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MECHANISM OF THE 2011 TOHOKU-OKI EARTHQUAKE: INSIGHT FROM SEISMIC TOMOGRAPHY

Dapeng ZHAO[1]

[1] Professor, Department of Geophysics, Tohoku University,
Sendai, Japan, zhao@aob.gp.tohoku.ac.jp

ABSTRACT: We relocated the great 2011 Tohoku-oki earthquake (Mw 9.0) and its foreshocks and aftershocks using a three-dimensional seismic velocity model and high-quality P and S wave arrival times recorded by the dense seismic network on the Japan Islands. Then we compared the distribution of the relocated hypocenters with a high-resolution tomographic image of the Northeast Japan forearc. The comparison indicates that the rupture nucleation of the largest events in the Tohoku-oki sequence, including the mainshock, was controlled by structural heterogeneities in the interplate megathrust zone.

Key Words: Great Tohoku-oki earthquake, seismic tomography, earthquake mechanism, structural heterogeneity, interplate megathrust zone

INTRODUCTION

Four lithospheric plates exist in and around the Japan Islands. The Pacific plate is moving toward the northwest and is subducting beneath Hokkaido and northern Honshu from the Kuril and Japan trenches, whereas the Philippine Sea (PHS) plate is moving northwestward and is descending beneath southwest Japan from the Nankai trough. Hokkaido and northern Honshu belong to the Okhotsk plate, whereas southwest Japan belongs to the Eurasian (or Amur) plate [Bird, 2003; DeMets et al., 2010; Zhao et al., 2011a]. The strong interactions among the four plates cause intense seismic and volcanic activities in and around the Japan Islands. A striking recent example of the intense seismicity in the region is the great 2011 Tohoku-oki earthquake (Mw 9.0) that occurred at 14:46 local time (05:46 UTC) on 11 March 2011 in the forearc region of the Northeast (NE) Japan subduction zone. This giant earthquake was caused by subduction of the Pacific plate beneath the Okhotsk plate. A large foreshock of this earthquake took place at 11:45 local time on 9 March 2011, with a magnitude (M_{JMA}) of 7.3, as determined by the Japan Meteorological Agency [www.jma.go.jp; Shao et al., 2011]. Following the Tohoku-oki mainshock and on the same day, three aftershocks occurred with $M_{JMA} \geq 7.4$, and many smaller aftershocks were recorded and located by the dense seismic network installed on the Japan Islands.

Soon after the occurrence of these earthquakes, JMA, United States Geological Survey (USGS) [earthquake.usgs.gov] and several other research agencies published hypocentral parameters for these earthquakes. The locations were similar, but significant differences were apparent. For example, with respect to the Tohoku-oki mainshock, the JMA location is: (38.103N, 142.861E, 24 km), whereas the USGS location is: (38.322N, 142.369E, 32.0 km). The difference between them is over 50 km and was caused by several factors, such as the differences in the arrival-time data sets and the velocity models used for the earthquake location. The JMA hypocenters are determined using the seismic stations on the Japan Islands and the JMA one-dimensional (1-D) velocity model [Ueno et al., 2002], whereas the USGS hypocenters are determined with the globally distributed seismic stations and a global 1-D velocity model [Kennett and Engdahl, 1991].

Precise hypocenters are of fundamental importance in many disciplines of seismology, being necessary to estimate the rupture process on the fault plane, strong ground motions and crustal and upper-mantle structure in the source area, and so on. The hypocentral distribution of earthquakes in the NE Japan forearc under the Pacific Ocean has been investigated by deploying ocean-bottom-seismometer (OBS) stations [Hino et al., 2000; Miura et al., 2003], and using sP depth phases detected on the seismograms from the dense seismic network on the Japan Islands [e.g., Umino et al., 1995; Mishra et al., 2003; Wang and Zhao, 2005; Gamage et al., 2009; Zhao et al., 2009]. In this work we used a three-dimensional (3-D) seismic velocity model [Huang et al., 2011] to relocate the great Tohoku-oki earthquake and its foreshocks and aftershocks. Then we compare the distribution of the relocated hypocenters with the tomographic image in the NE Japan forearc, which shed light on the generating mechanism of the 2011 Tohoku-oki earthquake sequence.

DATA AND METHOD

Several permanent short-period seismic networks have been deployed on the Japan Islands, including the JMA Seismic Network, the Japan University Seismic Network, and the High-Sensitivity Seismic Network [Okada et al., 2004]. These seismic networks have been combined in order to constitute a nationwide, high-quality network, known as the Kiban network that includes over 1,800 seismic stations densely and uniformly covering the Japan Islands [Okada et al., 2004; Hasegawa et al., 2009]. Since October 1997 waveform data recorded by the Kiban network have been transmitted to and processed by JMA to monitor the seismic activity in and around Japan [Okada et al., 2004]. High-quality P and S wave arrival times are measured from the three-component seismograms with an automatic processing system and monitored by the network staff daily. The accuracy of the arrival times is estimated to be 0.05-0.10 s for P-waves and 0.1 s for S-waves. The arrival-time data are used with the JMA 1-D velocity model [Ueno et al., 2002] to determine the hypocentral parameters for each earthquake. The resulting data base containing the P and S wave arrival times and the hypocentral parameters is known as the JMA Unified Catalogue [Okada et al., 2004].

We used the P and S wave arrival-time data recorded by the Kiban network stations in NE Japan to relocate the Tohoku-oki earthquake sequence. Data recorded by the six OBS stations located in the Pacific Ocean were also used, which provided valuable constraints on the locations of the suboceanic events, particularly for those events that occurred close to the OBS stations. We relocated 5,949 events of the 2011 Tohoku-oki earthquake sequence from 9 March 2011, when the M_{JMA} 7.3 foreshock occurred, to 27 March 2011 using the high-quality P and S wave arrival-time data from the JMA Unified Catalogue.

In this work the hypocentral parameters (i.e., the origin time, latitude, longitude, and focal depth) were determined for each earthquake by inverting the P and S wave arrival-time data iteratively using a least-squares method [Zhao et al., 1992, 2009]. A 3-D ray-tracing technique [Zhao et al., 1992] was used to calculate accurate travel times and ray paths in the 3-D velocity model [Huang et al., 2011]. The changes in the hypocenters before and after relocation are smaller (< 5 km) for the events beneath land, whereas the changes become larger for events under the Pacific Ocean, being 5-30 km, in particular, for events near the Japan Trench. After relocation most suboceanic events move toward the east, as compared with their JMA locations [Zhao et al., 2011b]. The relocated hypocenters of the 5 biggest events ($M_{JMA} \geq 7.3$) are all located at or very close to the upper boundary of the subducting Pacific slab, which is consistent with their thrust focal mechanism [JMA, www.jma.go.jp; Lay et al., 2011; Koper et al., 2011]. For the 5 biggest events, we examined their seismograms recorded by the

High-Sensitivity Seismic Network and searched for sP depth phases, but did not succeed because the seismograms are very complicated, possibly due to the complex rupture processes.

RESULTS

The 3-D velocity model [Huang et al., 2011] was determined by inverting 310,749 P and 150,563 S wave arrival times from 4,655 local earthquakes that occurred in the crust and the subducting Pacific slab from the Japan Trench to the Japan Sea. Huang et al. [2011] relocated the suboceanic events precisely using P and S arrival times as well as sP depth-phase data that were measured from the seismograms recorded by the seismic stations on the NE Japan land area, similar to the previous studies [Umino et al., 1995; Mishra et al., 2003; Wang and Zhao, 2005; Gamage et al., 2009; Zhao et al., 2009]. The 3-D velocity structure under the Pacific Ocean and the Japan Sea was determined reliably with a resolution of 30-40 km [Huang et al., 2011]. As compared with the previous tomographic studies [e.g., Zhao et al., 2009], Huang et al. [2011] used many more suboceanic events that were relocated with sP depth phase and the events are distributed more densely and uniformly in the forearc, so they could determine the 3-D velocity structure under the Pacific Ocean more reliably.

Significant velocity variations are noticeable in the megathrust zone under the NE Japan forearc. Three low-velocity (low-V) anomalies exist off Sanriku, off Fukushima and off Ibaraki [Zhao et al., 2011b]. There is a correlation between the velocity variation and the distribution of large earthquakes ($M_{JMA} \geq 6.0$) that occurred from 1900 to 2008, most of which are considered to be interplate thrust-type earthquakes [Umino et al., 1990; Usami, 2003; Yamanaka and Kikuchi, 2004; Zhao et al., 2009, 2011b]. These large earthquakes were located using the seismic network on the Japan Islands and their epicentral locations are accurate to 10 km [Umino et al., 1990; Usami, 2003; Yamanaka and Kikuchi, 2004]. Most of the large earthquakes are located in the high-velocity (high-V) patches or at the boundary between the low-V and high-V zones, with only a few situated in the low-V patches [Zhao et al., 2011b].

The 2011 Tohoku-oki mainshock and its foreshock (M_{JMA} 7.3) on 9 March 2011 are located in a significant high-V zone off Miyagi. The northern aftershock (M_{JMA} 7.4) that occurred at 15:08, 11 March 2011 is located at the boundary between the off-Sanriku low-V zone and a high-V zone in the north. The southern aftershock (M_{JMA} 7.7) that took place at 15:15, 11 March 2011 is located at the northern edge of the off-Ibaraki low-V zone. Such a pattern of the hypocenter distribution for the 2011 Tohoku-oki earthquakes is quite consistent with that of the large earthquakes from 1900 to 2008. The aftershock (M_{JMA} 7.5) that took place at 15:25, 11 March 2011 is located east of the Japan Trench and is considered to be an outer-rise earthquake [JMA, www.jma.go.jp; Lay et al., 2011; Kanamori, 1971] beyond the range of the 3-D velocity model.

The 3-D S-wave velocity model [Huang et al., 2011] has a lower resolution in the offshore region, but it shows the same pattern as the P-wave velocity model. In general, the low-V zones exhibit higher Poisson's ratio, whereas the high-V zones show lower Poisson's ratio [Zhao et al., 2009, 2011b; Huang et al., 2011].

DISCUSSION AND CONCLUSIONS

We suggest that the low-V patches in the megathrust zone may contain subducted sediments and fluids associated with slab dehydration [Mishra et al., 2003; Hyndman and Peacock, 2003; van Keken, 2003; Huang et al., 2011; Zhao et al., 2011b]. Thus the subducting Pacific plate and the overriding continental plate may become weakly coupled or even decoupled in the low-V areas. Large-amplitude reflected waves from the slab boundary were detected in a low-seismicity area under the forearc region off Sanriku [Fujie et al., 2002], as were some slow and ultra-slow thrust earthquakes [Heki et al., 1997; Kawasaki et al., 2001]. Both the seismic reflectors and slow thrust earthquakes are thought to be caused by fluids at the slab boundary [Fujie et al., 2002; Kawasaki et al., 2001], and they are all located in the off-Sanriku low-V zone. Recent studies have shown that the nucleation of large crustal earthquakes in Japan was also affected by structural heterogeneities including crustal fluids [e.g., Xia et al., 2008; Cheng et al., 2011; Padhy et al., 2011; Tong et al., 2011].

In contrast, the high-V patches in the megathrust zone may result from subducted oceanic ridges, seamounts and other topographic highs on the seafloor of the Pacific plate that become asperities where the subducting Pacific plate and the overriding continental plate are strongly coupled [Kanamori, 1986; Yamanaka and Kikuchi, 2004]. Thus tectonic stress tends to accumulate in these high-V areas for a relatively long time during subduction, leading to the nucleation of large and great earthquakes in those areas. The off-Miyagi high-V zone where the Tohoku-oki mainshock and its largest foreshock occurred corresponds to the area with large coseismic slip (> 25 m) during the Tohoku-oki mainshock [Lay et al., 2011; Iinuma et al., 2011]. This indicates that the off-Miyagi high-V zone is a large asperity (or a cluster of asperities) in the megathrust zone that ruptured during the 2011 Tohoku-oki mainshock.

The distribution of structural heterogeneities in the megathrust zone and its correlation with the distribution of large thrust earthquakes suggest varying degrees of interplate seismic coupling from north to south in the NE Japan forearc, possibly controlling the nucleation of the large interplate earthquakes. The great 2011 Tohoku-oki earthquake sequence may be related to such a process. Differences in interplate seismic coupling could result from variations in the frictional behavior of materials [Pacheco et al., 1993; Heki et al., 1997; Kato and Hirasawa, 1997; Miura et al., 2003]. The velocity variations in the tomographic image of the megathrust zone may be a manifestation of such variations in the frictional behavior [Zhao et al., 2011b].

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