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FULL PAPER

Geological structures controlled the rupture process of the 2011 M9.0 Tohoku-Oki earthquake in the Northeast Japan Arc

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Abstract

By interpreting the 2D/3D seismic survey data acquired in the surrounding ocean areas of the Northeast (NE) Japan Arc, we clarified the detailed geological structure and demonstrated that the basic structure in the hanging-wall plate of the subduction system consists of many structural blocks (segments) separated by NW–SE trending large transcurrent faults (strike-slip faults). This structural configuration showed a close relationship with the distribution of foreshocks, mainshock, and aftershocks, coseismic slip models of the 2011 M9.0 Tohoku-Oki megathrust earthquake, coseismic slip area of M-7 class earthquakes, quasi-static slip rates, back slip rate, and seismic tomography images. In addition, the coseismic slip models revealed that the trenchward forearc of the structural blocks between the Offshore Hidaka tectonic line and the Honjo-Sendai tectonic line fitted well with the coseismic slip area of the 2011 Tohoku-Oki earthquake. These findings suggest that the structural blocks bounded by these two tectonic lines slipped rapidly trenchward when the mainshock occurred. The M7 earthquakes were also concentrated along these two tectonic lines, thereby suggesting a close relationship between seismic activity and the inherited geological structure of the overriding plate in the NE Japan forearc.

Keywords: 2011 Tohoku-Oki earthquake, Transcurrent fault, Rupture process, Northeast Japan Arc, Hypocenter distribution, Segment boundary, Plate boundary megathrust

Introduction

Yoshida et al. (2017) reviewed the 2011 Tohoku-Oki earthquake, and suggested that it might have occurred below a segmented upper plate disrupted by large, steep, NW–SE trending transcurrent faults with the fault blocks clamped together by the NE–SW compressional stress arising from the SW indentation of the forearc sliver of the Kuril Arc (Kimura 1986; Acocella et al. 2008). However, the detailed relationship between the geological arrangement of such faulted segments and earthquake activity in the NE Japan forearc has not been sufficiently elucidated yet because of the lack of a detailed geological structure map based on the regional seismic interpretation. In this study, based on the detailed geological structure map of Baba (2017) created via offshore 2D/3D seismic survey and exploratory well data obtained around the NE Japan Arc, we compared the large geological structures, especially the large NW–SE strike-slip faults (large transcurrent faults), which act as structural block (segment) boundary faults, with the hypocenter distribution of foreshocks, mainshock, aftershocks, and the slip distribution of the 2011 Tohoku-Oki earthquake. In this paper, we will also show that the rupture process of the 2011 Tohoku-Oki earthquake was strongly controlled by the geological structure of the overriding continental crust.

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Marine geology of the NE Japan Arc

The marine geology of the NE Japan Arc was summarized by Baba (2017) using 2D/3D seismic survey data and exploratory well data obtained by the Ministry of International Trade and Industry of Japan and the Ministry of Economy, Trade and Industry of Japan as well as DSDP/ODP well data. The 2D seismic line spacing was shown to vary from 5 to 20 km in the continental shelf region around NE Japan and the eastern margin region of the Yamato Basin, and from 40 to 60 km in the trench-slope region of the Pacific Ocean side, and the Yamato Basin—Yamato Ridge in the Japan Sea side (Hayashi et al. 2010).

In the following section, we will describe the marine geology of the NE Japan Arc referenced in Figs. 1 and 2 (adapted from Baba 2017). Figure 1 shows the tectonic outline of the Japan Arc and its backarc systems. Figure 2 shows the geological structure and tectonic configuration of the NE Japan forearc. Details of the stratigraphy and geological structure are described in Additional file 1: Figs. S1: Regional stratigraphic chart; S2: Time contour map of the surrounding oceans of the NE Japan Arc; S3A and S3B: Typical seismic sections; and S4: Schematic cross-section of the NE Japan Arc).

Tectonic outline of the Japan Arc–Backarc system

Figure 1 shows the present tectonic configuration in and around the Japan Arc, which was generated from the Japan Sea opening (adapted from Baba 2017). This figure illustrates the right-lateral rotation of the NE Japan Arc against the Southwest (SW) Japan Arc along the Fossa Magna pull-apart basin. This rotation occurred during the spreading of the Japan Sea in the Early to Middle Miocene, and it involved a lateral displacement of approximately 200 km. The northern and southern margins of the Japan Arc are bounded by large transcurrent faults associated with the formation of the pull-apart basin system. The former is the Offshore Hidaka tectonic line (Faults A, B, C, and F) and the latter is the Tsushima–Goto tectonic line (Fault S). These two tectonic lineaments define large strike-slip zones developed at both ends of the Japan Arc during the opening of the Japan Sea in the Early to Middle Miocene. On the northern side of the Fossa Magna pull-apart basin, the Japan Arc is transected by several large NW–SE trending transcurrent faults as described below. The fault movement history of these faults is summarized in Additional file 1: Fig. S5.

Geological structure of the NE Japan forearc

The overriding plate in the NE Japan forearc is characterized by both the extension of the island arc basement towards the Japan Trench, and the small outgrowth of a modern accretionary prism along the Japan Trench (Kimura et al. 2012; Tsuji et al. 2013; Baba 2017; Yoshida et al. 2017). The structural configuration of the NE Japan forearc mainly consists of the Early Cretaceous–Paleogene forearc basins (the Offshore Sanriku Basin and Offshore Joban Basin: Osawa et al. 2002; Ando 2005) and the large transcurrent fault system. In the NE Japan Arc, four large transcurrent faults cutting through the NE Japan Arc to the surrounding ocean region are recognized (Figs. 1, 2, and Additional file 1: Figure S2). They are, from north to south, the Offshore Sanriku tectonic line (Fault G) that connects to the Kuromatsunai Lowland faults (Research Group for Active Faults of Japan 1991), the Hizume-Kesennuma fault (Fault H: Otsuki and Ehiro 1992) that connects to the Oppu–Morioka tectonic line (Ohguchi et al. 1989), the Honjo-Sendai tectonic line (Fault I: Taguchi 1960) and the Tanakura tectonic line (Fault T) that connects to the Nihonkoku-Miomote tectonic line (Fault N) (Yamamoto and Yanagisawa, 1989; Otsuki and Ehiro 1992). Hereafter, this fault system shall be referred to as the "Miomote-Tanakura tectonic lines" (Faults N to T: Niigata Prefecture, Commerce, Industry and Labour Department, Commerce Promotion Division 2000). The current arrangement of the large transcurrent faults (Figs. 1, 2, and Additional file 1: Figure S2) has been able to maintain those forms since the Japan Sea spreading from the Early to Middle Miocene (Baba 2017). The large transcurrent faults terminate toward the Japan Trench forming imbricate fans (Woodcock and Fisher 1986) or horsetail splay faults (Granier 1985), which are the typical termination styles of strike-slip faults (Figs. 2 and Additional file 1: Figure S2).

In terms of seismic interpretation, these large transcurrent faults were identified by tracing the large flower structure (i.e., the arrow marks at the top of the seismic sections in Additional file 1: Fig. S3A and S3B) associated with the linear or curvilinear principal displacement zone (Harding et al. 1985). Furthermore, their branched faults were recognized based on the features that show the lesser flower structure and oblique arrangement against the main fault (see Additional file 1: Fig. S3A and S3B).

Within this transcurrent system, Faults N to T are significant because they constitute a boundary separating the Pre-Cretaceous arc basement of NE and SW Honshu (Isozaki 1996; Ando 2005). In addition, a significant difference in the tectonic configuration is recognized on both sides of Fault H. The south side of Fault H is characterized by an NNE–SSW trending large horst named the Abukuma Ridge, and a graben named the Offshore Joban Basin, which is filled with a thick pile of Early Cretaceous to Neogene sediments (Lines 4 and 5 in Additional file 1: Fig. S3A). Conversely, the north side of Fault H is characterized by the development of a large NNW–SSE trending synclinal depression. This depression is named the Offshore

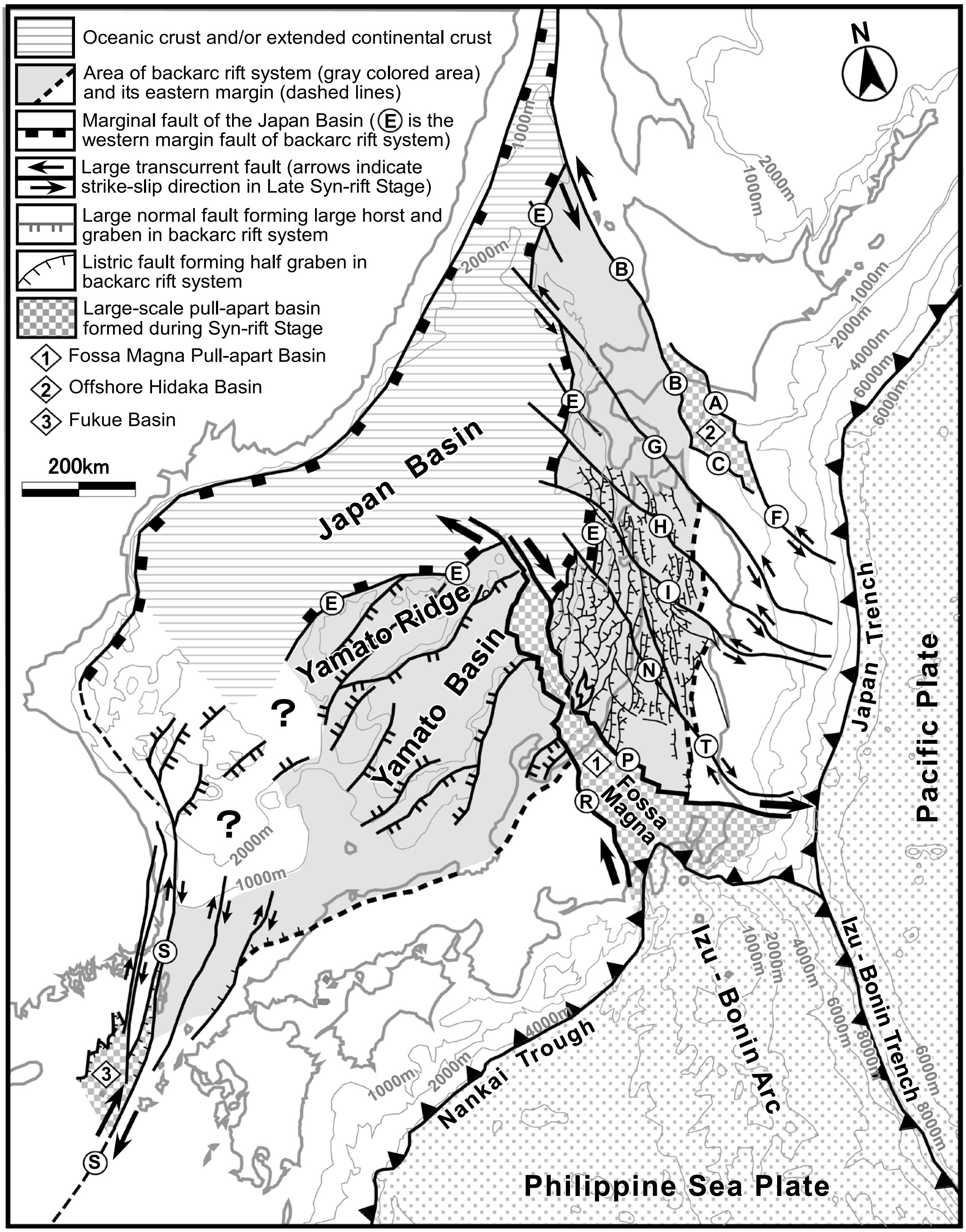

Fig. 1 Tectonic configuration in and around the Japan Arc generated since the Japan Sea opening to the present (adapted from Baba (2017)). The alphabetical symbols for large transcurrent faults are as follows: Offshore Hidaka tectonic line (Faults B, A, C, and F), Offshore Sanriku tectonic line (Fault G), Hizume-Kesennuma fault (Fault H), Honjo-Sendai tectonic line (Fault I), Miomote-Tanakura tectonic line (Faults N and T), Kashiwazaki-Choshi tectonic line (Fault P), Itoigawa-Shizuoka tectonic line (Fault R), and Tsushima-Goto tectonic line (Fault S)

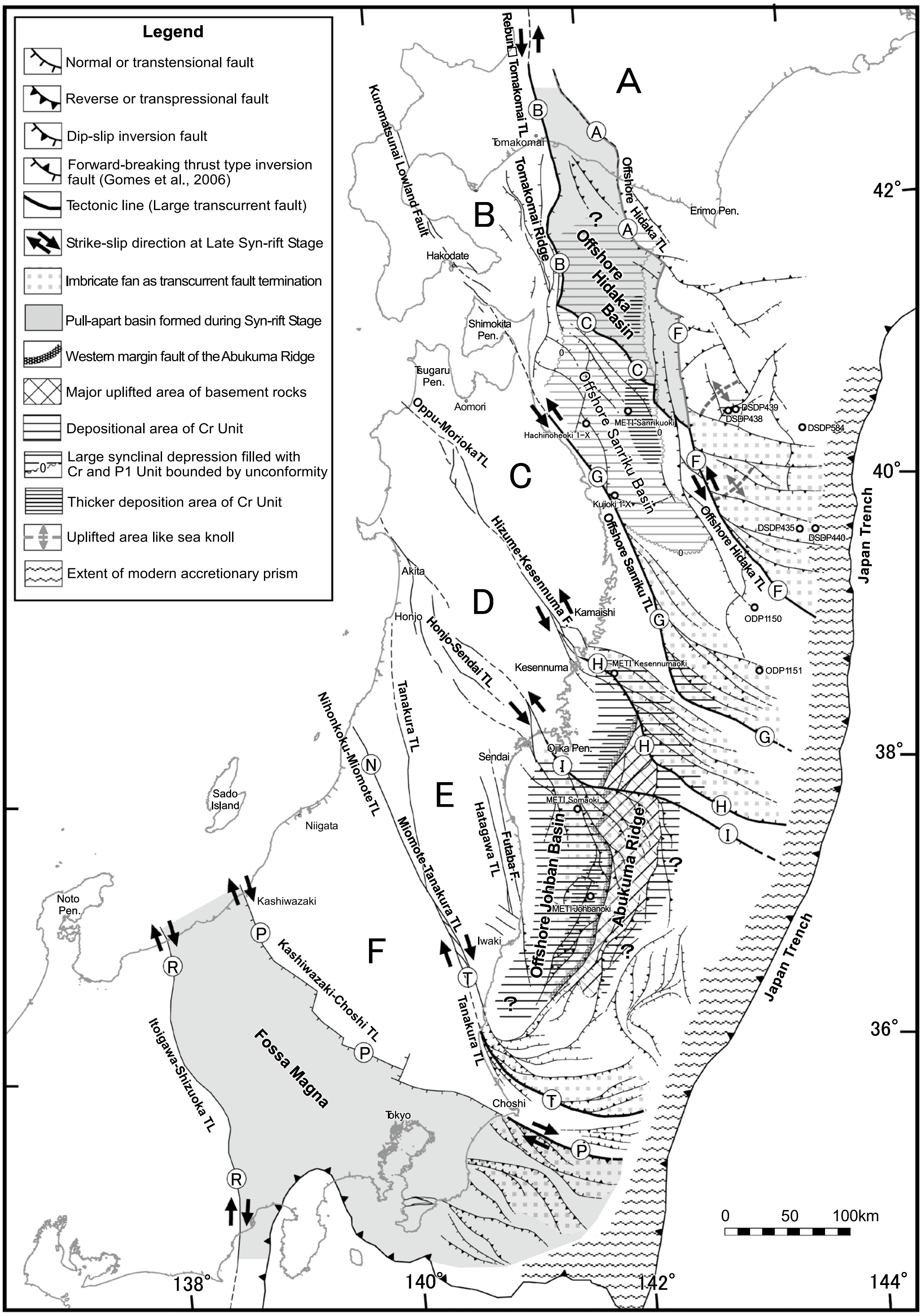

Fig. 2 Tectonic configuration of the NE Japan forearc (adapted from Baba (2017)). In this figure, the fault system on land was constructed based on GeomapNavi of the Geological Survey of Japan (2017), Japan Natural Gas Association and Japan Offshore Petroleum Development Association (1992) and Takahashi (2006). Letters "A" to "F" represent the structural blocks (segments) bounded on both sides by the NW–SE trending large transcurrent faults. The alphabetical symbols for large transcurrent faults are the same as those of Fig. 1

Sanriku Basin (Osawa et al. 2002), which is filled with Early Cretaceous to Early Oligocene sediments covered unconformably by Late Oligocene sediments (Lines 1 and 2 in Additional file 1: Fig. S3A).

The southern end of the NE Japan Arc is bounded by a large N–S trending right-lateral pull-apart basin extending from the east end of the Yamato Rise to the Fossa Magna through the Toyama Trough (Fossa Magna pull-apart basin) (Baba 1999, 2017). The eastern margin of the basin is bounded by the Kashiwazaki-Choshi tectonic line (Fault P, Yamashita 1970), while the western margin of the basin is bounded by the Itoigawa-Shizuoka tectonic line (Fault R). The formation of the pull-apart basin is closely related to the spreading process of the Japan Sea backarc basin (Baba 2017). According to paleomagnetic data (Otofuji et al. 1985), the backarc basin had been spreading with the clockwise rotation of SW Japan and the counterclockwise rotation of NE Japan during the Early to Middle Miocene. During this opening, the rotation of NE Japan was greater than that of SW Japan, and as a result, a large right-lateral displacement of approximately 200 km occurred along the Fossa Magna pull-apart basin (see Fig. 1 and Additional file 1: Figure S2).

The north end of the NE Japan Arc is bounded by the large left-lateral fault zone extending from Fault B to F through Faults A and C. Fault B is composed of the Mashike-Tobetsu fault (Masatani 1979), the Hiroshima-Tomakomai fault (Fujioka 1982), and the eastern margin fault of the Tomakomai Ridge (Masatani 1979). Fault A corresponds to the Umaoi-Iburi Fault Zone (Itoh and Tsuru 2006). During the opening of the Japan Sea through seafloor spreading, the NE Japan Arc moved southeastward along this strike-slip fault zone, thereby resulting in the formation of the Offshore Hidaka Basin. This left-lateral fault zone shall be hereinafter referred to as the "Offshore Hidaka tectonic line" (Faults A, B, C, and F). In the following sections, for simplicity, we will refer to the structural blocks (segments) bounded on both sides by the NW–SE trending large transcurrent faults as Blocks A, B, C, D, E, and F (see Fig. 3).

Dimensions of the large transcurrent faults in the NE Japan Arc

Deep seismic reflection profiling studies have led to the visualization of numerous examples of regional-scale strike-slip faults that cut through the entire crust and

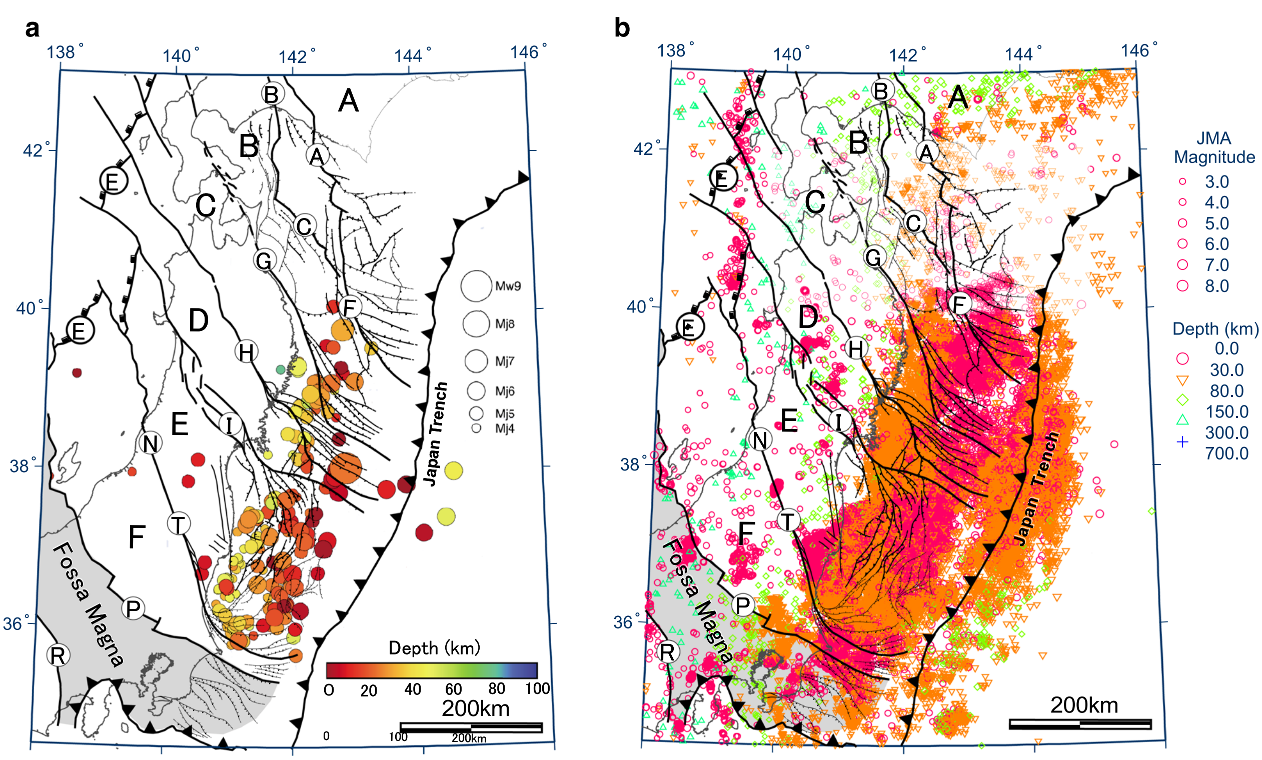

Fig. 3 **a** Distribution of hypocenters with an M_j greater than 4.0 within 24 h of the mainshock (Kurahashi and Irikura 2011). **b** Hypocenter distribution shallower than 700 km (M_j 2.0 to 9.9, duration: March 11, 2011 to March 10, 2012). The earthquake dataset was obtained from the JMA Earthquake catalog. Figure 3 and the subsequent figures are superimposed on the fault distribution map of the NE Japan Arc. The fault symbols are the same as those in Fig. 2

deeply penetrate the mantle (Storti et al. 2003). Vauchez and Tommasi (2003) also suggested that major intracontinental strike-slip faults crosscut through the entire lithosphere based on surface geological, seismic tomography, and magnetotelluric sounding studies. The size of such regional significant faults is typically a few tens of kilometers wide and several hundreds of kilometers long (Storti et al. 2003).

In the case of the NE Japan Arc, large NW–SE trending transcurrent faults have a maximum cross-strike width of 10 to 20 km (see red arrows in Additional file 1: Fig. S2) and a total length of 700 to 1000 km (see Fig. 1). The abovementioned scales suggest that these large transcurrent faults can deeply penetrate the mantle or crosscut through the entire lithosphere. This possibility is also corroborated by the seismic Q structure and the temperature distribution in the mantle wedge bounded by Faults N to T (Tsumura et al. 2000; Nakajima and Hasegawa 2003), the change in the down-dip limit of interplate earthquakes (Uchida and Matsuzawa 2013), and the back slip rate distribution (see Additional file 1: Fig. S8). The details of lateral displacement, total length, maximum cross-strike width, and tectonic history of each transcurrent fault are described in Section 3 of Additional file 1.

Tectonic control of earthquake distribution in the NE Japan Arc

Distribution of the mainshock and aftershocks within 1 day after the mainshock

Figure 3a shows the mainshock and aftershocks with a JMA (Japan Meteorological Agency) magnitude (M_j) greater than 4.0 occurring within 24 h of the M9.0 mainshock of the 2011 Tohoku-Oki earthquake (Kurahashi and Irikura 2011). The mainshock hypocenter was located in the trenchward forearc near the center of Block C. The aftershocks were distributed only between Faults F and T. The day after the mainshock, the southern end of the aftershocks extended to Fault P, according to the earthquake dataset of the JMA earthquake catalog.

Earthquake distribution after the 2011 Tohoku-Oki earthquake

Figure 3b shows the hypocenter distribution from March 11, 2011 to March 10, 2012 (JMA Earthquake catalog). Hypocenters shallower than 80 km are densely distributed along the forearc region between Faults T and F with their imbricate fan. The southern end of the dense hypocenter distribution is bordered sharply by Fault T. On the forearc side of Fault P, earthquake hypocenters shallower than 80 km are arranged linearly along the fault.

CMT distribution of interplate, upper plate and lower plate events before and after the 2011 Tohoku-Oki earthquake

Figure 4 shows the distribution of centroid–moment tensors (CMTs) with $M > 3.5$ from June 1, 2003 to September 30, 2011 (Hasegawa et al. 2012). In the CMT distribution of interplate events (Fig. 4a, b), the earthquakes are distributed widely along the NE Japan forearc. Furthermore, their southern margin seems to be limited by the down-dip limit of the Philippine Sea Plate (Uchida et al. 2009). Moreover, we can see that the interplate earthquakes after the 2011 Tohoku-Oki earthquake tend to have been distributed in the imbricate fan of Fault F, and that their southwestern margin was cut clearly by Fault F. In particular, the interplate earthquakes after the 2011 Tohoku-Oki earthquake (Fig. 4b) showed a lack of interplate aftershocks between Faults F and I. This region almost corresponds to the coseismic slip areas, as shown in Fig. 7.

In the CMT distribution of upper plate events before the 2011 Tohoku-Oki earthquake (Fig. 4c), a sparse distribution of earthquakes was recognized between Faults F and T, and these earthquakes tend to have been distributed along the trenchward region of Faults G, H, I, P, and the NNE–SSW trending faults developed in the Abukuma Ridge. It is notable that strike-slip earthquakes were well developed along Fault G. In the CMT distribution of upper plate events after the 2011 Tohoku-Oki earthquake (Fig. 4d), earthquakes were found to be densely distributed between Faults F and T, and along Fault P. The southern margin of this dense earthquake distribution is clearly limited by Fault T.

On the one hand, in the CMT distribution of lower plate events before the 2011 Tohoku-Oki earthquake (Fig. 4e), a sparse distribution of earthquakes was recognized between Faults F and T. On the other hand, in the CMT distribution of lower plate events after the 2011 Tohoku-Oki earthquake, a relatively dense distribution of earthquakes was recognized between Faults F and T.

Coseismic slip distribution of M7-class earthquakes

Figure 5 shows the coseismic slip distribution of M7-class earthquakes from 1930 (Murotani et al. 2003; Yamanaka and Kikuchi 2004). As shown in this figure, large coseismic slip areas of M7-class earthquakes are arranged linearly along Faults C and F, and are also arranged near and along Fault I. On the other hand, the coseismic slip areas are almost absent in the trenchward forearcs of Blocks B, C, and D. On the south side of Fault I, coseismic slip areas of M7-class earthquakes are distributed along the Abukuma Ridge, wherein numerous trench-parallel faults have developed.

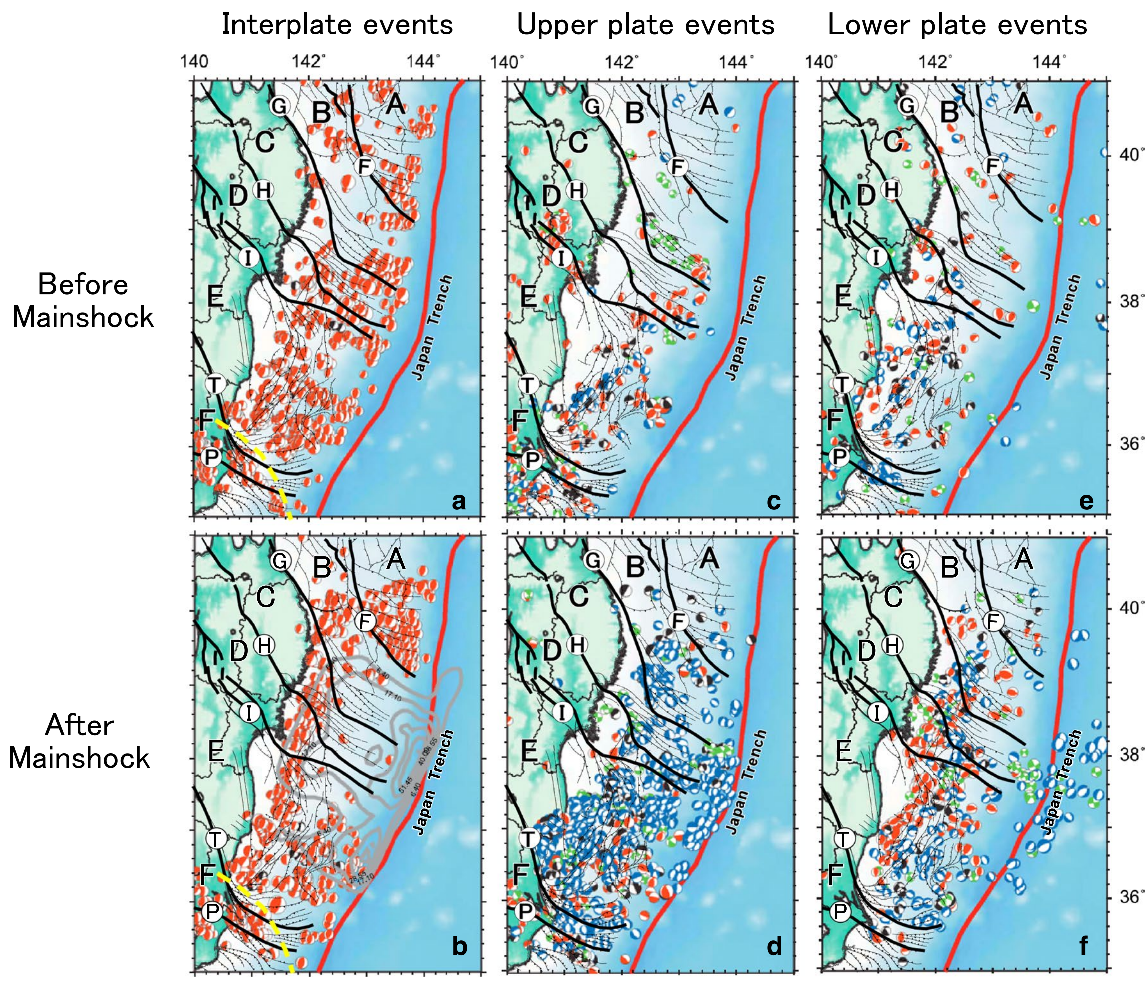

Fig. 4 Distribution of centroid–moment tensors (CMTs) with $M > 3.5$ from June 1, 2003 to September 30, 2011 (Hasegawa et al. 2012). CMTs in **a** and **b** represent interplate events, those in **c** and **d** represent upper plate events, and those in **e** and **f** represent lower plate events. The upper and lower panels in each pair show the CMTs before and after the 2011 Tohoku-Oki earthquake, respectively. Blue, green, red, and black beach balls denote normal, strike-slip, thrust, and other types of focal mechanisms, respectively. The contours in **b** show the mainshock slip distribution (Lay et al. 2011). The yellow dashed line shows the down-dip limit of the Philippine Sea Plate (Uchida et al. 2009). The thick red line shows the trench axis

Geological control of the nucleation process of the mainshock of the 2011 Tohoku-Oki earthquake

Stress transfer through slow-slip events is an important factor that increases the potential of a megathrust rupture. Preceding slow-slip events with anomalous earthquakes occurred around the source region in the pre-mainshock period of the 2011 Tohoku-Oki earthquake (Hasegawa and Yoshida 2015; Obara and Kato 2016). One month before the mainshock of the 2011 Tohoku-Oki earthquake, slow-slip events with three M5-class foreshocks occurred around Fault G near the shallow end of the slab-mantle contact zone (Hino et al. 2011; Ito et al. 2013; Yoshida et al. 2017). Two days prior to the mainshock, the largest foreshock (M_w 7.3) and the associated post-seismic slow-slip began at the shallow end of the slab-mantle contact zone around Fault G (Kato et al. 2012; Ito et al. 2013). This short-term preceding slow-slip broke the strongly coupled plate interface of Block C and propagated southwestward toward the hypocenter of the mainshock of the 2011 Tohoku-Oki earthquake, and finally led to the M9.0 main rupture (see Fig. 6). These facts imply that the initiation of the 2011 Tohoku-Oki earthquake started around the interplate thrust zone along Fault G.

Tectonic control of the coseismic slip distribution of the 2011 Tohoku-Oki earthquake

Many researchers have studied the coseismic slip distribution and rupture process of the 2011 Tohoku-Oki earthquake using seismic, geodetic, and tsunami data.

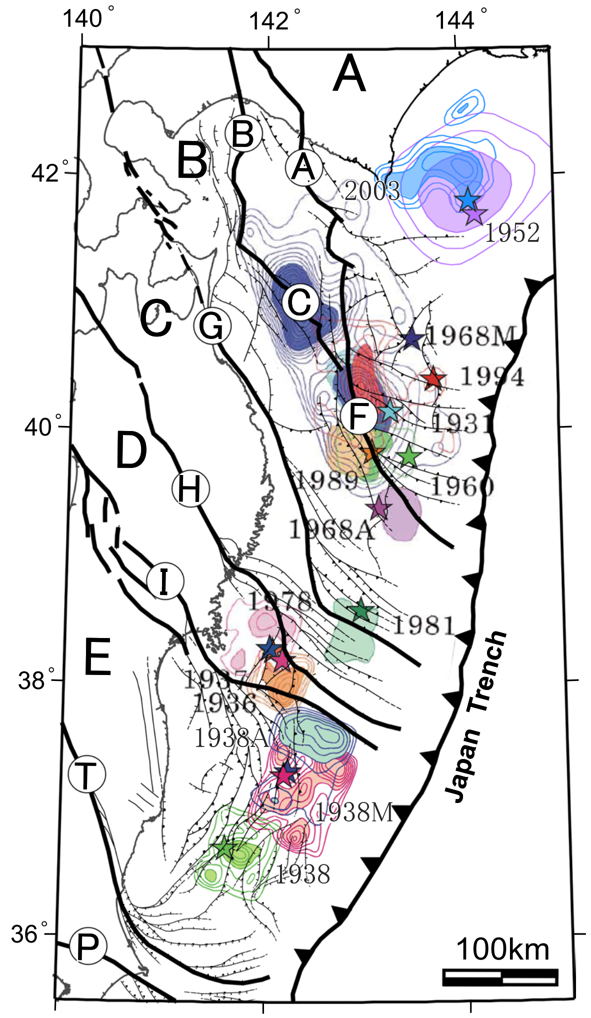

Fig. 5 Coseismic slip distribution of M7-class earthquakes since 1930, compiled from Murotani et al. (2003) and Yamanaka and Kikuchi (2004)

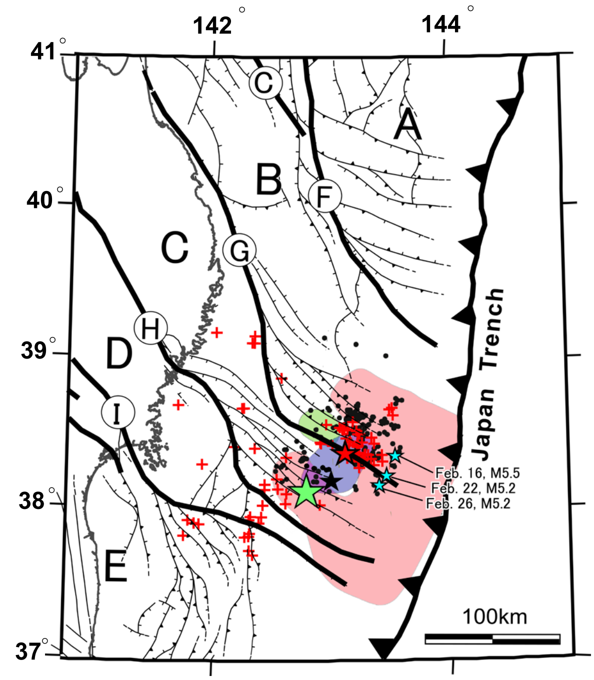

Fig. 6 Foreshocks, coseismic slip, and afterslip of the M_w 7.3 largest foreshock (Hino et al. 2014) superimposed on the fault distribution map. Green, red, and black stars represent epicenters of the M_w 9.0 mainshock, the M_w 7.3 largest foreshock, and the M_w 6.6 s largest foreshock of the 2011 Tohoku-Oki earthquake, respectively. Aqua stars represent the epicenters in February, 2011 foreshocks; the red plus signs indicate the epicenters of the seismicity from February 13, 2011 to the occurrence of the M_w 7.3 foreshock (Ito et al. 2013); and the black dots are the epicenters of foreshocks that occurred between the occurrence of the M_w 7.3 foreshock and the mainshock (Hino et al. 2014). The regions with more than 30 m coseismic slip in the mainshock (Iinuma et al. 2012), more than 1 m coseismic slip in the largest foreshock, and more than 0.3 m afterslip following the largest foreshock (Ohta et al. 2012) are shaded in pink, green, and blue, respectively

There are considerable differences among them (Yagi 2012), but subsequent studies using seafloor geodetic data have provided clear evidence in the understanding of the details of coseismic slip distribution and the rupture process of the 2011 Tohoku-Oki earthquake (Hasegawa and Yoshida 2015). Figure 7 shows the coseismic slip models of the 2011 Tohoku-Oki earthquake estimated from joint inversions of onshore GPS and seafloor geodetic data of Iinuma et al. (2012), Ozawa et al. (2012) and Sato et al. (2013) (Fig. 7a–c), and onshore GPS, seafloor geodetic, and tsunami data of Romano et al. (2014) (Fig. 7d). The coseismic slip models shown in Fig. 7 have the following common features: (1) the large coseismic slip regions are distributed in the trenchward forearc of Blocks B, C, and D, and the outline of the coseismic slip region nearly fits with Faults F and I, and (2) the large coseismic slip region is completely divided by Fault G into two patches and the region of maximum slip lies between Faults G and I, except for the model of Iinuma et al. (2012).

Geologic control of quasi-static slip rate distribution

The space–time distribution of the quasi-static slip rate on the plate boundary was estimated using small repeating earthquakes (Uchida and Matsuzawa 2013). In general, slow-slip rates correlate to almost totally locked regions, while large slip rates approaching the relative plate motion (8 to 9 cm/year; Sella et al. 2002) indicate regions of weak coupling (Igarashi, 2010). In contrast, the absence of small repeating earthquakes pertains to regions that are fully locked or those that slip completely

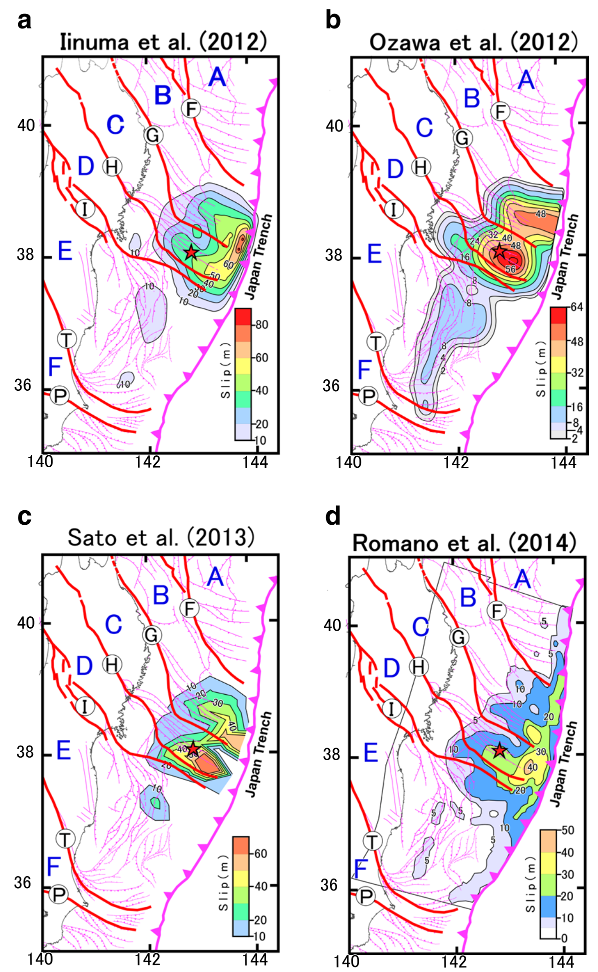

Fig. 7 Coseismic slip distribution of the 2011 Tohoku-Oki earthquake estimated from inversions of data including seafloor geodetic data. Slip models by **a** Iinuma et al. (2012), **b** Ozawa et al. (2012), **c** Sato et al. (2013), and **d** Romano et al. (2014)

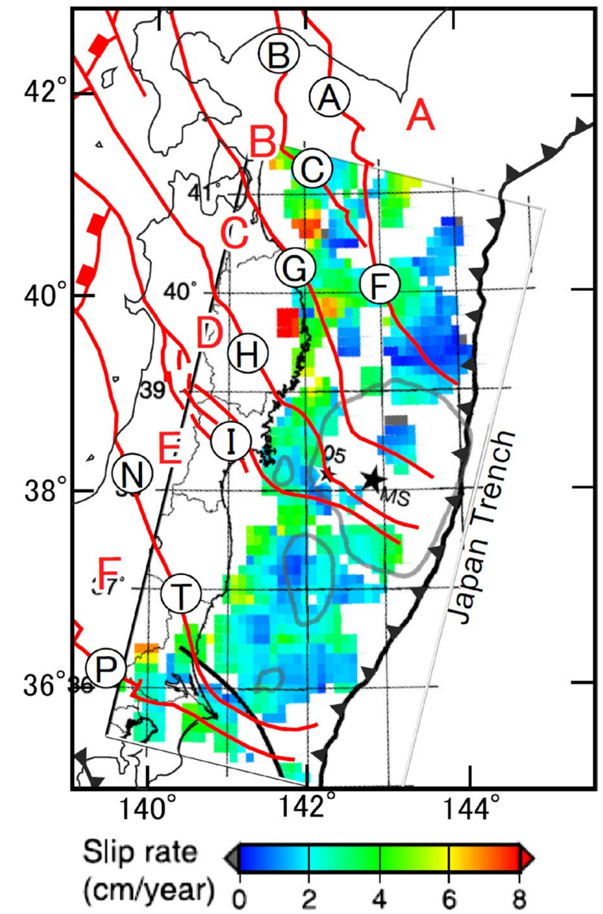

Fig. 8 Quasi-static slip rate distribution from March 11, 1996 to March 11, 2008 (Uchida and Matsuzawa 2013). The "white" regions represent the regions where there are no repeating earthquakes

a seismically. Figure 8 shows the wide regions without repeating earthquakes in the trenchward forearc regions of Blocks B, C, and D prior to the mainshock from March 11, 1996 to March 11, 2008 (Uchida and Matsuzawa 2013). The small-repeating-earthquake gap almost corresponds to the coseismic slip region of the 2011 Tohoku-Oki earthquake (see Fig. 7), and probably represents an almost fully locked region prior to the 2011 Tohoku-Oki earthquake (Uchida and Matsuzawa 2011, 2013). On the southern side of Fault I, quasi-static slip areas with an annual slip rate of 1 to 5 cm are recognized throughout the forearc region.

Geological control of seismic tomography images

Figure 9 shows the distribution of the P-wave velocity perturbations along the plate interface obtained from seismic tomography and exhibits the strong lateral heterogeneity of the seismic velocity structure along the NE Japan forearc.

Figure 9a, d shows the seismic tomography images of Zhao et al. (2009) and Liu and Zhao (2018), respectively. In these figures, a vast distribution of the low Vp region is recognized in the trenchward forearc of Block B, and both sides of this low Vp region fit well with Fault G and Faults C to F. Conversely, high Vp regions are widely distributed throughout the forearc regions of Blocks A, C, and D. In particular, the seismic tomography image in Fig. 9d was obtained from a new detailed P-wave tomography, which has a much better depth resolution ranging from 5 to 10 km in depth (Liu and Zhao 2018). Furthermore, it shows the low Vp region extending southeastward to near the Japan Trench.

Figure 9b, c shows the seismic tomography images of Zhao et al. (2011) and Huang and Zhao (2013), respectively. These figures exhibit two large low Vp areas in the trenchward forearc of Blocks B and E. It is important to

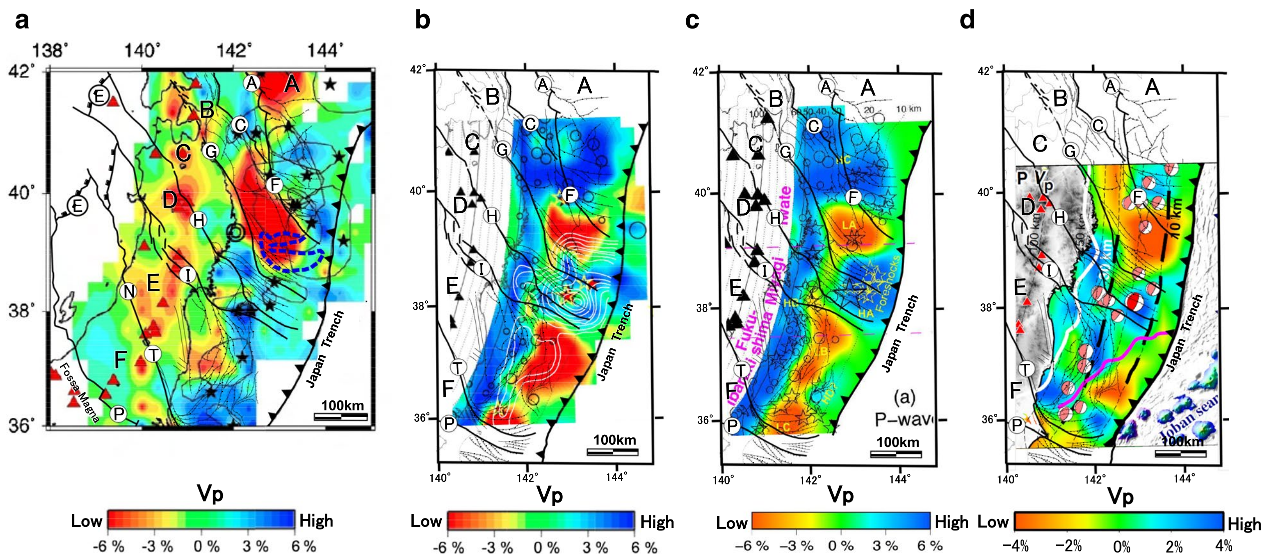

Fig. 9 P-wave tomography images along the upper boundary of the subducting Pacific slab in the forearc region. **a** Zhao et al. (2009), **b** Zhao et al. (2011), **c** Huang and Zhao (2013), and **d** Liu and Zhao (2018). In **a**, the tomography image along the NE Japan land region represents the central part of the mantle wedge (Zhao et al. 2009), while the blue dashed line indicates a low Vp region at the top of the plate boundary of Mochizuki et al. (2005)

note that the northern margin of the large low Vp area in Block E fits in well with Fault I. The low Vp region on the slab boundary is considered to be caused by the presence of fluid-related anomalies associated with slab dehydration or due to the entrapment of the fluid-filled unconsolidated sediments within the plate interface (e.g., Zhao et al. 2011; Liu and Zhao 2018).

The seismic reflection–refraction survey prior to the 2011 Tohoku-Oki earthquake (Mochizuki et al. 2005) also revealed the presence of a thin layer (c. 200 m) with low P-wave velocity (3 to 4 km/s) at the plate interface of the trenchward forearc side of Block B (blue dashed line in Fig. 9a), and that this low Vp area extends to near the Japan Trench. This result agrees with that of Liu and Zhao (2018), as shown in Fig. 9d. Therefore, we assumed that the low Vp area recognized in Block B extends up to near the Japan Trench.

According to geological information on the NE Japan forearc, the forearc side of Block B belongs to the North Kitakami Belt, which is composed of Paleozoic oceanic succession subducted to the South Kitakami Belt, which is composed of Paleozoic paleo-continental plutonic basements (Yoshida et al. 2017). Some geophysical and geological studies (Mishra et al. 2003; Seno 2005; Zhao et al. 2009; Yoshida et al. 2017) suggest that the forearc side of Block B has a thick serpentinized upper mantle and lower crust. In contrast, the upper plate on the southwest side of Fault G is characterized by paleo-continental plutonic basements. Plutonic basements with a thick lower crust of gabbroic composition (Nishimoto et al. 2008) in the overriding plate may result in average to high Vp anomalies (Liu and Zhao 2018). Therefore, the heterogeneous Vp image shown in Fig. 9 can be mainly controlled by the geological structure of the overriding plate along the NE Japan forearc (Yoshida et al. 2017).

Discussion

Rupture propagation process of the 2011 Tohoku-Oki earthquake

The moment magnitude of the plate boundary earthquake is directly related to the size of the seismic rupture zone. Large plate boundary earthquakes are usually restricted by breaks, such as fracture zones, large transcurrent faults, and related branched faults, with the seismogenic zone at the plate boundary segmented by these breaks (Sagiya and Thatcher 1999; Kimura and Kinoshita 2009). In this study, we have revealed the close relationship between the geological structure and the rupture process of the 2011 Tohoku-Oki earthquake. Most of the models show that the coseismic slip region of the 2011 Tohoku-Oki earthquake is situated in the trenchward forearc in Blocks B, C, and D, and the northern and southern margins of this large coseismic slip region fit well with Faults F and I, respectively. In other words, the main rupture region of the mainshock of the 2011 Tohoku-Oki earthquake corresponds to the trenchward forearc parts of Blocks B, C, and D. Therefore, it is inferred that these three blocks have been compressed toward the NE Japan Arc through long-term subduction of the Pacific Plate. When the accumulated stress exceeded the threshold value, the trenchward region of these three blocks started to slip rapidly toward the Japan Trench, which led to the occurrence of the 2011 Tohoku-Oki earthquake.

As discussed in "Geological control of seismic tomography images" section, the regions with no repeating earthquakes might be locked or slipped completely aseismically. The trenchward forearc parts of Blocks B, C, and D are characterized by a wide distribution of areas without repeating earthquakes prior to the mainshock (see Fig. 8). Furthermore, this area without repeating earthquakes almost corresponds to the coseismic slip region of the 2011 Tohoku-Oki earthquake (see Fig. 7). Therefore, the trenchward forearc parts of Blocks B, C, and D can be inferred to be an almost fully locked region prior to the 2011 Tohoku-Oki earthquake (Uchida and Matsuzawa 2011, 2013). According to Uchida and Matsuzawa (2011) as well as Hasegawa and Yoshida (2015), the coseismic slip area of the 2011 Tohoku-Oki earthquake was estimated to have been locked over a period of several hundred years.

The slip distribution models shown in Fig. 7 indicate that the coseismic slip was reduced toward Faults F and I. The cause for such a reduction is thought to be that the accumulated stress caused by long-term landward subduction of the Pacific Plate had already been released near and along Faults I and F by M7-class earthquakes that occurred along them prior to the 2011 Tohoku-Oki earthquake. This interpretation also explains why the outline of the coseismic slip area fitted well with Faults I and F. Furthermore, such interpretation may explain the reason why the coseismic slip area of the 2011 Tohoku-Oki earthquake was divided into two large patches, i.e., slow-slip events and foreshocks near and along Fault G (see Fig. 6) had already released the stress accumulated by long-term subduction of the Pacific Plate, and consequently, the coseismic slip of the mainshock may have been reduced around Fault G. According to the rupture propagation models listed in Additional file 1: Fig. S7, the coseismic slip in Block B may have occurred after those in Blocks C to D.

Importance of large transcurrent faults on earthquake distribution

We recognized six large transcurrent faults in the NE Japan Arc, as shown in Figs. 1 and 2. Among them, Faults C to F and Fault I show that the coseismic slip areas of M7-class earthquakes are arranged linearly along these tectonic lines (Fig. 5). As described in "Dimensions of the large transcurrent faults in the NE Japan Arc" section, these large transcurrent faults have a maximum cross-strike width of 10 to 20 km and a total length of 700 to 1000 km. In general, such a large strike-slip fault can reach the upper surface of the subducting Pacific Plate. This suggests that the large transcurrent faults may have exerted some kind of influence on the occurrence of the M7-class interplate earthquake.

On the forearc side of NE Japan, Faults N to T limited the southern margin of aftershock distribution for 24 h after the mainshock (Fig. 3a) and the southern margin of the dense earthquake distribution for 1 year after the 2011 Tohoku-Oki earthquake (Fig. 3b). Furthermore, the southern margin of the dense distribution of earthquakes for the 80-year period preceding the 2011 Tohoku-Oki earthquake was also limited by Faults N to T (Additional file 1: Fig. S6). According to the CMT distribution, most of the earthquakes that were limited clearly by Fault T are considered to have occurred in the upper plate (Fig. 4d). On the backarc side of NE Japan, earthquake hypocenters shallower than 30 km are densely arranged along Fault E, and the southern end of this concentrated earthquake zone is limited clearly by Faults N to T (Additional file 1: Fig. S6). Fault E forms the boundary between the arc crust of the NE Japan Arc and the Japan Basin, which is composed of oceanic crust or extended continental crust (Ruslan and Valtov 2011). These pieces of evidence indicate that Faults N to T serve an important purpose as geological boundary that controls the southern limit of the earthquake distribution in both the forearc and backarc of NE Japan.

Another feature of Faults N to T on the forearc side is that they form a sharp boundary of the dense earthquake distribution extending along the northeast side of the tectonic line (Figs. 3b). As described above, most of the earthquakes limited clearly by Faults N to T are considered to have occurred in the upper plate (Fig. 4d). The fault patterns of Faults N to T in this region are characterized by NW–SE to E–W trending branched fault arrays that develop only on the northeastern side of the tectonic line, and this is consistent with the leading extensional imbricate fan model of Woodcock and Fisher (1986). This means that the upper plate earthquakes are distributed within the branched fault array of the imbricate fan. Nakajima and Uchida (2018) suggested that supraslab earthquakes occurred because of the upward migration of overpressurized pore-fluids from the plate boundary through pre-existing highly fractured pathways in the overlying plate. Such a highly fractured pathway can be provided by the branched fault array of the imbricate fan.

Conclusions

Using offshore 2D/3D seismic survey data and exploratory well data obtained from all over the NE Japan Arc, we created a revised map of major geological structures in the forearc, demonstrating that the basic assemblage consists of segmented structural blocks defined by a series of NW–SE large transcurrent (strike-slip) faults. This structural assemblage does much in explaining the distribution and character of the seismic activity in the NE Japan forearc relating to the 2011 M9.0 Tohoku-Oki megathrust earthquake. The principal results obtained from this study are as follows:

1. The structural configuration of the NE Japan Arc is closely related to the distribution of foreshocks, mainshock, aftershocks and coseismic slip models of the 2011 M9.0 Tohoku-Oki megathrust earthquake, coseismic slip of M-7 class earthquakes, quasi-static slip rate, back slip rate, and seismic tomography images.
2. Recent coseismic slip models of the 2011 Tohoku-Oki earthquake obtained from seismic, geodetic, and tsunami data reveal that (i) the large coseismic slip regions are distributed in the trenchward forearc of Blocks B, C, and D, and (ii) the outline of the coseismic slip region nearly fits with the Offshore Hidaka tectonic line (Fault F) and the Honjo-Sendai tectonic line (Fault I). These observations suggest that most of the trenchward forearc of Blocks B, C, and D slipped rapidly toward the Japan Trench when the 2011 Tohoku-Oki earthquake occurred.
3. Foreshock activity and associated slow-slip events were initiated near and along the Offshore Sanriku tectonic line (Fault G), breaking the strongly coupled plate interface of Block C southwestward toward the hypocenter of the mainshock of the 2011 Tohoku-Oki earthquake, leading finally to the M9.0 megathrust rupture.
4. Some of the seismic tomography images and seismic reflection–refraction surveys show that the Offshore Sanriku tectonic line (Fault G) and the Offshore Hidaka tectonic line (Faults C to F) define the boundary that separates the low Vp area in trenchward Block B from the high Vp area in adjacent blocks (forearcs of Blocks A, C, and D).
5. The Miomote-Tanakura tectonic lines (Faults N to T) serve an important purpose as geological boundaries that control the southern limit of the earthquake distribution in both the forearc and backarc of NE Japan.

Supplementary information

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Additional file 1. The details of the stratigraphy and geological structure are described in additional file 1 using regional stratigraphic chart (**Figure S1**), time contour map of the surrounding oceans of the NE Japan arc (**Figure S2**), typical seismic sections (**Figure S3A and S3B**), and schematic cross section of the NE Japan arc (**Figure S4**). The fault movement history of large NW-SE trending transcurrent faults is summarized in **Figure S5**. The details of lateral displacement, total length, maximum cross-strike width, and tectonic history of each transcurrent fault are described in Section 3 in the additional file 1. **Figure S6** shows that the southern margin of the dense distribution of earthquakes for the 80 years period proceding the 2011 Tohoku-Oki earthquake was limited by Faults N to T. The coseismic slip in Block B may have occurred after those in Blocks C to D at the 2011 Tohoku-Oki earthquake (**Figure S7**). And, Figure S8 shows the relationship between the large transcurrent faults and the back slip rate distribution.

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Authors' contributions

KB compiled a large fault distribution. Manuscript preparation was carried out by KB and TY. Both authors read and approved the final manuscript.

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The datasets analyzed in the current study are attached as additional file.

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Competing interests

The authors declare that they have no competing interests.

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