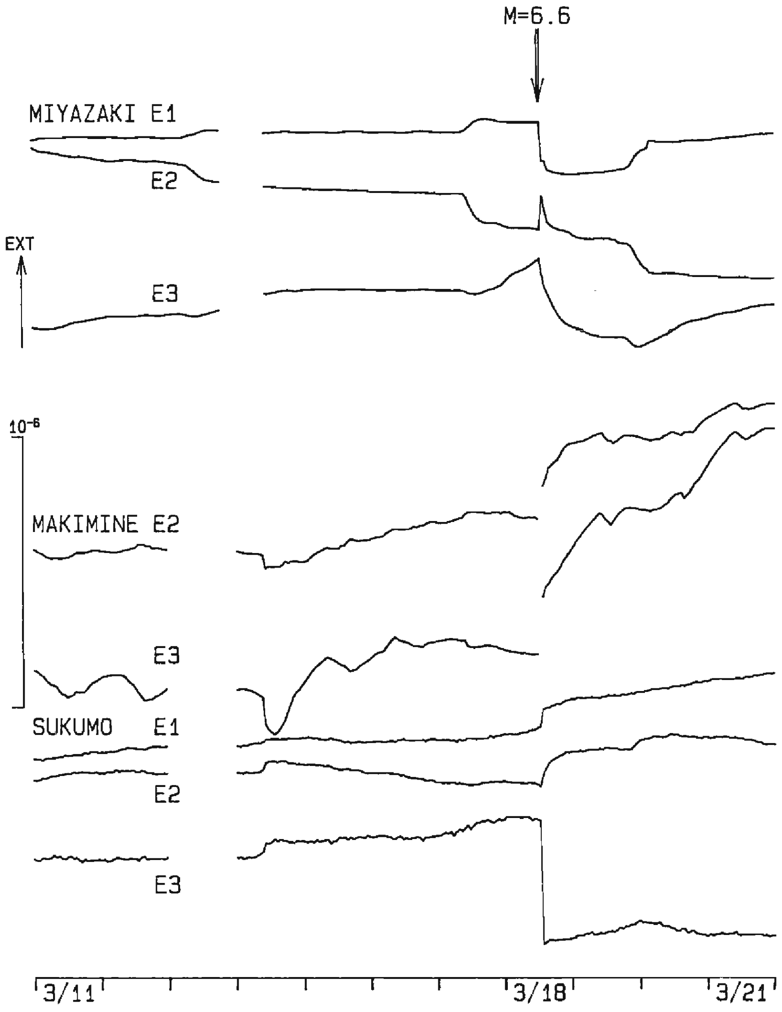


Fig. 3. Variations of ground-strains after removal of earth tides. The period and components correspond to **Fig. 2.**

to April 1987. The disturbed parts of the data due to rainfall or temperature changes were not used in the calculations. The strain changes that remain after subtracting the earth tides from observed data are plotted in **Fig. 3.** The data of the Sukumo observatory are clearly free from earth tides, but it is likely that periodic strain variations yet remain in those from the Makimine observatory. At Makimine, disturbances in the strain data increase in winter probably due to the temperature disturbances by the air flowing into the old adit where the observation vault is partitioned off.[8] Therefore, the

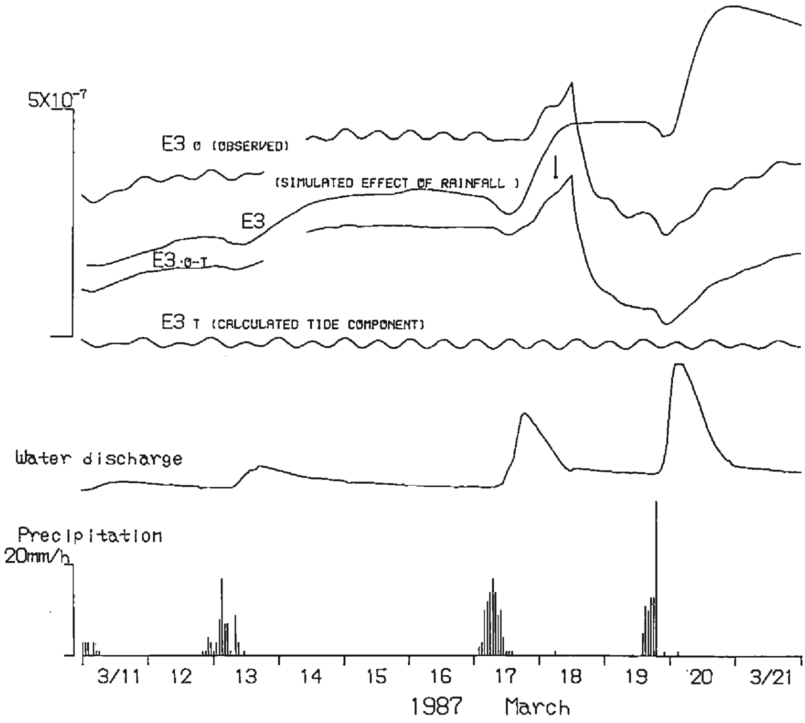


Fig. 4. Observed E-3 strain, its tidal component, residual corrected for the tides and simulated result by water discharge in the observation vault, the water discharge and precipitation at the Miyazaki observatory.

data in this season at the Makimine observatory might be difficult to be fully corrected by least squares fitting. In **Fig. 3,** any co-temporal, abnormal strain-changes which might have been hidden behind earth tides could not be found at Makimine and at Sukumo before the occurrence of the earthquake.

In **Fig. 3,** tidal fluctuations may still be slightly seen on the plotted curves of the Miyazaki observatory at the parts where the data are affected by rainfall on March 17. This suggests that rainfall affects not only the magnitudes of ground-strain directly, but also the amplitudes of earth tides. For complete removal of the earth tides from observed data of this period, coefficients for subtracting tidal constituents must be magnified by 1. 2-2. 5 times of the calculated results by the method of least squares. In **Figs. 3** and **4,** calculated tidal components with no magnification are subtracted from the observed data, but on the data used in latter discussions about post-seismic strain changes, subtracted terms are properly magnified so that the tidal residuals are diminished as much as possible.

At the Miyazaki observatory, the ground-strain changes nearly linearly from mid autumn to early spring when it rarely rains. And in the rest of the year, the ground deforms in the opposite direction to the linear change mentioned above at every rainfall when its amount exceeds some critical value, and thereafter the strains recover gradually.[8] The occurrence of the earthquake just coincided with the transit time from the period of the former linear change to the latter one of irregular changes due to rainfall. Therefore, it is necessary to take precipitation data into account to interpret strain changes during this season.

The precipitation and water discharge into the observation vault at the Miyazaki observatory are shown at the bottom of the **Fig. 4.** The strain changes of this observatory associated with rainfall are closely related to the water discharge volume in the vault rather than to the precipitation itself. The disturbances in the strain change due to rainfall are simulated from the data of water discharge in the vault by a formula with running exponential weighted summation as follows[12]

$$D(t)=K\sum_{i=1}^{n} d(t-i)\exp(-k(t-i))$$

$d(t)$; water discharge
$D(t)$; strain change
K, k ; constant

The simulation formula has a time constant term for the E-1 and E-2 components but has two terms which contain different time constants as

$$D(t)=K_1\sum_{i=1}^{n} d(t-i)\exp(-k_1(t-i))+K_2\sum_{i=1}^{n} d(t-i)\exp(-k_2(t-i))$$

for the E-3 component. The difference between the two types of formulas corresponds to the different modes of strain changes during and after rainfall. In the E-1 and E-2 components the strain shifts monotonously but in the E-3 component, the ground contracts slightly at first, and thereafter extends as the amount of water discharge increases.

The strain changes due to the rainfall on March 17 are typical for the E-1 and E-2 components, but for the E-3 component, the extension may not have ceased until the occurrence of the earthquake. A simulation curve for the E-3 component from the water discharge data is plotted in **Fig. 4.** Two of the curves in this figure, "O-T" and "SIMULATED EFFECT OF RAINFALL", have similar tendencies on the left side of the arrow except that the tidal component remains slightly on the "O-T" curve. However, on the right side of the arrow, the observed curve continues to extend while the simulated curve ceases. The same relation between observed and simulated curves are recognizable for the rainfall on March 19-20. But for the 20th, rate of increase of the observed strain diminishes at the time when the simulation curve begins to contract, which is clearly different from that of March 17. Moreover, the increment of water discharge on the 20th is larger than that on the 17th, while the increasing rate of strain is vice versa. Therefore, there remains a possibility that this extension just before the occurrence of the earthquake is a phenomenon related to the occurrence of this earthquake.

One problem is that if this extension reflects the change of strain fields generated at its source region just before the occurrence of the earthquake, similar phenomena should also have been detected in other records of extensometers or at other observatories. Yamauchi et al. reported that they could verify the existence of an abnormal response to rainfall before many earthquake occurrences at the Mikawa observatory.[13] But we have investigated only one event in relation to precipitation. Around Hyuganada, precipitation is large compared with that in most other regions of Japan. On the other hand, epicentral distances from earthquakes in the Hyuganada region to the stations in our network are so large that this kind of research must be carried out only on major or, in other words, fewer earthquakes. At the Miyazaki observatory, no other case has yet been found associated with previous earthquakes.[2),19]

4. Co-seismic strain step

Co-seismic strain steps appeared at all observatories. The data acquired on magnetic media from this telemeter system were mean values of every 5 minutes at that time, so exact strain changes at the instant of the earthquake were not recorded and the strain steps discussed here were deduced from these 5 minute means. At the Miyazaki observatory, strain steps were a contraction of 1.60×10^{-7} in the E-1 component, an extension of 1.77×10^{-7} in the E-2 and a contraction of 0.556×10^{-7} in E-3. At the Makimine observatory, extensions of all components recorded are far too large to be expected from the epicentral distance and magnitude of the earthquake. The E-1 component went out of the scale at the event, E-2 recorded an extension of 7.94×10^{-7} and E-3 extended above 2×10^{-6} in strain. These values are not taken into quantitative consideration in the next paragraph. At the Sukumo observatory, the E-1 component recorded an extension of 0.705×10^{-7} at the event, E-2 recorded no stepwise strain change and E-3 a contraction of 4.02×10^{-7}.

Expected strain steps are calculated by the formula derived by Sato and Matsu'ura who gave analytical expressions for the strain fields at the surface of a semi-infinite

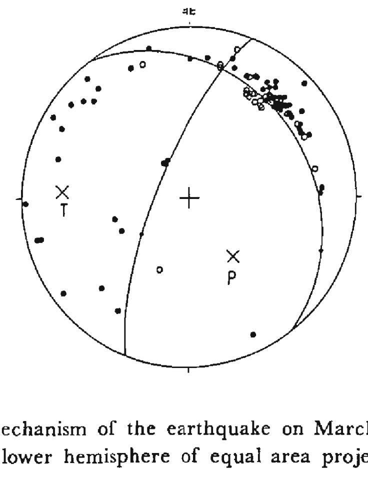
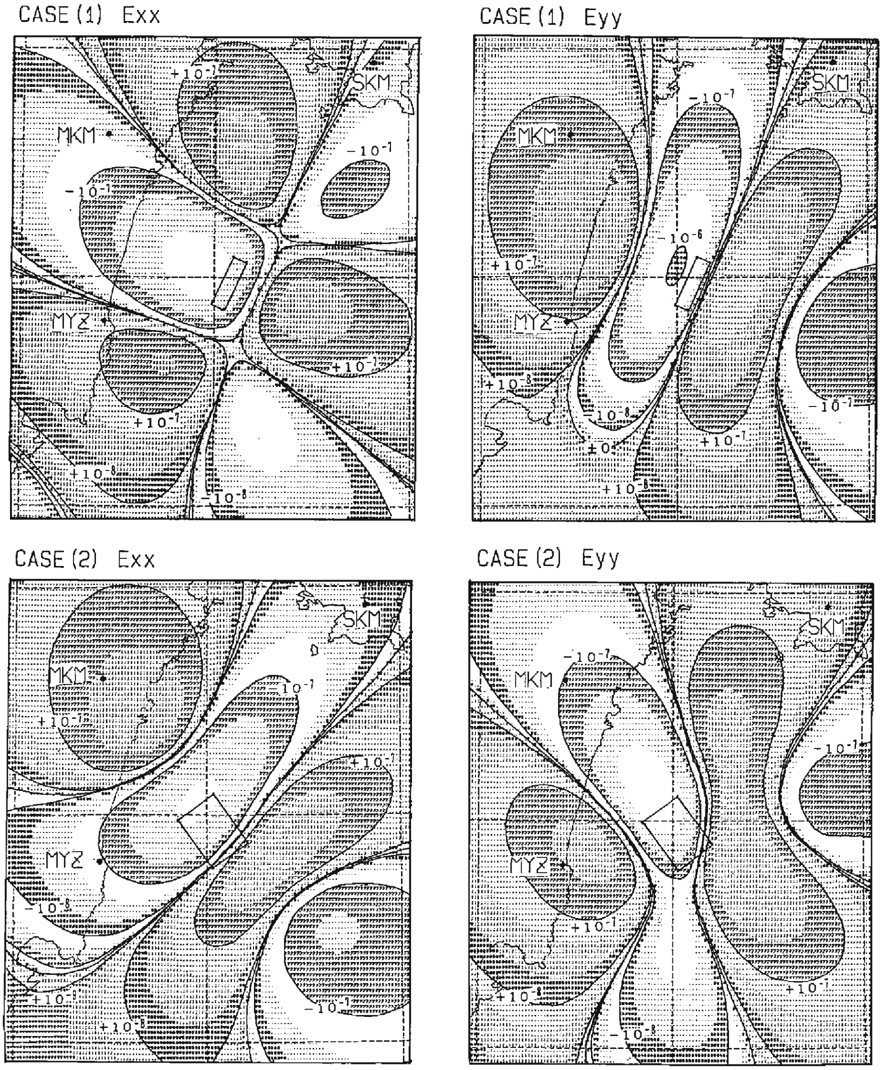


Fig. 5. Focal mechanism of the earthquake on March 18, 1987 by the JMA. (lower hemisphere of equal area projection)

medium due to an inclined rectangular fault by the dislocation theory.[16] The fault parameters are estimated from the focal mechanism and the distribution of the origins of the aftershocks by the JMA.[18),20] The focal mechanism by the JMA is shown in **Fig. 5.** Most of the focal mechanisms of the earthquakes in this region are the low-angled thrust type.[5),6] Accordingly, the mechanism of the present earthquake, a normal fault type, is not consistent with them. But it is not impossible for normal faulting earthquakes


CASE (1) Exx

CASE (1) Eyy

CASE (2) Exx

CASE (2) Eyy

Fig. 6. Strain distributions around the rectangular fault.
case(1) strike N 22°E, dip angle 74°
e_{xx} : N 22°E e_{yy} : W 22°N
case(2) strike N 37°W, dip angle 29°
e_{xx} : N 37°W e_{yy} : W 37°S

to occur in this region.[21] However, there are only the insufficient data of this network to discuss the focal mechanism itself. The dip angle and direction of each nodal plane are 74°, N 68° W and 29°, N 53° E respectively, and which is the fault plane that slipped at the earthquake can not be specified from the distribution of the origin of aftershocks. This circumstance requires the calculation of strain steps for both models. The former nodal plane is assigned to its fault plane in case(1) and the latter in case(2). Fault dimensions are assumed to be as follow in both cases.

fault length = 28 km
fault width = 25 km
dislocation = 1 m
position of the center of the fault =
31.97°N, 132.06°E, D = 48.1 km (origin by the JMA)

The slip angle on the fault surface is 62° (slip direction of the upper block is from SE to NW) in case(1) and 22° (WNW to ESE) in case(2). A few of the calculated strain distributions are shown in **Fig. 6.** Strains e_{xx} and e_{yy} are N 22°E and N 68°W in direction in case(1) and N 37°W and N 53°E in case(2), respectively.

In **Fig. 7,** calculated strain components corresponding to the direction of each extensometer at each observatory are plotted versus the observed one. In all components at Miyazaki and the E-1 component at Sukumo, the observed strain steps agree well with the theoretical ones within the ratio of 0.5-2. The theoretical value of the E-2 component at Sukumo is so small that the ratio becomes large, but the absolute difference between them is small. In the E-3 component at Sukumo, the observed value

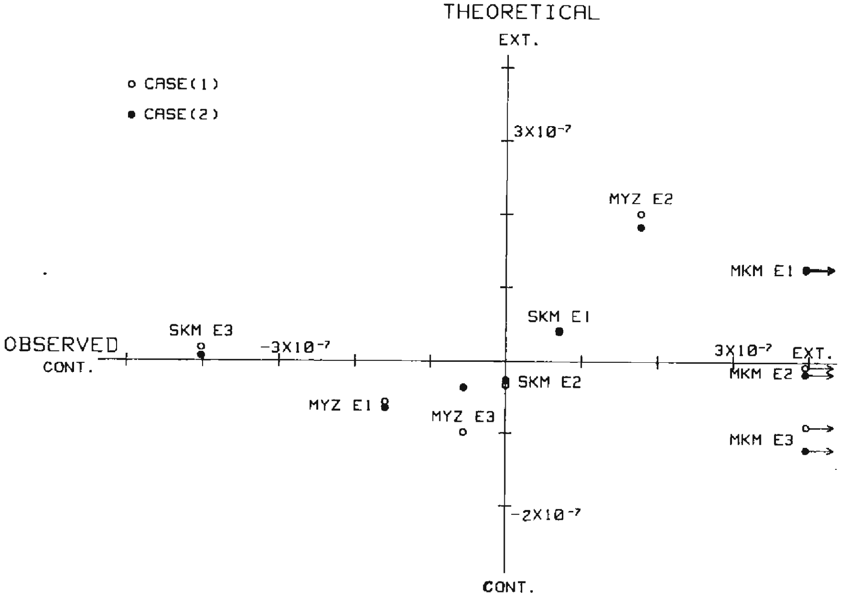


Fig. 7. Observed strain steps and theoretical one.

is far larger compared with the theoretical one. This component has some improper conditions : namely the shortest base line length of only 5 m, in the nine extensometers : low sensitivity as previously described : and its nearness to the entrance and a rectangular corner of the observation vault as seen in **Fig. 1.** Thus the disagreement of this component with theory must be due to these conditions.

At Makimine, observed strain steps are too large compared with the theoretical one in all components. At this observatory, super-invar bars of the extensometers are supported by rollers. It is reported that this type of suspention sometimes magnifies observed strain steps[22] and this may be the present case as well.

After all, except for the case of instrumental instability, observed strain steps are consistent with the calculated strain patterns based on the fault models. The strain patterns of the two models are different from each other, but the expected strains in the direction of each extensometer are fairly close for the two models. Therefore it is impossible at present to decide which nodal plane was the actual fault plane just from the strain step data.

5. Post-seismic aftereffects

In some components, post-seismic aftereffect strain changes were observed. Only the monotonously changing parts among these were extracted and plotted in **Fig. 8.** The sense of aftereffect was contraction at the Miyazaki observatory and extension at the Makimine and Sukumo observatory. Characteristic changes are seen in the E-1 component at Miyazaki and in E-2 at Makimine. In these components, the strains changed in reverse direction to the co-seismic strain steps within about one or half an hour after the earthquake, and thereafter reversed direction. The strain changes after the earthquake were linear in E-1 and E-3 of Sukumo so that they are not included in the following analysis of aftereffect.

The sense of aftereffects are the same as the direction of the co-seismic strain step in three components, reverse in one component and not comparable because of the lack of any strain step in the other components. Yamauchi classified the mode of aftereffects into two types according to their directions relative to that of strain steps.[23] The former three components belong to type I and the latter to type II in his classification. According to Yamauchi, the type II aftereffect is a rare case and is restricted to near fields of epicenters. The epicentral distance of the Miyazaki observatory where the type II aftereffect was observed is estimated to be about two times of the fault dimension of this earthquake, so this is not a case of exception.

To determine the nature of aftereffects, time variations of strain rates for each component in **Fig. 8** have been investigated. In **Fig. 9,** strain rates per hour are plotted on a semi-logarithmic scale. A sloped straight line means an exponential change in the original data, while a horizontal line is a constant rate change in the original records, so that exponentially changing parts can be exactly specified on the graph. Humps appear on the two components of Makimine and E-2 component of Miyazaki in **Fig. 9.** If they are the remnants of earth tide which should be removed, exponentially changing

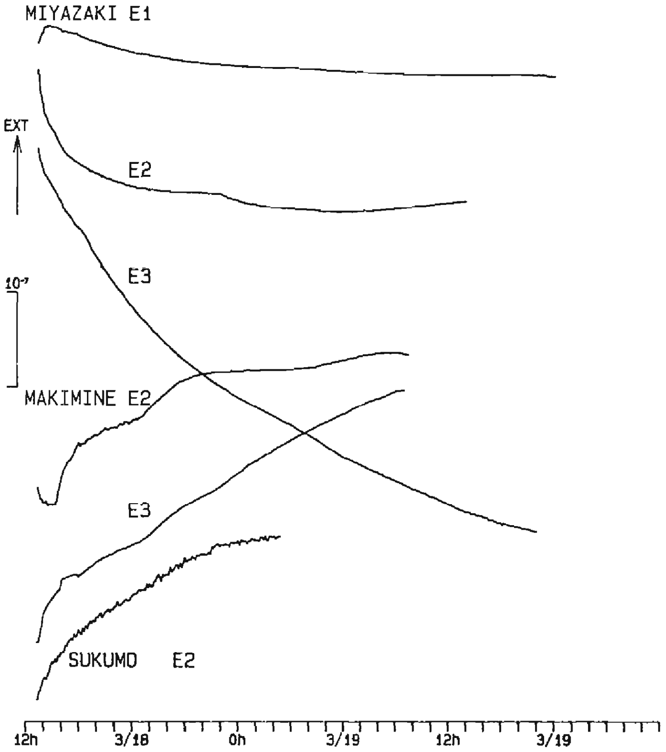


Fig. 8. Post-seismic aftereffects recognized in some components.

parts should be extended farther than that of the present analysis. In any way, **Fig. 9** shows that for a few hours to half a day after the earthquake the strain changes were exactly exponential and constant rate changes followed them.

The time constants of exponential changes in all components plotted in **Fig. 9** are shown in **Table 1.** Numerics with sign + in the table indicate the probability of a longer time constant or a longer duration time than the given values if the humps on the record are to be removed. This table shows that the time constants and the duration times of aftereffects are not identical among the observatories, but those of different components in the same observatory are nearly equal if the sign + in the table is taken into account. Therefore, they cannot be attributed to the earthquake origin, properties of material in the source region or its focal mechanism, but may be due to viscoelastic properties of the rock around the observatories. In the case of Miyazaki, these time constants correspond to a viscosity of about $10^{15}\sim5\times10^{15}$ poise on the assumption of stress relaxation in a Maxwell body with elasticity of 2×10^{11} dyne/cm, which was estimated from the seismic wave velocities around the observation vault.[25]

The singular strain changes as observed in the E-1 component at Miyazaki or the E-2 component at Makimine just after the occurrence of the earthquake are thought to be due to the properties of rocks close to the instrument or, as the case may be, some

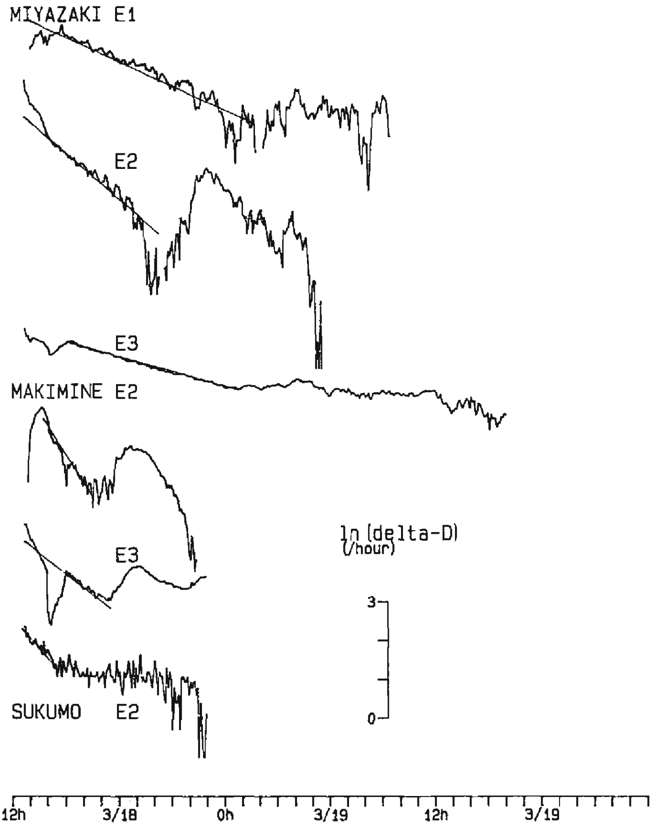


Fig. 9. Strain rates per hour in the same components as **Fig. 8.**

Table 1. Time constants and duration time of after effect plotted in **Figs. 8** and **9**

observatory	component	time constant	duration time
		hours	hours
MIYAZAKI	E-1	7.80	14
	E-2	2.53+	7.5+
	E-3	5.17	13
MAKIMINE	E-2	1.38+	5+
	E-3	2.81+	5+
SUKUMO	E-2	1.96	2

mechanism of the instrument itself. But we can find neither any concrete singularities nor defects in the installed conditions of these components. The sense of the strain change of this type is contrary to that of the change of longer duration following to this singular one in the above two components. We have no data to decide whether the reversal of sense in the strain change has a physical inevitability or not. If this contrariety has no physical meaning, it may be that we could recognize the singular strain changes of short duration merely due to reversed sense. Furthermore, they might have been hidden in the longterm aftereffects if both short and long duration strain changes had the same sense.

The case of the E-2 component at the Sukumo observatory, where no aftereffect appeared in the other two components, suggest that aftereffect is a very local phenomenon. In the vault of the Sukumo observatory, there exists a slightly fractured zone and it may have affected the behavior of the instrument or strain around the zone. But the true mechanism of the aftereffect cannot be determined only from the present data.

Yamauchi proposed the relation between the time constant of post-seismic strain changes and the magnitudes of earthquakes,[23] as

$$\log T = 1.43M - 8.05.$$

From this formula, the time constant of 33.3 hours is obtained for $M = 6.6$, at least 4 times longer than the values in **Table 1.** He assumed the exponential time function for rather longer durations of data than that determined in our analysis. Therefore it is natural that the present result is shorter than his value. For example, the data of the E-2 component at Makimine or the E-2 component at Sukumo can be fitted by exponential time functions with a longer time constant for a few days after the earthquake. He also argued that the aftereffect reflects the crustal movement at the origin, but the phenomenon treated in this article is not the case.

Tanaka discussed viscoelastic changes in secular ground strains.[24] His conclusion was that there were two groups of time constants, and he asserted that relaxations with time constants shorter than about three years are related to the rocks of the vault and the longer ones are related to the instruments. Though he excluded in his analysis, the deformations with time constants of a few days or shorter which we treated in present work, our conclusions that the post-seismic creeps at Miyazaki and Makimine are attributable to behavior of local rocks does not contradict his inference. We have found the possibility of instrumental sources in creeps of shorter duration than about a half to one hour just after the earthquake.

6. Conclusions

The strain changes observed at 3 observatories around Hyuganada associated with the earthquake of magnitude 6.6 at Hyuganada on March 18, 1987 have been analysed and discussed. The epicentral distances were 62 km to the nearest and 130 km to the farthest station.

The conclusions obtained are summarized as follows :

(1) Obvious precursory phenomena were not detected at any station. However, at the Miyazaki observatory, which is the nearest to the eqicenter, we did find an irregular strain change about 6 hours before the occurrence of the earthquake after removing the earth tides and rainfall effect. The possibility that this change was related to the occurrence of the earthquake can not be denied.

(2) Co-seismic strain steps were observed at all observatories and then were compared with the results of calculation based on a dislocation theory according to the focal mechanism by the JMA. At Miyazaki, strain steps in all components were consistent with the theoretical values. At Makimine where the epicentral distance was 92 km, the steps in all components were too much larger than the theoretical ones, which was probably due to instrumental instability. At Sukumo, the farthest observatory from the epicenter, observed strain steps are consistent with the theoretical values except the E-3 component which has a short base line length and was installed at an unsuitable position in the observation vault.

When considering the fault plane, it could not be decided from the strain step data which is the plane that slipped at the earthquake between two nodal plane of the focal mechanism.

(3) Post-seismic creeps were observed in most components of the three observatories. But the time constants of exponential strain changes, which ranged from 1.38 hours to 7.80 hours, were different from each other. Therefore these aftereffects are concluded not to be due to the properties of the origin, and must be attributed to the local rock conditions. In some components, the rate and sense of creep changed about a half to one hour after the earthquake.

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