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Paradoxical Vertical Crustal Movement Along the Pacific Coast of Northeast Japan

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Abstract Rapid subsidence had been observed along the Pacific coast of northeast Japan and the 2011 M_w9.0 Tohoku-oki earthquake caused additional subsidence over 1m. On the other hand, geomorphological evidence shows the same area is slightly uplifting in a long-term. In order to interpret this paradoxical vertical movement, we construct a simple model of earthquake deformation cycle. Viscous relaxation in the asthenosphere can significantly affect crustal deformation pattern over an earthquake cycle. When earthquake recurrence interval is longer than the asthenospheric relaxation time, temporal variation in the interseismic deformation pattern becomes significant. Spatially heterogeneous behavior in earthquake recurrence may be responsible for the enigmatic vertical movement in northeast Japan.

Keywords crustal deformation cycle · northeast Japan · 2011 Tohoku-oki earthquake

1 Introduction

Vertical crustal movement along the Pacific coast of northeast Japan has been controversial for a long time. Geomorphologists found Stage 5e marine terraces at an elevation of 20-60 m, implying a slight long-term uplift at the rate of less than 0.5 mm/year over 125,000 years [1]. On the other hand, leveling surveys and tidal records showed a rapid coastal subsidence as fast as 5 mm/year during the latter half of the 20th century[2]. Ikeda[3] postulated that a giant megathrust earthquake associated with the subduction of the Pacific plate may occur and recover the subsidence.

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On March 11, 2011, the M_w9.0 Tohoku-oki earthquake occurred and the Pacific coast of northeast Japan had a coseismic subsidence up to 1.1 m[4]. After the main shock, significant postseismic uplift has been observed. However, the postseismic uplift for 3 years from the main shock amounts to only a few tens of centimeters and it is uncertain if the coseismic as well as interseismic subsidence will be recovered (Fig. 1). So the question about the long-term and short-term vertical movements remains unresolved. We have to wait for at least several decades to answer the question through geodetic observations.

Crustal deformation around the subduction zone is an important manifestation of mechanical interaction at the plate interface. There have been various studies to estimate interplate slip deficit based on geodetic observations. As one of such studies, Suwa et al.[5] analyzed 3-dimensional GPS velocity data during the interseismic period to find the slip deficit existing down to a depth of about 100 km, while other studies based on horizontal data only reported much shallower locked zone (down to a depth of 50-60 km)[6][7]. Thus there exist large uncertainties regarding seismic potential evaluation along the Japan trench originated from vertical crustal movement.

Coseismic fault rupture of the 2011 earthquake occurred shallower than the depth of 40km and afterslip is estimated at the downward extension of the coseismic rupture[4]. How we can reconcile all these coseismic and interseismic observations is an essential question to understand physical mechanism of megathrust earthquakes at subduction zones. Vertical movement data is an important key to tackle such a problem.

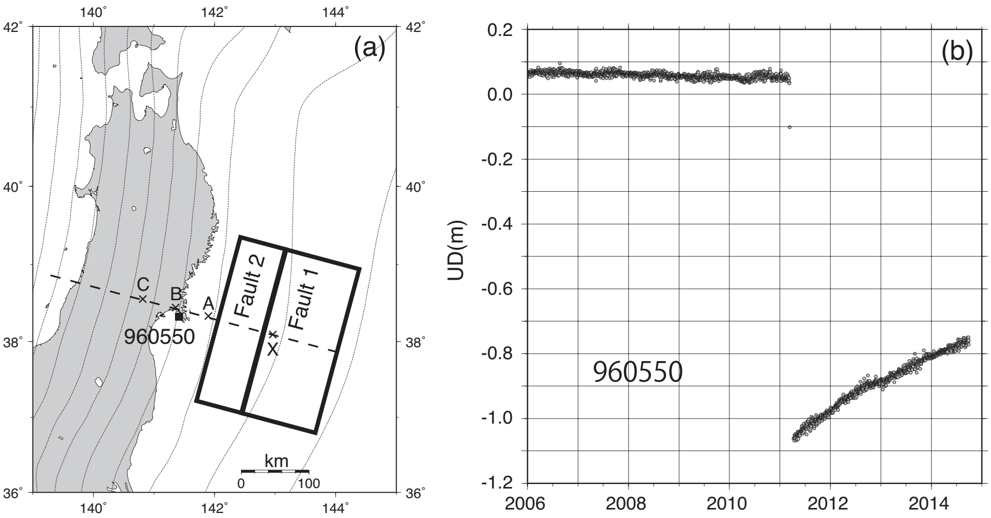

Fig. 1 (a) Map of northeast Japan. Configuration of the subducted Pacfic slab is denoted by dashed contour lines[22][23]. Rectangles are the location of model faults. Thick dashed line is the projection line. A, B, C, and X denote the location of displacement calculation. (b) Vertical displacement data at GEONET station 960550.

In this study, we present a simplified kinematic model of plate subduction to interpret the paradoxical vertical movements along the Pacific coast of northeast Japan, in which we consider an earthquake cycle with viscoelastic response of the asthenosphere and co-existence of the magnitude-9 and magnitude-8 class earthquakes at the same plate boundary. There are many studies to understand earthquake cycle at subduction zones with sophisticated numerical approaches and realistic structural model. Compared with such studies, our simplified model enables us to identify responsible sources for characteristic aspects in deformation patterns easily.

2 An earthquake cycle model

2.1 Formulation

In order to discuss time-dependent vertical crustal movements along the Pacific coast of northeast Japan, we construct a simple kinematic model of an earthquake deformation cycle. For our kinematic modeling, we apply an approach by Savage and Prescott[8]. That is, time evolution of the plate boundary fault slip is divided into the steady part Δu_s and the perturbation part Δu_p. When the relative plate velocity is v, the steady part is represented by a linearly increasing slip,

$$\Delta u_s(t) = vt \tag{1}$$

If we assume that interseismic locking is perfect and the whole slip deficit is released by regular earthquakes with a recurrence interval of T, the perturbation term becomes purely cyclic and can be described as follows.

$$\Delta u_p(t) = -vt + vT \sum_{k=1}^{\infty} H\left(t - kT\right) \tag{2}$$

Hashimoto et al.[9] calculated long-term contribution of steady plate subduction without interplate locking around Japan. They demonstrated that subduction of the Pacific and the Philippine Sea plates yields long-term deformation pattern of the Japanese islands, which resembles long-term vertical deformation shown by the free-air gravity anomaly. Their model predicted that the Pacific coast of northeast Japan has an uplift at about 1 mm/year. So the geological long-term uplift (0.5 mm/year) may be attributed to the steady plate subduction. However, the model of Hashimoto et al. was simple and other factors such as intraplate faulting can affect long-term deformation. Thus we just point out that steady plate subduction as a candidate mechanism of the long-term vertical movement and will not discuss it in the following. Observed interseismic subsidence rate is much larger than the long-term one. We deal with only the cyclic part of the crustal deformation associated with time-dependet plate interaction.

Surface deformation caused by the cyclic part $d(t)$ can be described by the following formula.

$$d(t) = \int_{-\infty}^{t} \Delta \dot{u}_p(\tau) G(t-\tau) d\tau \tag{3}$$

Here, $G(t)$ is the viscoelastic displacement response to a unit fault slip. From equations (2) and (3), the sur-

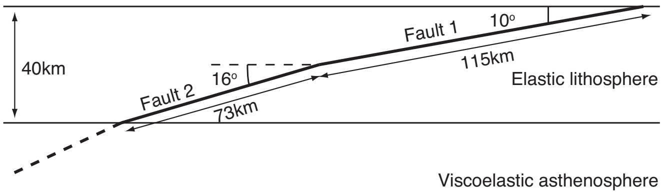

Fig. 2 Model configuration

face displacement due to a periodic earthquake cycle starting from $t = 0$ is written as follows.

$$d(t) = -v \int_0^t G(t-\tau)d\tau + vT \sum_{k=1}^{n} G(t-kT) \quad (4)$$

Here, n is the number of earthquakes until the time t. If t is much larger than the asthenospheric relaxation time, we can regard the response function $G(t)$ becomes constant $G(\infty)$ for $t > t_0$, and equation (4) can be rewritten as follows.

$$\begin{aligned} d(t) &= -v \int_0^{t-t_0} G(t-\tau)d\tau - v \int_{t-t_0}^{t} G(t-\tau)d\tau \\ &\quad + vT \sum_{k=1}^{n} G(t-kT) \\ &= -vG(\infty)t + vT \sum_{k=1}^{n} G(t-kT) + const. \end{aligned} \quad (5)$$

Then we can calculate cyclic crustal displacement pattern by using completely relaxed response $G(\infty)$ and a finite summation of viscoelastic response function $G(t)$.

2.2 Model setup

In our model, the seismogenic part of the subducting Pacific plate interface is represented by two rectangular faults embedded in the 40 km thick elastic lithosphere overlying a viscoelastic asthenosphere. The shallow fault covers the depth range of 0 - 20 km with a dip angle of 10 degree, while the deeper one covers the 20 - 40 km depth with a dip angle of 16 degree (Fig. 2). Both faults are 250 km long along the Japan trench. Plate subduction rate is 0.1 m/year in the perpendicular direction to the faults' strike so that only a dip slip component is considered. We only model faulting in the elastic lithosphere since the dislocation in the asthenosphere does not have a permanent contribution to the surface displacement after many cycles of earthquake occurrence [10]. We assume Maxwell viscosity of $1.0 \times 10^{19} Pa \cdot s$ for the asthenosphere. The corresponding asthenospheric relaxation time is 4.37 years but the effective relaxation time is larger by an order of magnitude due to interaction with the elastic lithosphere. Structural parameters are summarized in Table 1. Viscoelastic deformation response to a unit fault slip of each rectangular fault is calculated using PSGRN/PSCMP code[11].

As already mentioned, we assume perfect locking during interseismic periods and accumulated slip-deficit is fully released by earthquakes. Then variations in earthquake size is described by different recurrence intervals. That is, a recurrence interval of 50 years corresponds to coseismic slip of 5 m (magnitude-8 class), and a recurrence interval of 500 years corresponds to 50 m of coseismic slip (magnitude-9 class).

We consider such a simple earthquake cycle model to investigate consequences of an earthquake cycle with a viscoelastic relaxation effects. In addition, by introducing two faults in the shallow and the deeper parts, we can investigate the effects of heterogeneous earthquake recurrence intervals on the plate interface. This second effect may be important considering there apparently exist earthquake recurrences with different intervals and different earthquake sizes along the Japan trench.

We calculate two cases of long (500 years) and short (50 years) recurrence intervals for the shallow and the deeper faults. The calculated deformation shows regular behavior after 1000 years or two cycles of the longer recurrence interval. We evaluate crustal deformation after 9000 years from the beginning with a time interval of 5 years.

3 Results and discussion

In the following, we show calculated displacement time series at three points (A, B, and C) shown in Fig. 1. These points are located at 200 km, 250 km, and 300 km from the Japan trench or the shallower edge of the modeled shallow fault along the profile line running across the center of the two faults. Fig. 3 shows calculated deformation responses to an earthquake cycle for each fault. The shallow fault (Fault 1) does not contribute to the coastal vertical motion if the recurrence interval is 50 years (Fig. 3a). On the other hand, in the case of long (500 years) recurrence interval, postseismic uplift up to 2 meters occurs, for 50 to 200 years depending on the location, and an interseismic subsidence follows as the contribution of the shallow fault. In this case, interseismic subsidence rate caused by the shallow fault is around 5 mm/year (Fig. 3b), which is close to the observed value during the latter half of the 20th century.

The deeper fault (Fault 2) located close to the coastal area has significant effects on coastal crustal movement all through the earthquake cycle. Resultant displacement becomes too large in the case of the long (500 years) recurrent interval (Fig. 3d). However, in the case

Table 1 Structure model

Thickness(km)	$V_p(km/s)$	$V_s(km/s)$	$\rho(kg/m^3)$	$\eta(Pa \cdot s)$
40	6.70	3.87	2900	∞
∞	8.00	4.62	3400	1.0×10^{19}

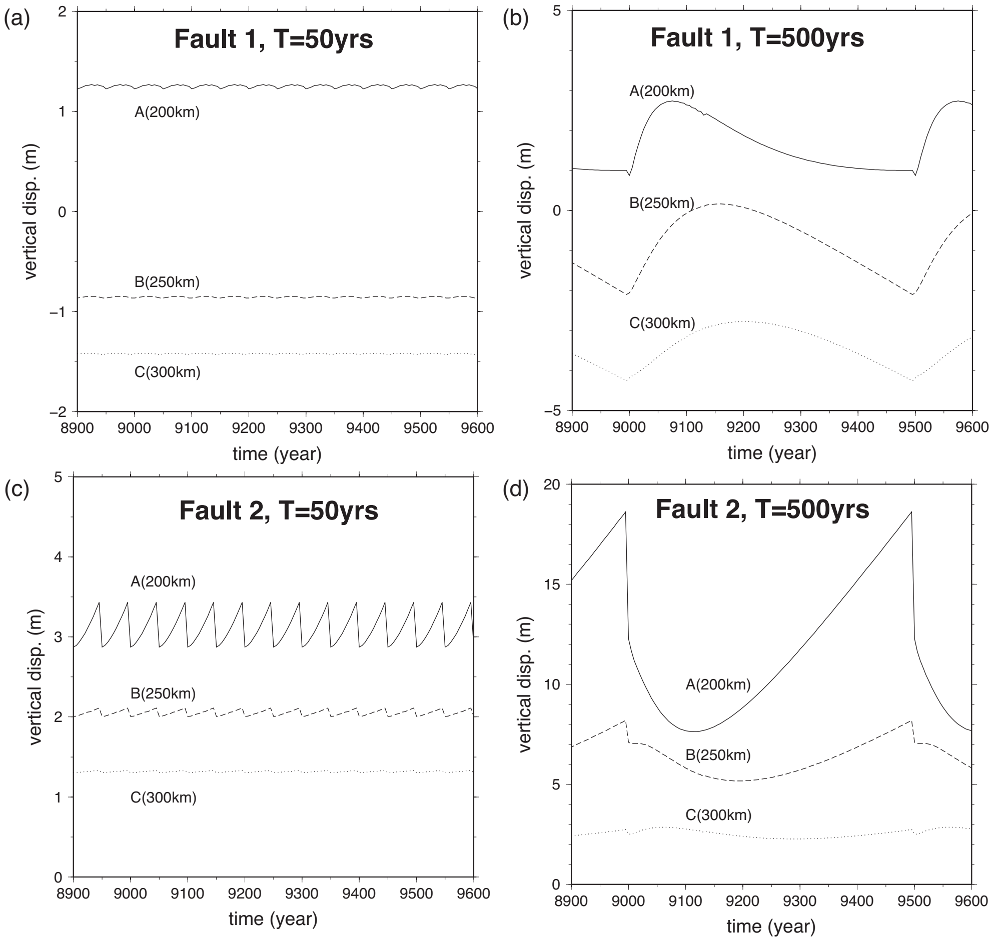

Fig. 3 Calculated vertical displacement for each fault. Two cases of recurrence intervals (50 and 500 years) are shown for each fault. Curves show results for different locations around the coastal region shown in Fig.1.

of the short recurrence interval, magnitude of interseismic uplift and coseismic subsidence is less than 1 m (Fig. 3c).

In our model, total surface displacement is represented by a sum of contributions from the two faults. In this calculation, we assume that less frequent shallow fault always ruptures with the deep fault. The calculation result is shown in Fig. 4. In order to reproduce characteristic features of the observed crustal deformation, that is, rapid interseismic subsidence (5mm/year), coseismic subsidence, and postseismic uplift, we need to combine the case of the long recurrence interval at the shallow fault and the short recurrence interval at the deep fault. As long as we consider in the current framework, this is the only possible combination to explain the observed pattern. This combination is also consistent with the seismicity. At the plate interface off Miyagi Prefecture, before the 2011 earthquake, M7- or M8-class earthquakes have repeatedly occurred in 1897, 1933, 1936, 1937, 1978, and 2005[12]. Though these events are not considered to be truly characteristic[13], the deeper part of the plate boundary had repeated large earthquakes. In the shallow portion of the plate boundary, earthquakes with estimated magnitude of 7.5 - 8.0 occurred in 1793, 1897, and 1915[12]. But it is possible that a large portion had remained unruptured for a long time until the 2011 Tohoku-oki earthquake. Such observation is in general consistent with a long recurrence interval of the shallow fault in our model.

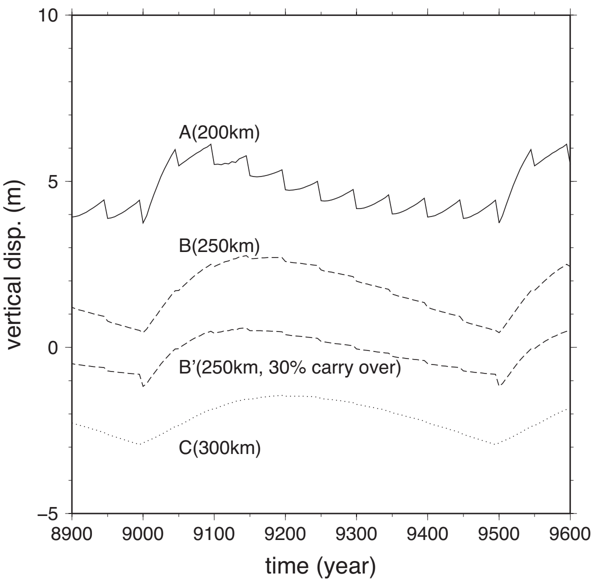

Fig. 4 Calculated vertical displacement time series. B' denotes the case of 30 % carry over of slip deficit at fault 2.

In Fig. 4, calculation result for point B is representative of the coastal displacement. It shows interseismic as well as coseismic subsidence followed by a postseismic uplift. Although the coseismic subsidence at point B is smaller than the observation, it can be increased by minor changes to the model. One possibility is to assume variable coseismic slip for the deep fault. If we assume the deep fault to carry its slip deficit over ordinary earthquake cycles and release all the accumulated slip deficit when the shallow fault ruptures, we can increase coseismic subsidence as shown by B' in Fig. 4. Coseismic slip analyses of the 2011 earthquake showed that the source area of the 1978 Miyagi-oki earthquake had a much larger fault slip in 2011. So modeling earthquakes with a short recurrence interval with variable coseismic slips is a reasonable assumption. In Fig. 4, it should be also noted that temporal change pattern of the vertical displacement is very sensitive to the location. Point A, located 50 km offshore, has totally different temporal change pattern from that of point B.

After the 2011 Tohoku-oki earthquake, significant postseismic signals have been detected by various geodetic observations such as satellite gravity, on-land GPS, and seafloor GPS-acoustic measurements. Viscoelastic relaxation is considered to be the most important origin of the postseismic deformation[14][15][16]. The viscoelastic cycle model in this study predicts horizontal crustal deformation pattern, which shows significant postseismic landward displacements just above the shallow fault (X in Fig. 5). Since this study applies various simplifying assumptions, a quantitative comparison with the observation data is beyond the scope of this paper. But it should be noted that even such a simplified model can reproduce a basic feature of the postseismic deformation, implying that viscoelastic relaxation has been playing an intrinsic role in the postseismic process.

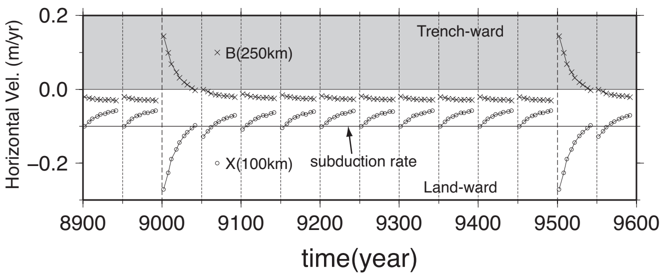

Fig. 5 Calculated temporal changes of interseismic horizontal displacement rate at points X and B.

This study demonstrates that viscoelastic relaxation in the asthenosphere causes significant temporal variation in crustal deformation pattern during the interseismic time period. This effect is of particular importance when an earthquake recurrence interval is longer than the asthenospheric relaxation time. The coastal area of northeast Japan is located above the down-dip edge of the interplate locked zone. Elastic dislocation models predict interseismic uplift due to interplate locking. But our model suggests that long-lasting interplate coupling in the shallow part may result in coastal subsidence. Thus, if we observe interseismic subsidence at the down-dip edge of the locked zone, the shallow part of the plate boundary may have been locked for a long time. In such a situation, a high potential for a big tsunami is implied. Actually, there is such a situation along the Pacific coast of eastern Hokkaido, northern Japan[17].

There are other factors not considered in this study but may affect the crustal deformation pattern significantly. First, structural heterogeneity can change viscoelastic relaxation pattern. Yoshioka and Suzuki [18] showed that postseismic relaxation pattern is largely affected by the subducting slab. For more realistic modeling, we need to consider heterogenous structure by using a numerical approach such as the finite element method.

Another factor to be considered is spatio-temporal change of the plate boundary slip. Our assumption that interplate locking is perfect and the accumulated slip deficit is totally released by the earthquakes is apparently too simple. Numerical modeling of earthquake cycles based on fault constitutive law suggests there occur aseismic fault slips before and after the earthquake[20]. There are also plenty of observational evidence of aseismic slow slip events on the plate boundary[21]. El-Fiky and Kato [2], through analysis of leveling and triangulation data, estimated about 64% of the plate motion was accommodated with an aseismic slip. On the other hand, recent studies with GPS data analysis have shown that interplate locking ratio was larger, close to full, at least in the deeper part of the off Miyagi region [5][6][7][19]. So the simplified assumption of full locking in this study can be considered as a possible end member. Also, it should be noted that a case of partial but steady locking can be considered by simply multiplying the coupling ratio to the calculated displacement results shown above since our calculation purely depend on the perturbation term of the plate boundary slip.

This study demonstrates that consideration of an earthquake cycle and viscoelastic relaxation is essential to make an appropriate interpretation of geodetic observation data. The model predicts that significant deformation pattern change will occur over decades to centuries. The prediction should be verified through comparison with actual observation in the future, and such effort is indispensable in improving our understanding about geodynamic processes.

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