Wide-angle seismic profiling across the middle Izu-Ogasawara Arc

– KR07-13 cruise –

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Abstract We carried out a wide-angle reflection and refraction experiment using 102 ocean bottom seismographs on a 679-km long seismic line crossing the middle Izu-Ogasawara Arc. The cruise was conducted by R/V Kairei of Japan Agency for Marine-Earth Science and Technology from September to October, 2007. The objectives of the cruise are to reveal the crustal and uppermantle structures across the middle Izu-Ogasawara Arc from Ogasawara Ridge to Shikoku Basin illuminating the structural variations associated with the arc evolution and back-arc openings. In this paper, we summarize the seismic experiment and show the acquired data of ocean bottom seismographs.

Keywords: Izu, Ogasawara, OBS, oceanic island arc, seismic

1. Introduction

The Izu-Ogasawara (Bonin)-Mariana Arc (IBM) is an oceanic island arc well studied, since oceanic island arcs are one of important tectonic region to generate continental crust of the earth. This was strongly promoted by the collaborated results of seismological and petrological studies^{1,2}.

The IBM is located eastern edge of the Philippine Sea Plate subducting the Pacific Plate at the Izu-Ogasawara and Mariana Trenches (Figure 1). The Shikoku and Parece Vela Basins are well developed at the back-arc side of the IBM. Between the back-arc basins and the IBM, there are en echelon seamount chains with NE-SW directions. In the middle of the Izu-Ogasawara Arc, there is a tectonic line named Sofugan Tectonic Line (STL) with NE-SW trend bordering the northern and southern part of the Izu-Ogasawara Arc. In the southern part, the Ogasawara Ridge and the Ogasawara Trough are elongated parallel to the Izu-Ogasawara Arc.

The history of the Philippine Sea Plate development is well revealed by many papers³. In this part, the history of the Philippine Sea Plate is overviewed mainly with the review of Stern et al.³. At the beginning of the history which is about 50-45 Ma, the convergence of oceanic lithospheres occurred and the boninitic activity was also confirmed in this time⁴. First arc activity was occurred about 40-30Ma, followed by the back-arc openings of the

Shikoku and Parece Vela Basins in the period of 30-15 Ma, which is well documented by the geophysical papers⁵. According to Okino et al.⁵, the rifting before the seafloor spreading was timing of 30-27 Ma, followed by the spreadings in E-W direction. The spreadings were continued during 27-23 Ma with the northward and southward propagations of Parece Vela Basin and Shikoku Basin, respectively. The propagations were reached and united together at 23 Ma and started the stable spreading until 20 Ma. Around 19 Ma, the spreading direction was changed to NE-SW direction with ridge segmentations and continued until 15 Ma. After the cease of the spreading, axial seamounts were formed in the Shikoku Basin until 12 Ma, although there was no axial seamount in the Parece Vela Basin⁶. The Mariana Trough opening was initiated sometime after 10 Ma for rifting stage, followed by the seafloor spreading from 3-4 Ma^{7,8}. As mentioned here, the IBM area has a cyclic history of arc evolutions and back-arc openings.

Around the IBM, many seismic surveys have been conducted intensely to reveal the crustal structure understanding the arc evolution associated with the continental crustal forming since 1960's⁹. The northern Izu-Ogasawara Arc transect using ocean bottom seismographs (OBS) reveals the middle crust with P-wave velocity of 6 km/s, which is thought to be an intermediate layer suggesting the formation of continental crust¹. The seismic

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survey using OBS in Mariana region confirmed the similar crustal characteristics with those of northern Izu-Ogasawara Arc suggesting transformation of the dense crustal materials to the upper mantle throughout the crustal evolution²⁾. According to Takahashi et al.²⁾, observed lower crustal volume is much less than those of calculated volume with petrological modeling, which requires the evolution process returning the crustal materials to the mantle. Moreover, the seismic surveys on the Izu-Ogasawara volcanic arc show the structural variation along the arc¹⁰⁾, which indicates that the evolution process varies along the arc.

The STL is a lineament with NE-SW trend bordering the northern and southern Izu-Ogasawara Arcs¹¹⁾ indicating the differences in topographic, geological and structural features and in distribution of hypocenters and back-arc depressions. Yuasa¹¹⁾ also suggests that the trend change of the minor ridge on the Shikoku and Parece Vela Basins seems to correspond the western extension of the STL. From the along-arc transect of OBS survey, crustal thick-

ness is smallest around the STL about 10 km bordering the southern juvenile and northern mature arcs¹⁰⁾. The isotopic characteristics of rock samples also show the along-arc variation and two gaps at Latitudes 27.5 and 25 degrees, of which former gap locates around the STL¹²⁾.

The Ogasawara Ridge is a topographic high locating in the forearc region of the Izu-Ogasawara Arc, thought to be a region holding the characteristics of old arc activity of the IBM because of the discovery of boninite⁴⁾. The middle crust of the Ogasawara Ridge has P-wave velocity of 6.5 km/s, which is meaningfully higher than those of current Izu-Ogasawara Arc, suggesting the difference of evolution process of arc activity¹³⁾.

The tectonics at the transition zone between the arc and back-arc region is also an important to understand the evolutions of arcs and back-arc basins. According to Takahashi et al.¹⁴⁾, the lower crust of the transition zone in northern Izu-Ogasawara Arc has high P-wave velocity about 7 km/s. This characteristic is also discovered in the transition zone in Mariana Region²⁾. From the MCS study,

Figure1: Bathymetric map of the experimental area. A black line with white and yellow circles, which are ocean bottom seismographs (OBS), is a seismic line for wide-angle reflection/refraction experiment using OBS. Yellow circles with three digits indicate every 10 OBS.

there are normal faults cutting the sedimentary layer and the basement thought to be active not only the back-arc opening period before 15 Ma but also the period after the back-arc opening suspend¹⁵⁾.

The objectives of this survey are following five points: 1) to confirm the existence of high velocity (~ 6.5 km/s) middle crust in the northern part of the Ogasawara Ridge, 2) to confirm the P-wave velocity of lower crust in northern part of the Ogasawara Trough, 3) to reveal the across arc distribution of the thin crust around the STL, 4) to confirm the existence of high velocity (~ 7 km/s) and reflective lower crust in the transition zone between the arc and back-arc basin, and 5) to reveal the crustal and mantle structure of the Shikoku Basin including the axial seamount (Hakuho Seamount). To reveal the crustal struc-

ture of the middle Izu-Ogasawara Arc achieving the objectives, a wide-angle reflection and refraction experiment of OBS has been conducted on a seismic line (IBr10: Figure 1) from September to October, 2007. The cruise was KR07-13 conducted by the R/V Kairei of Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

2. Experiment

The outline of the KR07-13 cruise and shiptracks are respectively shown by Table 1 and Figure 2. The R/V Kairei left the Yokohama port in September 30. OBS deployment was conducted from October 1 to 11, including first avoidance due to typhoon attack in the Mikawa Bay from October 6 to 9. During the OBS deployment,

Figure2: Map for ship's track. Red crosses and yellow four-digits indicate the position at noon in global standard time and date, respectively.

three OBS were re-deployed since deployment troubles in Site005, Site073 and Site075. In October 12, float towing test for the new MCS system of R/V Kairei was conducted. The airgun shooting on the Line IBr10 was continued from October 12 to 17 with 200-m interval for the OBS survey. After the airgun shooting, OBS were retrieved from October 17 to 25 including avoidance due to second typhoon attack off Shionomisaki from October 20 to 21. During the OBS retrievals, one OBS could not retrieve because of a recovery trouble in Site024. Finally, third avoidance due to typhoon attack in the Tokyo Bay from October 26 to 28 including transit from the survey area. The cruise was finished in October 29 arriving to the JAMSTEC port. Although there were three times of avoidance due to typhoon attack, a wide-angle reflection and refraction survey using 102 OBS was completed. The specifications of the OBS survey were basically same as those of surveys in Izu-Ogasawara region¹⁶⁾¹⁷⁾.

2.1 Airgun shooting

The seismic source of the cruise was an airgun array of BOLT1500LL type on the R/V Kairei. Total chamber size was 12000 cu. in. (200l), which was composed of eight 1500 cu. in. airguns. Air pressure was 2000 psi (140 atm). Towing depth of the airgun array was about 10 m. The eight airguns were shot simultaneously within 1msec. The center of source (COS) was located 198.6 m behind from the vessel reference point (VRP), which was addition of 76.7 m from the VRP to the stern and 121.9 m from the stern to the COS (Figure 3).

The Line IBr10 was 679-km length from the Shikoku Basin to the Pacific Plate subducting beneath the Izu-Ogasawara Arc. The western and eastern ends of the Line IBr10 were extended outside of OBS locations: the western end was 62-km west from OBS102 and the eastern end was 111-km east from OBS001. The shooting interval was 200-m, which was about 97 s with 4 knot ship speed. Total shot number was 3396, which was continuously conducted without shooting interruption on the Line IBr10 (Table 2).

2.2 OBS

One hundred and two OBS were deployed with 5-km interval on the Line IBr10. The OBS and the digital recorder system were originally designed by Kanazawa and Shiobara¹⁸⁾ and Shinohara et al.¹⁹⁾. The sensors of the OBS are 4.5 Hz geophones for one vertical and two horizontal components and one hydrophone. The signals recorded by hard disk drive (HDD) after 16 bit A/D converter with 100 Hz sampling rate (10 ms). The power supply for the electric is rechargeable battery, which is effective

Table1: Activity log during KR0713 cruise

Date	Remarks
September 30	Departure from Yokohama
October 01	OBS deployment (Site#001-Site#005)
October 02	OBS deployment (Site#006-Site#023)
October 03	OBS deployment (Site#024-Site#039)
October 04	OBS deployment (Site#040-Site#058)
October 05	OBS deployment (Site#059-Site#074)
October 06	Avoidance due to typhoon attack
October 07	Avoidance due to typhoon attack
October 08	Avoidance due to typhoon attack
October 09	Avoidance due to typhoon attack
October 10	OBS deployment (Site#075-Site#085)
October 11	OBS deployment (Site#086-Site#102)
October 12	Float towing test & IBr10 airgun shooting
October 13	IBr10 airgun shooting
October 14	IBr10 airgun shooting
October 15	IBr10 airgun shooting
October 16	IBr10 airgun shooting
October 17	IBr10 airgun shooting & OBS retrieval (Site#001-Site#005)
October 18	OBS retrieval (Site#007-Site#023)
October 19	OBS retrieval (Site#025-Site#038)
October 20	OBS retrieval (Site#039-Site#046) & Avoidance due to typhoon attack
October 21	Avoidance due to typhoon attack
October 22	OBS retrieval (Site#102-Site#091)
October 23	OBS retrieval (Site#090-Site#074)
October 24	OBS retrieval (Site#073-Site#053)
October 25	OBS retrieval (Site#052-Site#047)
October 26	Avoidance due to typhoon attack
October 27	Avoidance due to typhoon attack
October 28	Avoidance due to typhoon attack
October 29	Arrival to JAMSTEC

for one month survey. The time shifts between the internal clock of OBS and reference time (GPS) were measured before the deployment and after the retrieval for calibration during OBS deployment on seafloor.

The transponders of Kaiyodenshi type (KYD) and System Giken type (SYG) were used for communication in seawater to cut iron anchor and to measure the distance. Although the descending speeds for both types are about 82 m per minute, cutting time and ascending speed are different each other. The cutting times for iron anchor are about 15 minutes for KYD and 22 minutes for SYG, respectively. The ascending speeds for KYD and SYG are respectively 63 m per minutes and 68 m per minutes. For this survey, 60 KYD and 42 SYG were used (Table 3).

We deployed 102 OBS taking acoustic communication between the R/V Kairei and OBS to measure the location on seafloor. Most OBS were located within 200-m diameter from planned position, which was the airgun shooting interval. However, several OBS were positioned about 300-m away from the aimed position because of currents. Moreover, several OBS were deployed away from the first planned position avoiding the steep slope depending on the bathymetry.

2.3 Navigation Systems

The navigation of the survey was StarFire system, which was a Differential Global Positioning System (DGPS), enabling to navigate the R/V Kairei within 0.4 m

Figure3: Geometry of the airgun system for OBS survey

Figure4: Navigation system of R/V Kairei.

accuracy. The software SPECTRA of Concept Inc. was used to control the navigation system. The positioning data from the StarFire was sent to RTN μ (a network interface made by Concept Inc.) via a terminal server in the LAN system of the R/V Kairei. The RTN μ acquire the time signal of the StarFire from the original antenna. The navigation data is sent to the PC Linux machine installing the SPECTRA. The shottime and shotpoint (SP) were set by the SPECTRA and trigger signals were sent to the recording system and the airgun control system (GCS90).

The schematic diagrams of navigation and recording system is shown by Figure 4. At first, SPECTRA send the starting signal (System-start-signal) to the central control device via RTN μ (Real Time Navigation Unit). Secondly, SPECTRA send the trigger signal (Shot-trigger) to the airgun control system (GCS90). The GCS90 sends the signal (Internal-time-break-signal) back to the RTN μ , and simultaneously send the trigger signal to each airgun. The wave forms recorded by the monitor hydrophone are sent to the GCS90 and the airgun position is sent to the RTN μ .

3. OBS Data

The recording condition was good enough to identify the airgun signals to 250-km offset distances in some data. Figure 5 shows vertical component data of OBS019, 048 and 078. All traces were processed by 3-12 Hz band pass filter, deconvolution, and auto gain control of 2 sec.

OBS019 was located in the Ogasawara Trough, which is between the Ogasawara Ridge and the Izu-Ogasawara Arc. Apparent velocities of first arrivals in eastern side of the OBS in 9-12 km, 18-40 km, 40-54 km, 54-76 km and 76-93 km are 4.4 km/s, 6-7 km/s, 9 km/s, 5.2 km/s and 6.2 km/s, respectively. Those in western side of the OBS in 9-13 km, 13-17 km, 20-42 km, 45-57 km and 57-72 km are 3.1 km/s, 6.4 km/s, 7 km/s, 8 km/s and 8.6 km/s, respectively. The apparent velocity over 72 km west is continuously changed by seafloor topography until 200 km offset. The later reflection phases are observed in east side of the OBS in 15 km, 60 km and 100 km, and in west side of the OBS in 40 km, 60 km and 70 km.

OBS048 was on the Izu-Ogasawara Arc region. Apparent velocities of first arrivals in eastern side of the OBS in 4-12 km, 12-25 km, 25-32 km, 32-41 km, 41-48 km, 72-82 km, 82-110 km and 110-127 km are respectively 4.1 km/s, 5.0 km/s, 8.9 km/s, 5.8 km/s, 5.0 km/s, 5.5 km/s, 6.3 km/s and 8.6 km/s. Those in western side of the OBS in 4-6 km, 6-9 km, 18-32 km, 32-40 km, 40-53 km, 53-77 km and 77-89 km are 3.1 km/s, 5.4 km/s, 5.2 km/s, 7.1 km/s, about 10 km/s, 7.5 km/s and 7.0 km/s, respec-

tively. The apparent velocity between 48 and 72 km east of the OBS was continuously changed about 8 km/s for seafloor topography. In both sides of the OBS, there are clear later phases thought to be reflection signals from deep interfaces in 40-km offset distances.

OBS096 was positioned near the eastern edge of the Shikoku Basin. Apparent velocities of first arrivals in eastern side of the OBS in 6-9 km, 9-14 km, 14-21 km, 34-53 km, 63-100 km and 100-115 km are 4.3 km/s, 5.6 km/s, 6.7 km/s, 7 km/s, 8.6 km/s and 6.3 km/s, respectively. The apparent velocity between 48 and 72 km are continuously changed about 8 km/s. Those in western side of the OBS in 6-8 km, 8-13 km and 13-17 km are 4.0 km/s, 4.9 km/s and 6.3 km/s, respectively. The apparent velocity over 17 km west is about 8 km/s and continuously changed by seafloor topography.

From the general information of these OBS records, the crustal thickness is suggested as thick in arc and forearc region. For example, the OBS019 data shows that the intercept time of the first arrival of 7 km/s in west side is about 6 s. On the other hand in backarc region, the crustal thickness seemed to be thin, especially in the Shikoku Basin.

For an example of horizontal component, figure 6 shows the two horizontal component data of OBS078. All traces were processed by 3-12 Hz band pass filter, deconvolution, and auto gain control of 2 sec. In the western side of the OBS between 20 and 40 km offset and 11 sec, there are clear signals with 4.2 km/s apparent velocity, which are thought to be converted signals from P to S at deep interfaces.

4. Summary

We have conducted a seismic survey in the middle Izu-Ogasawara region of wide-angle reflection and refraction experiment using 102 OBS during September to October, 2007. The data acquisition of the OBS survey was successfully finished, although there were three interruptions of typhoon attacks. Acquired data quality is good. For example, some of the OBS data of vertical component have clear first arrivals until an offset of 250 km. Some clear signals in horizontal component data are thought to be P-S converted signals at the deep interfaces. From the information of apparent velocities and intercept times of OBS data, the crustal thicknesses of the middle Izu-Ogasawara Arc and the forearc region are thick, whereas the crustal thickness in the Shikoku Vela Basin is thin. In the future, we will constrain the velocity model transecting the middle Izu-Ogasawara Arc, followed by the interpretation for arc evolution and formation of back-arc basins using the OBS data.

Table2: Airgun shooting log

IBr10obs_0	Time (UTC)	Latitude (N)	Longitude (E)	Depth (m)	SP
First shot	2007/10/12 10:30	27° 49.6308'	136° 45.1800'	4579	963
First good shot	2007/10/12 10:30	27° 49.6308'	136° 45.1800'	4579	963
Last good shot	2007/10/16 14:59	29° 25.1894'	143° 27.4072'	6108	4358
Last shot	2007/10/16 14:59	29° 25.1894'	143° 27.4072'	6108	4358

Table3: OBS information. The "KYD" and "SYG" indicate the type of transponder Kaiyodenshi and System-Giken, respectively.

Site	Time UTC	Cast			Time UTC	Recovery			OBS Calibration position			Transponder		
		Lat(N)	Lon(E)	Depth		Lat(N)	Lon(E)	Depth	Lat(N)	Lon(E)	Depth			
1	2007/10/01 04:31:50	29.108913	142.206809	3049	2007/10/17 06:23:00	29.108993	142.204959	5045	29.109591	142.206017	5037.5	108.0	-154.7	SYG
2	2007/10/01 06:13:55	29.102393	142.176986	4717	2007/10/17 08:01:00	29.102094	142.174531	4709	29.102734	142.176051	4711.9	54.0	-152.0	SYG
3	2007/10/01 07:50:19	29.095832	142.147030	4419	2007/10/17 11:28:00	29.094008	142.143180	4390	29.095359	142.146454	4401.2	-94.0	-94.0	SYG
4	2007/10/01 09:11:59	29.089264	142.116889	3961	2007/10/17 14:32:13	29.089724	142.113301	3913	29.089596	142.115718	3953.8	-56.0	-220.0	KYD
5.1	2007/10/01 10:35:32	29.082677	142.087068	3660	-	-	-	-	-	-	-	-	-	KYD
5.2	2007/10/01 10:35:32	29.082677	142.087112	3657	2007/10/17 14:48:47	29.084091	142.082794	3624	29.082967	142.085335	3639.7	52.0	-290.0	KYD
6	2007/10/01 10:35:32	29.076140	142.057183	3425	2007/10/17 15:53:00	29.078814	142.055780	3437	29.077030	142.057630	3433.5	176.0	106.0	KYD
7	2007/10/01 18:21:51	29.069450	142.027164	3077	2007/10/17 16:59:00	29.071579	142.025689	3027	29.069859	142.027360	3069.3	74.0	20.0	KYD
8	2007/10/01 19:47:04	29.062822	141.597200	4086	2007/10/17 17:57:00	29.064413	141.594974	3691	29.062857	141.597278	2637.9	-30.0	-4.0	KYD
9	2007/10/01 20:57:57	29.056185	141.567337	2695	2007/10/17 18:59:00	29.058469	141.562944	2678	29.058630	141.566381	2684.2	82.0	-160.0	KYD
10	2007/10/01 22:05:11	29.049547	141.537486	2431	2007/10/17 20:11:00	29.052819	141.532608	2500	29.050140	141.537371	2442.4	112.0	-14.0	KYD
11	2007/10/01 23:14:41	29.042794	141.507496	2568	2007/10/17 21:08:00	29.045845	141.503880	2579	29.043542	141.506714	2574.4	124.0	-222.0	KYD
12	2007/10/02 00:23:31	29.036183	141.477581	2543	2007/10/17 22:04:00	29.038190	141.474077	2553	29.036576	141.476600	2550.1	70.0	-168.0	KYD
13	2007/10/02 01:37:59	29.029555	141.447781	2593	2007/10/17 23:08:44	29.031163	141.444888	2651	29.029890	141.447278	2597.8	70.0	-74.0	KYD
14	2007/10/02 02:43:02	29.022849	141.417843	2818	2007/10/18 00:09:53	29.024298	141.415823	2902	29.023312	141.417703	2835.6	92.0	-22.0	KYD
15	2007/10/02 03:51:43	29.016081	141.387825	3276	2007/10/18 01:20:26	29.017576	141.386291	3239	29.016518	141.388123	3274.2	76.0	28.0	KYD
16	2007/10/02 05:27:28	29.009138	141.358969	3894	2007/10/18 02:37:52	29.010305	141.355056	3891	29.008973	141.355982	3909.4	-1.0	-12.0	KYD
17	2007/10/02 06:46:13	29.002615	141.328200	3948	2007/10/18 04:00:00	29.003715	141.326771	3918	29.002908	141.328023	3933.2	46.0	-26.0	SYG
18	2007/10/02 08:03:49	28.995900	141.298317	3978	2007/10/18 05:29:00	28.986293	141.296751	3964	28.995918	141.297612	3976.2	0.0	-116.0	SYG
19	2007/10/02 09:26:16	28.989157	141.284559	4014	2007/10/18 06:55:00	28.989659	141.286621	4015	28.989578	141.287539	4014.6	76.0	-150.0	SYG
20	2007/10/02 10:47:05	28.982408	141.238501	4026	2007/10/18 08:19:00	28.983144	141.235688	4028	28.982891	141.237180	4028.2	90.0	-232.0	SYG
21	2007/10/02 12:04:23	28.975641	141.208670	4034	2007/10/18 09:40:00	28.976538	141.205874	4034	28.976194	141.207528	4134.5	104.0	-200.0	SYG
22	2007/10/02 13:25:15	28.968816	141.178872	4036	2007/10/18 11:05:00	28.969725	141.176211	4038	28.969452	141.178251	4035.1	112.0	-108.0	SYG
23	2007/10/02 14:44:17	28.962052	141.148958	4025	2007/10/18 12:48:30	28.963835	141.144881	4038	28.962557	141.146772	4038.0	112.0	-50.0	SYG
24	2007/10/02 16:10:51	28.955261	141.119164	4024	-	-	-	-	28.955420	141.119288	4025.6	34.0	6.0	SYG
25	2007/10/02 17:33:20	28.948469	141.089412	4023	2007/10/18 22:16:00	28.949841	141.087648	4020	28.948773	141.089686	4025.8	64.0	42.0	SYG
26	2007/10/02 18:57:30	28.941580	141.059568	4014	2007/10/18 23:43:40	28.943318	141.056876	4013	28.941641	141.059513	4024.2	8.0	-16.0	SYG
27	2007/10/02 20:23:03	28.934763	141.029819	3989	2007/10/19 01:11:06	28.936256	141.027524	3977	28.934965	141.030096	3985.7	38.0	48.0	SYG
28	2007/10/02 21:46:26	28.927879	141.000076	3888	2007/10/19 02:28:24	28.928589	140.997652	3886	28.927582	140.999000	3886.1	-64.0	-16.0	KYD
29	2007/10/02 23:10:56	28.921039	140.974811	3768	2007/10/19 03:45:00	28.921723	140.967611	3731	28.920431	140.969986	3752.3	-114.0	-38.0	KYD
30	2007/10/03 00:30:56	28.914133	140.940259	3911	2007/10/19 04:57:00	28.914733	140.937087	3900	28.914003	140.939596	3904.5	-32.0	-134.0	KYD
31	2007/10/03 01:44:22	28.907315	140.910570	3463	2007/10/19 06:18:00	28.907332	140.908036	3453	28.906900	140.910515	3451.9	-128.0	-18.0	KYD
32	2007/10/03 03:45:12	28.900413	140.880792	3343	2007/10/19 07:27:00	28.900950	140.878084	3350	28.900466	140.880297	3349.7	16.0	-90.0	KYD
33	2007/10/03 05:06:13	28.893486	140.851066	3093	2007/10/19 08:31:00	28.893875	140.848909	3079	28.893667	140.850440	3090.4	32.0	-104.0	KYD
34	2007/10/03 07:41:10	28.885908	140.818814	3160	2007/10/19 09:40:00	28.885553	140.815162	3153	28.885874	140.817411	3157.5	-4.0	-248.0	KYD
35	2007/10/03 08:47:31	28.879648	140.791488	3136	2007/10/19 10:50:00	28.880353	140.787535	3149	28.879327	140.790784	3143.4	-60.0	-126.0	KYD
36	2007/10/03 09:55:51	28.872670	140.761632	3045	2007/10/19 12:07:45	28.873348	140.757359	3079	28.872314	140.760307	3082.5	-74.0	-244.0	KYD
37	2007/10/03 11:36:54	28.866336	140.734813	3686	2007/10/19 13:27:33	28.866223	140.730332	3580	28.865277	140.732562	3588.1	-168.0	-294.0	KYD
38	2007/10/03 13:22:58	28.859739	140.706930	3315	2007/10/19 14:40:43	28.859293	140.703900	3362	28.859024	140.706133	3331.5	-40.0	-168.0	KYD
39	2007/10/03 14:05:03	28.851775	140.677524	3361	2007/10/19 15:48:00	28.852784	140.683018	3304	28.851913	140.685113	3333.6	14.0	-164.0	KYD
40	2007/10/03 15:42:00	28.844178	140.648127	2587	2007/10/19 16:50:00	28.845847	140.637073	2586	28.844473	140.638616	2584.2	82.0	-254.0	KYD
41	2007/10/03 16:41:17	28.837824	140.613040	2202	2007/10/19 17:45:00	28.839771	140.611475	2196	28.838742	140.612783	2195.8	162.0	-60.0	KYD
42	2007/10/03 17:46:18	28.830938	140.583307	2403	2007/10/19 18:41:00	28.832872	140.582211	2421	28.831782	140.583986	2407.4	170.0	-74.0	KYD
43	2007/10/03 18:53:08	28.823879	140.553724	2958	2007/10/19 19:42:00	28.825811	140.553459	2971	28.824564	140.555055	2959.3	132.0	52.0	KYD
44	2007/10/03 20:10:08	28.816833	140.524023	2908	2007/10/19 20:45:00	28.817704	140.524441	2922	28.817063	140.524333	2909.8	44.0	48.0	KYD
45	2007/10/03 21:19:59	28.809819	140.492823	2653	2007/10/19 21:44:00	28.809891	140.489889	2661	28.809877	140.490883	2645.6	16.0	84.0	KYD
46	2007/10/03 22:28:39	28.802674	140.464066	2544	2007/10/19 22:42:00	28.802679	140.461622	2557	28.802679	140.461622	2557.9	-36.0	-78.0	KYD
47	2007/10/03 23:33:24	28.795688	140.434826	2302	2007/10/20 00:40:00	28.796470	140.433722	2298	28.795438	140.435169	2297.9	-46.0	30.0	KYD
48	2007/10/04 00:37:20	28.788609	140.405250	2400	2007/10/20 01:42:00	28.789409	140.403478	2421	28.788545	140.405088	2400.7	-14.0	-40.0	KYD
49	2007/10/04 01:40:41	28.781588	139.575587	2594	2007/10/20 02:48:00	28.782458	139.573660	2620	28.781824	139.575354	2609.8	52.0	-48.0	KYD
50	2007/10/04 02:47:12	28.774413	139.545836	2417	2007/10/20 03:48:00	28.774387	139.543612	2416	28.774193	139.545476	2394.4	-48.0	-84.0	KYD
51	2007/10/04 03:51:31	28.766813	139.513943	2681	2007/10/20 04:16:00	28.767086	139.512668	2682	28.766951	139.514225	2683.3	24.0	32.0	KYD
52	2007/10/04 04:56:32	28.759233	139.486894	2837	2007/10/20 05:19:00	28.759751	139.485326	2882	28.758049	139.486585	2844.0	-36.0	-18.0	KYD
53	2007/10/04 06:03:24	28.752976	139.457023	3074	2007/10/20 06:29:59	28.753460	139.456551	3049	28.752865	139.456896	3074.3	-44.0	-26.0	KYD
54	2007/10/04 07:16:38	28.745889	139.427428	3613	2007/10/20 07:31:14	28.746874	139.427116	3615	28.745884	139.427393	3616.6	-18.0	-20.0	KYD
55	2007/10/04 08:37:57	28.738930	139.397716	3610	2007/10/20 08:00:00	28.739674	139.396553	3615	28.739216	139.397704	3610.0	66.0	-16.0	KYD
56	2007/10/04 10:11:18	28.731883	139.368164	352

Figure5: OBS data of vertical component of three sites: (a) Site019, (b) Site048, and (c) Site078. All traces are filtered by 3-12 Hz. Vertical and horizontal axes are offsets from OBS and reduced travel-times by 8 km/s, respectively. The bathymetries of the OBS data are also shown above the sections.

Figure6: OBS data of horizontal component of Site078: (a) H1, and (b) H2. All traces are filtered by 3-12 Hz. Vertical and horizontal axes are offsets from OBS and reduced traveltimes by 4.6 km/s, respectively. The bathymetries of the OBS data are also shown above the sections.

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