Anomalous Crustal Deformation in the Northeastern Izu Peninsula and Its Tectonic Significance
—Tension Crack Model—

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Since the autumn of 1978, anomalous crustal deformation, such as crustal extension and crustal uplift, and earthquake swarm activity have continued in the northeastern Izu Peninsula and its seas off the east coast (northwestern Sagami Bay). Repeated precise geodetic surveys have revealed the horizontal deformation as if the crust of the northwestern Sagami Bay has rifted. The horizontal deformation leads to the conclusions that the NE-SW extensional stress field is predominant and a tension crack (fissure), such as strike of N120°E, length of 15 km, and dislocation of 130 cm, has formed in the crust of the northwestern Sagami Bay. On July 13, 1989, a submarine eruption occurred at the northwestern extension of the tension crack and a monogenetic volcano, the Teisi Knoll, was born.

It is concluded from these events that the present-day stress state in the northwestern Sagami Bay and the northeastern Izu Peninsula is the NE-SW tension and that the monogenetic volcano is born in the NW-SE-trending tension crack (fissure zone) under the tensional stress field. It is supposed that the NE-SW tensional stress is caused by the bending of the Philippine Sea plate due to its subduction.

1. Introduction

The Izu Peninsula is situated at the northeastern margin of the Philippine Sea plate. The Philippine Sea plate has subducted under the Japanese Islands from the Suruga and the Sagami troughs which are in the west and the east sides of the Izu Peninsula. The Philippine Sea plate collides to the Japanese Islands at the northern margin of the Izu Peninsula.

The Izu Peninsula is a volcanic region belonging to the Izu-Bonin Volcanic Belt, and the Volcanic Front (VF) runs through the northeastern Izu Peninsula (NEIP). Therefore, the tectonic setting in and around the Izu Peninsula is very complex, and is also very interesting.

In 1930, a remarkable crustal uplift and earthquake swarm occurred in the NEIP (see Fig. 24). Kuno (1954) suggested that underground magma movement was the cause of the 1930 crustal activity.

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Recently, anomalous crustal deformation and earthquake swarm have occurred again in the NEIP and its vicinity. Figure 1 shows the typical crustal deformations and the earthquake swarm activity (star-like symbol denotes rough activity) in the NEIP with the time (year). It is clear that the anomalous crustal uplift and the anomalous crustal extension have continued since 1975. Crustal uplift at the Ito tide station and the crustal extension between the Hatsushima Island and the Komuroyama are especially distinct since autumn of 1978.

The purpose of this paper is to investigate the anomalous crustal deformation, especially the horizontal deformation related with the seismo-volcanic activity, in detail and its tectonic significance.

2. Crustal Deformation from 1978 to 1988

Geographical Survey Institute (GSI) has carried out the geodetic survey in the Izu Peninsula since the end of the 19th century. Figure 2 shows the recent geodetic survey network in the Izu Peninsula established by GSI. Since 1975, GSI has frequently carried out leveling and distance surveys and these results have been reported in the Report of Coordinating Committee for Earthquake Prediction (RCCEP). In the following discussion, we use these data taken by GSI and reported in RCCEP.

GSI has carried out the leveling survey twice in every year. Figure 3 shows the vertical deformation in the NEIP from March of 1978 to July of 1988 based on GSI's leveling data (GSI, 1989). Crustal uplift around the Ito tidal station is very distinct.
Fig. 2. Map showing the geodetic network in the Izu Peninsula established by the Geographical Survey Institute (GSI).

and its maximum amount is about 30 cm. It seems that the axis of the uplift extends to the NW-SE direction.

On the other hand, GSI has carried out two kinds of distance surveys in the NEIP. One is the long-distance survey around the Hatsushima (HTS) Island (Hatsushima Network), which has been measured once every year and second is the short-distance survey at the Kawana (KWN) and the Ajiro (AJR) radial base-lines, which have been measured twice every year. Figure 4 shows the annual change in distance at each side length at the Hatsushima Network (GSI, 1990a). Crustal extensions between the Hatsushima Island (HTS) and the Komuroyama (KMR), and the Tokunaga (TKN) are very distinct. Figures 5 and 6 show the secular changes in distances at the Kawana and the Ajiro radial base-lines. Extensional distance changes are observed at the Kawana but no distance changes are observed at the Ajiro.
Fig. 3. Observed vertical crustal deformation in the north-eastern Izu Peninsula (NEIP) from March 1978 to July 1988 based on GSI (1989). Contour lines are drawn by the authors.

Total changes in distance of each side and horizontal strain changes of the Hatsushima network during from November of 1978 to December of 1988 are shown in Fig. 7 with the vertical crustal movement. The inserted horizontal strain change is the observed one at the Kawana radial base-line, and the inserted earthquake hypocenters show a relation between the location of the Hatsushima network and the seismic source region.

In order to investigate the horizontal deformation in detail, we applied a free net-adjustment method to the observed distance change data which are shown in Fig. 4. The obtained horizontal deformation is shown in Fig. 7. Horizontal displacement vectors suggested that the crust between the Hatsushima and the Izu Peninsula has rifted and spread to the NE-SW direction, showing a typical crustal deformation due
Therefore, we assume a tension crack model to the above horizontal deformation, and examine a quantitative analysis by the elastic dislocation theory developed by Okada (1985), and Yang and Davis (1986). We referred to the vertical hypocenter distribution of earthquake swarms off the coast of Ito, which is shown in Fig. 8, to construction of the model. Hypocenters deepen to the southeast as shown in Fig. 8, so we assume that the southeastern upper margin of the tension crack is deeper than that of the northwestern.

Figure 9 shows the final model, which has been modified from Tada and Hashimoto's (1988, 1989 a) together with calculated horizontal and vertical deformations from the final model. Parameters of the model are as follows: length = 15 km, width = 10 km, depth of northwestern upper margin = 2 km, depth of southeastern upper margin = 4 km, strike = N 120°E, dip angle = 85°S, maximum dislocation = 1.3 m.

The inserted horizontal strain change is the calculated one at the Kawana radial
Fig. 5. Secular changes in distances of each side length of the Kawana radial base-line (GSI, 1991). Open circle: re-set data.

Fig. 6. Secular changes in distances of each side length of the Ajiro radial base-line (GSI, 1991).
Fig. 7. Observed horizontal crustal deformation in the NEIP from November 1978 to December 1988 based on GSI (1989) (after Tada and Hashimoto, 1988, 1989a). Inserted figure is earthquake hypocenters from January 1983 to October 1986 based on JMA and SEIS-PC (Ishikawa et al., 1985). Contour lines: vertical movement in Fig. 3.

base-line from the above parameters. The calculated horizontal deformations agree very well with the observed ones.

The crustal uplift around the Ito tidal station cannot be explained entirely by just the tension crack. In order to explain the residual of the uplift (10–20% of the total uplift), we assumed a magma reservoir at the depth of 10 km near the Ito tide station (star symbol in Fig. 9) and its volume inflation of $5 \times 10^7$ m$^3$.

3. 1989 Crustal Deformation and Submarine Eruption

On June 30, 1989, an earthquake swarm began at off the east coast Ito City, and its activity became higher and higher day by day. GSI had carried out the regular leveling survey in the NEIP since June 1, 1989, and the survey along the east coast of the Izu Peninsula was completed on June 30, 1989.
Fig. 10. Observed (closed circle, GSI, 1990a) and theoretical (open circle, Tada and Hashimoto, 1989b) vertical crustal deformations along the east coast of the Izu Peninsula before and after the 1989 submarine eruption. Top, July 15–20, 1989/July 10–13, 1989; Middle, July 10–27, 1989/June, 1989; Bottom, June, 1989/November, 1988; Numeral, observed date. Location and parameters of the tension crack model are shown in Fig. 14 and the text.

The bottom in Fig. 10 shows the result (GSI, 1990a) of the survey. An uplift of 3 cm during the past half year was observed. It was an anomalous uplift because the average uplift rate during the past 10 years was 2.5 cm/year as shown in Fig. 1. So, GSI began a re-survey along the above anomalous division of the leveling route between

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Fig. 8. Earthquake hypocenter distribution (left) and vertical distribution of along the A–B profile (right) from January 1983 to October 1986 based on JMA data and SEIS-PC (Ishikawa et al., 1985). Note that earthquake hypocenters deepen to the southeast.

Fig. 9. Theoretical horizontal and vertical crustal deformations calculated by the tension crack model (rectangle, modified from Tada and Hashimoto, 1988, 1989a). The length, the width, the depth of the upper margin and the dislocation of the tension crack are shown in the figure. Dip angles and strikes are 85°, SW and N 120°E for all fault segments.Broken line of rectangle: lower margin of tension crack. Star: magma reservoir (depth = 10 km, $dV = 5 \times 10^7$ m$^3$).
Fig. 11. Observed (GSI, 1990a) and theoretical (Tada and Hashimoto, 1989b) vertical crustal deformations along the leveling route from BM9400 to BM9343 (upper) and the leveling route from BM48-003-012 to BM48-003-000 (lower) related to the 1989 submarine eruption. Notations and parameters are the same as in Figs. 10 and 14, respectively.

BM48-003-000 and BM9343 from July 10, 1989. But on the evening of July 13, a submarine eruption occurred at off the northeast coast of Ito City.

The result (GSI, 1990a) obtained before the eruption is shown in the middle of Fig. 10, together with the observed date. It was surprising that the crustal uplift of 9 cm was observed during the past 10 days.

After the eruption, GSI carried out a leveling survey in the above-mentioned division again. The result (GSI, 1990a) is also shown in the top of Fig. 10, together with the observed date. It is clear that no crustal deformation associated with the eruption took place. Therefore, it is concluded that the crustal deformation which was observed immediately before and after the eruption was the crustal deformation that preceded the submarine eruption.

GSI also re-surveyed other leveling routes, which are perpendicular to the east coast leveling route, in the Izu Peninsula after the eruption. The results (GSI, 1990a) are shown in Fig. 11, with the observed date. The leveling surveys from BM48-003-012 to BM48-003-000 were carried out November of 1988 and July of 1989. It is supposed from the bottom of Fig. 10 that the vertical movement at BM48-003-000 during from November of 1988 to June of 1989 was negligibly small. Therefore, we can treat the result of this route together with the results of other routes.

By the above-mentioned reason, the vertical deformations which are shown in the
middle of Fig. 10, and Fig. 11 indicate a precursory phenomenon of the eruption. Figure 12 shows a net-adjustment precursory vertical crustal deformation obtained from those leveling surveys.

On the other hand, distances of HTS-KMR, HTS-TKN, and HTS-SGM were measured immediately after the submarine eruption, and remarkable elongations of distances were observed compared to the results from November of 1988. The results are shown in Fig. 13. Distances of HTS-KMR, HTS-TKN, and HTS-SGM had become longer by 16, 17, and 6 cm, respectively (GSI, 1990a). Horizontal strain is calculated from these distance change data. These distance changes are considered to be the crustal...
Fig. 13. Observed change in distances of HTS-SGM, HTS-TKN, and HTS-KMR, and each side length of the Kawana radial base-line (inserted figure), and crustal strain changes (GSI, 1990a). Other data are taken by Hirata et al. (1989).

Fig. 14
deformation preceding the submarine eruption by the consideration of the above-mentioned vertical crustal deformation. Distance observations at the Ajiro and the Kawana radial base-lines were carried out just before and just after the eruption, and the results are shown in Figs. 5 and 6. There were distinct distance changes at the Kawana but distinct distance changes were not observed at the Ajiro. Detailed distance changes and the crustal strain change at the Kawana are shown in the inserted figure of Fig. 13.

The location of the maximum uplift of the precursory movement (see Fig. 12) shifted to the north compared to the previous one which is shown in Fig. 3, and the distance change of HTS-TKN was larger than that of HTS-KMR, which is situated at southeast of HTS-TKN. These results suggested that the northwestern margin of the tension crack propagated to the northwestward and to the more shallow depth. Tada and Hashimoto (1989b) calculated theoretical distance changes and crustal strain.
changes based on a tension crack model which is shown in Fig. 14. The most reliable fault parameters of the tension crack are as follows: length = 5 km, width = 5 km, depth of upper margin = 1 km, dislocation = 70 cm, dip = 85° S, strike = N 120° E. A right-lateral strike-slip fault in Fig. 14 shows the fault corresponding to the largest earthquake among the swarm, but crustal deformation due to this fault is so small that its contribution is negligible.

The vertical deformations calculated from this model are shown by open circles.
Fig. 17. Summary of the observed vertical crustal movement in the NEIP from March 1978 to July 1991.

Concordance between the observed results and the theoretical ones is fairly good. It is noted that the upper margin of the tension crack is very shallow.

The bottom of Fig. 10 shows the vertical deformation obtained by the surveys at November of 1988 and June of 1989. We could not identify when the deformation took place. As mentioned above, distance changes before the submarine eruption could be
explained only by the formation of the tension crack; therefore, it is supposed that this vertical deformation did not affect the horizontal deformation. In order to explain this vertical deformation, it is assumed that inflation of the magma reservoir, which was described in the former chapter, took place with a volume increase of $2 \times 10^7$ m$^3$ which took place. The calculated vertical deformation due to the inflation is shown by open circles in the bottom of Fig. 10. In this case, the distance change between Hatsushima and Komuroyama (HTS-KMR) is only a few millimeters.


The distance survey all over the NEIP after the submarine eruption was completed in January of 1990, and the leveling survey was also completed in July of 1990. Figure 16 (GSI, 1991) shows the vertical crustal deformation between two years containing the submarine eruption, that is, from July of 1988 to July of 1990. The summary of the vertical crustal deformation from March of 1978 to July of 1990 is shown in Fig. 17 (Fig. 3+Fig. 16). And the summary of the horizontal crustal deformation from
Fig. 19. Theoretical horizontal and vertical crustal deformations based on the tension crack model in order to explain the total observed crustal deformations (Fig. 18). Fault parameters are shown in the figure. Dips, dip directions and strikes are 85°S, SW and N 120°E for all fault segments. Notations are the same as in Fig. 9.

November of 1978 to January of 1990 is displayed in Fig. 18. These two figures show that the crustal deformation due to the formation of the tension crack (tensile fault or fissure) is very clear. The maximum amount of horizontal displacement and vertical uplift exceeds 40 and 30 cm, respectively. A tension crack model to explain the total observed crustal deformation and the calculated crustal deformation are shown in Fig. 19. The crustal deformations after the submarine eruption are small as shown in Figs. 1 and 4, and GSI (1991). Then, it is possible to explain the crustal deformation only by a little change of the dislocation of the northwestern part of the tension crack, that is, the increase of 10 cm. This suggests that the post eruptive crustal deformation may be an after-effect of the opening of the northwestern tension crack.
5. Discussion and Conclusions

Precise geodetic survey in the NEIP has revealed that the tension crack (fissure) has formed in the crust of the northwestern Sagami Bay as summarized in Fig. 19. This suggests that the present-day stress field in the northwestern Sagami Bay is the NE-SW tensional. The other evidence is the great fissure eruption of Izu-Oshima Volcano on November of 1986. A tension crack, whose strike was NW-SE and dislocation was 2 m, was formed in the Izu-Oshima Island (Tada and Hashimoto, 1987; Hashimoto and Tada, 1990).

There are many monogenetic volcanos in the NEIP and its east off sea bottom as shown in Fig. 20 (Aramaki, 1976; Aramaki and Hamuro, 1977). These monogenetic volcanos have a tendency to align themselves in the NW-SE direction, which is in the same direction as the above-mentioned tension crack.

Nakamura (1986) pointed out that a monogenetic volcano is born in the tensional stress field. Then it is concluded from these characteristics of monogenetic volcano and

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Fig. 21. Schematic interpretation of the tectonics in and around the northwestern Sagami Bay by Nakamura's (1980) plate bending model. The NE-SW extensional stress becomes strong in the upper part of the Philippine Sea plate due to the bending of the plate associated with the subduction from the Sagami trough.

Why does the NE-SW tensional stress predominate in the northwestern Sagami Bay? Nakamura (1980) explained the cause of the tensional stress as follows. The Philippine Sea plate must bend to the northeast in order to subduct from the Sagami trough, and this bending result in the NE-SW tensional stress. In this case, the upper part of the Philippine Sea plate shows the state of the tensional stress field and the lower part shows the state of the compressional one as illustrated in Fig. 21. Then, the tension crack is formed in the upper part, and the magma reservoir in the lower part is compressed and thus the magma is squeezed.

The internal structure of the tension crack is not obvious, but a volcanic earthquake model (Fig. 22) of Hill (1977), such as the complex structure of micro-fissures and micro-faults, may be considered as a suitable model. It is supposed that the squeezed magma from the magma reservoir flows in the tension crack, although its mechanism is not clear. The magma moves in the micro-fissures accompanying the micro-earthquakes, that is, fracturing of the crustal layer. There are two seismic reflection profiles across the tension crack as shown in Fig. 23. One (A–A' line) was obtained in 1980 (Kato et al., 1983) and the other (B–B') was obtained in 1989 (Kasahara et al., 1989).
Fig. 22. Hill's earthquake swarm model by tension crack and shear fault (Hill, 1977).

Fig. 23. Location of the tension crack and the seismic reflection profiles (Kato et al., 1983; Kasahara et al., 1989), and obtained crustal structure (Kato et al., 1983). Disturbance of the crustal layer at 'a' may show the tension crack. Figure 23 shows the migrated depth section of line A–A' (Kato et al., 1983). We can see a disturbance of crustal layer at the depth of 3–4 km under the cross point of the tension crack and the profile (a in Fig. 23). It is considered that this crustal disturbance is the tension crack itself (Kasahara, personal communication). In the case of the 1989 event, it seems that a part of the magma flowed out to the sea bottom, i.e., a submarine eruption occurred, and a monogenetic volcano, the Teisi Knoll, was born.

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It is very important to know when the anomalous crustal uplift and the seismo-volcanic activity will be over. Figure 24 (Fujita and Tada, 1981, with additions by the authors) shows the secular change in height of BM9337 (Ito) relative to BM9328 (Atami) since 1904 and the main earthquake activity. It is clear that the vertical crustal deformation at Ito (BM9337) correlates with the earthquake activity in the Izu Peninsula and its vicinity. In the case of the 1930 event, earthquake activity was over when the vertical crustal deformation at Ito (BM9337) changed to subsidence, as shown in Fig. 24. Therefore, it is supposed that the present seismo-volcanic activity may be over when the crustal uplift at Ito changes to subsidence.

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REFERENCES


