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Undersea crustal movement off the Tokai District, central Japan, detected by GPS/Acoustic seafloor geodetic observation†

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Key words : GPS/Acoustic, seafloor geodetic observation, intraplate deformation, Tokai Earthquake

Abstract

We have been carrying out GPS/Acoustic seafloor geodetic observations at a reference point situated off the Tokai District, central Japan, where the Tokai Earthquake is expected to occur in the near future. A linear fit to the time series of horizontal coordinates at the reference point obtained from five campaign observations for the period 2002-2007 gives an intraplate crustal movement velocity, which is in realistic range and implies strong interplate coupling around this region.

1 Introduction

The Tokai District is located in central Japan, in the offing of which major convergent plate boundaries, the Nankai Trough and its northeast extension, the Suruga trough, run through. Subduction of the Philippine Sea Plate beneath the Japanese islands has been causing huge interplate earthquakes repeatedly at relatively regular intervals of 100-200 years (e.g. Ando, 1975). Since Ishibashi (1976) predicted the occurrence of a huge earthquake in the eastern part of the Tokai District on the basis of the seismic gap hypothesis, various geophysical and geodetic observations have been intensively directed toward prediction of the Tokai Earthquake. Taking into consideration the series of newly obtained knowledge from those observations during more than twenty years, the Central Disaster Management Council (2001) has proposed an improved focal model of the hypothetical Tokai Earthquake.

Among a variety of studies, the distribution of locked zones inferred from seismicity pattern around the plate interface (Matsumura, 1997) and back-slip distribution estimated from inversion of GPS displacement rates (Sagiya, 1999) were informative for re-consideration of the focal model based on interplate coupling, but on the other hand, those two results spatially disagree. On this issue, Matsumura (1999) points out that the back-slip distribution possibly extends toward the

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trough farther than the locked zone inferred from micro-earthquake seismicity and that land-based geodetic observations can hardly demonstrate whether the locked zones actually extend to the seafloor. The focal model proposed by the Central Disaster Management Council (2001) includes most part of both two resultant areas.

In this context, crustal deformation data in the offshore region closer to the convergence boundary can provide critical information to indicate the existence of interplate coupling. Precise seafloor geodetic observation with a GPS/Acoustic combination technique has recently been a useful methodology to complement lacked data on crustal deformation in the sea area, and the original basis for this approach dates back to the early work carried out by scientists at the Scripps Institution of Oceanography (Spiess, 1985). In Japan, our team at the Japan Coast Guard (JCG) and the Institute of Industrial Science, the University of Tokyo, has been developing this technique using a survey vessel and making repeated campaign observations along the major trenches (Asada and Yabuki, 2001; Mochizuki *et al*., 2003, 2005; Fujita *et al*., 2006). Fujita *et al*. (2006) have shown that the repeatability of the position determination reaches a couple of centimeters under good conditions.

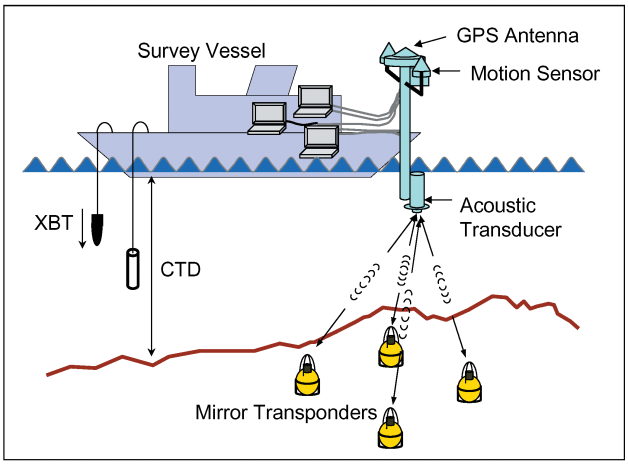

Fig. 1 Schematic picture of the GPS/Acoustic seafloor geodetic observation system.

In the Tokai District, we have established a seafloor reference point on the landward side of the Suruga Trough. The primary purpose of our observation in this region is to detect and monitor the secular intraplate crustal movement near the plate boundary caused by the subduction of the Philippine Sea Plate (PH). A research group of Nagoya University has also installed some seafloor transponders in Suruga Bay, and Tadokoro *et al*. (2007) report that they derived a displacement vector of 3 cm westward on the PH side of the Suruga Trough from one-year observation with a similar observation system.

In this paper, we present and discuss the undersea crustal movement that we have detected at our seafloor reference point off the Tokai District (labeled as 'TOKE') during 2002-2007.

2 Seafloor Geodetic Observation and Analysis

A schematic picture of the seafloor geodetic observation system that we have developed is shown in Fig.1. This system consists of a seafloor unit with four or three acoustic mirror-type transponders and an on-board unit with a GPS antenna and an acoustic transducer installed on the rigid observation pole (8 m in length) to which a motion sensor is also attached.

The system measures ranges from the on-board transducer to the seafloor acoustic transponders through round-trip travel times in-between, while simultaneously determining coordinates of the on-board transducer that are transferred from those of the GPS antenna, with the attitude of the observation pole measured with the motion sensor taken into account. Positions of the GPS antenna are determined using a kinematic GPS software called 'IT' (for Interferometric Translocation), which was developed for the precise determination of the trajectory of a rover over very long baselines (Colombo and Evans, 1998; Colombo *et al*., 2000, 2001). The acoustic wave velocity profile in the seawater, which is necessary for transforming travel times into ranges, is obtained from CTD, XCTD and XBT measurements.

Positions of the transponders are finally calculated by a linear inversion method based on least squares formulation combining round-trip travel times and KGPS positions. The positions of grouped transponders are finally averaged to be a virtual position of the reference point.

For more details on the methodology, the reader is referred to Fujita *et al*. (2006)

3 Location of the Seafloor Reference Point and Observation Result

The seafloor reference point TOKE is situated about 30 km landward from the axis of the Suruga Trough (Fig. 2). TOKE is located just on the southeast outer edge of the Tokai earthquake's assumed focal area proposed by the Central Disaster Management Council (2001). A set of four acoustic transponders has been installed on the seafloor, at a depth of about 2400 m. The transponders are placed to form a square whose corners are directed to the north, south, east and west. This reference point has been working since 2002. We have carried out five campaign observations at TOKE for the period from August 2002 to April 2007.

Data numbers for each campaign epoch used in this paper are listed in Table 1. Each epoch consists of 3-5 observation days. The RMS of round-trip travel time residuals for each campaign analysis, also shown in Table 1, is 60-110 ms, which corresponds to 4-9 cm in the one-way range.

Fig. 3 shows the time series of estimated horizontal coordinates. Each solid circle represents the average of the coordinates of four acoustic transponders on the seafloor, relative to the reference campaign epoch of August 2002. Error bars demonstrate changes in the configuration of the four transponders compared to that of the reference solution (see Fujita *et al*. (2006) for more details). The position reference is the Shimosato site, in Wakayama Prefecture, in central Japan, which is one of the ITRF stations also equipped for Satellite Laser Ranging (SLR) observations (Altamimi *et al*., 2002). It must be noted that Shimosato underwent coseismic displacement, amounting to 1.5 cm to the south and 0.9 cm to the west, due to the earthquakes off SE Kii Peninsula (M 6.9, M 7.4) which occurred in September 2004, revealed by the continuous GPS measurement (Japan Coast

Table 1 List of numbers of data for each campaign observation at the seafloor reference point TOKE used in this study. RMS of round-trip travel time residuals for each campaign analysis is also listed.

Epoch	Aug 2002	Nov 2003	Jul 2004	Aug 2006	Apr 2007
Days	3	3	5	4	3
Shots	2294	1005	2962	5270	4720
Residuals RMS (ms)	0.109	0.081	0.065	0.081	0.061

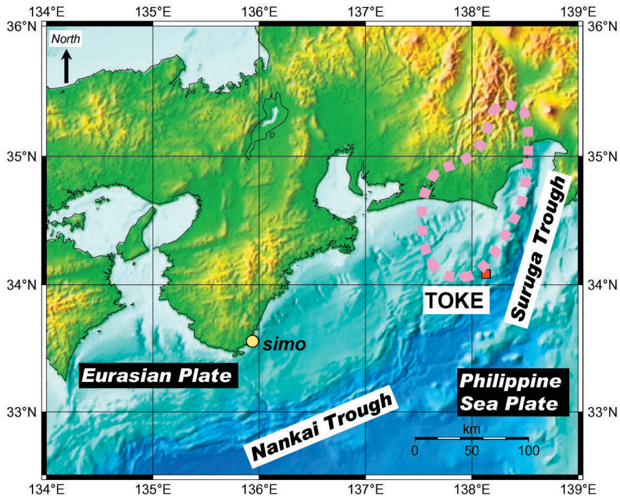

Fig. 2 Location of the seafloor reference point TOKE (a red square) used in this study shown on the topographic map around the Tokai District, central Japan. Also shown are the Tokai earthquake's assumed focal area (purple broken line) proposed by the Central Disaster Management Council (2001) and the position reference, the Shimosato site (a yellow circle labeled as 'simo').

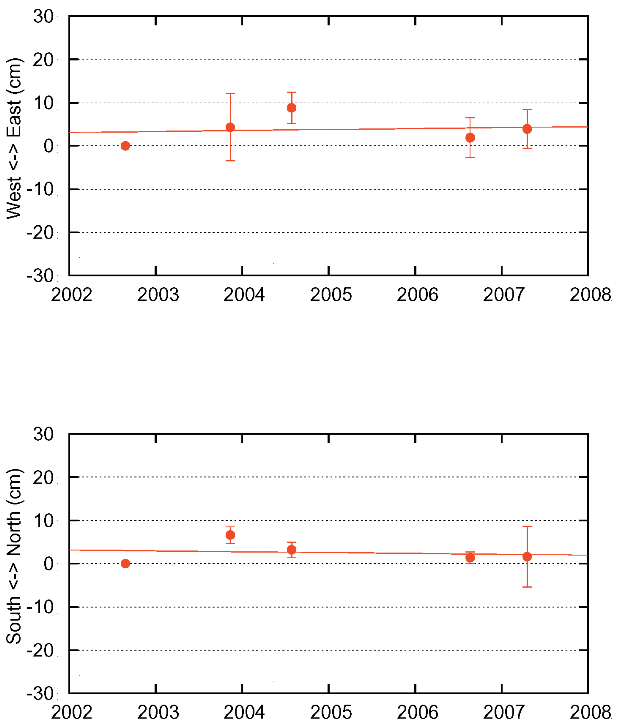

Fig. 3 Time series in the horizontal coordinates obtained at the seafloor reference station TOKE from five campaign observations during the period from August 2002 to April 2007. The top and bottom panels correspond to the EW and NS components, respectively. The position reference is the Shimosato site, in central Japan.

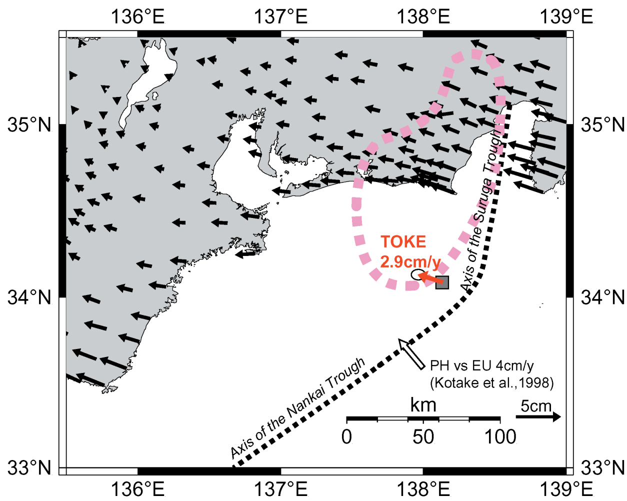

Fig. 4 Crustal movement velocity vector at TOKE relative to the Eurasian plate (a red solid arrow) evaluated from the time series shown in Fig. 3 after correcting for the intraplate velocity at Shimosato (3.2 cm/year, 291 ° ; Sengoku, 1998). Attached to the arrow, the one-sigma estimation error in the linear fit to the time series.The crustal movement velocity vectors (averaged for five years between May 2002 and May 2007) at GEONET on-land GPS stations are shown with black solid arrows. The velocity of the Philippine Sea Plate relative to the Eurasian Plate at the Suruga Trough calculated from the plate motion model (Kotake *et al*., 1998) is also shown with an open arrow. Also shown is the Tokai earthquake's assumed focal area (purple broken line) proposed by the Central Disaster Management Council (2001).

Guard, 2005). The plot of the last two epochs in Fig. 3, August 2006 and April 2007, represents the value after the correction with this displacement. Besides, it should also be noted that Shimosato is located on the eastern edge of the Eurasian Plate (EU), known to undergo there intraplate deformation at a rate of about 3 cm/year WNW due to the pressure of the Philippine Sea Plate subduction.

The time series shown in Fig. 3 exhibits a linear trend in time with the repeatability of several centimeters. A linear fit to the time series gives a rate of 0.2 ± 0.8 cm/year eastward and 0.2 ± 0.6 cm/year southward. The root mean squares around the fitted line are 2.9 cm in the EW component and 2.2 cm in the NS component. We add the intraplate movement velocity of Shimosato (3.2 cm/year, 291 ° ; Sengoku, 1998) to the above rate, and obtain 2.9 cm/year, with an azimuth of 288 °, relative to the stable part of EU, which is exhibited with an arrow in Fig.4.

4 Discussion

In the Tokai District, it is known from GPS static observations at a number of stations, mainly from the GEONET network developed by the Geographical Survey Institute of Japan (Hatanaka *et al*., 2003), that the crust undergoes intraplate deformations in the W-WNW direction with velocities of a few centimeters per year. As shown in Fig. 4, the amount of velocity relative to the stable part of EU varies between 1-3 cm/year on the shore, and is larger along the coast of the Suruga Bay. The basic trend of our velocity vector at TOKE is consistent with the trend of crustal deformation, when we assume that the velocity distribution is extended to the offing. Moreover the possible maximum of the velocity is supposed to be the value of subducting velocity of PH relative to EU along the Suruga Trough, which is estimated to be about 4 cm/year from contemporary plate motion models (e.g. Kotake et al, 1998). Thus our resultant value, 2.9 cm/year, is in realistic range and as large as the velocity at the on-land GPS stations inside the assumed focal area.

Back-slip distribution around TOKE is estimated by several studies. According to the estimation by Sagiya (1999) from continuous GPS data from January 1997 to March 1999, the magnitude of back-slip rate at TOKE is about 2.5 cm/yr. However, he notes that back-slip at depths of 10 km or shallower, where TOKE is located, is not well resolved in his analysis and may be truncated due to the smoothness constraint. Our resultant velocity vector could support the existence of back-slip at this site.

Larger magnitude of back-slip does not always mean being locked. That is because, as Matsumura (1999) discusses, locked subduction causes back-slip not only to the locked zone itself but also to the surrounding unlocked zone. Nevertheless, some geophysical studies imply the interplate locking around TOKE. According to Mochizuki and Obana (2003), seismic activity along the Suruga Trough around TOKE is low. They conducted micro-earthquake observation using ocean bottom seismometers in this area, but through 82-day-long observations, the hypocenters determined in this area numbered only seven, and the depths of these events were determined to be deeper than the expected depth of the interplate interface. This fact could imply complete tectonic interplate locking

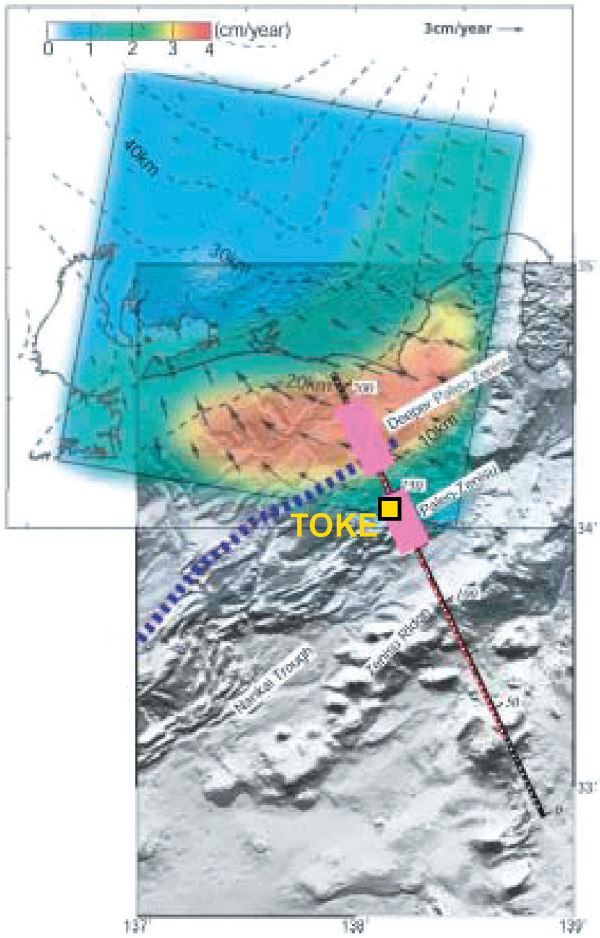

Fig. 5 Locations of the subducted deeper and the Paleo-Zenisu ridges are shown by thick pink lines after Kodaira et al. (2003). Color map, arrows and dotted contours show the back-slip distribution, the back-slip vectors and the depth of the plate boundary used for the calculation of the back-slip, respectively (Sagiya, 1999). Location of the seafloor reference point TOKE is added by the author with a yellow square.

around the area. Furthermore Kodaira et al. (2003) has imaged a trough-parallel cyclic ridge subduction from integrated seismic profiles. According to their result, Paleo-Zenisu Ridge has subducted beneath TOKE, as shown in Fig.5. The coincidence between large back-slip rate and existence of subducted seamount possibly supports the interplate locking.

Although the estimated error of our resultant vector from the linear fit shown in Fig.3 is below 1 cm/year, the obtained result is still preliminary and the number of obtained campaign epochs is not enough to get the statistically stable result. Thus, we need to improve the accuracy of our velocity determination by accumulating further good data from further surveys.

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要　旨

我々は近い将来東海地震の発生が想定されている東海沖海底に設置した海底基準点においてGPS/音響結合方式による海底地殻変動観測を実施してきた．2002年から2007年までに実施された5回のキャンペーン観測によって得られた水平位置座標の時系列を直線近似することによりプレート内変動速度ベクトルが求められた．この値は現実性をもつ範囲にあり，この領域のプレート間カップリングが強いことを示唆している．