Crustal deformation at the Nankai subduction zone, southwest Japan, derived from GPS measurements

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Abstract. The interseismic strain accumulation process at the Nankai subduction zone, the plate-boundary region between the Philippine Sea and the Eurasian plates off Southwest Japan, has been revealed by GPS measurements spanning five years. Large strains characterized by a contraction of $2.2\text{--}3.4 \times 10^{-7}$ /yr have accumulated in a narrow region extending parallel to the strike of the plate boundary. The contraction axes lie in a northwest-southeast direction nearly parallel to the direction of relative motion of the Philippine Sea plate with respect to the Eurasian plate. GPS-derived deformation data, including both rate and direction, are consistent with the expected earthquake deformation cycle at the Nankai subduction zone. Current interplate coupling in this zone is strong; much of the relative plate motion has been taken up by deformation of the marginal parts of the Eurasian plate.

Introduction

The Nankai trough is the plate boundary between the Eurasian plate (EU) and the Philippine Sea plate (PH) off Southwest Japan (Figure 1). Low-angle subduction of PH has caused a series of great interplate earthquakes within the short span of roughly 100-130 years [Ando, 1975]. The most recent events were the 1944 Tonankai ($M=7.9$) and the 1946 Nankai ($M=8.0$) earthquakes. According to many studies that estimated fault parameters using seismic, geodetic, and/or tsunami data [e.g., Fitch and Scholz, 1971; Kanamori, 1972; Ando, 1982; Yabuki and Matsu'ura, 1992; Satake, 1993], these two earthquakes ruptured the region to a depth of 30 km at a small dip angle of 10 to 30 degrees and to a lateral extension of 500 km.

Repeated geodetic surveys by the Geographical Survey Institute (GSI) and long-term tide-gauge records obtained by the Japan Meteorological Agency, the Hydrographic Department, and GSI in Southwest Japan have revealed interseismic strain accumulation, coseismic strain release, and postseismic transient movement. These data enable us to discuss crustal deformation in connection with the earthquake deformation cycle and the interplate coupling along the Nankai trough [Thatcher, 1984; Yoshioka, 1991; Savage and Thatcher, 1992]. In association with the 1944 and the 1946 events, a horizontal displacement of up to two meters and an uplift of far larger than one meter were observed on the Pacific side of Southwest Japan [Miyabe, 1955;

Ando, 1975]. Triangulation and trilateration results after the 1946 event reveal that current interseismic strain accumulation is characterized by a northwest-southeast contraction of about $3\text{--}6 \times 10^{-7}$ /yr (over 3×10^{-7} /yr in maximum shear strain rate) [Hashimoto, 1990]. The direction of maximum contraction is nearly parallel to the relative motion of PH with respect to EU. However, geodetic data are still insufficient for discussing temporal and spatial variations of interplate interaction in detail, since surveys are too laborious and time-consuming to be repeated frequently.

In recent years, precise relative positioning with the Global Positioning System (GPS) has enabled us to detect highly-precise three-dimensional crustal deformation within a shorter time period than that of conventional surveys. We started GPS observation in 1990 to better clarify the strain accumulation process at the Nankai subduction zone. In this paper we present a model of crustal deformation derived from intermittent GPS observations during the period from 1990 to 1995.

Observation and Analysis

The Shikoku district, located adjacent to the hypocenter of the 1946 event, is one of the most tectonically active regions in Japan. We constructed a local GPS observation network in March 1990. The station distribution is shown in Figure 1. Up to 1992, GPS campaigns were held approximately once a year. Each campaign consisted of four to five eight-hour sessions on consecutive days. Dual-frequency receivers of type WM102 were used and data were taken at a sampling interval of 60 seconds from satellites with an elevation higher than 15 degrees. Unfortunately, WM102 performance has been degraded since mid-1991 due to the implementation of Selective Availability, to which the WM102 offers no countermeasures. The campaign was therefore abandoned in 1993.

We re-started GPS observations at the beginning of 1994 using new Ashtech Z-12 receivers. Since October 1994, five permanent stations have been operated and continuous data have been taken at a sampling interval of 30 seconds. There are three supplementary stations, where five- to six-day campaigns have been conducted once or twice a year.

All data from 1990 to 1995 were processed with Bernese GPS Software Version 3.4 [Rothacher et al., 1993]. Phase-data screening was usually done automatically, with no additional manual operations. However, the data recorded by WM102 receivers under the Selective Availability were heavily contaminated with a large number of cycle slips which could not be removed by editing. We therefore excluded these data from our analysis. Similarly, Kure (KURE) and Matsuyama (MATS) were excluded from this analysis due to the insufficient amount of data obtained there.

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Figure 1. GPS station distribution in the Shikoku region, Southwest Japan, and horizontal station velocities with respect to Ikeda (IKED) with 95% confidence ellipses. Stations denoted by circle with dot indicate permanent stations in operation since October 1994. Star symbols indicate the epicenters of the 1944 Tonankai ($M=7.9$) and the 1946 Nankai ($M=8.0$) earthquakes. The large open arrow shows the direction of relative motion of the Philippine Sea plate against the Eurasian plate, where a velocity of 61 mm/yr has been estimated from earthquake slip vector inversion, and another of 49 mm/yr from earthquake data taking the Pacific-Caroline plate boundary condition into account [Seno *et al.*, 1993].

For highly-precise baseline determination with GPS, precise satellite ephemerides are indispensable even in a local network analysis. Since 1994, we have used precise ephemerides produced from global data by the Center for Orbit Determination in Europe (CODE) for our processing of Z-12 data. By contrast, precise ephemerides were not regularly produced from global data prior to 1992, so we use broadcast ephemerides for processing WM102 data.

Station coordinates are estimated using L3 ionosphere-free linear combination of L1 and L2 carrier-phases together with the tropospheric zenith delay at each station every two hours. During parameter estimation, most of the L5 wide-lane, L1 and L2 carrier-phase ambiguities are resolved. Finally we calculate the campaign solution, which is a weighted mean of the daily solutions taking the associated variance-covariance into account. Standard deviations of the estimated coordinates in each campaign are defined as the square roots of the diagonal components of the covariance matrix scaled by taking the post-fit residuals into account [Heki, 1992]. In the case of the continuous Z-12 measurements since October 1994, we regard the weighted monthly mean as a campaign solution.

Results

With regard to horizontal baseline components, the standard deviation in each campaign was roughly from 10 to 20 mm in 1990 and 1991, while a standard deviation of much less than 10 mm has been achieved since 1994. Because station separation in the Shikoku region ranges from about 40 to 150 km, the current precision relative to baseline length is thus on the order of 10^{-8} .

Figure 2(a) shows length changes in three baselines of approximately equal length. We are interested in these length changes because they extend nearly parallel to the direction of relative motion of PH with respect to EU. In general all three are contracting at constant rates over time, though slightly larger scatter is seen in the 1990 and 1991 campaigns. The rates of change are roughly comparable: approximately 15 to 19 mm/yr, convertible to strain rates of $2.2\sim 2.8 \times 10^{-7}$ /yr. Figure 2(b) shows length changes in baselines which are nearly perpen-

dicular to the relative motion of PH with respect to EU. Rates are smaller than 1 mm/yr and almost negligible, in contrast to those of Figure 2(a).

Regarding the baseline changes in Figures 2(a) and 2(b) (MURO-KOCH, IKED-KOCH, and KOCH-ASHI), although long-term linear trends are dominant, annual variations with small amplitudes appear to be superimposed on them. However, it remains uncertain whether the annual variations are real deformations, or whether they are caused either by instability of station monuments or by mismodeling in parameter estimation (e.g., insufficient correction for tropospheric delay).

Figure 2(a). Length changes on three baselines having nearly equal lengths and extending parallel to the direction of relative motion of the Philippine Sea plate. GPS campaign solutions are plotted with plus and minus one standard deviation.

Figure 2(b). Length changes on three baselines extending nearly perpendicular to the direction of relative motion of the Philippine Sea plate.

The precision of the vertical component is generally about two to three times worse than that of the horizontal. Even utilizing data obtained after 1994, we found that scatter in the vertical component (still larger than that in the horizontal) made it difficult to estimate the linear trend of vertical deformation in only a short observation period. Accordingly, for the rest of this paper we will present only the horizontal data.

Horizontal station velocity vectors are determined from station coordinate changes assuming linear motions over time. They are plotted in Figure 1 with 95% confidence ellipses (2.45 standard deviation), while the velocity components are listed in Table 1. These velocities represent displacement rates with respect to Ikeda (IKED), the station located the farthest from the plate boundary. All the velocities are oriented from N58°W to N74°W directions. The velocity is maximum at Muroto (MURO) and Ashizuri (ASHI), at about 34 mm/yr, then rapidly decreases with increasing distance from the Nankai trough. A large displacement gradient thus exists in a narrow region with a width of about 100 km extending parallel to the strike of the plate boundary.

Discussion

The choice of a single reference site sometimes has a critical effect on the inferred displacement field. Nakano [1996] estimated the velocity at Ikeda with respect to the stable interior of EU. At first, he determined coordinates and velocity at Ikeda relative to Tsukuba, located about 620 km east-northeast. At

Tsukuba, both very long baseline interferometry (VLBI) and GPS stations have been established, and their coordinates and velocities have been cataloged in a series of IERS Terrestrial Reference Frames (ITRF) [e.g. Boucher *et al.*, 1993]. Three-dimensional velocity at Tsukuba has been determined with respect to the interior of EU from VLBI data by Heki [1996]. Adding the two velocities, the horizontal velocity at Ikeda can be estimated as 14 mm/yr in N17°W direction [Nakano, 1996].

The above result implies that the subduction of PH may affect areas slightly further inland than Ikeda. On the other hand, according to the displacement field derived from the Japanese nationwide GPS array [GSI, 1996] and a numerical simulation using a three-dimensional finite element method [Yoshioka, 1991], it appears that the subduction of PH leads to large deformation in the southern part of Shikoku but does not affect the region located further inland than Shikoku. We cannot conclude from our local network analysis how far the effects of the subduction of PH reach. However, the shortening toward the northwest observed in the narrow region extending parallel to the strike of the plate boundary will remain unchanged regardless of the velocity at the local reference site Ikeda.

Figure 3 shows horizontal strain rates averaged over the period from 1990 to 1995, with bias to the station velocity caused by the local displacement at the reference site excluded. Interseismic strain accumulation appears spatially uniform east-to-west, as characterized by a contraction of $2.2\sim 3.4 \times 10^{-7}$ /yr in a northwest-southeast direction. These strains are in good agreement with the average interseismic strains derived from long-term triangulation and trilateration surveys conducted after the 1946 event [Hashimoto, 1990].

The southeastern part of Shikoku provides a good observation field for monitoring the earthquake deformation cycle at the Nankai trough. Since this southeastern region overlapped the hypocentral area of the 1946 event, both horizontal and vertical displacements were somewhat remarkable [Miyabe, 1955], illustrating an elastic rebound from the low-angle thrust faulting. On the basis of the fault model by Ando [1982], coseismic displacement at Muroto with respect to Kochi is estimated as 2.11 m in the east-southeast direction. On the other hand, GPS measurement has revealed that when fixing Kochi, Muroto has been displaced toward the west-northwest at a rate of 17 mm/yr at the interseismic stage. Assuming this rate remains constant with time, the integrated interseismic displacement will exceed

Table 1. Station Velocity with Respect to Ikeda (IKED).

Station	ID	Horizontal Velocity	Azimuth
Ashizuri	ASHI	33.6 ± 2.3 mm/yr	N71.1°W $\pm$ 3.1°
Kainan	KAIN	22.0 ± 1.0	N72.3 W $\pm$ 2.3
Kochi	KOCH	18.7 ± 1.2	N58.5 W $\pm$ 3.2
Muroto	MURO	33.6 ± 0.7	N68.0 W $\pm$ 1.1
Uwajima	UWAJ	7.2 ± 2.3	N73.7 W $\pm$ 14.2

Figure 3. GPS-derived horizontal principal strain rates averaged over the period from 1990 to 1995.

the amount of coseismic displacement at the 1946 event in 124 years. The above estimation of the coseismic displacement is dependent on a specific fault model and therefore not a unique solution. Nevertheless an estimate of 124 years is consistent with the recurrence time of great interplate earthquakes at the Nankai trough as derived from historical documents [Ando, 1975].

The history of deformation in the southwestern part of Shikoku is different from that in the southeastern region. Coseismic deformation at the 1946 event was small, suggesting that the rupture did not reach this region [e.g., Yabuki and Matsu'ura, 1992], and that most of the accumulated strain was not released by this event [GSI, 1987]. Since the interseismic strain has been superimposed on the non-released strain, the total strain now accumulated in the southwestern area may be larger than that in the southeast.

We interpret the strain accumulation derived from GPS observations over five years in terms of models of the earthquake deformation cycle at the Nankai subduction zone. The contrast between coseismic and interseismic deformations, i.e. coseismic rebound appearing only in the southeastern part of Shikoku, and nearly uniform interseismic strain accumulation appearing from the southeastern to southwestern regions, may be dependent on temporal and spatial variations in interplate coupling. Presently, it is impossible to answer when and how the coupling off Southwest Japan changed. We hope that further GPS observation in a wider and more dense network, such as the Japanese nationwide GPS array [GSI, 1996], will improve temporal and spatial resolutions of crustal deformation and lead to full understanding of the earthquake deformation cycle at the subduction zone.

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