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Surface displacements in Japan before the 11 March 2011 M9.0 Tohoku-Oki earthquake

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ABSTRACT

Daily resolution data retrieved from the 1243 ground-based Global Positioning System (GPS) stations in Japan are utilized to expose surface displacements before the destructive M9 Tohoku-Oki earthquake (March 11, 2011). Variations in the residual GPS data, in which effects of the long-term plate movements, short-term noise and frequency-dependent variations have been removed through a band-pass filter via the Hilbert–Huang transform, are compared with parameters of the focal mechanism associated with the Tohoku-Oki earthquake for validation. Analytical results show that the southward movements, which were deduced from the residual displacements and agree with the strike of the rupture fault, became evident on the 65th day before the Tohoku-Oki earthquake. This observation suggests that the shear stress played an important role in the seismic incubation period. The westward movements, which are consistent with the angle of the maximum horizontal compressive stress, covered entire Japan and formed an impeded area (142°E, 42°N) about 75 km away from the epicenter on the 47th day prior to the earthquake. The horizontal displacements integrated with the vertical movements from the residual GPS data are very useful to construct comprehensive images in diagnosing the surface deformation from destructive earthquakes along the subduction zone.

1. Introduction

Japan is located along the northwestern margins of the circum-Pacific seismic zone. Intense interaction among five plates (i.e. the Eurasia, Amur, Okhotsk, Pacific, and Philippine Sea plates; also see Fig. 1) (Wei and Seno, 1998; Hashimoto and Jackson, 1993; Taira, 2001) causes complex tectonic structures and generates many destructive earthquakes. At 05:46:18 UT (universal time), 11 March 2011, a most destructive M9.0 earthquake (142.86°E, 38.10°N) occurred near the Miyagi city, off the east coast of Honshu, Tohoku area, Japan. The earthquake occurred on the plate boundary between the Okhotsk and the Pacific plates and was hereafter referred as the Tohoku-Oki earthquake by scientists. The Centroid Moment Tensor analysis indicates that the Tohoku-Oki earthquake is the reverse fault type, with the strike 202°, dip 10°, and rake 90° (Lay et al., 2011). The significant co-seismic displacements associated with the 2011 Tohoku-Oki earthquake were mainly observed at the eastern part of Japan (i.e. $\gtrsim 139°$E) and reported in many studies (Nishimura et al., 2011; Ozawa et al., 2011, 2012; Simons et al., 2011; Wei et al., 2012). The co-seismic displacements of the seafloor benchmarks associated with the Tohoku-Oki earthquake estimated by the Japan Coast Guard were 22 m eastward and 10 m southward (Sato et al., 2011). Intense co-seismic dislocation happened on the seafloor caused a huge tsunami killing more than 10,000 people (Shao et al., 2011).

Global Positioning System (GPS) is one of the common measurements to expose surface displacements resulted from stress disturbance. Chen et al. (2011) utilized a band-pass filter of 20–150 days in period via the Hilbert–Huang transform (Huang et al., 1998, 2003; Huang and Wu, 2008) to effectively mitigate effects of noise, long-term plate movements (Reilinger et al., 1997;

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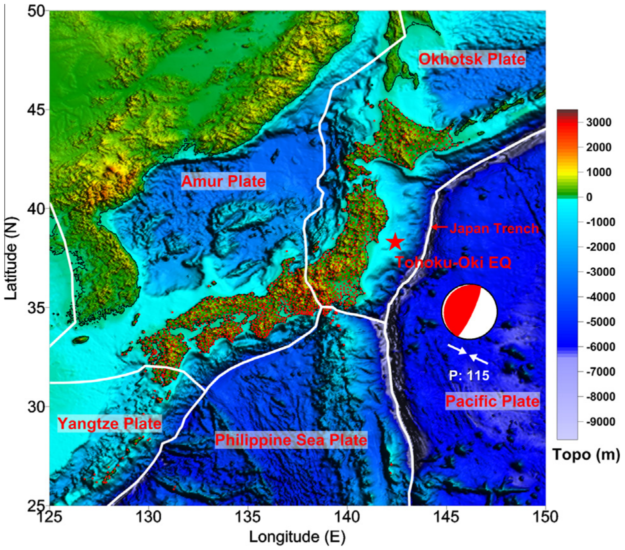

Fig. 1. Locations of the 1243 ground-based GPS stations in Japan. GPS stations utilized in this study are plotted with the seabed topology and the focal mechanism, retrieved from USGS reports. The principal axis, *P* (most compressive), is about 115° derived by the method of Robinson and McGinty (2000).

McClusky et al., 2003; Prawirodirdjo and Bock, 2004; Wernicke et al., 2004; Geirsson et al., 2006), instantaneous co-seismic dislocation (Yu et al., 2001; Gahalaut et al., 2006) and frequency dependent semi-annual and annual cycles (Van Dam et al., 2001; Blewitt and Lavallee, 2002; Ray et al., 2008; Yeh et al., 2008) from GPS continuous data to adapt non-linear and non-stationary nature. Chen et al. (2011) observed that horizontal orientations of the residual surface displacements are generally in random nature because effects of the long-term plate movements have been removed. The disordered orientations gradually become aligned toward a similar direction and are consistent with the angle of the maximum horizontal compressive stress associated with forthcoming thrust earthquakes. Meanwhile, the aligned orientations are orthogonal to the strikes of reverse faults and yield totally inverse rotations before and after earthquakes that agrees with the seismic rebound theory (Reid, 1910). Chen et al. (2013a) utilized the orientations of the residual displacements deduced from 100 GPS stations in Taiwan constructing temporal–spatial maps to comprehensively understand stress disturbance through earthquake processes. The agreement between the evolutions of the orientations and earthquake parameters (i.e. fault strike, earthquake location, horizontal stress axis, and so on) has been repeatedly observed for many thrust earthquakes in Taiwan. Meanwhile, changes in the residual displacements can be related with depression and/or uplift in groundwater levels during the Chi–Chi M7.6 earthquake (on September 20, 1999) through physical mechanisms (Chen et al., 2013b).

Here, surface displacements data at the 1243 ground-based GPS stations from January 1, 2010 to March 10, 2011 retrieved from Geospatial Information Authority of Japan are used to examine and understand stress disturbance in seismogenic processes of the Tohoku-Oki earthquake. The method proposed by Chen et al. (2011) is applied on filtering long-term plate movements, short-term noise and frequency dependent (i.e. semi-annual and annual) variations from the 3-component GPS data for all stations. The residual GPS data at the NS and EW components are utilized to compute the orientations of the horizontal azimuths (i.e. the GPS-azimuths). Meanwhile, quantities of the residual GPS data at the vertical components are also conducted and further integrated with the horizontal azimuths to yield comprehensive images for comparing with parameters of the focal mechanism associated with the Tohoku-Oki earthquake and understanding evolution of tectonic movements relating to the earthquake in the subduction zone.

2. Data and analysis

Residual GPS data are retrieved from the continuous data at the 1243 GPS stations in Japan from January 1, 2010 and March 10, 2011 via a band-pass filter (20–150 days in period) through HHT to avoid influence resulted from great co-seismic changes of the Tohoku-Oki earthquake. The GPS-azimuths and quantities of the residual GPS data at the horizontal and vertical components, respectively, ranged from the 90th through 1st days prior to the Tohoku-Oki earthquake are examined. To understand disturbance of earthquake-related stress in the spatial domain, an average of differences, which are computed from the GPS-azimuths between every two stations within a spatially moving window of 0.5° × 0.5°, are calculated. In practice, the GPS index is further deduced by using an inverse of the average value. Generally, the GPS index is about 0.011 (=1°/90°; the pink color in Fig. 2) due to that the long-term plate movements have been removed and disordered orientations of the residual displacements generally yield the average differences of about 90° (for detail, also see Chen et al., 2011, 2013a). When earthquake-related stress disturbs on the shallow crust, the disordered orientations of the residual displacements are gradually aligned toward a similar direction for adapting stress loading. These aligned orientations yield the relatively small average from the differences and the relatively large GPS index (i.e. the yellow color in Fig. 3). Note that the relatively small GPS index (≅0.011) can also be observed a few days before the earthquake occurrence because disturbance of earthquake-related stress is restored as the elastic potential energy for the preparation of forthcoming fault rupture. On the other hand, an average of the quantities, which are computed from the vertical residual displacements at the entire stations within the same spatial moving window (i.e. 0.5° × 0.5°), is integrated with the GPS-azimuth in constructing comprehensive images to understand tectonic evolutions associated with the Tohoku-Oki earthquake.

3. Observation and interpretation

Figs. 2 and 3 show the temporal-spatial GPS-azimuth maps and vertical residual displacements on the 90th, 80th, 65th, 57th, 47th, 30th, 10th, 3rd as well as 1st days before the Tohoku-Oki earthquake, respectively. Random orientations of the GPS-azimuths yielded the GPS index of about 0.011 (≅1°/90°) covering entire Japan from the 90th to 80th days prior to the Tohoku-Oki earthquake. By contrast, minor rise and depression areas (<±1 mm) deduced from the vertical residual displacements existed in Japan. Analytical results suggest that no significant earthquake-related stress disturbed on the shallow crust in Japan at this time period. Random orientations of the GPS-azimuths were gradually aligned toward the southern direction, which results in the increase of GPS index > 0.04 (=1°/25°), from the 80th to 65th days prior to the Tohoku-Oki earthquake. This suggests that stress disturbed on and moved the shallow crust toward the southern direction. Note that the study area with intense uplift > 10 mm was clearly observed in the vertical residual component (Fig. 3). The aligned orientations became random in order again about the 57th day before the Tohoku-Oki earthquake that suggests a shift of earthquake-related stress disturbance. Approximately on the 47th day prior to the earthquake, the orientations of the residual displacements are re-aligned and moves toward the western direction, except for an area (142°E, 42°N) about 75 km away from the

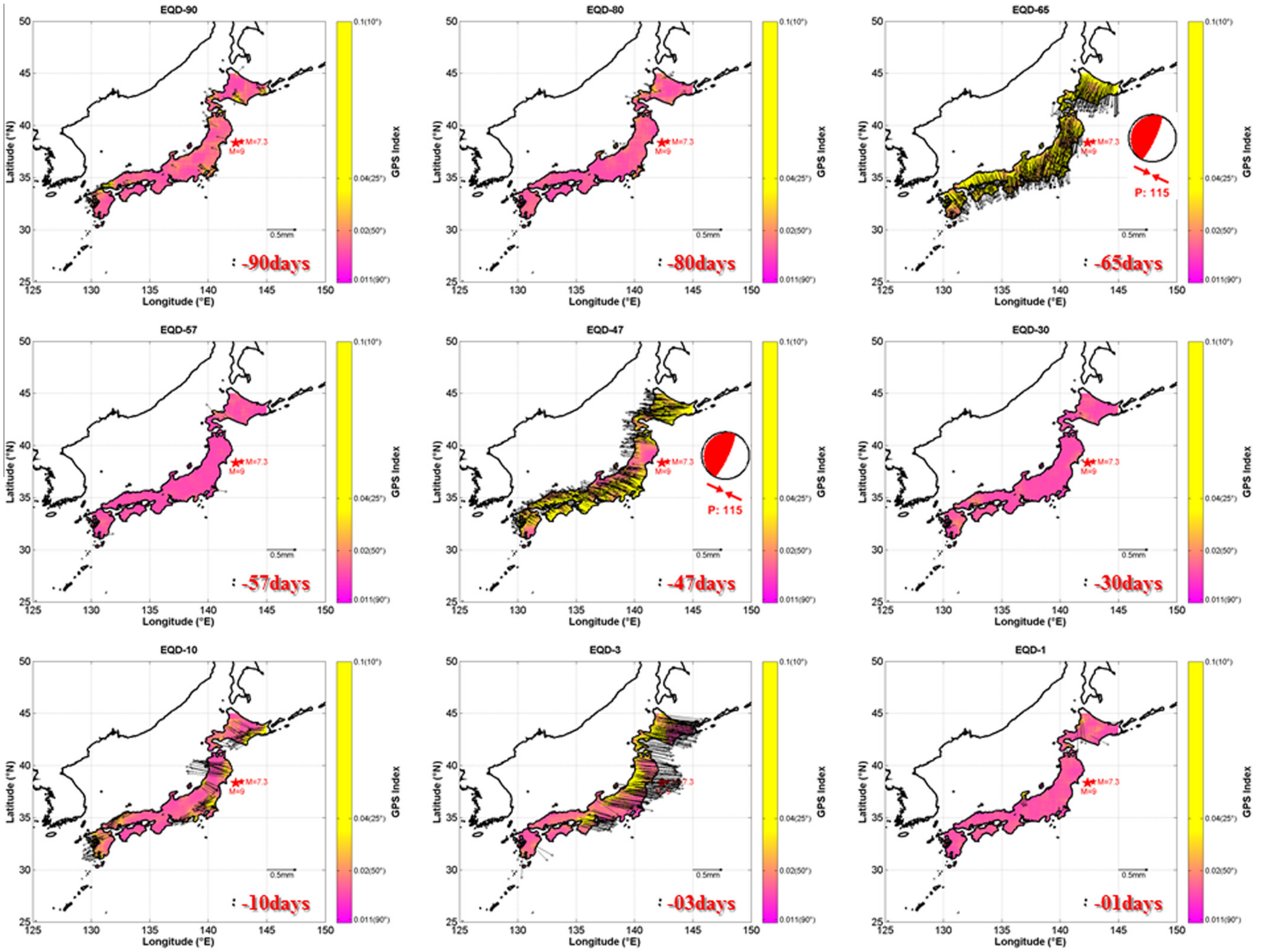

Fig. 2. Temporal–spatial variations of the GPS-azimuths before the Tohoku-Oki earthquake. The color shades on land (from yellow to pink) show inverse values of the average differences of the GPS-azimuths (i.e., GPS index) within the spatially moving window of 0.5° × 0.5°. When the inverse value is > 0.02 (i.e., the average difference of the GPS-azimuth < 50°; yellow color) due to stress accumulation, direction and magnitude of surface displacements are denoted by arrows. Directions of magnitude are computed using the median of the GPS-azimuths within spatial areas relative to the inverse values > 0.02. When the inverse value < 0.02 (pink color), suggesting indistinct orientations of GPS-azimuths (i.e., the average difference of the GPS-azimuth > 50°) within spatial areas, no significant direction of surface displacements can be determined. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

epicenter of the Tohoku-Oki earthquake. The intense uplift observed on the 65th day was gradually mitigated and became as a depression on the 47th day prior to the earthquake. From the 47th to 1st days prior to the Tohoku-Oki earthquake, the orientations of the residual displacements became random in order again, except for small regions located at continental margins of Japan. The persistent and minor uplift (1–4 mm) of the study area was detectable from the vertical residual displacements till the Tohoku-Oki earthquake occurrence. It is worth mentioning that significant influence from the foreshock (*M* = 7.3, March 9, 2011), which resulted in westward movement in partial areas and extensive depression (<4 mm) in entire Japan, was rapidly overridden by the subsequent M9 Tohoku-Oki earthquake.

In short, the stress disturbance before the Tohoku-Oki earthquake can be separated into four phases. The first phase (i.e. from the 90th to 80th days): no significant stress disturbance was observed on the crust surface in Japan. The second phase (i.e. from the 80th to 65th days): disordered orientations transferred into southward movements and crust uplifted. The third phase (i.e. from the 65th to 47th days): the westward movements replaced the southward ones and crust depressed. The fourth phase (i.e. from the 47th to 1st days): the stress disturbance gradually approached to the threshold of the fault rupture. No significant orientations of the GPS azimuths and quantities of vertical movement can be observed in this phase. Notably, Tsuruta et al. (2012) examined time series variations from surface displacement data in Japan and found obviously anomalous changes in the horizontal component in January 2011. The timing (i.e. in January 2011) of the anomalous changes in the raw data is consistent with those retrieved from the residual data.

4. Discussion and conclusions

The disordered orientations of the residual displacements observed in the first phase suggests insignificant stress disturbance in the studied area and is consistent with previous studies (Chen et al., 2011, 2013a). In the second phase, orientations of the GPS-azimuths oriented toward a similar direction of about 160–200° that was in accordance with the strike (202°) of the fault. Note that the SSE, *S* and SSW directions induced from aligned orientations can be observed at the SW, center and NE parts of Japan,

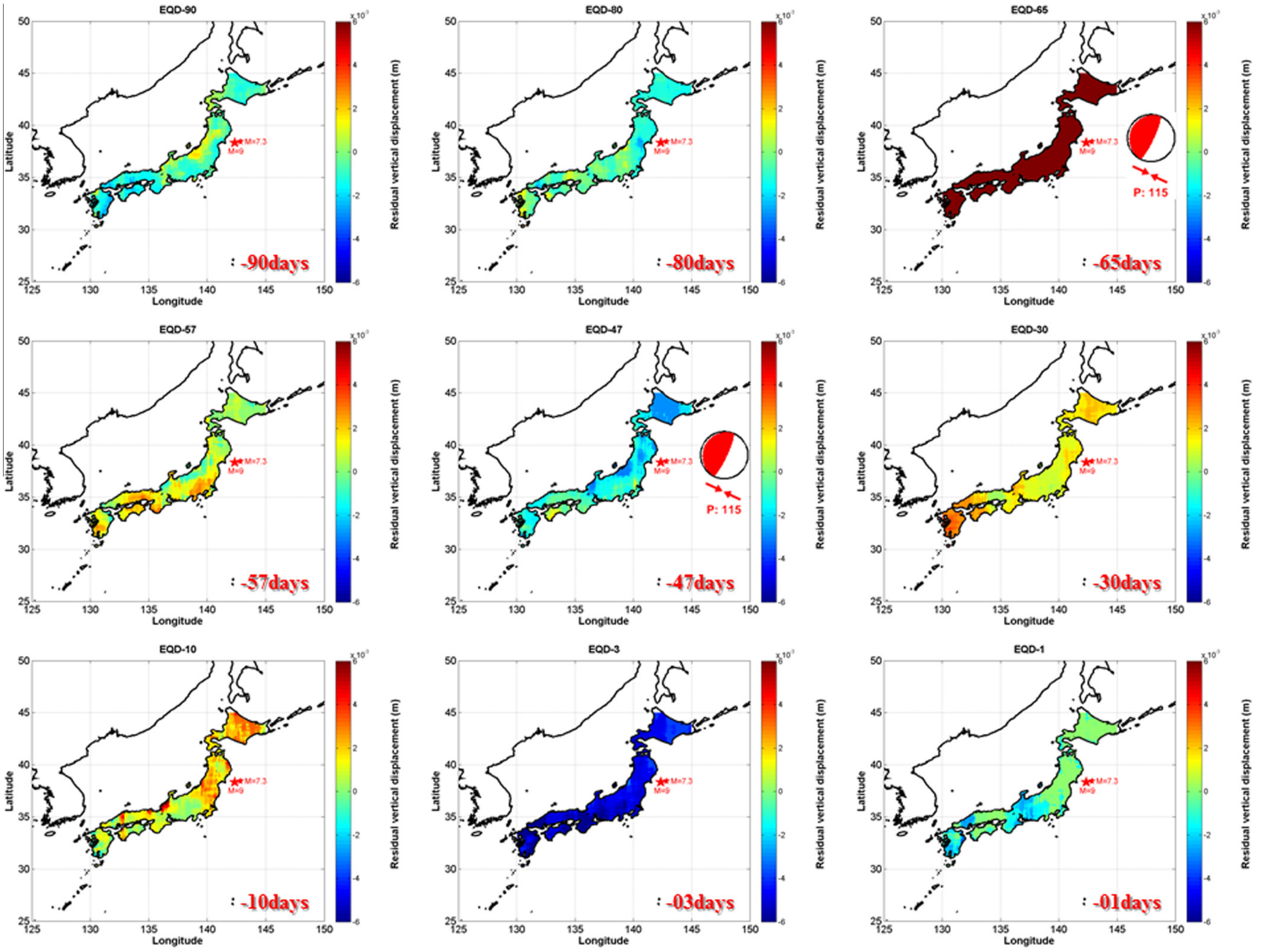

Fig. 3. Temporal–spatial variations of the residually vertical displacement before the Tohoku-Oki earthquake. The color shades on land (from blue to red) show quantities of vertical residual displacement within the spatial moving window of 0.5° × 0.5°. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respectively. At the same period, the significant uplift over the Okhotsk and Amur plates can be found in Fig. 3. These analytical results suggest that the southward stress mainly happened on the Okhotsk and Amur plates and was blocked in the both side of the Okhotsk and Amur plates and somewhere in the Pacific and Philippine Sea plates. Nonetheless, the uplift of the Okhotsk and Amur plates would partially reduce the loading on the subduction of Pacific and Philippine Sea plates, respectively. The uplift would then decrease the resistance of the Okhotsk and Amur plates and/or increase the mobility of subduction for Pacific and Philippine Sea plates. Thus, the southward stress, which was swiftly shifted toward west on the 57th day before the Tohoku-Oki earthquake, would play an important role on breaking and/or unlocking the original status between two wedged plates.

In the third phase, orientations of the GPS-azimuths were aligned toward the western direction that is consistent with the angle (about 115°) of the maximum horizontal compressive stress (Hasegawa et al., 2011). An area of disordered orientations surrounded by aligned orientations indicates that movements resulted from stress disturbance were impeded in this particular region (142°E, 42°N). Westward movements of the Okhotsk plate accompanying with slight depression suggest the Pacific plate under subduction. No apparent orientations and little vertical displacements indicate that the subduction of Pacific plate was greatly blocked in the fourth phase. The kinetic energy regarding movements of the Okhotsk plate would be transferred and/or restored as elastic potential energy for the preparation of a subsequent earthquake. The M7.3 foreshock occurred 2 days before the Tohoku-Oki earthquake and resulted in eastward movements of the Okhotsk plate associated with extensive depression. Co- and/or post-seismic effects caused by a major earthquake should maintain for a long period (Chen et al., 2011, 2013a). However, the obvious co- and/or post-seismic effects were quickly mitigated in the case of M7.3 foreshock. The sudden mitigation would be resulted from either the forthcoming of a higher M9.0 destructive earthquake or boundary effects due to one end of the utilized data.

It is worth mentioning that areas of orientations in the GPS-azimuths related with earthquake parameters (i.e. the strike of the fault and the axis of maximum horizontal compressive stresses) are rather larger than those from co-seismic displacements. Dobrovolsky et al. (1979) utilized surface deformation to construct the relationship between the radius of earthquake preparation zones and magnitudes. The relationship shows that the radius is about 7400 km in regards with a M9 earthquake. Thus, the observed residual displacements are not resulted from co-seismic displacements but the preparation zones of earthquakes. The observed residual displacements should be mainly affected by large-scale tectonic evolution during the incubation of the Tohoku-Oki

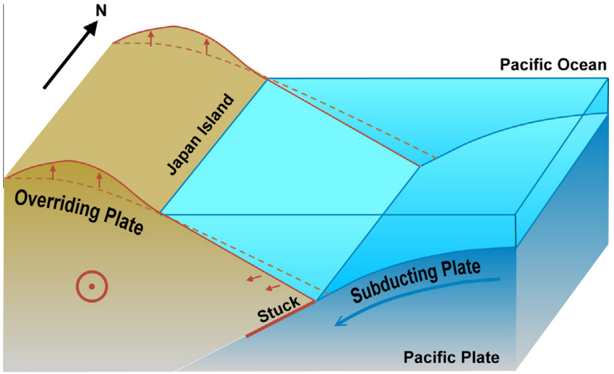

Fig. 4. A hypothetical diagram of tectonic evolution of the subducting Tohoku-Oki earthquake.

earthquake. Here, tomographic images of velocity structures and the crustal deformation of earthquakes along the subduction zone are taken into consideration to examine changes in the residual displacements observed in this study. Tomographic images of velocity structures, which can be evaluated by using *P* and *S* arrival time, are one of the methods to expose causal mechanisms of earthquakes (Tong et al., 2012). Significant heterogeneity of velocity structures can be found from north to south (Zhao et al., 2011) and from west to east (Zhao et al., 2009; Huang and Zhao, 2013) in the magethrust zone associated with the Tohoku-Oki earthquake. Earthquake-related surface displacements could be probably caused by discrepancy in the crustal heterogeneity and be observed in continental areas using a spatial high dense GPS array. On the other hand, evolutions of crustal deformations along a subduction zone with strong earthquakes have been widely reported (Davis and Hyndman, 1989; Dragert et al., 1994; Stern, 2002; Rogers and Dragert, 2003; Goren et al., 2008). When the subducting plate is getting stuck, the overriding plate would be squeezed (Fig. 4). This interaction causes that leading edges are dragged down, while hinterland areas bulge upward. Random orientations in the particular region surrounded by westward movements in the third phase before Tohoku-Oki earthquake suggest the stuck of the subducting plate (see Figs. 3 and 4). Minor depression appeared in the vertical residual displacements that agreed with dragged down areas in the leading edge (Fig. 3). When the strong earthquake along the subduction zone occurred, the leading edge of the jammed overriding plate was released and the bulge behind the leading edge collapsed. Extensive depression recorded in the vertical residual displacements due to occurrence of the M7.3 foreshock is expected with collapse of the bulge behind the leading edge. The observation in this study and the model in the previous reports are not entirely consistent in the either temporal or spatial domain, but yield an agreement in the tectonic evolution in respect with earthquake occurrence along the subduction zone.

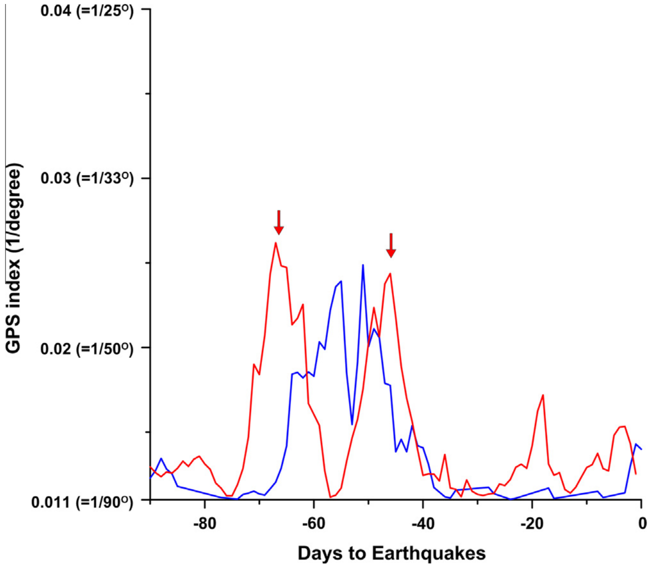

Fig. 5. Variations of the GPS index prior to the 2011 Tohoku-Oki and 1999 Chi–Chi earthquakes. The red and blue lines denote the variations of the GPS index before the Tohoku-Oki and Chi–Chi earthquakes, respectively. The red downward arrows show the aligned orientations of the GPS azimuths during the second and third phases in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In general, development of a large earthquake ($M > 7$) is considered to be taken months of time. The extreme-short interval (only 2 days at the same region) of the Tohoku-Oki and its foreshock refreshes the record of scientific observation in terms of frequency of earthquake occurrence and/or seismic cycles. However, analytical results in this study show that the earthquake-related displacements possibly become obvious and/or detectable when the short- and long-term effects on GPS data are mitigated. The phenomena of aligned orientations from the GPS-azimuths are not only observed prior to the Tohoku-Oki earthquake in Japan but also perceived for several M5-7 earthquakes in Taiwan (Chen et al., 2011, 2013a). Fig. 5 reveals variations of the GPS index computed by using GPS stations in Japan (1243 sites) and Taiwan (15 sites) about 85 days before the 2011 Tohoku-Oki and 1999 Chi–Chi earthquakes (also see Appendix A and Chen et al., 2013b), respectively, for cross-comparison. Similar changes in the GPS index (i.e. normally maintaining at low stage, then suddenly increasing from earthquake-related stress disturbance and gradually decreasing as approaching the thresholds of the fault rupture) are consistently observed. It is interesting that distinct leading time from peaks of the GPS index to earthquake occurrence can be found. This diagram suggests that the leading time would be proportional to earthquake magnitude. Note that the leading times are 68 and 58 days for the M9 Tohoku-Oki and M7.6 Chi–Chi earthquakes, respectively. Another case of the leading time is 12 days for the M5.1 earthquake in Taiwan (see Chen et al., 2011). However, studies regarding relationship between the leading time and earthquake magnitude need more work to get the meaningful statistics.

In conclusion, random and indeterminate surface deformations were normally observed in the long-term development about 80 days before the Tohoku-Oki earthquake. Orientations of obviously southward displacements accompanying with intense uplift that agrees with the strike of the rupture fault can be retrieved from the residually GPS displacements since the 80th to 65th days prior to the Tohoku-Oki earthquake. The southward displacements were shifted into the western direction on the period from the 65th to 47th days that would suggest compressive stress disturbed on the shallow crust of the studied area. Meanwhile, the subducting plate was stuck and resulted in slight depression at the leading edge. Although the detecting of earthquake-related minor deformation is a great challenge, from the analytical results in this study, the GPS residual displacements can provide more valuable information for understanding the incubation of the Tohoku-Oki earthquake. More studies along this line are urgently needed to clearly catch the pre-earthquake signals.

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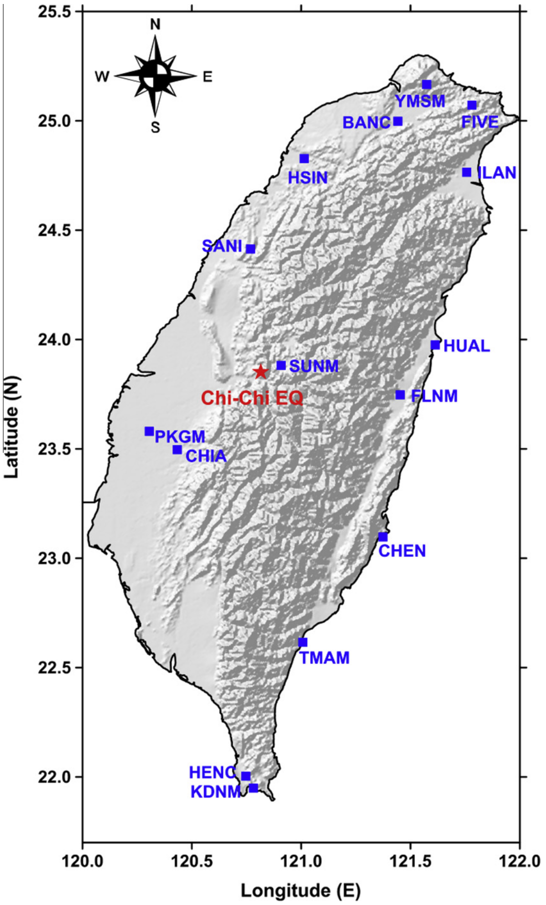

Fig. A. Location of the GPS stations utilized to compute orientations of GPS-azimuths during the M7.6 Chi–Chi earthquake (September 20, 1999) in Taiwan.

Appendix A

Fig. A.1

References

Blewitt, G., Lavallee, D., 2002. Effect of annual signals on geodetic velocity. Journal of Geophysical Research 107 (B7). http://dx.doi.org/10.1029/2001JB000570.

Chen, C.H., Yeh, T.K., Liu, J.Y., Wang, C.H., Wen, S., Yen, H.Y., Chang, S.H., 2011. Surface deformation and seismic rebound: implications and applications. Surveys in Geophysics 32, 291–313. http://dx.doi.org/10.1007/s10712-011-9117-3.

Chen, C.H., Wen, S., Yeh, T.K., Wang, C.H., Yen, H.Y., Liu, J.Y., Hobara, Y., Han, P., 2013a. Observation of surface displacements from GPS analyses before and after the Jiashian earthquake ($M = 6.4$) in Taiwan. Journal of Asian Earth Sciences 62, 662–671, <http://dx.doi.org/10.1016/j.jseaes.2012.11.016>.

Chen, C.H., Wang, C.H., Wen, S., Yeh, T.K., Lin, C.H., Liu, J.Y., Yen, H.Y., Lin, C., Rau, R.J., Lin, T.W., 2013b. Anomalous frequency characteristics of groundwater level before major earthquakes in Taiwan. Hydrology and Earth System Sciences 17, 1693–1703. http://dx.doi.org/10.5194/hess-17-1693-2013.

Davis, E.E., Hyndman, R.D., 1989. Accretion and recent deformation of sediments along the northern Cascadia subduction zone. Geological Society of America Bulletin 101, 1465–1480.

Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. Pure and Applied Geophysics 117, 1025–1044.

Dragert, H., Hyndman, R.D., Rogers, G.C., Wang, K., 1994. Current deformation and the width of the seismogenic zone of the northern Cascadia subduction thrust. Journal of Geophysical Research 99, 653–668.

Gahalaut, V.K., Nagarajan, B., Catherine, J.K., Skumar, S., 2006. Constraints on 2004 Sumatra Andaman earthquake rupture from GPS measurements in Andaman–Nicobar Islands. Earth and Planetary Science Letters 242, 365–374.

Geirsson, H., Árnadóttir, T., Völksen, C., Jiang, W., Sturkell, E., Villemin, T., Einarsson, P., Sigmundsson, F., Stefánsson, R., 2006. Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland. Journal of Geophysical Research 111, B09407. http://dx.doi.org/10.1029/2005JB003717.

Goren, L., Aharonov, E., Mulugeta, G., Koyi, H.A., Mart, Y., 2008. Ductile deformation of passive margins: a new mechanism for subduction initiation. Journal of Geophysical Research 113, B08411. http://dx.doi.org/10.1029/2005JB004179.

Hasegawa, A., Yoshida, K., Okada, T., 2011. Nearly complete stress drop in the 2011 M_w 9.0 off the Pacific coast of Tohoku earthquake. Earth Planets Space 63, 703–707.

Hashimoto, M., Jackson, D.D., 1993. Plate tectonics and crustal deformation around the Japanese Islands. Journal of Geophysical Research 98, 16149–16166.

Huang, N.E., Wu, Z., 2008. A review on Hilbert–Huang transform: method and its applications to geophysical studies. Review of Geophysics 46, RG2006. http://dx.doi.org/10.1029/2007RG000228.

Huang, Z., Zhao, D., 2013. Mechanism of the 2011 Tohoku-Oki earthquake (Mw 9.0) and tsunami: insight from seismic tomography. Journal of Asian Earth Sciences 70, 160–168.

Huang, N.E., Shen, Z., Long, S.R., Wu, M.C., Shih, H.H., Zheng, Q., Yen, N.-C., Tung, C.C., Liu, H.H., 1998. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. Proceedings of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences 454, 903–995.

Huang, N.E., Shen, Z., Long, S.R., Shen, S.S.P., Hsu, N.H., Xiong, D., Qu, W., Gloersen, P., 2003. On the establishment of a confidence limit for the empirical mode decomposition and Hilbert spectral analysis. Proceedings of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences 459, 2317–2345.

Lay, T., Ammon, C.J., Kanamori, H., Xue, L., Kim, M.J., 2011. Possible large near-trench slip during the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake. Earth Planets Space 63, 687–692. http://dx.doi.org/10.5047/eps.2011.05.033.

McClusky, S., Reilinger, R., Mahmoud, S., Ben Sari, D., Tealeb, A., 2003. GPS constraints on Africa (Nubia) and Arabia plate motions. Geophysical Journal International 155, 126–138. http://dx.doi.org/10.1046/j.1365-246X.2003.02023.x.

Nishimura, T., Munekane, H., Yarai, H., 2011. The 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks observed by GEONET. Earth Planets Space 63, 631–636. http://dx.doi.org/10.5047/eps.2011.06.025.

Ozawa, S., Nishimura, T., Suito, H., Kobayashi, T., Tobita, M., Imakiire, T., 2011. Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. Nature 475, 373–376.

Ozawa, S., Nishimura, T., Munekane, H., Suito, H., Kobayashi, T., Tobita, M., Imakiire, T., 2012. Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan. Journal of Geophysical Research 117, B07404. http://dx.doi.org/10.1029/2011JB009120.

Prawirodirdjo, L., Bock, Y., 2004. Instantaneous global plate motion model from 12 years of continuous GPS observations. Journal of Geophysical Research 109, B08405. http://dx.doi.org/10.1029/2003JB002944.

Ray, J., Altamimi, Z., Collilieux, X., Van Dam, T., 2008. Anomalous Harmonics in the spectra of GPS position estimates. GPS Solutions 12, 55–64.

Reid, H.F., 1910. The mechanics of the earthquake. The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, vol. 2. Carnegie Institution, Washington, DC, pp. 1–192.

Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O., Sanli, I., 1997. Global positioning system measurements of present-day crustal movements in the Arabia–Africa–Eurasia plate collision zone. Journal of Geophysical Research 102 (B5), 9983–9999. http://dx.doi.org/10.1029/96JB03736.

Robinson, R., McGinty, P.J., 2000. The enigma of the Arthur's Pass, New Zealand, earthquake 2. The aftershock distribution and its relation to regional and induced stress field. Journal of Geophysical Research 105, 16139–16150.

Rogers, G., Dragert, H., 2003. Episodic tremor and slip on the Cascadia subduction zone: the chatter of silent slip. Science 300, 1942. http://dx.doi.org/10.1126/science.1084783.

Sato, M., Ishikawa, T., Ujihara, N., Yoshida, S., Fujita, M., Mochizuki, M., 2011. Displacement above the hypocenter of the 2011 Tohoku-Oki earthquake. Science 332, 1395. http://dx.doi.org/10.1126/science.1207401.

Shao, G., Li, X., Ji, C., Maeda, T., 2011. Focal mechanism and slip history of 2011 Mw 9.1 off the Pacific coast of Tohoku earthquake, constrained with teleseismic body and surface waves. Earth Planets Space 63, 559–564.

Simons, M., Minson, S.E., Sladen, A., Ortega, F., Jiang, J., Owen, S.E., Meng, L., Ampuero, J.-P., Wei, S., Chu, R., Helmberger, D.V., Kanamori, H., Hetland, E., Moore, A.W., Webb, F.H., 2011. The 2011 magnitude 9.0 Tohoku-Oki earthquake: mosaicking the megathrust from seconds to centuries. Science 332, 1421–1425.

Stern, R.J., 2002. Subduction zones. Reviews of Geophysics 40, 1012. http://dx.doi.org/10.1029/2001RG000108.

Taira, A., 2001. Tectonic evolution of the Japanese island arc system. Annual Review of Earth and Planetary Sciences 29, 109–134.

Tong, P., Zhao, D., Yang, D., 2012. Tomography of the 2011 Iwaki earthquake (M 7.0) and Fukushima nuclear power plant area. Solid Earth 3, 43–51.

Tsuruta, H., Hattor, K., Han, P., 2012. Surfacemotions Prior to Mega Earthquakes by Using GPS Data, JpGU Meeting, Japan Geoscience Union, Chiba, Japan.

Van Dam, T., Wahr, J., Milly, P.C.D., Shmakin, A.B., Blewitt, G., Lavallee, D., Larson, K.M., 2001. Crustal displacements due to continental water loading. Geophysical Research Letters 28, 651–654.

Wei, D., Seno, T., 1998. Determination of the Amurian plate motion. In: Flower, M., Chung, S., Lo, C., Lee, T. (Eds.), Mantle Dynamics and Plate Interactions in East Asia, Geodynamics Series 27. American Geophysical Union, Washington, DC, pp. 337–346.

Wei, S., Graves, R., Helmberger, D., Avouac, J.-P., Jiang, J., 2012. Sources of shaking and flooding during the Tohoku-Oki earthquake: a mixture of rupture styles. Earth and Planetary Science Letters 333–334, 91–100.

Wernicke, B., Davis, J.L., Bennett, R.A., Normandeau, J.E., Friedrich, A.M., 2004. Tectonic implications of a dense continuous GPS velocity field at Yucca Mountain, Nevada. Journal of Geophysical Research 109, B12404. http://dx.doi.org/10.1029/2003JB002832.

Yeh, T.K., Hwang, C., Xu, G., 2008. GPS height and gravity variations due to ocean tidal loading around Taiwan. Surveys in Geophysics 29, 37–50.

Yu, S.B., Kuo, L.C., Hsu, Y.J., Su, H.H., Liu, C.C., Hou, C.S., Lee, J.F., Lai, T.C., Liu, C.C., Liu, C.L., Tseng, T.F., Tsai, C.S., Shin, T.C., 2001. Preseismic deformation and coseismic displacements associated with the 1999 Chi–Chi, Taiwan earthquake. Bulletin of the Seismological Society of America 91, 995–1012.

Zhao, D., Wang, Z., Umino, N., Hasegawa, A., 2009. Mapping the mantle wedge and interplate thrust zone of the northeast Japan arc. Tectonophysics 467, 89–106.

Zhao, D., Huang, Z., Umino, N., Hasegawa, A., Kanamori, H., 2011. Structural heterogeneity in the megathrust zone and mechanism of the 2011 Tohoku-Oki earthquake (Mw 9.0). Geophysical Research Letters 38, L17308.