

Seabass and Seismoacoustic Noise Below the Seafloor

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Introduction

The Seafloor Borehole Array Seismic System (SEABASS) was originally developed to study the ambient noise at and below the seafloor. This paper summarizes the ambient noise results of the SEABASS-1 deployment in the Blake-Bahama Basin in August-September 1989. We will also discuss the development plans for SEABASS-II, a broadband (330 sec-5 Hz) system which will be used for the OSN (Ocean Seismic Network) Pilot Experiment off Oahu in September 1997.

Are borehole seismometers better than seafloor or shallow buried seismometers? This is not a simple question. The answer depends on many factors and in some cases we simply do not have the necessary information to make a reliable judgment. We give an overview below of some of the issues that need to be considered.

SEABASS

The Seafloor Borehole Array Seismic System was originally developed as a VLF system (2-50Hz) to study ambient noise at and below the seafloor (SEABASS-1) (Stephen, et al., 1994). The system has been modified to deploy a broadband borehole seismometer and to record data in the band, 330sec-Hz (SEABASS-II). Both SEABASS-1 and SEABASS-II use the wireline re-entry system developed to re-entry boreholes on the seafloor (Spiess, et al., 1992, Figure 1). After re-entry electronic connection is maintained to the seafloor packages to clamp the sensors and to acquire data on board ship. Once the system is properly in place, the cable is released at the top

of the recording package and the system autonomously records data on the seafloor for periods up to three months. After the recording period the system is recovered by grappling.

On both SEABASS systems, a frame carrying recording and telemetry equipment sits in the re-entry cone on the seafloor (Figure 2). The SEABASS frame contains an electronic and telemetry module, the data recording unit, batteries, and acoustic transponders. The borehole array on SEABASS-1 consists of four three-component, individually clamped, 4.5Hz borehole geophones and a borehole hydrophone. It was built by Compagnie Generale de Geophysique (CGG). On the deployment at Site 534 in the Blake-Bahama Basin in 1989 (Stephen, et al., 1994) the sondes were clamped at depths of 10m, 40m, 70m, and 100m. SEABASS-II is a ULF system (330s-5Hz) with a single, three component sensor (Teledyne KS54000).

VLF Ambient Noise

Acceleration spectra from SEABASS-1 (Bradley, 1994; Bradley, et al., in press) are valid down to 0.3Hz but do not show the noise notch between 0.1 and 0.2Hz which is seen on the adjacent OBS (Figure 3). The noise notch marks the transition from infragravity waves whose wavelengths are long enough to directly force the crust (less than 0.05Hz) (Webb et al., 1991) to the microseism band (from 0.1Hz to 5Hz) where nonlinear wave-wave interaction is acoustically interacting with the crust (Hasselman, 1963; Kibblewhite and Wu, 1991; Longuet-Higgins, 1950). Above Hz

local wave breaking, shipping, biologics and industrial sources have been postulated to control ambient noise levels (Urick, 1986).

SEABASS-1 and the OBS used 4.5Hz and 1.0Hz geophones respectively. The 4.5Hz phones are not sufficiently sensitive at low frequencies to detect the noise notch. The slope of the SEABASS spectra below 0.2Hz suggests that the spectra is saturated by the Least Significant Bit (LSB) noise.

Figure 4 summarizes ambient noise results from the LFASE experiment in the Blake-Bahama basin with sediments over 1 km thick in 4,971m of water (Bradley, 1994; Stephen, et al., 1994). The microseism band can be further subdivided into four bands: 0.2-0.4, 0.4-0.75, 0.75-2.1 and 2.1-5.0Hz. At the microseism peak (0.2-0.4Hz) spectral values vary by less than 1 and 2dB respectively for vertical and horizontal components over the full 100m length of the array.

However at frequencies just above the peak (0.4-0.75Hz) depth dependence becomes evident. The OBS and 10m satellite have similar levels on both horizontal and vertical components. But at 70 and 100m depth the horizontal spectra are 15dB quieter and at 100m depth the vertical spectrum is 5dB quieter.

The 0.75-2.1Hz band is characterized by peaks in the OBS spectra near 0.75, 1 and 2Hz. These peaks have significant depth dependence. On the horizontal channels, the 10m spectrum shows comparable levels for the 0.75 and 1.0Hz peaks, and a reduction of about 6dB (and an increase in frequency to about 2.5Hz) for the 2.0Hz peak. On the vertical channel, the 10m spectrum has slightly reduced levels (about 3dB) for the 0.75 and 1.0Hz peaks and does not have a 2Hz peak at all. Essentially none of the peaks are observed on the horizontal or vertical channels at 70 and 100m. It is unlikely that these peaks are associated with instrument resonance since they appear on both the OBS and the shallow (10m) seismometer and they have non-uniform

behaviors on the other borehole sensors.

The 2.1-5.0Hz band has been labeled the 'Holu' spectrum by McCreery et al (1993). Within the Holu band the spectral slope is determined by sea state directly over the sensors. Levels in this band reach a maximum when the surface gravity wave spectrum saturates. Higher wind speeds cannot generate more gravity waves in this band. In the Holu spectrum the borehole sondes all have comparable levels which are about 20dB and 10dB lower than the OBS for horizontal and vertical sensors respectively. (At the lower end of the spectrum the 10m horizontal channel does rise about 6dB above levels on the other sondes.) At 5.0Hz there is a strong peak on the OBS horizontal components, which rises 40dB above borehole levels. We suspect that this may be associated with an instrument resonance in the OBS.

Between 5.0 and 20.0Hz the borehole sensors have uniform values and are 20 and 10dB quieter than the OBS for horizontal and vertical sensors respectively. Above 3.0Hz for horizontal channels and above 2.0Hz for the vertical channels most of the improvement in ambient noise occurs in the upper 10m. The 70m and 100m ambient noise levels are similar throughout the band observed and are quieter, by up to 20dB, than 10m levels in the band from 0.4Hz to 3.0Hz.

Are borehole seismometers "better" than seafloor or shallow buried seismometers?

Although broadband measurements have been made on the seafloor with both seismometers (Auld, et al., 1969; Barstow, et al., 1989; Dozorov and Soloviev, 1992; Latham and Sutton, 1990; Prothero and Moore, 1971; Sutton and Barstow, 1990; Webb, 1988; Webb, et al., 1994 and hydrophone (Webb and Schultz, 1992), the issue of what can be gained by placing a sensor below the seafloor is still unresolved. It is convenient in our discussion

to define "broadband" as frequencies between 0.001Hz and 100Hz; ULF can be defined as the band from 0.001Hz to 1Hz; and VLF can be defined as the band 1Hz to 100Hz. The largest ambient noise levels at the seafloor in acceleration units occur at the microseism peak(s) near 0.16Hz and 0.3Hz, and the microseism peak effectively the ULF and VLF bands. It is challenging to develop a seismic sensor which will span the full band from 0.001Hz to 100Hz. Practical Installations would generally require two systems: a modern active feedback seismometer for the ULF range and a passive more traditional sensor for the VLF range. In both cases the proper installation of broadband seismometers on or below the seafloor is an outstanding issue, that must be resolved prior to committing to an expensive permanent network.

Observations and models of ambient noise near the seafloor indicate a preponderance of interface waves, perhaps generated by scattering from seafloor heterogeneities (Bradley, 1994; Bradner, et al., 1965; Dougherty and Stephen, 1988; Latham and Nowroozi, 1968; Latham and Sutton, 1966; Orcutt, et al., 1993a; Orcutt, et al., 1993b; Schreiner and Dorman, 1990; Webb, 1992). Also large eddies in the ocean near the seafloor induce pressure fluctuations which tilt the seafloor and produce a seismic signal at frequencies below a few Hertz, particularly on horizontal components (Webb, 1988). The very low shear modulus of most sea-bottom sediments also causes them to act as mechanical amplifiers for shear wave amplitudes, so that the ratio of compressional to shear displacements observed on the seafloor can be dramatically different from those observed on competent rock or in boreholes. This will affect both signals and noise and could contribute to anomalous behavior even at very low frequencies where the wavelengths are much longer than the sediments are thick. It could be viewed as an advantage (for example in Love

wave studies) or a disadvantage (for example in shear wave ringing in the sediments). Even aside from these mechanisms that affect real noise at the seafloor, obtaining faithful ground motion records with a sensor directly on a fluid-solid boundary is a challenging task (Barash, et al., 1994; Duennebier and Sutton, submitted; Sutton and Duennebier, 1988; Sutton, et al., 1981; Trehu and Sutton, 199 and deep sea currents flowing against the seismograph cause instrument noise (Duennebier, et al., 1981). So there is ample justification for considering shallow buried and deep borehole sensors for seafloor seismometry.

In shallow water studies, experiments have shown that burying the seismometer reduces ambient noise levels (Sutton and Duennebier, 1988; Trevorrow, et al., 1989a; Trevorrow, et al., 1989b). A number of studies have observed that ambient noise at frequencies above the microseism peak at about 0.16Hz to 0.3Hz is consistently quieter for both vertical and horizontal sensors in boreholes than on the seafloor (Adair, et al., 1984; Bradley, 1994; Bradley, et al., in press; Duennebier, et al., 1987; Hedlin and Orcutt, 1989; Stephen, et al., 1994).

There are considerably fewer observations of ambient noise below the seafloor at frequencies below the microseism peak. The first broadband seismic observation in a borehole in competent rock beneath the deep seafloor was carried out in the Japan Sea in the fall of 1989 but reliable ambient noise data below 0.1Hz was not obtained (Kanazawa, et al., 1992; Suyehiro, et al., 1992). Montagner et al (1994a; 1994b), on a short term borehole experiment near the Mid-Atlantic Ridge, observed that between about 0.01 Hz and 0.3Hz the borehole sensor was noisier than a seafloor sensor. However, during the course of the short, one week deployment the borehole sensor became progressively more quiet. No effort was made in this deployment to clamp the

sensor in the hole, it just sat on the bottom of the hole, or to prevent flow in the hole. Also the seafloor measurements were so quiet compared to both land and other seafloor observations that the calibration of the seafloor sensor has been questioned [Webb, pers. comm.] It is fair to say that the international community is still learning the correct way to install seafloor borehole stations. Both the French and Japanese are continuing their broadband borehole seismometer development efforts. Observations and inferences from modeling give somewhat conflicting evidence regarding the merits of buried and borehole sensors. We need more experiments.

There are a number of issues that need to be considered in evaluating the benefits of borehole seismometers over seafloor or shallow buried seismometers in the seafloor. Although we have begun to make measurements to compare the performance of sensors, it is too early to say which is better for OSN or ION objectives. Measurements of ambient noise on and within the seafloor to date in the ULF and VLF bands indicate that performance will depend on at least the following factors:

- Type of sensor: vertical versus horizontal components (or, in some cases, even hydrophones or differential pressure gauges), arrays of receivers. etc;
- Geological factors such as sediment thickness, rigidity, shear wave attenuation, water depth, etc. (Does the low rigidity sediment itself move faithfully with the "true" basement motion?);
- Proximity to land and beaches;
- Sea state and weather (see Babcock et al (1994) for examples of the dependence of ambient noise on weather conditions);
- Frequency band of interest and the nature of the signals of interest;
- Depth of the seismometer below the seafloor and/or depth into basement ;
- Clamping of seismometers in basement or in sediments, or in or out of casing;
- Influence of bottom currents;

- In the case of borehole sensors, the clamping mechanism, seismometer design (weight, length, density, etc), the presence or absence of fluid flow in the borehole and formation, the effects of cables, reentry cones, and even the borehole itself on the received field;

- In the case of shallow buried seismometers, the aspect ratio and density of the sensor;

- Electrical system noise from preamplifiers, digitizers, power supplies, and recorders; electrical crosswalk in the electronics or cables; mechanical vibrations from recorders;

Variation with time of the ambient noise; and

- Geographical variations of noise (Pacific versus Atlantic; variations with latitude).

An evaluation of the "best" sensor has to be made in the context of a given application and costs. What "signals" are we looking for? Ambient noise may decrease (or increase) with depth below the seafloor, but signal strength may also decrease (or increase). We need to evaluate signal-to-noise ratios for signals of interest. Enough signal events and noise intervals need to be observed to provide a statistically meaningful result. A single observation of an earthquake, for example, is not sufficient.

The ambient noise field is non-stationary and the behavior of ambient noise under various weather and swell conditions is important. For example, environmental conditions near OSN-1 are quite different from conditions between 40 degrees and 60 degrees South. For pilot experiments to be relevant, installations should be run for a long enough period of time to acquire data over a range of environmental conditions. The U.S. OSN effort has estimated that a continuous acquisition of data over a three month period is necessary to ensure a sufficient number of seismic events to evaluate a system. Prior to an at-sea test, land testing of various sensors and clamping strategies needs to be carried out in wet holes and the performance of the sensors compared with reliable land instruments.

Seafloor borehole experiments to date that have sampled limited regions of the overall parameter space include:

- The Japanese experiment in deep water and thin to thick sediments (200-700m) in the Sea of Japan;
- The French experiment in deep water and thin sediments near the mid-Atlantic Ridge (single, three component, ULF borehole sensor and quasi-buried ULF OBS);
- The HIG ULF/VLF experiment in shallow water, and thick sediments off Oregon (OBS and shallow buried OBS only);
- The U.S. LFASE experiment in deep water and thick sediments off the coast of Florida (four three-component, VLF sensors at various depths down to 100m in the seafloor and VLF OBS's); and,
- A suite of borehole experiments carried out by OUT, HIG, and SIO as part of the DSDP program (e.g., Ngendie, Site 581, Sites 504B, 417D, etc) (Adair, et al., 1986; Adair, et al., 1984; Byrne, et al., 1987; Carter, et al., 1984; Duennebie, et al., 1986; Duennebie, et al., 1987; Stephen, 1987).

In addition there have been a large number of ocean bottom seismometer, ocean bottom hydrophone and differential pressure gauge measurements on the seafloor and considerable experience has been acquired from borehole installations on land in wet and dry holes. These have contributed greatly to models for the sources and propagation mechanisms of ambient noise and to our knowledge of the relationships between ambient noise and environmental factors.

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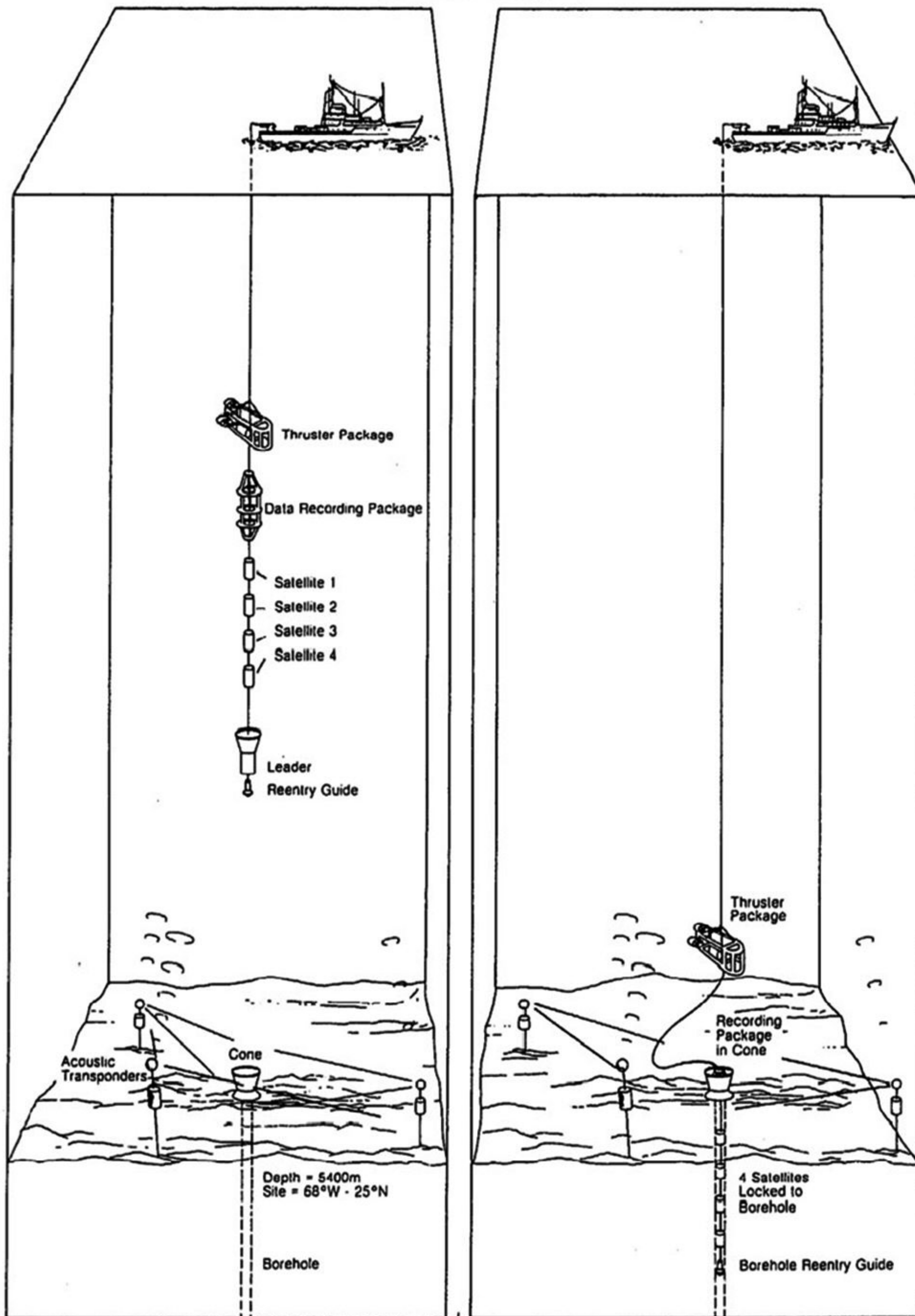
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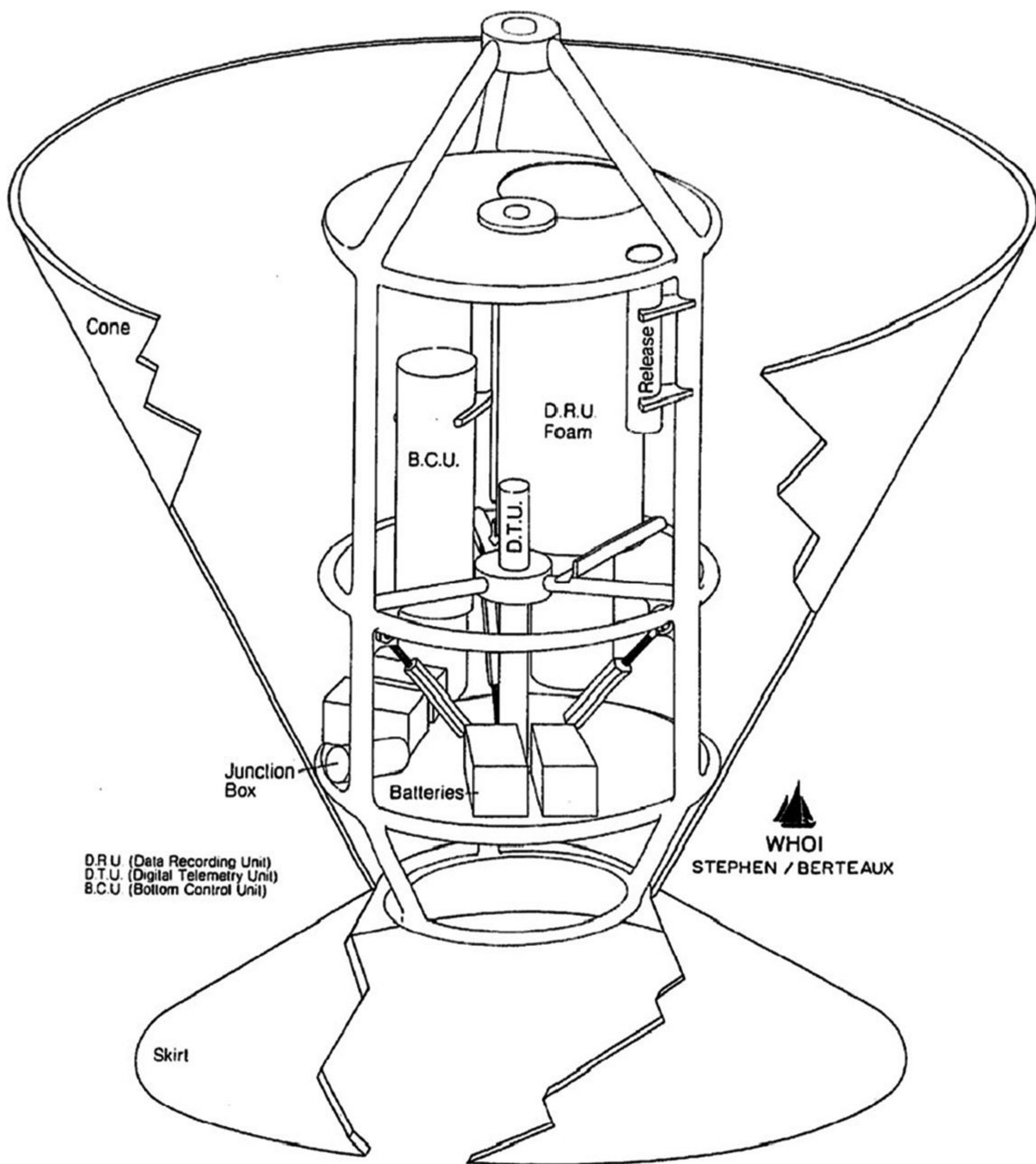
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*Seismic Array Deployed and
Connected to Ship*



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Figure 1: Wireline re-entry (Spiess, et al., 1992) is a convenient and inexpensive way to install equipment into boreholes on the seafloor from a conventional, surface research vessel. Cameras and sonar in the re-entry guide are used to locate the re-entry cone. The array location is controlled by the dynamically positioned surface ship and the thruster package on the wire. One advantage of this system is that seismic data can be acquired on the surface ship for days before disconnecting the wire from the autonomously recording seafloor package.



*LFASE Recording Package
in Reentry Cone*

Figure 2: The recording package fits in the re-entry cone. A portion of the frame sticks out above the cone so that the package can be recovered by grappling.

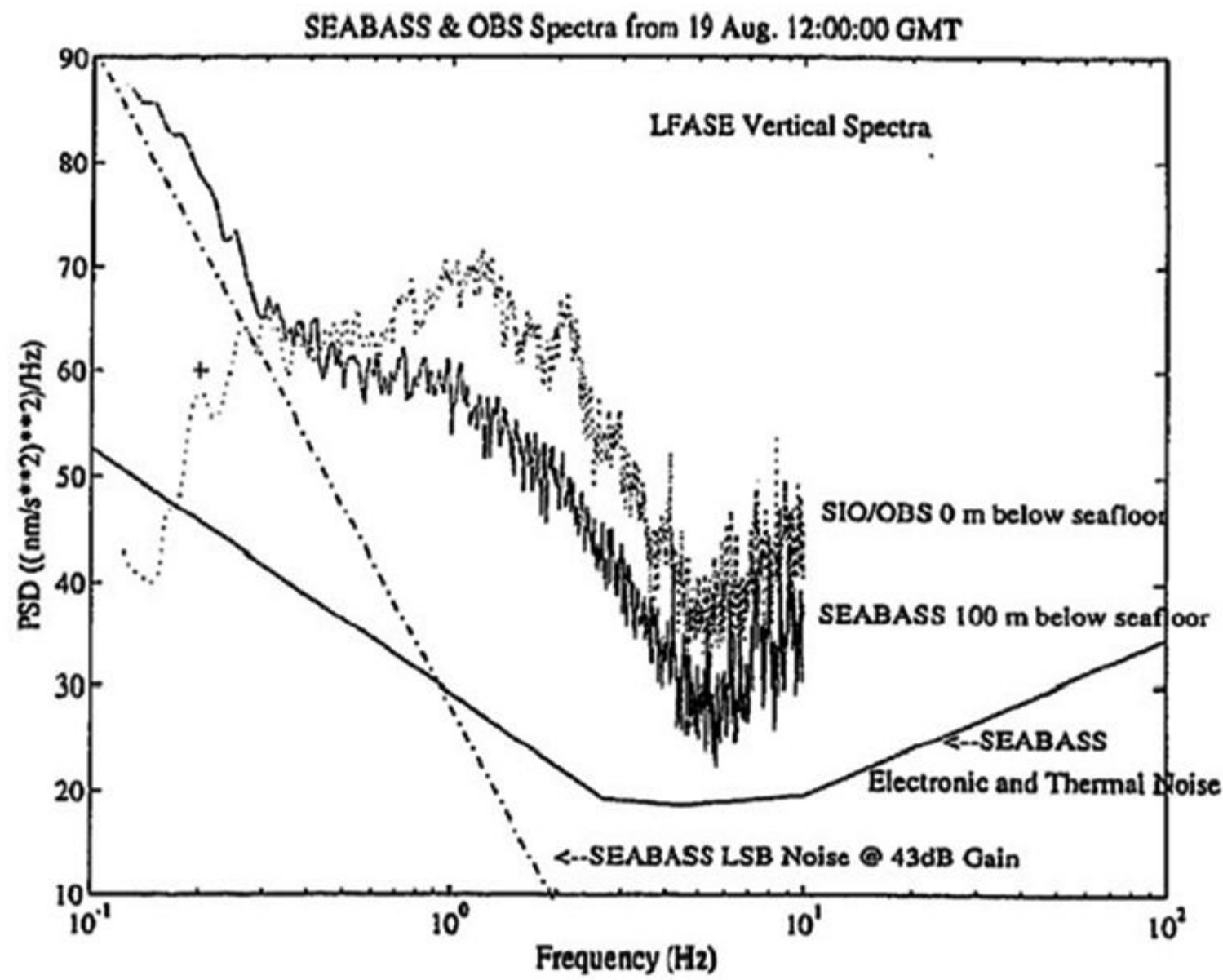


Figure 3: SEABASS and OBS vertical component spectra are compared for data acquired on the LFASE experiment (Bradley, et al., in press; Stephen, et al., 1994). SEABASS which uses 4.5Hz sensors, rather than 1.0Hz sensors on the OBS, cannot resolve the 'noise notch' below 0.1Hz because of Least Significant Bit (LSB) noise.

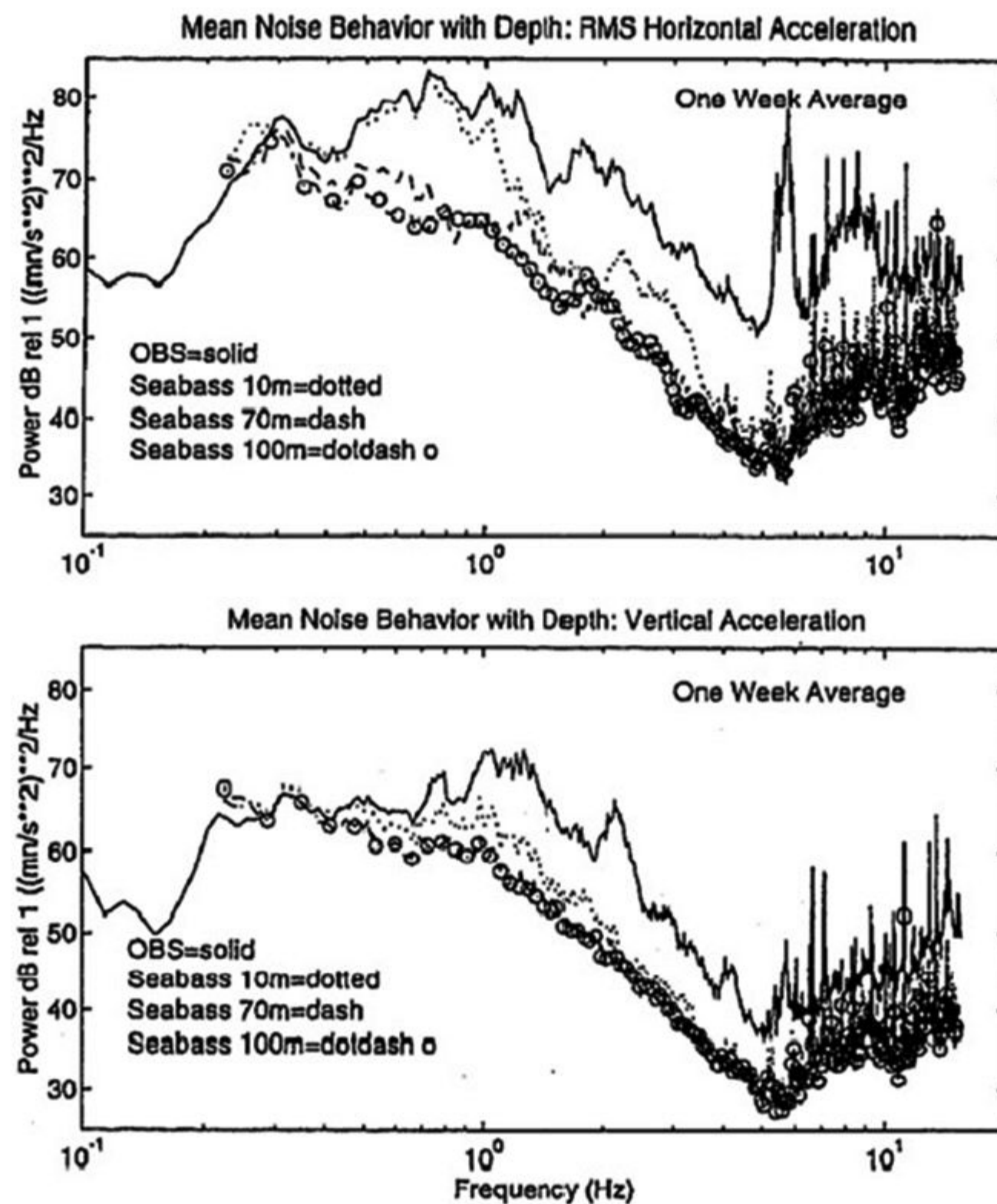


Figure 4: Comparisons of SEABASS and OBS spectra for Horizontal (above) and vertical (below) components shows that borehole sensors are generally quieter than seafloor sensors from 0.3-20Hz. Details are discussed in the text.