Ocean Downhole Seismic Project

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In the fall of 1989, a broadband digital seismic sensor system (OBDS: Ocean Broadband Downhole Seismometer) was successfully emplaced in an ODP drill hole in the Japan Sea. The site is located in the northern part of the Yamato Basin about 160 km west from the northern Japan west coast. The instrument was clamped within a basalt section beneath 543 m of sediments at 715 m below seafloor and 3,523 m below sea surface. We obtained a continuous real-time seismic recording of 60 h length and an off-line and intermittent sea-floor recording of 30 days operation. The dataset includes airgun signals for studying the local crustal structure, several local earthquakes, and a teleseismic event. An array of OBS's was also deployed during the airgun shooting to study detailed local crustal structure including anisotropy. The results of our experiment may be summarized as follows. We obtained for the first time a digital long-period seismic record from beneath the seafloor. The structural environment of OBDS could be constrained from results of drilling and airgun profiling; the crust is nearly identical to that of the southern Yamato Basin, which is about 14 km thick, and the upper crust possesses anisotropy in agreement with the present E-W compressive state of stress. Noise is generally lower than island or seafloor stations, and is as low as about 10^4 (nm/s)²/Hz at about 0.2 Hz, where normally a noise peak is found. Signals from local events and airguns exhibit less reverberations as compared with OBS records; i.e. they are less affected by signal-generated noise, thus allowing better phase identifications. Surface wave dispersion from an event ($M_b=5.4$) at 39° distance was clearly observed. Thus, our results indicate that downhole emplacement of a seismometer beneath an ocean provides higher quality data than alternative seafloor or island observations. At frequencies lower than 0.1 Hz, however, our OBDS did not have sufficient sensitivity to detect the background noise level.

Received July 1, 1992; Accepted December 12, 1992

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1. Introduction

The Ocean Drilling Program (ODP) is an internationally driven program for earth sciences. A scientific deep sea drill ship is the unique tool of the program which provides earth samples from drill holes beneath the seafloors around the globe. Present drilling technology has made drilling into the lower crust feasible. Among numerous scientific objectives for drilling that may span the whole earth sciences spectrum, seismology may seem most remote from the benefits of drilling. However, a drilled hole provides a most stable and quiet environment for high quality seismic observation, similar to borehole or vault installation of land seismic stations.

It is now widely recognized among seismologists that a global seismic network equipped with modern seismographs with large dynamic-range and broad frequency range would bring about vital information for understanding the dynamics of the convecting mantle and core. Such a network cannot be completed unless we can put seismic stations in oceanic areas which cover more than 2/3 of the earth's surface. It is then a technical challenge to establish such a station.

The ODP recognizes the importance of this scientific objective and suggests utilization of a drilled hole as a platform for seismic observation (COSOD II, 1987). Compared to seafloor or island observations, a drilled hole should offer a better environment for a stable seismic observation. However, this will be the most expensive method. Therefore, clearly we need to gather concrete data to assess which method we should pursue before starting to construct a practical seismic network covering the oceanic area. The present design of a global network as advocated by FDSN (Federation of Digital Seismic Networks) is to have a broadband station in $2,000 \times 2,000 \text{ km}^2$ area. The Japanese POSEIDON Project aims at four times density in the western Pacific area. An even more dense array is necessary if we wish to solve regional problems.

In August–September, 1989, ODP Leg 128 was carried out in the Japan Sea aiming at understanding the evolution and tectonics of the back-arc basin. At the same time, our proposal to emplace a broadband seismograph system in the northern Yamato Basin, in order to understand the transitional structure of the arc-back-arc system was adopted. This paper presents a summary of the Japanese broadband downhole seismometer experiment, emphasizing the high quality of the obtained dataset. Detailed descriptions and discussions on specific results can be found elsewhere (Ingle *et al.*, 1990; Shinohara *et al.*, 1991; Hirata *et al.*, 1992a; Kanazawa *et al.*, 1992; Shinohara *et al.*, 1992a; Suyehiro *et al.*, 1992).

We first describe the instrumental aspects briefly. Then, the results on local crustal structure are given. Finally, the noise and signal characteristics, which are most pertinent to future plans, are presented.

2. OBDS System

There are two types of ocean borehole seismic observations. One is made with a drill string attached and the other, without a drill string. The latter is the only choice for a seismic station aiming at a less noisy environment. Previously, such observations had been made in the DSDP (Deep Sea Drilling Project) era by the Hawaii Institute

of Geophysics (HIG) group at four sites on Legs 65, 67, 78A, and 88 (Lewis *et al.*, 1983; Aubouin *et al.*, 1982; Biju-Duval *et al.*, 1984; Duennebie *et al.*, 1987) and by the Navy Ocean Research and Development Activity on Legs 78B, 88, and 91 (Hyndman *et al.*, 1984; Duennebie *et al.*, 1987; Menard *et al.*, 1987). The sensors used in these experiments were of short-period type. Their sub-seafloor data showed improvement in S/N ratio over seafloor records by up to 30 dB with better improvements for horizontal components (Duennebie *et al.*, 1987; Menard *et al.*, 1987).

Our OBDS (Ocean Broadband Downhole Seismometer) system was constructed in 1988–1989, after deciding in 1985 on a design similar to that adopted by the HIG group but with a considerably wider frequency range (Suyehiro *et al.*, 1992). First, the downhole instrument was to be lowered through the drill string in the same manner as the normal downhole logging procedure from the drill ship. So, the instrument was restricted to have less than 75 mm diameter. On the other hand, this meant that we could utilize the drill ship's capability of cleaning the hole, guiding down the hole, or more control on the installation as compared with other hole-re-entry possibilities (e.g., Legrand *et al.*, 1989; Spiess and Boegeman, 1990).

The installation site (40°11.366' N, 138°13.944' E) had a water depth of 2,807 m, sediment thickness of 543 m, and was drilled to 734 mbsf (m-below-seafloor). The sediment section was cased to avoid obstruction of the hole because of swelling clay. The bottom part in a competent basalt rock section remained open, which meant about 10" (~25 cm) diameter. Therefore, the instrument had a clamping device to lock itself within this part (Fig. 1).

The sensor system we chose was Guralp's modified CMG-3 3-component feed-back accelerometer, which was specially manufactured for the Japan Sea experiment (Fig. 1). Table 1 shows its specifications. Only acceleration output was to be recorded. The A/D conversion was made by a C-MOS 16-bit converter, which was practically the only choice at the time considering the low-power requirement. The sampling rate was set to 80 Hz. This oversampling allows for better resolution at lower frequencies. The sensor outputs were split into high- and low-gain components to enhance the dynamic range. The high-gain channels were fed through low-cut filters (Table 1).

The seismic digital data from the downhole instrument were sent through the logging cable normally used in downhole logging operations at 19,200 bps rate as differential phase shift key (DPSK) modulated signals and were demodulated uphole (Fig. 2). This rate was required to send 15 bytes of 6 seismic channel data, state-of-health information, and parity check. Various controls could be made from uphole. Each sensor mass could be locked, unlocked, or centered. The horizontal sensor base could be tilted to compensate the possible hole's deflection from normal or time-dependent hole tilting if they were within 5°.

The data recording was made shipboard in real-time continuous mode and then by an off-line seafloor recorder system. Figure 3 shows the layout for the off-line observation. The data are stored on a digital 1/4" cartridge tape with 60-Mb capacity. The recording occurs intermittently upon significant event signals and on pre-determined time windows for noise recordings. The power for the seafloor recorder and the downhole instrument was supplied by lead-acid type batteries (Table 1).

The seafloor package is retrievable by pulling in the rope system, which floats up

Fig. 1. Schematic diagram of pressure housing of downhole seismometer (left) and internal sensor package (right). Extension pad is retracted when inside the drill pipe and extends out by pad motor housed near bottom to clamp itself in open hole. Guralp three-axis feed-back type accelerometer sensor stack-up constitutes of a vertical sensor and two mutually orthogonal horizontal sensors. Bases of horizontal sensors tilt in the direction of inverted pendulum movement to become horizontal accommodating up to 5° deviation from vertical. Signals are amplified, filtered, digitized, and telemetered uphole.

Table 1. Specifications of OBDS.

Sensor			
Guralp Slimline CMG-3 3-component feed-back type accelerometers			
Vertical	Low gain*	DC-30 Hz	2,566 V/m/s ²
Horizontal**	Low gain	DC-30 Hz	2,854 V/m/s ²
Resolution	0.346 mV (LSB)		
Dynamic range 16-bit (96 dB) each gain; 112 dB total			
Power requirements			
Downhole via logging cable	-48 V	-148.5 mA	7.1 W
	+48 V	200 mA	9.6 W
Seafloor demodulator	-12 V	26 mA	0.3 W
	+12 V	96 mA	1.2 W
Seafloor controller	1.92 W		
Seafloor power supply***	24 V 38 AH x 20		

* High-gain has +15.6 dB gain over low-gain channel and a frequency band of 10 m-30 Hz. ** H-2 sensor data. *** 20AH independent battery for seafloor recorder.

to the surface upon an acoustic command to release the weight attached to the glass-sphere buoy at the tail of the rope system (Fig. 3). Then, the status of the downhole instrument can be checked in real time. A ship of about 50 m length is capable of servicing the package.

Fig. 2. Data and power link between downhole unit and uphole. Power is sent via #2 (+48V), #5 (-48V), and #1 + armor (GND) of seven-conductor double armored logging cable. Data are transmitted uphole (#4; #6-common) and commands sent downhole (#3; #6-common). Pad motor uses #7 and GND (not shown).

Fig. 3. Layout of the OBDS system at off-line observation phase. A recorder/battery unit on the seafloor supplies power to and receives data from OBDS near bottom of Hole 794D via seven-conductor logging cable. Recovery unit releases from its weight by acoustic command from a ship and floats up to surface. Then, 6,000 m long rope is spooled to retrieve data without stressing OBDS.

3. Installation on ODP Leg 128

During Leg 128 of the drill ship JOIDES Resolution, the downhole instrument installation, real-time recording of seismic data after lowering the instrument and during a controlled-source seismic experiment, passing the logging cable to a chartered ship and deploying the seafloor package for the off-line experiment were accomplished. The downhole package was lowered and clamped in Hole 794D at 714.5 mbsf on September 26, 1989 (Fig. 4).

The logging cable had to be spliced on the drill ship to recover drill pipes. After the ship moved southward by about 1,500 m, an airgun-OBS seismic survey to study the detailed local crustal structure in the vicinity of the site was carried out by R/V Tansei-maru of the University of Tokyo Ocean Research Institute. Since the drill ship was not immediately above the hole and the drill string was no longer attached, it was expected that noise induced and transmitted by the ship and drill string would be minimized.

Unfortunately, one horizontal component was malfunctioning as we could not center its mass. On September 29, the airgun experiment was completed and the deployment of the seafloor unit was made by the chartered ship less than 20 h after passing of the cable. The seafloor unit was recovered in May 1990 after 8 months of deployment. No electrical corrosion or mechanical damage was found. However, the actual data recording scheme did not work well and failed to record any events by our event-triggering algorithm. Only noise recordings by time-windowing were available in the buffer IC memory (Kanazawa *et al.*, 1992). Presently, the downhole instrument still

Fig. 4. Detailed map of Site 794 vicinity. OBS-array location and airgun profiles in solid lines are shown. Two straight profiles, Line-NS shot in NW-SE direction and Line-EW shot in NE-SW direction, and two circle profiles were shot. Seafloor recorder unit and recovery unit lie westward of Hole 794D.

resides in the hole and the cable end on the seafloor is attached to the rope system without the seafloor package to be serviced.

The azimuth of the horizontal component could be estimated from the circle shooting record (Fig. 4). The amplitude variation of the horizontal component and H/V ratio, and the polarity change were all in agreement with a sensor orientation of 270° azimuth (Kanazawa *et al.*, 1992).

4. High Resolution Crustal Image of the Site

The purpose of the airgun experiment was to obtain a detailed crustal structure in the vicinity of OBDS in the northern Yamato Basin of the Japan Sea. The basin is known to possess anomalously thick crust for an oceanic basin but about half the crustal thickness beneath the northern Japan arc (e.g., Hirata *et al.*, 1989). The resolution and accuracy of the results owe greatly to precise ship positioning by GPS navigation and the geometry of the seismic profiles, which also allowed re-location of OBS's from direct water wave traveltimes.

Figure 4 shows the configuration of shots and receivers. Note the close spacing of OBS's. Depth control is excellent since the OBDS and OBS-JRT4 immediately above were spaced 0.7 km vertically. Two circle shootings were conducted to study anisotropy inside the crust. Two linear shootings were to obtain the basic local 2-D structure. Since usually the largest heterogeneities are introduced by the seafloor topography and the basement relief, these factors were measured independently by a digital single channel seismic reflection profiling using the same airgun shootings as the source.

Logging and core sample measurement results from ODP Legs 127 and 128 provide another source for confirmation of OBS results. Figure 5 compares these ODP data (Tamaki *et al.*, 1992; Ingle *et al.*, 1990) with OBS-JRT4 result (Shinohara *et al.*, 1992c). As can be seen, there is good agreement between the two results. The OBS result was obtained by the tau-sum inversion method (Diebold and Stoffa, 1981) using the semblance wavefield rather than the tau-p mapped actual data (Shinohara *et al.*, 1992c).

Fig. 5. Comparison of acoustic wavespeeds of core samples (right) and sonic logging data (middle) from ODP Site 794 with results from OBS JRT4 (left) (from Shinohara *et al.*, 1992c).

The predominant seismic frequency is about 8 Hz, so the rule-of-thumb resolution of $1/4$ wavelength varies from about 50 to 90 m within the drill hole section.

Figure 6 shows a 2-D model of the northern Yamato Basin crust (Shinohara *et al.*, 1992 a, b). Immediately below the sediments is a very high wavespeed gradient zone with about 9 s^{-1} (P-wave) in about 300 m thickness. The bottom part of Fig. 5 shows an overall increase in wavespeed with depth but with a large short wavelength variation. This corresponds to a sediment-sill complex as evidenced by drilling (Tamaki *et al.*, 1992; Ingle *et al.*, 1990). There is no evidence of a previously postulated 3.5 km/s layer presumed to be composed of green tuff prevailing in the northern Japan arc (Ludwig *et al.*, 1975).

Further below is a layer of a few km thickness in which the P-wavespeed increases from about 4.5 to 5.2 km/s (gradient 0.25 s^{-1}). This part is similar to the upper crust of the Japan Basin (Hirata *et al.*, 1992 b) and resembles oceanic Layer 2 though slightly thicker.

The lower crust distinguishes the Yamato Basin from a normal ocean. Its thickness is estimated to be about 10 km from PmP phase assuming the lowermost crustal wavespeed.

If we compare the record section with that obtained in the southern part of the

Fig. 6. P and S wavespeed structure models for EW (top) and NS (bottom) directions. Squares are the locations of OBDS and OBS array. Vertical exaggeration is about 2.8.

Yamato Basin (Hirata *et al.*, 1987), they look almost identical, suggesting that the same crustal formation mechanism operated. In other words, there is no indication of the effect of the Yamato Rise structure and the OBDS was not emplaced in a locally anomalous structure (Fig. 6).

The upper crust anisotropy was studied by Hirata *et al.* (1992a). Although both the inner and outer circle shooting data may be interpreted in terms of anisotropy in the upper crust and lower crust, respectively, only the upper crust result can reject the cause of azimuthal wavespeed dependence due to lateral heterogeneity. This is not immediately clear from the raw record section since it is contaminated by topography and distance variation. These were corrected by precise GPS measurements taken every

Fig. 7. Observed traveltimes of refracted arrivals (circles) and calculated traveltimes by the best-fit models with azimuthal wavespeed dependence (solid curves). Inner circle shooting records of OBDS, JRT3, JRT4, and JRT6 are shown from top to bottom. JRT3 was on Line-EW and JRT4 was on Line-NS, and were about 2.8 km away from Site 794 (see Fig. 4).

4 s and the seismic reflection record of seafloor and basement relief. Assuming a general $k\theta$ dependence to fit the observations, where θ is the azimuth, a statistically significant fit was obtained for $k=1$ to $k=6$ (Fig. 7). Among these 2θ fit is the most significant, which strongly suggests anisotropy.

This analysis was made for 3 instruments and similar results were obtained. The direction of fast wavespeed of about 124° coincides with the present compressive stress orientation inferred from earthquake mechanisms (e.g., Yamazaki *et al.*, 1985). If crack anisotropy was present, cracks would open nearly in N-S direction, which would become the slow direction. On the other hand, if dikes formed after the basin formation were responsible, they would align in N-S direction and would not explain our observation.

These results have brought us a new and detailed image of the Yamato Basin crust. If we could further ascertain the lowermost crustal wavespeed, it will be of significance whether we find a high wavespeed as was found at some Atlantic margins believed to be due to igneous intrusion (e.g., Tréhu *et al.*, 1989).

5. Signal and Noise Characteristics

In this section, the signal and noise characteristics of the OBDS will be presented. The first part will discuss the high frequency range which is the range normally observed by the conventional OBS equipped with velocity-type sensors. Then, the low frequency range will be discussed showing a teleseismic event recording in comparison with the land observation by STS broadband sensor. The event is buried in noise at high frequencies. Finally, the noise spectrum is compared with other available measurements in DSDP holes, on the seafloor, islands, and land. The spectra are all presented by one-sided power spectral density per unit time for acceleration, velocity, or displacement.

All the data discussed here were obtained during the real-time observation. Very long period change recorded by the seafloor unit is given in Kanazawa *et al.* (1992). Both the vertical and horizontal sensors registered similar changes in magnitude over about 30 days, corresponding to about several degrees change if they were due to temperature change. Since we did not have recordings of temperature or tilt, it is difficult to discriminate these factors. Noise from water convection inside the drill hole was not evident in hourly filtered values as only about 30-day period drift stood out.

5.1 OBS and OBDS

A comparison can be made for frequencies above a few Hz since the sensors used in the OBS's had natural frequencies of 4.5 Hz. Observations of local events and airgun signals are presented in this section.

5.1.1 Local events

Figure 8 compares the local event records of OBDS and OBS immediately above the OBDS in both the time and frequency domains. Though this event was not detected by the land network and thus could not be located, its S-P time and waveform are similar to those of an event also registered by OBDS which is an aftershock of the 1983 Japan Sea earthquake (Kanazawa *et al.*, 1992). The onset of the P arrival is impulsive on the OBDS record but buried in noise on the OBS record. It can also be observed that the P_n phase arrives ahead of the large arrival. A precursor, about 2.1 s ahead of

Fig. 8. Example of a local event recorded by OBDS (A, B) and OBS JRT4 (C). A: High-gain acceleration outputs of vertical and horizontal sensors. B: Same as A with expanded time scale. Maximum P and S amplitudes are about 12 and 119 $\mu\text{m/s}^2$ on vertical and horizontal components, respectively. C: Velocity records for vertical low-gain and horizontal outputs. Maximum S amplitude is about 18 $\mu\text{m/s}$, which corresponds to 180 $\mu\text{m/s}^2$ at 10 Hz.

Fig. 9. Velocity power spectra of the earthquake in Fig. 8. A: Velocity power spectra of OBDS vertical high-gain output and JRT 4 vertical low-gain output around P arrivals. OBS frequency response was assumed flat, so less than 3 dB fluctuation occurs between 5 and 22 Hz. For an absolute comparison, OBS curve should be lowered by 26 dB. B: Velocity power spectra of OBDS horizontal high-gain output and JRT4 horizontal output H1, around S arrivals.

the S phase, conspicuous only on the OBS vertical record is interpreted to be an S-to-P converted phase. This time difference is also found for P-to-S conversions of OBS airgun signals and not in OBDS records. It can be explained if the conversion took place above OBDS at the bottom of the sediment, which is about 0.7 km thick with P and S wavespeeds of 1.65 and 0.3 km/s, respectively.

Fig. 10. Comparison of airgun shot records by OBS and OBDS. Vertical and horizontal high-gain records of OBDS and JRT-4 are shown on the top and bottom, respectively. S/N ratio is better for OBDS, especially the difference between horizontal components is outstanding.

The horizontal record is much more reverberatory for OBS. This reverberatory frequency is about 3.5 Hz and is not recorded by OBDS (Fig. 9).

5.1.2 Airgun signals

Figure 10 compares airgun record sections of NS profile recorded by OBDS and OBS (JRT4) at Site 794D. As was the case for the local events comparison, phases can be identified more clearly for OBDS records. The S/N ratio is better for OBDS by more than 20 dB.

5.2 Teleseismic event recording

We observed a teleseismic event which occurred in Myanmar at 21:52 20.7s on September 28, 1989 [UT] with $M_b = 5.4$ as determined by USGS. The epicentral distance was 38.99° . This event was also recorded by an STS-1 seismograph at Tsukuba station of the Earthquake Research Institute of the University of Tokyo. Both records are shown in Fig. 11.

First, the record clearly proves the OBDS was indeed capable of registering distant earthquakes at long periods. Second, the OBDS amplitudes were about a few $\mu\text{m/s}^2$, similar to amplitudes at TSK. Third, surface wave dispersion is observed between about

Fig. 11. OBDS record of a teleseismic event of M_b 5.4 (USGS est.) occurred in Myanmar. Low gain outputs of vertical and horizontal sensors are shown on top. Cyclic changes at 11-min intervals were caused by the automatic mass centering function of the system. Velocity records of VBB vertical and horizontal components at Tsukuba land station (TSK) are also shown for comparison in lower figures. Two stations recorded similar amplitudes.

Fig. 12. OBDS record of surface waves of the teleseismic event shown in Fig. 11. The wave dispersion occurs from a period of about 40 to 15 s.

40 and 15 s (Fig. 12). The resolution better than a digital count is achieved due to the oversampling rate of 80 Hz. Note also that the S/N ratio is good at this frequency range, although artificial noise is introduced due to the automatic 11-min mass centering of the sensors.

This recording proves that an OBDS can serve well as an instrument for global seismology.

5.3 Noise spectrum

Two velocity noise spectra are combined to represent the noise under fair weather conditions between about 200 s and 30 Hz for the horizontal low gain component (Fig. 13). No airgun shots are included. For the lower frequency range (up to about 2 s), the average of four spectra between 06:00 to 10:00 on September 27, 1989 [UT], each obtained from 8,192 samples of 2-Hz high-cut filtered data sampled at a 0.125 s interval, is plotted. For the higher frequency range, the average of four spectra between 21:35–38 on September 26, 1989 [UT], each obtained from 8,192 samples of data sampled at a full rate of 80 Hz, is shown. The increase in OBDS noise level below 0.1 Hz is probably due to system noise rather than natural noise, because OBDS has only acceleration outputs with a resolution of about $1.2 \times 10^{-7} \text{ m/s}^2$, which is equivalent to about $1.9 \times 10^2 \text{ nm/s}$ at 0.1 Hz. Therefore the results for frequencies above 0.1 Hz are mainly discussed in the following.

We find that above 10 s period the OBDS noise level falls between that of noisy and quiet conditions for a typical land station on hard basement rock (Aki and Richards, 1980) (Fig. 13). Among the few previous ocean bottom long-period seismic observations (Sutton *et al.*, 1988; Trevorrow *et al.*, 1990; Dozorov and Soloviev, 1991; Crawford *et al.*, 1991), we first compare our results with the results obtained from the Columbia-Point Arena Ocean Bottom Seismic Station (OBSS) in Fig. 13 (Sutton *et al.*, 1988). Their results are comparable to or quieter than other results below 10 Hz (Dozorov and Soloviev, 1991). The OBDS noise level is lower than OBSS above 0.1 Hz. Crawford *et*

Fig. 13. Velocity power spectral density per unit-time (one-sided) from OBDS horizontal low-gain component. OBDS curve for frequency band below about 0.5 Hz is the mean of four 1,022 s long datasets between 06:00 and 10:00 on Sep. 27, 1989. The mean of four 102 s long datasets between 21:35 and 21:38 on Sep. 26 is shown for frequencies above 0.5 Hz. The system resolution level is shown by a dotted line. Also shown are typical land noise curves from Aki and Richards (1980) and vertical component spectra of OBSS during a quiet period from Sutton *et al.* (1988).

Fig. 14. Noise power spectra of Fig. 13 in displacements. Displacement power decay is about 43 dB/decade. Also shown for comparison are MSS, Queen Creek, and Lajitas stations results from Adair *et al.* (1986), and GUMO station results from Hedlin and Orcutt (1989).

al. (1991) obtained acceleration noise spectra using a gravimeter. Their quieter result from an axial seamount of northern East Pacific Rise shows about $2.5 \times 10^4 \text{ nm}^2/\text{s}^2/\text{Hz}$ at 0.1 Hz, which is comparable to OBDS noise.

Figure 14 represents the spectra in displacement. The displacement power density falls at about 43 dB/decade. This figure may be compared with the noise spectra from Marine Seismic System (MSS) and quiet continental sites at Queen Creek, Arizona,

Fig. 15. Temporal change of weather, sea state, and long-period seismic noise between 06:00, Sep. 27, 1989 (shown as 0 on panels A–C) and 03:00, Sep. 29, 1989 (60 on panels A–C). A: Atmospheric pressure change as observed on drill ship. B: Sea state observation. Atmospheric pressure drop coincides with a wind speed maximum and sea height maximum. C: Long period change of OBDS sensors from about 51 s length data. D: Temporal contour plot of acceleration power spectral density. No data were available between 05:00 and 07:00 on Sep. 28. The energy from a teleseismic event is found in Sep. 28 22:00 spectra. Noise level increases with time to Sep. 28 11:00 between 0.3 and 1 Hz with the approach of a storm.

and Lajitas, Texas (Adair *et al.*, 1986), and Seismic Research Observatory (SRO) station on Guam Island (GUMO), which was quieter than Taiwan and Easter Island stations (Hedlin and Orcutt, 1989). Hedlin and Orcutt (1989) find that island stations and OBS or MSS noise spectra are comparable between 0.1 and 10 Hz, and thus, seafloor stations are practical where there are no nearby islands for stations.

The OBDS is quieter than MSS below 0.1 Hz and quieter than GUMO above about 0.15 Hz. Below 0.1 Hz, island stations show a reduction in displacement power, whereas the OBDS does not, because of the resolution problem given above.

The outstanding peaks between 0.1 and 1 Hz are at 0.3 and 0.5 Hz (Fig. 13). These are different from the frequencies of noise due to ocean waves, namely 0.07-Hz noise generated by waves acting on coasts and 0.14-Hz noise due to standing ocean waves, originally explained by Wiechert and Longuet-Higgins (Aki and Richards, 1980). While available noise spectra observations in oceans show peaks at about 0.2 Hz, the OBDS spectra has a trough with a small peak at about 0.14 Hz (Fig. 13).

The temporal change of the acceleration power spectral density is shown in Fig. 15. This was obtained by contouring the spectra calculated for 8,192 samples at 0.125-s intervals starting at hour intervals from 06:00 on September 27 to 03:00 on September 29. A decade change in power spectral density level corresponds to a gray-scale level change. The conspicuous spectra at 22:00 on September 28 is the result of an earthquake (Fig. 11).

Comparing this with the sea state and atmospheric pressure (Fig. 15A, B), it can be seen that above about 0.3 Hz, the change corresponds to the change in pressure and sea state except for swell height. Apparently, below this frequency, the noise level is not affected by these factors. Figure 15C was obtained by calculating the mean values of 4,096 samples at about 51 s intervals and substituting DC offsets caused by the 11-min mass centering function by interpolations. The vertical component does not seem to be affected by the weather, whereas the horizontal component seems to have changed its trend at a maximum in atmospheric pressure rate, although the physical relationship is not clear.

6. Conclusions

In this paper, we have presented a summary of results from OBDS observation in the northern Yamato Basin of the Japan Sea. The OBDS experiment was conceived as a chief project of ODP-Japan during the period of 1988–1990. The instrument was successfully installed during Leg 128 of ODP cruises in fall, 1989. It marked the first attempt towards wide-dynamic range and broad frequency band digital seismic observation below seafloor utilizing a drilled hole.

A real-time observation was made aboard D/V JOIDES Resolution for about 60 h capturing airgun shots for studying the local crustal structure, aftershocks of 1983 Japan Sea earthquake, and a teleseismic event in Myanmar with M_b of 5.4. Comparisons in the same high frequency band with simultaneously obtained OBS-array data proved that OBDS supersedes in S/N ratio by more than 20 dB and in seismic phase identifications. The teleseismic event was not detected by OBS, whereas OBDS data clearly showed different phase arrivals and surface wave dispersion, similar to land

observation by an STS system. The OBDS noise at long periods above 0.1 Hz is less than other available results on islands or seafloor. Below 0.1 Hz, the background noise level seems to be below detection threshold. Noise level increase above about 0.3 Hz was observed as a storm approached. An interesting characteristic is that the OBDS noise spectra has a trough at about 0.2 Hz, whereas other results have peaks.

A seafloor recording package was deployed immediately after real-time observation for a long-term observation. The seafloor system operated for about 35 days after installation and was recovered 8 months afterwards. The event recording scheme did not record events due to an algorithm problem, but obtained noise level changes. The main technical problem was the power supply, more than half of which was dissipated by the 4.5 km cable. Since a much larger digital data storage is now possible in various media, the power supply seems the only remaining major obstacle towards establishing seismic stations in oceanic areas. Once technical problems are solved, it is important that ocean bottom instruments are placed at optimum sites for scientific objectives.

The purpose of our OBDS experiment was aimed to establish a seismic station in a back-arc marginal sea environment to study lateral heterogeneity probably caused by the plate subduction. We need to observe more natural earthquake data to meet this prime objective, which requires the seismic sensor package to be re-serviced.

The seismograms from TSK station of Earthquake Research Institute, the University of Tokyo were provided by K. Abe.

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