Strain Event in 1985−1987 in the Tokai Region, Central Japan

(東海地域における1985−1987年ストレインイベント)

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ABSTRACT

Electro-optical distance measurements (EDM) for the baseline networks of Sangane and Awagatake in the Tokai region began in 1978. The rangings of two baselines, Sangane-Zaoh and Awagatake-Megami, have been repeated four times a year on average. The directions of the baselines are parallel to that of the convergence of the Philippine Sea plate. In order to minimize the EDM error, distance measurements are carried out at sunset. The results of distance measurements for the thirteen years are summarized as follows: (1) The accuracy of EDM around sunset is generally better than 5 x 10^{-7}. (2) A NW-SE contraction and a NE-SW extension are common to both networks. A shear strain at a rate of 1 to 3 x 10^{-7}/year is consistent with the geodetic surveys carried out in the last 100 years. (3) Both baselines, 80 km apart from each other, indicated a similar strain event, suggesting the accelerated contraction amounting to 1 to 2 x 10^{-6} in 1985-1987. The contraction is concordant with the change in geodetic tilt near Zaoh and the change in seismic activity in the Ise Bay area. The result obtained from observations might be evidence of the remarkable strain event that occurred in the Tokai region in 1985-1987.

1. INTRODUCTION

Harada and Kasai [1971], Nakane [1973] and Hashimoto [1990] indicated a high strain rate in the Tokai region from the triangulations by Geographical Survey Institute (GSI) in the past about 100 years. The average strain rate is in the order of 10^{-7}/year in this region. Hashimoto [1990] showed that such a large strain rate as observed in the Tokai region is rarely found in other regions in central Japan, and he suggested that the effect of converging Philippine Sea plate is weak in the inner part of central Japan. Ishibashi [1977] investigated the historical earthquakes along the Suruga and Nankai troughs, and suggested a large scale seismic gap in the Suruga Bay area. These suggestions have accelerated the intensified observations in this region. Kimata and Yamauchi [1983] started measuring the distances by EDM to detect ongoing strain accumulation in the Tokai region.

The accuracy of EDM is about 10^{-6} (1ppm) for distances ranging from 10 to 30 km in ordinary use. The major part of error sources in EDM is inaccuracy of the refractivity correction. It is very difficult to estimate the accurate refractive index of air along the light path from the meteorological observations on the ground surface. The direct observation of air temperature along EDM path is the most effective method to estimate the average atmospheric refractive index. U.S. Geological Survey (USGS) used a small aircraft flying along the line of sight to measure temperature and humidity at the time of distance measurements. They were able to obtain an accuracy of 10^{-7} (0.1ppm) by this method [Savage and Prescott, 1973; Savage et al. 1991]. An alternative method to reduce the correction error for refraction is to execute EDM when the boundary layer near the ground surface becomes isothermal [Tousya, 1953]. The vertical temperature gradient in a boundary layer generally approaches zero at sunset [Tousya,1953]. In this paper, we investigate the crustal strain accumulation in 1978 - 1990 together with its temporal change in the Tokai region estimating the accuracy of EDM that were frequently repeated at sunset.

2. BASELINES IN THE TOKAI REGION

The present strain accumulation in the Tokai region is characterized by a NW-SE contraction and a NE-SW extension [Nakane, 1973; Hashimoto, 1990]. We have frequently repeated EDM observations in this region to investigate the strain accumulation in more detail than has been studied before [GSI, 1974]. As frequent measurements are hard to execute, we established only two baselines in the Tokai region in 1978. One is the Sangane-Zaoh (hereafter referred as SNG-ZOH) baseline across Mikawa Bay and the other is the Awagatake-Megami (hereafter referred as AWG-MGM) baseline which is located to the north of Omae-zaki [Figure 1]. Both baselines run in the same direction NW-SE, the direction of the maximum contraction in the Tokai region. In 1980, we supplemented the SNG-ZOH baseline with two additional lines, and the AWG-MGM baseline with a trilateral network to estimate principal strain rates in the respective regions. We set the lengths of these baselines to be longer than 10 km to delineate areal crustal deformations effectively. Locations of EDM stations are listed in Table 1.

2.1 SANGANE BASELINE NETWORK

The network consists of three baselines radiating from Sangane (SNG) station to Ishigami (ISG), Zaoh (ZOH) and Tame (TAM) stations across Mikawa Bay. These baselines are in the directions of south (SNG-ISG), southeast (SNG-ZOH) and east-southeast (SNG-TAM), as shown in Figure 1. The length of SNG-TAM, which is 29 km, seems beyond the capability of frequent EDM with a Geodimeter 6BL™, because the measurements are often interrupted by unclear visibility at such a long distance. Most of the measurements were made for the SNG-ZOH baseline, less frequently for the SNG-ISG baseline, and sometimes for the SNG-TAM baseline when visibility is good enough for EDM.

The 1945 Mikawa earthquake (M=7.1) occurred in the west of the Sangane network. The Median Tectonic line lies across the network. It is the greatest tectonic line in Japan, though less active in the Quaternary age. Geodetic survey has revealed uniform strain accumulation in this region [Nakane, 1973; Hashimoto, 1990].

2.2 AWAGATAKE BASELINE NETWORK

The other baseline network for EDM was established to the west of Suruga Bay. The area is located in the middle of the intensified observation area for the anticipated Tokai earthquake. There is the Omaezaki radiant baseline network that was established by GSI in 1973 and it has been surveyed almost every year since then [GSI, 1974, 1991]. GSI has also repeated the precise levelling along the route between Kakegawa and Omaezaki almost quarterly since 1978 [GSI, 1991].

The AWG-MGM baseline was first established in June 1978. As shown in Figure 1, the station of Megami is about 20 km southeast of Awagatake station. The distance measurements along this baseline have been repeated three to seven times a year. In December 1980, a triangular baseline network (AWG-MKN-KKG-AWG) with sides about 10-km long were supplemented the AWG-MGM baseline to measure principal strains.

3. METHOD OF EDM

The major error sources in EDM include a random instrumental error and inaccurate estimation of light speed in the air. The former is independent of distance while the later is proportional to distance. The refractive index is a function of atmospheric temperature, pressure and humidity along the line of sight. An error of 1×10^{-6} in light speed is caused by an error of 1° C in air temperature, 3 mmHg in air pressure or 30 mmHg in air humidity [Owens, 1967]. Annual changes in atmospheric temperature, pressure and humidity reach 30 °C, 20 mmHg and 30 mmHg, respectively. The refractivity of the air is therefore most affected by the temperature.

An alternative method to estimate the average temperature along the line of sight is based on the fact that a surface boundary layer near ground becomes nearly isothermal at sunset. Kimata [1984b, 1986b] confirmed that this holds true throughout the year. In the previous paper [Kimata and Yamauchi, 1981], we pointed out that the distance measurements using EDM which are carried out at sunset and corrected for the temperature, atmospheric pressure and humidity on the ground surface, have accuracies better than 1 x 10^{-6}. We carry out the EDM observations in the period between one hour before sunset and one hour after it. Every baseline is measured almost continuously; fifty to one hundred measurements are possible within two hours. Such measurements are repeated for two or three consecutive days. We used a programable calculator to process the data on the spot until 1983 and it was replaced with a personal computer in 1984.

As measurements have been repeated for more than ten years, there has been considerable improvement in the observational method. We have adopted the following method. The air temperature is measured at 10 m above each EDM station with a quartz thermometer (Tokyo Denpa Kiki). Its accuracy is ± 0.05° C. We measure the atmospheric pressure at each station with a precise altimeter (Poling) calibrated against a mercury barometer in the laboratory before and after the survey. A standard calibration error of the altimeter is ± 0.49 mmHg. Humidity data are adopted from the Omaezaki Weather Station 10 km south of Megami and the Atsumi Weather Station about 10 km southwest of Zaoh.

We also calibrate the modulation frequency of Geodimeter™ (AGA) using a frequency counter of 1 x 10^{-8} stability before and after each survey. The drift rate of the modulation frequency of the

Geodimeter™ during survey amounted to 2.7 ± 3.2 Hz corresponding to an error of (0.09 ± 0.11) x 10^{-6}. We replaced a Geodimeter 6BL™ with a Geodimeter 600™ in 1986 for efficient measurements on long baselines. In order to minimize errors due to instrumental bias, Kimata [1986a] made side-by-side measurements using different instruments. The discrepancies between the instrumental offsets of the two Geodimeter™ were as small as 1 ± 3 mm for various distances ranging from 40 m to 18 km.

4. RESULTS OF MEASUREMENTS

Lengths of the SNG-ZOH and AWG-MGM baselines were most frequently measured. Figure 2 shows the linear strain changes plotted against time for these two baselines. Similar results on the Awagatake and Sangane networks are shown in Figures 3 and 4. EDM observations on the SNG-ZOH baseline and the Awagatake baseline network are conducted for two or three consecutive days, and then average line lengths are plotted in each figure. Strain rates were obtained by the method of least squares, as shown by the linear fits data in Figures 2 and 3. They are also listed in Table 2.

If the strain changes steadily with time, the irregular deviations of data from linear fits can be regarded as observational errors. They are partly due to random observational errors shown by error bars, and partly due to inaccurate refractive corrections. Some systematic or slowly varying deviations of data from the linear fits are also recognized in these figures. Some of them may represent mere meteorological changes in the area concerned but they might be evidence of some real crustal movement.

Savage and Prescott [1973] estimated the error of EDM in central California. Under the assumption of a constant strain rate during the survey period, they proposed the following formula for standard error of EDM;

$\text{Sigma} = \{a^2 + (b \text{ x } L)^2\}^{1/2}$, (1)

where a (= 3 mm) is the instrumental error independent of distance; b (= 0.2 x 10^{-6}), an error factor due to inaccurate refractivity correction; and L, the baseline length in km. Assuming a constant strain rate, Kimata and Yamauchi [1983] estimated the error of EDM as 4-7 mm for baselines ranging from 5.5 to 18.1 km.

Our survey includes an episodic strain event in the period of 1985 - 1987 for both baselines SNG-ZOH and AWG-MGM, which will be discussed later. The hypothesis of a constant strain rate does not hold for the whole period. The precision of EDM is therefore estimated separately for the two periods with different constant strain rates. One is the period before the strain event, the other, the period after the event. Figure 5 shows the rms deviations of data obtained from the linear fits in Figures 2 and 3 against baseline length. Results of Savage and Prescott [1973], and Kimata and Yamauchi [1983] are also plotted in Figure 5.

5. DISCUSSION

5.1 STRAIN RATE ALONG BASELINE

As shown in Figures 2 and 3, the average rates of linear strains along the SNG-ZOH and AWG-MGM baselines are as small as 3×10^{-7}/year during the thirteen year period from 1978 through 1990. Linear strains except for the baseline between Awagatake (AWG) and Kakegawa (KKG) show contractions in this period. In the early stage, 1978-1985, the strain rate was as small as $-(0.13 \pm 0.10) \times 10^{-6}$/year along the SNG-ZOH baseline, and negligibly small along the AWG-MGM line. However, the contractions of the line lengths of these two baselines were accelerated in 1985 and reached to $-(1\text{-}2) \times 10^{-6}$ by the end of 1987. After 1988, they returned to as slow rates as those before 1984.

The baseline between Awagatake (AWG) and Makinohara (MKN) is in the direction NW-SE and almost in line with the AWG-MGM baseline (see Figure 1). The features of each strain change are very similar to each other (as shown in Figure 6): The strain rates for AWG-MGM and AWG-MKN baselines are $-(0.17 \pm 0.09) \times 10^{-6}$/year in 1978-1990, and $-(0.13 \pm 0.10) \times 10^{-6}$/year in 1980-1990 respectively. Since these values seem almost the same, it may be concluded that the contraction between Awagatake and Megami has been uniform. These strain rates are consistent with the NW-SE contraction deduced from geodetic survey [Nakane, 1973].

5.2 STRAIN COMPONENTS

Temporal changes in principal strains, the maximum shear strain, and the areal dilatation which were obtained by repeating trilateration in the Awagatake network are shown in Figure 7. The maximum shear strain is the most reliable among these quantities because it is independent of the common errors in the distance measurements. In the period from 1980 to 1989, the rates of shear and principal strains for the Awagatake network are (0.24±0.14) x 10^{-6}/year, 0.10 x 10^{-6}/year N50°E extension, and 0.14 x 10^{-6}/year N40°W contraction, respectively. The strain field is shown in Figure 8 and listed in Table 3.

At the Omaezaki radiant baseline network adjacent to the Awagatake network, GSI has frequently repeated the ranging since 1974 [GSI,1991]. The horizontal strain rates at this network in the period from 1974 to 1989 are obtained from the linear strain rates for baselines that are estimated by the least squares method: The shear strain rate is (0.44±0.46) x 10^{-6}/year, and the principal strain rates are 0.29 x 10^{-6}/year N73°E extension and 0.15 x 10^{-6}/year N17°W contraction (Figure 8 and Table 3). Although strain rates in the GSI Omaezaki network show rather larger value than those in our Awagatake network, the strain fields deduced from these two networks are similar.

GSI has also repeated the triangulation or trilateration surveys in the Tokai region since 1882 - 1909. The rates of shear strain estimated from the GSI's surveys are listed in Table 4. Most of the discussions on the strain accumulation in the Tokai region are based on the triangulation surveys in 1882-1909 and trilateration surveys after 1970. According to these reports, a shear strain is accumulating at a rate of (2-3) x 10^{-7}/year, and the principal strains are a NW-SE contraction and a NE-SW extension [Nakane, 1973; Kaidzu and Sato, 1978; Fujii and Nakane, 1979, 1980; Dambara, 1980; Hashimoto, 1990]. The horizontal strain estimated from our measurements for the period of the last thirteen years agrees with that determined by GSI's survey for the period of the last 100 years. It is likely that the crustal strain in the Tokai region in the last thirteen years accumulates at the same rate in the last 100 years.

On the other hand, Fujii and Kadowaki [1987] reported the maximum shear strain of 0.34 x 10^{-6}/year for the Omaezaki network and suggested a strain acceleration in the Tokai region in the 1974-1984 interval. However, we obtained a little lower maximum shear strain rate of (0.24 ± 0.14) x 10^{-6}/year for the Awagatake network in 1980-1989.

The SNG-ZOH baseline extending in a NW direction shows the maximum contraction, although the strain tensor for the Sangane network was not fully determined because of infrequent measurements to other directions. The contraction observed on the SNG-ZOH baseline is consistent with a NW-SE contraction in the Awagatake network about 80 km east of the baseline. The rate of the maximum shear strain estimated for the Sangane network is also consistent with that for the Awagatake network. All these results suggest that the horizontal strain in the Tokai region accumulates uniformly in a regional scale. Its contraction axis is parallel to the direction of convergence of the Philippine Sea plate off the Tokai region [Seno et al., 1987].

5.3 A STRAIN EVENT IN 1985-1987

As shown in Figure 2, some impulsive deviations of data are distinct in Oct.1980, Oct.1983 and July 1984 for the SNG-ZOH baseline, and in Sept.1979 and Dec.1981 for the AWG-MGM baseline. On this point, Kimata and Yamauchi [1983], and Kimata [1984a] suggested an impulsive crustal movement associated with the earthquake occurrence. Such an impulsive changes was a sudden contraction of the line lengths before the occurrence of a nearby earthquake and its recovery within one year. The peak amplitude is less than 10^{-6} in strain.

However, the increase of strain rate that began in 1985 were much different from these impulsive contractions of line lengths. The length of the SNG-ZOH baseline accelerated its contraction in 1985 after a sinuous change in 1984. The contraction continued until July 1987, and amounted to (2 - 3) x 10^{-6} during these three years. Although the impulsive contractions of line lengths were observed at the individual period for the SNG-ZOH and AWG-MGM baselines, the contractions of line length were accelerated on both baselines in 1985 simultaneously. Changes in line lengths of these baselines ceased and turned to extension in 1987 and returned again to contraction in 1988. The strain rate after 1988 remains about twice of that before 1985, but a period of three years (1988-1990) may be too short to derive any conclusion on accelerated strain accumulation.

The crustal strain rate in the Tokai region has been estimated as (0.2 - 0.3) x 10^{-6}/year in the past several tens of years [Nakane, 1973]. However, our frequent measurements of the SNG-ZOH baseline show a low strain rate of 0.1 x 10^{-6}/year in the 1978-1984 interval, a high strain rate of (1 - 2) x 10^{-6}/year in 1985-1987, and again a low rate of 0.26 X 10^{-6}/year after 1988. Namely, the crustal strain rate does not seem to be steady. A high rate of strain accumulation amounting to about ten times of that at the quiet period is outstanding in the Tokai region. This abrupt change in strain occurred on a regional scale as verified by the similarity between the observational results at places which are seperated from each other by about 80 km. We call this change the 1985/1987 strain event in the Tokai region. It may be regarded as a piece of evidence for an intermittent coupling between the Eurasian and the Philippine Sea plate. We suggest that either the acceleration of the convergence rate of the Philippine Sea plate or the temporal change in the coupling condition between the Eurasian and Philippine Sea plates would cause the 1985/1987 strain event in the Tokai region.

5.4 COMPARISON WITH VERTICAL MOVEMENTS AND SEISMIC ACTIVITY

The horizontal strain observed by EDM is compared with the results of precise levelling at the respective regions. Aichi-ken [1991] has conducted precise levelling to investigate the ground subsidence in Aichi-ken, west of Tokai region, every year or two. As shown in Figure 1, some parts of the levelling routes pass near Sangane and

Zaoh stations, although a remarkable ground subsidence is not observed around these stations. Shown in Figure 9 is the change in height difference between Zaoh and Sangane. We averaged altitudes at four bench marks near Zaoh and three near Sangane as the height data at each station. Zaoh was upheaved slightly until 1985, and then subsided in 1986 or 1987. The reversal of vertical movement around the SNG-ZOH baseline seems to have coincided with the 1985/1987 strain event detected on the SNG-ZOH baseline.

Another precise levelling between Kakegawa and Omaezaki has been repeated every year since 1976, twice a year since 1979, and four times a year since 1981 by GSI [1991]. The levelling route runs parallel to the AWG-MGM baseline at a distance of about 10 km, as shown in Figure 1. Shown in Figure 10 is the strain changes reproduced from Figure 2 and the tilt change based on the precise levelling between Kakegawa and Omaezaki. The geodetic tilt rate along the levelling route is 0.29 x 10^{-6} rad/year dipping toward Omaezaki on average, and characterized by an annual variation with an amplitude of 0.5 x 10^{-6} rad/year. Looking at the tilting in detail, however, we find that the geodetic tilt might have ceased dipping during the strain event in 1985 - 1987.

Shown in Figure 11 is the seismic activity of shallow earthquakes in the Ise Bay area. Ooida [personal communication, 1991] pointed out that the seismic activity in the polygon that includes Nobi plane, Ise Bay and Mikawa Bay decreased since 1987. He stated that the decrease of seismic activity was not caused by the decline in detection capability of the seismic observation. The annual frequency of shallow earthquakes in the polygon is plotted against time in the middle of Figure 9. As shown in this figure, the annual frequency of earthquakes began to decrease in 1985, and remained at a low level less than 100 /year since 1987. Yoshida and Maeda [1990] showed that a seismic quiescence for M>2.5 appeared around the west coast of Suruga Bay since 1988. It is clear that the seismic activity in the crust in the southern part of Tokai region decreased after the 1985/1987 strain event and the change in mode of geodetic tilts at Zaoh and Omaezaki.

Ishii [personal communication,1992] found that some BMs along the east coast of Suruga Bay clearly showed an accelerated subsidence by 1cm /year or more since 1985.

These simultaneous occurrences of tectonic events are considered to be caused by episodic changes in the convergence rate of the Philippine Sea plate or by the similar change in the coupling between the Philippine Sea and Eurasian plates. The cause or mechanism of these phenomena has yet to be classified. It depends upon future studies.

6. CONCLUSIONS

In order to monitor the crustal movements in detail, EDM observations on the Sangane and the Awagatake networks have been repeated more than three or four times a year since 1978 to 1990. The vertical gradient of air temperature in the surface boundary layer is approximately zero at sunset. Our rangings were therefore repeated almost continuously for two hours from one-hour before to one-hour after sunset with the meteorological observation on the ground surface, only.

The conclusions from the improved EDM for thirteen years on the same baselines are as follows:

(1) A precision of about 5 x 10^{-7} is attained by the frequent distance measurements at sunset with refraction corrections by the meteorological data obtained on the ground surface. This technique of EDM proved reliable for the measurement of highly time-dependent crustal movements.

(2) The strain field in the Tokai region is a NW-SE contraction at a rate of (1 - 2) x 10^{-7}/year, a NE-SW extension at a rate of (0 - 1) x 10^{-7}/year, and the maximum shear strain at a rate of 2 x 10^{-7}/year. These strain accumulations are consistent with the result obtained by surveys in the Tokai region in the last 100 years.

(3) The 1985/1987 strain event was observed at the baselines SNG-ZOH and AWG-MGM. It seems correlated with the decline of the seismic activity in the Ise Bay area, the seismic quiescence around the west coast of Suruga Bay, and with the change in geodetic tilt near Zaoh and Omaezaki. It is therefore suggested that the strain event did occur in a large scale including the area from Suruga Bay to Ise Bay. The strain event might be caused by an intermittent plate motion or by the change in plate coupling between the Philippine Sea plate and the Eurasian plate in the Tokai region.

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REFERENCES

Aichiken, Annual report of observation of subsidence in Aichi-ken, Aichi-ken, 1-44, 1991 (in Japanese).

Dambara, T., Some problems on prediction of the Tokai earthquake in future, Proceedings of Earthquake Prediction Research Symposium(1980), 98-90, 1980 (in Japanese with English abstract).

Fujii, Y., and T.Kadowaki, Earth's strain deduced from repeated observations for multi-side lengths and their error evaluation, Zishin(J.Seismol.Soc.Jpn.), Ser.2, 40, 111-113, 1987 (in Japanese with English abstract).

Fujii, Y., and K.Nakane, Earth's horizontal strain across the Suruga Bay, Honshu, Japan(1), J.Geod.Soc.Jpn., 25, 289-301, 1979 (in Japanese with English abstract).

Fujii, Y., and K.Nakane, Earth's horizontal strain across the Suruga Bay, Honshu, Japan(2), J.Geod.Soc.Jpn., 26, 104-112, 1980 (in Japanese with English abstract).

Geographical Survey Institute, Results of side-length observations for concentrated base-line network in Tokai district, Report of the coordinating committee for earthquake prediction, 12, 132-134, 1974 (in Japanese).

Geographical Survey Institute, Crustal movements in Tokai district, Report of the coordinating committee for earthquake prediction, 46, 272-289, 1991 (in Japanese).

Harada, T., and A.Kasai, Horizontal strain of the crust in Japan for the last 60 years, J.Geod.Soc.Jpn., 17, 4-7, 1971 (in Japanese with

English abstract).

Hashimoto, M., Horizontal strain in the Japanese Islands during interseismic period deduced from geodetic surveys. Part I. Honshu, Shikoku and Kyushu, Zishin (J.Seismol.Soc.Jpn.), Ser. 2, 43, 13-26, 1990 (in Japanese with English abstract).

Ishibashi, K., Re-examination of a great earthquake expected in the Tokai district, Central Japan - possibility of the "Suruga Bay Earthquake", Report of the coordinating committee for earthquake prediction, 17, 126-132, 1977 (in Japanese).

Kaidzu, M., and H.Sato, Accuracy of crustal strains through geodetic data, J.Geod.Soc.Jpn., 24, 43-47, 1978.

Kimata, F., Distance measurements in the Sangane-Zaoh baseline, before and after Dec.19, 1983 Earthquakes (M=4.0), Zishin (J.Seismol.Soc.Jpn), Ser. 2, 37,307-309, 1984a (in Japanese).

Kimata, F., Diurnal variations of temperature lapse rate in planetary boundary layer near the ground, J.Geod.Soc.Jpn., 30, 59-60, 1984b (in Japanese with English abstract).

Kimata, F., Detection of instrument Bias between Geodimeters, J.Geod.Soc. Jpn., 32,140-141, 1986a (in Japanese with English abstract).

Kimata, F., The temperature distribution within a boundary layer before and after sunset, J.Geod.Soc.Jpn., 32, 224-225, 1986b (in Japanese with English abstract).

Kimata, F., and T.Yamauchi, A correction for temperature on electro-optical distance measurement, J.Geod.Soc.Jpn., 27, 173-182, 1981 (in

Japanese with English abstract).

Kimata, F., and T.Yamauchi, Electro-optical distance measurements in the Tokai region, Central Japan (1977-1981), Zishin (J.Seismol.Soc.Jpn.), Ser. 2, 36, 203-211, 1983 (in Japanese with English abstract).

Nakane, K., Horizontal tectonic strain in Japan (I and II), J.Geod.Soc. Jpn., 19, 190-208, 1973 (in Japanese with English abstract).

Owens,J.C., Optical refractive index of air : Dependence on pressure, temperature, and composition, Appl. Opt., 6, 51-59, 1967.

Savage, J.C., M.Lisowski, and W.H.Prescott, Strain accumulation in Western Washington, J.Geophys.Res. 96, 14493-14507, 1991

Savage, J.C., and .H.Prescott, Precision of Geodolite distance measurements for determining fault movements, J.Geophys.Res. 78, 6001-6008, 1973.

Seno, T., Y.Moriyama, S.Stein, D.F.Woods, C.Dewets, D.Argus, and R.Gordon, Redetermination of the Philippine Sea plate motion, EOS Trans.AGU, 68,1474, 1987.

Tousya, M., Forming and disappearing of the reversal layer near the ground surface, J.Meteorolog.Res., 5, 649-654, 1953 (in Japanese).

Yoshida, A., and K.Maeda, Seismic quiescence appearing in the west coast region of Suruga bay, Zishin (J.Seismol.Soc.Jpn.), Ser. 2, 43, 27-42, 1990 (in Japanese with English abstract).

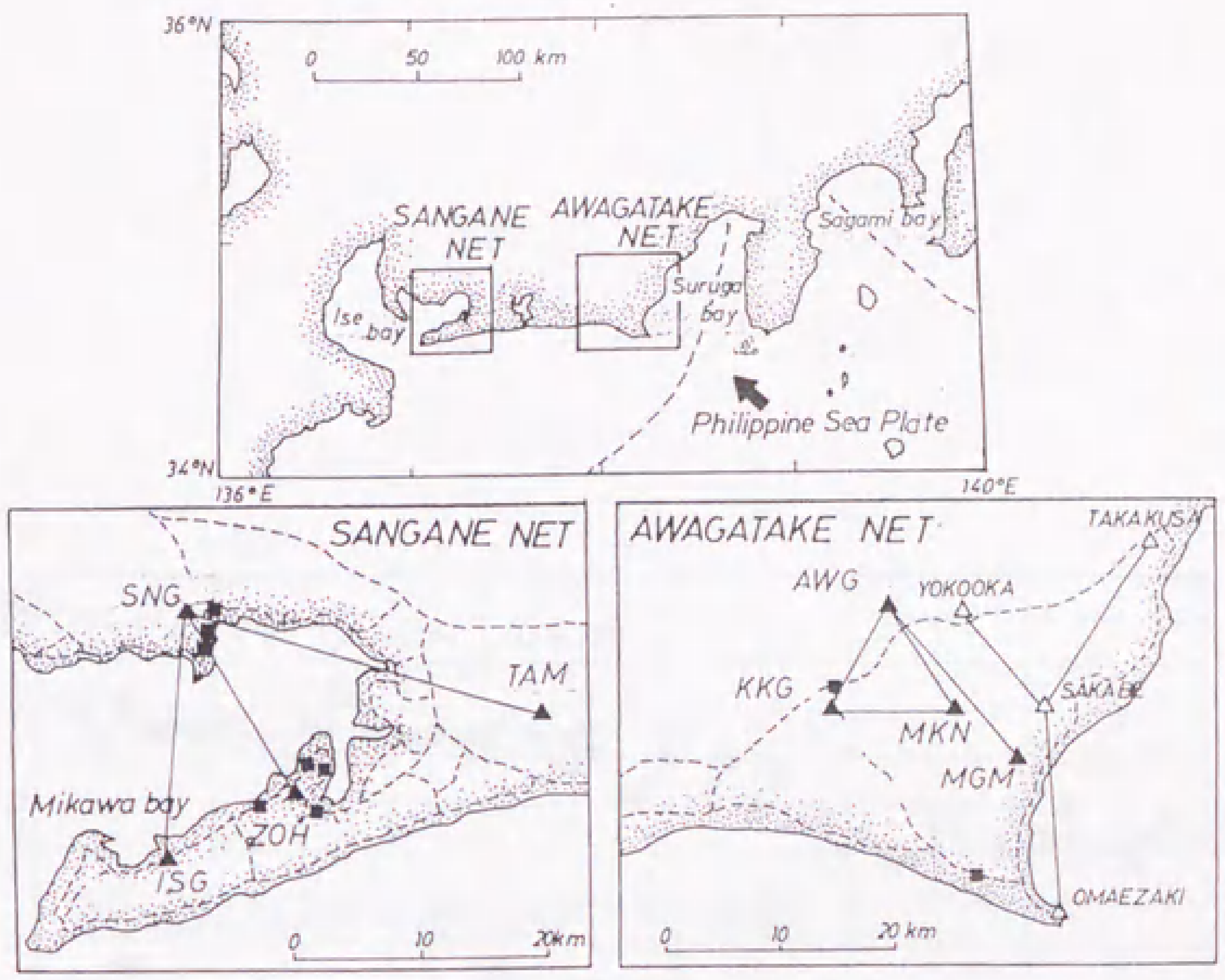

Figure 1

Map of the Tokai region showing the location of baseline networks. The Sangane network consists of three baselines, SNG - ZOH (16 km), SNG - TAM (19 km) and SNG - ISG (29 km); and the Awagatake network, four baselines, AWG - MGM (18 km), AWG - MKN (10 km), MKN - KKG (9 km) and KKG - AWG (9 km). Closed squares show the bench marks of levelling discussed in text. Open triangles (Takakusa, Yokooka, Sakabe, Omaezaki) are the stations of the Omaezaki radiant baseline network by GSI [GSI,1974,1991].

SNG; Sangane, ZOH; Zaoh, TAM; Tame, ISG; Ishigami, AWG; Awagatake, MGM; Megami KKG; Kakegawa, MKN ; Makinohara

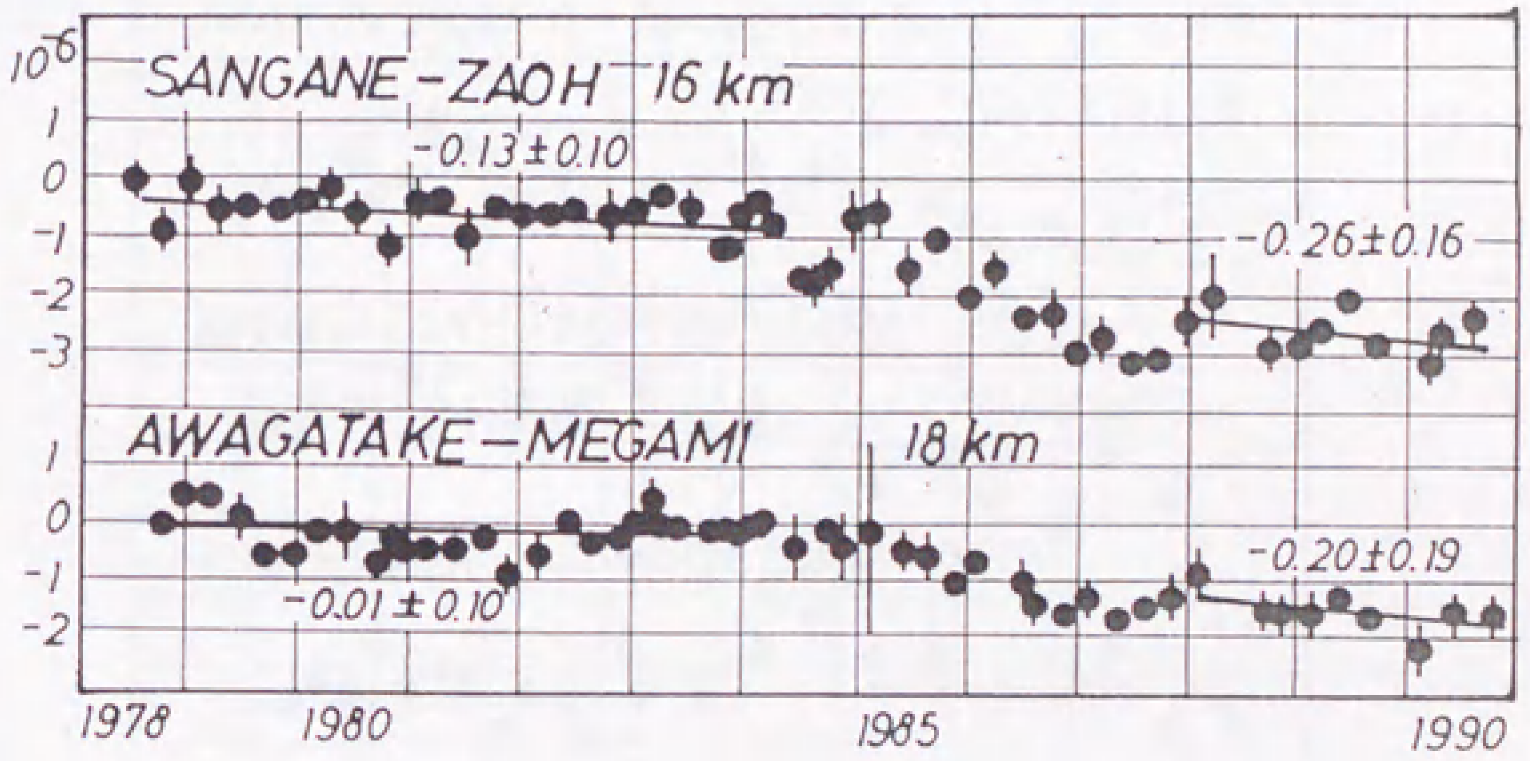

Figure 2

Linear strains plotted against time for the baselines SNG-ZOH and AWG-MGM. Linear strains are the ratios dL/L, where dL is the change in baseline length L since 1978. The error bars denote the standard error of measurements. Strain rates are given from linear fits for two periods, 1978-1985 and 1988-1990.

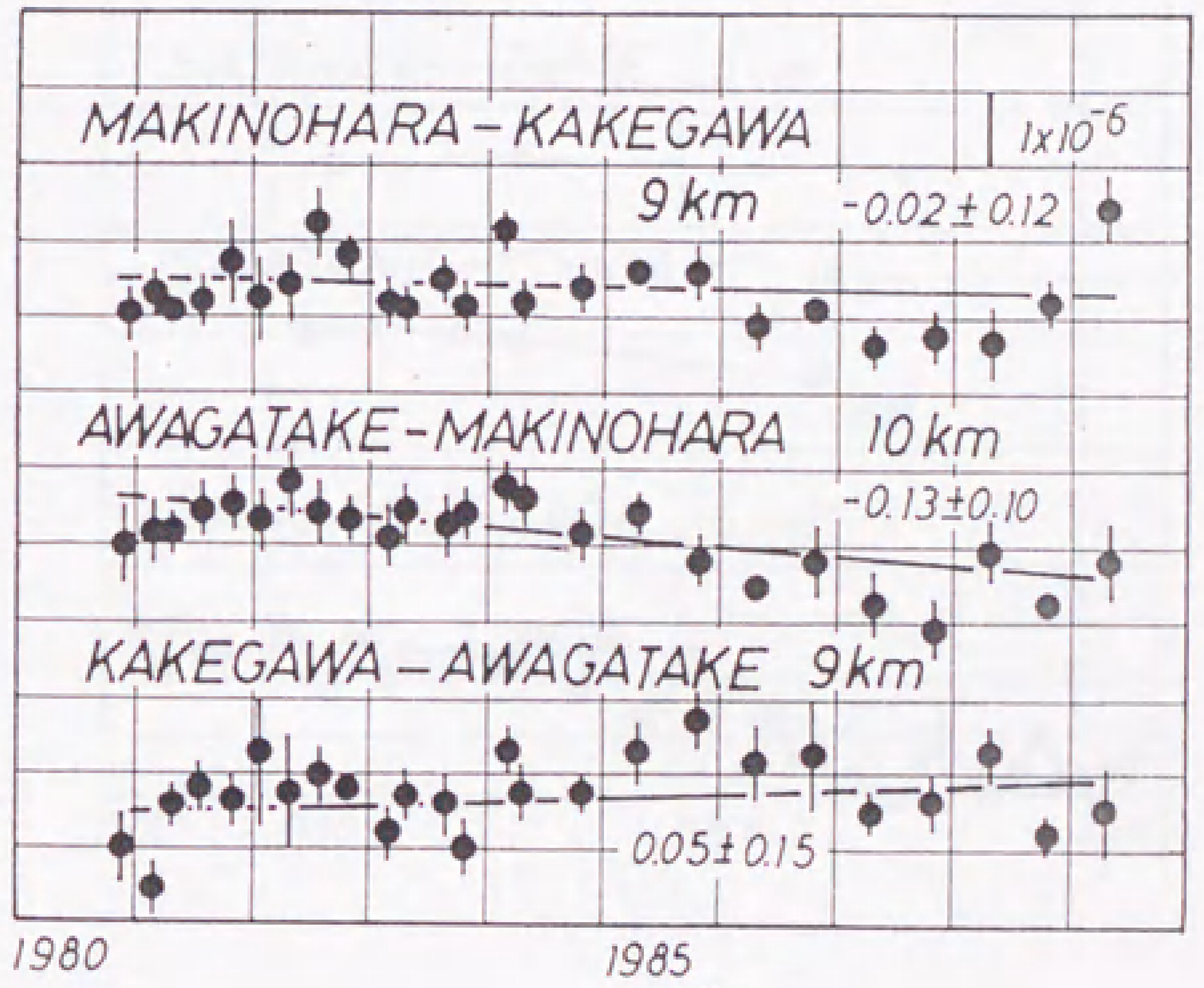

Figure 3

Linear strains plotted against time for the baselines of the Awagatake network. Notations are the same as in Figure 2.

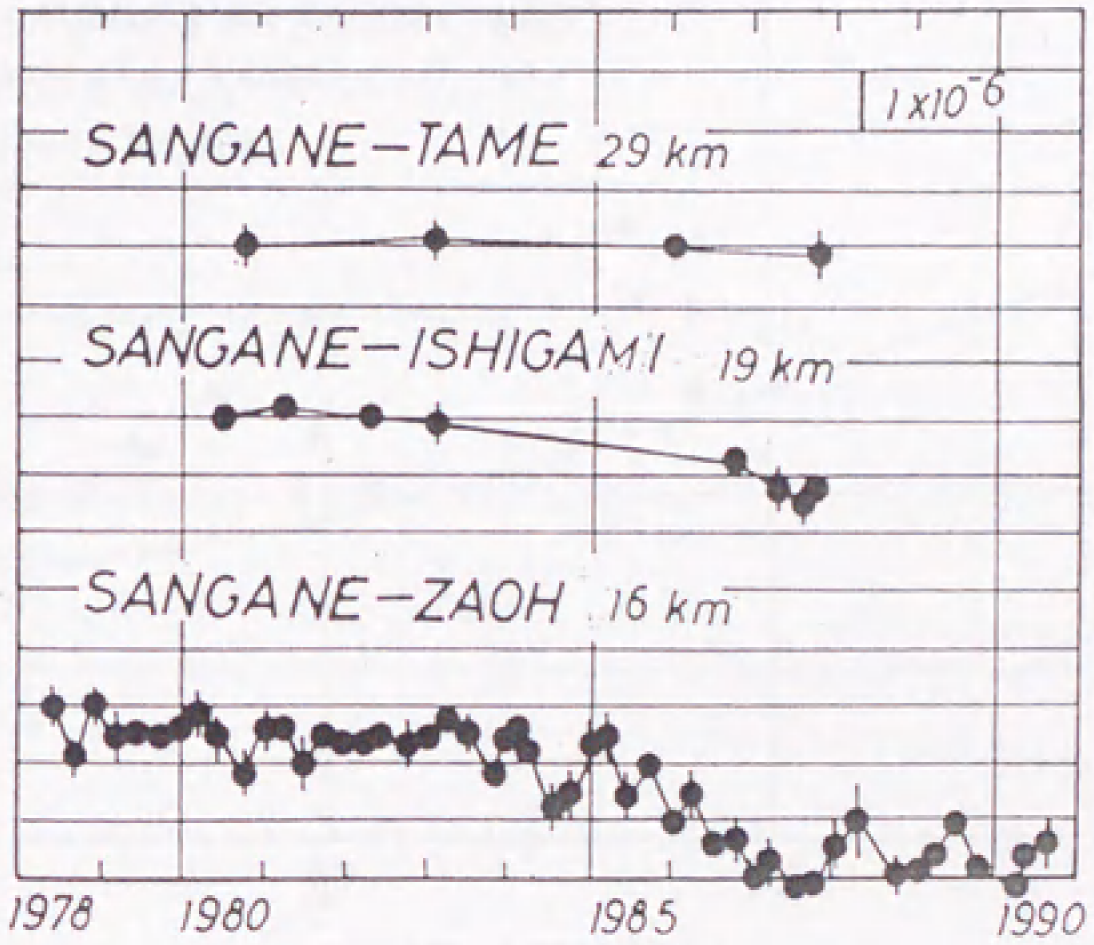

Figure 4

Linear strains plotted against time for the baselines of the Sangane network. Notations are the same as in Figure 2.

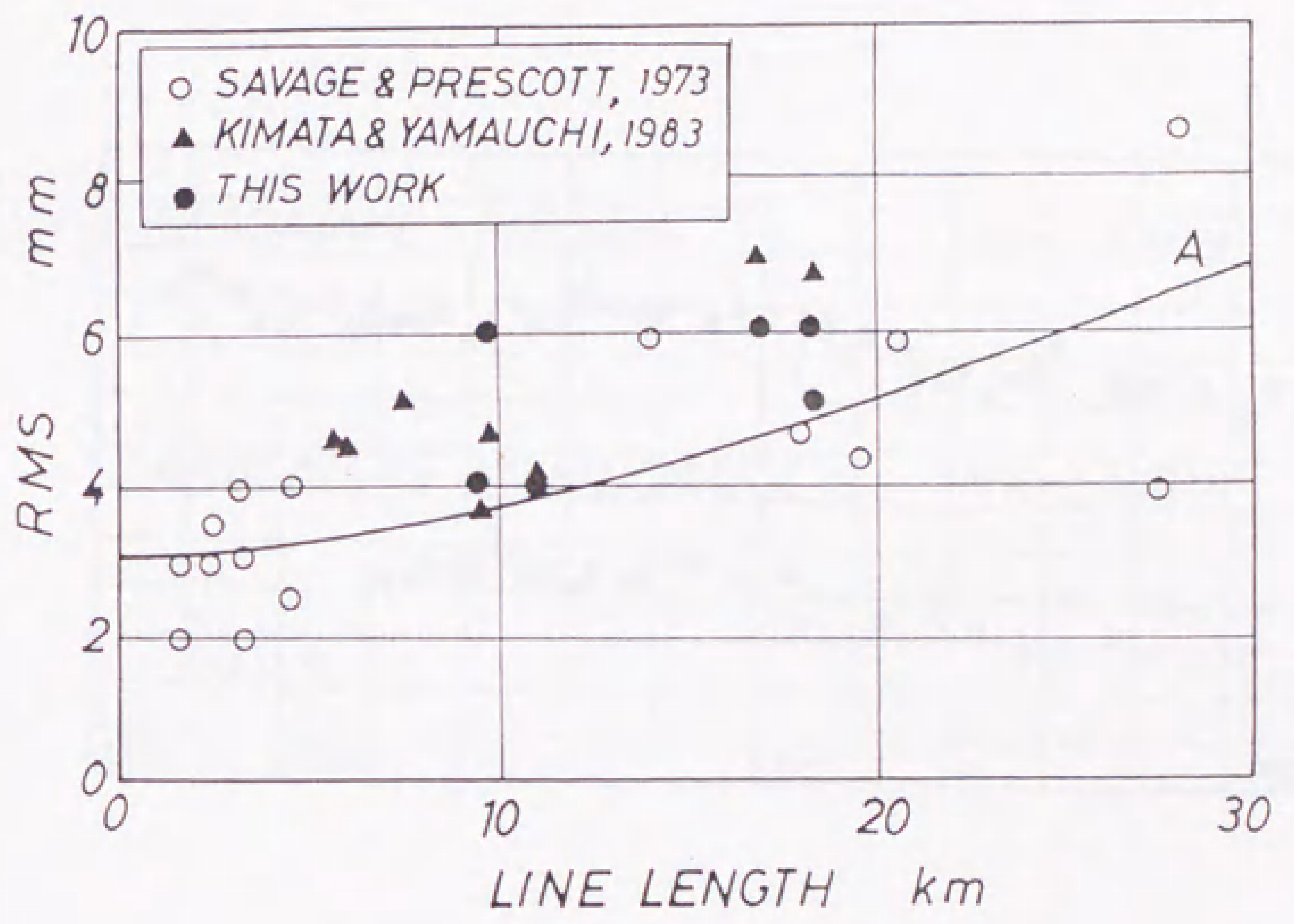

Figure 5

EDM errors plotted against baseline length. Line A stands for the equation (1) in the text. Open circles are due to SAVAGE and PRESCOTT [1973]; closed triangles, KIMATA and YAMAUCHI [1983]; and closed circles, this paper.

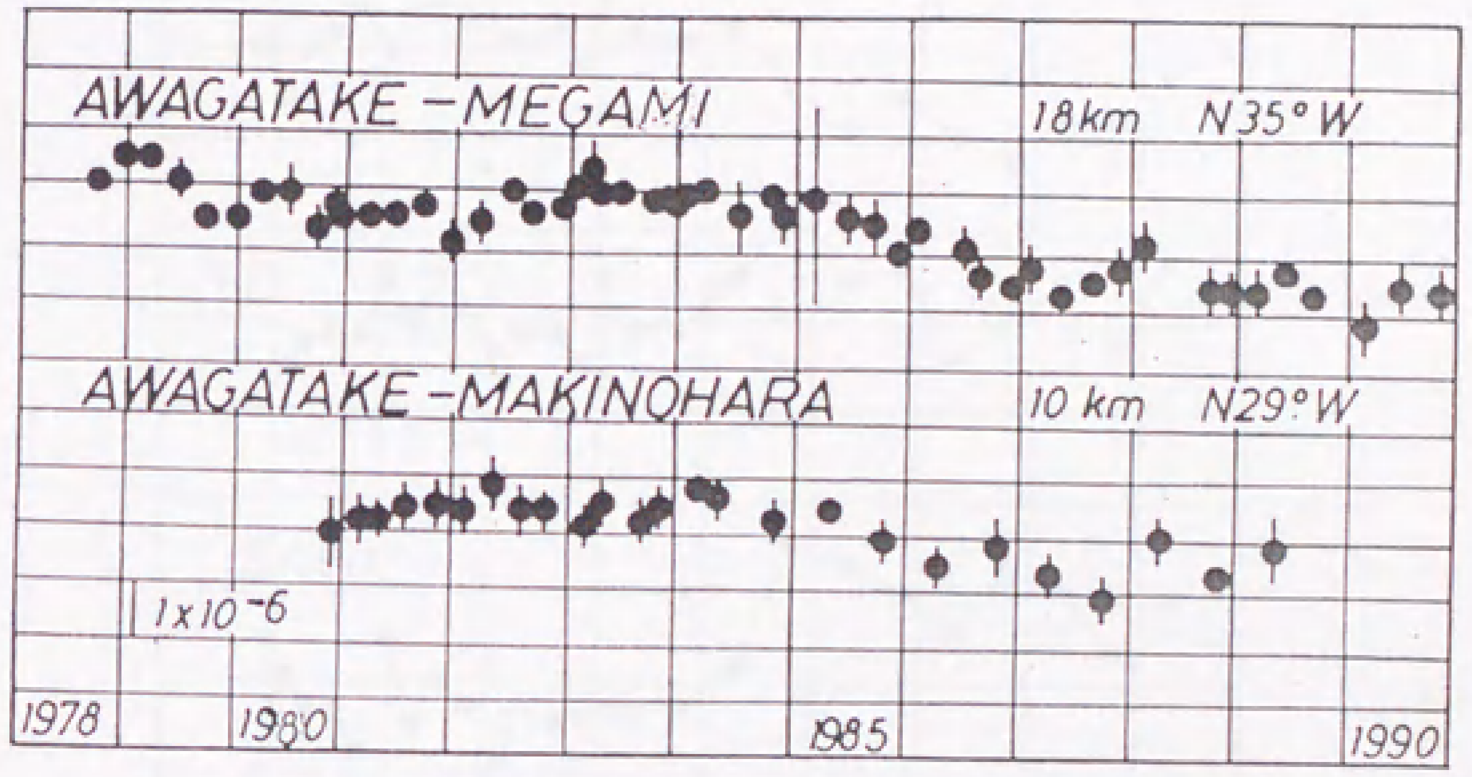

Figure 6

Comparison between strain changes along baselines Awagatake-Megami (AWG-MGM), and Awagatake-Makinohara. The error bars represent one standard error on either side of the plotted mean value.

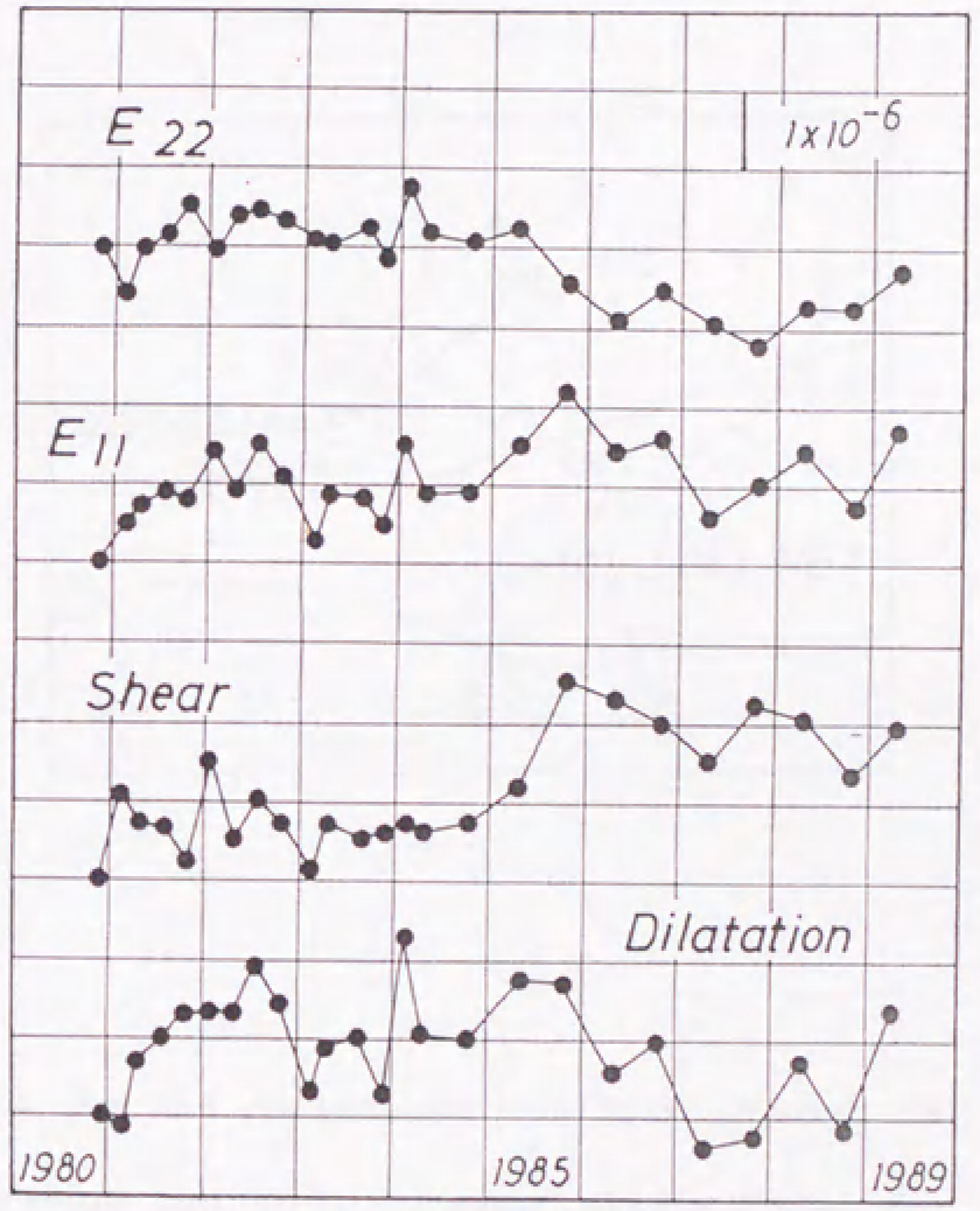

Figure 7

Temporal changes in strain components in the Awagatake baseline network. E_{11} and E_{22} are principal strain components; the maximum shear strain ($E_{11}-E_{22}$); dilatation ($E_{11}+E_{22}$).

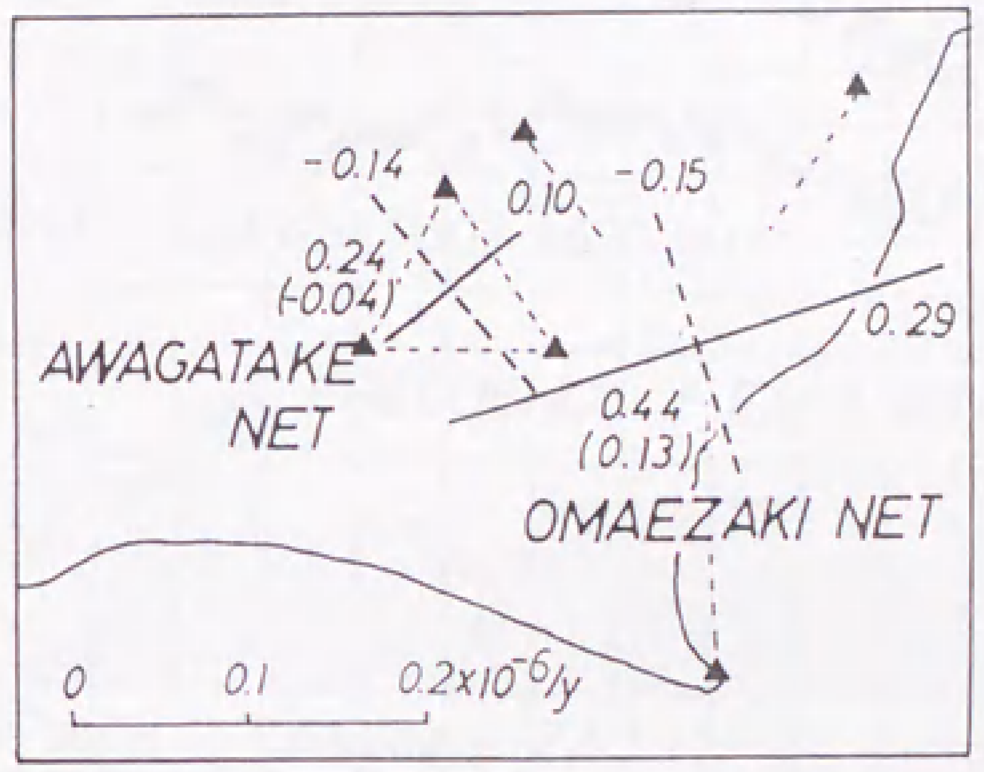

Figure 8

Strain fields for the Awagatake baseline network and the Omaezaki radiant baseline network. Linear strain rates for baselines are determined by the method of least squares and are used in the calculation of horizontal strains for the networks. GSI [1991] had conducted survey for the Omaezaki network. Solid and dashed lines mean extension and contraction, respectively. Numeral along the lines; principal strain, the value at the center; shear strain, the value in the blanket; dilatation.

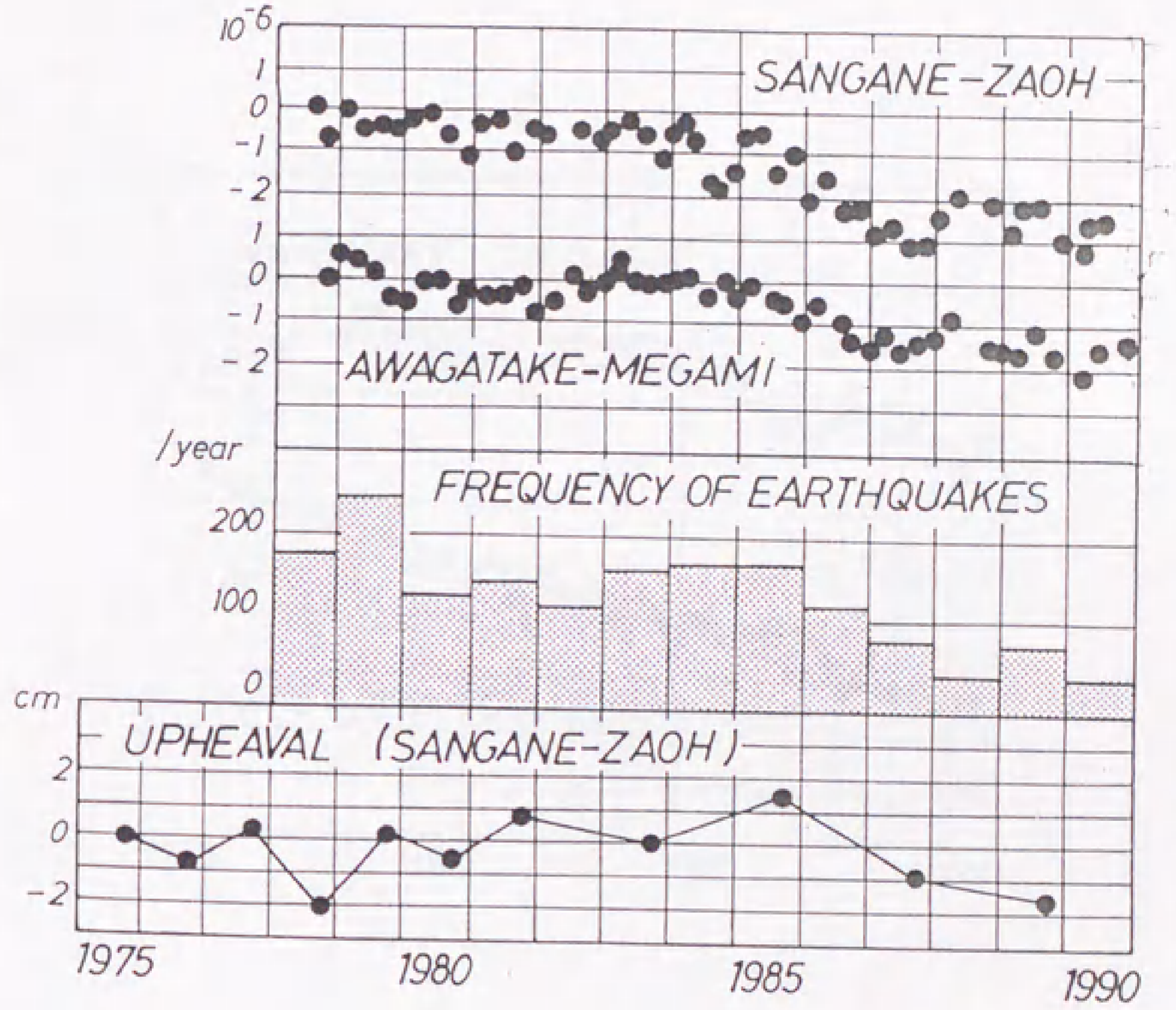

Figure 9

Comparison between changes of baseline length, seismic activity and vertical movement. Above: Change in length for the baselines SNG-ZOH and AWG-MGM. Middle: Annual frequency of earthquakes ($M > 0$, depth < 20 km) in the polygon shown in Figure 11. Below: The average altitude of BMs near Sangane relative to that of from BMs near Zaoh. Levelling data are due to Aichi-ken [1991].

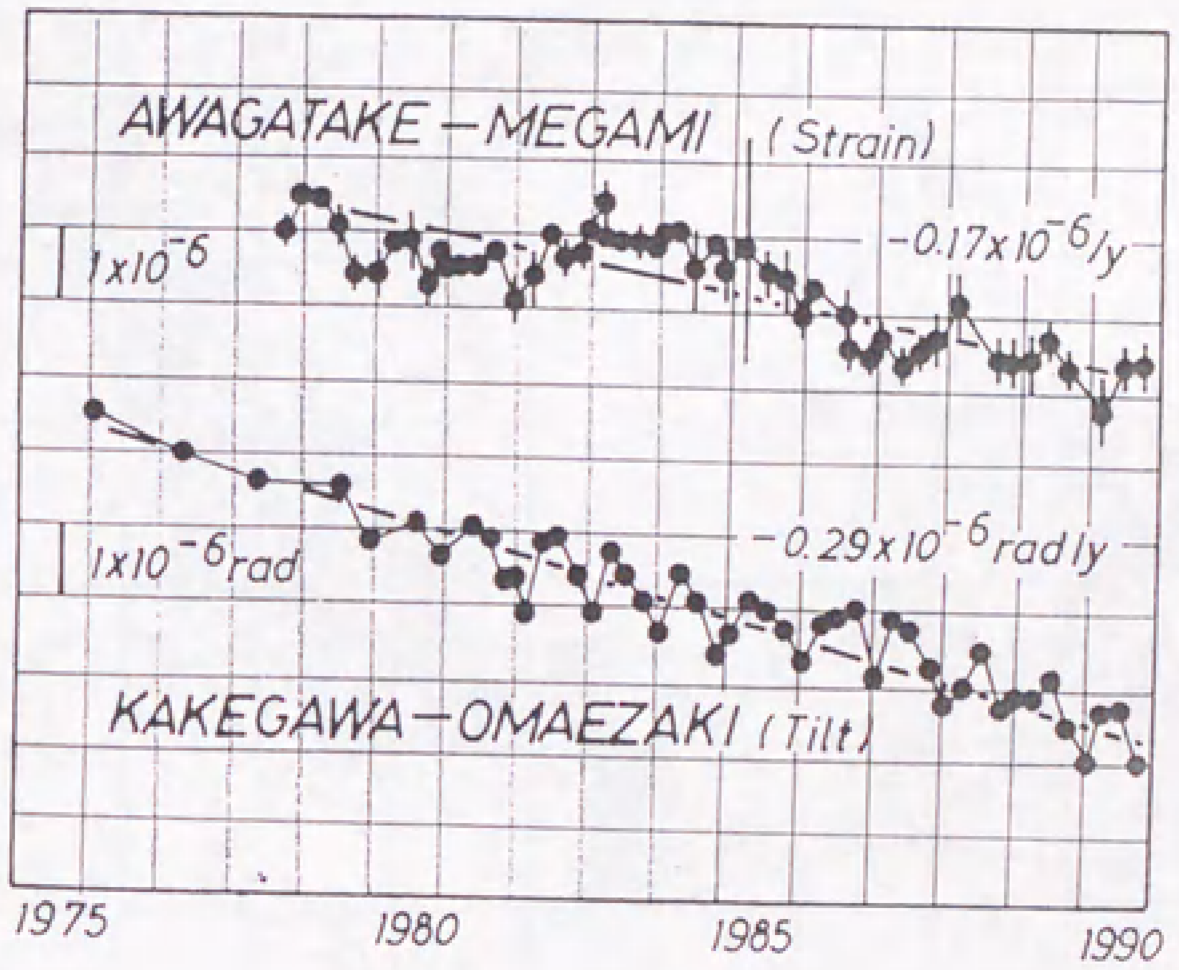

Figure 10

Comparison between horizontal strain change along the AWG-MGM baseline and the geodetic subsidence of Omaezaki relative to Kakegawa. The strain rate and the geodetic tilt rate are estimated by the linear fits of data for the two periods 1978-1990 and 1975-1990. Data of precise levelling are obtained by GSI (1991), and no correction for seasonal variation was made to the levelling data.

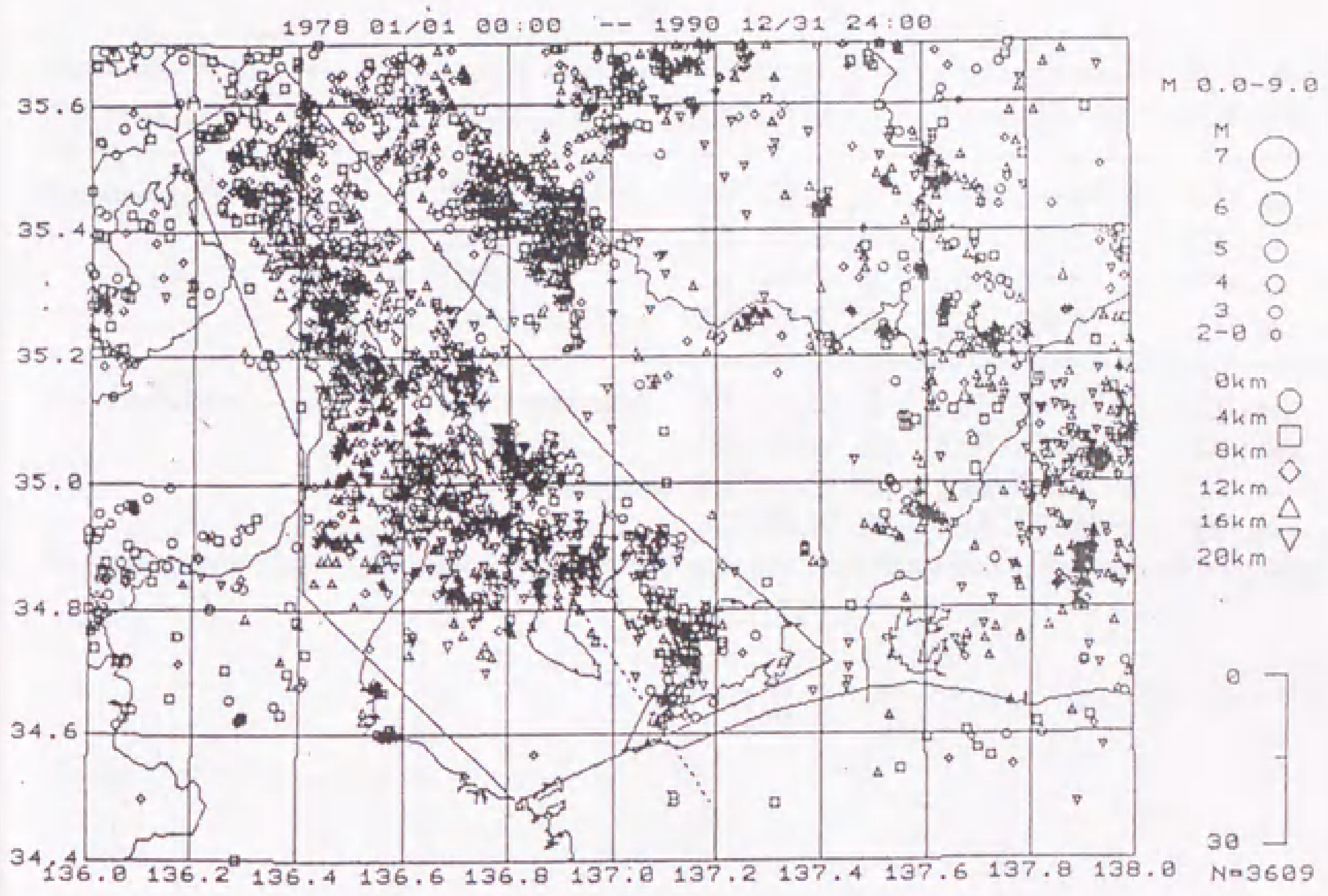

Figure 11

Seismicity in the Tokai region. Epicenters of events shallower than 20 km in depth for the period in 1978-1990 are plotted. Magnitude and depth are illustrated on the right. The epicentral map is due to the Research Center for Seismology and Volcanology, School of Science, Nagoya University.

Table 1

Location of EDM stations of the Sangane and Awagatake networks.

Network	Station	Latitude	Longitude	Height
Sangane	Sangane	34°48.5’ N	137°09.8’ E	320 m
	Zaoh	34°40.9’ N	137°15.5’ E	220 m
	Tame	34°44.8’ N	137°28.6’ E	320 m
	Ishigami	34°38.3’ N	137°08.2’ E	60 m
Awagatake	Awagatake	34°50.5’ N	138°04.3’ E	510 m
	Megami	34°45.4’ N	138°11.0’ E	100 m
	Makinohara	34°44.9’ N	138°08.3’ E	150 m
	Kakegawa	34°45.2’ N	138°01.7’ E	100 m

Table 2

Average strain rates of baseline networks Sangane, Awagatake and Omaezaki.

Baseline	Length (km)	Azimuth (degree)	Strain rate (10^{-6}/year)	RMS (mm)	Period
Sangane-Zaoh	16.8	N38°W	- 0.24 ± 0.10	8	1978-1990
			- 0.13 ± 0.10	6	1978-1984
			- 0.26 ± 0.16	6	1988-1990
			- 0.10 ± 0.15	7	1978-1981*
Awagatake-Megami	18.0	N35°W	- 0.17 ± 0.09	8	1978-1990
			- 0.01 ± 0.10	6	1978-1984
			- 0.20 ± 0.17	5	1988-1990
			- 0.28 ± 0.13	7	1978-1981*
Awagatake-Kakegawa	9.8	N25°E	0.05 ± 0.15	6	1980-1989
Kakegawa-Makinohara	9.7	N85°W	- 0.02 ± 0.12	4	1980-1989
Makinohara-Awagatake	10.9	N29°W	- 0.13 ± 0.10	4	1980-1989
Sakabe-Takakusa	18.3	N34°E	0.12 ± 0.24	25	1974-1989**
Sakabe-Omaezaki	18.5	N 6°W	- 0.13 ± 0.27	15	1974-1989**
Sakabe-Yokooka	13.0	N45°W	- 0.06 ± 0.36	14	1974-1989**

* ; KIMATA and YAMAUCHI [1983] **; GSI [1991]

Table 3

Strain fields observed at the Awagatake and Omaezaki net

		Awagatake net	Omaezaki net
Period		1980 -1989	1974 - 1989
Shear strain	(10^{-6}/year)	(0.24±0.14)	(0.44±0.46)
Dilatation	(10^{-6}/year)	-(0.04±0.20)	(0.14±0.58)
Maximum strain	(10^{-6}/year)	0.10	0.29
	(azimuth)	N 50°E	N 73°E
Minimum strain	(10^{-6}/year)	- 0.14	- 0.15
	(azimuth)	N 40°W	N 17°W

Table 4

Strain rate in the Tokai region

Strain rate* 10^{-6}/year	Period	Method of measurements	Reference
0.19 ± 0.14	1884-1968	ANG	NAKANE(1973)
0.32 ± 0.12	1884-1973	ANG EDM	KAIDU and SATO(1978)
0.23	1884-1973	ANG EDM	FUJII and NAKANE(1979,1980)
0.35	1884-1973	ANG EDM	DAMBARA(1980)
0.34 ± 0.16	1974-1984	EDM	FUJII and KADOWAKI(1987)
0.24 ± 0.14	1980-1990	EDM	THIS WORK

ANG; triangulation
EDM; trilateration
* ; rate of shear strain