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Source parameters of the 2011 Yellow Sea earthquake (M_L 5.3): Different features from earthquakes on the Korean Peninsula

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A moderate earthquake of magnitude M_L 5.3 occurred in the Yellow Sea on January 12, 2011. We estimated the source parameters and found that the quake was a shallow strike-slip fault event with a moment magnitude of 4.6. The stress drop of this event, 1.2–2.0 MPa, is lower than that of moderate earthquakes inland and at the eastern offshore of the Korean Peninsula, and also that of the typical value for shallow intraplate earthquakes. A stronger event (M 6) in the southern Yellow Sea in 1984 was previously reported to have a low stress drop. Therefore the low stress drop is probably characteristic of earthquakes in the Yellow Sea region. We found that aftershocks of the 2011 Yellow Sea event, with magnitudes greater than 2, occurred for about 5 days, while similar-sized aftershocks of some inland earthquakes of the Korean Peninsula continued for several hours only. The lower stress drop and greater active aftershocks in the Yellow Sea region might re ect a different tectonic setting from that on the Korean Peninsula.

Key words: Moderate earthquake, source parameter, Yellow Sea, Korean Peninsula.

1. Introduction

A moderate earthquake of magnitude M_L 5.3 occurred in the Yellow Sea on January 12, 2011, according to the Korea Meteorological Administration (KMA) catalog. The epicenter was located over 200 km away from both the Korean Peninsula and China (Fig. 1); however, this event was large enough to be felt in the southwestern region of South Korea as well as in Shanghai, China. Figure 1 shows the epicenters of shallow earthquakes (shallower than 70 km) with magnitudes greater than 4 in the last 30 years (1981–2010) according the International Seismological Centre (ISC) catalog. Many earthquakes are located along plate boundaries around Japan and Taiwan, and in the western part of China, with a cluster related to the 2008 Wenchuan earthquake. Seismic activity around the Korean Peninsula is very low compared to that in the surrounding regions, such as Japan and China. Several events occurred near the eastern coast of the peninsula, and some more events occurred in the Yellow Sea. The region where the 2011 Yellow Sea event occurred does not seem to be very seismically active. Even though there are several events in the Yellow Sea, there does not seem to be a considerable difference in seismic activity on the Korean Peninsula and in the Yellow Sea.

We have assessed seismic activity in the last 30 years around the Korean Peninsula and the Yellow Sea; this activity is illustrated in Fig. 2. The circles indicate shallow earthquakes reported by the ISC; the sizes of the circles re ect the earthquake magnitude. Figure 2 also shows seismicity (denoted by diamonds) determined by the KMA during the same time period. The size of the diamonds depends on the magnitude. Earthquakes recorded as having a magnitude greater than 5 in both catalogs, except those in Japan, are indicated by bold symbols along with the year and magnitude. Earthquakes mentioned in this paper are shown with the date (yyyy/mm/dd) and magnitude, and are listed in Table 1. None of the events on land in South Korea is greater than M 5 (where M refers to Magnitude) and some events in the M 5 class occurred offshore. Many other small events within the seismic network were also observed by the KMA. If we assume that the rate of seismicity is similar between small events ($M < 5$) and larger events ($M > 5$) in the two regions, inland of the Korean Peninsula and the Yellow Sea, we may expect more small earthquakes in the Yellow Sea. These earthquakes might be undetected because of their small size and their large distance from seismic networks.

The Korean Peninsula and northeastern China are thought to be located on the Amur Plate (Heki, 1999; Bird, 2003; Petit and Fournier, 2005). The boundaries of the Amur Plate suggested by Bird (2003) and Petit and Fournier (2005) are shown in Fig. 1. As can be seen in the figure, these suggested boundaries are mostly similar but are vastly different around the Yellow Sea and Mongolia. The 2011 Yellow Sea event occurred along the boundary of the Amur Plate suggested by Bird (2003) but was slightly distant from that suggested by Petit and Fournier (2005). Although we cannot judge which proposed boundary is correct, tectonic conditions around the 2011 Yellow Sea event might be different from those on the Korean Peninsula. If so, the earthquake generation mechanism and the seismic features between the two regions, near the 2011 event and on the Korean Peninsula, may be different.

The 2007 Odaesan earthquake, which is one of the largest

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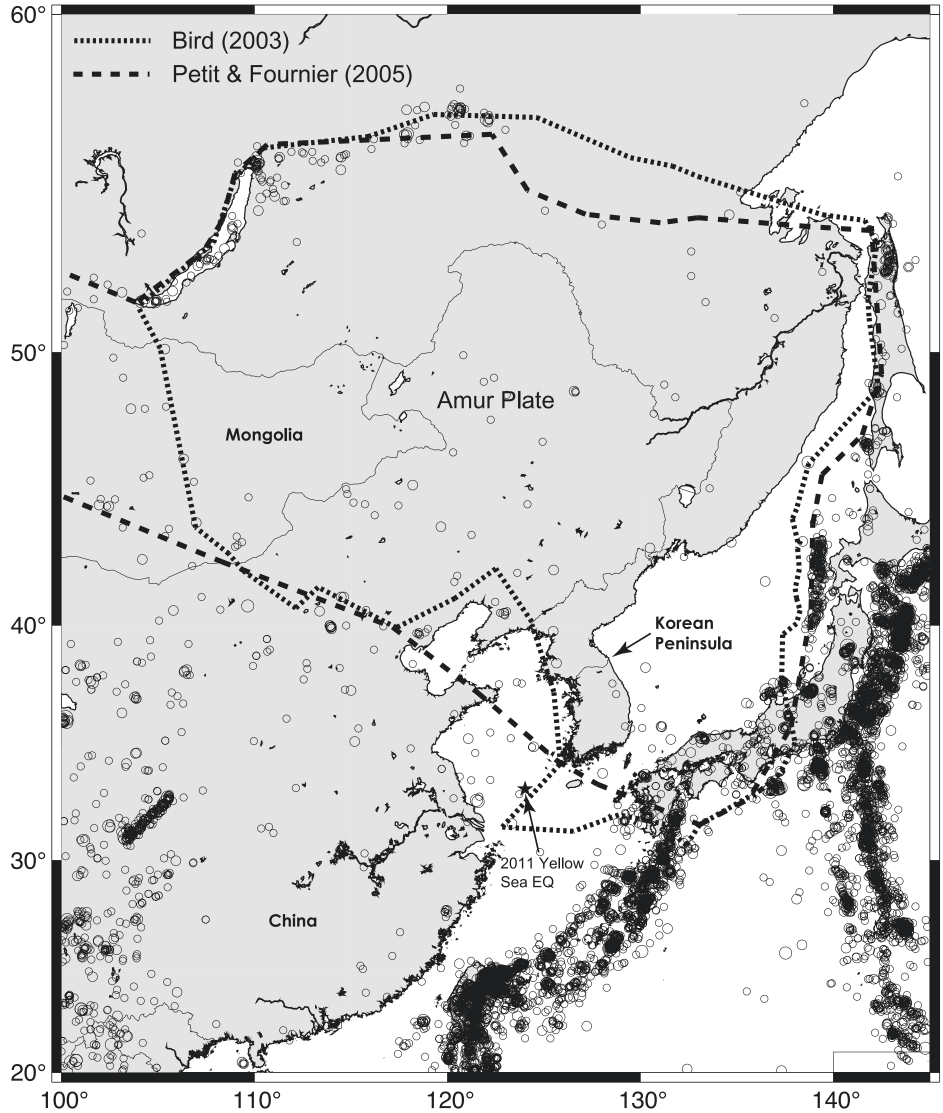

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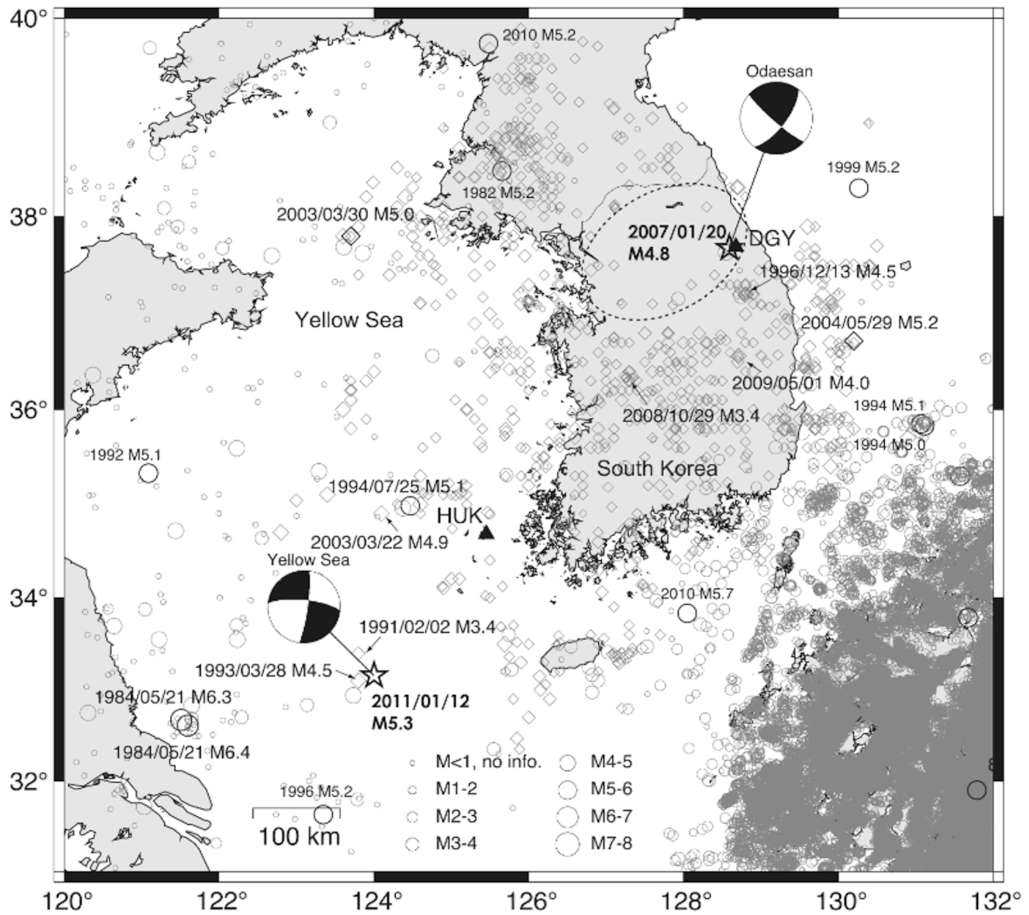
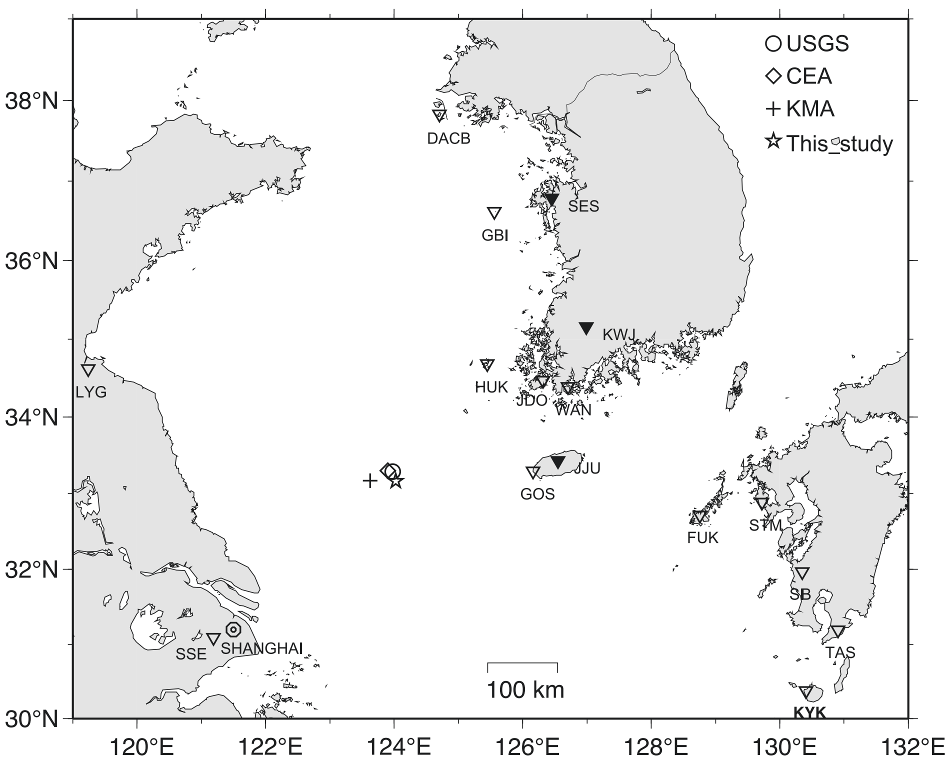
2. Source Parameters


Yellow Sea
South Korea
Odaesan
2007/01/20
M4.8
DGY
HUK
2011/01/12
M5.3
2010 M5.2
1982 M5.2
1999 M5.2
2003/03/30 M5.0
1996/12/13 M4.5
2004/05/29 M5.2
2009/05/01 M4.0
2008/10/29 M3.4
1994 M5.1
1994 M5.0
1992 M5.1
1994/07/25 M5.1
2003/03/22 M4.9
2010 M5.7
1991/02/02 M3.4
1993/03/28 M4.5
1984/05/21 M6.3
1984/05/21 M6.4
1996 M5.2
100 km
M<1, no info.
M1-2
M2-3
M3-4
M4-5
M5-6
M6-7
M7-8
40°
38°
36°
34°
32°
120°
122°
124°
126°
128°
130°
132°

	M	


USGS
CEA
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FUK
STM
SB
TAS
KYK
SSE
SHANGHAI
100 km
38°N
36°N
34°N
32°N
30°N
120°E
122°E
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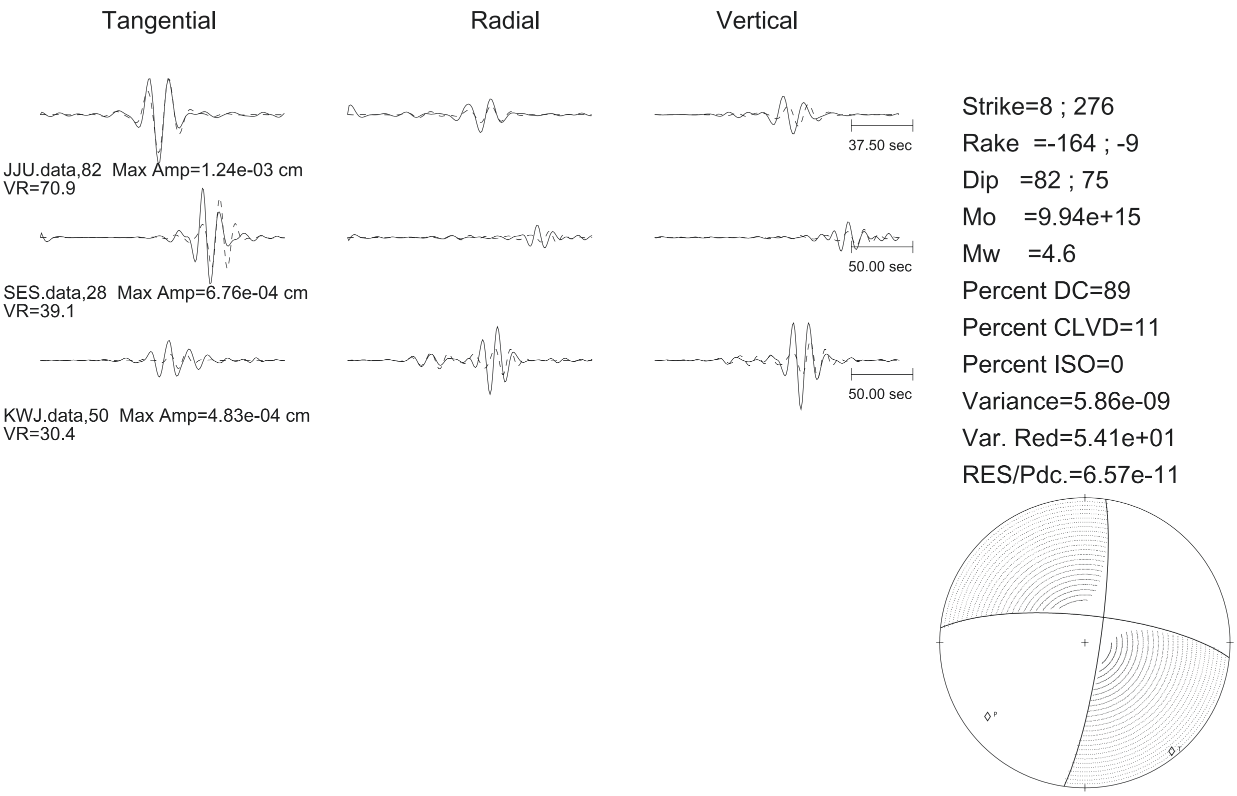

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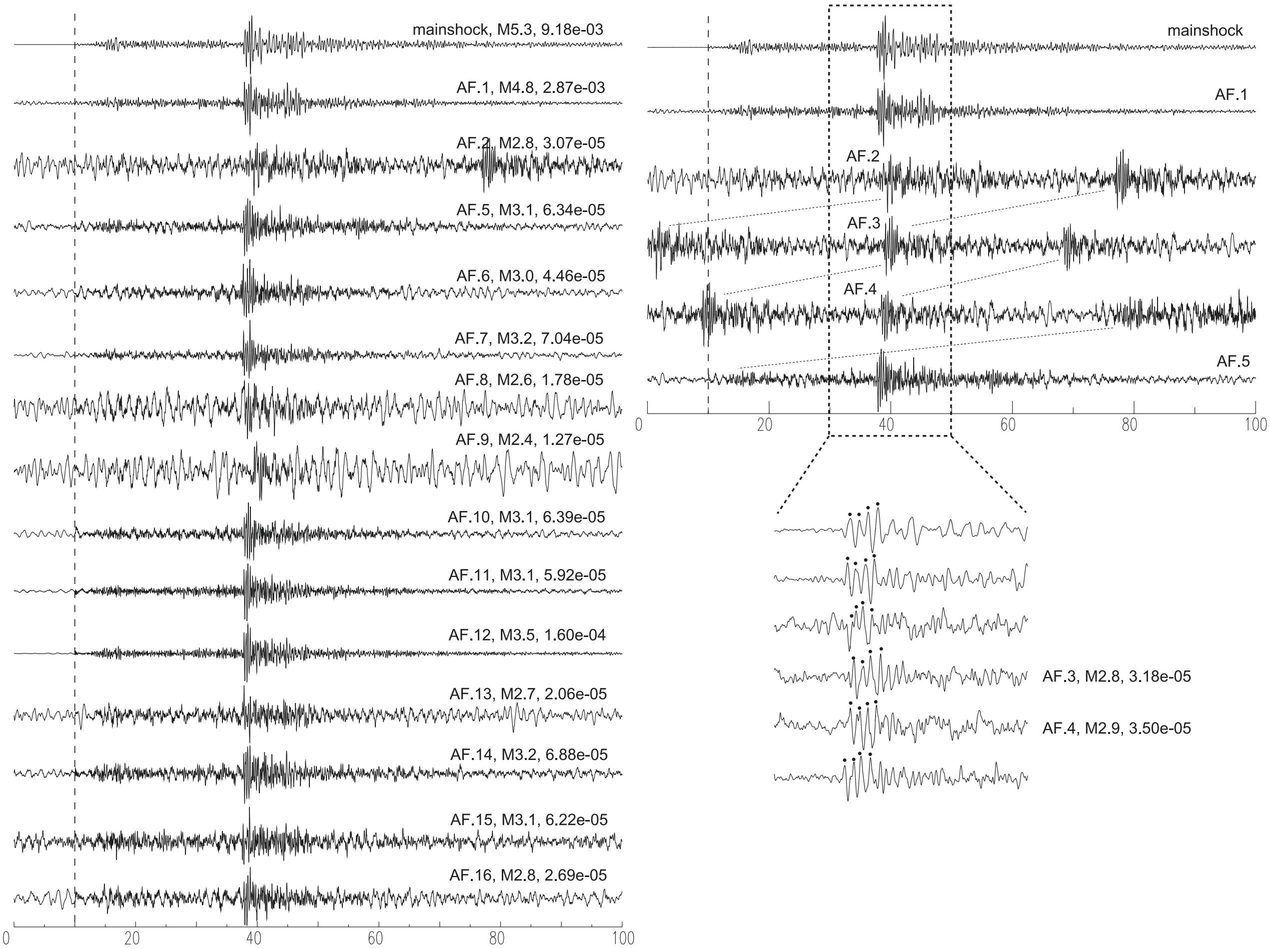
mainshock, M5.3, 9.18e-03
AF.1, M4.8, 2.87e-03
AF.2, M2.8, 3.07e-05
AF.5, M3.1, 6.34e-05
AF.6, M3.0, 4.46e-05
AF.7, M3.2, 7.04e-05
AF.8, M2.6, 1.78e-05
AF.9, M2.4, 1.27e-05
AF.10, M3.1, 6.39e-05
AF.11, M3.1, 5.92e-05
AF.12, M3.5, 1.60e-04
AF.13, M2.7, 2.06e-05
AF.14, M3.2, 6.88e-05
AF.15, M3.1, 6.22e-05
AF.16, M2.8, 2.69e-05
0
20
40
60
80
100
mainshock
AF.1
AF.2
AF.3
AF.4
AF.5
AF.3, M2.8, 3.18e-05
AF.4, M2.9, 3.50e-05

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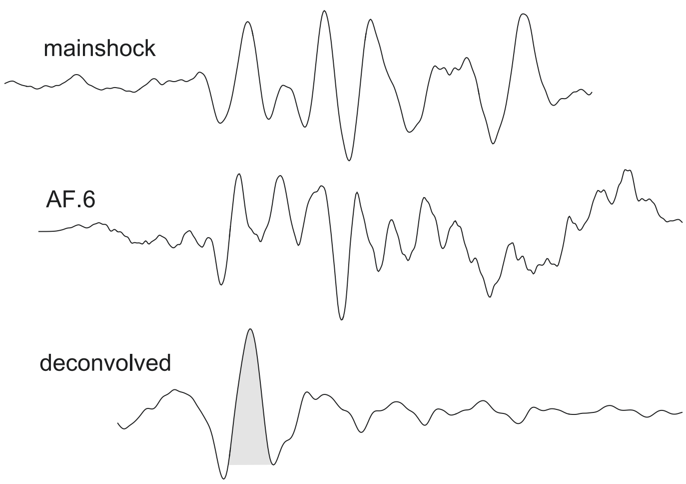
mainshock
AF.6
deconvolved
0.5s

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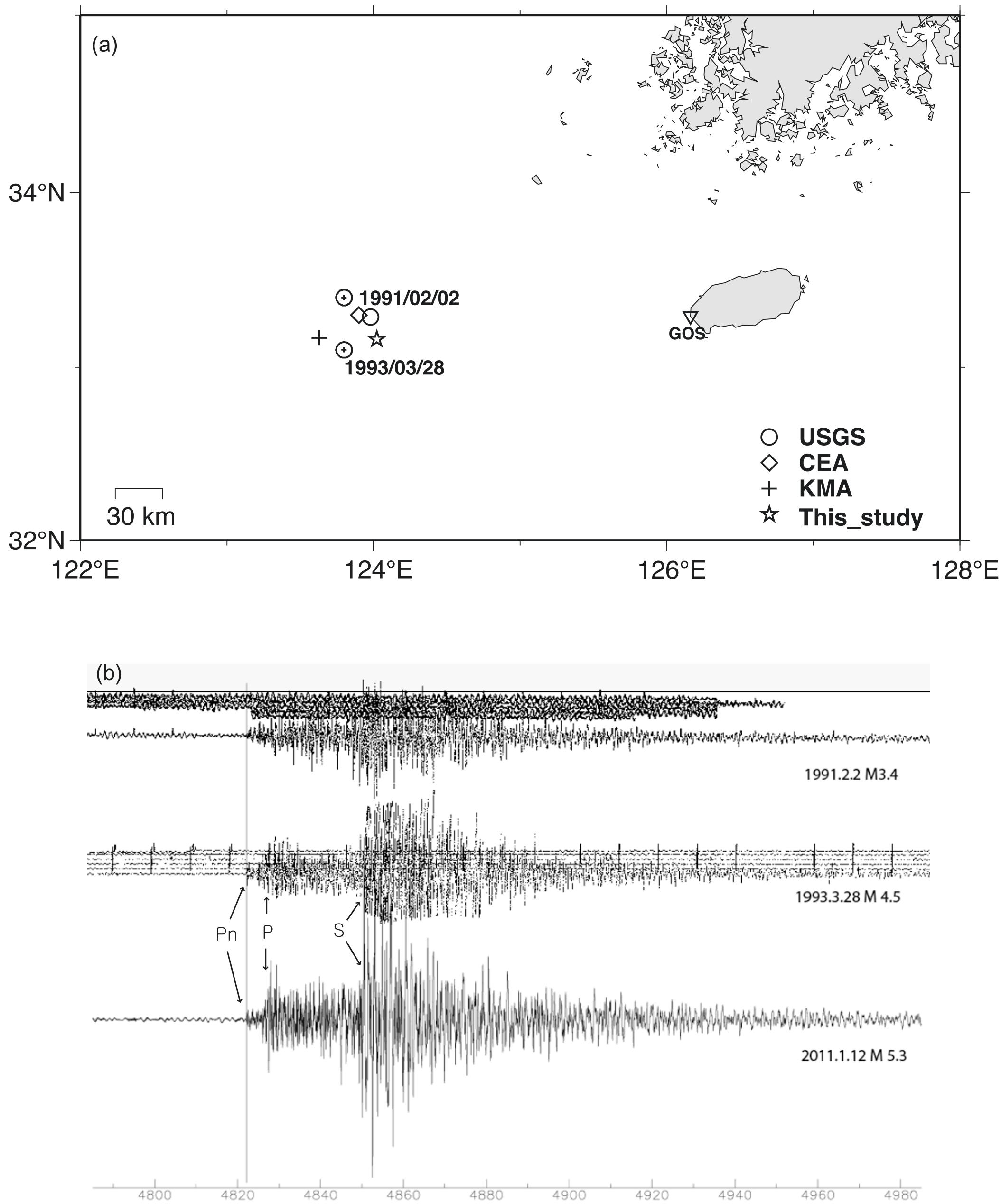

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3. Seismic Activities

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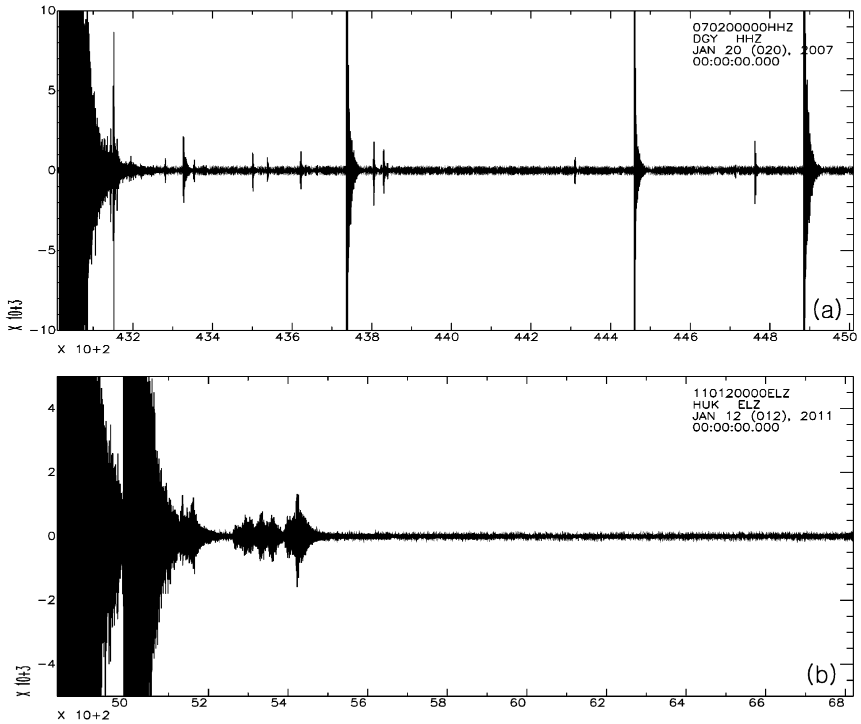

Fig. 8. Vertical velocity seismograms high-pass filtered at 5 Hz of 2000 s duration. Waveforms of the earthquake sequence of (a) the 2007 Odaesan event at the DGY station at an epicentral distance of 7.2 km, and (b) the 2011 Yellow Sea event at the HUK station at an epicentral distance of 215 km.

quakes have occurred in the region around the 2011 Yellow Sea event. The 1991 and 1993 events may be examples of a higher seismicity in this region relative to on the Korean Peninsula. The 2007 Odaesan event occurred in the region with the lowest seismicity (dotted ellipse in Fig. 2) on the peninsula. To see if there are some differences in seismic activity between the two regions, we investigated fore- and after-shock activities related to the two events. Figure 8 shows examples of aftershock waveforms of the two events. Seismograms in Fig. 8 show vertical velocity data from the 2007 event at the DGY station (a) and from the 2011 event at the HUK station (b). The data are 2000 s in duration and high-pass filtered at 5 Hz. The amplitude was magnified to see the small aftershocks. Many small phases, corresponding to aftershocks, are observed in Fig. 8(a). Because of the short epicentral distance of the DGY station (7.2 km) for the 2007 event, we were able to observe such small events. Meanwhile, in Fig. 8(b), aftershock waveforms of the 2011 event seem to have longer durations, and there are a small number of aftershocks visible. This is because the P-S time is long, and small aftershocks cannot be detected due to the long epicentral distance of the HUK station (215 km) for the 2011 event.

We measured the Peak Ground Accelerations (PGAs) of the fore-, main- and after-shocks of the two events and show them as a function of time in the top and bottom parts of Fig. 9(a). The triangle, crosses and circles represent fore-, main- and after-shocks, respectively. The horizontal axis indicates the time difference from the origin time of the mainshock in hours. We searched for fore- and after-shocks from continuous waveform data within 5 days before and after the mainshock. We used 100-Hz continuous data to identify earthquakes as small as possible. We found 27 foreshocks and 91 aftershocks of the 2007 event and no foreshocks and 16 aftershocks for the 2011 event.

To generalize the seismic activity on the Korean Peninsula, we looked at other earthquakes. Because 100-Hz continuous data have been available only since 2007, only two inland events could be analyzed. One is the 2008 Gongju event with a local magnitude of 3.4, and the other is the 2009 Andong event with a magnitude of 4.0. The earthquake parameters are listed in Table 1 and the epicenters are shown in Fig. 9(b). For these two events, we investigated fore- and after-shocks in the same way as the 2007 and 2011 events. For the 2008 Gongju event, we used the vertical seismogram at the TEJ station at an epicentral distance of 11.3 km and found 10 aftershocks. Unfortunately, about 60 hours of data were unavailable for this event and we could not detect any foreshocks, even if there might have been some. We used vertical waveform data from the ADO station of a distance of 22.9 km for the 2009 Andong event and found 12 aftershocks. There were no foreshocks for the 2009 event.

PGAs as a function of time for all four events are compared in Fig. 9(a). Foreshocks were observed only for the 2007 Odaesan event. Aftershocks of earthquakes on the Korean Peninsula followed within 3 days, while those of the 2011 Yellow Sea event followed by as long as 5 days. The last aftershock of the 2011 event that we observed occurred about 118 hours after the mainshock. We investigated seismograms of 5 more days for the 2011 event, but could not find any other aftershocks. Because the epicentral distances of the stations are quite different from each other, it is impossible to compare the absolute number of aftershocks. Instead we compare the number of aftershocks that are large enough to be detected at a distance of 215 km. The

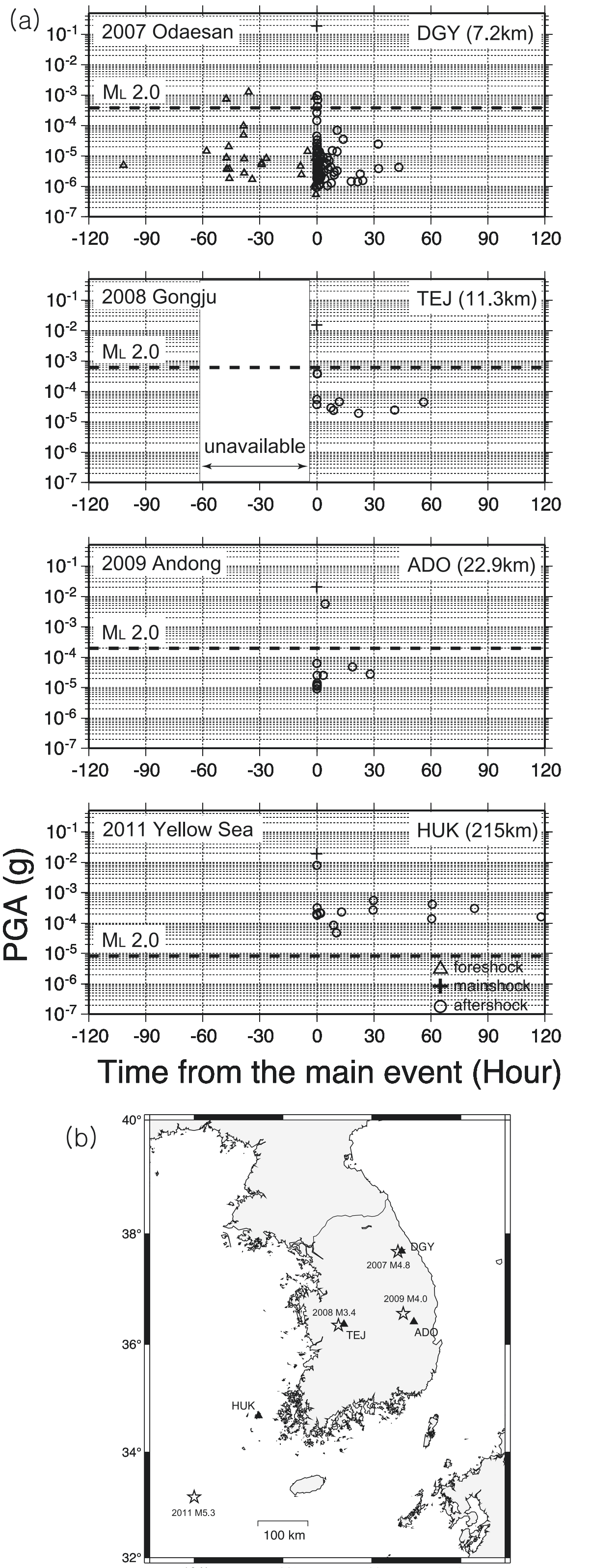

Fig. 9. (a) Peak Ground Accelerations (PGA) of fore-, main-, and after-shocks as a function of time for the four events. The values of the PGA are measured at the DGY, TEJ, ADO and HUK stations for the 2007, 2008, 2009 and 2011 events, respectively. Time 0 indicates the origin time. The broken horizontal lines on each graph indicate the relative values of PGA corresponding to M_L 2.0. Considering events larger than M_L 2.0, three inland earthquakes on the Korean Peninsula have very few aftershocks within several hours, while aftershocks of the 2011 Yellow Sea event continued for at least 5 days. (b) Locations of the four events and stations used to compare the aftershock activity.

broken horizontal lines on each graph indicate the relative values of the PGA corresponding to M_L 2.0, to the PGA of the mainshock assuming M_L reported by the KMA. Considering events larger than M_L 2.0, inland earthquakes of the Korean Peninsula have very few aftershocks within several hours. However, aftershocks of the 2011 Yellow Sea event continued for at least 5 days. This may indicate that the seismic activity is relatively higher in the region around the 2011 Yellow Sea event than on the Korean Peninsula.

4. Discussion and Conclusion

We estimated the source parameters of a moderate 2011 Yellow Sea earthquake in order to see if there are any differences in the characteristics of earthquake generation in the Yellow Sea and on the Korean Peninsula. The 2011 Yellow Sea event is a shallow strike-slip fault event and the moment magnitude was 4.6. The fault radius, rise time, and stress drop were determined to be 1.5–1.8 km, about 0.2 s and 1.2–2.0 MPa, respectively.

The stress drop of this event, 1.2–2.0 MPa, is lower than that of many earthquakes on the Korean Peninsula, including the Odaesan earthquake in 2007 at more than 8 MPa (Jo and Baag, 2007; Kim *et al.*, 2010; Park and Hahm, 2010), a moderate earthquake in 2004 (2004 *M* 5.3 event in Fig. 2) at about 7–14 MPa (Park and Mori, 2005), and the 1996 quake (1996 *M* 4.8 event in Fig. 2) at about 14 MPa (Choi, 2009). Chung and Brantley (1989) determined the stress drop of the 1984 *M* 6.0 (M_s 6.3) Southern Yellow Sea event (Fig. 2) to be 4.2 MPa and summarized the values of some large earthquakes (M_s 7) in northern China as 10–20 MPa. They suggested that the southern Yellow Sea region is characterized by short recurrence intervals while the northern China region has very long recurrence intervals. Additionally, they argued that short recurrence intervals and low stress drops reflect a lower material strength in the region of the southern Yellow Sea. The 2011 Yellow Sea event also has a low stress drop, which is lower than the typical value for shallow intraplate earthquakes, similar to the 1984 Southern Yellow Sea event. Meanwhile, earthquakes on the Korean Peninsula and just off the east coast seem to have higher stress drops, indicating that they are typical intraplate events. Therefore, the Yellow Sea region may be in a different geologic, or tectonic, setting from that of the Korean Peninsula or northern China. Choi (2010) estimated stress drops of two moderate Yellow Sea events (2003 *M* 4.9 and 2003 *M* 5.0 events in Fig. 2) to be about 10–30 MPa. So the southern part of the Yellow Sea may be characterized by low stress drop.

From examination of continuous waveform data following the 2011 Yellow Sea earthquake, we found 16 aftershocks with magnitudes greater than 2 that occurred over 5 days. However, following three earthquakes on the Korean Peninsula, aftershocks with a magnitude greater than 2 followed within several hours. The low level of aftershock activity and high stress drop on the Korean Peninsula may indicate that earthquakes are not so easily triggered on the Korean Peninsula than in the Yellow Sea. The Korean Peninsula seems to be different from the Yellow Sea, but is, however, similar to northern China.

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Acknowledgments.

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