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Key Points:

- The stress drop for intermediate-depth intraslab earthquakes are examined
- The stress drop in the oceanic mantle are larger than that in the oceanic crust
- The results are useful for understanding the intermediate depth earthquakes

Supporting Information:

- Readme

Correspondence to:
S. Kita,
kita@bosai.go.jp

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Stress drops for intermediate-depth intraslab earthquakes beneath Hokkaido, northern Japan: Differences between the subducting oceanic crust and mantle events

Saeko Kita[1] and Kei Katsumata[2]

[1]National Research Institute for Earth Science and Disaster Prevention, Earthquake and Volcano Research Unit, Tsukuba, Japan, [2]Hokkaido University, Graduate School of Science, Sapporo, Hokkaido, Japan

Abstract Spatial variations in the stress drop for 1726 intermediate-depth intraslab earthquakes were examined in the subducting Pacific plate beneath Hokkaido, using precisely relocated hypocenters, the corner frequencies of events, and detailed determined geometry of the upper interface of the Pacific plate. The results show that median stress drop for intraslab earthquakes generally increases with an increase in depth from ∼10 to 157 Mpa at depths of 70–300 km. More specifically, median stress drops for events in the oceanic crust decrease (9.9–6.8 MPa) at depths of 70–120 km and increase (6.8–17 MPa) at depths of 120–170 km, whereas median stress drop for events in the oceanic mantle decrease (21.6–14.0 MPa) at depths of 70–170 km, where the geometry of the Pacific plate is well determined. The increase in stress drop with depth in the oceanic crust at depths of 120–170 km, for which several studies have shown an increase in velocity, can be explained by an increase in the velocity and a decrease in the water content due to the phase boundary with dehydration in the oceanic crust. Stress drops for events in the oceanic mantle were larger than those for events in the oceanic crust at depths of 70–120 km. Differences in both the rigidity of the rock types and in the rupture mechanisms for events between the oceanic crust and mantle could be causes for the stress drop differences within a slab.

1. Introduction

Since the stress drop associated with an earthquake is an important measure that characterizes earthquake faulting, knowing the characteristics of stress drops is very important for making reliable strong motion predictions. Several studies have examined spatial variations in the stress drops associated with earthquakes. For example, *Shearer et al*. [2006] observed spatially coherent stress drop variations for ∼60,000 small earthquakes ($M_L < 3.1$) in southern California, but they were unable to obtain a correlation between stress drop and distance from the San Andreas and other major faults. *Allmann and Shearer* [2009] investigated the global variation in stress drop for ∼2000 earthquakes ($M_b > 5.5$) and found a certain level of dependence on the focal mechanism and tectonic region. Meanwhile, *Oth* [2013] estimated the stress drop for ∼4000 events ($2.7 < M_w < 7.9$), mainly in the crust beneath the Japan archipelago, in order to examine spatial variations in stress drop, and found differences in stress regimes tend to be related to variations in the stress drop for events. In northeastern Japan, *Uchide et al*. [2014] examined spatial variations in stress drop for ∼1500 earthquakes (M_w 3.0–4.5) at depths shallower than 80 km beneath Tohoku-oki prior to the M 9.0 Tohoku-oki earthquake, and suggested a depth dependence of stress drop for interplate earthquakes at depths of 30–60 km.

Furthermore, while numerous studies on the stress drop associated with large intraslab earthquakes have been conducted [e.g., *Mikumo*, 1971; *Wyss and Molnar*, 1972; *Chung and Kanamori*, 1980; *Fukao and Kikuchi*, 1987; *Takeo et al*., 1993; *Ide and Takeo*, 1996; *Houston*, 2001; *Asano et al*., 2003; *Miyatake* et al., 2004; *Suzuki et al*., 2009; *Oth et al*., 2009; *Kuge et al*., 2010; *Prieto et al*., 2012; *Oth*, 2013], but only a few studies have examined the stress drop associated with small to midsize intraslab earthquakes, or the stress-drop characteristics (e.g., spatial variations) for intraslab earthquakes. *Asano et al*. [2003] estimated the stress drop for six large shallow-depth intraslab earthquakes, and found that it tends to increase with the depth of the event.

Large intraslab earthquakes tend to exhibit strong short-period ground motion [e.g., *Morikawa and Sasatani*, 2003], and the stress drop for such earthquakes tends to be larger than that for interplate earthquakes or

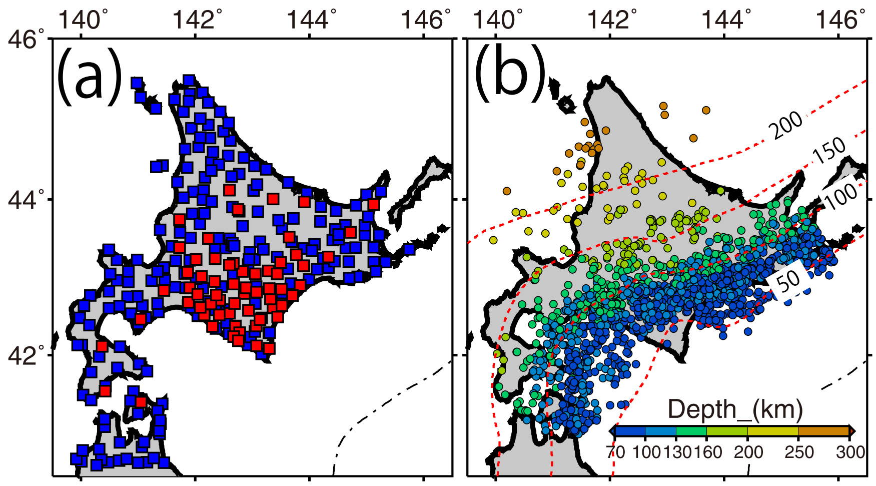

Figure 1. (a) Distribution of permanent seismic stations (blue squares) and temporary seismic stations (red squares [*Katsumata et al*., 2002]) used in this study. (b) Distribution of earthquakes (circles color-coded by depth) shown in map view. Red-dashed lines show the iso-depth contours of the upper surface of the Pacific plate. Color scale shows the depth of events.

inland earthquakes with the same seismic moment [e.g., *Morikawa and Sasatani*, 2003; *Asano et al*., 2003]. Large intraslab (intraplate) earthquakes have occurred below populated or nearby city areas, causing severe damage as a result of strong motion (such as the 1987 M_j (JMA magnitude) 6.7 off the East Coast of Chiba Prefecture [*Mizokami*, 1990] earthquake; the 1993 M_j 7.8 Kushiro-oki earthquake; the 2001 M_j 6.7 Geiyo earthquake [e.g., *Kahehi*, 2004]). Therefore, knowing the stress-drop characteristics for intraslab earthquakes in advance is very important for implementing realistic disaster-prevention measures.

A dense nationwide seismic network, with a station separation of approximately 20 km, has been developed to cover the entire Japanese archipelago. This network integrates data from Hi-net, operated by the National Research Institute for Earth Science and Disaster Prevention (NIED), with data from seismic networks operated by universities, the Japan Meteorological Agency (JMA), and various municipal governments. In the present study, stress drops were estimated for 1726 intraslab events ($2.0 < M_j < 5.0$) at depths of 70–300 km, and spatial variations (dependence on focal depth and normal distance from the plate interface) were investigated in order to clarify the nature of intraslab earthquakes, using results (relocated hypocenters, corner frequencies of events, and a detailed geometry of the Pacific plate) obtained by analysis of data obtained from the dense nationwide seismic network beneath Hokkaido (Figure 1a).

2. Data and Methods

Assuming the circular crack model [*Eshelby*, 1957], a static stress drop $\Delta\sigma$ was calculated using the fault radius *r* as follows:

$$\Delta\sigma = \frac{7M_0}{16r^3} \tag{1}$$

where M_o is the seismic moment.

Using the fault plane radius *r* expressed by *Sato and Hirasawa* [1973], equation (1) can be expressed as:

$$\Delta\sigma = \frac{7M_0}{16} \cdot \left(\frac{2\pi f_c}{CsVs}\right)^3 \tag{2}$$

where f_c, C_s, and V_s are the corner frequency, a constant, and the S-wave velocity, respectively. In this study, C_s is assumed as 1.9, and V_s is assumed to be 4.6 km/s (for oceanic mantle) or 4.0 km/s (for oceanic crust). The corner frequencies used were those estimated by *Kita et al*. [2014] using the S-coda wave spectral ratio method [e.g., *Mayeda et al*., 2007]. Using the S-coda wave, the effect of ray paths from sources to stations can be removed, which allows corner frequencies for events to be estimated more accurately. The seismic moments used in the present study were estimated from the JMA magnitude (M_j) and the relationship

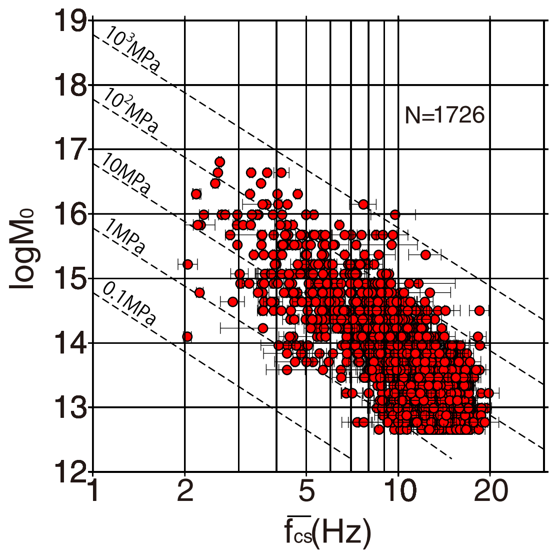

Figure 2. Corner frequencies for events plotted against seismic moment used in this study (originally estimated by *Kita et al*. [2014]). Black bars show standard errors in the estimation of the corner frequencies. Dashed lines denote isovalue lines of static stress drops at 0.1, 1, 10, 100, and 1000 MPa, using equation (2) (C_s and V_s were, respectively, assumed as 1.9 and 4600 km/s). The seismic moment, M_0, is estimated from $\log M_0 = 1.5M_w + 9.1$ [*Kanamori*, 1977]. The value of M_w for each event is estimated using $M_w = 0.439M_j + 0.0689\ M_j^2 + 1.22$ [*Edwards and Rietbrock*, 2009].

between the moment magnitude and the seismic moment [*Kanamori*, 1977]. The value of M_w for each event was estimated using the relationship between the JMA magnitude and the moment magnitude [*Edwards and Rietbrock*, 2009]. A plot of the obtained corner frequencies values versus seismic moment for the events used in this study is presented in Figure 2.

To obtain a detailed spatial distribution of stress drops for intermediate-depth intraslab events, it was necessary to use the precise locations of events with an estimated corner frequency. Therefore, earthquakes beneath the island of Hokkaido were relocated, and events in the oceanic crust and mantle were selected using the detailed geometry of the upper surface of the subducting Pacific plate [*Kita et al*., 2010b].

To avoid a systematic shift of hypocenters caused by differences in the velocity structure, hypocenters were determined using the velocity structure model used in the routine procedure for hypocenter location at Tohoku University [*Hasegawa et al*., 1978]. This is because the geometry of the surface of the Pacific plate (Figure 1b) is determined using hypocenters relocated by *Kita et al*. [2010a], which uses the same structure model. A total of 11,949 events that occurred in Hokkaido at depths of 70–300 km (August 1999 to December 2012) were relocated using the code for the double-difference location method (DDLM) [*Waldhauser and Ellsworth*, 2000]. Not all of the earthquakes had corner frequency data, but approximately 12,000 events were obtained for problems of forming event pairs during the DDLM relocation. Hypocenter parameters and phase data in the JMA catalog were used as initial hypocenters and arrival time data, respectively, for the relocations. Arrival time data at temporary stations reported by *Katsumata et al*. [2002] (August 1999 to April 2001) were also used. The spatial distribution of the stations used in the relocation process is shown in Figure 1a. Event pairs were selected that had epicentral separations of less than 20 km and more than eight arrival time differences with respect to their neighbors. In total, 1,040,807 arrival time differences were obtained from catalog data for P-waves, and 619,478 for S-waves. The final results of the inversion were obtained after 12 iterations, which reduced the average root mean square value of double differences from 0.214 s to 0.0677 s. Estimated relocation errors using the singular value decomposition method were ~1.0 km in both the depth and horizontal directions in the cluster beneath southern Hokkaido. The spatial distributions of all relocated hypocenters and relocated hypocenters with corner frequencies are shown in supporting information Figure S1 and Figure 1b, respectively.

For events at depths of 70–170 km, earthquakes beneath the island of Hokkaido were classified into oceanic crust or oceanic mantle events, according to the normal distance from the upper interface of the subducting Pacific plate beneath Hokkaido [*Kita et al*., 2010b]. Additionally, oceanic mantle events were classified into interplane events (i.e., events that are located between the upper and lower planes of the double seismic zone in the oceanic mantle) and lower-plane events, according to the classification criteria for intraslab earthquakes reported by *Kita et al*. [2010b]. Earthquakes occurring between 0 and 10 km from the plate interface were classified as upper plane events in double seismic zones (events expected to occur in the oceanic crust). Earthquakes 10–23 km deeper than the plate interface were classified as interplane events, and earthquakes more than 23 km from the interface were classified as lower plane events. Since the thickness of the oceanic crust is generally reported to be 7 km [e.g., *Minshull et al*., 1998], 10 km was used for the Moho depth, while taking into consideration estimation errors in the location of the plate interface and

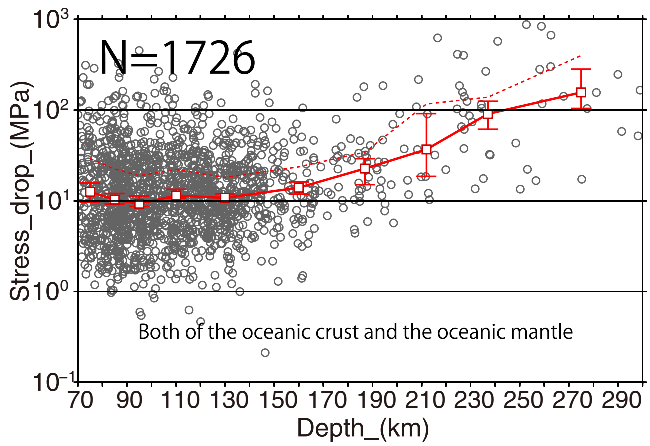

Figure 3. Estimated stress drops for all intraslab earthquakes plotted against depth. Gray dots show individual stress drops for events. Red open squares and red error bars, respectively, denote the median stress drops and the 95% confidence level for the median stress drop at depths of 70–80 km, 80–90 km, 90–100 km, 100–120 km, 120–140 km, 140–175 km, 175–200 km, 200–225 km, 225–250 km, and 250–330 km. The 95% confidence levels for the median stress drops are based on the results of 2000 times bootstrap resampling. The red line and colored dashed line, respectively, connect the median stress drop points and the average stress drop points.

hypocenters. As the lower depth limit of low-angle thrust-type events and repeaters, which are expected to occur on the plate boundary, is ~70 km beneath Hokkaido [*Kita et al.*, 2010a], upper plane events in this study are expected not to include interplate events.

3. Results

Figure 3 shows the stress drop and median stress drop for all intraslab earthquakes at all depth ranges (70–300 km), assuming 4.6 km/s for Vs. The median stress drop generally increases from approximately 10–157 MPa with focal depth, whereas it decreases slightly at depths of 70–100 km. The average stress drop for events at depths of 70–300 km also shows generally increase with focal depth. The values of the median stress drop for events and the average stress drop used in Figure 3 are shown in Table 1.

Figure 4 shows the stress drop for intraslab earthquakes at depths of 70–170 km in the oceanic crust and mantle, assuming 4.6 km/s for V_s. The values of the median stress drop and the average stress drop in the oceanic crust and oceanic mantle used in Figures 4a and 4b are shown in Tables 2 and 3. As can be seen in the figure, stress drop for upper plane events (events in the oceanic crust) was mainly from 2 to 30 MPa (Figure 4a), whereas that for both interplane and lower plane events is from 4 to 70 MPa (Figures 4b and 4c). The median stress drop for events in the oceanic crust (upper-plane events) is 5–13 MPa (generally less than 10 MPa) (Figure 4a), whereas in the oceanic mantle it is 11–21 MPa (generally more than 10 MPa) (Figure 4b). The median stress drop for events in the oceanic crust decreases slightly at depths of 70–110 km and increases at depths of 110–170 km, whereas the median stress drop for events in the oceanic mantle did not change significantly at depths of 70–170 km. Comparing the median stress drop for events in the oceanic crust with that for events in the oceanic mantle at the same depths, the former tends to be smaller than the latter at depths of 70–140 km (Figures 4a and 4b). The average stress drop in the oceanic crust also tends to be smaller than that in the oceanic mantle at the same depths (Figures 4a and 4b, and Tables 2 and 3).

The stress-drop characteristics for interplane events (events between the double seismic zone) and lower plane events, both of which are in the oceanic mantle, are almost the same, with a median stress drop of

Table 1. Values of Median Stress Drops and Average Stress Drop for Events Within the Pacific Slab With a vs of 4.6 km/s at Depths of 70–300 km Shown in Figure 3

	Events of Median Stress Drop									
Depth (km)	The Values of the Median Stress Drop (Mpa)		f c (Hz)		Mo (N·m)		Mj		95% Confidence Level of the Median Stress Drop (Mpa)	The Value of the Average Stress Drop (Mpa)
70–80	12.6	(12.4, 12.8)	8.75	14.3	9.2E+13	2.2E+13	3.1	2.6	9.74-15.8	29.1
80–90	10.3		15.9		1.3E+13		2.4		9.22-12.0	22.4
90–100	9.32		8.78		6.8E+13		3		8.66-11.3	19.0
100–120	11.4		16.5		1.3E+13		2.4		10.8-13.3	22.2
120–140	10.7		10.1		5.1E+13		2.9		10.1–11.9	18.0
140–175	14.0	(13.9, 14.1)	12.2	14.8	3.8E+13	2.2E+13	2.8	2.6	11.9–16.2	23.6
175–200	22.8	(22.4, 23.1)	3.63	15.8	2.3E+15	2.9E+13	4.1	2.7	15.1–29.2	34.4
200–225	36.8		12.6		9.2E+13		3.1		18.6–91.2	117
225–250	90.4	(86.7, 94.0)	9.96	4.11	4.4E+14	6.7E+15	3.6	4.4	61.7–125	139
250–300	157		13.5		3.2E+14		3.5		104–283	400

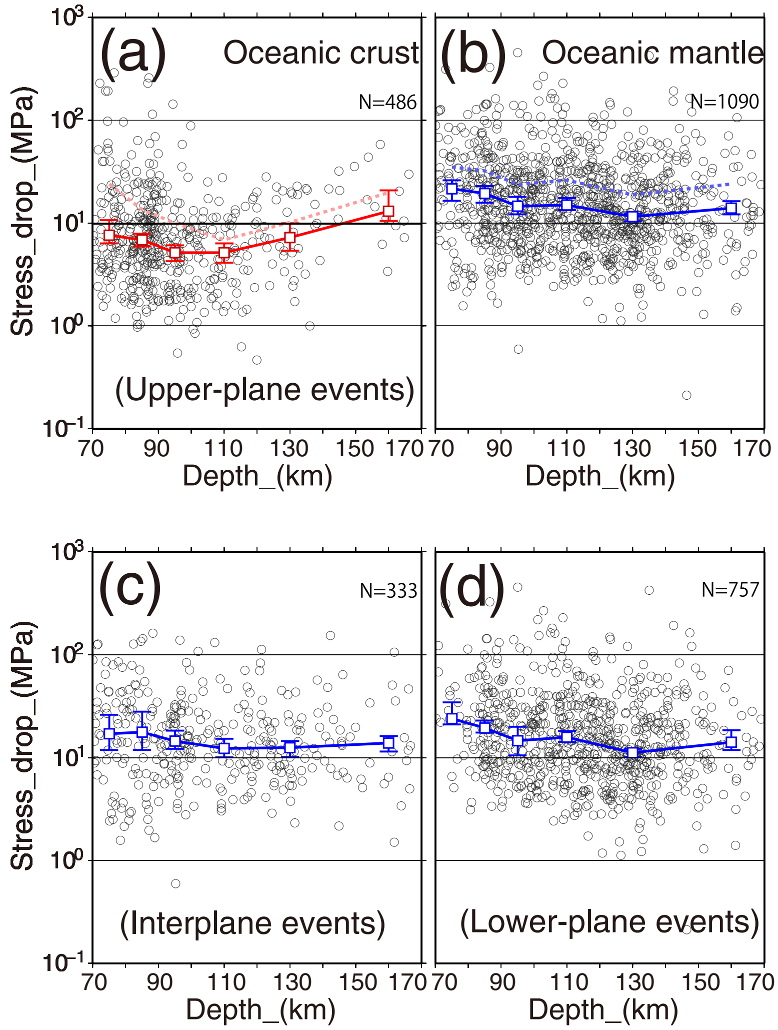

Figure 4. Estimated stress drops at depths of 70–170 km plotted against depth for (a) events in the oceanic crust, (b) events in the oceanic mantle, (c) interplane events in the double seismic zones, and (d) lower-plane events. Gray dots show the individual stress drops for events. Color-coded open squares and error bars, respectively, denote the median stress drops and 95% confidence level for the median stress drops at depths of 70–80 km, 80–90 km, 90–100 km, 100–120 km, 120–140 km, and 140–180 km. The colored lines (in Figures 4a–4d) and colored dashed lines (in Figures 4a and 4b), respectively, connect the median stress drop points and the average stress drop points.

more than 10 MPa (Figures 4c and 4d). Both are larger than the median stress drop for upper plane events (Figure 4a) at depths of 70–140 km. An examination of the lateral stress-drop variation for intraslab earthquakes showed that stress drops with these characteristics could also be found beneath eastern and western Hokkaido.

Table 2. Values of Median Stress Drops and Average Stress Drop for Events in the Oceanic Crust With a vs of 4.6 km/s in the Pacific Slab at Depths of 70–180 km Shown in Figure 4a

	Events of Median Stress Drop									
Depth (km)	The Values of the Median Stress Drop (Mpa)		f c (Hz)		Mo (N·m)		Mj		95% Confidence Level of the Median Stress Drop (Mpa)	The Value of the Average Stress Drop (Mpa)
70–80	7.60		9.95		3.8E+13		2.8		6.33-10.7	24.3
80–90	6.84	(6.8, 6.9)	13.9	12.7	1.3E+13	1.7E+13	2.4	2.5	5.91-7.91	13.7
90–100	5.14	(5.1, 5.2)	11.5	13.8	1.7E+13	9.8E+12	2.5	2.3	4.27-6.09	10.2
100–120	5.18	(5.1, 5.2)	15.0	6.55	7.6E+12	9.2E+13	2.2	3.1	4.13-6.36	6.96
120–140	7.25		13.9		2.2E+13		2.6		5.37-10.0	10.3
140–180	13.1		13.5		2.9E+13		2.7		10.5–20.8	20.0

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Table 3. Values of Median Stress Drops and Average Stress Drop for Events in the Oceanic Mantle With a vs of 4.6 km/s in the Pacific slab at Depths of 70–180 km Shown in Figures 4b and 5

	Events of Median Stress Drop									
Depth (km)	The Values of the Median Stress Drop (Mpa)		f c (Hz)		Mo (N·m)		Mj		95% Confidence Level of the Median Stress Drop (Mpa)	The Value of the Average Stress Drop (Mpa)
70–80	21.6		15.5		2.9E+13		2.7		16.5–26.2	35.6
80–90	19.4		13.6		3.8E+13		2.8		15.7–22.9	32.7
90–100	14.6		19.5		9.8E+12		2.3		12.2–18.0	24.1
100–120	14.9		15.0		2.2E+13		2.6		13.4–17.5	26.4
120–140	11.5	(13.9, 14.1)	12.2	14.75	3.8E+13	2.2E+13	2.8	2.6	10.4–12.4	19.1
140–180	14.0	(11.5, 11.5)	9.43	5.65	6.8E+13	3.2E+14	3	3.5	12.2–16.3	24.2

Figure 5 shows the median stress drop for events in the oceanic crust and mantle. For events in the oceanic crust, the stress drop was also estimated using 4.0 km/s for V_s, which is assumed for a realistic velocity for the oceanic crust beneath Hokkaido based on the results using guided wave beneath eastern Hokkaido [*Shiina et al*., 2014] and the results of seismic imaging beneath the Hokkaido corner [*Kita et al*., 2012], eastern Hokkaido [*Nakajima et al*., 2009] and Tohoku [*Tsuji et al*., 2008]. The values of the median stress drop (and the average stress drop) in the oceanic crust with a Vs of 4.0 km/s and in the oceanic mantle with a Vs of 4.6 km/s used in Figure 5 are shown in Tables 4 and 3. The median stress drop for events in the oceanic crust decreases from 11.6 to 7.87 MPa at depths of 70–120 km, and it increases from 7.89 to 19.9 MPa at depths of 120–170 km (Figure 5b). Comparing the median stress drop for events in the oceanic crust with a V_s of 4.0 km/s and that in the oceanic mantle with a V_s of 4.6 km/s, it can be clearly seen that the stress drop in the oceanic crust is smaller than that in the oceanic mantle at depths of 70–120 km. In addition, taking into account the 95% confidence level, which is obtained from the results of 2000 times bootstrap resampling, the median stress drop in the oceanic crust is clearly different from that in the oceanic mantle at depths of 70–120 km, but appears to be almost the same as that in the oceanic mantle at depths of 140–170 km.

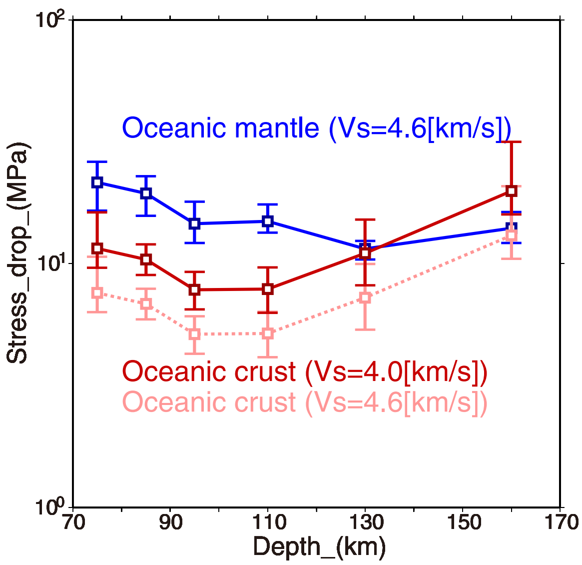

Figure 5. Median stress drops for intraslab events at depths of 70–80 km, 80–90 km, 90–100 km, 100–120 km, 120–140 km, and 140–180 km plotted against depths. Blue, red, and pink squares, respectively, denote the median stress drops for events in the oceanic mantle with V_s of 4.6 km/s, events in the oceanic crust with V_s of 4.0 km/s, and events in the oceanic crust with V_s of 4.6 km/s. Blue, red, and pink error bars, respectively, denote a 95% confidence level of the median stress drops for events in the oceanic mantle with V_s of 4.6 km/s, events in the oceanic crust with V_s of 4.0 km/s, and events in the oceanic crust with V_s of 4.6 km/s. The colored lines connect the median stress drop points.

4. Discussion

4.1. Interpretations of Differences in Stress Drop Between Oceanic Crust and Oceanic Mantle

In this study, we presented a stress drop difference for oceanic mantle and oceanic crust events. In order to test that this stress drop difference is convincing at depths of 70–120 km, we assume that the stress drop is constant and calculated rigidity μ using equation (2), $Vs=\sqrt{\mu/\rho}$ and the parameters of median stress drop events. In our test, we assumed ρ (2996 kg/m^3 for the oceanic crust and 3310 kg/m^3 for the oceanic mantle) measured by *Christensen* [1996]. If constant stress drop is 15 MPa, calculated rigidity was 27–34 GPa for the oceanic crust and 59–77 GPa for the oceanic mantle. The former is smaller than the rigidity measured by *Christensen* [1996] (45–48 GPa) for oceanic crust, whereas the latter is not particularly unreasonable for mantle (67–75 GPa, *Christensen* [1996]). If

Table 4. Values of Median Stress Drops and Average Stress Drop for Events in the Oceanic Crust With a vs of 4.0 km/s in the Pacific Slab at Depths of 70–180 km Shown in Figure 5

	Events of Median Stress Drop									
Depth (km)	The Values of the Median Stress Drop (Mpa)		f c (Hz)		Mo (N·m)		Mj		95% Confidence Level of the Median Stress Drop (Mpa)	The Value of the Average Stress Drop (Mpa)
70–80	11.6		9.95		3.8E+13		2.8		9.63–16.3	36.9
80–90	10.4	(10.4,10.4)	13.9	12.7	1.3E+13	1.7E+13	2.4	2.5	8.99–12.0	20.9
90–100	7.82	(7.8,7.8)	11.5	13.8	1.7E+13	9.8E+12	2.5	2.3	6.50–9.26	15.5
100–120	7.87	(7.8,7.9)	15.0	6.55	7.6E+12	9.2E+13	2.2	3.1	6.28–9.67	10.6
120–140	11.0		13.9		2.2E+13		2.6		8.16–15.2	15.7
140–180	19.9		13.5		2.9E+13		2.7		15.9–31.7	30.5

stress drop was a constant 8 Mpa, calculated rigidity was 41–52 GPa for the oceanic crust and 118–190 GPa for the oceanic mantle. Therefore, the value of calculated rigidity of mantle is much larger than the measured rigidity, whereas the former is not particularly unreasonable for crust. The results of these tests imply that the stress drops could not be constant among oceanic crust and mantle, and that stress drops for events in the oceanic mantle could be larger than those in the oceanic crust if the measured rigidities for rocks are adopted.

A larger stress drop for events in the oceanic mantle than in the oceanic crust has been reported by several authors for individual large intraslab earthquakes. *Kakehi* [2004] examined the source process for the 2001 Mj 6.7 Geiyo earthquake and indicated that the asperity of an intraslab earthquake consists of two patches: one in the oceanic crust, and the other in the slab mantle. *Miyatake et al*. [2004] also estimated the stress drop at two patches of the asperity of the 2001 Mj 6.7 Geiyo earthquake, and found that the stress drop at the deeper patch was larger than that at the shallow patch. Taking into account the results of *Kahehi* [2004], the results of *Miyatake et al*. [2004] suggest that stress drop in the slab mantle is larger than that in the slab crust. *Kuge et al*. [2010] examined the source process for the 2005 M_w7.8 Tarapaca earthquake beneath northern Chile using regional and teleseismic waveforms. That study also identified one patch in the oceanic crust, and one in the slab mantle. The fault plane for this earthquake was horizontal, and based on the optimal solution, the stress drop in the slab mantle was larger than that in the slab crust. All the above observations are consistent with the results of the present study.

The findings of the present study regarding the difference in stress drop for events in the oceanic crust and in the oceanic mantle, which are constrained by numerous earthquake events, are very important for understanding the nature of intermediate-depth intraslab earthquakes. Possible interpretations of the findings are given below. A schematic cross-sectional view of the oceanic crust and mantle in the Pacific slab beneath Hokkaido is shown in Figure 6a.

Kita et al. [2010b] applied stress tensor inversion methods to investigate the focal mechanisms for intermediate-depth intraslab events, including events between the double seismic zones beneath northeastern Japan, and estimated the neutral plane of the stress field from the downdip compression to downdip tension in the Pacific plate. The results showed that the neutral plane in the plate is located about 10 km from the plate interface beneath eastern Hokkaido. The stress field for the downdip compression is dominant at depths of 0–9.5 km beneath the interface, whereas that for the downdip extension is dominant at depths of more than 9.5 km. As the depth of the neutral plane beneath east Hokkaido is almost the same as that of the oceanic Moho (when the errors in estimating the interface and relocation are considered), the results of the present study regarding the difference in stress drop between the oceanic crust and mantle could be a reflection of the intermediate-depth stress regime in the Pacific plate.

Allmann and Shearer [2009] found some degree of dependence of the stress drop on the focal mechanism of earthquakes. *Oth* [2013] estimated the stress drop for events beneath the Japan archipelago and showed that the stress drop for normal fault events in the continental crust and uppermost mantle is larger than that for thrust-type events. The stress regime difference between the oceanic mantle and crust possibly cause a difference in the stress drop for events in the two areas.

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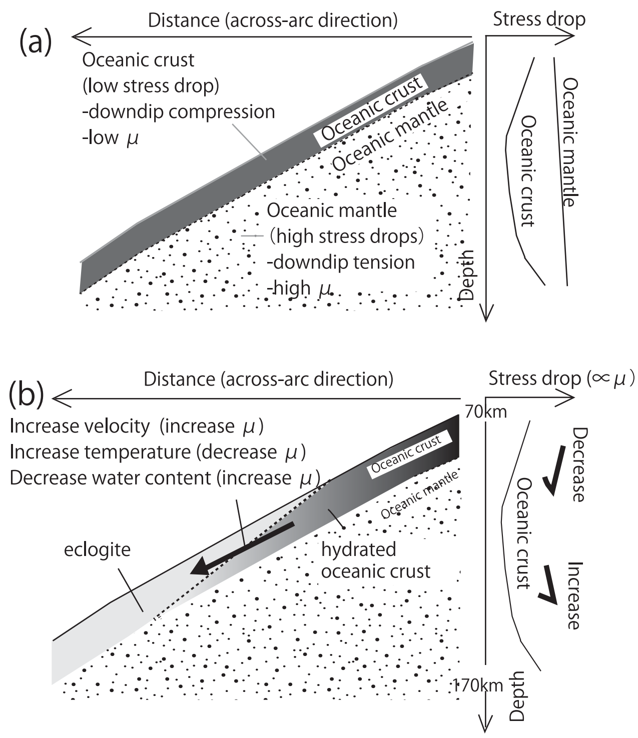

Figure 6. (a) Schematic cross-sectional view beneath Hokkaido including the subducting Pacific plate and pattern diagram of median stress drops for events in the Pacific plate. (b) Detailed schematic view of the oceanic crust beneath Hokkaido and a pattern diagram of median stress drops for events in the oceanic crust.

It is also possible that the difference between the rigidity (μ) of the rock types in the oceanic crust and mantle is responsible for the difference in the stress drop, because the stress drop is generally thought to be proportional to the rigidity. Since the seismic moment M_o can be written as $M_o = \mu DS = \mu D\pi r^2$ (where D is the average displacement on a fault plane), assuming a circular crack model, equation (1) can also be expressed as:

F

$$\Delta\sigma = \frac{7\pi}{16r} \cdot \mu D. \qquad (3)$$

If D/r is almost the same (constant) for events in the oceanic crust and mantle, the stress drop is then simply proportional to the rigidity. From the measurement, results for density and V_s for rock under a confining pressure of 1.0 GPa obtained by *Christensen* [1996], the value of rigidity for the uppermost mantle rock is about 67–75 GPa, and that for crustal rock (assumed depths range are 70–120 km) is 45–48 GPa. This would lead to oceanic crust event rigidity values that are 60–71% of that for mantle events. On the other hand, the observed stress-drop ratio (oceanic crust/oceanic mantle) at the same depth is about approximately 53% at depths of 70–120 km with a Vs of 4.6 km/s for oceanic mantle and of 4.0 km/s for oceanic crust. The stress-drop ratio at the same depths is about 46% with a Vs of 4.6 km/for oceanic mantle and of 4.2 km/s for oceanic crust. It is somewhat unpersuasive that the rigidity differences for events between oceanic mantle and oceanic crust are the only causes of oceanic crust and mantle stress drop differences. Moreover, the values of D/r for oceanic crust (at depths of 70–120 km) are 74–89% of that for mantle events at the same depths if the observed stress-drop values and the rigidities mentioned above are used (see supporting information Table S1), which implies that the values of D/r are not the same both in oceanic crust and oceanic mantle at the same depths. Therefore, the magnitude of the difference in stress drop between the oceanic crust and mantle could be explained by the differences in both rigidity and D/r.

The reason why D/r differences exist for oceanic crust and mantle events at the same depth, which would imply different rupture mechanisms in the oceanic crust and mantle, will be considered next. Several hypotheses for the cause of intermediate-depth intraslab earthquakes have been proposed. These include dehydration embrittlement [e.g., *Raleigh and Paterson*, 1965; *Green and Houston*, 1995; *Kirby*, 1995; *Houston*, 2007] and thermal runaway [e.g., *Keleman and Hirth*, 2007]). Dehydration embrittlement is thought to be the dominant cause of intraslab earthquakes, as evidenced by the results of several petrological experimental studies [e.g., *Jung et al*., 2004, 2009; *Dobson et al*. 2002]. Precise studies as to the cause of the intermediate-depth events in the oceanic crust beneath northeastern Japan show that the dehydration embrittlement hypothesis can explain the peak depth of the seismicity concentration in the oceanic crust (upper plane seismic belt, Tohoku and/or eastern Hokkaido [*Kita et al*., 2006; *Tsuji et al*., 2008]; the Kanto area [*Hasegawa et al*., 2007]; and the Hokkaido corner [*Kita et al*., 2010a]). However, few precise observational studies regarding dehydration embrittlement have been performed for the oceanic mantle. Therefore, the occurrence mechanisms for oceanic mantle events could be different from those in the oceanic crust.

4.2. Similarity of stress Drop for Events on the Interplane and Lower Plane of Double Seismic Zones in the Oceanic Mantle

Beneath northeastern Japan, double seismic zones are well developed in the subducting Pacific plate [e.g., *Hasegawa et al.*, 1978]. Recently, events occurring between double seismic zones were found by *Kita et al.* [2010b] using seismic observational data from the nationwide network. Investigating the nature of interplane earthquakes is important for understanding the cause of intraslab earthquakes. In the present study, interplane events are found to have a similar median stress drop as lower-plane events. This is probably because: (1) the stress regime for interplane events beneath Hokkaido is downdip tension and is the same regime as that for lower-plane events, and (2) both interplane and lower plane events occur in the oceanic mantle, so the physical properties of the component rock are similar.

4.3. Focal-Depth Variation in Stress Drop for Events in the Oceanic Crust

In the oceanic crust, the median stress drop for upper plane events in the depth range of 110–170 km tends to increase with depth, whereas that in the depths range of 70–110 km tends to decrease with depth. A schematic cross-sectional view of the oceanic crust in Pacific slab beneath Hokkaido is shown in Figure 6b. Taking into account the eclogite formation phase boundary with dehydration [e.g., *Hacker et al.*, 2003] and the results of seismic imaging [*Nakajima et al.*, 2009; *Kawakatsu and Watada*, 2007; *Tsuji et al.*, 2008], an increase in velocity and a decrease in water content in the oceanic crust would cause such an increase in rigidity (stress drop) with depth, and an increase in temperature would cause a decrease in rigidity. *Tsuji et al.* [2008] imaged the seismic structure around the upper plane seismic belt (seismicity peak in the oceanic crust) [*Kita et al.*, 2006] beneath Tohoku, in which it was revealed that a low-velocity zone at the top of the Pacific slab disappears at a depth of about 100 km. They also reported that the lower limit of the low-velocity zone at the top of the Pacific slab roughly coincides with the location of the eclogite formation phase boundary with dehydration in the oceanic crust [*Hacker et al.*, 2003]. The seismic structure results obtained by *Nakajima et al.* [2009] also showed that a low-velocity zone at the top of the Pacific slab disappears at a depth of $\sim$100 km beneath eastern Hokkaido. In general, experimental studies show that as the water content of rock decreases, the velocity and modulus of rigidity increases [e.g., *Inoue et al.*, 1970, 1971]. Thus, the increase in the median stress drop observed at depths of 110 to 170 km in the oceanic crust is possibly related to the eclogite formation metamorphic process with dehydration in the oceanic crust of the subducting Pacific plate beneath Hokkaido. At depths of 110–170 km, the effect of the rigidity increase with depth caused by the velocity increase and the water content decrease in the oceanic crust would be stronger than the effect of the rigidity decrease with depth caused by the temperature increase. At depths of 70–110 km, the decrease in the median stress drop in the oceanic crust caused by the temperature-induced rigidity decrease would be larger than that of the rigidity increase caused by velocity and water content.

4.4. Depth Dependence of Stress Drop Within the Subducting Plate

Figure 3 shows the stress drop and median stress drop for all depth ranges (70–300 km). As can be seen in this figure, the median stress drop generally increases with focal depth. This trend is consistent with the stress drop findings associated with intermediate-depth large intraslab earthquakes beneath the Japan archipelago reported by *Asano et al.* [2003], and the results for the stress drop for events at depths of 10–100 km beneath the Japan archipelago reported by *Oth* [2013]. Similar trends on a regional scale have been found in other studies, such as the Java subduction zone [*Allmann and Shearer*, 2009] and California [*Shearer et al.*, 2006; *Allmann and Shearer*, 2007]. *Bilek and Lay* [1998, 1999] examined the stress drop associated with large interplate events in six subduction zones, including northeastern Japan, and found that both the stress drop and the rigidity of the location increased with depth. *Allmann and Shearer* [2007] indicated the possibility that the depth dependence of the shear-wave velocity and rigidity within a subduction zone could explain the apparent depth dependence of the stress drop for events at a regional scale. Thus, the trend for the focal-depth dependence for intraslab events in the present study can be explained by the depth dependence of V_s and μ at the event location.

5. Conclusions

Based on relocated hypocenters and the corner frequencies of events, the stress-drop characteristics of intermediate-depth intraslab earthquakes in the Pacific slab were examined beneath Hokkaido, Japan. For events at depths of 70–300 km, it was generally found that the stress drop increases with depth. At shallow depths of 70–170 km, where the detailed determined geometry of the upper interface of the Pacific plate is known, the stress drop for events more than 10 km beneath the upper interface (the oceanic mantle) was larger than that for events 0–10 km beneath the upper interface (approximately the oceanic crust). As the neutral plane of the stress field in this area is located near the oceanic Moho beneath eastern Hokkaido, this difference in stress drop for earthquakes in the slab would appear to be related to the neutral plane of the stress regime in the subducting Pacific plate. The difference of the rigidity in the rock types and that of the ratio of average displacement to fault radius (D/r) for events between the oceanic crust and the oceanic mantle could also be causes for the difference. The stress drop for interplane events was similar to that for lower-plane events. In the oceanic crust, the stress drop decrease with depths at depths of 70–120 km. The stress drop increased with depth at depths of 120–170 km, where several previous studies showed that the seismic velocity in the oceanic crust drastically increases and the phase boundary with dehydration is expected to be located. The stress-drop trend for interplane earthquakes was almost the same as that for lower plane earthquakes, and the stress drop for interplane events tended to be larger than that for upper plane events. These results can help clarify the nature of intraslab earthquakes and provide information useful for the prediction of strong motion associated with earthquakes in the slab at intermediate depths.

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