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Time Evolution of the Eastern Part of the Ongoing Tokai Slow Event

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Abstract

Slow event in Tokai area, central Japan, is ongoing and probably caused by the slow-slip between the subducting Philippine Sea slab and the subducted Eurasian plate (Ozawa *et al*., 2002). We summarized the time evolution of the slow event in the eastern part of this highly dynamic region through continuous Global Positioning System (GPS) measurements. Our analysis of the observations indicates that the dynamic activities appear to be episodic. The rate of displacement was fast and the area was wide in 2001, then became slow and narrow in 2002, and then became fast and wide again since 2003 on.

Key words : Slow crustal event, Global Positioning System, Tokai area, Crustal movement observations

1. Introduction

Slow crustal events are widely recognized after the dense GPS permanent networks were introduced in Japan and other major plate convergent regions. It is known that there are two types of such events; the event associated with a large (usual) earthquake, and the event not associated with a large earthquake. The examples of the former cases are the Sanriku-oki, northern Japan, slow after-slip (Heki *et al*., 1997), and the Bungo Channel, southwest Japan, slow slip (Hirose *et al*., 1999). The latter examples are the Cascadia subducting zone (Dragert *et al*., 2001; Miller *et al*., 2002) and the case in this study (Ozawa *et al*., 2002). The Cascadia case is accompanied with episodic tremor (Rogers and Dragert, 2003), but the Tokai case (this case) without tremor.

Abnormal crustal movements were observed since the beginning of 2001 in the Tokai region by measurements taken from the Geographical Survey Institute (GSI) and the National Research Institute for Earth Science and Disaster Prevention (NIED) permanent GPS networks. Using the GPS data collected during the mid-2000 and the mid-2002, the observed abnormal crustal movements were interpreted as the slow slip event as a result of the interaction between the subducting Philippine Sea plate (PHS) and the subducted southwest Japan (Eurasian plate; SW Japan) (Ozawa *et al*., 2002). The studies of Ozawa *et al*. (2002) and Ozawa *et al*. (2004) revealed that the center of the slow slip along the upper boundary of the PHS slab was near Lake Hamana, moving northeastward 40 km over the period 3 year from the beginning of 2001 to the beginning of 2004. Yamamoto *et al*. (2004) pointed out that the same kind of slow event also occurred around 1988 from the borehole tiltmeter observation, although the period is only about two years and the magnitude of the slow event is smaller than the ongoing event.

Using data collected from five NIED permanent GPS sites and about fifty GEONET sites (**Fig. 1**), NIED has been monitoring the crustal movements in the region of collision of the northern tip of the PHS to the main part of central Honshu since year 1996. GEONET is the nationwide GPS network composed of more than 1000 stations established by GSI (Miyazaki *et al*., 1997). In Tokai region, which covers the west coast of the Suruga Bay, most of the sites analyzed by NIED are within the hypothesized epicentral area of the Tokai earthquake by the Central Disaster Management Council of the Japanese government.

In this paper we present the time evolution of the abnormal crustal movement in the eastern part of the Tokai region, which is still ongoing. In the analysis we used GAMIT/GLOBK software (King and Bock, 2004; Herring, 2004), following the procedure described in Dong *et al*. (1998). We summarize the procedure; The GPS sites in the analyzing area are divided to four groups and each group includes regional fiducial sites, that is, YELL in central Canada, MKEA in Hawaii, GUAM in Guam, SHAO in Shanghai, WUHN in Wuhan, China,

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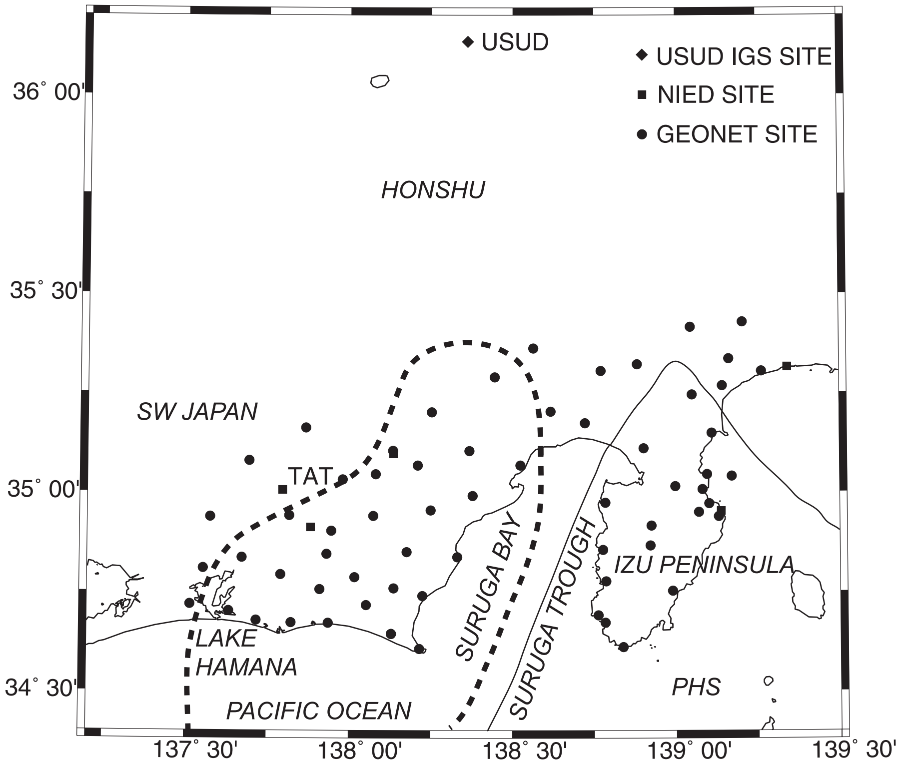

Fig. 1 GPS sites monitored in NIED with the tectonic setting of the area. The Izu Peninsula, the northern tip of the Philippine Sea Plate (PHS) is colliding to the main part of Honshu, Japan. PHS is subducting along the Suruga trough. The dashed line is the focal region of the hypothesized Tokai earthquake, which is thought to occur between the SW Japan and the subducting Philippine Sea slab. The Usuda (USUD) IGS site indicates a solid diamond, the NIED GPS sites solid squares, and the GEONET sites solid circles.

DAEJ in South Korea, TSKB in Tsukuba, and USUD in Usuda, central Japan, and all fiducial sites belong to the IGS (International GPS Service) global network. We analyze each group using the GAMIT software, constraining the fiducial site coordinates. Then we combine four GAMIT regional solutions with SIO (Scripps Institution for Oceanography) IGS global network solution also obtained by the GAMIT software, using GLOBK Kalman filtering software, constraining the horizontal coordinates of the following IGS sites, that is, ONSA in Sweden, KOSG in the Netherlands, WTZR in Germany, ALGO in the east coast of Canada, YELL, DRAO in the west coast of Canada, SANT in Chili, MKEA, TID2 and YAR1 in Australia, TSKB, and USUD. Thus we obtain the daily solution reference to the global fiducial sites. At last one-week solutions are combined and we obtain weekly solution using GLOBK software and the same constraining sites as the daily solution. We use the weekly solutions in this paper.

2. Background secular motion and ongoing slow event

Usual secular motion is shown in terms of the velocity field during September 1996 and June 2000 (**Fig. 2**). In Tokai region, the velocities were large along the western coast of the Suruga Bay and along the southern coast faced to the Pacific Ocean, and smaller in the inland of the Tokai region. During the period of July and August 2000, there was a dike opening and strike-slip slow event taking place in the Izu Islands (southwest of the Izu Peninsula) (Nishimura *et al*., 2001). Therefore, the large (typically 30mm) surface displacements contaminated the velocity estimates of some sites we analyzed.

Fig. 3 shows the mean velocity field of the ongoing slow event over 3.4 year period (from January 2001 and May 2004) in the inland area of SW Japan. Excluding the area in and around Izu Peninsula, the fastest slow event can be seen in the area around the site TAT, just covering some part of the boundary of the focal area of the Tokai earthquake. The slow event area extended to the southern coast region facing the Pacific Ocean and the west coast of the Suruga Bay. The western extension was not obvious in terms of observed velocities. According to Ozawa *et al*. (2002), slow event area extended 50 km more to the west in SW Japan.

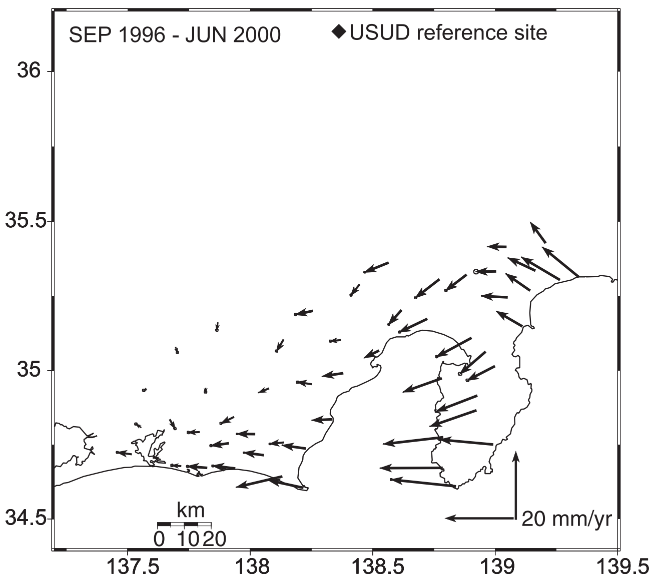

Fig. 2 The velocity field during September 1996 and June 2000 as background secular motion. Circles indicate 90% confidential ellipses.

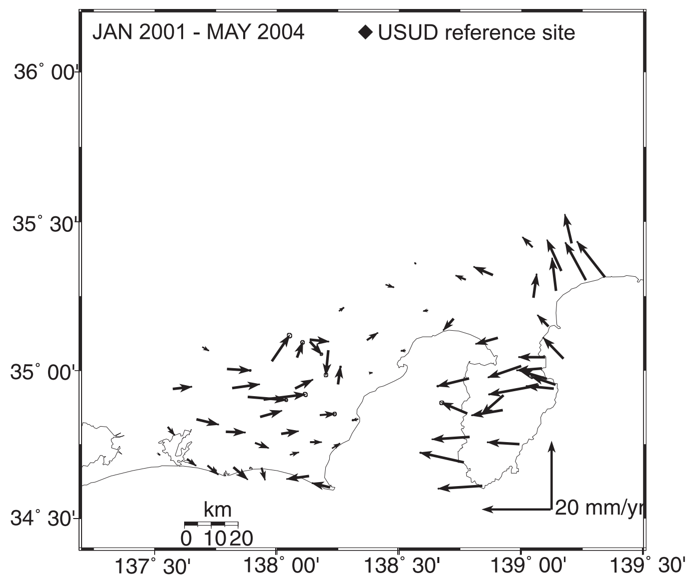

Fig. 3 The velocity field during January 2001 and May 2004, showing the velocity field of the whole period of the slow event ongoing. Circles indicate 90% confidential ellipses.

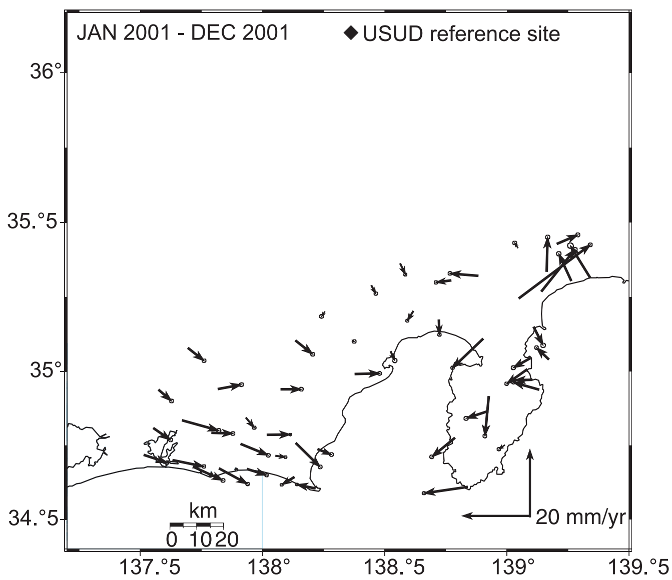

Fig. 4 The velocity field during January and December 2001. Circles indicate 90% confidential ellipses.

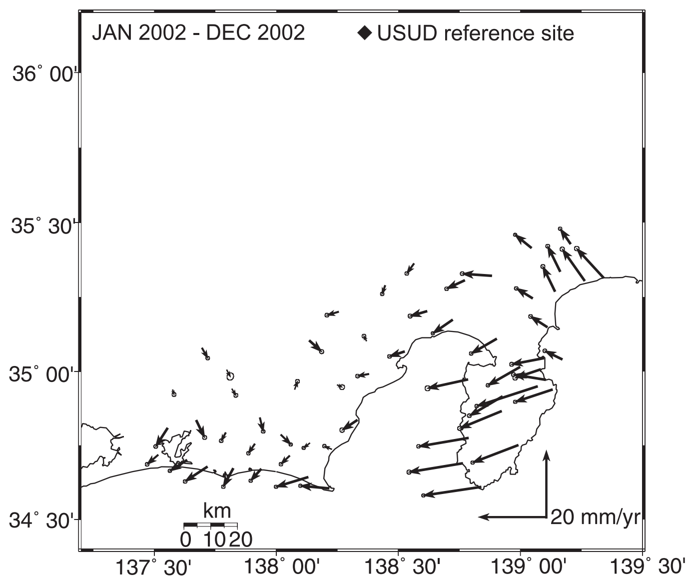

Fig. 5 The velocity field during January and December 2002. Circles indicate 90% confidential ellipses.

3. Time evolution of the slow event

By estimating the velocity fields using shorter time span, it is possible to study the episodic feature of the slow event. **Figs. 4** to **6** shows the time evolution of the annual slow event velocity field. In 2001 (**Fig. 4**), the area affected by the slow event was very wide, extending to the areas facing the Pacific Ocean in the south and facing the coast of the Suruga Bay to the east. The affected area must continue to the ocean bottom of the Pacific Ocean in the south. The velocities were also very fast in general. In 2002 (**Fig. 5**), the areas affected by the slow event shrank only to the inland Tokai area, and the velocities also became slower. During the period of February and May 2003, GEONET system was upgraded by replacing the antenna, the antenna radome, and the receiver at each site to minimize the multi-path effects and to improve the phase center variation correction. However, the upgrade caused offsets in the site coordinate solutions in our GPS analysis. GSI also changed the elevation cut-off angle of the GEONET receiver from 15˚ to 5˚ to improve the vertical repeatability.

This change caused significant offset in the vertical component of the site coordinate solutions. It is very difficult to obtain the accurate offset estimates due to such a major change in the observation setup. Therefore we omitted the data during January and May 2003, **Fig. 6** shows the annual velocity field during June 2003 and May 2004, revealing that the areas affected by the slow event again became very wide and the velocities were also very fast, about the same as in the period of 2001.

Fig. 7 shows the baseline time series of the north, east, up components and length between USUD and TAT. The TAT site is one of the NIED site. Both are free from the artificial offset caused by the GEONET system revision. The TAT site started observation since the beginning of 2001. In the E-W component, the episodic feature of the velocity is noticeable; fast in 2001, slowed down in 2002, and speeded up again in 2003 and still maintained fast up to the present.

4. Discussion and conclusion

The comparison between the velocity field in 2001 and during the period of June 2003 and May 2004 suggests that the

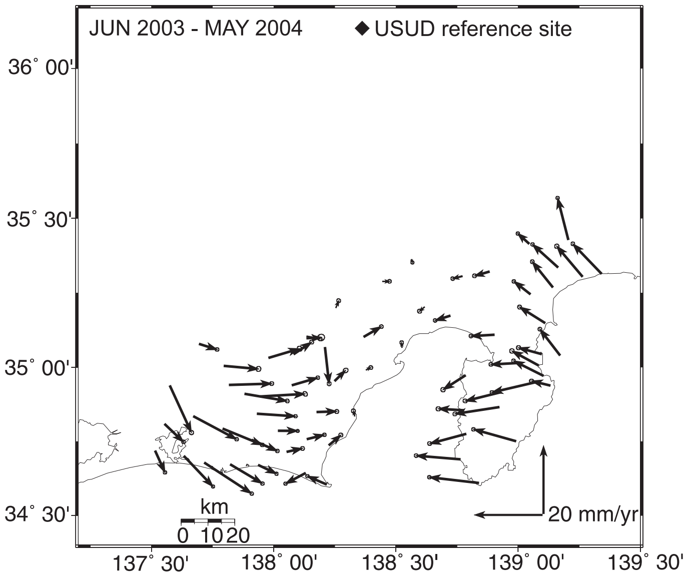

Fig. 6 The velocity field during June 2003 and May 2004. Circles indicate 90% confidential ellipses.

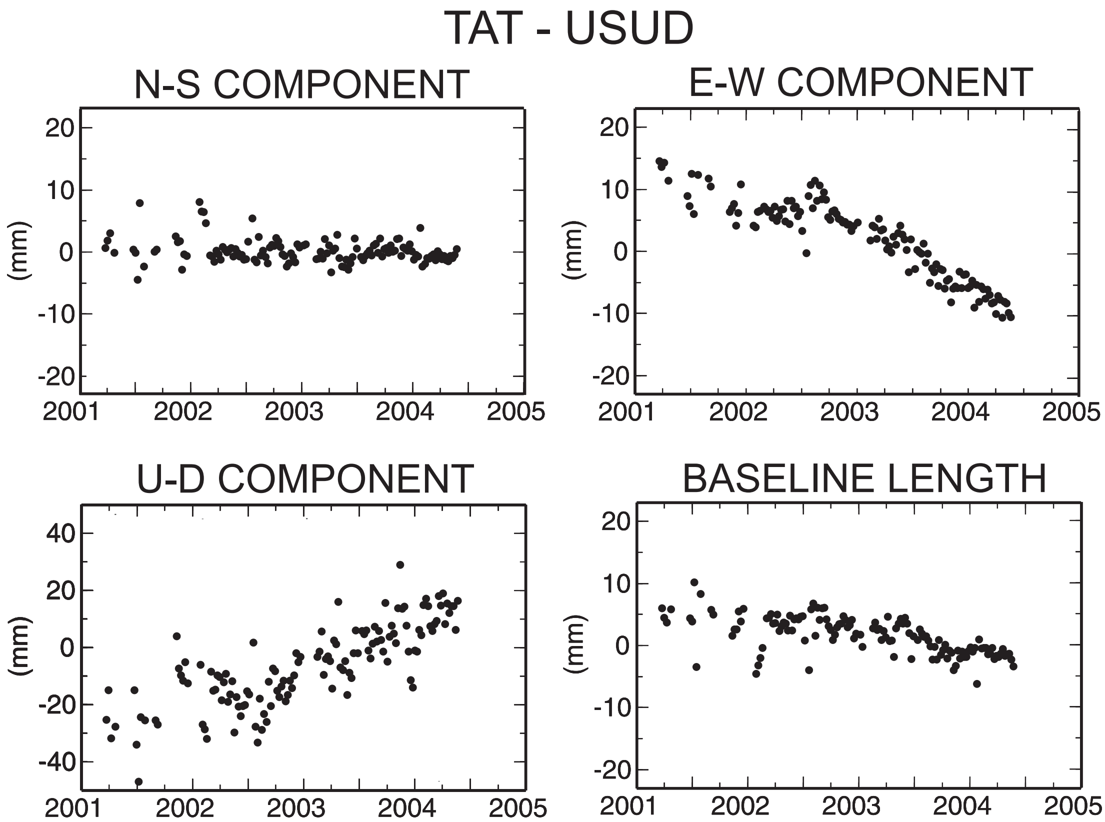

Fig. 7 Time series of the TAT-USUD baseline during 2001 and 2004. The data are the weekly values estimated from the daily values using the Kalman filtering.

velocities are faster in 2003-2004 than in 2001 and the affected areas of the fastest velocity are wider in 2003-2004 than in 2001. However, it should be noted that the GPS sites operational were fewer in 2001 than 2003-2004. The time series of the TAT-USUD baseline do not appear to be in agreement with all site inclusive solutions.

The rate change on an annual basis (the beginning of 2001, 2002, and 2003) must be just occasional, and thus there are no physical sources to make the rate change at the beginnings of the year.

We compare our analyzing results with the solutions by GSI (GSI, 2004). GSI (2004) shows the annual horizontal movements by the slow slip in Tokai Region during October 2000 and April 2004. In the routine analysis carried out in GSI (Miyazaki *et al*., 1998), they fix the coordinates of the TSKB site of the IGS network and obtain the coordinates of the nation-wide selected sites among GEONET, then obtain the coordinates of all the regional GEONET sites referencing to the coordinates solutions of the selected sites both using the Bernese Software (Rothacher and Mervart, 1996). Although the approaches to resolve the coordinates of the Japanese network sites are so different between our and GSI's methods, the obtained solutions of the coordinates of the sites generally coincide for both methods. GSI (2004) gives the annual horizontal movements as vector reference to the Ohgata sites, more than 100 km north of USUD reference site in this study. Judging the motion around the USUD site reference to the Ohgata sites by GSI solutions, the motion is negligible small and we conclude the effect of the ongoing Tokai slow event does not reach the USUD site. The annual velocity fields during January and December 2001 (**Fig. 4**), and January and December 2002 (**Fig. 5**) are able to be compared directly with the result by GSI (2004). GSI's results have generally westward offset in the Tokai-Izu region where the analysis is done in this study. Because of the offset, the velocity field in Tokai area in 2002 is generally south-eastward in GSI although the field is south to south-westward in this study. Major differences are seen in sites in the Izu Peninsula and around the Omaezaki Point, the cape of the southeastern end of the Tokai area facing the entrance of the Suruga Bay. In the both area, GSI's result shows eastward motions, although this study shows the westward motion. In 2001, the central region of the eastward motion generally coincided for both solutions although the center may locates a little more westward for GSI's solution than this study.

The area near the Omaezaki Point, especially two GEONET sites in the southeastern end of the Tokai area, indicates the largest westward motion in the background secular motion in the Tokai area (**Fig. 2**), and those two points still indicates westward motions even in the slow slip period (**Figs. 3**, **4**, **5**, and **6**), which suggests that the slow slip event does not reach the upper-most end of the PHS slab along the Suruga Trough near the Omaezaki Point.

Closely examining the TAT-USUD time series in **Fig. 7**, at first annual movements are scarcely seen. According to GSI (2004), in the time series of the baseline length among GEONET sites, the annual motions are seen almost every baseline. According to Hatanaka (2004), the annual motions are mostly not realistic phenomena, but are caused by a bug of the Bernese software, which is contaminated in the K1 earth tide theoretical phase. Some of the annual motions of the GEONET sites were thought to be caused by the thermometric tilting of the metal antenna pillars which are more than four-meter tall. In the site TAT, the antenna pillar is made by ferro-concrete and only about three-meter tall. In the USUD site, the antenna is installed at the roof of the ferro-concrete building. The difference of the antenna-mounted materials is thought to be the cause of some parts of the annual motions. In the second, the E-W component of the baseline vector, during the spring and fall of 2002, the polarity of the trend seems to reverse to the other period. For only this period the slow slip might stop and the regular secular motion might arise. Although for the 2001 event the plot is so scattered to discuss the slip rate time variations, from the fall 2002 to the spring 2004 the slip rate seems to be constant.

According to Ozawa *et al*. (2002), the slow event is caused by the slow slip occurring between the subducting PHS and the SW Japan. The fast and wide velocities at the midst of 2001 were caused by the fast slip in the plate boundary centered beneath Lake Hamana. The slow and narrow velocities at late 2001 to the midst of 2002 were brought by the slow slip in the plate boundary centered beneath the area slightly northeast of the Lake Hamana. According to their calculation, the extension of the slow event was caused by the slip rate change on the plate boundary, not the extension of the area of the slip. Adopting the calculation by Ozawa *et al*. (2002), the time evolution of the slow event, that is, the fast and wide event in 2001, and the slow and narrow in 2002, and the fast and wide in 2003 - 2004, may be caused by the changes of the speed of the slow slip in the plate boundary zone, and some moving of the center of the slip. The physics that promotes the slow slip is not yet clear.

In summary, the time evolution of the slow event ongoing in the Tokai area indicated relatively high velocity and wide area in 2001, relatively slow velocity and narrow area in 2002, and again relatively high velocity and wide area in 2003 and ongoing in 2004.

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References

1) Dong, D., Herring, T. A., and King, R. W. (1998): Estimating regional deformation from a combination of

space and terrestrial geodetic data. *J. Geod*., **72**, 200-214.

2) Dragert, H., Wang, K., and James, T. S. (2001): A silent slip event on the deeper Cascadia subduction interface. *Science*, **292**, 1525-1528.

3) Geographical Survey Institute (2004): Crustal movements in the Tokai District, *Rep. Coord. Comm. Earthquake Prediction*, **72**, 311-412.

4) Hatanaka, Y. (2004): Re-evaluation of seasonal variations of scale in the GEONET solutions, Program and Abstracts 102nd Meet. Geod. Soc. Jpn., 71-72.

5) Heki, K., Miyazaki, S., and Tsuji, H. (1997): Silent fault slip following and interpolate thrust earthquake at the Japan Trench. *Nature*, **386**, 595-598.

6) Herring, T. A. (2004): GLOBK global Kalman fiter VLBI and GPS analysis program. Mass. Inst. of Technol., Cambridge, Massachesetts.

7) Hirose, H., Hirahara, K., Kimata, F., Fujii, N., and Miyazaki, S. (1999): A slow thrust slip event following the 1996 Hyuga-nada earthquakes beneath the Bungo Channel, southwest Japan. *Geophys. Res. Lett*., **26**, 3237-3240.

8) King, R. W., and Bock, Y. (2004): Documentation for the GAMIT GPS analysis software. Mass. Inst. of Technol., Cambridge, Massachusetts.

9) Miller, M. M., Melbourne, T., Johnson, D. J., and Sumner, W. Q. (2002): Periodic slow earthquakes from the Cascadia subduction zone. *Science*, **295**, 2423.

10) Miyazaki, S., Saito, T., Sasaki, M., Hatanaka, Y., and Iimura, Y. (1997): Expansion of GSI's nationwide GPS array. *Bull. Geogr. Surv. Inst*., **43**, 23-34.

11) Miyazaki, S., Hatanaka, Y., Sagiya, T., and Tada, T. (1998): The nationwide GPS array as an Earth observation system, *Bull. Geogr. Surv. Inst*., **44**, 11-22.

12) Nishimura, T., Ozawa, S., Murakami, M., Sagiya, T., Tada, T., Kaidzu, M., and Ukawa, M. (2001): Crustal deformation caused by magma migration in the northern Izu Islands, Japan. *Geophys. Res. Lett*., **28**, 3745-3748.

13) Ozawa, S., Murakami, M., Kaidzu, M., Tada, T., Sagiya, T., Hatanaka, Y., Yarai, H., and Nishimura, T. (2002): Detection and monitoring of ongoing aseismic slip in the Tokai Region, Central Japan. *Science*, **298**, 1009-1012.

14) Ozawa, S., Murakami, M., Kaidzu, M., Imakiire, T., and Hatanaka, Y. (2004): Recent transient crustal deformation in the Tokai region. Abstracts 2004 Japan Earth and Planetary Sci. Joint Meeting.

15) Rogers, G., and Dragert, H. (2003): Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip. *Science*, **300**, 1942-1943.

16) Rothacher, M. and Mervart, L., (eds.) (1996): Documentation of the Bernese GPS software version 4.0, 418pp., Astronomical Institute, University of Berne.

17) Yamamoto, E., Matsumura, S., and Ohkubo, T. (2005): Repeatedly occurring slow rebound of the continental plate at the Kanto-Tokai area of Japan detected by continuous tilt observation. *Earth Planetary Space, in press*.

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東海スローイベント東部の時間推移

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要　旨

東海地域でスローイベントが現在発生しており，これはおそらく沈み込んでいるフィリピン海スラブと陸側のユーラシアプレートとの間で発生しているスロー•スリップに起因していると考えられる（Ozawa *et al*., 2002）. 本論文では，この活動による異常地殻変動が発生している地域のうち，東部域についての活動の時間変化を，GPS（全地球測位システム）による観測により明らかにした．観測データの解析により，異常地殻変動は，顕著な変動を示していることが明らかになった．変位速度場は，2001 年には速く，また広範囲に発生しており，2002 年には遅く，狭い範囲となり，2003 年以降は再び速く広い範囲で発生している．

キーワード：スローイベント，GPS，東海地域，地殻変動観測