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ASPERITY SOURCE MODEL OF THE 1993 KUSHIRO-OKI EARTHQUAKE (Mw7.6): A LARGE INTRA-SLAB EARTHQUAKE

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SUMMARY

The 1993 Kushiro-oki earthquake is a large intra-slab earthquake that ruptured through a substantial part of the subducting plate. We construct the asperity source model of the Kushiro-oki earthquake, which well explains broadband strong ground motions, using the empirical Green's function method. The source model has the following characteristics comparing with those of in-land and plate-boundary earthquakes: the total asperity area is much small and the stress drop is extremely high (100~200MPa). These indicate that the Kushiro-oki earthquake radiates seismic energies from a small area in a short time. This rupture process results in extremely strong radiation of short-period seismic waves as observed during this event. We confirm a correlation between outer fault parameters (the entire source area and seismic moment) and inner fault parameters (the asperity areas, stress drops of the asperities, and short-period level of the S-wave source spectrum); these parameters characterize the asperity source model. This indicates applicability of the asperity source model to large intra-slab earthquakes for prediction of strong ground motions from scenario earthquakes.

INTRODUCTION

Great earthquakes along the southern Kurile-Hokkaido arc show an episodic activity. The latest episode started in 1952 and apparently ended in 1973; great earthquakes occurred successively along segments A to F as shown in Fig. 1. The focal mechanisms of these earthquakes are low-angle thrust faulting which represents slip between the oceanic and continental lithospheres. Thus these are called plate-boundary earthquakes. The episodic activity has the great earthquake recurrence-interval of about 100 years. Recently the Tokachi-oki earthquake (Mw8.0) occurred at the 1952 source region on September 26, 2003; this may indicate a restart of the episodic activity.

Two large earthquakes occurred in 1993 and 1994 along the southern Kurile-Hokkaido arc after the latest episodic activity (Fig.1); the 1993 Kushiro-oki earthquake (Mw7.6) and the 1994 Hokkaido Toho-oki or Shikotan earthquake (Mw8.2). These earthquakes are not plate-boundary earthquakes but intra-slab earthquakes occurring within the subducting slab (Fig. 2), and caused severe damage around their

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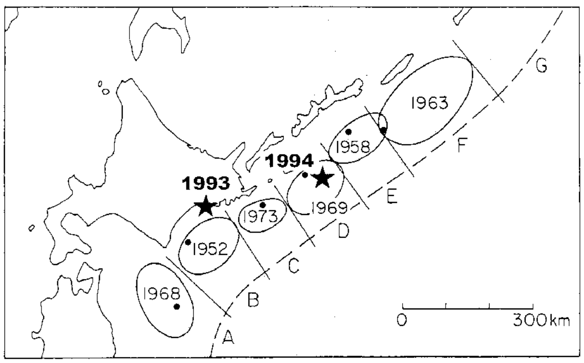
epicentral areas. These intra-slab earthquakes have been recognized as disastrous earthquakes at a subduction zone nowadays.



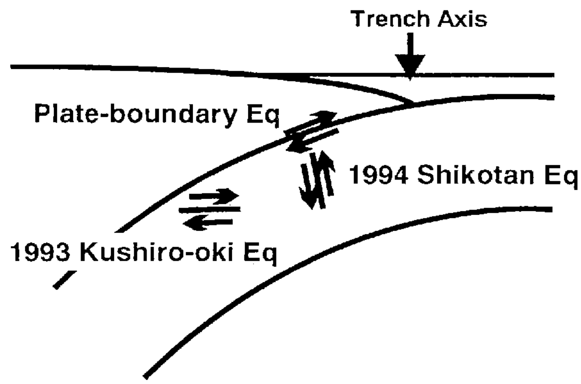


Fig. 1 (left). Episodic activity of great earthquakes along the southern Kurile-Hokkaido arc. Each ellipse represents an aftershock area. Solid stars represent the epicenters of the 1993 Kushiro-oki and the 1994 Hokkaido Toho-oki earthquake.
Fig. 2 (right). Schematic fault motions for the 1993 Kushiro-oki, the 1994 Hokkaido Toho-oki (Shikotan) and the plate-boundary earthquake.

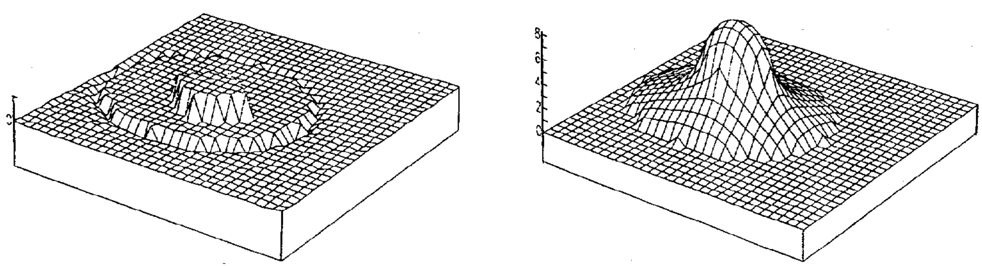


Fig. 3. **Stress change (left) and slip (right) for the asperity model (after Boatwright [2]).**

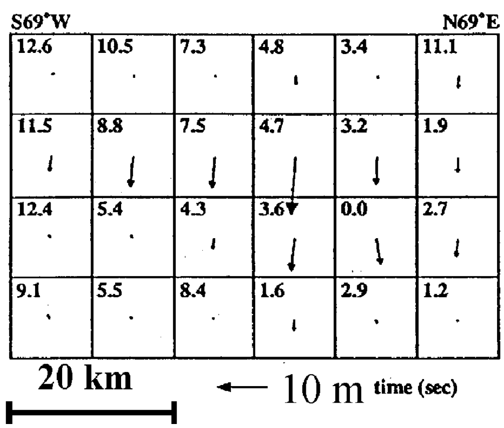
It goes without saying that predicting of strong ground motions from scenario earthquakes is important to make seismic disaster prevention measures. Recently Irikura et al. [1] proposed a recipe to predict strong ground motions from scenario earthquakes which are caused by active faults and plate-boundary slips. In their recipe, the earthquake source is based on an asperity model (Fig. 3) characterized by two kinds of parameters: outer fault parameters (e.g., the entire source area and seismic moment) and inner fault parameters (e.g., the asperity area and stress drop). They have confirmed that that the scaling relations for the inner fault parameters as well as the outer fault parameters are valid for characterizing earthquake sources and calculating ground motions from recent large earthquakes. However, it is not yet clear that the intra-slab earthquake source is reasonably characterized by the asperity model.

In this paper, we investigate the outer and inner fault parameters of the 1993 Kushiro-oki earthquake to check applicability of the asperity source model to intra-slab earthquakes. The Kushiro-oki earthquake occurred beneath the eastern Hokkaido on January 15, 1993, and the hypocenter lies within the subducting plate at about 100km depth. The intermediate-depth seismicity in the area of Hokkaido clearly delineates a double seismic zone (Suzuki et al. [3]). The aftershocks of the 1993 event show that its fault plane lies between the planes of the double seismic zone (Kasahara et al. [4]). This earthquake is the first intra-slab earthquake, from which many strong motion records have been obtained by modern instruments. We observed strong ground acceleration of about 900 cm/s^2 at Kushiro city located just above the focus.

OUTER FAULT PARAMETERS

Takeo et al. [5] constrained a spatial slip distribution on the fault plane using near-field data (ground displacements obtained by two times integration of accelerograms). They made waveform inversion assuming the fault area of 60 km x 40 km based on the aftershock distribution (Kasahara et al. [4]), but their result shows that the large slips are restricted to a small area of about 40 km x 20 km (Fig. 4). This small fault area is confirmed by analyzing far-field P-wave pulse width (displacement pulse) as shown in Fig. 5. The P-wave pulse of about 10 sec indicates the fault length of about 40 km assuming unilateral rupture propagation with a velocity of 3.6 km/s (~ 80% of an S-wave velocity at the source). We should note that the aftershock distribution is wider than the entire source area of the main shock.

The other source parameters obtained by Takeo et al. [5] are: seismic moment = 3.3x10^{20} Nm, source time duration = 10 sec, average slip = 5.5 m (the largest local slip of 11 m), and average stress drop = 42 MPa. Ide and Takeo [6] also analyzed the near-field data to construct a dynamic rupture model of the Kushiro-oki earthquake that is consistent with the data, and obtained approximately the same results as shown above.



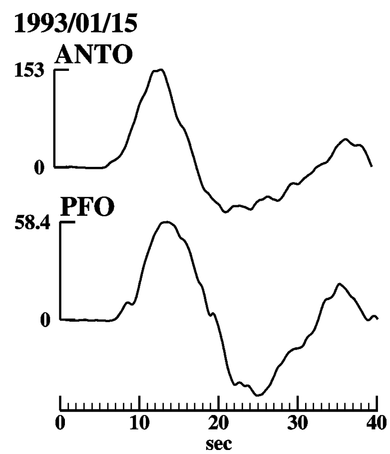


Fig. 4 (left). Slip distribution on the fault of the 1993 Kushiro-oki earthquake. An arrow: a slip vector. A number: an onset time of the rupture. (after Takeo et al. [5])
Fig. 5 (right). An example of the far-field P-wave displacement from the 1993 Kushiro-oki earthquake.

INNER FAULT PARAMETERS

Most of slip models have been derived from long-period ground motions using the waveform inversion. The slip has been found not to be uniform in the source areas, in particular for large earthquakes with magnitude more than 7. Somerville et al. [7] defined fault asperities in a deterministic manner to quantify the properties of heterogeneous slip models; an asperity is defined to enclose fault elements whose slip is 1.5 or more times larger than the average slip in the fault. Kamae and Irikura [8] demonstrated that the asperity source models even for high-frequency motions are derived from the heterogeneous slip distribution by the waveform inversion of long-period ground motions.

The slip model of the 1993 Kushiro-oki earthquake shown in Fig. 4 has been derived from long-period ground motions (Takeo et al. [5]). However, the subfault (fault element) dimension is too large to quantify the asperity model applying the method of Somerville et al. [7]. Morikawa and Sasatani [9] constructed the asperity source model of the Kushiro-oki earthquake, which well explained broadband strong ground motions, using the empirical Green's function method (Irikura [10]). We cite their study hereafter.

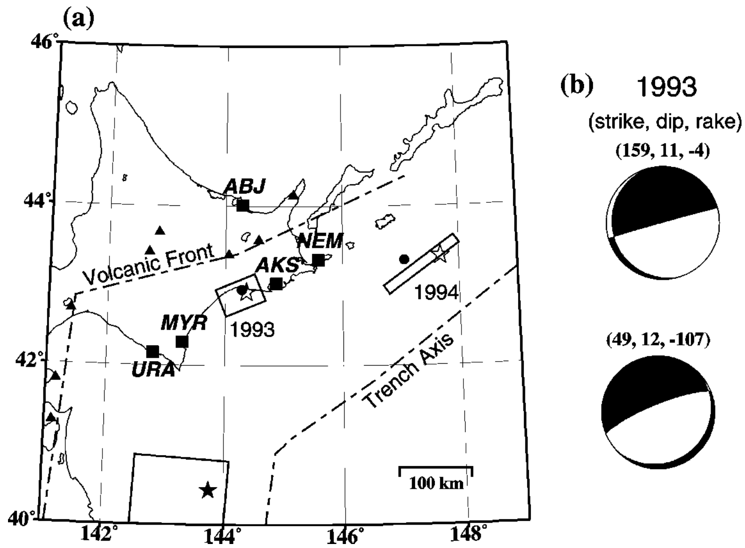


Fig. 6. (a) Location map showing strong motion stations (solid squares). Open stars are epicenters of the 1993 Kushiro-oki and the 1994 Hokkaido Toho-oki earthquake. A solid star is an epicenter of the 1994 Sanriku Haruka-oki earthquake. (b)Focal mechanism solutions for the main shock and the aftershock used in the EGF method. (after Morikawa and Sasatani [9])

Table 1. Strong motion stations

Station	MYR	AKS	NEM	URA	ABJ
Sensor	VS-3	VS-1	87-type	87-type	87-type
Frequency range (Hz)	0.002-30	0.025-20	0-10	0-10	0-10
Sampling rate (Hz)	50	200	50	50	50

Strong motion stations used in their study are shown in Fig. 6. MYR is a station of Hokkaido University and here a very wide frequency-band, velocity-type strong motion seismometer (VS3; Muramatsu et al., [11]) has been installed. AKS is a station operated by Central Research Institute of Electric Power Industry. The others are JMA (Japan Meteorological Agency) stations and an acceleration-type strong motion seismometer (JMA-87 type) was installed at these stations. NEM, AKS and MYR are located on a rock site, while ABJ and URA are located on a terrace. The data acquisition system at each station is listed in Table 1. They used only horizontal components of the observed records paying attention to S-waves.

First, Morikawa and Sasatani [9] examined the number of asperities and their locations of the Kushiro-oki earthquake based on the velocity waveforms as shown Fig. 7(c). At MYR and URA, located southwest of the epicenter, one large S-pulse is clearly observed in the waveforms while three S-pulses are found at ABJ, AKS and NEM which are located north and northeast of the epicenter. In addition to these, the duration of

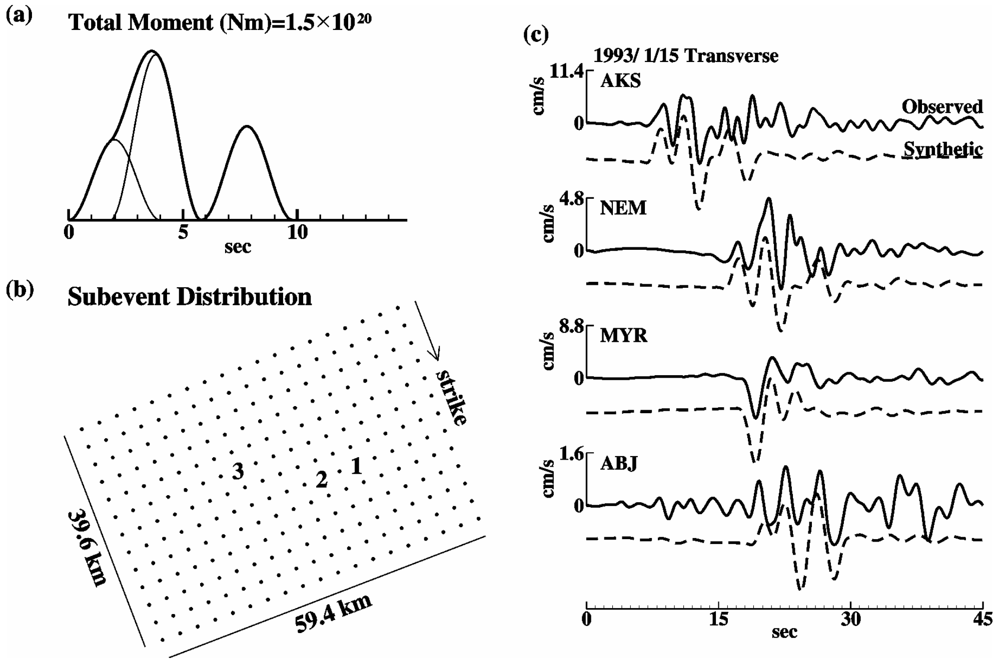


Fig. 7. **(a) Moment-rate function used in syntheses of strong motion records shown in (c). (b) Assumed fault plane and estimated locations of subevents (numbers 1, 2 and 3). (c) Comparison of observed velocity seismograms (solid lines) with synthetic ones (dashed lines). Both seismograms are high-cut filtered with a corner frequency of 0.5 Hz. (after Morikawa and Sasatani [9])**

Table 2. **Source parameters of element event used in EGF analysis.**

Date (UT)	1993/02/04/ 14:43
Epicenter	42.95^{0}N, 144.28^{0}E
Focal Depth	95 km
Seismic Moment	2.0 x 10^{16} Nm
Fault Area	1.44 km^2
Stress Drop	27.2 MPa

S-wave portion at the northeast side stations is longer than that at the southwest side stations. These facts imply that the rupture propagates to the southwest direction as noted by Takeo et al. [5] and that this event consists of three distinct asperities. They estimated the distribution of three asperities on the fault plane by matching the synthetic waveforms to the observed ones. Based on the aftershock distribution (Kasahara et al. [4]) and focal mechanism (Fig. 6(b); Takeo et al. [5]), the fault plane is assumed as shown in Fig. 7(b). They arranged 247 grid points at intervals of 3.3 km to cover the fault plane and simply treated an asperity as a point source on the grid point. The synthetic seismograms were calculated using reflection-transmission matrices (Kennett and Kerry [12]) and the discrete wave number method (Bouchon [13]). A bell shaped time function with a width of 4 sec (Fig. 7(a)) was used as the moment rate function; this width was obtained by a trial and error research. The initial break point, that is the location of the first asperity, was fixed to the hypocenter location after JMA. The locations of other two asperities were determined by using a grid search approach. Figures 7(b) and (c) show the estimated distribution of asperities and the comparison of observed velocity waveforms with synthetic ones. The synthetic waveforms calculated for the three-asperity model reproduce the observed ones well. The three-asperity model is qualitatively consistent with the slip distribution by Ide and Takeo [6].

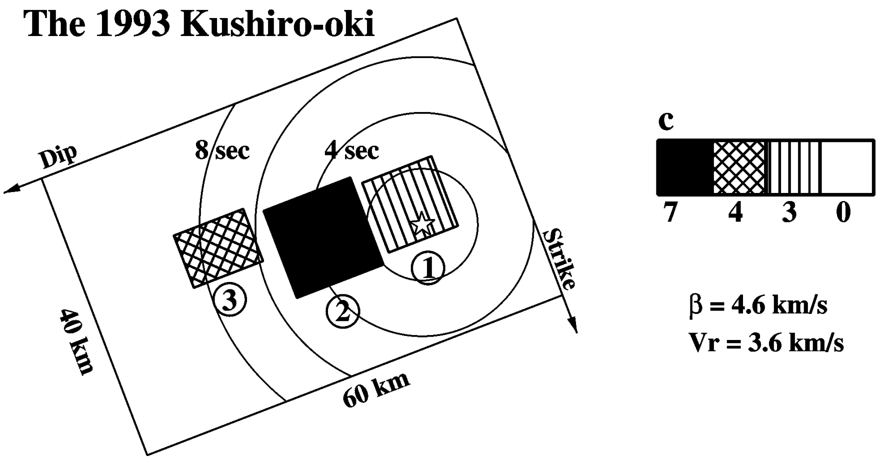


Fig. 8. Asperity source model of the 1993 Kushiro-oki earthquake estimated from the EGF method. A star and circles indicate the initial rupture point and rupture front, respectively. The asperity parameters are shown in Table 3. (after Morikawa and Sasatani [9])

Table 3. Asperity parameters of the 1993 Kushiro-oki earthquake.

Asperity No.	Area	Seismic moment	Stress drop
1	92.2 km^2	$3.1x10^{19}$ Nm	82 MPa
2	144.0	$1.4x10^{20}$	190
3	69.1	$2.7x10^{19}$	109
Total	305.3	$2.0x10^{20}$	-
#	800	$3.3x10^{20}$	42

#: Outer fault parameters by Takeo et al. [5]

Next, Morikawa and Sasatani [9] estimated the area, stress drop and rise time for each asperity by matching synthetic waveforms (displacement, velocity and acceleration seismograms) and acceleration spectra to the observed strong motion records and spectra. The synthetic waveforms and spectra were calculated by using the empirical Green's function method (Irikura [10]) and the asperity locations estimated above. For simplicity, they considered each asperity as a rectangular-shaped high stress drop area. They also assumed that the rupture started from a point on the fault plane and radially propagated with a constant velocity. After many trials, they obtained source (asperity) model and parameters of each asperity as shown in Fig. 8 and Table 3. The rupture process time is about 9 sec that is consistent with the estimate (about 10 sec) by Takeo et al. [5]. The comparison of the synthetic strong motion records and acceleration spectra with observed ones is show in Fig. 9. The synthetic waveforms considerably well reproduce not only the amplitudes but also the remarkable pulses of observed acceleration, velocity and displacement records; the synthetic spectra consequently reproduce the observed ones in the wide frequency range. A unique point in their source model is an existence of the asperity with extremely high stress drop of 100~ 200 MPa (Table 3). This extremely high stress drop is needed to explain the strength of high frequency strong motions.

The total seismic moment of their source model is about 60 percent of that of Takeo et al. [5] as shown in Table 3. This may indicate that the seismic moment is also released from the neighborhood of the asperities, but the extra moment release mainly contributes to the very low-frequency seismic waves which are outside of our target frequency range (0.3 – 10 Hz).

Finally, Morikawa and Sasatani [9] estimated the short-period level of the acceleration source spectrum, A, by averaging the amplitudes of the S-wave acceleration source spectrum through 1 to 10 Hz (Dan et al. [14]). They estimated the S-wave source spectrum of the Kushiro-oki earthquake at three rock site stations (MYR, AKS and NEM in Fig. 6), and obtained the average $A=4.2(\pm 0.26) \times 10^{20}$ Nm/s^2.

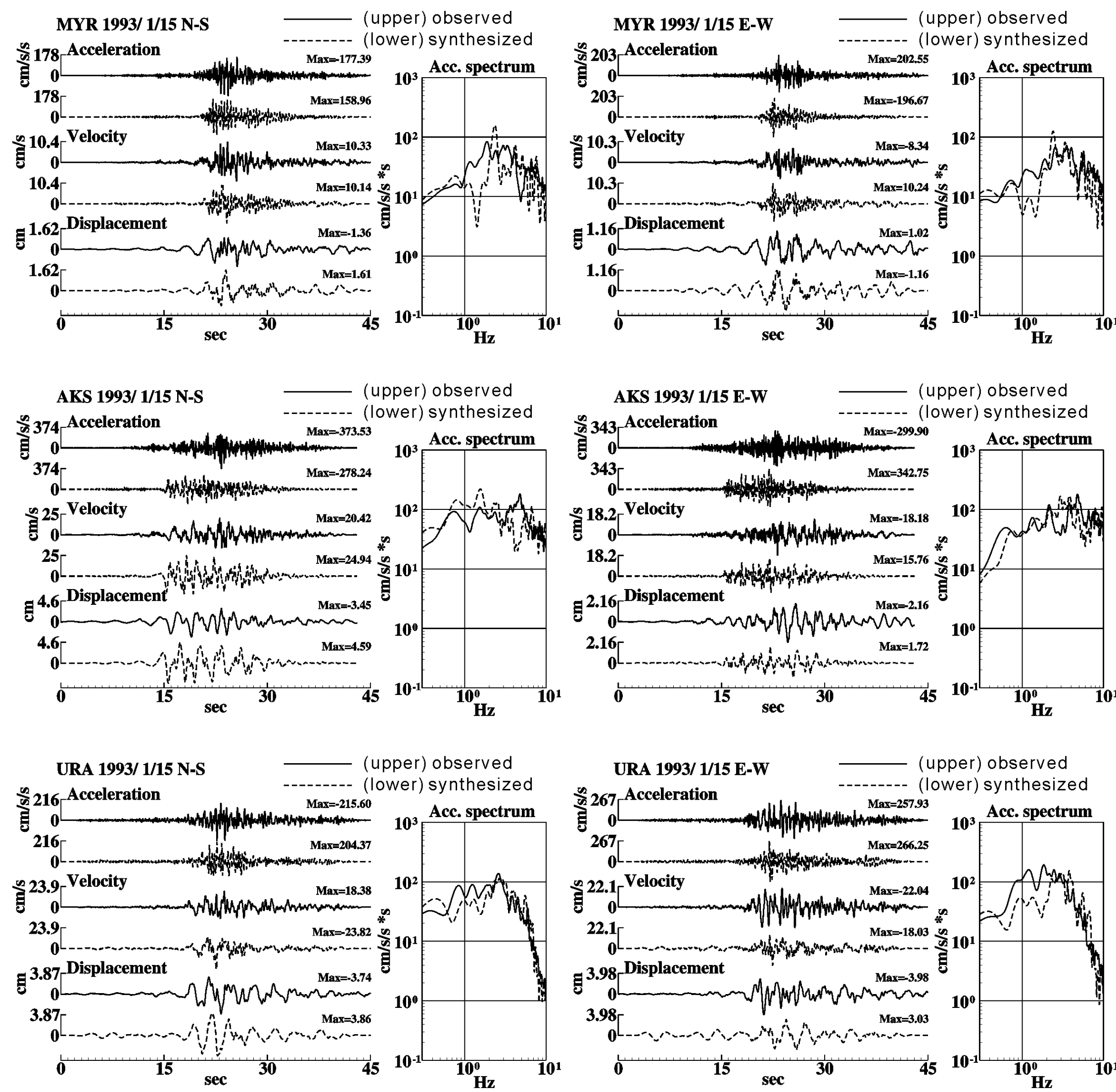


Fig. 9. **Comparison of observed strong motion records (acceleration, velocity and displacement time histories) and acceleration spectra with synthetic ones calculated from the source model shown in Fig. 8. (after Morikawa and Sasatani [9])**

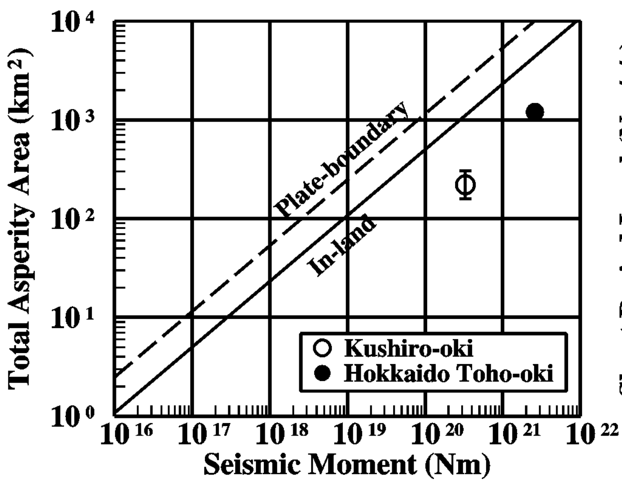
CORRELATION BETWEEN OUTER AND INNER FAULT PARAMETERS

Morikawa and Sasatani [9] examined a correlation between the outer (the entire source area and seismic moment) and inner (the areas and stress drops of asperities, and short-period level of the source spectrum) fault parameters. Based on an asperity model by Das and Kostrov [15] and short-period seismic wave radiation from a circular crack by Madariaga [16], Dan et al. [17] and Irikura et al. [1] obtained the correlation between the outer and inner fault parameters as

$$Mo = \frac{16}{7} r_f \cdot \sum_n (r_n{}^2 \Delta\sigma_n) , \quad (1)$$

$$A = 4\pi\beta^2 \sqrt{\sum_n (r_n \Delta\sigma_n)^2} \quad (2)$$

Here r_f is the radius of the entire source area, r_n and $\Delta\sigma_n$ is the radius and stress drop of n-th asperity, respectively, β is the S-wave velocity at the source region; a circular shape is simply assumed for the entire source area and the asperity. Above formulas are obtained assuming that the stress drop on the neighborhood of the asperities is zero. Substituting the asperity (inner) parameters in Tables 3 into equations (1) and (2), they got Mo=4.9 x 10^{20} Nm and A=3.9 x 10^{20} Nm/s^2 for the Kushiro-oki earthquake. These values for the Kushiro-oki earthquake are approximately the same as those (Mo=3.3 x 10^{20} Nm by Takeo et al. [5]; and A=4.2 x 10^{20} Nm/s^2 shown above) estimated from the different methods. The examination of the correlation between the outer and inner fault parameters for the Kushiro-oki earthquake indicates that the source model corresponds to the asperity model by Dan et al. [17] and Irikura et al. [1].



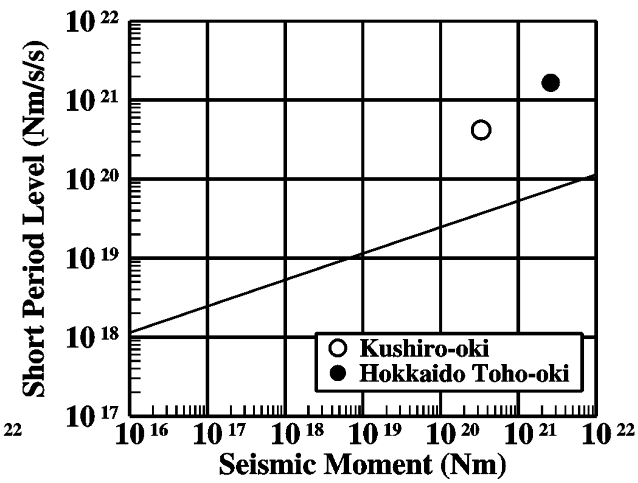


Fig. 10 (left). Total asperity area versus seismic moment for the 1993 Kushiro-oki and the 1994 Hokkaido Toho-oki earthquake. A solid line indicates the relationship for shallow in-land earthquakes by Somerville et al. [7] and a dashed line, that for plate-boundary earthquakes by Ishii and Sato [20]. (after Morikawa and Sasatani [9])

Fig. 11 (right). Short-period level of the acceleration source spectrum versus seismic moment for the 1993 Kushiro-oki and the 1994 Hokkaido Toho-oki earthquake. A solid line indicates the relationship for shallow in-land and plate-boundary earthquakes by Dan et al. [14]. (after Morikawa and Sasatani [9])

DISCUSSIONS

Somerville et al. [7] constructed the self-similar scaling relation between total areas of asperities and total seismic moments for California earthquakes. Miyakoshi et al. [18] and Miyake et al. [19] concluded that in-land earthquakes occurring in Japan also satisfied the same relation. For plate-boundary earthquakes Ishii and Sato [20] summarized the relationship between the main rupture area and total seismic moment.

Figure 10 shows the relationships between the total asperity areas and the total seismic moments for two intra-slab earthquakes (the 1993 Kushiro-oki and 1994 Hokkaido Toho-oki earthquakes) by Morikawa and Sasatani [9], in-land earthquakes by Somerville et al. [7] and plate-boundary earthquakes by Ishii and Sato [20]. Obviously the asperity areas for the two intra-slab earthquakes are considerably smaller compared with those for the in-land and plate-boundary earthquakes. The asperities for the intra-slab earthquakes have the extremely high stress drop as shown in Table 3. These facts indicate that the large intra-slab earthquakes radiate seismic energies from a mach small area in a short time compared with the in-land and plate-boundary earthquakes. This rupture process results in extremely strong radiation of short-period seismic waves from the source region as demonstrated by Morikawa and Sasatani [21].

In Fig.11, we compare the relationship between the short-period levels of the acceleration source spectrum (A) and the seismic moments for the intra-slab, in-land and plate-boundary earthquakes (Morikawa and Sasatani [9]). The A values for the large intra-slab earthquakes are much higher than those for the in-land and plate-boundary earthquakes. This fact is also related to characteristics of the asperity source model of intra-slab earthquakes mentioned above.

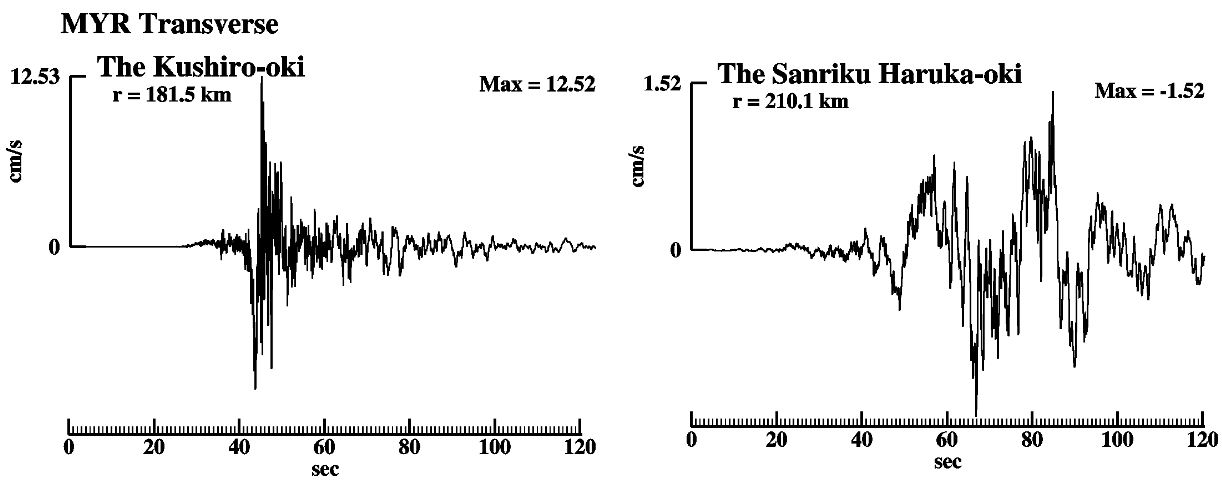


Fig. 12. Comparison of the velocity seismogram (transverse component) at MYR during the 1993 Kushiro-oki (intra-slab) earthquake with that during the 1994 Sanriku Haruka-oki (plate boundary) earthquake. r indicates the hypocentral distance. (after Morikawa and Sasatani [9])

Morikawa and Sasatani [9] directly showed the difference of the rupture process between the intra-slab and plate-boundary earthquakes by comparing observed strong motion records. Figure 12 shows the velocity waveforms during the Kushiro-oki earthquake and the 1994 Sanriku Haruka-oki earthquake (Mw=7.7; plate-boundary earthquake) at the station MYR. The epicenters of these events are shown in Fig. 6. Although the seismic moments and hypocentral distances are almost the same for both earthquakes, the Kushiro-oki record shows much short duration and very large amplitude compared with the 1994 Sanriku Haruka-oki record.

CONCLUSIONS

The 1993 Kushiro-oki earthquake (Mw7.6) is a large intra-slab earthquake that ruptured through a substantial part of the subducting plate. We investigated the outer and inner fault parameters of the Kushiro-oki earthquake to check applicability of the asperity source model to intra-slab earthquakes. The asperity (the inner fault) parameters of the Kushiro-oki earthquake are characterized by the small area and high stress drop. From confirmation of the correlation between the outer and inner fault parameters, we concluded the asperity source model to be applicable to large intra-slab earthquakes for prediction of strong ground motions from scenario earthquakes. However, we have to make more studies of asperity source models for intra-slab earthquakes to construct the self-similar scaling relation

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