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https://doi.org/10.5109/1546871

出版情報：九州大学大学院理学研究院紀要 : Series D, Earth and planetary sciences. 31 (3), pp.93-104, 2005-02-28. Faculty of Science, Kyushu University
バージョン：

Mem. Fac. Sci., Kyushu Univ., Ser. D, Earth & Planet. Sci., Vol. XXXI, No. 3,
pp. 93-104, text-figs. 1-7, tables 1-2, February, 2005

Horizontal Strain Changes in Southwest Japan Using Partitioning Model and GPS Data (1997-2000)

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Abstract

In order to estimate the horizontal strain of southwest Japan for the period of Nov. 1997 to Nov. 2000, using GPS data of the Geographical Survey Institute of Japan, after making an unbiased data, we derived two empirical covariance functions by applying least-square prediction method. During a repeated calculation, we compared the effect of correlation distances with the measurement vectors of different points and partitioned whole Japan into two main regions, where the correlation distances for two E-W and N-S components could be equal. The partitioning boundary has a good coincidence with the Fossa Magna which is considered to be a plate boundary between the Okhotsk and the Eurasian plates. We estimated the correlation distance of southwest Japan as 250 km and derived two new covariance functions to compute the horizontal strain of this region. During Nov. 1997-Nov. 1998, from central to east Kyushu, there is a widespread shear anomaly, 0.24×10^{-6}/yr, that may refer to the effect of the Hyuganada earthquakes on Oct. 19, 1996 and Dec. 03, 1996. Also this anomaly is extended into Shikoku Island and could be related to some slow slip displacements because of lacking any large events. Most of the Shikoku Island is under shear strain that extended to the southern part of the Kinki area too. The strain state in southwest Japan is characterized by NW-SE contraction in most places that may be attributed to the convergence of the Eurasian, the Philippine Sea and the Pacific plates. In central Kyushu Island, N-S extension could be due to the mantle pluming under western off Kyushu. Also the NW-SE and E-W extension in the southwestern part of Kyushu and west off Yakushima Islands could be caused by the expansion of the Okinawa trough.

Keywords: GPS, strain, Japan, partitioning model

I. Introduction

A dense array of continuous GPS tracking network in Japan is a good tool for monitoring crustal deformation. The Geographical Survey Institute of Japan (GSI) has increased the number of the GPS sites to about 1000 by 1997 as shown in Fig. 1.

Manuscript received September 7, 2004; accepted December 15, 2004.
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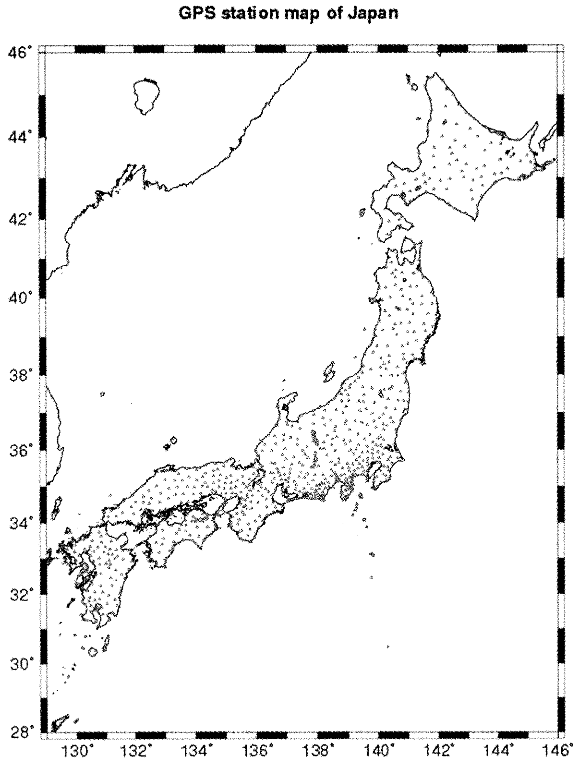

Fig. 1. Distribution of continuous GPS station array have been operating by the Geographical Survey Institute of Japan (GSI) with approximately 20km in density.

MIYAZAKI *et al.* (1977) estimated the velocity field of the Japanese Islands relative to the Eurasian plate by using this network. The results indicated a prominent westward motion of the northeastern part of Japan and a northwestward movement of its southwest part. This clearly could be due to the effects of subduction of the oceanic plates under the Japanese Islands. In this paper, in order to estimate the horizontal deformation of Japanese Islands from 1997 to 2000, the average of latitude and longitude of daily GPS data of GSI, was used to calculate the velocity fields from 1997 to 2000. By using these data, we derived two empirical covariance functions of the horizontal crustal movements, one for the East-West and the other for the North-South component. As the displacement components in E-W and N-S directions were assumed to be homogenous and isotropic, the correlation distance in these directions should be equal. For achieving this aim in our calculations, by checking different latitudes and longitudes throughout Japan, we find only two major parts, Southern and Northern parts (Fig. 2), that the correlation distances of E-W and N-S components in every part could be equal. The differences between the correlation distances in these two parts could be due to the different tectonic setting of these areas.

Then we use the covariance functions of northern and southern parts separately to estimate the displacement vectors or signals of any arbitrary points by using least-square prediction method (EL-FLKY *et al.*, 1999). After all by getting spatial differentiation, we estimate the strain components in terms of the covariance function.

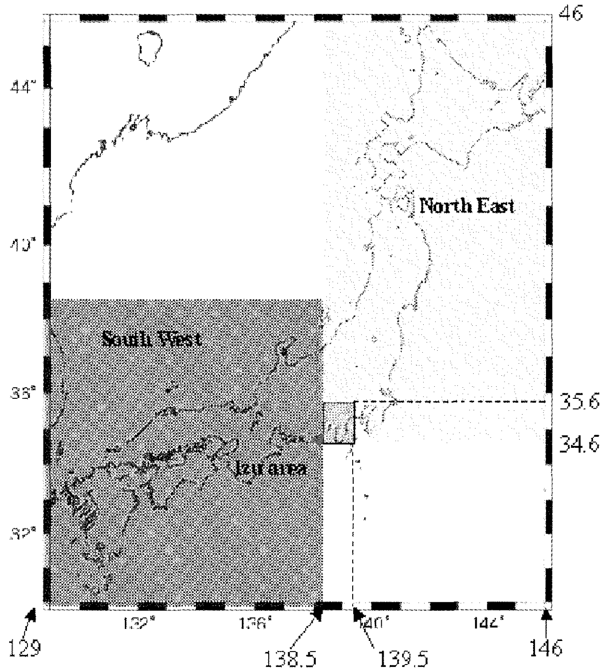

Fig. 2. Partitioning map of Japan for estimating the horizontal strain by using PMSD. We referred the Izu area as a subdivision of the northeast part.

II. Method

We discuss about the methodology of estimating the horizontal strain by using least-square collocation and partitioning model. The least-square collocation at first proposed by MORITS (1962) for application in the gravity anomalies and also KRARUP (1969) as a general least-squares theory for estimating any element of earth's gravity field. Later this method was used by FUJII and XIA (1993) and EL-FIKY *et al.* (1997) for estimating the vertical strains. EL-FIKY and KATO (1999) used the least-squares collocation technique (*e.g.*, HEIN 1986; HEIN and KISTERMANN 1981; BENCINI *et al.*, 1982) for estimating the tectonic signal and horizontal strain components.

For estimating the signal at any arbitrary points we used the following formula (MORITZ, 1962).

$$\hat{S} = C_{st} C_L^{-1} L \qquad (1)$$

where C_L is the total covariance of observations and is expressed as

$$C_L = C_t + C_n \qquad (2)$$

C_t and C_n are covariance summation of signal and noise, respectively. L is the total measurement vector. After removing systematic parameters, it could be defined as

$$L = t + n \qquad (3)$$

where $\boldsymbol{t}$ is the signal vector at the observation points, and $\boldsymbol{n}$ is the vector of the noise that represents the measurement error. Therefore, by calculating the $\hat{S}$, we can predict the signals at any arbitrary points.

C_{st} is the covariance matrix between signal $\boldsymbol{t}$ at the observation points and signal $\boldsymbol{s}$ at any arbitrary points and may be calculated by

$$C_{st} = \sum_{i=1}^{N} C_t \exp(-k^2 d_t^2) \qquad (4)$$

where N is the number of observation points, $\boldsymbol{d}$ is the distance between observation point and any other points. Two parameters C_t and $\boldsymbol{k}$ are estimated from a covariance plot of the data and are represented the expected variance at the observation sites, $C_t\,(0)$, and correlation distance indicator,

Table 1. Changes of parameter $\boldsymbol{k}$ in different latitude and longitude for both E-W and N-S components for three periods.

I : 1997-1998

Longitude	Latitude	k_x	k_y	$\lvert((k_x - k_y) / k_y)\rvert \times 100$	$C_n(0)_x$	$C_n(0)_y$
129-138.5	**28-38**	**0.007785**	**0.00759**	**2.56**	**0.1504**	**0.1048**
138.5-146	**34.6-46**	**0.009538**	**0.013022**	**26.75**	**0.2278**	**0.0169**
138.5-146	32-46	0.009416	0.012022	21.68	0.2433	0.0813

II : 1998-1999

Longitude	Latitude	k_x	k_y	$\lvert((k_x - k_y) / k_y)\rvert \times 100$	$C_n(0)_x$	$C_n(0)_y$
129-131	28-38	0.009406	0.010223	7.9	0.2813	0.091
129-132	28-38	0.011113	0.009376	18.5	0.2775	0.3849
129-133	28-38	0.008358	0.008046	3.7	0.4199	0.1386
129-135	28-38	0.008755	0.007277	16.1	0.3189	0.0947
129-136	28-38	0.00832	0.006798	22.38	0.4307	0.158
129-137	28-38	0.00795	0.007048	11.9	0.4258	0.1479
129-138	28-38	0.007702	0.00748	2.6	0.3762	0.1382
129-138.5	**28-38**	**0.007892**	**0.007613**	**3.8**	**0.2639**	**0.1338**
129-139	28-38	0.00719	0.007631	6.12	0.2638	0.13
129-140	28-38	0.006059	0.007894	30.19	0.2615	0.1675
129-141	28-38	0.00538	0.008035	32.9	0.3704	0.1562
129-142	28-40	0.00529	0.0082	34.89	0.3076	0.1355
138.5-146	32-46	0.010133	0.013755	26.33	0.294	0.045
138.5-146	34.2-46	0.009338	0.011054	15.52	0.2993	0.0406
138.5-146	**34.6-46**	**0.010246**	**0.014505**	**29.36**	**0.2811**	**0.004**

Ⅲ : 1999-2000

Longitude	Latitude	k_x	k_y	$\|((k_x - k_y) / k_y)\|$x100	$C_n(0)_x$	$C_n(0)_y$
129-138.5	**28-38**	**0.006846**	**0.006664**	**2.73**	**0.6159**	**0.3295**
137-141	32-38	0.009747	0.013528	27.95	0.544	0.152
137.3-141		0.010782	0.01396	22.77	0.528	0.1614
139-146	32-46	0.00952	0.016176	41.15	0.7948	0.0079
138.5-146	**34.6-46**	**0.0107**	**0.012186**	**12.19**	**0.6554**	**0.1309**

x and y: E-W and N-S directions, respectively.
C_n (0): covariance of noise at the observation points.

respectively. $C_n(0) = C_L(0) - C_t(0)$ is considered as the noise component at the station. We have assumed a homogeneous and isotropic area in this method. Therefore, our calculation should be done on a homogeneous and isotropic region with a same tectonic setting. In this case, the correlation distances of EW and NS components should be equal. For improving this hypothesis HOSSEINI (2002) had calculated repeatedly by using formula (4) through different longitudes and latitudes all over Japan (Table 1). In Table 1 we showed a part of calculated results. It is not unique but we show the two major parts called SW-Japan and NE-Japan. Their correlation distances of each part for both E-W and N-S components are nearly equal. The partitioning boundary locates nearly along 138.5 °E. It may show a coincidence with Fossa Magna where is assumed to be a plate boundary between the Okhotsk and the Eurasian plates.

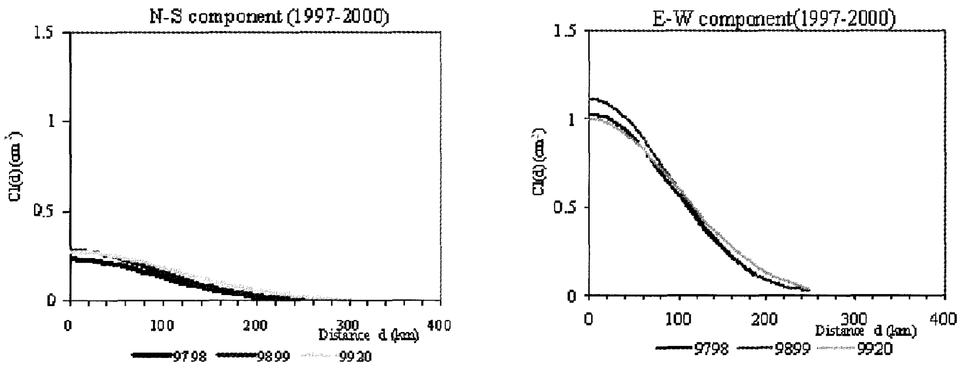

Fig. 3. Fitted curves using variance and covariance samples of displacement vectors for three periods of study. As it is shown, the correlation distances for both E-W and N-S components could be considered as 250 km.

III. Partitioning model

By using the parameter $\boldsymbol{k}$ in Eq. 4, which has the dimension of inverse of distance and is called the inverse characteristic of correlation distance, we had repeated calculations on different latitudes and longitudes throughout Japan. We showed a part of our calculations in Table1. It is not unique but we suggested two major parts with different amount of correlation distance in the end of the former section. In each part the constant $\boldsymbol{k}$ in E-W and N-S directions (k_x, k_y) comes to be nearly equal (Table 1). From 129°E to 139°E, the differences between $\boldsymbol{k}$ parameters of both components are less than 23% and in the area between 129°E-138°E and 129°E-138.5°E, these differences come to be less than the others for about 2.6 and 3.8 percent, respectively (Table 1b). The covariance of noise in 129°E-138.5°E is less than the area between 129°E-138°E therefore, we choose the area between 129°E-138.5°E as a part where the correlation distances in the E-W and N-S directions could be considered as equal($\boldsymbol{k_x}= \boldsymbol{k_y}= 0.008$). However there are smaller differences between $\boldsymbol{k}$ parameters in 129°E-138°E. By extending the area into140°E and more, the differences of $\boldsymbol{k}$ parameters will increase rapidly to more than 30%. In the same way, from 138.5°E to 146°E, we found some other amount of $\boldsymbol{k}$ parameters, $k_x= 0.010246$, $k_y= 0.014505$, which their difference is about 29.36% in this area. Relatively, the large differences of $\boldsymbol{k}$ parameters in this area could be due to some earthquakes that have occurred frequently. However, we had to remove some data points in Izu area (Fig. 2). As a result, the correlation distance that we may consider for SW part is about 250 km (Fig. 3). The amount of $\boldsymbol{k_x}$ and $\boldsymbol{k_y}$ during 1999-2000 is a little different from that in other years that may be due to the occurrence of some large events which have caused a lot of noise (*e.g.* Western Tottori and Miyakejima earthquakes).

IV. Covariance samples and horizontal strains

In order to estimate the covariance function of the horizontal displacement in two areas that was derived by partitioning model, we used the horizontal displacement data for the three periods of 1997-1998, 1998-1999, and 1999-2000. In all the periods we consider the data from the first of November of every year to the end of November of its next year. Therefore, we have just one month covering of data between two adjacent periods. Since some observation points in Fig. 1 had some abnormal displacement that may be caused by some artificial movements or occurrence of some earthquakes, we omitted these data from our calculations and therefore the number of data point comes to be different in each period. The total numbers of used data points are listed in Table 2 for three periods from I to III. For making a non-biased set we removed the average of the displacement vectors from each site. After determining the covariance functions, we could predict the signals for both components $\boldsymbol{u}$ and $\boldsymbol{v}$ at any arbitrary point by using Eq. (1).

Table 2. Total number of GPS sites and the number of used data points for three periods.

Period	Total number of data points	Used data points in South part
I. 1997-1998	888	457
II. 1998-1999	888	472
III. 1999-2000	969	459

We make a 20 km by 20 km grid map for Japanese Islands and estimated the horizontal displacement components or the signals at all the grid points by using the observed signals at the GPS stations. For estimating the horizontal strain components, we used the following equations:

$$\varepsilon_{xx} = \partial U / \partial x \ , \qquad \varepsilon_{yy} = \partial V / \partial y \ , \qquad \varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right)$$

where $\boldsymbol{U}$ and $\boldsymbol{V}$ are the velocity vectors in the East-West and the North-South directions, respectively.

Dilatation: $$\Delta = \varepsilon_{xx} + \varepsilon_{yy}$$

Shear strain: $$\gamma_{xy} = \frac{\varepsilon_{xy} + \varepsilon_{yx}}{2}$$

Maximum shear strain: $$\gamma_{max} = \sqrt{\left(\frac{\varepsilon_{xx} - \varepsilon_{yy}}{2} \right)^2 + \varepsilon_{xy}^{\ 2}}$$

Principal strain: $$\varepsilon_{1,2} = \frac{\Delta}{2} \pm \gamma_{max}$$

We showed the maps of maximum shear, dilatation and principal strain axis of Southwest part of Japan estimated by using partitioning model for the three periods in Figs. 4 to 6.

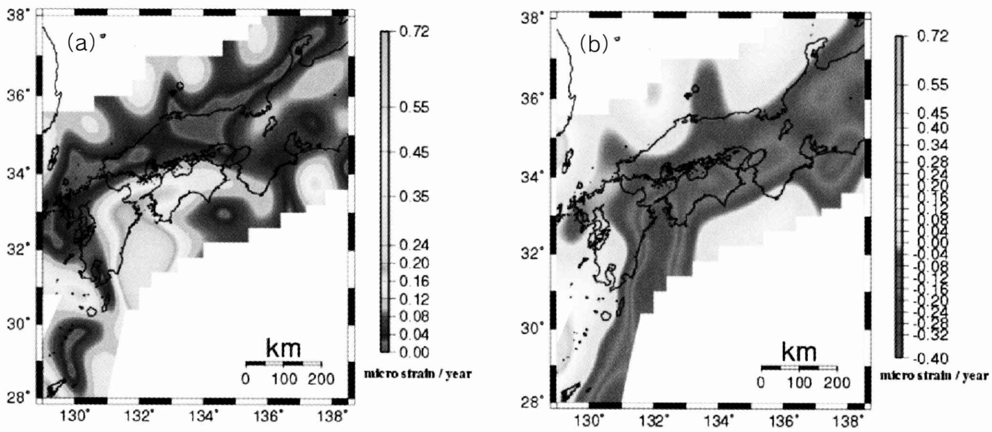

Fig. 4. (a) Maximum shear and (b) Dilatation map of Southwest part of Japan estimated by using Partitioning model for strain distribution (PMSD) during Nov. 1997 - Nov. 1998.

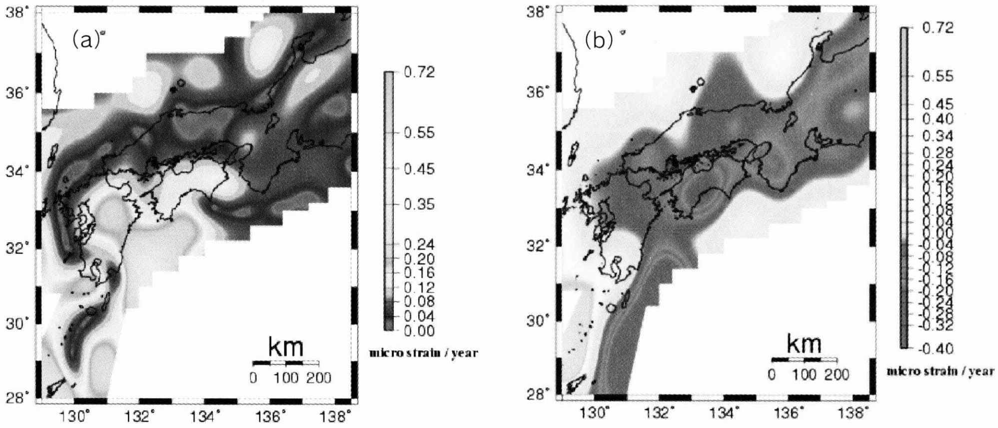

Fig. 5. (a) Maximum shear and (b) Dilatation map of Southwest part of Japan estimated by using Partitioning model for strain distribution (PMSD) during Nov. 1998 - Nov. 1999.

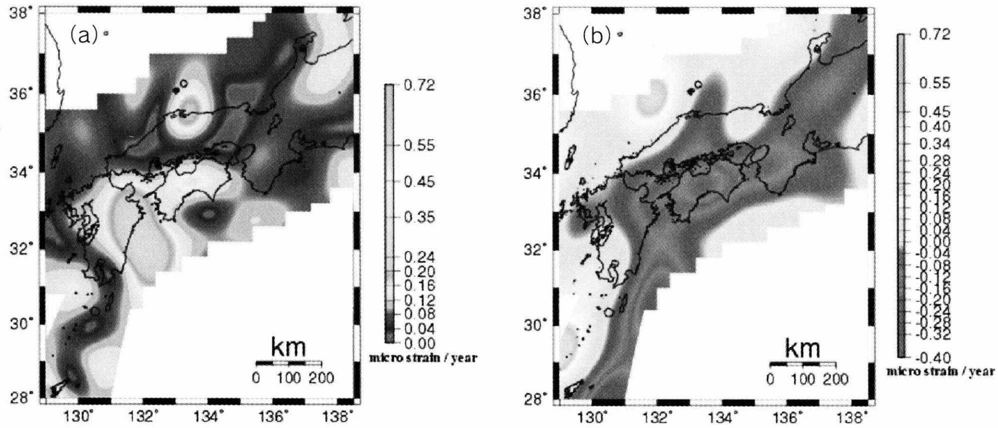

Fig. 6. (a) Maximum shear and (b) Dilatation map of Southwest part of Japan estimated by using Partitioning model for strain distribution (PMSD) during Nov. 1999- Nov. 2000.

V. Results and discussion

SW Japan is located at the east to central margin of the Eurasian plate and is underthrusting beneath the Nankai Trough by the Philippine Sea plate, converging with the margin suborthogonally along a general northwesterly trend, 310° ± 5° , and at a moderate slow rate of 3.5-5.0 cm/yr that increases from east to west (*e.g.* SENO *et al.*, 1993). The current episode of the motion of the Philippine Sea plate with respect to the SW Japan margin began about 5 Ma after a temporary lull in activity for about 7 million years, in NNW direction (SEMO, 1989). Subsequently, the NNW direction of the convergence changed to the current more westerly NW trend at 1-1.5 Ma (NAKAMURA *et al.*, 1984), although this change could have occurred earlier as well (YAMAMOTO, 1993). According to HUZITA (1973, 1980) and KAIZUKA (1980), the current style and the mode of the deformation in SW Japan began especially in late Quaternary. ITOH *et al.* (1998a) reported that the active dexteral motion along the Median Tectonic Line (MTL) intensified at about 1.5 Ma. The source of the stress system is variously attributed to the force transmitted by the convergence of (1) the Pacific plate, affecting eastern SW Japan more than the western parts (HUZITA, 1976; 1980), (2) NE Japan and/or by the Okhotsk-Eurasia relative convergence (SENO, 1985; OIKE and HUZITA, 1988), (3) the Philippine Sea plate (SHIMAZAKI, 1976 b; OKADA, 1989), and (4) the combined effects of the Pacific and the Philippine Sea plates (OKADA, 1980).

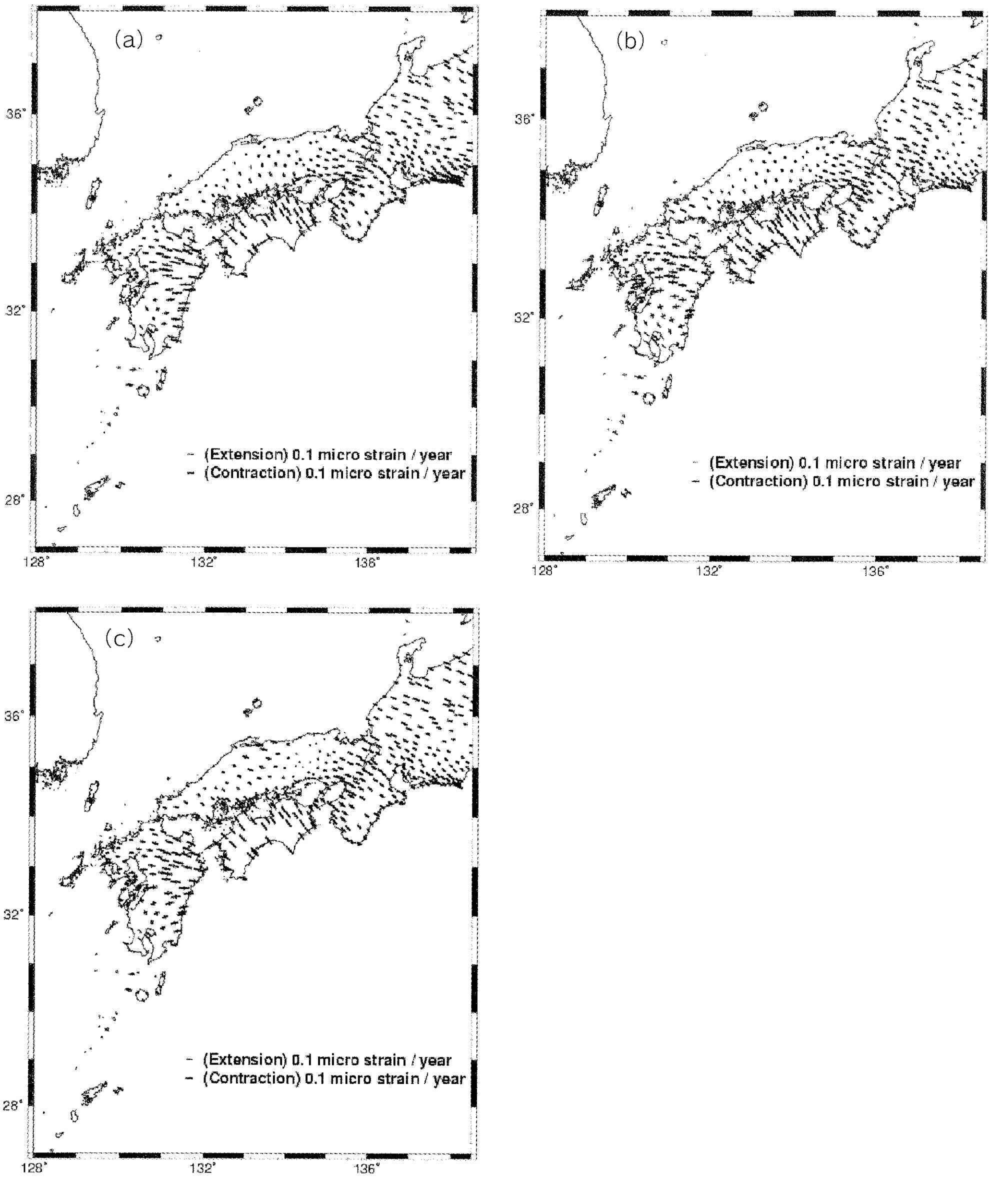

Fig. 7. Principal strain axis of observation points in Southwestern part of Japan after applying the PMSD. (a) Nov. 1997 - Nov. 1998, (b) Nov. 1998 - Nov. 1999, (c) Nov. 1999 - Nov. 2000 . The thin and bolded thick dash lines show the rate of extension and contraction in their specific directions, respectively.

The most important strain changes during 1997-2000, in southwest Japan are as follows:

1) From Yakushima Island toward WNW, there is a shear anomaly with the rate of about 0.16×10^{-6}/yr, but during 1998-1999 this anomaly is shifted as much as to the north so that it can cover the southwestern part of Kyushu. This change of strain can not be explained by earthquake because of no any large occurrences. During 1997-1998, from the central Kyushu toward east there is a widespread shear anomaly of about 0.24×10^{-6}/yr, which is extended into Shikoku Island, too. This anomaly can be related to the slow slip motion because of lacking any large events in this vicinity.
2) Most of Shikoku Island is under shear strain. This anomaly extended to the southern part of Kinki area too. Also no special events have occurred in Shikoku Island in spite of its high rate of shear strain.
3) During 1997-1998, around the Tottori area the maximum shear strain is too small, 0.04×10^{-6}/yr, and during 1998-1999, its rate has increased to 0.08×10^{-6}/yr and finally the Western Tottori earthquake occurred by increasing the maximum shear strain up to 0.2×10^{-6}/yr. However it seems that the Tottori earthquake had not caused any special deformation before its occurrence.

The principal strain rate maps (Figs. 7a,b, and c) show that strain state is NW-SE contraction in most part of Southwest Japan, except in the Kyushu Island where N-S extension could be due to the mantle pluming under western off the Kyushu (SADEGHI *et al.*, 2000). The NW-SE and E-W extension in southwest of Kyushu and west off Yakushima Islands could be considered as the result of the expansion of the Okinawa trough. Compressional state of strain in southwest Japan may attribute to the convergence of the Philippine Sea, the Eurasian and the Pacific plates. Shikoku and southwest and east of Kyushu Islands show relating high rate of shear strain anomaly in spite of lacking any large earthquakes.

VI. Conclusion

We have presented Partitioning Model for Strain Distribution, PMSD, to estimate the displacement vectors and horizontal strain components by using least-square prediction method. This model shows that during our estimation we should be aware of differences of correlation distances between two horizontal components when we suppose a homogeneous and Isotropic area. We applied our model, PMSD, to the Japanese Islands and introduced two major parts as northeast and southwest, where the difference of correlation distance components in each part is minimum.

We estimated the correlation distance of the SW part as 250 km and found that the partitioning boundary of the SW and NE parts has a nearly good coincidence with the Fossa Magna which is assumed to be the plate boundary between the Okhotsk and the Eurasian plates. Strain state in most part of SW Japan is NW-SE contraction because of the Philippine Sea plate conversion. N-S extension of Kyushu Island may be due to the mantle pluming under its west off (SADEGHI *et al.*, 2000). E-W extension in southwest Kyushu and also in west off the Yakushima Island could be considered as a result of the expansion of the Okinawa trough.

Our results suggest that in some parts of SW Japan shear strain is high, especially between Kyushu and Shikoku Islands and also between east and southwest of Kyushu.

Acknowledgment

We would like to appreciate Prof. T. Kato of Earthquake Research Institute, the university of Tokyo and Dr. H. Takenaka of Kyushu University for their valuable discussion, and also two anonymous reviewers for their effective comments to improve the manuscript. We also thank Geographical Survey Institute of Japan (GSI) for providing the continuous GPS data. This research was done under Monbukagaku-sho Research Scholarship, Ministry of Education, Culture, Sports, Science and Technology, Japan. A software package, Generic Mapping Tool (GMT), was used to plot the figures.

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