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LONG-TERM STRAIN BUILDUP IN THE NORTHEAST JAPAN ARC-TRENCH SYSTEM AND ITS IMPLICATIONS FOR THE GIGANTIC SUBDUCTION EARTHQUAKE OF MARCH 11, 2011

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ABSTRACT: Recent GPS observations have made it possible to detect crustal strain precisely and extensively, but are not sufficient in time to cover a whole cycle of strain buildup and release in a subduction-related orogen. From the viewpoint of earthquake forecasting, we need to extract elastic strain from GPS-derived strain data. Based on the lesson from the 2011 Tohoku earthquake of Mw 9.0, we propose that geological methods should be used to estimate inelastic strain buildup quantitatively, thereby to evaluate present-day elastic strain buildup, which may eventually result in gigantic earthquakes.

Key Words: geologic time scale, geodetic time scale, interseismic coupling, decoupling event, subduction-related orogen, elastic strain, inelastic strain

INTRODUCTION

In this paper, we review the process of strain buildup and release in the Northeast Japan (NEJ) arc on a geologic time scale and discuss its implications for gigantic subduction earthquakes. Crustal strain is build up in and around a subduction zone in association with interseismic coupling on the plate interface. The elastic portion of the crustal strain is released during episodic decoupling events on the plate boundary; the remainder is accommodated as permanent (= inelastic) deformation mainly within the subduction-related orogenic zone, which is thermally weakened by magmatic heating. Coseismic deformation is basically elastic, although damped by asthenospheric viscosity and thereby followed by postseismic deformation decaying exponentially with time.

Recent GPS observations have made it possible to detect crustal strain precisely and extensively. However the duration of such advanced observations are too limited to cover a whole cycle of strain buildup and release in subduction-related orogens. Accordingly, it is almost impossible to discriminate elastic strain from inelastic strain in GPS-derived strain data. From the viewpoint of earthquake forecasting, we need to know how much elastic strain has been build up in a subduction zone. We propose here that geological methods should be used to evaluate inelastic strain buildup quantitatively, thereby to evaluate present-day elastic strain buildup, which may eventually result in gigantic earthquakes.

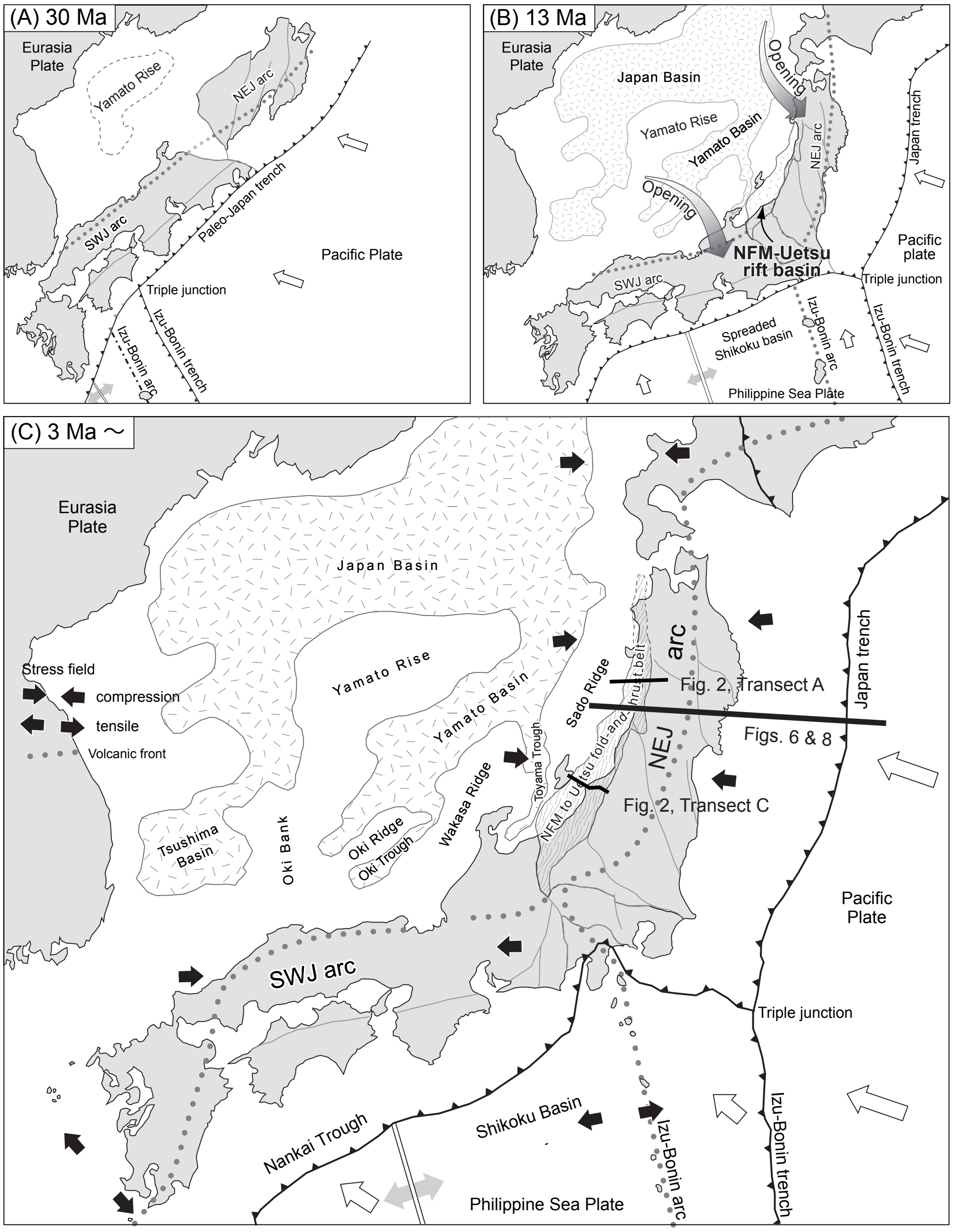

Fig. 1. Tectonic history of the Northeast Japan (NEJ) arc and its environs since Oligocene time (Okada and Ikeda, 2012; simplified after Takahashi, 2008). Transect for Figs. 6 and 8 and two geologic transects A and C in Fig. 2 are located in the bottom figure. (A) 30 Ma (just before the Japan Sea opening). The proto-Japan arc had been situated at the Eurasian continental margin until Late Oligocene time. (B) 13 Ma (at the end of the Japan Sea opening). The Japan Basin, Yamato Basin, and Uetsu-Northern Fossa Magna (NFM) Basin were developed during the back-arc spreading stage from 25 to 13 Ma. (C) 3.5 Ma to the present. Contractive deformation is concentrated in the Uetsu-Northern Fossa Magna (NFM) Basin in Miocene time. Abbreviations: NEJ, Northeast Japan; SWJ, Southwest Japan; NFM, Northern Fossa Magna. Note that recent contractive deformation is concentrated in the Uetsu–Northern Fossa Magna Basin, across which two representative cross sections (transects A and B) are shown in Fig. 2.

GEOLOGICAL SETTING

Rheological structure of the Japan arc based on explosion seismology, heat-flow measurements, and laboratory experiments indicates that the back-arc region (west of the volcanic front) of NEJ arc, including continental slopes on the Japan Sea side, is mechanically very weak (e.g., Shimamoto, 1989); only the upper ~15 kilometers of crustal rocks behaves elastic, and ductile lower crust is underlain directly by asthenospheric mantle (e.g., Iwasaki et al., 2001). As described below, this zone of weakness was rifted and stretched during the Miocene back-arc spreading event, and coincides broadly with the distribution of active faults since Pliocene time.

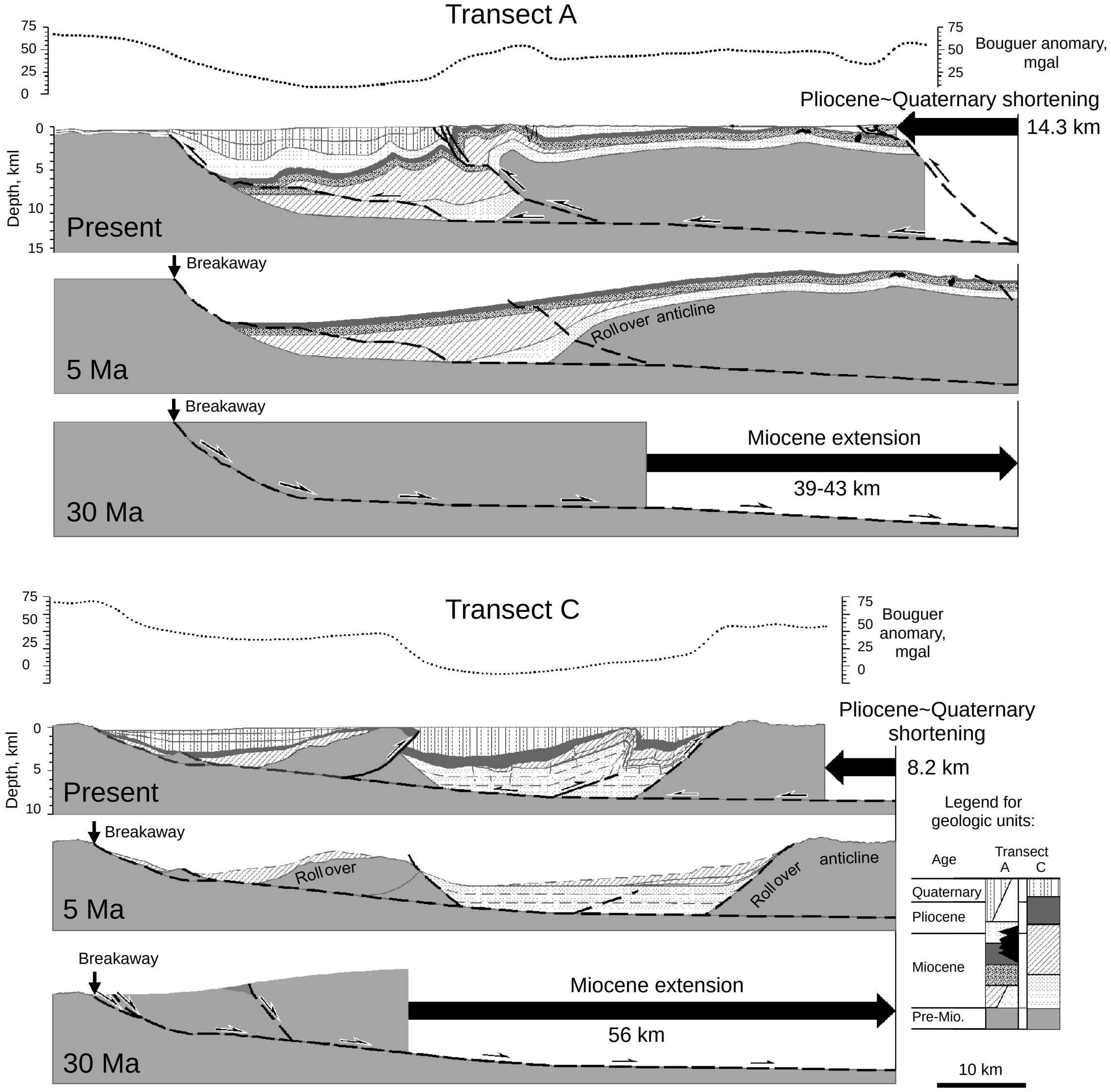

Fig. 2. Present-day and restored geologic cross-sections along two transects across the Uetsu–Northern Fossa Magna Basin on the back-arc side of Northeast Japan (simplified from Okada and Ikeda, 2012). See Fig. 1 for location. Each set of four figures shows, from the top to the bottom, Bouguer gravity anomaly, present-day geologic section, restored geologic section before the Pliocene positive tectonic inversion, and restored geologic section before Miocene extension.

The geologic structure of the Japan arc is a product of multiple phases of tectonic activity since Mesozoic time. The proto-Japan arc had been situated at the Eurasian continental margin until Late Oligocene time, forming an Andean-type volcanic arc associated with subduction of the Pacific plate beneath Eurasia (Fig. 1A). Major geologic structures of the present-day Japan arc were formed during the period from Late Oligocene to Middle Miocene time, when the proto-Japan arc separated from Eurasia in association with the back-arc opening of the Japan Sea (Fig. 1B). Later tectonic inversion (from extension to contraction) in Pliocene time also has modified the NEJ arc significantly (Fig. 1C).

The back-arc opening of the Japan Sea started at ~24 Ma in the north of the Japan Basin with the focus of spreading migrating southward (e.g., Kaneoka et al., 1992), possibly due to the southward migration of subduction-related magmatic activity (Tamaki et al., 1992; Yoshida et al., 1995; Sato et al., 2004). Paleomagnetic data suggest clockwise rotation of Southwest Japan by as much as ~50° during a very short period (~2 Myr) around 15 Ma (Otofuji et al., 1985). Crustal extension within the NEJ arc occurred mainly in the later stage (16-13 Ma) of the Japan Sea opening (Sato, 1994). Extension was particularly strong in the eastern margin of the Japan Sea, where abnormally deep basins, such as the Uetsu Basin, the Northern Fossa Magna (NFM) Basin, and the Toyama Trough, developed (Fig. 1).

The style of the Miocene extension in the back-arc region of NEJ is highly asymmetric with a zone of concentrated extension along the NFM-Uetsu Basin (Fig. 1C). This extension zone is characterized by a break-away fault on the west, a rollover basement anticline on the east, and abnormally deep (~10 km) basins and strongly rotated fault blocks in between (Fig. 2; Okada and Ikeda, 2012), suggesting the existence of a large-scale detachment fault at a mid-crustal level beneath the extended zone. Such a style of deformation is best explained by Weissel and Karner's (1989)

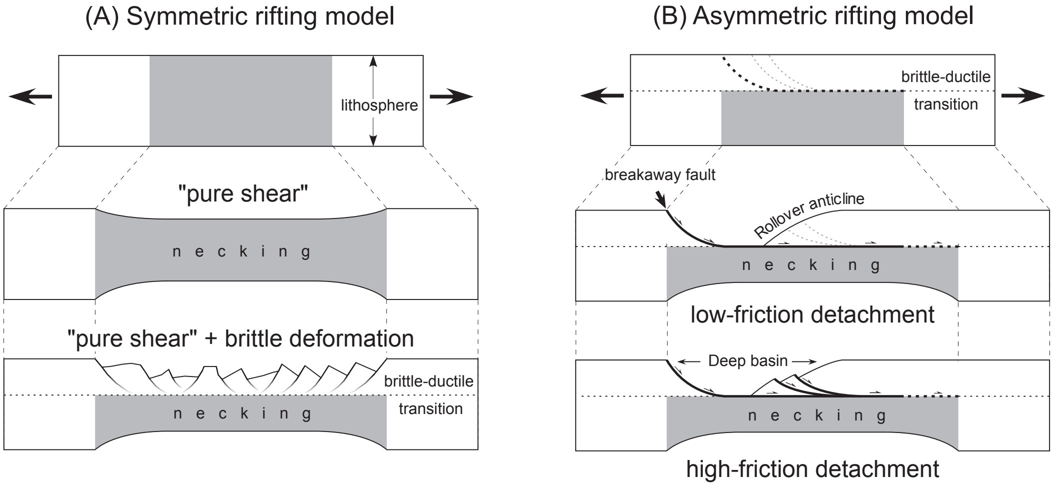

Fig. 3. Symmetric and asymmetric rifting models (Okada and Ikeda, 2012). (A) Symmetric "pure shear" rifting model proposed by McKenzie (1978), and modified by Le Pichon and Sibuet (1981) with brittle deformation in the upper crust. (B) Asymmetric rifting model proposed by Weissel and Karner (1989), with modification into "high friction detachment" and "low friction detachment" cases by Okada and Ikeda (2012). Note that symmetric "pure shear" extension occurs below the brittle-ductile transition depth, whereas the upper crustal deformation is highly asymmetric. The asymmetric rift zone typically consists of a breakaway fault scarp on one side, a rollover basement anticline on the other side, and an abnormally deep basin in between. The asymmetric rifting becomes identical to the symmetric rifting with increasing friction on the detachment fault at the brittle-ductile transition. Note also that, under compressive stress field after positive tectonic inversion, deformation could occur in the opposite sense.

model, in which the brittle upper crust is capable of being deformed independently from the ductile lower crust and uppermost mantle. This model requires a detachment fault that mechanically decouples the upper crust from the lower crust and uppermost mantle; a beak-away fault soles onto the detachment fault, forming a large-scale listric normal fault (Fig. 3; Okada and Ikeda, 2012). The total amount of crustal extension across the NFM-Uetsu Basin is estimated by area-balancing restoration using seismic reflection, gravity, and surface-geologic data, and is found to be as large as 31-56 km (Fig. 2; Okada and Ikeda, 2012).

After ~10 Myr of tectonic quiescence following the opening of the Japan Sea, the NEJ arc has been subjected to crustal shortening perpendicular to the arc since 3.5-5 Ma (Sato and Amano, 1991; Sato, 1994; Moriya et al., 2008). The Pliocene and Quaternary contractive deformation is concentrated again within the NFM–Uetsu Basin (Figs. 1C and 2), where Miocene and younger rift-fill sediments have been folded and faulted to form a fold-and-thrust belt (Matsuda et al., 1967; Sato, 1989). The total amount of crustal shortening across the NFM–Uetsu Basin during the past 3.5-5 Myr is estimated at 8-14 km (Fig. 2; Okada and Ikeda, 2012). It should be noted that the highly asymmetric surface deformation is likely to be caused by tectonic inversion (reactivation) of the preexisting large-scale detachment fault that had been formed in Miocene time at the brittle-ductile transition (Figs. 2 and 3; Okada and Ikeda, 2012). The asymmetric crustal extension model proposed for the Miocene NEJ (Fig. 3B) implies that, under compressive stress field after the Pliocene tectonic inversion, deformation could occur in the opposite sense both in the upper and lower crustal layers. It follows from this that lower-crustal strain is distributed across a much wider zone beneath the detachment (Fig. 3).

LONG-TERM VERSUS SHORT-TERM STRAIN OBSERVATIONS

Horizontal shortening

Recent continuous GPS observations have indicated that the rate of horizontal shortening across the NEJ arc is in a direction almost parallel to the direction of convergence between the Pacific plate and Eurasia, and is as high as 30-50 mm/yr (Fig. 4), which is about a half of the plate convergence rate (80-90 mm/yr) at the Japan trench. The GPS-derived horizontal strain rate is on an order of 10^{-7} strain/yr, which value is broadly concordant with the horizontal shear strain rate derived from triangulation and trilateration survey data for the past ~100 years (e.g., Nakane, 1973). Thus, it is likely that the NEJ arc has been contracted at a very high rate for at least the last ~100 years.

On the other hand, geologically derived, long-term-averaged values of horizontal strain/shortening are one order of magnitude smaller than geodetically derived values. As already shown above (Fig. 2), Pliocene-Quaternary horizontal shortening in the upper crust of the NEJ’s back-arc is definitely inelastic (permanent), and amounts to 8-14 km. The amount of shortening outside the transects is estimated to be not more than a few kilometers (Okada and Ikeda, 2012). Because the present-day contractive tectonic regime started at 3.5-5 Ma (Sato and Amano, 1991; Sato, 1994; Moriya et al., 2008), the average rate of inelastic shortening is 3-5 mm/yr, which value is one order of magnitude slower than the GPS-derived shortening rate (30-50 mm/yr). Therefore we conclude that most of the horizontal strain that has been accumulating at abnormally high rates in the past ~100 years is elastic; only a fraction (~10%) of the geodetically observed strain is inelastic, and is accommodated in the NEJ arc as permanent deformation (Ikeda, 1996, 2003, 2005, 2006).

Vertical movements

Discrepancy between long-term (geologic) and short-term (geodetic) observations exists also in vertical movements. Figure 5 (right) shows vertical crustal movements revealed by tide-gauge observations during the period 1955-1981 (Kato and Tsumura, 1979; Kato, 1983). Particularly striking in this figure is that the Pacific coast of NEJ and Hokkaido subsided at very high rates. Subsidence rate increases toward the trench, and reaches the maximum value as high as ~10 mm/yr (Fig. 5). Time series data at tide gauge stations along the Pacific coast of NEJ and Hokkaido indicates that the rapid subsidence has continued for at least 60-80 years (Fig. 7; Kato and Tsumura, 1979; Kato, 1983; Geographical Information Authority of Japan, 2010).

However, there is no evidence for long-term subsidence along the Pacific coast. Instead, late Quaternary marine terrace data indicate slow uplift (e.g. Koike and Machida, 2001; Ota and Saito, 2001). Figure 5 shows height distribution of Last Interglacial (~125 ka) shorelines. Since the eustatic sea level at the Last interglacial maximum (LIM; ~125 ka) is believed to be nearly the same as the present-day sea level, the height of a LIM shoreline relative to the present-day sea level approximately equals the amount of uplift during the past 125 kyr. Rates of uplift thus estimated are 0.1-0.5 mm/yr along the Pacific coast of NEJ and Hokkaido. Such long-term uplift at moderate rates is not local but extensive over the NEJ (Fig. 5, left), and is attributed to isostatic uplift due to crustal thickening, which in turn is caused mainly by (inelastic) crustal shortening possibly enhanced by magmatic underplating (Tajikara, 2004).

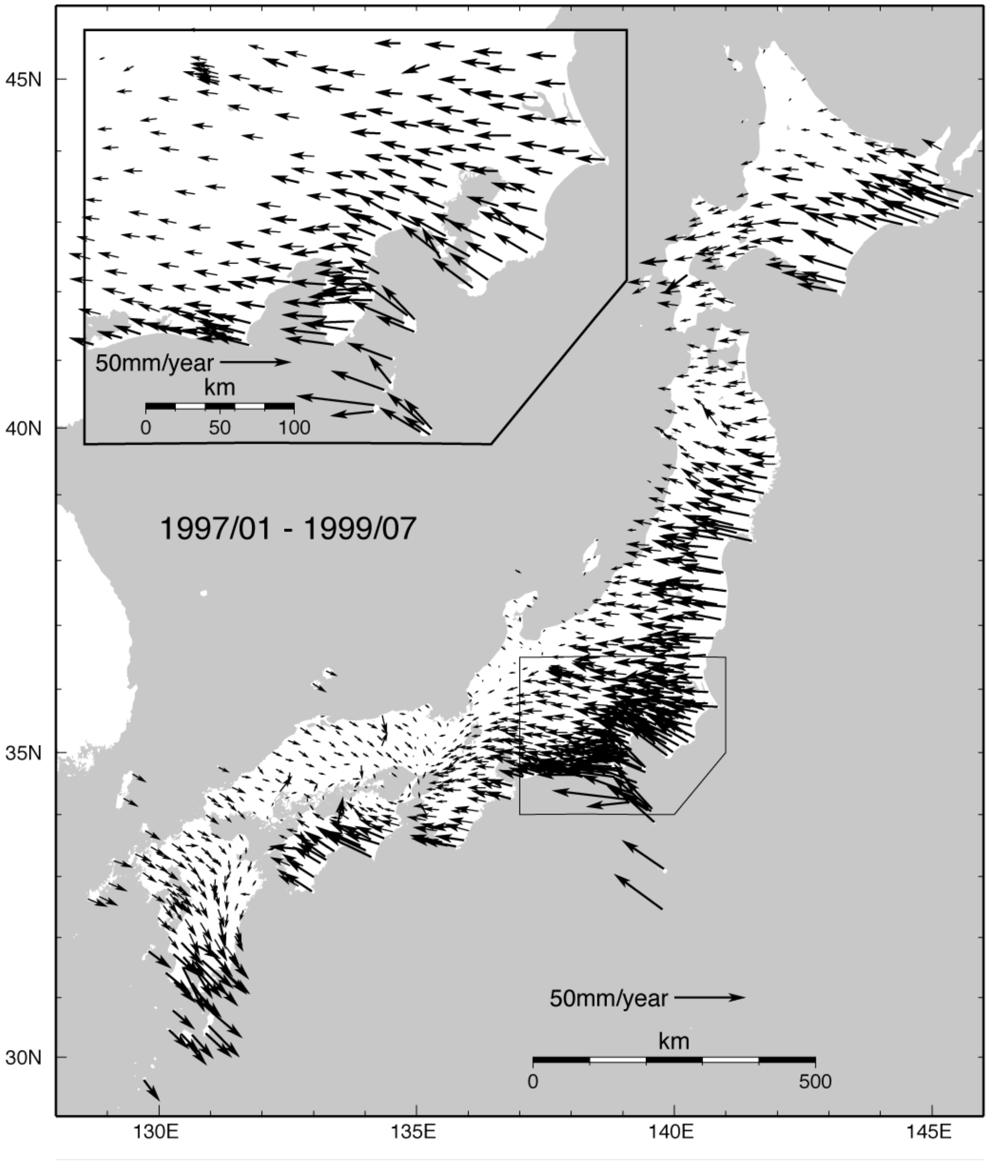

Fig. 4. Horizontal velocity field revealed by continuous GPS measurements (Sagiya *et al.*, 2000). Vectors are relative to the stable part of Eurasia. Inset magnifies Kanto area. Note high rates (30-50 mm/yr) of horizontal shortening across Northeast Japan.

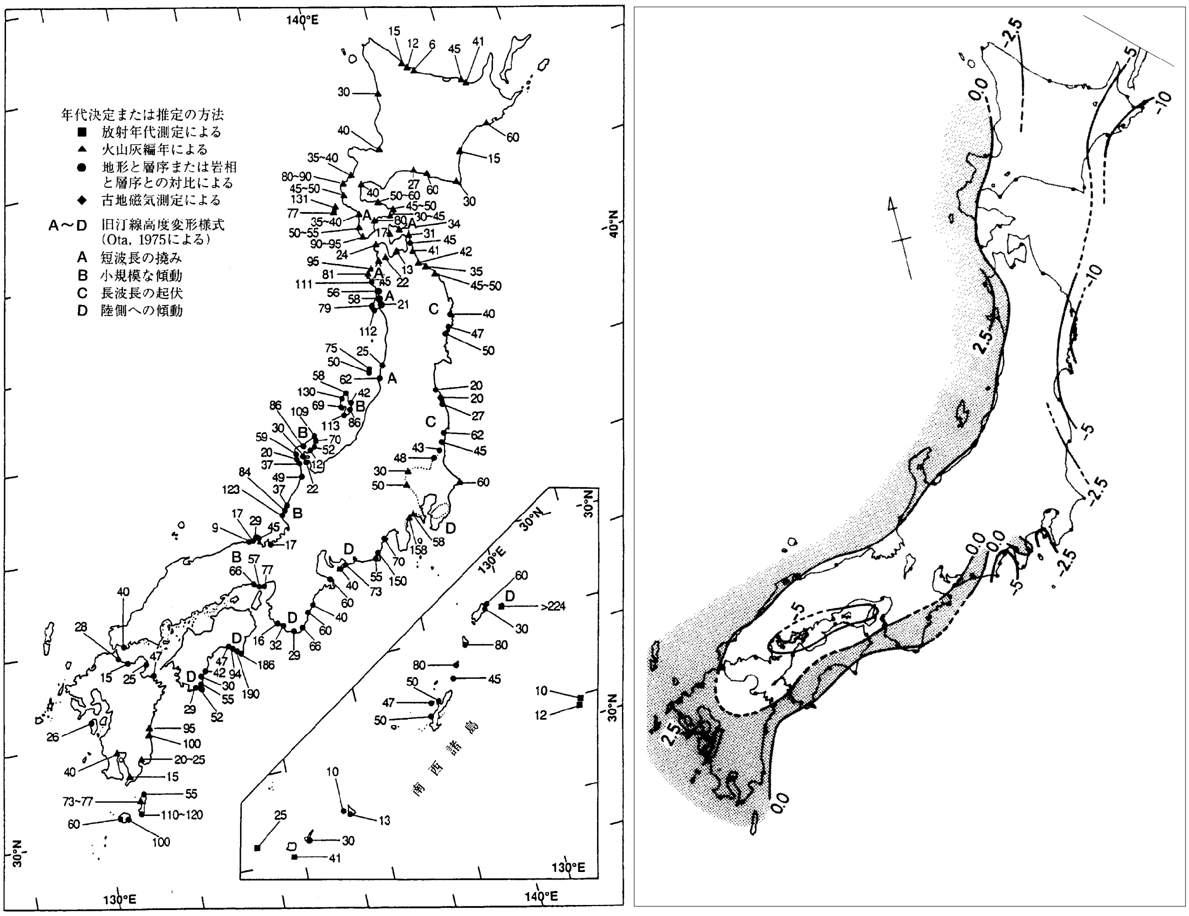

Fig. 5. Rates of vertical deformation over the Japan arc on different time scales. [Left] Height distribution (in meters) of Last Interglacial (~125 ka) shorelines (Ota and Saito, 2001). [Right] Recent vertical crustal movements revealed by tide-gauge observations during the period 1955-1981 (Kato, 1983). Contours indicate rates of uplift (in mm/yr). Shadow indicates positive areas. Note that the Pacific coast of NEJ and Hokkaido has been subsiding at extremely high rates (as large as 10 mm/yr), whereas marine terrace data (left figure) indicate moderate rates (0.1-0.5 mm/yr) of uplift.

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SCENARIO OF STRAIN BUILDUP AND RELEASE

Interseismic coupling

Observational data that we have reviewed so far indicate that most of the strain (both vertical and horizontal) that has accumulated in the NEJ arc during the last ~100 years at abnormally high rates is elastic. The cause of the elastic strain buildup is coupling on the plate interface; the overriding plate is shortened and dragged down by the subducting Pacific plate when the plate interface is mechanically coupled (e.g., Shimazaki, 1974). Figure 6 shows calculated pattern of interseismic deformation along a transect crossing the Northeast Japan and the Japan Trench. The calculation was performed by the simple back-slip model (Savage, 1983) in an elastic half space. Since a calculated pattern of displacements is sensitive to the geometry of plate interface, we determined the geometry by using a simple elastic plate-bending model (e.g., Watts, 2001) fitted with hypocenter distribution (Hasegawa et al., 1994).

In the NEJ-Kuril subduction zone, the depth to the down-dip limit of subduction-type earthquakes (i.e., shallow-angle, thrust-type earthquakes that occur on the plate interface) is about 50 km, which depth is similar to (or slightly deeper than) those in other subduction zones in the world (i.e., Oleskevichet al., 1999). Many researchers have believed that subduction interface deeper than the ~50 km down-dip limit is not coupled. However, the observed interseismic subsidence along the Pacific coast (Fig. 5, right) cannot be explained by such shallow coupling (Fig. 6). Our forward model calculations indicate that deep coupling (to a depth ~100 km) and a back-slip rate of 50 mm/yr is needed to subside the Pacific coast at a maximum rate ~10 mm/yr (Fig. 6).

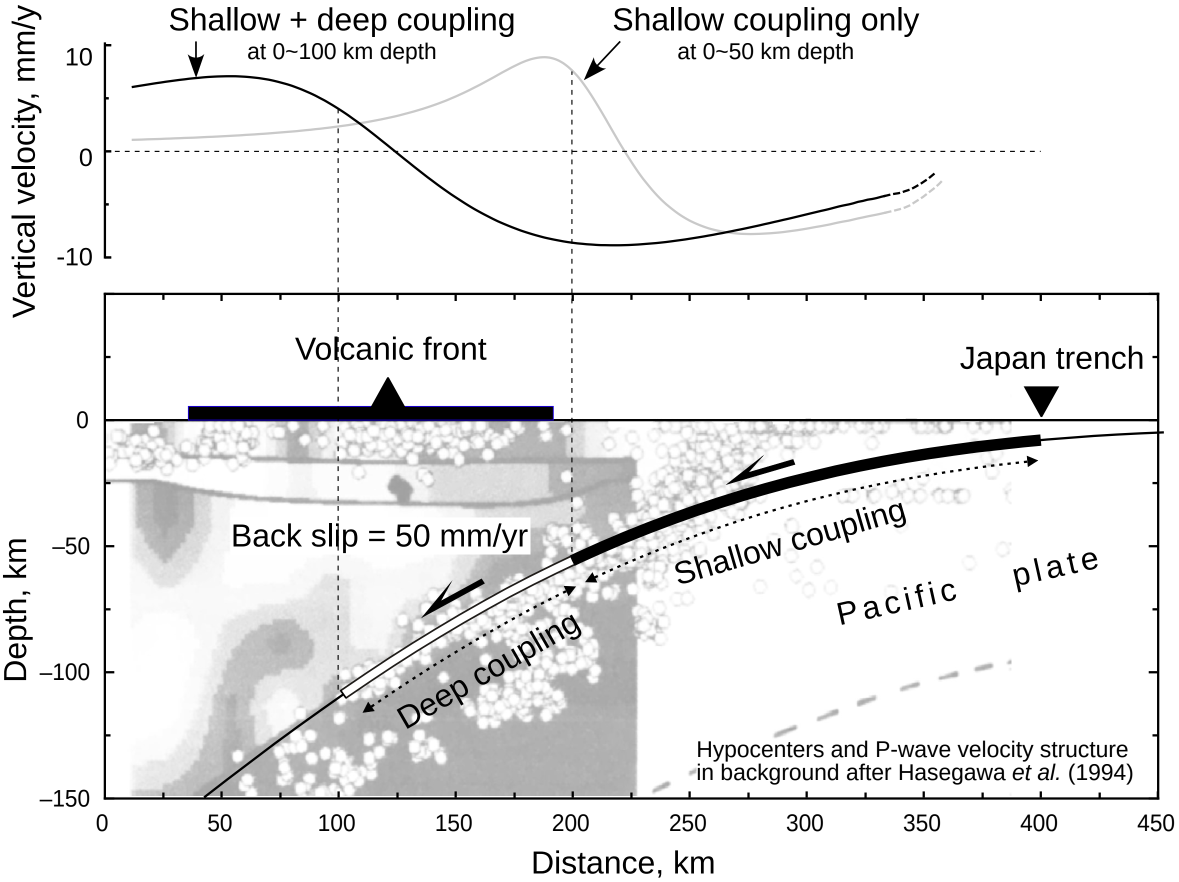

Fig. 6. [Top] Calculated patterns of interseismic deformation along a transect crossing the Northeast Japan and the Japan Trench. See Fig. 1 for the location of transect (Ikeda and Okada, 2011; Ikea et al., 2012). Calculations were performed by using a dislocation fault model in an elastic half space. Black line curve shows interseismic deformation caused by shallow coupling (thick black line in the bottom figure) on the plate interface at 0~50 km depths. Gray line curve shows interseismic deformation caused by deep coupling (thick black line plus thick white line in the bottom figure) at 0~100 km depths. A uniform back-slip rate of 50 mm/yr over the deeply coupled plate interface is needed to subside the Pacific coast at a maximum rate ~10 mm/yr. [Bottom] Geometry of plate interface along the same transect as of the top figure. Earthquake hypocenters and P-wave velocity structure in the background are after Hasegawa et al. (1994). Thick black and white lines indicate the areas of plate coupling.

Episodic decoupling

Elastic strain that has progressively build up in and around the NEJ subduction zone is to be eventually released in association with episodic slip on the plate interface that has been coupled so far. Many seismologists had believed before the Mw 9.0 Tohoku earthquake of 2011 that, because there were many subduction-type earthquakes of Mw 7-8 on the NEJ-Kuril subduction zone during the past ~100 years (Fig. 7, left), elastic strain due to interseismic coupling should has been released. Figure 7 (right) shows tide-gauge records along the Pacific coast, indicating progressive subsidence due to drag of the subducting Pacific plate during the past at least 60-80 years. It is clearly demonstrated in this figure that subduction earthquakes of Mw 7-8 during this period had nothing to do with strain release, i.e., uplifting the Pacific coast (Fig. 7, right). Instead, some of these Mw 7-8 earthquakes further enhanced coastal subsidence (Fig. 7, right).

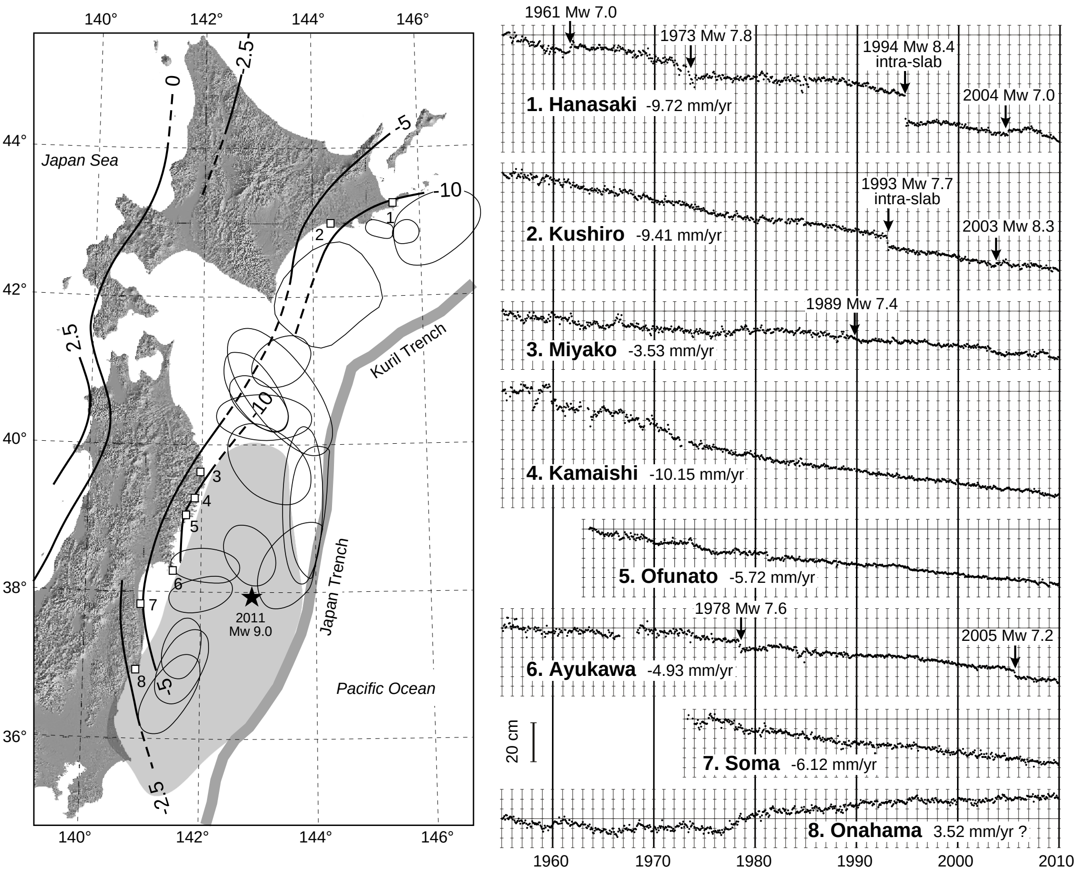

Fig. 7. [Left] Map showing recent vertical crustal movements and source areas of large subduction earthquakes (Ikeda and Okada, 2011; Ikea et al., 2012). Contour lines indicate rates of uplift (in mm/yr) revealed by tide gauge observations during the period 1955-1981 (Kato, 1983). Open ovals indicate source areas of subduction earthquakes of Mw ≥ 7.0 since 1896. The epicenter and source area of the 2011 Tohoku earthquake of Mw 9.0 are indicated by an asterisk and a shaded oval, respectively. Open squares indicate tide-gauge stations; station numbers correspond to those in the right figure. [Right] Selected tide-gauge records along the Pacific coast (Geographical Information Authority of Japan, 2010). See the left figure for the location of each station. Arrows indicate large earthquakes (Mw ≥ 7.0) that occurred near each station. Note progressive subsidence of the Pacific coast at rates as high as 5-10 mm/yr, except for the Onahama station, which has likely been affected by coal mining.

As shown in Fig. 7 (left), the source areas of these Mw 7-8 earthquakes are just small patches isolated within the coupled plate interface as wide as ~300 km (Compare Fig. 6 and Fig. 7 left). Seismic moment release due to slip on such a small rupture surrounded by coupled areas is not proportional to L^2 (i.e., the area of rupture) but is proportional to L^3, where L is the characteristic length of the rupture area (e.g., Matsuura and Sato, 1997; Fujii and Matsuura, 2000), and therefore crustal strain was not effectively released by slip on such (relatively) small rupture surfaces. Thus, in order to release the elastic strain that has been build up in interseismic period, a very large (Mw >> 8) decoupling event is necessary; its rupture surface should extend over the whole area of the interseismic coupling, so as to cancel the interseismic deformation completely (Fig. 8, top).

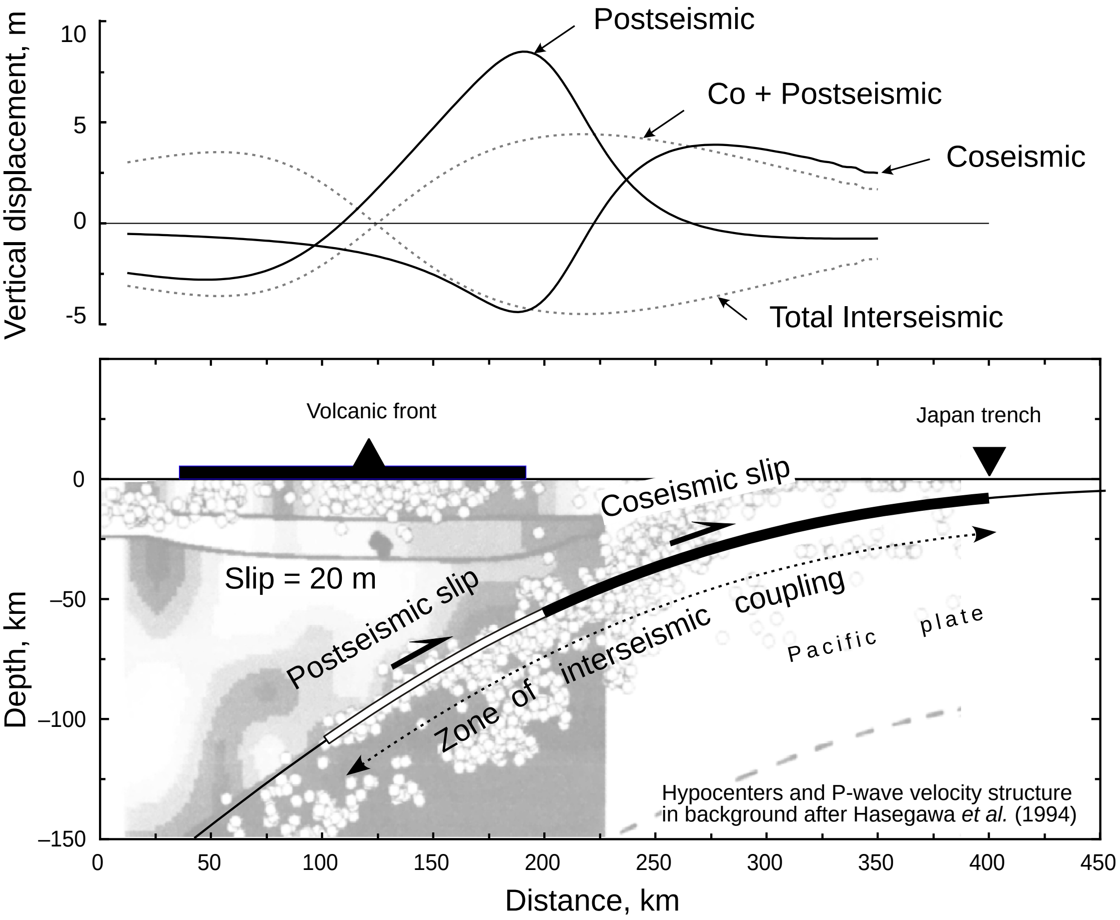

Fig. 8. Highly simplified patterns of coseismic, postseismic and interseismic deformation during a whole cycle of strain buildup and release over the Northeast Japan arc–trench system (Ikeda and Okada, 2011; Ikea et al., 2012). The line of profile and the geometry of plate interface are the same as those in Fig. 5. Total amount (= 20 m) of back slip is given over the coupled plate interface at 0-100 km depths; slip is assumed to be uniform (20 meters) over the coupled portions of the plate interface down to ~100 km depth. Coseismic slip on the shallow plate interface at 0-50 km depths results in coseismic subsidence along the Pacific coast, whereas subsequent aseismic slip at 50-100 km depths causes uplift, thereby cancelling both the interseismic and the coseismic subsidence along the Pacific cast. The 2011 Tohoku event is unique in that the decoupling occurs seismically on the shallower interface (0~50 km depths) and probably aseismically on the deeper interface (50~100 km depths).

THE 2011 TOHOKU EARTHQUAKE OF Mw 9.0

Coseismic deformation

The 2011 earthquake of Mw 9.0 is likely to be such a decoupling event that effectively releases strain due to plate coupling, because its rupture surface (~500 km long along strike and ~200 km wide) encompassed those of previously occurred Mw 7-8 subduction earthquakes (Fig. 7, left). However, the Pacific coast was not uplifted but further subsided by 120 cm at the maximum (Geographical Information Authority of Japan, 2011). This is because the down-dip limit of the coseismic rupture was ~50 km deep, and the deeper coupled interface (50-100 km depths) remains still unbroken (Fig. 8). Note again that the down-dip limit of the 2011 coseismic rupture coincides approximately with the maximum depth of previously occurred subduction-type earthquakes in the NEJ-Kuril subduction zone. Then, what will happen on the deeper coupled interface?

Postseismic deformation

Paleoseismological observations give some insights into the decoupling process below seismogenic depths in the NEJ-Kuril subduction zone. Paleo-tsunami and coastal-uplift evidence has indicated the occurrence of a gigantic earthquake off the Pacific coast of Hokkaido in the 17th century (Hirakawa, 2000; Atwater et al., 2004; Nanayama et al., 2003). Atwater et al. (2004) and Sawai et al. (2004) investigated coastal uplift associated with this 17th-century event on the basis of environmental-change analysis using diatom microfossils in tidal-flat sediments, and found that, following the deposition of tsunami sand, the tidal flat was gradually uplifted over tens of years to become emerged.

The above observations suggest that, in the NEJ-Kuril subduction zone, the deep decoupling at 50-100 km depths occurs aseismically following a sudden (i.e., seismic) decoupling event at shallower depths (0-50 km). Simple dislocation calculation (Fig. 8) predicts that aseismic after-slip on the deeper coupled interface will cause uplift along the Pacific coast of the NEJ and eventually will cancel the subsidence that has been accumulated before and during the 2011 Tohoku earthquake (Fig. 10B; Ikeda, 2011; Ikeda and Okada, 2011; Ikeda et al., 2012). Uplift along the Pacific coast has been detected by GPS observations at rates of 5-8 cm/month during one month after the 2011 earthquake (Geographical Information Authority of Japan, 2011), and is continuing at reduced rates.

Gigantic decoupling cycles

Recurrence interval of a gigantic decoupling event from the NEJ-Kuril subduction zone is not only a key to quantitatively understanding strain buildup-and-release process, but also is crucial to assess earthquake hazards. Studies of tsunami deposits in Sendai-Ishinomaki area first revealed that a tsunami with large inundation depths and distances occurred in association with the AD 869 Jogan earthquake (Minoura and Nakaya, 1991; Minoura et al., 2001; Sawai et al., 2008). The magnitude of the tsunami is similar to that associated with the 2011 earthquake. Therefore the AD 869 Jogan earthquake could be a predecessor of the 2011 earthquake of Mw 9.0. Hirakawa (2000) examined tsunami deposits at many sites at different altitudes along the Hokkaido coast, and revealed that tsunamis with exceptionally large inundation heights have repeatedly occurred at an average recurrence interval about 500 years. Thus, available data suggest that the average recurrence interval of gigantic decoupling events is 500-1100 years.

A global comparison

A global survey was made of subduction zones that have produced gigantic ($\geq$ 9.0) subduction earthquakes. There are two types of subduction zones that produce gigantic earthquakes: the Northeast Japan type and the Chilean type (Fig. 9; Ikeda et al., 2012). The Chilean type strain buildup/release process is simple and straightforward in the sense that seismogenic zone (down to a 40-50 km depth) plays everything (Fig. 9A). The source areas of the 1960 Chile, 1964 Alaska, and 1700 Cascadia earthquakes lack evidence for interseismic deep coupling. Paleoseismological evidence indicates interseismic uplift around the down-dip edge of coseismic rupture, where coseismic subsidence is observed (e.g., Atwater, 1987; Atwater et al., 1992; Cisternas et al., 2005; Shennan and Hamilton, 2006). This implies that the deeper plate interface is basically decoupled in interseismic periods, although subtle postseismic slip could exist on a transition zone down-dip of the coseismic rupture (e.g., Wang et al., 2003; Freymueller et al., 2000; Suito and Freymueller, 2009).

On the other hand, the Northeast Japan type strain buildup/release process seems to be exceptional (Fig. 9B). In the Northeast Japan subduction zone, interseismic coupling occurs to a depth as deep as ~100 km. Its decoupling process is two-fold: seismic decoupling occurs only on the shallower plate interface (0~50 km depths) while the deeper interface (50~100 km depths) decouples aseismically following the earthquake. Although we do not know the mechanism controlling the complex behavior of the NEJ-Kuril subduction zone, a possible cause for such deep coupling would be thermal; the oceanic lithosphere of the western Pacific is very old and therefore cold, and it has been subducted beneath the NEJ-Kuril arc.

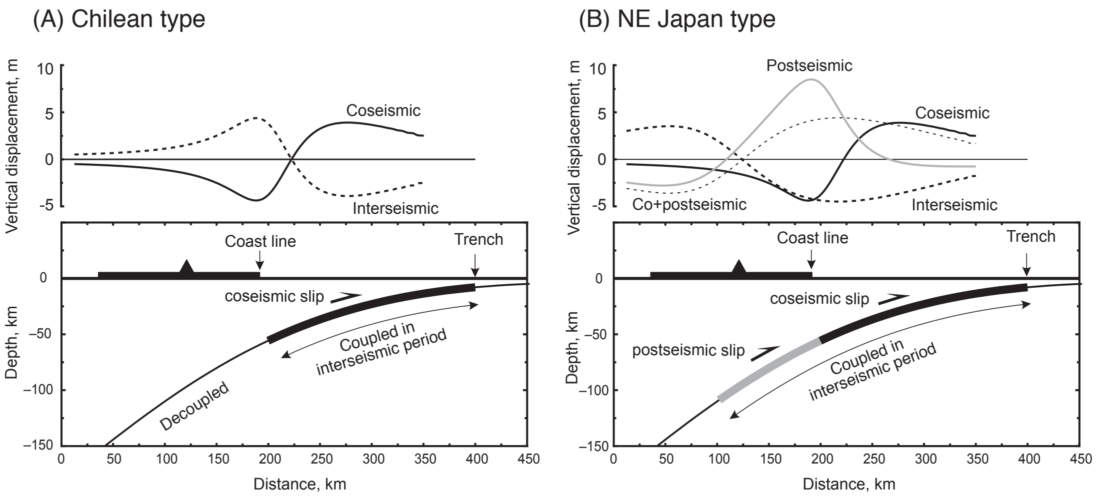

Fig. 9. Two types of strain buildup and release at subduction zones that produce gigantic (≥ 9.0) subduction earthquakes (Ikeda et al., 2012). The geometry of plate interface and amounts of surface deformation could be arbitrary but are represented in this figure by those of the 2011 Tohoku earthquake (Figs. 6 and 8). (A) Chilean type strain buildup/release process. The source areas of the 1960 Chile, 1964 Alaska, and 1700 Cascadia earthquakes lack evidence for interseismic deep coupling. Paleoseismological evidence indicates interseismic uplift around the down-dip edge of coseismic rupture, where coseismic subsidence is observed. This implies that the deeper plate interface is basically decoupled in interseismic periods, although subtle postseismic slip could exist on a transition zone down-dip of the coseismic rupture. (B) Northeast Japan type strain buildup/release process. The Northeast Japan subduction zone is, on the other hand, likely to be unique in that interseismic coupling occurs to a depth as deep as ~100 km, and that seismic decoupling occurs only on the shallower plate interface (0~50 km depths) while the deeper interface (50~100 km depths) decouples aseismically following the earthquake.

CONCLUSIONS

There has been a discrepancy between long-term (geologic) and short-term (geodetic) strain observations in both horizontal and vertical directions over the NEJ arc. Since Pliocene time to the present, the NEJ arc has been subjected to east-west compression due to the westward convergence of the Pacific plate at the strongly coupled Kuril-Japan trench. Geodetic observations in the past ~100 years have revealed strain accumulation over the NEJ arc at a rate as high as 10^{-7} strain/yr, whereas geologically observed strain rates are one order of magnitude slower. A similar discrepancy exists also in vertical movements; tide gauge records along the Pacific coast have indicated subsidence at a rate as high as ~10 mm/yr during the last ~80 years, despite the fact that late Quaternary marine terraces along the Pacific coast indicate long-term uplift at 0.1-0.3 mm/yr.

The ongoing rapid subsidence of the Pacific coast is due to dragging by the subducting Pacific plate beneath the NEJ arc. Thus, most of the strain accumulated in the last 100 years at abnormally high rates is elastic, and is to be released by slip on the coupled plate interface. Only a fraction (~10%) of geodetically-observed crustal shortening is accommodated within the NEJ arc as long-term (inelastic) deformation (Fig. 10A).

However, large (Mw 7~8) subduction earthquakes in the past ~100 years had nothing to do with strain release or coastal uplift. The 2011 earthquake of Mw 9.0, whose rupture surface encompassed those of previously occurred Mw 7-8 subduction earthquakes, is likely to be such a decoupling event that effectively releases strain due to plate coupling. Pattern of interseismic subsidence indicates that, at 50~100 km depths down-dip of the 2011 rupture, there still exists a coupled part of plate interface, on which a large amount of aseismic after slip may occur in the coming decades (Fig. 10B).

The 2011 event could be unique in that the decoupling occurs seismically on the shallower interface (0~50 km depths) and aseismically on the deeper interface (50~100 km depths), because a tentative global survey of other gigantic (Mw > 9.0) subduction earthquakes suggests no such deep coupling in interseismic periods (Fig. 9).

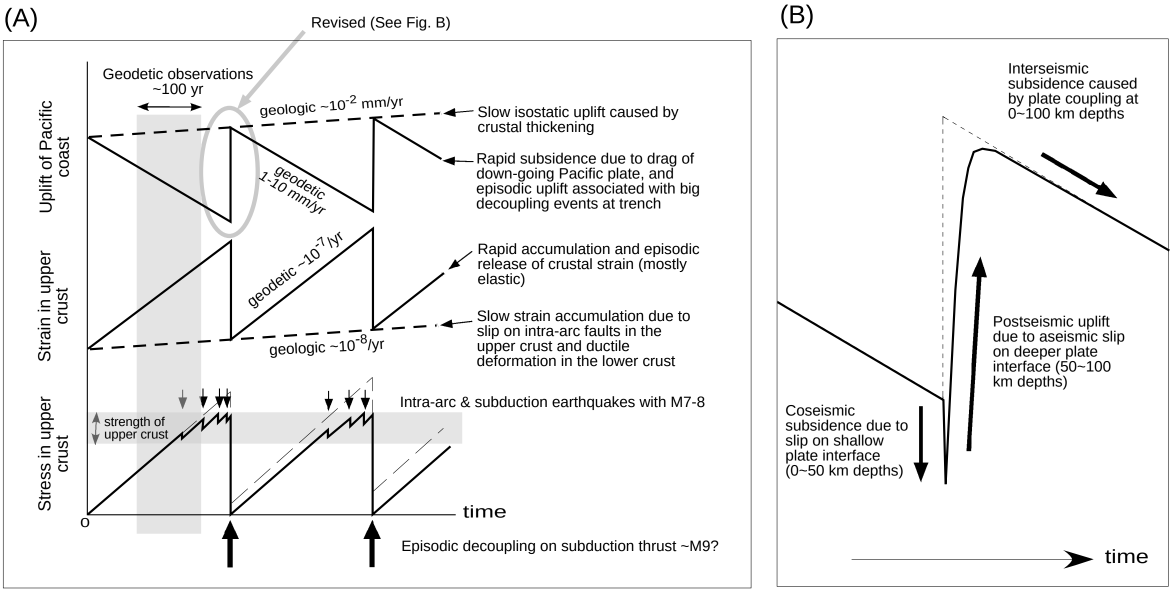

Fig. 10. Summary of strain buildup and release in the NEJ arc (Ikeda and Okada, 2011; Ikea et al., 2012). (A) The process of strain buildup and release in the NEJ arc proposed by Ikeda (2003, 2005, 2006). A modification is needed for detailed coseismic response. (B) A likely coseismic response. Observations of the 2011 earthquake (Mw 9.0) off the Pacific Coast of Tohoku indicated that the decoupling process of the Japan Trench is not straightforward; coseismic response along the Pacific coast was not uplift but further subsidence. This is because coseismic slip occurred only on the shallower part (0~50 km depths) of the locked plate interface. Following the main shock, aseismic slip started on the deeper plate interface (50-100 km depths), thereby resulting in coastal uplift.

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