Source Characteristics of Large Outer Rise Earthquakes in the Pacific Plate

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SUMMARY
We estimate source models of three large outer rise earthquakes in the Pacific Plate by using the EGF (Empirical Green's Function) method. The three earthquakes are the 2005 and 2011 large Sanriku-oki earthquakes, and the 2007 great Central Kurile Islands earthquake. The estimated SMGA (strong motion generation area) parameters are compared with the self-similar scaling of total seismic moment to the SMGA parameters for intraslab earthquakes (Sasatani et al., 2008). We find the SMGA parameters of the three outer rise earthquakes are similar to those of intraslab earthquakes despite the shallow focal depths of the former events. Finally we compare the SMGA parameters between the outer rise earthquakes in the Pacific plate and the shallow intraplate earthquakes in the Philippine Sea plate. The stress drops on the SMGA for the Pacific plate outer rise earthquakes are considerably higher than those for the Philippine Sea shallow intraplate earthquakes.

Keywords: Outer rise earthquake, Empirical Green's function method, Strong motion generation area, Intraslab earthquake,

1. INTRODUCTION

Intraslab earthquakes that occur within the subducting oceanic plate have peculiar source characteristics compared with those of plate boundary and inland crustal earthquakes (Sasatani et al., 2008). Since the intraslab earthquakes generate strong short-period seismic waves, it is now recognized that even intermediate-depth intraslab earthquakes with a depth of about 100 km are disastrous ones. There exist another intraplate earthquakes that occur in the outer rise region seaward of trench; these are called outer rise (OR) earthquakes. The OR earthquake is characterized by normal faulting occurring at shallow part of the oceanic plate; the largest OR normal faulting event is the 1933 Sanriku-oki, Japan, earthquake (Mw8.4; Kanamori, 1971). It is important for earthquake disaster mitigation planning to understand source characteristics of the OR earthquakes.

In this paper, we estimate source models of three large OR earthquakes in the Pacific Plate by using the empirical Green's function method (EGF method; Miyake et al., 2003). The three earthquakes are the 2005 and 2011 Sanriku-oki, Japan, OR earthquakes (Mw7.0 and Mw7.6) and the 2007 great OR earthquake (Mw8.1) in the Central Kurile Islands (Fig. 1). Source parameters of strong motion generation areas (SMGAs) are estimated by modeling the observed acceleration, velocity and displacement waveforms; the SMGAs are defined as extended areas with relatively large slip velocities within a total rupture area (Miyake et al., 2003). Next, we examine the SMGA parameters (area and stress drop on it) of these OR earthquakes by comparing with the self-similar scaling of total seismic moment to the SMGA parameters for intraslab earthquakes (Sasatani, et al., 2008). Finally we discuss differences of the SMGA parameters between the OR earthquakes in the Pacific plate and the shallow intraplate earthquakes in the Philippine Sea plate. The source parameters of earthquakes used in this study are summarized in Table 1.

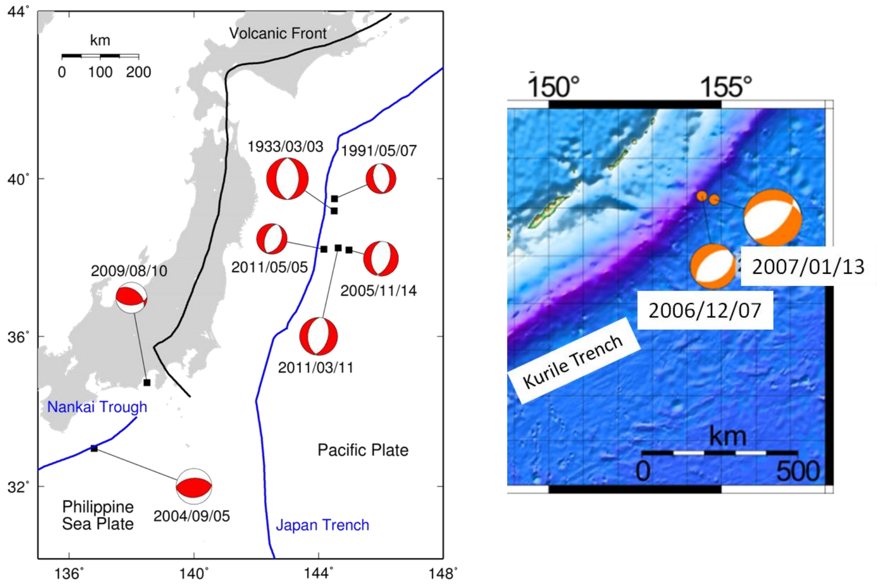

Figure 1. Map showing the epicenters and focal mechanisms of earthquakes used in this study.

Table 1. Source parameters of earthquakes used in this study.

Plate and Region	Year/Month /Day	Focal mechanism Strike/ Dip/ Rake	Depth km	Seismic Moment Nm	Remarks / References
Pacific Plate Sanriku-oki	1991/05/07	359/42/-80	15.0	1.12x10**18	GCMT, Element Event
	2005/11/14	19/49/-78	18.0	3.70x10**19	GCMT, Target Event
	2011/03/11	182/42/-100	21.1	3.10x10**20	GCMT, Target Event
	2011/05/05	197/52/-95	13.9	1.52x10**18	GCMT, Element Event
Pacific Plate Central Kurile Is.	2007/01/13	43/59/-115	12.0	1.78x10**21	GCMT, Target Event
	2006/12/07	57/41/-82	15.4	4.42x10**18	GCMT, Element Event
Philippine Sea Plate	2004/09/05	267/52/91	37.6	7.73x10**19	Suzuki et al., 2005
	2009/08/10	88/51/63	23.0	2.25x10**18	Asano and Iwata, 2010

2. SOURCE MODELING OF THREE OUTER RISE EARTHQUAKES

Since the OR earthquake occurs fairly far from an island arc, the wave observed on land passes through the long propagation path and is affected by the complex underground structure. In this case, it might be difficult for a theoretical approach to reproduce the strong motion records. So we use the EGF method which calculates a record of a large (target) earthquake by summing up that of a smaller (element) event located near the target one (Hartzell, 1978; Irikura, 1986; Miyake et al., 2003).

2.1. Empirical Green's Function Method

Here we calculate the synthetic waveforms according to the EGF method developed by Miyake et al. (2003). This method simulates the observed wide-band strong-motion records well on the assumption of a characterized simple fault model (SMGA model) which is a rectangle in shape with a constant slip and stress drop. First the number to divide the SMGA into subfaults (N x N) and the ratio of the stress drop of the target event to the element one (C) are determined from the S-wave spectral ratio of the target event to the element event. Next the fault plane is determined based on the focal mechanism of the target event and relevant information such as the aftershock distribution. Finally we estimate the following parameters: the size and rupture starting point for the SMGA, the rise time for the target event (this is related to the filtering function to adjust the difference in the slip velocity functions between the target and element events), and the rupture velocity (rupture is assumed to propagate radially from the starting point). The estimation is done by fitting the synthetic waveforms (acceleration, velocity and displacement) to the observed ones by forward modelling. The above mentioned EGF method is applied to a single SMGA model; for a multiple SMGA model, N and C are also parameters to be estimated.

2.2. The 2005 Large Sanriku-oki Outer Rise Earthquake

A large shallow earthquake (Mw7.0) occurred on November 14, 2005 in the outer rise region seaward of Japan Trench. This earthquake is the first large event after the 1933 great Sanriku-oki OR earthquake. Figure 2 shows the epicenter and focal mechanism of this event. Though many aftershocks occurred, they were not large enough to trigger strong motion instruments. Here we select the 07 May 1991 OR earthquake as the element event (Fig. 2(a)). Strong motion records observed at fourteen JMA stations shown in Fig. 2(a) are used in the EGF analysis. Source parameters of the target and element events are shown in Table 1.

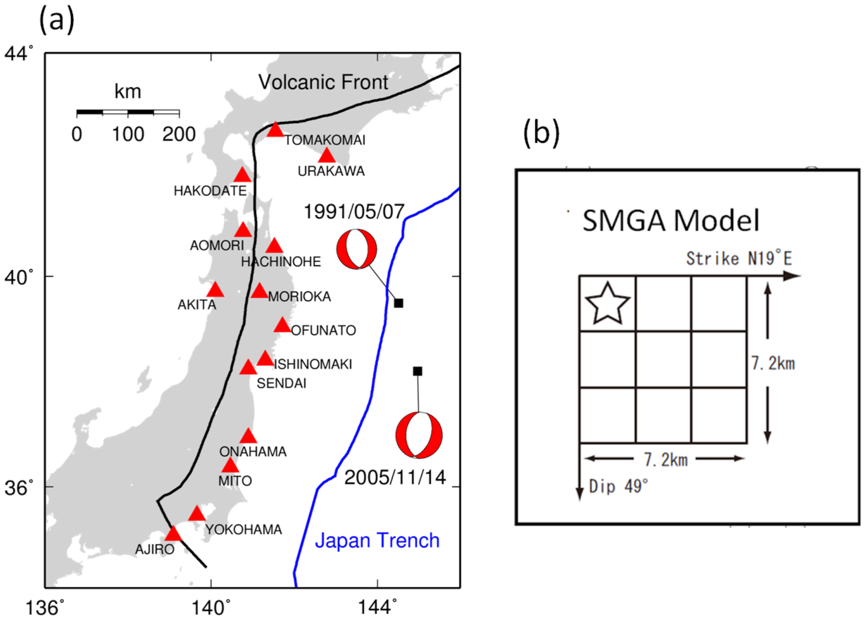

Figure 2. (a) Epicentres and focal mechanisms for the target and element events. Stations used in analysis are also shown. (b) SMGA model for the 2005 Sanriku-oki outer rise earthquake.

Figure 3 shows the S-wave spectral ratios of the 2005 event to the 1991 event. The results indicate that the high-frequency level is about 4 in the frequency range of 1 to 10 Hz. However, the low-frequency level is not reasonable due to low signal-to-noise ratio of the element event. We estimate the low-frequency level based on the GCMT seismic moments for the target and element events (Table 1). From *Mo*/*mo*=*CN***3, where *Mo* is moment of the target event and *mo*, moment of the element event (Miyake et al., 2003), we have *N* (integer)=3 and *C*=1.2. Here we simply assume a square SMGA.

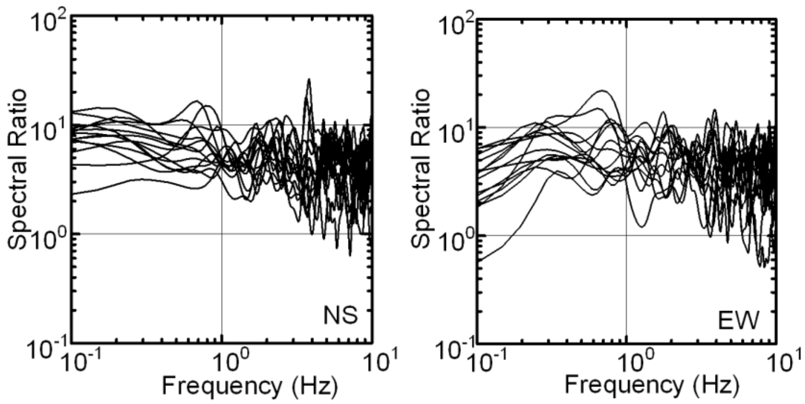

Figure 3. S-wave acceleration spectral ratios of the target event to the element event for the 2005 OR event.

We select the eastward dipping nodal plane as the fault plane because the aftershock distribution roughly aligns along the strike of this nodal plane. After these examinations, we perform the EGF simulation of wide-band strong-motion records to estimate the appropriate SMGA parameters of the 2005 event. The SMGA model estimated is shown in Fig. 2(b) and the parameters are shown in Table 2. Figure 4 shows the comparison of the observed and synthetic wide-band strong-motion records at URAKAWA and AJIRO; the former and latter are located in the north-west and south-west directions (Fig. 2). The fitting of acceleration and velocity waveforms is fairly good. The estimated SMGA parameters are shown in Table 2.

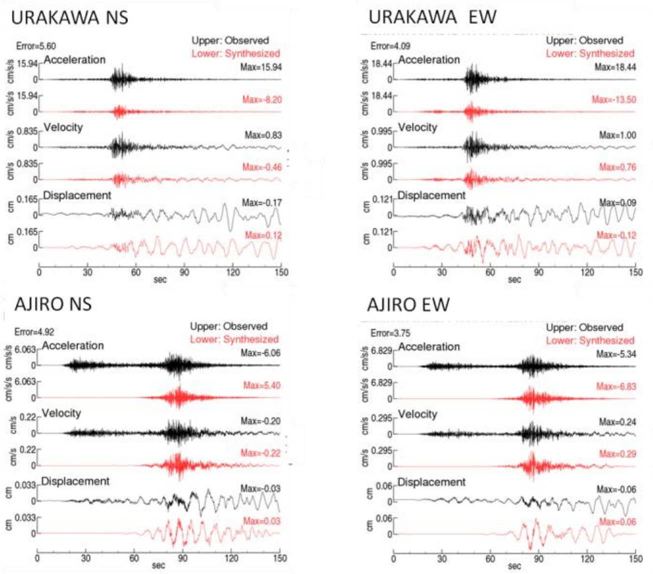

Figure 4. Comparison of the observed waveforms with the synthesized ones for the 2005 OR event.

Table 2. Source parameters of the SMGA for the 2005 Sanriku-oki outer rise earthquake.

	N	*C*	Area [km^2]	Rupture Vel. [km/s]	Rise Time [s]	Rupture Time [s]	Stress Drop [MPa]
Target Event	3	1.2	51.8	2.1	0.52	0	236
Element Event	-	-	5.8	-	-	-	197

2.3. The 2011 Large Sanriku-oki Outer Rise Earthquake

The great Tohoku thrust faulting earthquake (Mw9.0) occurred at 14:46 on 11 March 2011. About 40 minutes after the Tohoku earthquake, a large normal faulting earthquake (Mw7.6) took place in the outer rise region seaward of Japan Trench. This is the second largest outer rise normal faulting event next to the 1933 Sanriku-oki earthquake in Japan. Here we call this normal faulting event the 0311 OR event. The epicentre and focal mechanism of the 0311 OR event are shown in Fig. 1. The source model of the 0311 OR event is estimated by using the EGF method. The 05 May 2011 aftershock of the Tohoku earthquake is used as the element event; here, this event is called the 0505 OR event. This event has the same normal faulting mechanism as the 0311 OR event (Fig. 5(a)). The source parameters for the target and element events are shown in Table 1. In Fig. 5(a), eight strong motion stations used in analysis are also shown; the azimuthal coverage of the stations is fairly good.

Figure 6 shows observed acceleration waveforms at KSRH10 and SITH06; the former is located in the north of the epicentre and the latter, in the south-west of it (Fig. 5(a)). The S-wave accelerations at KSRH10 have shorter duration of strong shaking than those at SITH06. The S-wave spectral ratios of the target event to the element event are shown in Fig. 7. The spectral ratios at the northern stations are higher than those at the southern stations in the frequency range of 0.1 to 1 Hz. These facts are related to directivity effects owing to the northward propagation of rupture (Miyake et al., 2001). We select the west dipping nodal plane as the fault plane based on aftershock distribution of the 0311 OR event by OBS (ocean bottom seismograph) observations (Obana et al., 2012). From *Mo*/*mo*=C*N***3, we have *N*=5 and *C*=1.6. These parameters predict the S-wave spectral ratio of 8 at high frequencies; the S-wave spectral ratios in Fig. 7 show roughly the same level at the frequency range of 1 ~ 20 Hz.

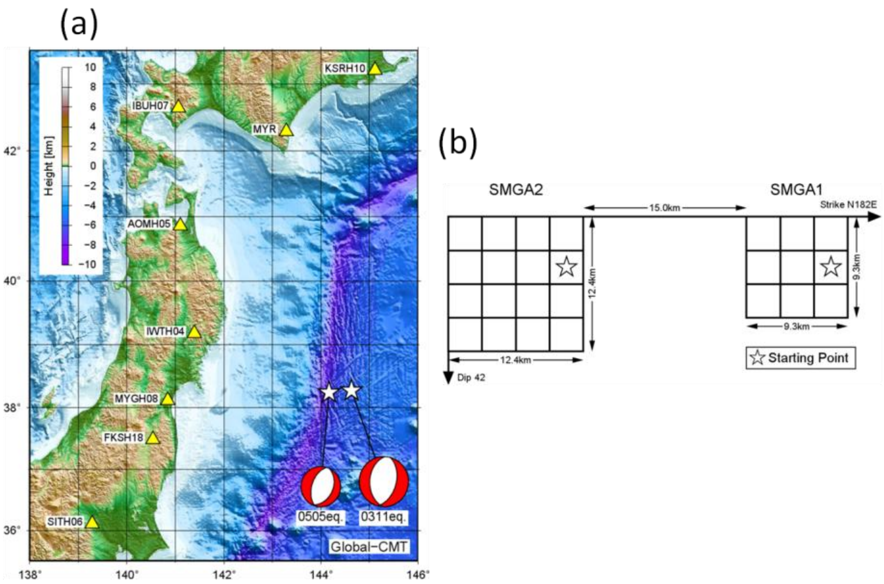

Figure 5. (a) Epicentres and focal mechanisms for the target and element events. Stations used in analysis are also shown. (b) SMGA model for the 2011 Sanriku-oki outer rise earthquake.

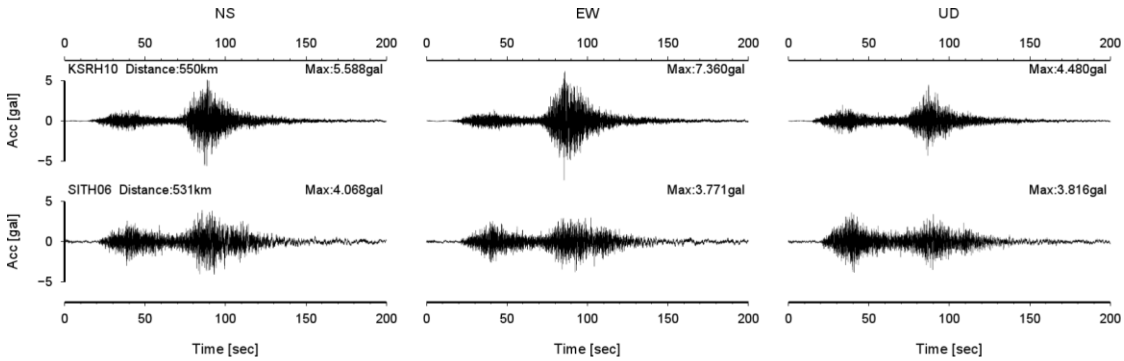

Figure 6. Observed acceleration waveforms at KSRH10 (Upper) and SITH06 (Lower).

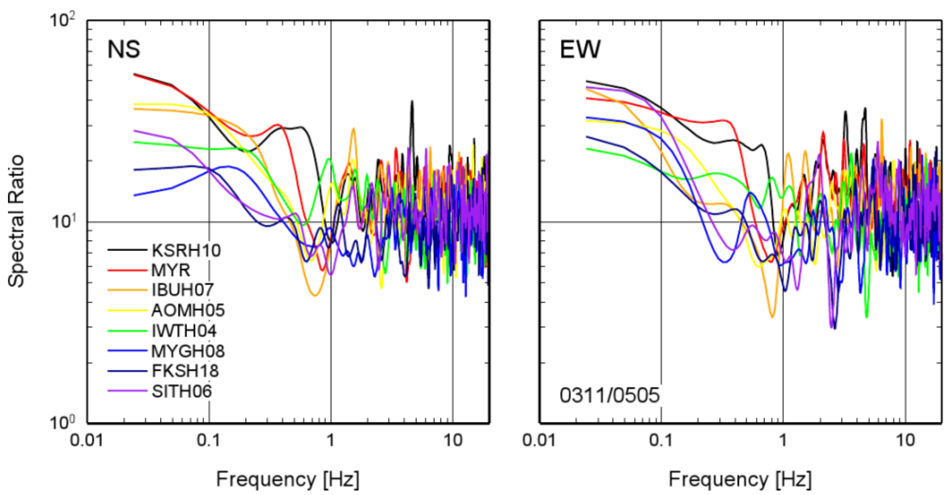

Figure 7. S-wave acceleration spectral ratios of the target event to the element event for the 2011 OR event.

After above examination, we perform the EGF simulation of wide-band strong-motion waveforms assuming the single SMGA. However, it is difficult for the single SMGA model to reasonably reproduce the observed waveforms shown in Fig. 6. Next we assume the source model composed of two SMGAs. After several trials by changing the each size of the two SMGAs and the distance between the two SMGAs, we estimate the source model which well reproduces the observed waveforms as shown in Fig. 8. The estimated source model is shown in Fig. 5(b) and the SMGA parameters are shown in Table 3.

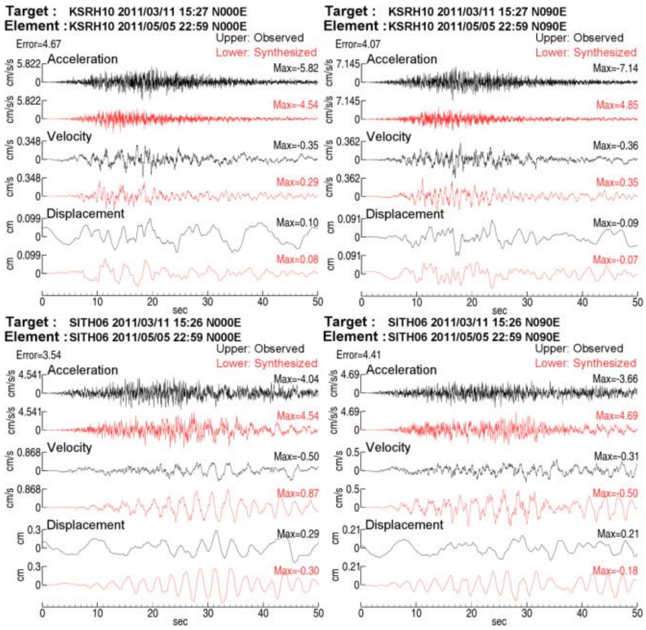

Figure 8. Comparison of the observed waveforms with the synthesized ones for the 2011 OR event.

Table 3. Source parameters of the SMGAs for the 2011 Sanriku-oki outer rise earthquake.

Parameters	SMGA 1	SMGA 2	Element Event
N	3	4	-
C	2.0	1.6	-
Area [km^2]	86.5	153.8	9.6
Rupture Vel. [km/s]	1.8	1.5	-
Rise Time [s]	0.9	0.9	-
Rupture Time [s]	0.0	7.0	-
Stress Drop [MPa]	248	198	124

2.4. The 2007 Great Kurile Outer Rise Earthquake

In the central Kurile islands, the great thrust faulting earthquake (Mw8.3) occurred on November 15, 2006, and about two months after this event, the great outer rise (normal faulting) earthquake (Mw8.1) occurred on January 13, 2007; this energetic earthquake sequence is known as a great earthquake doublet (Ammon et al., 2008). We estimate the source model of the 2007 OR earthquake using the 7 December 2006 foreshock (Mw6.4) as the element event. Figure 9 shows the epicentres and focal mechanisms for the target and element events; these source parameters are listed in Table 1. We use strong motion records observed at four stations in Hokkaido, Japan (Fig. 9). Figure 10 shows one of observed records from the target and element events. Duration of strong shaking for the target event is about 80 sec while that for the element event is only 10 sec, and the envelope of the target event is surprisingly different from that of the element event.

The available stations are very far (750~1200 km) from the 2007 OR source region. Furthermore, these stations are located in the SW direction only. In this case, it is considerably difficult to apply the usual EGF method to estimate of the source model. Here we refer to the waveform inversion result by Ammon et al. (2008). Their rupture model is shown in Fig. 11. They selected the southeast-dipping nodal plane of the GCMT solution as the fault plane. The rupture propagated bilaterally with the velocity of 3.5 km/s and the main rupture lasted about 40 sec. The slip distributions suggest a multiple SMGA model. We estimate the source model of the 2007 OR event by using the EGF method referring to their rupture model. The frequency band used in the EGF simulation is set to be 0.1~20Hz.

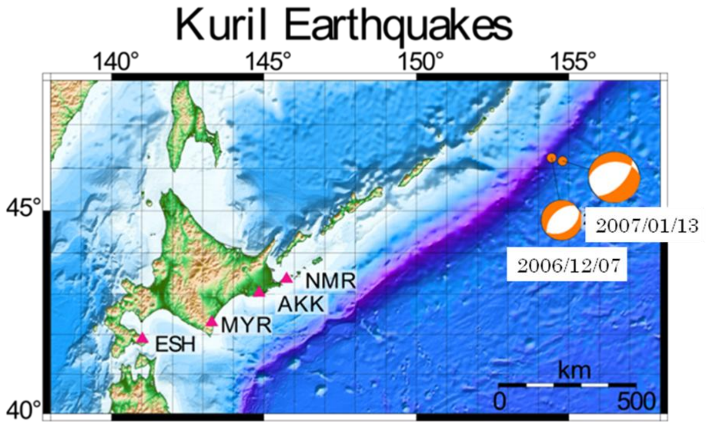

Figure 9. Epicenters and focal mechanisms for the target and element events. Stations used in analysis are also shown.

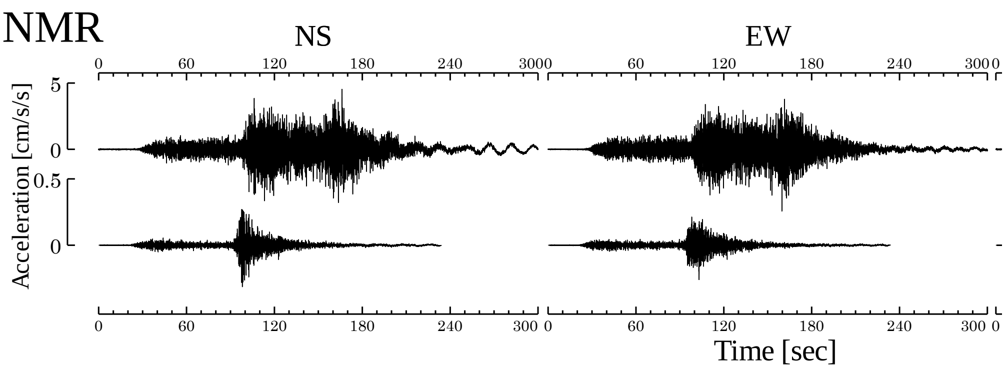

Figure 10. Observed acceleration waveforms at NMR. Upper: the target event, Lower: the element event.

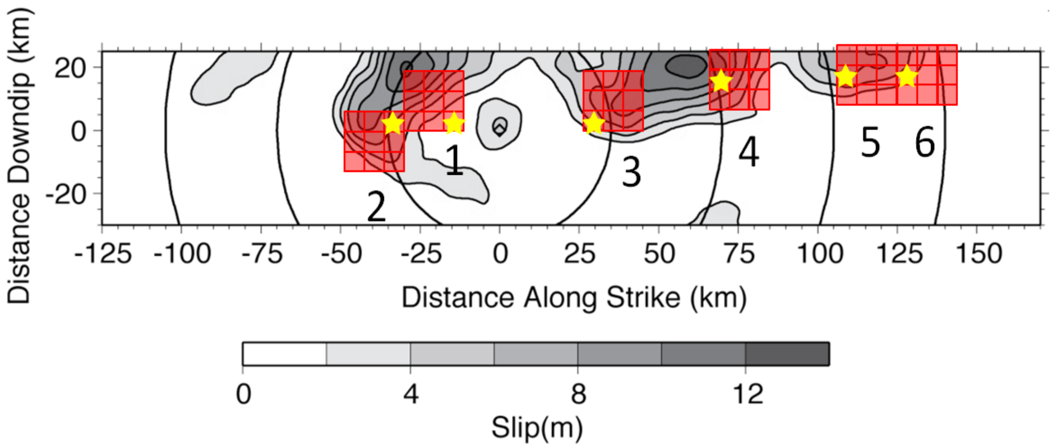

Figure 11. The estimated SMGA model that is overlaid on the slip distributions by Ammon et al. (2008). A star in each SMGA indicates the rupture starting point.

Figure 11 shows the estimated SMGA model that is overlaid on the slip distributions by Ammon et al. (2008). The source model has six SMGAs each of which has the same square in shape. The SMGA parameters are shown in Table 4. In Fig 12, we compare the observed and synthetic wide-band waveforms at two stations (NMR and MYR). The S-wave envelope shapes on the acceleration waveforms and S-wave ripples on the velocity waveforms are fairly well reproduced by our SMGA model.

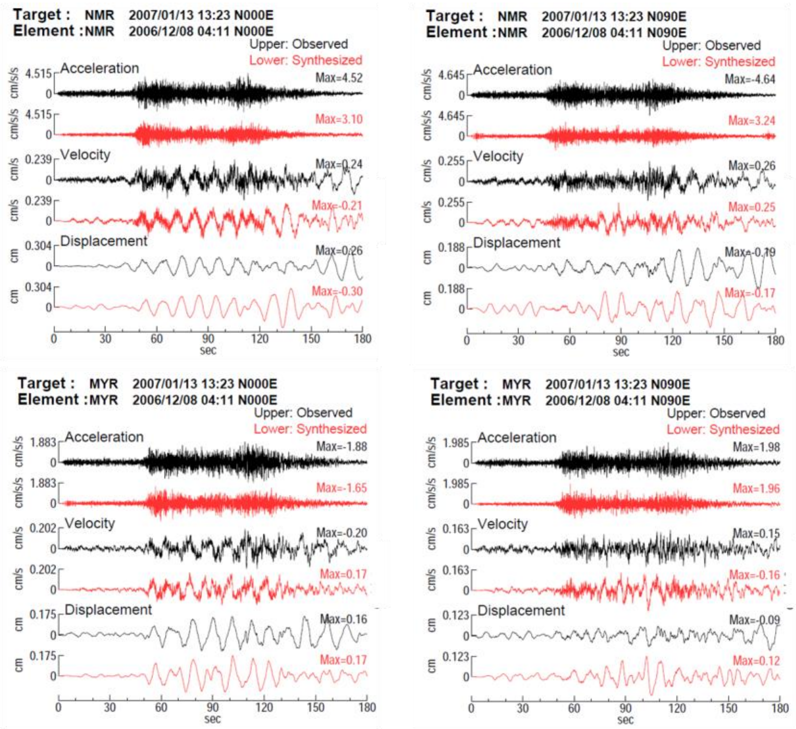

Figure 12. Comparison of the observed waveforms with the synthesized ones for the 2007 Kurile OR event.

Table 4. Source parameters of the SMGAs for the 2007 great Kurile outer rise earthquake.

Parameters	SMGA 1	SMGA 2	SMGA 3	SMGA 4	SMGA 5	SMGA 6	Element Event
N	3	3	3	3	3	3	-
C	2.4	2.2	2.2	2.4	2.9	2.8	-
Area [km^2]	324	324	324	324	324	324	36
Rupture Vel. [km/s]	3.0	2.8	2.8	3.0	2.8	2.6	-
Rise Time [s]	1.0	1.0	1.0	1.0	1.0	1.0	-
Rupture Time [s]	5.0	11.0	8.5	19.0	31.0	38.0	-
Stress Drop [MPa]	107	98	98	107	130	125	45

3. DISCUSSIONS

We have estimated the source models of three large OR earthquakes in the Pacific Plate. First the source parameters of the SMGAs are compared with the self-similar scaling of total seismic moments to the SMGA parameters for the intraslab earthquakes. Figure 13 shows relationship between the combined SMGAs and the total seismic moments for three large OR earthquakes. In the figure, a bold line shows the relationship for the intraslab earthquakes (Sasatani et al., 2008). We find that the relationship for three OR earthquakes is similar to that for the intraslab earthquakes.

Next we examine the stress drop on the SMGA for three large OR earthquakes. The stress drop on the SMGA is obtained by multiplying the stress drop of the element event by the estimated parameter *C* (the stress drop ratio between the target event and the element event); the stress drop of the element event is obtained assuming the crack model. The stress drops on the SMGAs are shown in Tables 2, 3 and 4. The stress drops for three large OR earthquakes are 100 ~ 200 MPa; these are also similar to those for the intraslab earthquakes (e.g., Morikawa and Sasatani, 2004). We conclude that the SMGA parameters of the large outer rise earthquakes are similar to those of the intraslab earthquakes despite the shallow focal depths of the former events.

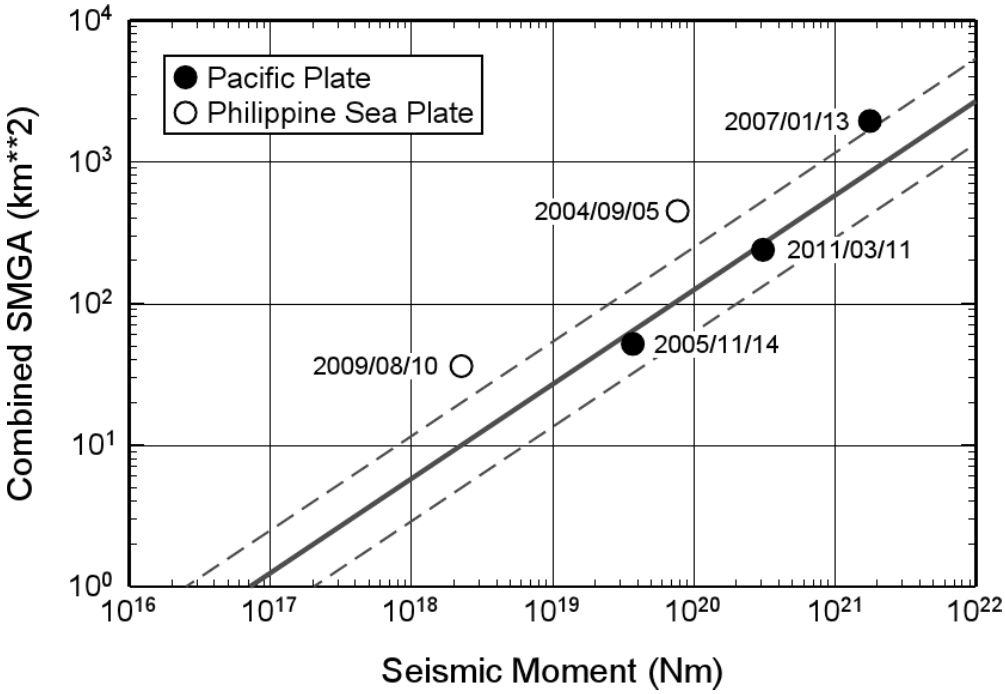

Figure 13. Relationship between the combined SMGA and the seismic moment. A bold line indicates the relationship for the intraslab earthquakes by Sasatani et al. (2008).Dashed lines indicate the factors of 2 and 0.5.

Finally we compare the SMGA parameters between the OR earthquakes in the Pacific Plate and the shallow intraplate earthquakes in the Philippine Sea Plate. Two shallow intraplate earthquakes near the Nankai trough in the Philippine Sea Plate have been studied by using the EGF method. The epicentres and focal mechanisms are shown in Fig. 1; the source parameters are shown in Table 1 and the SMGA parameters are listed in Table 5. These are not normal faulting events but reverse faulting events. In Fig. 13, we show the relationship between the combined SMGAs and the total seismic moments for these earthquakes. It is clear the combined SMGAs of the shallow intraplate earthquakes in the Philippine Sea Plate are considerably larger than those of the OR earthquakes in the Pacific Plate when compared for a comparable moment. This is directly related to the stress drop difference between them; the stress drops of the shallow intraplate earthquakes in the Philippine Sea Plate are 10 ~ 40 MPa (Table 5), much smaller than those of the OR earthquakes in the Pacific Plate. This may indicate significant differences in faulting environments near trench in the Pacific Plate and the Philippine Sea Plate.

Table 5. Source parameters of the SMGAs for the two shallow intraplate earthquakes in the Philippine Sea Plate.

Earthquake	Area [km^2]	Stress Drop [MPa]	Reference
Kii Peninsula 2004/09/05	450	8.3	Suzuki et al., 2005
Suruga Bay 2009/08/10	SMGA 1 13.0 SMGA 2 23.0	SMGA 1 35.7 SMGA 2 27.5	Asano and Iwata, 2010

4. CONCLUSIONS

We estimated the source models of three large outer rise earthquakes in the Pacific Plate by using the EGF method. We found that the SMGA parameters of these earthquakes are similar to those of intraslab earthquakes. This indicates that the outer rise earthquakes generate strong short-period seismic waves, despite the shallow focal depths. Takai et al. (2012) obtained a similar conclusion based on a study of characteristics of strong ground motions from the Sanriku-oki outer rise earthquakes. Finally we pointed out that the stress drops on the SMGA for the Pacific Plate outer rise earthquakes are considerably higher than those for the Philippine Sea Plate shallow intraplate earthquakes.

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