Research Paper

Pre-, co-, and post-seismic deformation of the 2011 Tohoku-oki earthquake and its implication to a paradox in short-term and long-term deformation

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Abstract. The 2011 Tohoku-oki earthquake caused large eastward displacement and subsidence along the Pacific coast of northeastern Japan. This earthquake partly solved a well-known paradox holding that sense and rate of deformation differ greatly between geologic and geodetic estimates. A paradox remains, however, in explaining long-term uplift along the Pacific coast on a geologic time-scale. Geodetic data show that coastal subsidence continued at a nearly constant rate of ~ 5 mm/yr with small fluctuations associated with *M* 7-8 interplate earthquakes for ~ 120 years before the Tohoku-oki earthquake. In an area near the Oshika Peninsula where coseismic subsidence is largest, extrapolation of a logarithmic function fitting observed postseismic deformation suggests that coseismic subsidence may be compensated for by the postseismic uplift for several decades but it is difficult to expect the postseismic uplift exceeding 2 meters, so it is implausible that the observed rapid subsidence continued throughout an entire interseismic period in a great megathrust earthquake cycle. We propose a hypothetical model in which the sense of vertical deformation changes from uplift to subsidence during the interseismic period. Using simple elastic dislocation theory, this model is explained by the shallow coupled part of a plate interface in an early interseismic period and the deep coupled part of a late interseismic period.

Keywords: Crustal deformation, interplate coupling, GNSS, leveling

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku earthquake (hereafter Tohoku-oki earthquake) with M_w 9.0 caused significant coseismic deformation not only in the Japanese islands [1] but also on the Eurasia continent ~ 3000 km away from the earthquake epicenter [2, 3]. Coseismic and postseismic deformation in Japan is

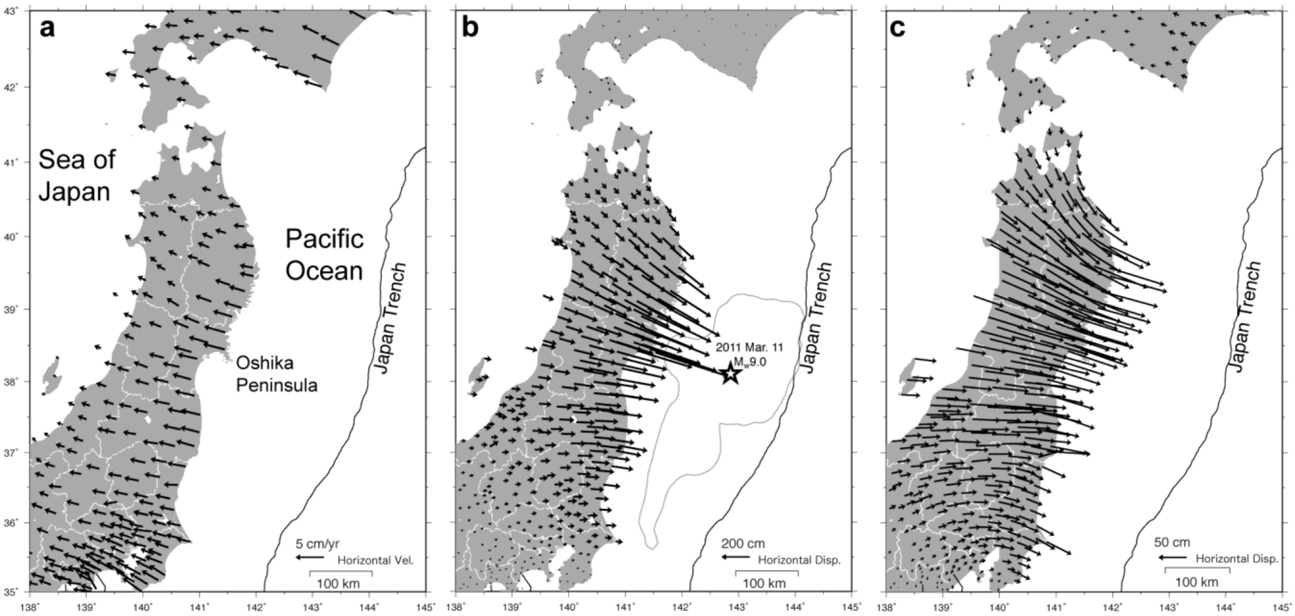

Fig. 1 Horizontal deformation of northeastern Japan before, during, and after the 2011 Tohoku-oki earthquake. Daily coordinates of GEONET GNSS stations are used to plot the deformation. Reference station is Fukue which is located ~1000 km west of the plotted area. (a) Preseismic velocity from April 1997 to March 2000. (b) Coseismic displacement. The star and the shaded region represent the epicenter and a slip area of ≥ 5 m for the Tohoku-oki earthquake (Ozawa et al., 2012), respectively. (c) Postseismic displacement from March 12, 2011 to November 20-29, 2013.

monitored by a dense Global Navigation Satellite System (GNSS) network called GEONET [4]. We use the term GNSS rather than that of Global Positioning System (GPS) throughout the paper. Deformation of the Japanese islands have been measured by the Military Land Survey and its successor the Geospatial Information Authority of Japan (GSI), formerly the Geographical Survey Institute with modern geodetic surveys including triangulation, trilateration, leveling, tide-gauge, and GNSS since the late 19th century [5, 6]. Nishimura et al. (2012) [7] briefly summarizes the geodetic data showing deformation in northeastern Japan before the Tohoku-oki earthquake.

A well-known paradox about deformation in northeastern Japan [8, 9] holds that long-term deformation, i.e. ≥10,000 years, deduced from geologic and geomorphologic studies differs in sense and rate from short-term deformation, i.e. ≤ 100 years, measured by geodetic surveys. The strain rate for horizontal deformation measured by geodetic methods is 5-10 times as high as that from geologic studies. The Pacific coast was uplifted at 0.1 – 0.5 mm/yr in vertical deformation, whereas it had subsided in the last century at ~5 mm/yr before the Tohoku-oki earthquake. Ikeda (1996) [8] proposed that the difference between the geologic and geodetic time scale was attributable to elastic deformation accumulated and released in a megathrust earthquake cycle. Ikeda, thus, forecast an "Armageddon" megathrust earthquake for releasing accumulated strain observed in the last century would solve the paradox. On March 11, 2011, the M_w 9.0 Tohoku-oki earthquake released huge elastic strain in northeastern Japan, but its coseismic deformation solved only part of the deformation paradox. The Tohoku-oki earthquake caused the Pacific coast to subside against the expectations of researchers, who are still looking for clues solving the vertical deformation paradox.

In this paper, we give an overview of crustal deformation in northeastern Japan before, during, and after the 2011 Tohoku-oki earthquake that adds re-analyzed and latest geodetic data to the dataset of Nishimura et al.(2012) [7] as of late 2013. We then focus on coastal vertical deformation and propose a hypothetical model explaining the deformation paradox on different time-scales.

2. OBSERVED DEFORMATION

2.1. Horizontal deformation

Horizontal deformation before the 2011 Tohoku-oki earthquake was characterized by east-west compression based on GNSS observation starting in 1994 (**Fig. 1a**). We used 950462 (Fukue) as a reference site for all horizontal and vertical GNSS data plots because it is regarded as being located on the stable Amurian plate. This compression is parallel to a relative plate motion between the subducting Pacific plate and the overriding Okhotsk plate along the Japan trench and its rate is ~ 2 cm/yr between the coasts of the Pacific Ocean and the Sea of Japan. This compression suggests strong interplate coupling on the subduction interface [10, 11]. The compressional rate was not constant, however, over this 16-year period and was affected by M~7 earthquakes and postseismic deformation [12]. A decadal decrease in the compression rate in the southern part of northeastern Japan is also reported by Nishimura et al. (2012) [7]. Before GNSS observations, triangulation and trilateration data showed that north-south extension rather than east-west compression dominated during 1883-1991 [7]. This may imply that the average coupling in the last century was weaker than that for the GNSS observation period. It has been pointed out, however, that data have systematic scale error derived from distance measurement [13]. Data on triangulation and trilateration are not yet fully understood.

The Tohoku-oki earthquake caused an east-west extension in northeastern Japan. The observed horizontal displacement is at most 5.3 m east-southeast on the Oshika Peninsula (**Fig. 1b**). Extension of 4 m across the Honshu arc occurred because GNSS stations on the west coast also moved eastward 1 m. Eastward displacement in northeastern Japan has continued since the main-shock (**Fig. 1c**), with the largest postseismic displacement exceeding 1.0 m as of November 2013. Coseismic and postseismic displacement appears similar but differ distinctly in at least two ways:

(i) Postseismic displacement is broadly distributed along the Pacific coast whereas coseismic displacement near the epicenter of the main shock is much greater than that in the surrounding region.

(ii) The difference in eastward displacement is small between the east and west coasts, meaning that postseismic extension east-west is much smaller than coseismic extension. A back arc near the Sea of Japan coast continues to extend but a fore arc near the Oshika Peninsula contracts postseismically, explained by coseismic and postseismic slip distribution. Although the coseismic slip is located shallow and far offshore on the plate interface, postseismic slip is located deep on the interface near the coast [15].

2.2. Vertical deformation

2.2.1 Preseismic deformation

Vertical deformation before the Tohoku-oki earthquake is characterized by rapid subsidence in the fore arc facing on the Pacific Ocean and gentle uplift in the back arc. The subsidence rate is not constant, however, along the coast. **Fig. 2a** shows decadal

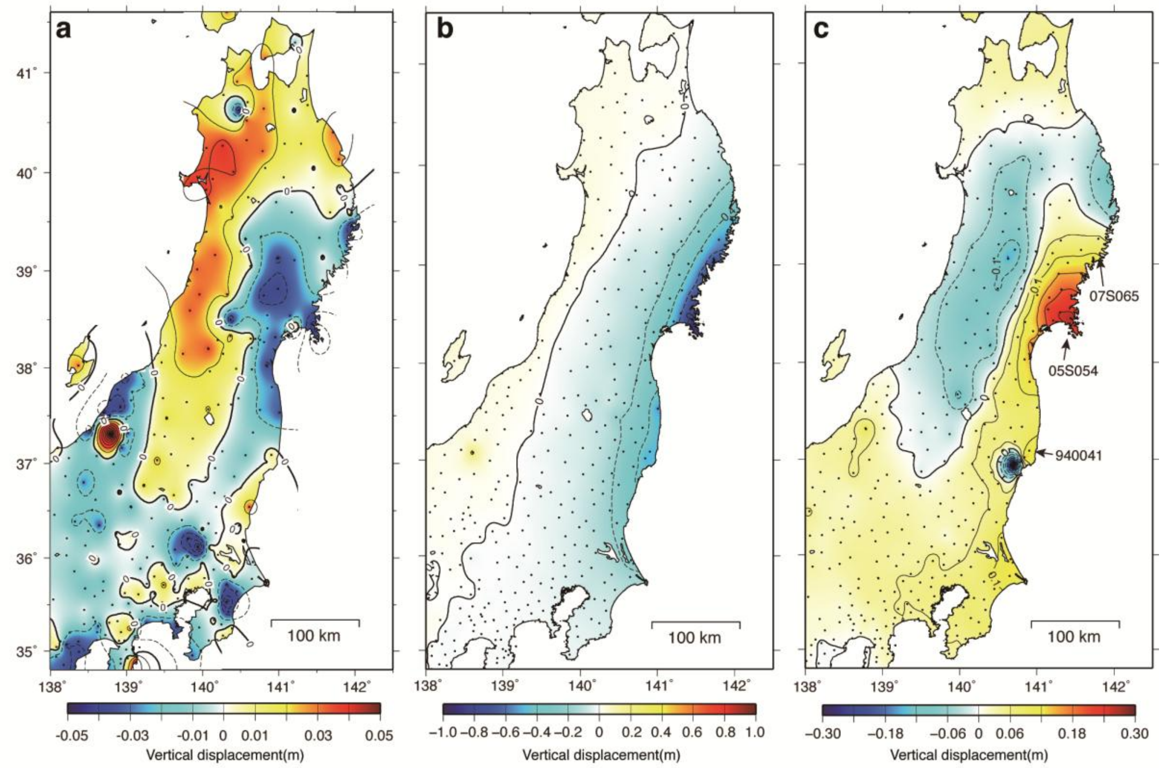

Fig. 2 Pre-, co-, and post-seismic vertical displacement at GEONET stations in northeastern Japan. (a) Preseismic vertical displacement from October 2000 to October 2010. A contour interval is 2 cm. (b) Coseismic vertical displacement. A contour interval is 20 cm. (c) Postseismic vertical displacement from March 12, 2011 to November 20-29, 2013. A contour interval is 5 cm.

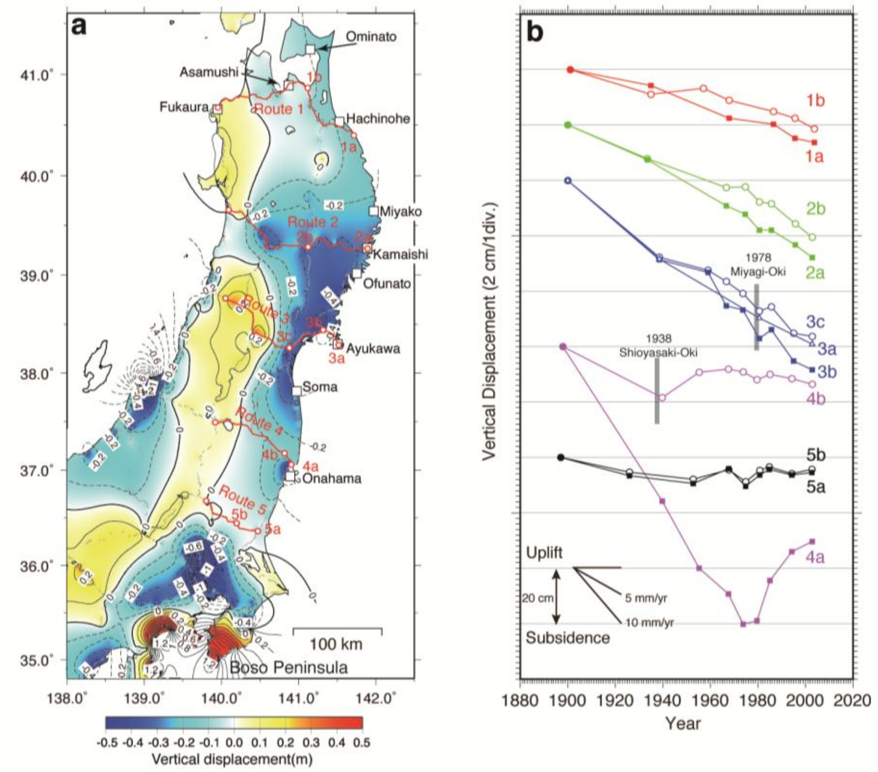

Fig. 3 Vertical displacement before the 2011 Tohoku-oki earthquake deduced from leveling. (a) Total vertical displacement from 1983-1906 to 1986-1999 [7, 16]. A contour interval is 10 cm. Routes 1-5 represent a location of leveling routes. Open squares represent tide-gauge stations. (b) Temporal change of vertical displacement on the leveling route across the Honshu island arc. A symbol represents the vertical displacement at a benchmark relative to that at the westernmost benchmark on each leveling route. Horizontal locations of the symbol represent the middle of a leveling measurement because each leveling measurement was conducted for a few years typically and for 9 years in the longest case.

preseismic deformation observed by GNSS. Large subsidence along the Pacific coast was observed only in a latitude range between 37º and 40º. A similar distribution is recognized in a deformation measured by leveling for a century (**Fig. 3a**). The area of subsidence exceeding 20 cm is limited to the middle of the Pacific coast. The large subsidence area for both 10 and ~100 years corresponds roughly to areas of large offshore slip during the Tohoku-oki earthquake. One distinct feature is identified in the distribution of subsidence. Subsidence is not always the largest in the easternmost coastal area. An area several tens of kilometers west of the coast has subsided equally as manifested in Routes 2 and 3 in **Fig. 3b**.

The next question arising concerns a temporal change in vertical displacement. We use leveling and tide-gauge data to answer it. Leveling data shown in **Fig. 3b** is more precise but less frequent than the tide-gauge data (**Fig. 4**). We say roughly that the both types of data show nearly constant subsidence in the last century. In **Fig. 3b**, benchmarks on Routes 1, 2, and 3 show steady subsidence over the period of observation. Route 5 shows small deformation. In contrast, benchmarks on Route 4 across southern Fukushima Prefecture show significant temporal change. Benchmark 4b subsided before 1940 and was uplifted until the 1960s then subsided again after the 1970s. This temporal evolution probably is attributable to coseismic subsidence and postseismic uplift due to the 1938 Shioyasaki-oki earthquakes [7, 17]. Benchmark 4a shows rapid subsidence that become uplift in the 1970s. Large horizontal and vertical deformation were observed locally in the Joban area in which benchmark 4a and the Onahama tide-gauge station are located [18]. This deformation was considered nontectonic and affected by Joban coalfield mining. Intense shallow seismicity including the M_w 6.6 April 11, 2011, earthquake [19] was activated in the Joban area after the 2011 Tohoku-oki earthquake. These earthquakes are a normal-faulting type that is rare in northeastern Japan. Imanishi et al. (2012) [20] proposed that the 2011 Tohoku-oki earthquake triggered these normal-faulting earthquakes in the Joban area under a locally formed preshock normal-faulting stress regime. Large deformation in the Joban area may be related with local preshock stress. Reexamining and reinterpreting preseismic deformation is thus important for understanding the intense seismicity was triggered.

Tide-gauge data from Asamushi to Soma (**Fig. 4**) also show not only a long-term trend with a subsidence rate of 2-8 mm/yr but coseismic offsets and postseismic transients of M 7-8 interplate earthquakes. Coseismic subsidence in the M_w 8.3 1968 Tokachi-oki earthquake is clearly identified at Asamushi, Ominato, Miyako, Kamaishi and Ofunato. For ~20 years after the 1968 earthquake, the uplift or suspension of subsidence was observed at Ominato,

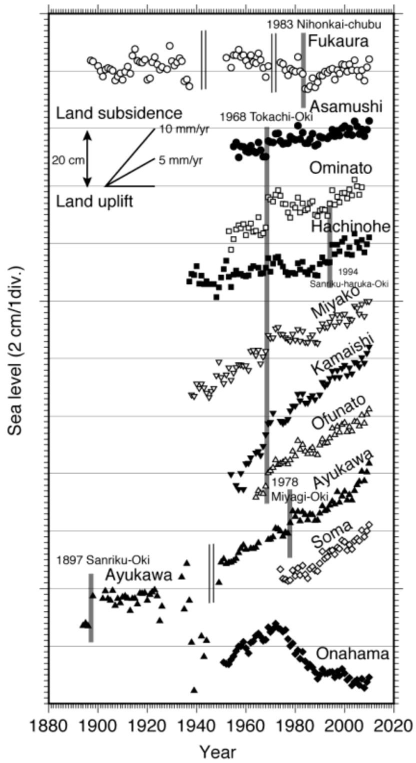

Fig. 4 Annual sea level changes at tide-gauge stations. Vertical double lines represent a discontinuity of observation with an arbitrary shift of the data. Thick vertical lines represent occurrence of large earthquakes probably related with changes in a time-series. The locations of the stations are plotted in Fig. 3. The original data is from the Coastal Movements Data Center (http://cais.gsi.go.jp/cmdc/centerindex.html).

Hachinohe and Miyako. Data at Ayukawa on the Oshika Peninsula was largely disturbed in the 1930s and disrupted in 1949 but instantaneous subsidence and ensuing suspensions of subsidence are clear and probably associated with the M 7.7 1897 Sanriku-oki and the M_w 7.5 1978 Miyagi-oki earthquakes. We shifted the data after the 1949 disruption to make it consistent with the leveling data. Considering the tide-gauge and leveling data, it is likely that the Oshika Peninsula continued to be stable for two decades after the 1897 earthquakes and started to subside in the 1930s.

From leveling and tide-gauge data, we summarize vertical deformation along the Pacific coast before the Tohoku-oki earthquake as follows: Secular coastal subsidence continued at a rate of ~5 mm/yr for a century before the Tohoku-oki earthquake. M 7-8 interplate earthquakes generally caused coseismic subsidence and postseismic uplift but their deformation is minor compared to secular subsidence.

2.2.2 Coseismic deformation

Coseismic vertical deformation shows a rather simple distribution (**Fig. 2b**) characterized by subsidence along the Pacific coast and small uplift along the Sea of Japan coast. Subsidence simply increases eastward in the same latitude and reaches a

1.2 m maximum on the Oshika Peninsula. Hence, spatial distribution thus differs in coseismic and preseismic deformation, although they show subsidence along the Pacific coast.

Large subsidence in addition to a devastating tsunami on March 11, 2011, caused a new type of natural hazard for local societies along the Pacific coast. Because sea levels rose due to crustal subsidence, residential and agricultural lands dropped below mean sea level. Subsidence also caused local port facilities including pillars and wharfs to become unusable. Large public works for reclaiming and heaping earth is ongoing.

2.2.3 Postseismic deformation

Postseismic deformation over the space of 2.7 years shows uplift in the fore arc and subsidence in the back arc (**Fig. 2c**). The largest uplift exceeds 25 cm in the

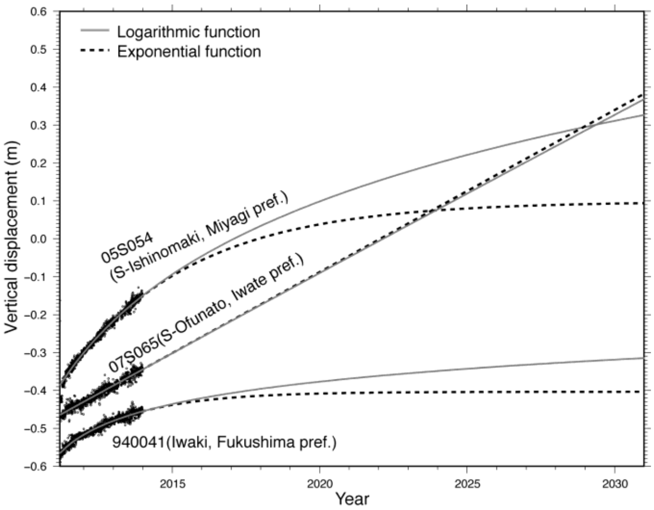

Fig. 5 Observed and predicted vertical displacement after the 2011 Tohoku-oki earthquake at the selected GEONET stations. Arbitrary vertical offsets are added to clarify a plot. 6 digit numbers are station ID and their locations are shown in Fig. 2c. Fitted curves of two functions are plotted (See the text).

Table. 1 Observed and predicted vertical displacement associated with the 2011 Tohoku-oki earthquake

Station	**Coseismic Disp.** (m)	**Postseismic displacement**					
		Logarithmic funcntion[a]		Exponential function[a]		10 yrs[b] (m)	50 yrs[b] (m)
		a (m)	b (days)	a (m)	b (days)		
07S065	-0.718	21.5	183000	877	7470000	0.425 0.428	2.05 2.14
05S054	-1.00	0.343	1030	0.483	1550	0.519 0.438	1.00 0.483
940041	-0.484	0.0827	365	0.158	917	0.198 0.155	0.325 0.158

a. Parameters of the best-fitting functions. See the text for a form of the functions.
b. Upper and bottom values are uplift predicted by the best-fitting logarithmic and exponential decay functions, respectively

middle part of the Pacific coast. There are two areas of subsidence along the Pacific coast at N40º and N37º. The first area was subsided for half a year just after the Tohoku-oki earthquake but became stable or was uplifted in 2012. The second area was mainly affected by intense seismicity in the Joban area. Subsidence in the back arc roughly matches the uplift in the fore arc. This pattern is explained by aseismic interplate slip in the downdip extension of the coseismic slip [15]. An interesting point is that the pattern of the observed uplift and subsidence across the island arc in the middle of northeastern Japan, e.g., N38.5º, is opposite to that in the preseismic period (**Fig. 3a**).

Postseismic uplift recovered several tens of a percent in coseismic subsidence in most Pacific coastal areas as of late 2013. Future sequences of postseismic deformation hold large interest for two reasons. – the first being to solve scientific paradox of long-term and short-term deformation and the second to overcome hazard to local society caused by land subsidence. Here, we tried to predict how large postseismic uplift would evolve. The fitting of relaxation functions is often studied for cases of observed postseismic deformation [21, 22, 23]. We used the simplest form of logarithmic and exponential decay functions predicted by frictional afterslip and viscoelastic relaxation in the asthenosphere. The functions used are expressed as follows:

$$U = a\log(1+t/b)+c$$

$$U = a\{1-\exp(-t/b)\}+c \qquad (2)$$

where U and t are displacement and time, a and b are parameters for an amplitude and relaxation time for postseismic displacement, and c is a parameter for initial offset. We fitted these functions to vertical daily coordinates of selected GNSS stations in the postseismic uplift area. Here, we described a result observed at stations 07S065(S-Ofuato) in Iwate, 05S054(S-Ishinomaki) in Miyagi, and 940041(Iwaki) in Fukushima prefectures (**Figs. 2c and 5**). Parameters are estimated by least squares fitting of data from April 8, 2011, to November 30, 2013, that is, from 28 to 995 days after the main shock. To avoid the effect of early postseismic deformation and a coseismic offset an M_w 7.1 intraslab aftershock on April 7, 2011, we did not use the first 27 days. Estimated parameters are listed in Table 1. Both functions fit observed uplift reasonably except a few months just after the main shock (**Fig. 5**). It is difficult to judge which function gives a better prediction for the present dataset, because both functions give similar misfits.

In an area near the Oshika Peninsula where both coseismic subsidence and postseismic uplift are large, fitted exponential functions give 3-5 years of relaxation time and ~0.4-0.5 m of uplift after full relaxation. This means that significant postseismic uplift ceases in a decade and coseismic subsidence does not recover in the coastal area. Observed postseismic deformation for previous great earthquakes including the M_w 9.5 1960 Chile [24], the M_w 9.2 1964 Alaska [25], and the M_w 9.2 2003 Sumatra earthquakes [26] suggests, however, that postseismic uplift for the M_w 9.0 Tohoku-oki earthquake is unlikely to end within a decade. In this study, we thus prefer to use the logarithmic decay function, which predicts 0.8-1.0 m of uplift in the 50 years after the main shock. Coseismic subsidence may be recovered by postseismic uplift in the most part of the coastal area by the mid 21st century.

Estimated parameters for the postseismic uplift differ with the station. At station 940041, estimated relaxation times for both functions are shorter than those near the Oshika Peninsula. The fitted logarithmic function predicts 350 years will be required to compensate for coseismic subsidence. In contrast, almost constant uplift was observed at station 07S065 (**Fig. 5**) and 17 years are expected to be needed for fitted functions to recover subsidence. In a coastal area south of N35.5º, postseismic uplift has already exceeded coseismic subsidence. It has also been pointed out that estimated parameters of function fitting highly depend on the data period used [23] making it difficult to assert that the postseismic uplift will compensate for coseismic subsidence in all areas.

3. DISCUSSION

3.1. Coastal uplift and subsidence model

Ikeda et al.(2012) [9] proposed a model for explaining the paradox of long-term and short-term deformation (**Fig. 6a**). In their model, the Pacific coast subsides at a constant rate during the interseismic period of a great earthquake. It also subsides at the occurrence of a great earthquake. Large postseismic uplift recovers interseismic and coseismic subsidence to realize slight long-term uplift clarified by geologic studies. If we assumed a constant subsidence rate of ~5 mm/yr, that is geodetically measured in the last 120 years and a recurrence interval of ~800 years for the great earthquake [14], subsidence reach ~4 m in the overall interseismic period. Considering ~1 m of the coseismic subsidence in the mid Pacific coast, the model of Ikeda et al. [9] requires ~5 m of uplift in postseismic deformation, but such a large uplift seems unlikely based on fitting relaxation functions to the observed postseismic uplift examined in section 2.2.3. The logarithmic relaxation function predicts ~1 m of postseismic uplift for the first 50 years and additional ~0.2 m of uplift for the next 50 years. Because the

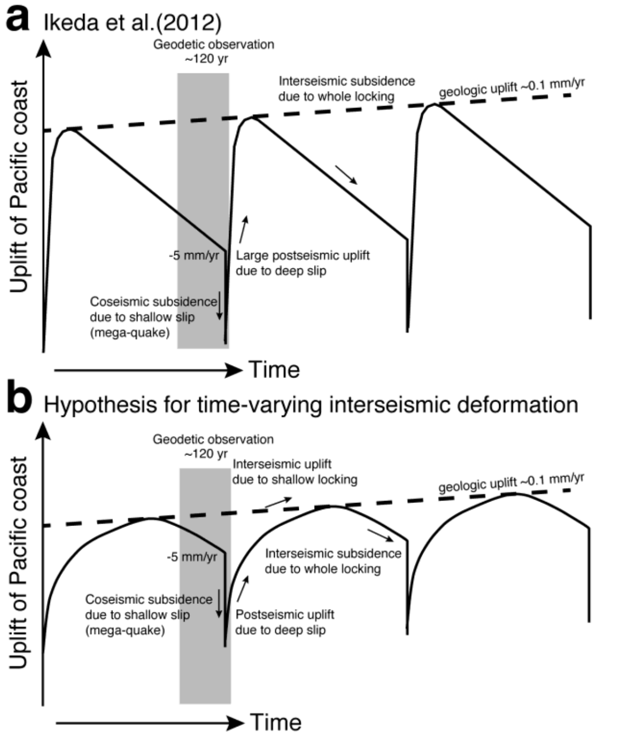

Fig. 6 Models for vertical deformation along the Pacific coast of northeastern Japan. (a) A model of Ikeda et al. (2012). (b) A hypothetical model proposed in this study.

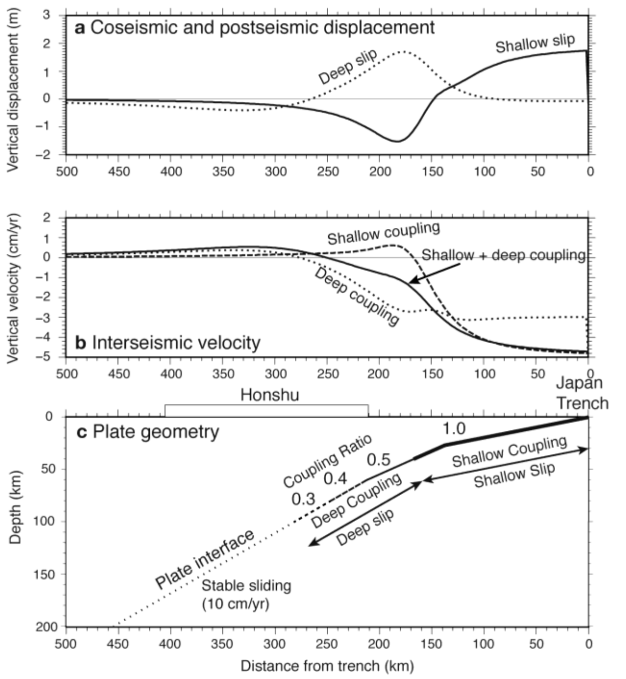

Fig. 7 Vertical deformation due to interplate slip and coupling. (a) Surface vertical displacement across the island arc due to interplate slip models using dislocation theory. Solid and dotted curves represent vertical velocities due to shallow and deep slip, respectively. (b) Surface vertical velocity due to interplate coupling models. Broken, dotted and solid curves represent vertical velocities due to shallow, deep, and both coupling, respectively. (c) Geometry of plate interface across the island arc. Solid and broken lines represent locations of shallow and deep slip, respectively. In an interseismic period, stable sliding occurs on the deepest (depth ≤100 km) part. Surface velocities are calculated in three cases of coupling distribution (i.e., a shallow part (depth ≤ 40 km), a deep part (40 km < depth ≤ 100 km), and both shallow and deep parts).

uplift rate gradually decreases over time, it is difficult to expect postseismic relaxation to recover both coseismic and interseismic subsidence.

We propose a model in which interseismic subsidence occurs only in the latter part of the interseismic period, as shown in **Fig. 6b**. During the interseismic period, uplift turns to subsidence along the Pacific coast. The rapid subsidence observed geodetically means the latter part of the interseismic period in a great earthquake cycle. Postseismic uplift is roughly equal to coseismic subsidence, which is inferred based on observed postseismic deformation. This model is not entirely new, and similar ideas have been proposed by Atwater et al.(2004) [27], Shishikura et al.(2009) [28], and Sagiya et al.(2013) [29].

In the next section, we explain the model by using a simple dislocation in an elastic half-space.

3.2. Elastic deformation due to slip and coupling on shallow and deep plate interfaces

Subsidence and uplift along the Pacific coast is caused by slip and coupling on the plate interface between overriding and subducting plates [9]. We consider the 2-dimensional simplified plate geometry shown in **Fig. 7c**. Based on results of seismic refraction and reflection experiment [30] and aftershock distribution of the M_w 7.2 2005 Miyagi-oki interplate earthquake [31], we assumed that the dip of a plate interface changed at depths of 27 and 60 km. Dip increased from shallow to deep segments at 11º, 24º, and 30º. We calculate surface deformation due to dislocation in a homogeneous elastic half-space [32]. For interplate slip, we consider shallow and deep slip -- slip in the shallow part of the plate interface of 0 to 40 km deep and that in the deep part of 40 to 100 km deep. We assigned 10 m of uniform slip for the shallow slip model and slip decreasing from 5 m in the shallow part to 3 m in the deep part for the deep slip model. Shallow slip causes subsidence at the Pacific coast and offshore uplift as denoted by the solid line in **Fig. 7a**, explaining coseismic deformation for both the 2011 Tohoku-oki earthquake (**Fig. 2b**) and M 7-8 interplate earthquakes, although the amount of displacement is not on the same scale as earthquake magnitude. The deep slip caused uplift on the Pacific coast and inland subsidence denoted by the dotted line in **Fig. 7a**. This deformation was actually observed for ~3 years following the 2011 Tohoku-oki earthquake (**Fig. 2c**). Uplift or suspension of preseismic subsidence after many M 7-8 earthquakes was also observed as shown in **Figs. 3b** and **4**. One well-studied example is the case of the M_w 7.5 1978 Miyagi-oki earthquake [33]. It is a common feature for M≥7 interplate earthquakes along the Japan trench to have shallow seismic slip accompanying subsequent deep afterslip.

For interplate coupling, we consider three models. That is, the coupled part on the plate interface is limited in the shallow part, the deep part, or both (**Fig. 7c**). Depth ranges for shallow and deep parts are the same for interplate slip. The coupling ratio for deep coupling gradually decreased from 0.5 to 0.3. We calculated surface deformation by assigning reverse slip on a plate interface with slip velocity of 10 cm/yr -- not back-slip in a coupling zone [34]. A reference point is located on the overriding plate far from the trench to plot vertical velocity in **Fig. 7b**. Shallow coupling caused uplift. Deep coupling caused subsidence on the Pacific coast and uplift in the back arc. Shallow and deep coupling caused a deformation similar to deep coupling where a hinge point between subsidence and uplift shifts trenchward. Vertical deformation in mid northeastern Japan before the Tohoku-oki earthquake (**Figs. 2a** and **3a**) is explained fairly well by both shallow and deep coupling in terms of subsidence on the Pacific coast and uplift in the inland area. Both shallow and deep coupling is also suggested by estimates of interplate coupling using GNSS data [10, 11].

In the coastal uplift model in earthquake cycles (**Fig. 6b**), we speculate that coupling only in the shallow part on the plate interface caused uplift in the first part of an interseismic period. In the latter part of an interseismic period, the deep part of the plate interface become coupled, which makes the coast subside. From the viewpoint of frictional fault behavior, it is plausible that a shallow seismogenic fault recovers strength quickly and that a deep fault where afterslip occurs needs more time to recover. It is doubtful, however, whether the deep part of the plate interface needs several hundred years to recover its strength. Numerical simulations of an earthquake cycle [35] suggest that deep coupling is weakened in the latter part of an interseismic period, which contradicts our hypothetical mechanism. Sagiya et al. (2013) [29] proposed that a viscoelastic response in the asthenosphere caused the change from uplift to subsidence along the Pacific coast during an interseismic period. Because the mechanism of coastal uplift and subsidence discussed in this paper is simplified, we may need to examine a more practical mechanism to prove the feasibility of our proposed hypothetical model.

3.3. Implication of geodetic data for the potential of great earthquakes along the Japan trench

Rupture of the 2011 Tohoku-oki earthquake is limited to between N36º and N39.5º. Its northern and southern limits are bounded by the source are of the M_w 7.7 1994 Sanriku-haruka-oki earthquake and the northeastern limit of the subducted Philippine Sea plate [36]. There is a variety of vertical displacement along the Pacific coast in the last century (**Fig. 3**) and the large subsidence area corresponds roughly to the offshore source area of the Tohoku-oki earthquake, which raises the paradox for long-term and short-term deformation. Marine terraces along the Pacific coast facing the Japan trench suggest 20-62 m of uplift over 120,000 years [37], which is on the order of submillimeters per year for long-term uplift rate throughout the coast. We discuss centennial vertical deformation along the Pacific coast (**Fig. 3**) implying the potential of great earthquakes such as the Tohoku-oki earthquake.

In coastal area south of N36º, small uplift was observed in the past century for other than the Boso Peninsula, where the M_w 7.9 1923 Kanto earthquake caused large deformation. There was no significant discrepancy between long-term and short-term deformation. Although there is the possibility that small vertical deformation indicates a transient stage from uplift to subsidence in an earthquake cycle under the proposed hypothesis, we do not think the potential of great earthquakes in the area south of the Tohoku-oki earthquake is high because weak interplate coupling in the last decade is estimated from GNSS observation [38]. However, we cannot rule out the possibility of large earthquakes near the trench where onland deformation has a little resolving power. On the other hand, significant subsidence exceeding 10 cm was observed in the area north of the source area of the Tohoku-oki earthquake, i.e., between N40º and N41.5º. Deformation associated with the Tohoku-oki earthquake is small in this area (**Figs. 2b and 2c**). The paradox of long-term and short-term deformation is unsolved there, whereas a subsidence rate of 1-2 mm/yr in the north area is smaller than that in the region corresponding to the source of the Tohoku-oki earthquake. Steady subsidence was also measured at tide-gauge stations (**Fig. 4**). The M_w 8.3 1968 Tokachi-oki and M_w 7.7 1994 Sanriku-haruka-oki earthquakes occurred in the corresponding offshore region but caused rather small fluctuations compared to steady subsidence (See benchmarks 1a and 1b in **Fig 3b** and Asamushi, Ominato and Hachinohe in **Fig. 4**). These events do not appear to solve the paradox, so observed subsidence may imply the potential of great earthquakes along the northernmost part of the Japan Trench, whose rupture possibly extends toward the Kuril trench.

4. CONCLUSIONS

Geodetic data including GNSS, leveling and tide-gauge has been examined to clarify deformation in northeastern Japan before, during, and after the 2011 Tohoku-oki earthquake. The Pacific coast of northeastern Japan subsided steadily at a rate of ~5 mm/yr over the century before the Tohoku-oki earthquake, accompanying small coseismic subsidence and postseismic transient associated with *M* 7-8 interplate earthquakes. Such rapid subsidence was limited, however, mid northeastern Japan corresponding to the large slip area of the 2011 Tohoku-oki earthquake. Coseismic deformation is characterized by an extension of ~ 4 m across the Honshu arc east-west and subsidence of up to ~1 m along the Pacific coast. Postseismic deformation for 2.7 years shows uplift of up to ~25 cm on the Pacific side and inland subsidence. Postseismic uplift is fitted by a logarithmic relaxation function. Extrapolation of the fitted function predicts ~1 m of postseismic uplift over a 50-year period in an area near the Oshika Peninsula. This suggests that coseismic subsidence would be compensated for in the mid 21st century. The model we propose has the Pacific coast uplift first and then subside during an interseismic period to explain rapid subsidence observed for the previous century and long-term uplift from geologic estimates. Simple elastic dislocation theory explains that uplift in an early interseismic period and subsidence in a late interseismic period are caused by deep and shallow coupling on the plate interface. Subsidence has accumulated in northernmost Honshu over the last century, which may imply the potential for a great earthquake in the region north of the Tohoku-oki earthquake.

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REFERENCES:

[1] T. Nishimura, H. Munekane, and H. Yarai, "The 2011 Off the Pacific Coast of Tohoku Earthquake and its aftershocks observed by GEONET", Earth Planets Space, vol. 63, pp. 631–636, 2011.

[2] M. Wang et al., "Far-field coseismic displacements associated with the 2011 Tohoku-oki earthquake in Japan observed by Global Positioning System", Chinese Sci. Bull., vol. 56, pp. 2419−2424, 2011.

[3] N. V. Shestakov et al., "Analysis of the far-field crustal displacements caused by the 2011 Great Tohoku earthquake inferred from continuous GPS observations", Tectonophys., vol. 524, pp. 76–86, 2012.

[4] T. Sagiya, "A decade of GEONET: 1994–2003–The continuous GPS observation in Japan and its imapct on earthquake studies", Earth Planets. Space, vol. 56, xxix-xli, 2004.

[5] T. Dambara, "Synthetic vertical movements in Japan during the recent 70 years", J. Geod. Soc. Jpn., vol. 17, pp. 100–108, 1971. (in Japanese with English abstract)

[6] K. Nakane, "Horizontal tectonic strain in Japan (I)", J. Geod. Soc. Jpn., vol 19, pp. 190–199, 1973. (in Japanese with English abstract)

[7] T. Nishimura, "Crustal deformation of northeastern Japan based on geodetic data for recent 120 years", J. Geol. Soc. Jpn., vol 118, pp. 278-293, 2012. (in Japanese with English abstract)

[8] Y. Ikeda, "Implications of active fault study for the present-day tectonics of the Japan arc", Active Fault Res., vol. 15, pp. 93-99, 1996. (in Japanese with English abstract)

[9] Y. Ikeda, S. Okada, and M. Tajikara, "Long-term strain buildup in the northeast Japan arc-trench system and its implications for gigantic strain-release events", J. Geol. Soc. Jpn., vol. 118, pp. 204-312, 2012. (in Japanese with English abstract)

[10] T. Nishimura, T. Hirasawa, S. Miyazaki, T. Sagiya, T. Tada, S. Miura, and K. Tanaka, Temporal change of interplate coupling in northeastern Japan during 1995-2002 estimated from continuous GPS observations, Geophys. J. Int., vol. 157, pp. 901-916, 2004.

[11] Y. Suwa, S. Miura, A. Hasegawa, T. Sato, and K. Tachibana, Interplate coupling beneath NE Japan inferred from three-dimensional displacement field, J. Geophys. Res., vol. 111, B04402, 2006.

[12] H. Suito, T. Nishimura, M. Tobita, T. Imakiire, and S. Ozawa, "Interplate fault slip along the Japan Trench before the occurrence of the 2011 off the Pacific coast of Tohoku earthquake as inferred from GPS data", Earth Planets Space, vol. 63, pp. 615–619, 2011

[13] T. Sagiya, N. Matta, A. Meneses, S. Nomura, S. Suzuki, and Y. Ohta, "Triangulation scale error as a possible cause for overlooking seismic potential along the Japan trench", Abstract G43B-0933 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec. 2012.

[14] K. Minoura, and S. Nakaya, "Traces of tsunami preserved in inter-tidal lacustrine and mash deposits: some examples from northeast Japan", J. Geol., vol. 99, pp. 265–287, 1991.

[15] S. Ozawa et al., "Preceding, coseismic, and postseismic slips of the 2011 Tohoku earthquake, Japan", J. Geophys. Res., vol. 117, B07404, doi:10.1029/2011JB009120, 2012.

[16] T. Kunimi et al., "Vertical crustal movements in Japan estimated from the leveling observations data for the past 100 years", J. Geograph. Surv. Inst., vol. 96, pp. 23–37, 2001. (in Japanese)

[17] K. Abe, "Tectonic implication of the large Shioya-oki earthquakes of 1938", Tectonophys., vol. 41, pp. 269–289, 1977.

[18] Geographical Survey Institute, "Crustal Movement in the Tohoku District", Rep. Coord. Comm. Earthq. Pred., vol. 38, pp. 81–103, 1987. (in Japanese)

[19] S. Toda, and H. Tsutsumi, "Simultaneous reactivation of two subparallel, Inland Normal Faults during the M_w 6.6 11 April 2011 Iwaki earthquake triggerred by the M_w 9.0 Tohoku-oki, Japan, Earthquake", Bull. Seim. Soc. Am., vol. 103, pp. 1572–1583, 2013.

[20] K. Imanishi, R. Ando, and Y. Kuwahara, "Unusual shallow normal-faulting earthquake sequence in compressional northeast Japan activated after the 2011 off the Pacific coast of Tohoku earthquake", Geophys. Res. Lett., 39, L09306, doi:10.1029/2012GL051491, 2012

[21] Z. K. Shen et al., "Postseismic deformation following the Landers earthquake", Bull. Seim. Soc. Am., vol. 84, pp. 780–791, 1994.

[22] S. Ergintav et al., "Postseismic deformation near the Ízmit earthquake (17 August 1999, M7.5) rupture zone", Bull. Seimol. Soc. Am., vol. 92, pp. 1194–1207, 2002.

[23] H. Kimura, B. Miyahara, and K. Miyagawa, "Postseismic deformation following great earthquakes, based on GEONET", J. Geosp. Info. Auth., vol 124., pp. 47–55, 2013. (in Japanese)

[24] S. E. Barrientos, G. Plafker, E. Lorca, "Postseismic coastal uplift in southern Chile", Geophys. Res. Lett., vol. 19, pp. 701–704, 1992.

[25] H. Suito, and J. T. Freymueller, "A viscoelastic and afterslip postseismic deformation model for the 1964 Alaska earthquake", J. Geophys. Res., vol. 114, B11404, 2009.

[26] J. Paul, C. P. Rajendran, A. R. Lowry, V. Andrade, and K. Rajendran, "Andaman postseismic deformation observations: Still slipping after these years?", Bull. Seim. Soc. Am., vol. 102, pp. 1343–1351, 2012.

[27] B. F. Atwater et al., "Seventeenth-century uplift in eastern Hokkaido, Japan", Holocene, vol. 14, pp. 489–501, 2004.

[28] M. Shishikura, O. Fujiwara, Y. Sawai, S. Fujino, and Y. Namegaya, "Forecasting multi-segment earthquakes by coastal paleoseismological survey", Chishitsu News, no. 663, pp. 23–28, 2009.

[29] T. Sagiya, "A simple model for vertical crustal movement along the Pacific coast of the Tohoku distrcit", Abstract C22-13 presented at 2012 Fall Meeting, SSJ, Yokohama, 7-9 Oct. 2013.

[30] A. Ito, G. Fujie, S. Miura, S. Kodaira, Y. Kaneda, and R. Hino, "Bending of the subducting oceanic plate and its implication for rupture propagation of lagre interplate earthquakes off Miyagi, Japan, in the Japan Trench subduction zone", Geophys. Res. Lett., vol. 32, L05310, doi:10.1029/2004GL022307, 2005.

[31] R. Hino et al., "Hypocenter distribution of the main- and aftershocks of the 2005 Off Miyagi Prefecture earthquake located by ocean bottom seimographic data", Earth Planets Space, vol. 58, pp. 1543-1548, 2006.

[32] Y. Okada, "Surface deformation due to shear and tensile faults in a half-space", Bull. Seim. Soc. Am., vol. 75, pp. 1135–1154, 1985.

[33] H. Ueda, M. Ohtake, and H. Sato, 2001, "Afterslip of the plate interface following the 1978 Miyagi-Oki, Japan, earthquake, as revealed from geodetic measurement data", Tectonophys., vol. 338, pp. 45–57, 2001.

[34] J. C. Savage, "A dislocation model of strain accumulation and release at a subduction zone", J. Geophys. Res., vol. 88(B6), pp. 4984–4996, 1983.

[35] T. Hori, and S. Miyazaki, "A possible mechanism of M 9 earthquake generation cycles in the area of repeating M 7~8 earthquakes surrounded by aseismic sliding", Earth Planets Space, vol. 63, pp. 773–777, 2011.

[36] S. Ozawa et al., "Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake", Nature, vol. 475, pp. 373–376, doi:10.1038/nature10227, 2011

[37] Y. Ota and A. Omura, "Late Quaternary shorelines in the Japanese islands", Quaternary Res., vol. 30, pp. 175–186, 1991.

[38] T. Nishimura, "Back-arc spreading of the northern Izu-Ogasawara (Bonin) Islands arc clarified by GPS data", Tectonophys., 512, pp. 60–67, doi:10.1016/j.tecto.2011.09.022, 2011.

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