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Review article

The 2011 Tohoku earthquake (Mw 9.0) sequence and subduction dynamics in Western Pacific and East Asia

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ABSTRACT

We review recent findings on the causal mechanism of the great 2011 Tohoku earthquake (Mw 9.0) sequence and related issues on seismic structure and subduction dynamics in Western Pacific and East Asia. High-resolution tomography revealed significant lateral heterogeneities in the interplate megathrust zone beneath the Tohoku, South Kuril and Southwest Japan forearc regions. Large megathrust earthquakes since 1900 generally occurred in or around high-velocity (high-V) patches in the megathrust zone, which may reflect asperities resulting from subducted seamounts, oceanic ridges and other topographic highs on the Pacific seafloor. In contrast, low-velocity (low-V) patches in the megathrust zone may contain more sediments and fluids, where the subducting oceanic plate and the overlying continental plate are less coupled or even decoupled. The nucleation of large crustal earthquakes in the Japan Islands, including the 11 April 2011 Iwaki earthquake (M 7.0) in SE Tohoku, is affected by arc magma and fluids resulting from slab dehydration. The Philippine Sea plate has subducted aseismically down to 430–460 km depth under East China Sea, Tsushima Strait and Japan Sea. A window in the aseismic Philippine Sea slab is detected, which may be caused by splitting of weak parts of the slab at the subducted ridges (e.g., Kyushu-Paula ridge) and hot upwelling in the mantle wedge above the Pacific slab. The intraplate volcanism in Northeast Asia is caused by hot and wet upwelling flows in the big mantle wedge above the stagnant Pacific slab in the mantle transition zone. Frequent generation of large deep earthquakes (>500 km depth) in the Pacific slab may supply additional fluids preserved in the slab to the mantle wedge under the Changbai volcano, making Changbai the largest and most active intraplate volcano in Northeast Asia. Fluids may be involved in nucleation and rupture processes of all types of earthquakes.

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1. Introduction

The great 2011 Tohoku-oki earthquake (Mw 9.0) sequence wrote a new chapter of active seismotectonics and subduction dynamics in the Western Pacific and East Asian region. This earthquake sequence, taking place in the Northeast Japan (Tohoku) forearc area (Figs. 1 and 2), started with a foreshock (M 7.3) at local time 11:45 on 9 March 2011 (Shao et al., 2011; Huang and Zhao, 2013a). Its main shock (Mw 9.0) occurred at 14:46 on 11 March, which was followed by two big aftershocks at 15:08 off Iwate (M 7.4) and at 15:15 off Ibaraki (M 7.7) on the same day (Fig. 2). All of the four big events had megathrust mechanisms, which were caused by sudden ruptures of the boundary between the subducting Pacific plate and the overlying Okhotsk plate beneath the Tohoku forearc. About 40 min after the main shock, a big outer-rise event (M 7.5) took place at 15:25 with a normal-faulting mechanism (Fig. 2). On April 7, a big intraslab earthquake (M 7.1) occurred within the subducting Pacific plate with a focal depth of ~70 km and a normal-faulting mechanism. On April 11, one month after the main shock, the Iwaki earthquake (M 7.0) took place at ~8 km depth in the upper crust of the Okhotsk plate beneath SE Tohoku, which was caused by rupture of the Idosawa normal fault. Four months after the main shock, on 10 July another megathrust aftershock (M 7.3) occurred in the middle between the Japan Trench and the main shock hypocenter (Fig. 2). To date, more than 100 aftershocks with M ⩾ 6.0 and tens of thousands of smaller events have occurred in the Tohoku forearc region (e.g., Huang and Zhao, 2013a). The overall level of seismicity in the Japan Islands has increased significantly soon after the Mw 9.0 main shock (e.g., Okada et al., 2011).

The Japanese Islands are part of the Western Pacific trench – arc–back-arc system, forming a typical subduction zone (Fig. 1). At least four lithospheric plates exist in and around this region and they are strongly interacting with each other. The Pacific plate is subducting beneath Hokkaido and eastern Honshu at the Kuril and Japan trenches at a rate of 7–10 cm/year (Bird, 2003). The Philippine Sea plate is descending beneath Central and SW Japan at the Sagami and Nankai troughs at a rate of 4–5 cm/year. Hokkaido and Tohoku belong to the Okhotsk plate, whereas SW Japan belongs to the Eurasian (or Amur) plate (e.g., Seno et al., 1996; Bird, 2003). Because of the strong interactions of the four lithospheric plates, seismicity is very active in this region (Fig. 1b). Approximately 10,000 earthquakes (M ⩾ ~1.5) take place every month in and around Japan, which have been recorded by the dense and high-sensitivity seismic networks on the Japan Islands (Fig. 1a). Because of the high level of seismicity and availability of the dense and high-sensitivity seismic networks (Fig. 1a) operated by the Japan Meteorological Agency (JMA), the Japanese national universities, and the National Research Institute for Earth Science and Disaster Prevention (Okada et al., 2004), a great amount of high-quality seismic data have been accumulated for a long time and they have been used to study seismotectonics and the three-dimensional (3-D) seismic structure of the crust and upper mantle of the Japan subduction zone. These studies have been made continuously in

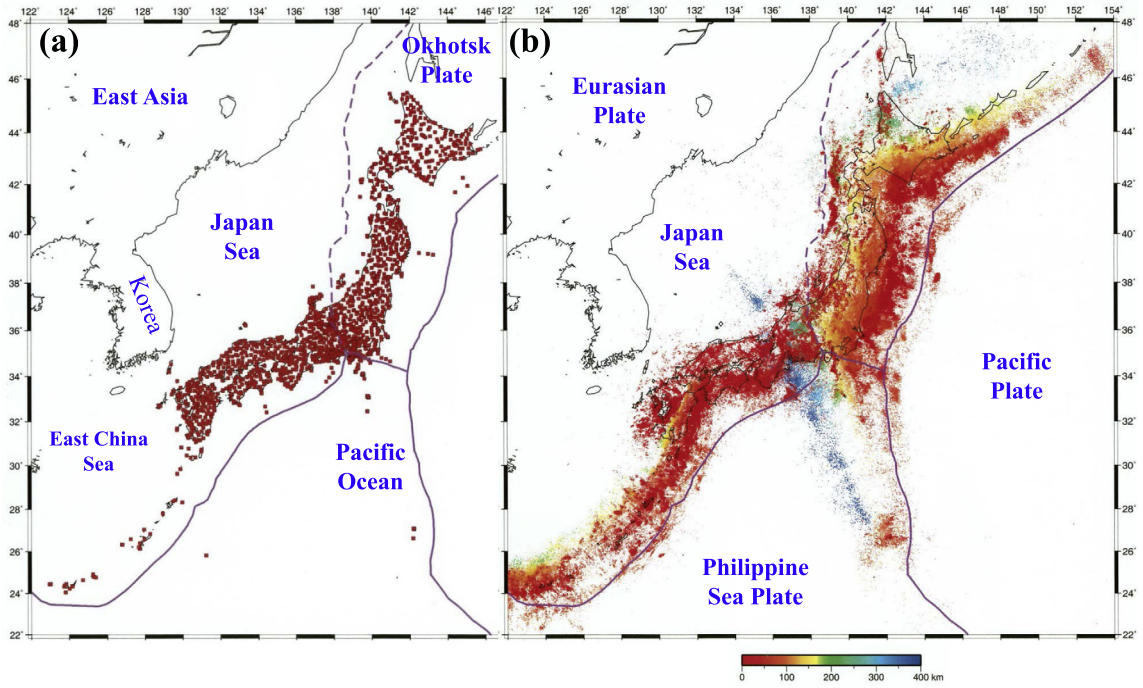

Fig. 1. (a) Distribution of seismic stations on the Japan Islands. (b) Distribution of earthquakes in and around the Japan Islands during June 2006 to September 2010. The color shows the focal depth; its scale is shown at the bottom. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)