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Interplate coupling along the Nankai Trough, southwest Japan, inferred from inversion analyses of GPS data: Effects of subducting plate geometry and spacing of hypothetical ocean-bottom GPS stations

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ABSTRACT

We estimated the slip-deficit rate distribution on the plate boundary between the subducting Philippine Sea plate and the continental Amurian plate along the Nankai Trough, southwest Japan. Horizontal and vertical displacement rates were calculated from land-based Global Positioning System (GPS) data during the 5-year period from 1 January 2005 to 31 December 2009. We employed an inversion analysis of geodetic data using Akaike's Bayesian information criterion (ABIC), including an indirect prior constraint that slip distribution is smooth to some extent and a direct prior constraint that slip is mainly oriented in the plate-convergent direction. The results show that a large slip deficit exists at depths ranging from 15 to 20 km on the plate boundary in a belt-like form. The maximum slip-deficit rate was identified off Shikoku and reached 6 cm/year. The slip-deficit rate differed by as much as 1 cm/year when using a different geometric model of the subducting plate. On the basis of the spatial distribution of estimation errors and the resolution of the obtained slip-deficit rate on the plate boundary, we also found that the offshore slip-deficit rate cannot be estimated with sufficient accuracy using only land-based GPS data. Therefore, we tested the improvement in results when introducing hypothetical ocean-bottom GPS stations. The stations were arranged in four along-arc and across-arc spacings of 80 km and 40 km. The ocean-bottom data improved the estimation errors and resolutions, and successful results were obtained for a checkerboard with each square 75 km × 76 km. Our results indicate that 40-km along-arc and across-arc two-dimensional spacing of ocean-bottom GPS stations is required to obtain reliable slip-deficit distributions near the trough axis, assuming the current estimation accuracy for ocean-bottom horizontal displacement rates.

1. Introduction

In southwest Japan, interseismic crustal deformation is caused by interaction of the subducting oceanic Philippine Sea (PHS) plate with the overriding continental Amurian plate along the Nankai Trough (Fig. 1). According to the plate motion model by Sella et al. (2002), subduction directions are oriented N57.5°–59.0°W, and subduction velocities are 6.8–6.0 cm/year from off Shikoku to off the Kii Peninsula. On the plate boundary, megathrust earthquakes have occurred repeatedly with a recurrence interval of about 90 to 150 years (e.g., Ando, 1975). The most recent events were the 1944 Tonankai (M 7.9) and 1946 Nankai (M 8.0) earthquakes. Coseismic slip distributions for these events were obtained by inversion analyses of geodetic data such as triangulation and leveling data (e.g., Ito and Hashimoto, 2004; Sagiya and Thatcher, 1999; Yabuki and Matsu'ura, 1992) and tsunami waveforms (e.g., Baba and Cummins, 2005). Because largely slipped areas at the time of a megathrust earthquake are considered strongly coupled regions, we can roughly estimate expected coseismically slipped regions for a future megathrust event by estimating the spatial distribution of coupled regions during an interseismic period.

Fig. 1 is a tectonic map showing the epicenter distributions of earthquakes with depths ranging from 20 to 180 km that occurred during the 5-year period from 1 January 2005 to 31 December 2009. Most of these events were thrust-type earthquakes on a plate boundary or intraslab earthquakes. Earthquakes of M 6 to M 7 occurred frequently on the plate boundaries in the Tohoku and Kyushu districts during the study period, whereas such earthquakes rarely occurred in association with subduction of the PHS plate beneath Shikoku and the Kii Peninsula.

In Japan, Global Positioning System (GPS) observation was initiated by the Geospatial Information Authority of Japan (GSI) in 1994, and operation of the GPS continuous observation system (GEONET) started in 1996. More than 1200 land-based GPS stations were in operation across the Japanese islands by 2004. GPS continuous observation can observe not only coseismic and postseismic crustal deformations associated with a large earthquake, but also steady crustal deformation associated

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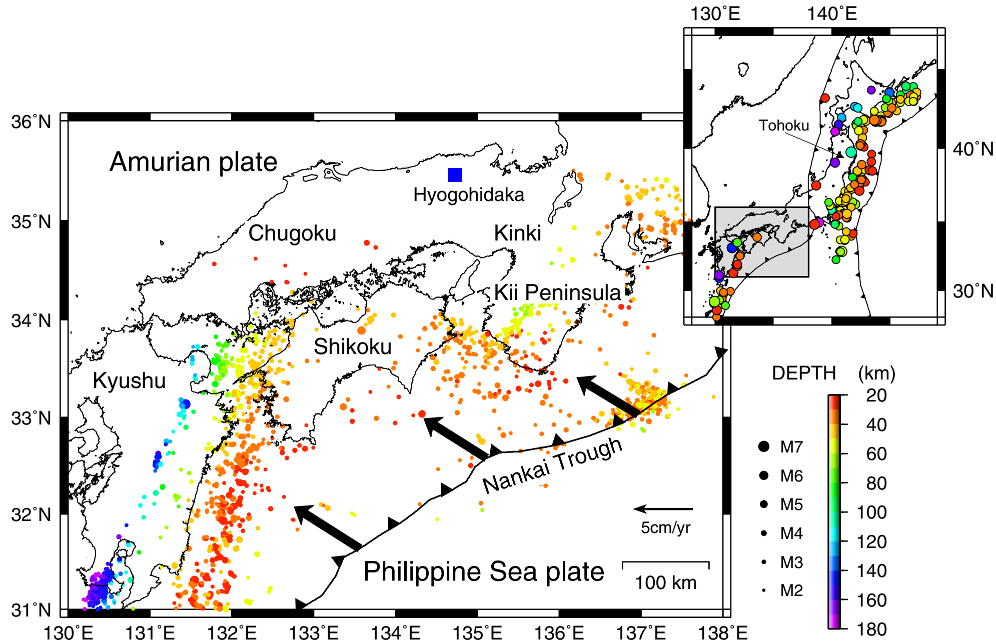

Fig. 1. Tectonic map of southwest Japan. The black arrows are plate motion velocity vectors of the PHS plate with respect to the Amurian plate (Sella et al., 2002) along the Nankai Trough. The blue solid square is the reference point for the investigated GPS data. The solid color circles represent unified hypocenters determined by the JMA whose sizes are depicted in proportion to their magnitudes, and colors denote their depths. Plotted are all the events with magnitude greater than 2.5 and depth range from 20 to 180 km that occurred during the period from 1 January 2005 to 31 July 2009. Depicted in the inset are all the events with magnitude greater than 5 for the same depth range during the same period.

with subduction of an oceanic plate. Using such GPS data, as advocated by Savage (1983), slip-deficit rate distributions on a plate boundary during an interseismic period have been estimated in southwest Japan (e.g., Ichitani et al., 2010; Ito et al., 1999; Liu et al., 2010; Loveless and Meade, 2010; Miyazaki and Heki, 2001; Nishimura and Hashimoto, 2006).

In this study we obtained displacement rates from a time series of GPS continuous data collected from 1 January 2005 to 31 December 2009 and estimated the distribution of the slip-deficit rate on the plate boundary in southwest Japan. We chose this period because the following were not observed during it: crustal deformations caused by long-term slow slip events, afterslips following large earthquakes, and crustal deformations associated with stress relaxation of the uppermost mantle followed by earthquakes. We conducted an inversion analysis of geodetic data using Akaike's Bayesian information criterion (ABIC; Akaike, 1980), including an indirect prior constraint that slip distribution is smooth to some extent and a direct prior constraint that slip is mainly oriented in the plate-convergent direction (Matsu'ura et al., 2007). This method is useful because the slip-deficit rate on the plate boundary is considered to be parallel to the plate-convergent direction.

When estimating the slip-deficit rate distribution, the geometry of the upper surface of the subducting plate is essential. Various geometric models of the plate have been proposed, including the Crustal Activity Modeling Program (CAMP) standard model determined from International Seismological Center (ISC) hypocenter data (Hashimoto et al., 2004), a model obtained from seismic tomography (e.g., Hirose et al., 2008), and a model obtained from receiver function analysis (e.g., Shiomi et al., 2008). The respective geometric models of the upper surface of the PHS plate have some slight differences. We investigated the extent to which differences in geometric models of the slab affect estimations of the slip-deficit rate distribution.

Furthermore, although GEONET stations are densely spaced at approximately 20 km intervals on land, there is no observation network in the ocean. The Japan Coast Guard has progressively initiated operation of an ocean-bottom crustal deformation observation network. Using checkerboard tests, we also investigated whether estimation errors and the resolution of the estimated slip-deficit rate could be improved if certain distributions of ocean-bottom GPS stations are installed.

2. Data

2.1. Horizontal and vertical displacement rates

For this study, we used observation data from land-based GPS stations provided by the GSI. Daily coordinate values (F3 solution; Nakagawa et al., 2009) were obtained for the 5 years from 1 January 2005 to 31 December 2009. We employed times series of north–south, east–west, and up–down components obtained at 360 land-based GPS stations located in the eastern Kyushu, Chugoku, Shikoku, and Kinki districts. Following Yoshioka et al. (2004), we obtained crustal deformations caused by slip-deficit rate, using the following equation:

$$y(t) = a + bt + c\sin\left(\frac{2\pi t}{T}\right) + d\cos\left(\frac{2\pi t}{T}\right) + e\sin\left(\frac{4\pi t}{T}\right) + f\cos\left(\frac{4\pi t}{T}\right) + gH(t) \quad (1)$$

where a, b, c, d, e, f, and g are unknown parameters to be determined by least-square fitting to time series of respective components at land-based GPS stations, and $T = 1$ year. The first and second terms in the right side of Eq. (1) represent the linear trend, and b is the displacement rate caused by the slip-deficit rate. The third and fourth terms are annual variations, and the fifth and sixth terms are semi-annual variations. Annual variations are noises caused by atmospheric conditions such as temperature, humidity, and atmospheric pressure, whereas semi-annual variations can originate from variations in the ionosphere, temperature, and tide. The seventh term $H(t)$ represents the Heaviside step function, which we used when there was a step in a time series due to coseismic crustal deformation