UNDERWATER DRILLING - MEASUREMENT OF SOUND LEVELS AND THEIR EFFECTS ON BELUKHA WHALES

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Underwater Drilling - Measurement of Sound Levels and their Effects on Belukha Whales

OVERVIEW

Marine mammals make extensive use of underwater sound and recently various groups have become concerned that noise, which is transmitted more efficiently through water than air, may disturb these animals. In particular, the petroleum industry, government agencies and the general public have raised questions about the effects of underwater sounds from oil and gas drilling rigs.

To study this subject the American Petroleum Institute commissioned two complementary studies: First, Polar Research Laboratory (PRL) was contracted to measure and record underwater sounds from a semi-submersible drilling rig and to study the transmission loss of these sounds. Second, Hubbs Marine Research Institute (HMRI) studied both the behavioral and physiological responses of captive belukha whales to playbacks of these sounds. Reports of both projects are contained in this volume.

PRL measured underwater sounds from the SEDCO 708, a representative semi-submersible rig operating in the Bering Sea. The measurements were taken at distances of 0.1, 0.2, 0.5, 1, 2, 5, and 10 nautical miles (nmi) from the rig and at depths of 2.5, 5, 10, and 30 meters (m) to determine frequency composition, sound pressure levels and transmission loss. Measurements were also made at 0.5 nmi from the rig at depths of 10 and 30 m in all four cardinal directions to test for directional differences in sound radiation.

The broad band sound pressure level (80 - 4000 Hz) measured at 0.1m was 117 dB i.e. 1uPa, with the majority of the energy occurring below 2000 Hz. Ambient sound levels were 102 - 112 dB i.e. 1Pa under the prevailing conditions (wave heights of 1 - 2 m). Although some tonal components from the rig were detectable at 10 nmi, sound at most frequencies became indistinguishable from ambient at a distance of 0.5 nmi.

The pattern of sound transmission loss approximated that of cylindrical spreading. Sound levels, especially at the lower frequencies, were lower at shallower depths. There was no difference in the sound radiated in the different directions from the rig.

HMRI studied the response of four captive belukha whales to playbacks of sound from SEDCO 708. During a 30-day period baseline observations were made of certain aspects of the whales behavior. These behaviors included blows/min, dives/min, number of 'heads up'/min, number of 'heads down'/min, the proportion of time spent in each of 14 possible social combinations, the proportion of time spent

in each of ten areas of the pool, the time between consecutive blows, and the time between consecutive dives. A further and unique aspect of this study was the examination of blood levels of epinephrine and norepinephrine (catecholamines, which are indicators of stress). Because the belukhas had been trained to present their tail flukes, it was possible to draw blood samples without stressing the whales in the process.

The sound was played into the tank containing the belukhas at a level which simulated the presence of the SEDCO 708, at a distance of 180 m (0.1 nmi). There were nine playback sessions, each lasting 30 min. When playback began, the whales showed a startle response, but otherwise behaved as they had during the baseline periods. The blood catecholamine levels were not elevated after exposure to the sound. The observations of the response of the captive animals were consistent with the uncontrolled observations made of free-ranging belukhas near actual full-scale offshore exploration operations in the Mackenzie River estuary in Canada, and also with controlled observations of free-ranging belukhas exposed to experimental playbacks of drilling sounds conducted in western Alaska.

Hearing threshold measurements were made to determine the hearing sensitivity of belukhas at various sound frequencies. The results showed that belukhas are relatively insensitive to sounds below about 4 kHz, the frequency of most industrial sounds. Thus beukhas, like other toothed cetaceans, have a hearing range of greatest sensitivity distinct from the frequency range of industrial sound.

In conclusion, these studies indicate that underwater sounds produced by a semi-submersible rig will not significantly affect belukha whales or, by extrapolation, other toothed cetaceans. The playback of drilling sounds to captive belukhas did not result in changes in behavior or in increased levels of catecholamines (stress-related hormones). Any theoretical models of the impact of noise on marine mammals must take into account the frequency composition and level of the underwater sound and transmission losses in the water. Additionally, the marine environment is often noisy and the animals there probably are adapted to these conditions.

UNDERWATER SOUNDS FROM THE SUBMERSIBLE DRILL RIG SEDCO 708 DRILLING IN THE ALEUTIAN ISLANDS

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ABSTRACT

Underwater sounds from the semisubmersible drilling rig SEDCO 708 were recorded during drilling operations in the Aleutians on 29 September 1982. The objective of the study, funded by the American Petroleum Institute, was to quantify the rig sounds in terms of acoustic pressure and frequency. The results were needed to assess the spatial extent of the radiated noise and the associated acoustic influence on marine mammals. The water depth was 114 m. Recordings were made at ranges of 0.1, 0.2, 0.5, 1, 2, 5, and 10 nm at depths of 2.5, 5, 10, and 30 m. Recordings were also made at depths of 10 and 30 m, range 0.5 nm, to the south, west, north and east of SEDCO 708 to test for azimuthal dependencies. The results showed that numerous tonal components of sounds were received as far as 10 nm, although they were not strong. Broadband components were generally down to background levels for ranges of 1 nm and greater. Background levels were estimated to be from 102 to 112 dB//1uPa for the 10 to 4000 Hz band and from 72 to 79 dB//1uPa /Hz at 100 Hz. Source levels for tones at 60, 181, and 301 Hz are estimated to be 149, 137, and 136 dB//1uPa-m, respectively. The source levels for the 10-500 and 80-4000 Hz bands are both estimated to be 154 dB//1uPa-m. The variations with azimuth are on the same order as temporal variations. Signal level generally increased with depth, especially for low frequencies.

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INTRODUCTION

The petroleum industry, governmental regulatory agencies, and the general public have become increasingly concerned about the underwater sounds from offshore oil- and gas-related activities and how such sounds may disturb marine mammals. In this connection, the U.S. Department of the Interior's Minerals Management Service (MMS) has been supporting separate research projects concerning bowhead and grey whales. The importance of noise from drilling has been recognized by MMS in its support of work in the Canadian Beaufort Sea to measure, among other things, noise from drillships and the response of bowhead whales exposed to it (Richardson 1982). MMS has also supported playback tests with drilling and other industrial noises in the presence of grey whales off the California coast (work not yet completed). Other pertinent studies include those of Buerkle (1975) of the sounds from SEDCO J, a semisubmersible drill rig operating in the Bay of Fundy, and of Gales (1982) who measured noises from a variety of drilling platforms. Greene (1982) reported measurements of sounds from a drillship in the eastern Beaufort Sea. Their work will be compared with the results of the present work later in this report.

The American Petroleum Institute, Environmental Affairs Department, supported this study of the underwater sounds from a semisubmersible drilling rig operating near the Aleutian Islands, Alaska. The objective was to quantify the sounds in terms of acoustic pressure (decibel with respect to 1 microPascal, or dB//1uPa) and frequency. The results were to be used in assessing the spatial extent of noise radiating from a drilling vessel and the region of acoustic influence using what was known or suspected about the hearing capabilities of various marine mammals. This report presents the results of the acoustic study and quantifies the radiated noise from the drilling rig as it was received at depths to 30 meters (m) and ranges to 10 nautical miles (nm).

TECHNICAL APPROACH

The plan to accomplish the project objective involved two basic efforts: a field experiment to record the sounds from SEDCO 708 followed by analysis in the laboratory. First, we discuss the field site and the drilling vessel SEDCO 708. Then, we discuss the methods and equipment used in the experiment and the analysis.

Semisubmersible SEDCO 708

The drilling vessel studied was SEDCO 708, a semisubmersible rig with a drill tower height of 43 m (81 m above the water) and a platform surface about 90 m square. At the time of the measurements the rig was at 56 deg 16 min north, 161 deg 58 min west, drilling in water about 114 m deep at depths near 1600 m. Two pumps were operating at about 54 strokes per minute. No ballast pumps or thrusters were operated during the time of the tests. The drill itself is electrically powered and turns at 100 to 120 rpm. The date of the measurements was 29 September 1982.

Field Experiment

The plan required the use of a boat for the hydrophones and recording equipment. A fishing boat was available and the boat crew was agreeable to shutting down all engines, generators, and other noise-making equipment to minimize the local noise during each recording. Radar provided range information to the drill rig.

Two hydrophones were suspended from a 4.6 m sparbuoy made of 3 inch PVC pipe. The sparbuoy (or a similar device) served to decouple the hydrophones from surface wave motion. Otherwise the large changes in hydrostatic pressure would saturate the electronic amplifiers and block out the acoustic signals. In fact, there were periods of saturation even with the sparbuoy, as will be discussed later.

One hydrophone was a PRL 'bender' unit sensitive to frequencies below 1000 Hz. It included a very low noise preamplifier. Signals from this unit were further amplified by a postamplifier with gain adjustable in 10 dB steps. This signal was applied to the input of a voltage controlled oscillator, providing a frequency modulated signal as input to the left channel on the tape recorder. This FM process provided both low noise and a very low frequency response. In our system the low frequency break point was at 5 Hz.

The second hydrophone was a U.S. Navy reference hydrophone model H56. This unit has a frequency response extending from 10 Hz to 65 kHz and a low noise preamplifier, although it is not optimized for low frequencies. Signals from the H56 were further amplified by a

broadband postamplifier with 40 dB fixed gain and additional gain selectable in 10 dB steps. This signal was recorded on the right channel of the tape recorder.

The tape recorder was a Sony Model TC-D5M stereo cassette recorder with servo controlled capstan drive. This feature is important in assuring constant recording speed and therefore faithful recording of narrowband tonal components of sound. Calibrated, its frequency response is useful from 10 Hz to 17,000 Hz. The use of FM recording for the bender hydrophone permitted recording fidelity to below 5 Hz as noted above.

Recordings were made at seven ranges: 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 nm. At each range, recordings at four depths were made: 2.5, 5.0, 10.0, and 30.0 m. To test for azimuthal dependencies in the radiated sound we followed the recordings at different ranges by making recordings at a range of 0.5 nm, using only the 10 and 30 m depths, at positions south, west, north, then east again. This also replicated the measurements at 0.5 nm during the range tests; they had been made along a line to the east of SEDCO 708.

The sparbuoy/weight suspension system was rigged to permit adjusting the hydrophone depths in stages. Because it was not practical to know whether the rig was actually drilling or adding a section of drill pipe at any specific time, recordings were made for six to eight minutes at each depth to assure that at least some of each recording contained drilling noises. (In fact, we were unable to distinguish sound changes attributable to drilling or not drilling.) As already mentioned, the fishing boat secured all machinery during recording sessions to assure a quiet background. There was some noise from waves hitting the sparbuoy and the boat, however. The sparbuoy drifted between 3 and 5 m from the fishing boat.

The weather during the measurements was near optimum for that season and region of the world. Recording began at 10:26 am local time with the wind speed from 7 to 8 knots, a moderately high overcast, visibility of 23 miles, and waves from 1 to 2 m with a period of 5 seconds (s). During the day the wind picked up to about 9 knots, then dropped back to 3 to 4 knots by the time recording ended at 11:33 pm. Wave heights remained about the same.

We had planned to measure the temperature vs depth profile at the field site both before and after the sound measurements, but it was not possible. Therefore we obtained archival data on sound velocity profiles computed from salinity-temperature-depth profiles measured in the area during September. There was not much data, but the results of a summary of data for July through September are probably representative. Figure 1 shows the sound speed profile to 125 m. For a source at the surface, Figure 2 shows the paths of sound rays with initial angles 5, 10, 15, and 20 deg below the horizontal plane. In the

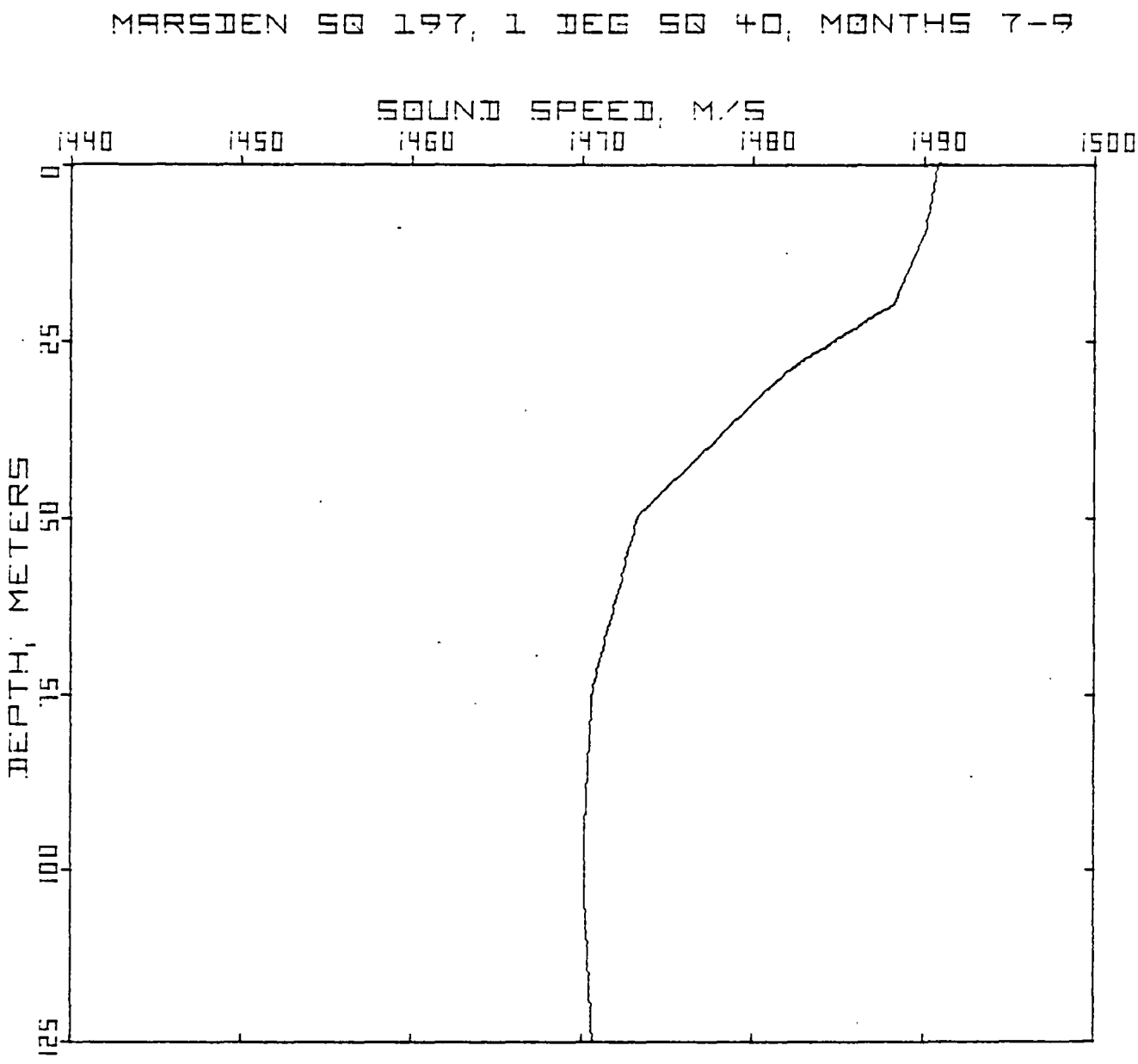

Fig 1. An average sound speed profile for the area of SEDCO 708, July - September.

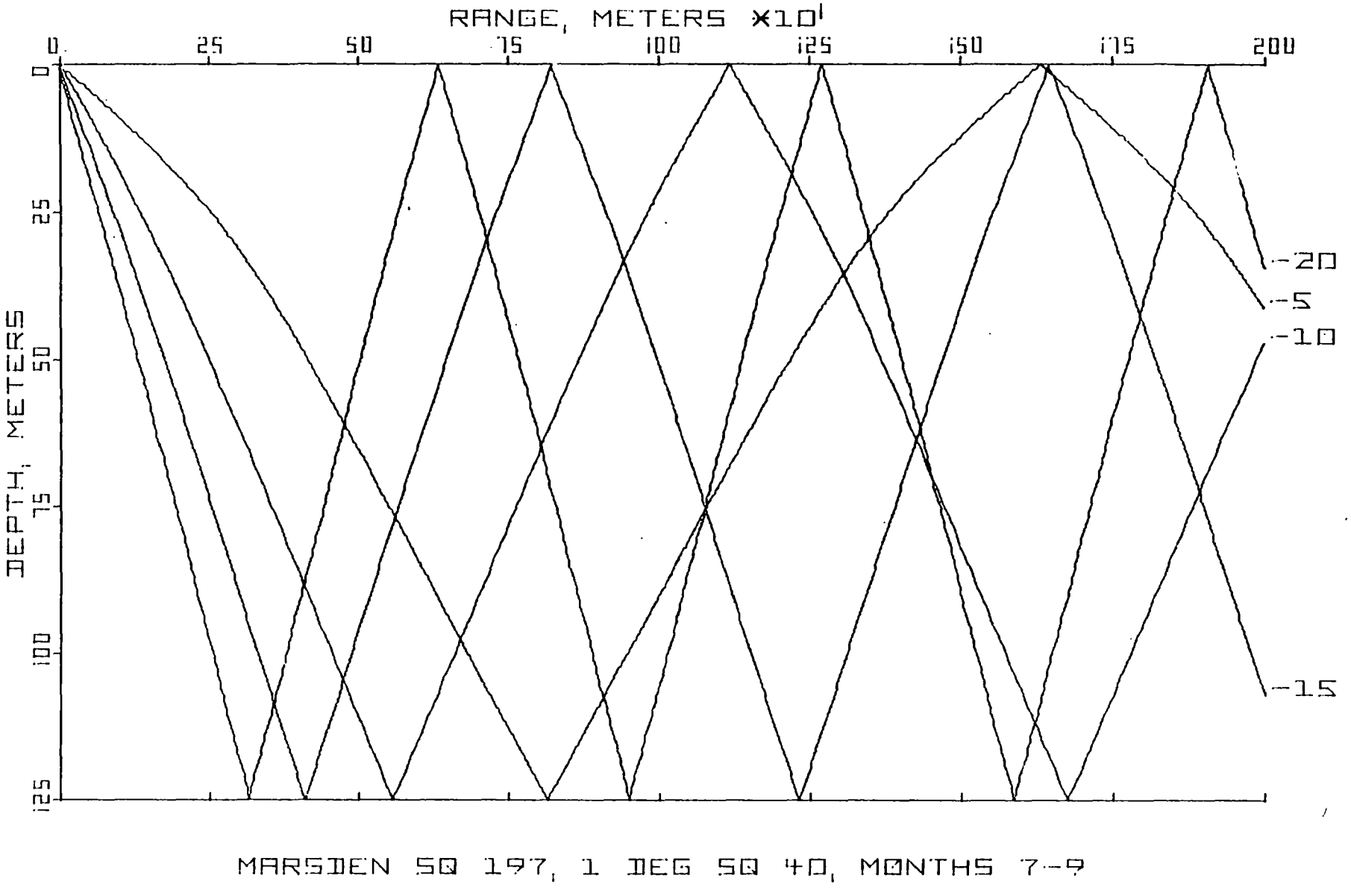

Fig 2. Some sound ray paths, starting at the surface, for the sound speed profile in Fig 1 (July - September). The intial vertical angles, in degrees, are noted at the end of each ray path.

figure, the horizontal range was limited arbitrarily to 2 km, resulting in a vertical exaggeration of 10:1. Note that for this profile the sound rays are all refracted downward, assuring bottom interaction. During the winter months the surface will cool, lowering the surface sound speed and causing sound rays to refract upward. There is little that is remarkable in the sound ray structure shown other than the interaction of the multipaths.

Data Analysis

We used PRL's NOVA 3/12 minicomputer to perform the data analysis. This machine has a 12 bit analog-to-digital converter. For analysis, signals from the left channel of the tape recorder (the bender hydrophone channel for low frequencies) were played back through a discriminator demodulator, then a low pass filter with amplification, then to the A/D converter. For this channel, the sampling rate was 2048 samples per second and the low pass filter setting was 1000 Hz to avoid aliasing effects from signal components greater than half the sampling frequency. A total of 17,408 samples per conversion period were saved on the computer disk for spectrum analysis. The parameters of each type of conversion/analysis are presented in Table 1.

Table 1. Analog-to-digital conversion and spectrum analysis parameters. The size of each segment was 17,408 samples.

Hyd	Sample Freq (Hz)	Length of Seg (sec)	Xform size (pts)	Freq Cell spacing (Hz)	Freq Resol (Hz)	Spectrum Scale (Hz/in)	Graph Limits (Hz)
Bender	2048	8.5	2048	1	1.7	62.5	10 - 500
Bender	2048	8.5	1024	2	3.4	125.	20 - 1000
H56	8192	2.125	1024	8	13.6	500.	80 - 4000
H56	16384	1.0625	1024	16	27.2	1000.	160 - 8000

Signals from the right channel, the H56 wideband hydrophone signals, were played back directly through the low pass filter to the A/D converter. The sampling rate was either 8192 or 16,384 samples per second, the corresponding filter settings were 4000 or 8000 Hz, and 17,408 samples per segment were saved on the disk. Again, Table 1 lists the analysis parameters.

During playback, the analyst listened to the signals with earphones or a speaker and watched the waveform on an oscilloscope. Finding a segment of recording to analyze, he would set the low pass filter gain appropriately to assure that the signal did not saturate the converter. Two segments per channel were analyzed for each range/depth

combination, one near the beginning and one near the end of the recording.

Analyses of the samples from the bender hydrophone were with Fast Fourier Transforms (FFTs) using 2048 samples per transform for the frequency range to 500 Hz and 1024 samples per transform for the frequency range to 1000 Hz. (Table 1 contains the parameters.) The power spectrum was computed from each FFT. Because there were 17,408 samples to analyze, several FTTs were computed and the results averaged. The technique used is called the Weighted Overlapped Segment Averaging (WOSA) method. It involves segmenting the total sample into blocks 2048 samples long, then analyzing each block and blocks formed with 50% overlap. A tapered data window was applied to each block to minimize some undesirable effects of non-tapered analyses--especially 'leakage' where energy from a strong tonal component appears in adjacent frequency cells at significant levels, thereby giving not only an erroneous computation but possibly hiding weaker components that might be present in the adjacent cells. A total of 16 such blocks were analyzed and the results averaged for each set of 17,408 samples. The resulting power spectrum had 1025 frequency cells spaced 1 Hz apart and spanning the frequency range from 0 to 1024 Hz; however, only the results from 10 to 500 Hz were retained for plotting. The effective resolution (width) of each frequency cell was 1.7 Hz, compared to the 1 Hz spacing, because of the data window. Analyzing the same set of samples using blocks 1024 points long resulted in a 2 Hz per cell spacing, 3.4 Hz resolution, and frequencies to 1000 Hz.

The units on the power spectrum graphs are dB//(1uPa)^2/Hz, appropriate for spectral density. If tonal components are present, they will be incorrectly represented because their true (ideal) spectral density is infinite--the pressure at the tonal frequency is non-zero. The sound pressure level for a tonal can be computed from the plotted amplitudes by adding the bandwidth correction (2.3 dB for the 1.7 Hz resolution, for example); the result will be so many dB//1uPa.

Sound pressure spectra are useful because they depict a sound decomposed by frequency, showing how the sound power is distributed and what tonal components exist. However, we also need to know the sound power itself; that is, the level of the sound across all the frequencies, or at least across bands of frequencies thought to be relevant to marine mammal hearing sensitivity or communications. We compute such levels by integrating the sound pressure spectra over the desired frequency bands to obtain band levels. The contributions of the tonal components are included automatically. The bands chosen here were selected somewhat arbitrarily but with the idea that they could be combined (by addition and subtraction of the powers, of course, and not the dBs) to compute levels of the sound in other bands.

RESULTS

The results of the study have been influenced to some extent by problems encountered in doing the work. We discuss those problems, then discuss the interpretation of tonal spectrum levels in the results, then present the results.

Problems

There were three primary problems encountered in the study. The first was that the hydrophone motion beneath the sparbuoy, or the height of the waves passing overhead, created changes in hydrostatic pressure that were large compared to the acoustic signals and caused the postamplifiers to 'block', or 'drop out' so that the acoustic signal was not recorded for brief periods. The result was that the recordings are not useful continuously, but only in sections. The problem was most severe at the shallow depths (2.5 and 5 m). In the recording for each range/depth combination we were always able to find two segments for each hydrophone that were longer than 8.5 s, our longest analysis length. However, we would have had difficulty finding three or more such segments in many recordings.

The second problem was the interference on the direct channel (the H56 signal channel) of the FM carrier from the bender channel. The carrier center frequency was 5 kHz, and the deviation limits were 3 kHz and 7 kHz. Thus, the spectra for the H56 signal to 8 kHz usually manifest the carrier with a band of higher levels, sometimes with strong tonal qualities. We saw evidence of tones from SEDCO 708 at such high frequencies only once (discussed later). The carrier interference was easily identified and disregarded, although readers must do so for themselves in studying the spectral graphs. The major impact was on the computation of band levels above 4 kHz, which would have been erroneous. We do not present them.

The third problem was that the results from the two hydrophones were not as consistent as we expected. The bender was used for frequencies from 10 to 1000 Hz and the H56 was used for frequencies from 80 to 8000 Hz. Ideally, the results in the overlap band would have been the same; they were not. If the problem had been a simple calibration error the difference would be expected to be essentially constant. Some variability is expected from the fact that the bender signals were always sampled for 8.5 s segments while the H56 signals were sampled for just 1 or 2 s in each segment. In the tables of band levels (Appendix D) we have printed the 200 to 400 Hz band levels as computed for each hydrophone so the reader may see the differences.

Levels of Tones in Spectrum Graphs

Readers should not expect the spectrum levels corresponding to tones in a given figure to be the same. For example, the 301 Hz tone

in Fig A-1 appears at about 108 dB in the 10 - 500 Hz graph and at about 105 dB in the 20 - 1000 Hz band. The reason for this difference comes from the 1.7 Hz effective filter bandwidth in the first case and 3.4 Hz bandwidth in the second, and the fact that the tonal power is entirely within the effective filter band in each case. The tonal power is the same, but the power in every frequency cell is corrected for the bandwidth to convert the power to a 'power per Hz', or uPa^2/Hz; that should not be done for tones. Thus, the 'correction' of 2.3 dB (for an analysis width of 1.7 Hz) for the 10 - 500 Hz graph should be added back to the 108 dB level on the graph to yield a tonal power of 110 dB; the 'correction' of 5.3 dB (for the analysis width of 3.4 Hz) should be added back to the 105 dB level on the graph for 20 - 1000 Hz for a tonal power of 110 dB.

Spectra vs Range

To preserve continuity of the report we have put the figures containing the results for this section in Appendix A. Sound pressure spectra are in Figs A-1 through A-7 for the received signals at a depth of 2.5 m (the shallowest) and in Figs A-8 through A-14 for 30 m (the deepest) for all seven ranges. Thus, there are two sets of seven figures. Each figure consists of four graphs corresponding to the frequency ranges (listed in Table 1) to 500, 1000, 4000, and 8000 Hz. The vertical scales, for sound pressure spectrum level in $dB//(1uPa)^2/Hz$, are always 10 dB per division but generally have different origins as the plotting program adjusts the range limits to assure the spectrum falls within the top division at one point at least. The reader should use caution in comparing the spectrum in one graph to spectra in adjacent graphs or those in other figures as the vertical scale origins may not be the same.

Spectra vs Depth

Appendix B contains the figures for the sound pressure spectra vs depth. Figures B-1 through B-4 are for the signals received at a range of 0.5 nm at all four depths (2.5, 5, 10, and 30 m). Figures B-5 through B-8 are for signals at 10 nm from SEDCO 708. Where a figure would repeat the graphs in another series (for instance, Figs A-3 and B-1 are both for 0.5 nm, 2.5 m) we have used the results of the two analyses for the one combination of range and depth. The reader can then see directly the variability encountered in a period of a few minutes.

Spectra vs Azimuth

Appendix C contains spectra for signals received at a range of 0.5 nm and a depth of 30 m. Figs C-1 through C-4 are for azimuths south, west, north, and east, respectively. The heading of SEDCO 708 was 280 deg, or almost west. Figure C-4 may be compared with Figs A-10 and B-4 as these present spectra for recordings from 0.5 nm, east, and 30 m depth.

Tonal Components

Tonal components manifest periodic pressure variations and are important when studying sounds from machinery. Any repetitive action, such as cylinders firing, propeller blades turning, or the drill string turning, may cause tones to be radiated. With an adequate description of the machinery, it is possible to relate the received tones to the source machine. For example, in studying the signature from an airplane powered by a piston engine and a propeller, one expects to see tones at both the cylinder firing rate and the blade rate.

On SEDCO 708, the drill string turns at 100 to 120 rpm. This speed corresponds to frequencies from 1.67 to 2 Hz, well below the frequencies in our analysis bands. However, harmonics might be seen if present. Often, the acoustic coupling to the water is very poor at such low frequencies and little energy is present, although there may be modulation components within the signal. That is, the broadband energy at higher frequencies may be modulated by the drill rotation rate and perceived by a listener as a low frequency variation in the signal.

We found tones at a great variety of frequencies, but few that persisted throughout the data. That is, the set of tones observed at the first recording station was by and large different from the set at the last station. The explanation is probably that the machinery on the drill rig is actually operated at different speeds depending on the loading and activities at any given moment. There is one exception; alternating current electric power is generated at as constant a frequency as possible with the available generators. Thus, 60 Hz tones will not vary in frequency, although they may vary in amplitude as the total electric power load varies. On SEDCO 708, a tone at 60 Hz never varied in frequency. Other tones at 122, 181, and 301 Hz were nearly as constant. The 60, 181, and 301 Hz tones may be harmonically related; a fundamental at 60.2 Hz would appear in the 60 Hz cell, the third harmonic at 180.6 Hz would appear in the 181 Hz cell, and fifth harmonic would be 301.0 Hz. The 122 Hz tone is not in the family, although it is close to the second harmonic. Other tones appeared at frequencies of 52, 76, 265, 356, and 634 Hz to mention a few.

An interesting harmonic family appears in Fig C-2. The recording was made 0.5 nm west of SEDCO 708, hydrophone depth 30 m, and machinery sounds could be heard clearly. The fundamental frequency is close to 330 Hz and harmonics are present through the 20th harmonic near 6600 Hz. Such a family would be expected to result from a series of impulses (short spikes of sound) occurring at a rate of 330 per second, or almost 20,000 per minute.

Received levels of tones, averaged over the two segments analyzed for each condition of range and depth, are presented in Tables 2 through 6. Blank places correspond to segments in which the tone was either missing or less than 3 dB above the background spectrum. Tables 2 through 5 show how the levels of the steadiest tones varied with range for each of the four depths. Table 6 shows how 5 tones

varied with azimuth at depths of 10 and 30 m. Table 7 shows how the measured levels (no averaging) of tones and bands changed at 4 times when the conditions of range, azimuth, and sensor depth were all the same. For this one table we averaged the dBs to obtain the figures in the AVG column; in every other case we averaged the powers.

Table 2. Average tonal levels in dB//1uPa vs range from SEDCO 708 at a hydrophone depth of 2.5 m.

Frequency (Hz)	Range, nm 0.1	0.2	0.5	1.0	2.0	5.0	10.0
23	96	95		87		92	90
30	95						
44	95			88	87		90
60	98	93	97	91	83		79
122	94	94		80	79		
181	97	93	87	79	82		
301	110	94	85	88	82	71	

Table 3. Average tonal levels in dB//1uPa vs range from SEDCO 708 at a hydrophone depth of 5.0 m.

Frequency (Hz)	Range, nm 0.1	0.2	0.5	1.0	2.0	5.0	10.0
23	97	95	93		92	94	
30	99	93		93		95	91
44		98	92		87		88
60	102	101	94	91	88		
122		99		87	85		
181	98	98	88		85		76
301	103	96		86	83		

Table 4. Average tonal levels in dB//1uPa vs range from SEDCO 708 at a hydrophone depth of 10 m.

Frequency (Hz)	Range, nm 0.1	0.2	0.5	1.0	2.0	5.0	10.0
23		97	96		89		91
30	105	96		95	91	92	91
44		104	98				89
60	105	96	102	102	95	88	88
122		95	90	91	93		
181	100	90	88	89			81
301	108	97	94	88			80

Table 5. Average tonal levels in dB//1uPa vs range from SEDCO 708 at a hydrophone depth of 30 m.

Frequency (Hz)	Range, nm 0.1	0.2	0.5	1.0	2.0	5.0	10.0
23		102	96			90	89
30	106	104		96	92	91	
44	106	102	99	97	92		90
60	110	103	102	98	96	92	80
122	102	99	90	91			
181	100	97	88	87	85	80	78
301	99	94	85	87	82	78	74

Table 6. Average tonal levels in dB//1uPa vs azimuth for a range of 0.5 nm from SEDCO 708 and at depths of 10 and 30 m.

Frequency (Hz)	South	West	North	East
	10 m depth			
30	95	99		92
60	102	99	104	96
122	91	94	98	95
181	93	95	100	94
301	90	94	90	85
	30 m depth			
30	101	97	101	93
60	97	99	107	97
122		89	98	92
181	91	90	88	94
301	91	92	86	

Table 7. Levels of selected tones and frequency bands from SEDCO 708 analyzed at four times. The range was 0.5 nm, the depth was 30 m, levels are dB//1uPa, and times are hours and minutes.

Frequency (Hz)	Time of Day 1421	1424	2330	2332	AVG	STD DEV
23	95.7					
30			92.7			
44	99.6	98.6	98.9	100.1	99.3	0.7
60	103.9	98.7	97.7	96.8	99.3	3.2
122	90.4	89.1	92.2	92.1	91.0	1.5
181	90.3	85.4	93.4	94.9	91.0	4.2
301		85.4				
10- 500	111.5	112.3	110.9	111.2	111.5	0.6
100- 500	106.5	104.3	107.8	108.2	106.7	1.8
10- 20	96.4	107.9	97.8	96.3	99.6	5.6
20- 40	102.3	104.4	100.3	100.0	101.8	2.0
40- 80	108.4	106.8	105.8	106.4	106.8	1.1
80- 160	102.0	101.7	103.7	104.5	103.0	1.3
160- 320	102.5	98.9	103.5	104.6	102.4	2.5
25- 50	104.8	105.5	104.0	105.1	104.8	0.6
50- 100	107.5	105.4	104.2	104.2	105.3	1.6
100- 200	102.0	10.9	103.8	105.0	102.9	1.8
200- 400	102.9	99.6	103.6	104.2	102.6	2.1
400- 800	105.2	104.1	104.4	107.2	105.2	1.4
800-1600	103.1	102.5	104.7	103.3	103.4	0.9
1600-3200	99.2	96.8	99.2	100.3	98.9	1.5
80-4000	110.3	109.3	111.0	112.6	110.8	1.4

Broadband Components

The sound pressure spectra in Appendices A through C present detailed information on both the tonal and broadband components of the sound from SEDCO 708. However, the levels of the sound in ranges of frequencies are potentially useful summary numbers, and we have presented some in Appendix D. Tables D-1 through D-4 contain band

levels vs range for each of the four depths studied. Tables D-5 through D-13 present band levels vs depth for the seven ranges studied. It is in these 13 tables that the disparity between the bender and the H56 hydrophones is manifest. The levels for the 200 - 400 Hz band appear to be higher, usually but not always, for the H56.

Ambient Noise Levels

With the exception of tonal components, it appears that the received level spectra for ranges greater than 1 nm are largely ambient spectra. The variations in band levels vs range (Tables D-1 through D-4) fluctuate in a manner one would expect from temporal variations of the ambient rather than from distance variations of radiated noises. Thus, for the 30 m depth and the 10-500 Hz band, the levels vary from 101 to 108 dB//1uPa. For 30 m and the 80-4000 Hz band, the variation is from 100 to 105 dB//1uPa. Examining both 10 and 30 m depths and the total band from 10-4000 Hz, the levels varied from 102 to 112 dB.

Examining the spectrum graphs in Appendices A and B for the ranges greater than 1 nm and depths of 10 or 30 m, the spectrum level at 100 Hz varied from 72 to 79 dB//1uPa^2/Hz. The spectrum level at 1000 Hz varied from 63 to 73 dB//1uPa^{2}Hz. These levels fall within the upper range of ambient noises in the world's oceans at those frequencies.

Source Levels

It is most useful and important to convert the received levels at the hydrophones into hypothetical levels at unit distance, say 1 m, from the drill rig. Then we would have a 'source level', and its unit would be dB//1uPa-m. The utility of a source level is that one can predict what the received level would be in any other ocean area for SEDCO 708 if one knew the source level and the acoustic transmission loss.

Similarly, to convert received level into source level one also needs to know the transmission loss. Having measured received level at ranges between 0.1 and 10 nm, we should have the information from which to derive transmission loss, but there are complications. We would like to derive source levels for both tonals and band level components, which would mean deriving transmission loss for both types of signals. Each has separate problems, but there is one potential problem in common to be discussed first: the problem of an extended source. With a highly localized source of sound (like a ship's propeller, for example) the transmission loss can be expected to obey the inverse square spreading law corresponding to spherical spreading in the immediate vicinity of the source. This implies a loss of 6 dB when the range to the source is doubled. With SEDCO 708, going from 0.1 to 0.2 nm doubles the range, but the received level appears to change

randomly, sometimes being higher for the greater range. (Refer to the tables in Appendix D.) Wide variability should be expected for the shallow depths, but not so much at 10 and 30 m. The problem here is that the source is probably not highly localized and is in fact 'extended'. Thus we cannot expect consistent measurements when we are too near, and evidently 0.1 nm is too near, especially at the low frequencies.

The primary difficulty with the tonal components is their variability. This is not unexpected, considering the effects of waves on multipath interference, limited measurement time, and changes in operating conditions on the rig. Focusing on the most stable tones--60, 181, and 301 Hz--provides the best results.

The broadband components are generally weak compared to the background, even on the relatively calm day of the field measurements. Thus, the band levels for ranges of 0.5 nm and greater often do not show a dependence on range. We focus our attention on the broadest bands--10 to 500 and 80 to 4000 Hz--for useful results.

We address the question of source levels for tones and band levels separately in the following two subsections.

TONES. The variability of the frequency of the tones made most of them useless for modeling transmission loss. However, the 60 Hz tone was always 60 Hz, although there were some analysis segments in which it was too weak to measure. We also had some success with 181 and 301 Hz.

The simplest analysis was to compute the regression coefficients in a pure spreading loss model RL = A + B*log(R), where RL is the received level, R is the range in km, and A and B are to be derived. The results are in Table 8.

The A coefficients show a depth dependence to 30 m for 60 Hz, to 5 m for 181 Hz, and none for 301 Hz, which is consistent with the theory for the Lloyd mirror effect. In addition, the highest frequency shows the largest spreading loss coefficients; this would be expected considering that all range-dependent losses, including surface scattering and bottom absorption, must appear in the B term.

Table 9 presents the results for a model allowing both spreading (log R) and absorption losses: RL = A + B*R + C*log(R).

Table 8. Regression coefficients for the equation
RL = A + B*log(R) (R in km)

Freq Hz	Depth m	# of points	A	B	r squared
60	2.5	6	91.6	-9.7	0.84
60	5.	5	94.4	-11.6	0.97
60	10.	7	98.7	-7.8	0.69
60	30.	7	100.6	-12.5	0.91
181	2.5	5	86.6	-13.4	0.88
181	5.	5	90.5	-11.4	0.95
181	10.	5	90.1	-7.9	0.80
181	30.	7	90.8	-11.0	0.96
301	2.5	6	90.3	-19.4	0.88
301	5.	4	90.8	-15.1	0.98
301	10.	5	94.3	-12.9	0.91
301	30.	7	88.7	-11.7	0.95

Table 9. Regression coefficients for the equation
RL = A + B*R + C*log(R) (R in km)

Freq Hz	Depth m	# of points	A	B	C	r squared
60	2.5	6	92.5	-0.21	-8.2	0.85
60	5.	5	93.5	+0.44	-13.4	0.97
60	10.	7	99.8	-0.15	-8.2	0.84
60	30.	7	102.3	-0.69	-6.8	0.96
181	2.5	5	81.6	+3.10	-21.7	0.95
181	5.	5	90.2	+3.10	-21.7	0.95
181	10.	5	88.8	+0.33	-10.7	0.82
181	30.	7	90.1	+0.25	-13.1	0.98
301	2.5	6	89.7	+0.31	-20.9	0.87
301	5.	4	86.9	+2.25	-20.9	0.99
301	10.	5	91.8	+0.66	-18.9	0.95
301	30.	7	88.5	+0.11	-12.8	0.96

Most of these results are physically intractable because of the positive values for B.

A final attempt at modeling with regression was to force a cylindrical spreading loss term. The results are in Table 10.

Generally the B term has the requisite negative sign, but the 'quality of fit' as given by r squared is poor.

Overall, the simple equations in Table 8 provide the best insight. Considering the results for the 30 m depth to be the least confounded by surface reflection effects, the equations as they stand predict source levels of 138 dB//1uPa-m at 60 Hz, 124 dB at 181 Hz, and 124 dB at 301 Hz. These are lower bounds, as we expect the spreading loss to be effectively larger at very close ranges.

One may reasonably postulate spherical spreading from one meter to a range of one-quarter of the water depth (28.5 m), then accept the received level equations in Table 8 for greater ranges. The spherical spreading loss is then 20*log(28.5) = 29 dB. Using the equation in Table 8 for 60 Hz, 30 m, and range 0.0285 km, the received level is found to be 120 dB. Adding the 29 dB for the spherical spreading from 1 to 28.5 m yields a source level of 149 dB//1uPa-m for 60 Hz. The source levels at 181 and 301 Hz are 137 and 136 dB, respectively. The spread between bounds of 11 dB at 60 Hz, 13 dB at 181 Hz, and 12 dB at 301 Hz is not as severe as it might seem because the lower bound is so weak.

Table 10. Regression coefficients for the equation
RL = A + B*R - 10.*log(R) (R in km)

Freq Hz	Depth m	# of points	A	B	r squared
60	2.5	6	92.1	-0.05	0.01
60	5.	5	95.3	-0.71	0.41
60	10.	7	99.5	+0.01	0.001
60	30.	7	101.7	-0.40	0.58
181	2.5	5	88.0	-082	0.15
181	5.	5	90.7	-0.12	0.15
181	10.	5	89.1	+0.26	0.35
181	30.	7	90.7	-0.004	0.02
301	2.5	6	93.3	-1.44	0.43
301	5.	4	93.7	-1.59	0.60
301	10.	5	94.6	-0.12	0.07
301	30.	7	89.1	-0.15	0.19

BAND LEVELS. Restricting consideration to the bands from 10 to 500 and from 80 to 4000 Hz and to signals at a depth of 30 m, the regression equations are as follows:

RL = 111.9 - 8.2*log(R), r squared = 0.99, 10 - 500 Hz

and

RL = 110.3 - 9.3*log(R), r squared = 0.97, 80 - 4000 Hz.

Extended to 1 m, these equations yield source levels of 136 dB//1uPa-m for 10 - 500 Hz and 138 dB for 80 - 4000 Hz. Assuming these equations apply only to ranges beyond one quarter of the water depth and that spherical spreading occurs within that range, the source levels are 154 dB//1uPa-m for both bands. The spread between the limits is again large, being 18 dB for the lower band and 16 dB for the wider band, but the lower bound is clearly too low.

DISCUSSION

The underwater radiated noise levels of SEDCO 708 are generally low. In most cases the broadband levels become indistinguishable from the background noise (wave heights from 1 to 2 m) at ranges beyond 0.5 nm. Some tonal components were detectable at the 10 nm range, but not at levels as much as 10 dB above the background. Sounds attenuated with increasing range in approximate accordance with cylindrical spreading. Sound levels were lower at shallower depths, especially at lower frequencies. Variations in level with azimuth corresponded to variations with time; no azimuthal dependence was noted.

Buerkle (1975) measured sounds from the semisubmersible drilling rig SEDCO J in the Bay of Fundy on April 25, 1975, during slack tide. His hydrophone was on the bottom (63 m depth) 580 m off the starboard bow. He studied sounds from tripping and drilling. His analysis did not identify tonal components, which if present (as they undoubtedly were) would result in higher computed spectrum levels than would be valid for the broadband components. His mean level for 100 Hz is 153.2 dB//(1uPa-m)^2/Hz for drilling, 158.7 dB for tripping, and 164.4 dB for high level tripping. Our data indicate a spectrum level of 126 dB//(1uPa-m)^2/Hz for 100 Hz using spherical spreading from 1 m to one-quarter of the water depth, then a cylindrical spreading fit of the 30 m measurements at 0.1, 0.2, 0.5 and 1.0 nm. Our measured data over those ranges fit cylindrical spreading very well. Buerkle had data from only 0.58 km (0.31 nm) and used spherical spreading to derive his results.

Gales (1982) reports on underwater noise from two semisubmersibles while drilling, one at lower Cook Inlet and the other at Baltimore Canyon. Qualitatively he gave each a noise rating of 'moderate'. He reports a 'source level (1/3 octave band at 1 yard)' of 125 dB//1uPa at 250 Hz, for example, which would be 107 dB//(1uPa-m)^2/Hz, assuming no tones and a reasonably flat spectrum over the 57 Hz wide 1/3 octave band at 250 Hz. Our data, processed in the manner described in the previous paragraph for comparison with Buerkle's result at 100 Hz, indicate a source level of 116 dB//(1uPa-m)^2/Hz at 250 Hz. The difference of 9 dB may easily be ascribed to differences in the rigs and approximations in the techniques for comparison.

Measurements have been reported of the radiated noise from a drillship operating in the Beaufort Sea (Greene, 1982). The ship was Dome Petroleum/Canmar's 'Explorer II' operating at 70 05.6'N, 134 26.7'W, water depth 27 m, drill bit depth 2031 m, and hydrophone depth 9 m. Sounds were measured at ranges from 0.1 to 4 nm. Strong tonal components in the signature occurred at 254 and 278 Hz. Regression forcing cylindrical spreading over the six ranges yielded equations for received level as follows:

$$RL_{254Hz} \quad (dB//1uPa) = 115.1 - 1.70R - 10 \log (R)$$

$$RL_{278Hz} \quad (dB//1uPa) = 122.9 - 1.52R - 10 \log (R)$$

where R is in kilometers. Using the same general procedure followed for SEDCO 708 data and assuming spherical spreading from 1 m to one-quarter of the depth (6.75 m) and the validity of the above equations for greater ranges, the source levels for the two tones would be 153 and 161 dB respectively. Those are far stronger levels than the 137 dB at 181 Hz and 136 dB at 301 Hz computed for SEDCO 708 for a reciever depth of 30 M. Although the nature of the machinery responsible for the tones on the two ships masy be significantly different, the fact that the levels are higher for the drillship than for the semisubmersible rig supports the idea that the hull of the drillship couples sound to the water better than the pontoons and upright supports of the semisubmersible.

It is disappointing that source levels cannot be estimated with more confidence. However, the effect of the relatively shallow water at the field site coupled with the large size of the rig made the close-in measurements unreliable for determining transmission loss over the shorter ranges.

There are two types of paths which sound may follow in traveling from the machinery into the water. The vessel floats on submerged pontoons from which large diameter risers support the drilling platform and tower. The noise-making machinery is clear of the water. In addition to the vibration paths from the machinery through the structure into the water, there is also the air-to-water path. The theory of air-to-water sound transmission has been developed (Young, 1973) although few experiments have been reported. In modeling sound transmission, the actual source is replaced by a virtual source beneath the actual source at a height given by the actual height times the ratio of the speed of sound in air to the speed of sound in water. The angle a of the line between the virtual source and the receiver is an important parameter as the sound falls off with 20.*log(cos a). A rough sea surface helps couple the sound into the water, and shallow water provides bottom-bounce multipaths to enhance sound transmission. In general, one does not expect sound from a source in air to travel well in water, and our measurements of relatively low levels of sound are in line with such a theory. However, measurements of airborne sound at the rig would be necessary to establish the validity of actual air-to-water sound transmission for SEDCO 708.

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Young, R.W. 1973. Sound pressure in water from a source in air and vice versa. J. Acoust. Soc. Am. 53:1708-1716.

APPENDIX A

Sound pressure spectra vs range

for depths of 2.5 and 30 m.

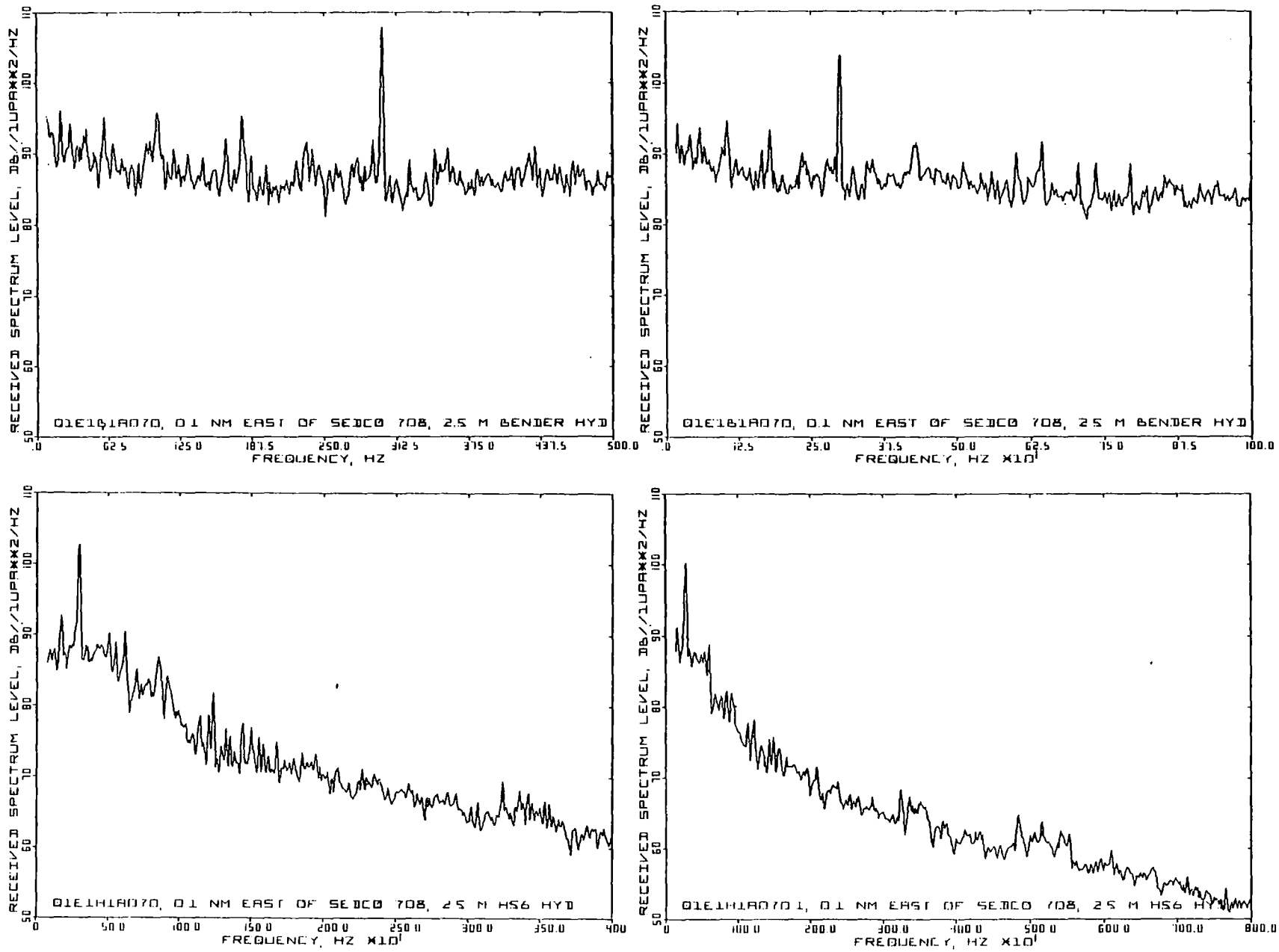

Fig A-1. Sound pressure spectra 0.1 nm east of SEDCO 708, 2.5 m depth.

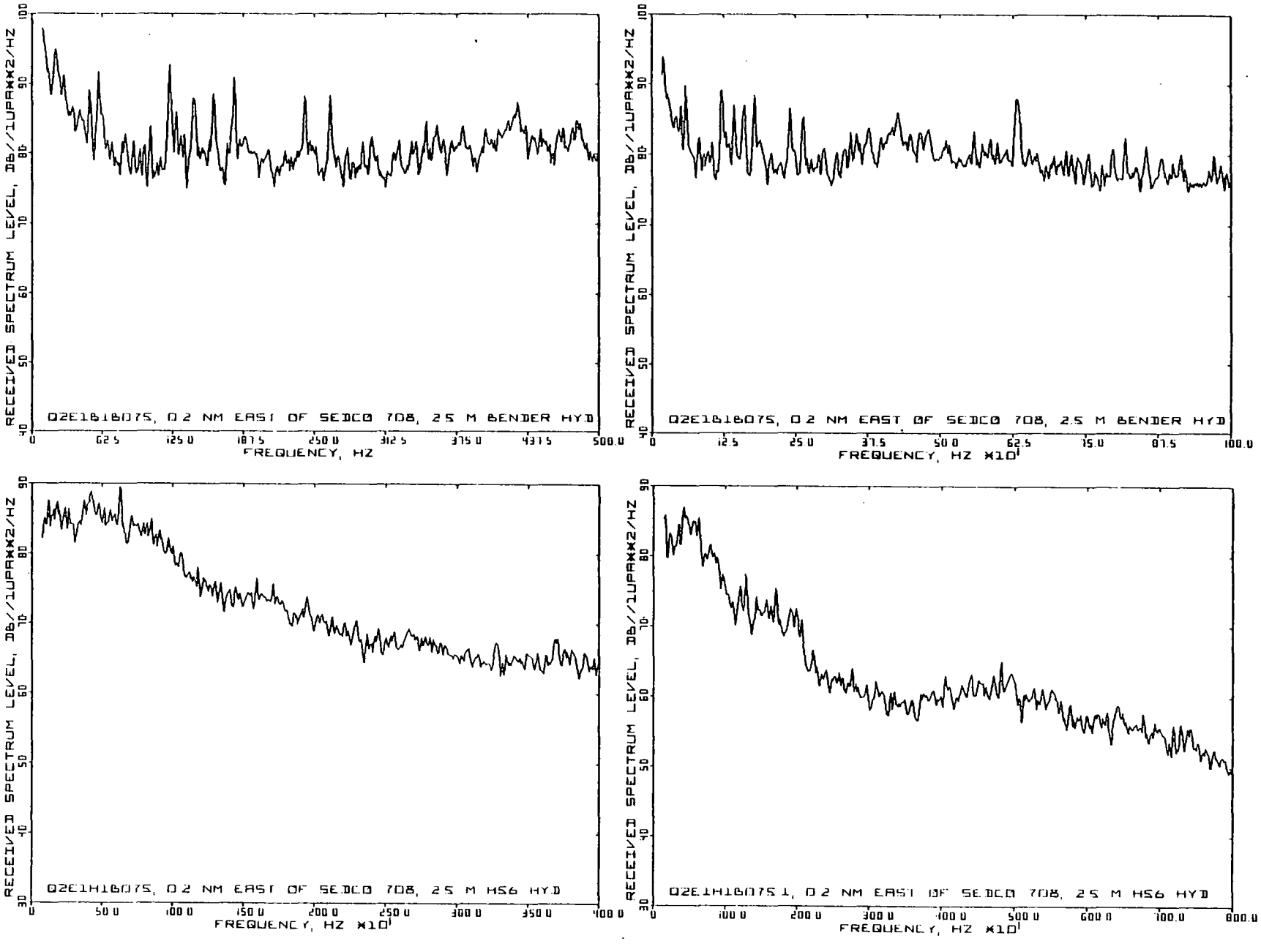

Fig A-2. Sound pressure spectra 0.2 nm east of SEDCO 708, 2.5 m depth.

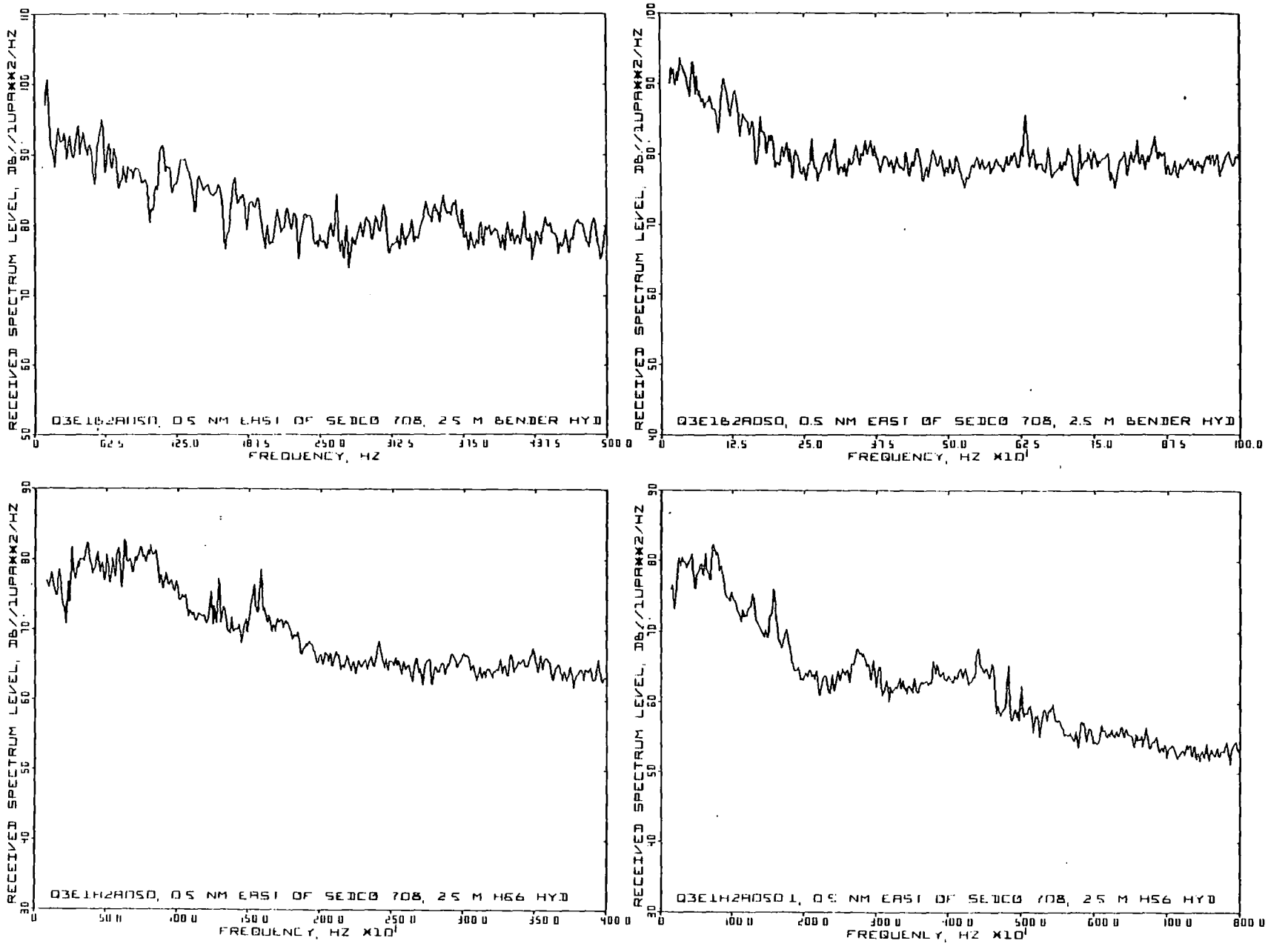

Fig A-3. Sound pressure spectra 0.5 nm east of SEDCO 708, 2.5 m depth.

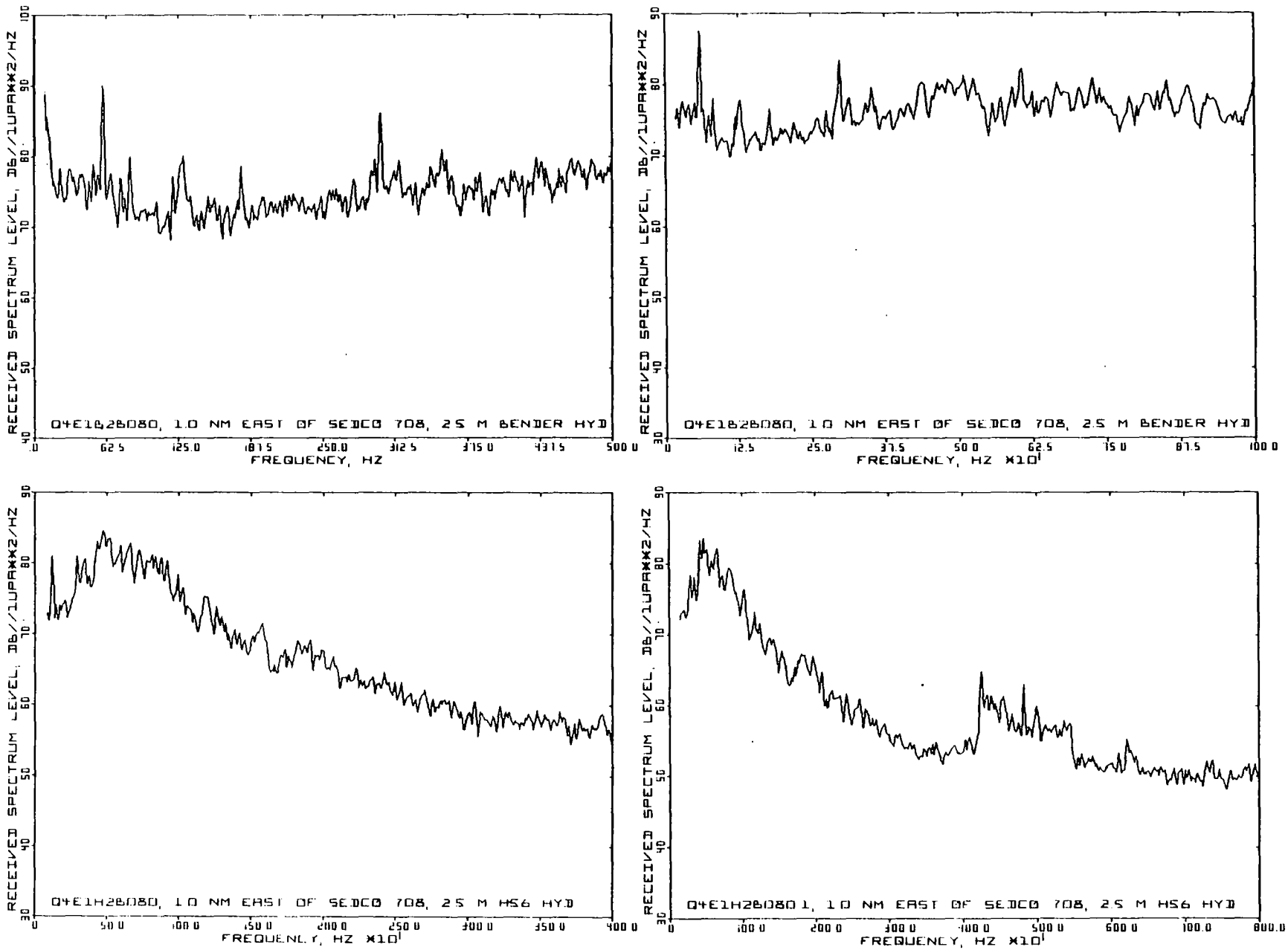

Fig A-4. Sound pressure spectra 1.0 nm east of SEDCO 708, 2.5 m depth.

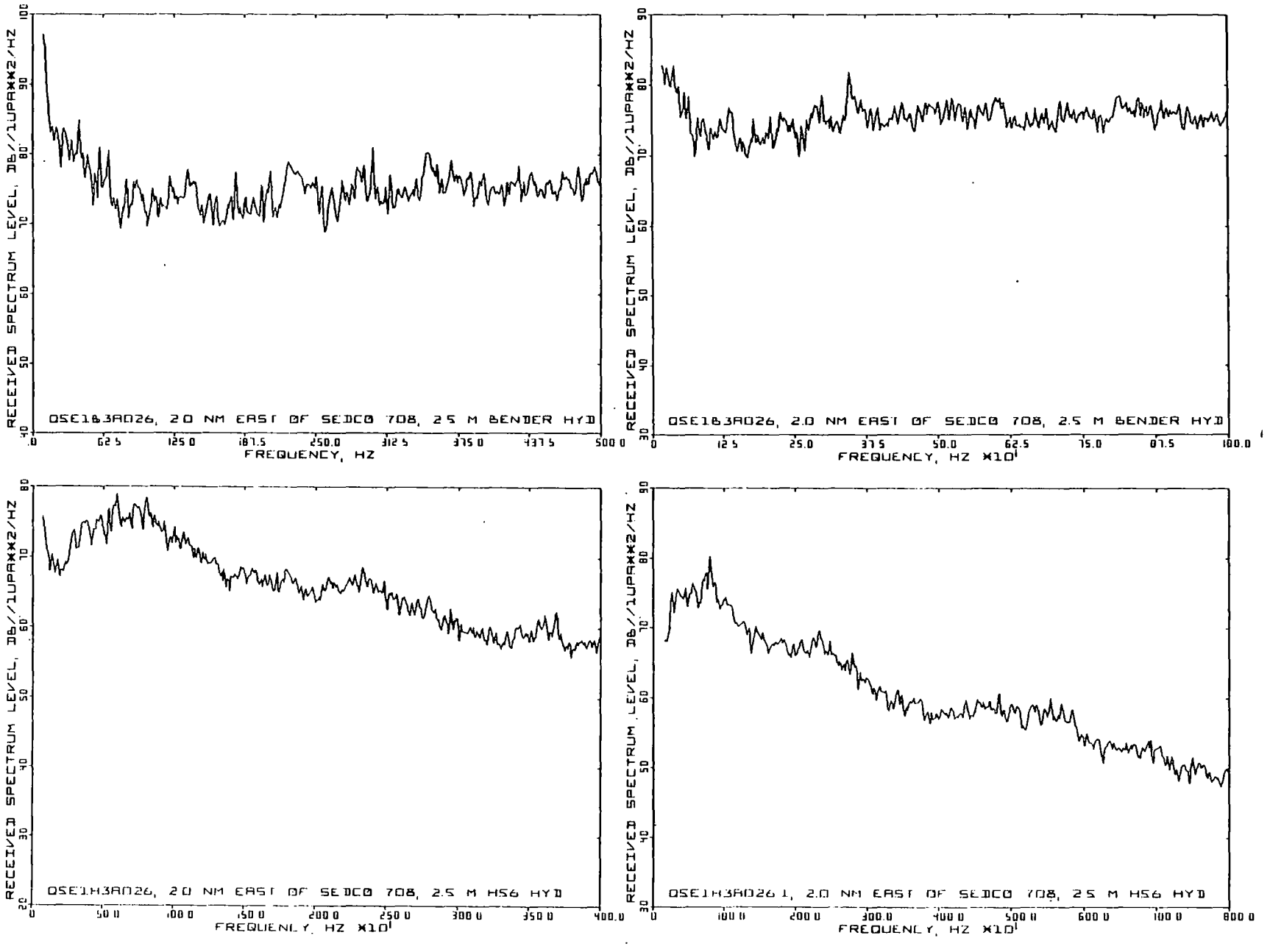

Fig A-5. Sound pressure spectra 2.0 nm east of SEDCO 708, 2.5 m depth.

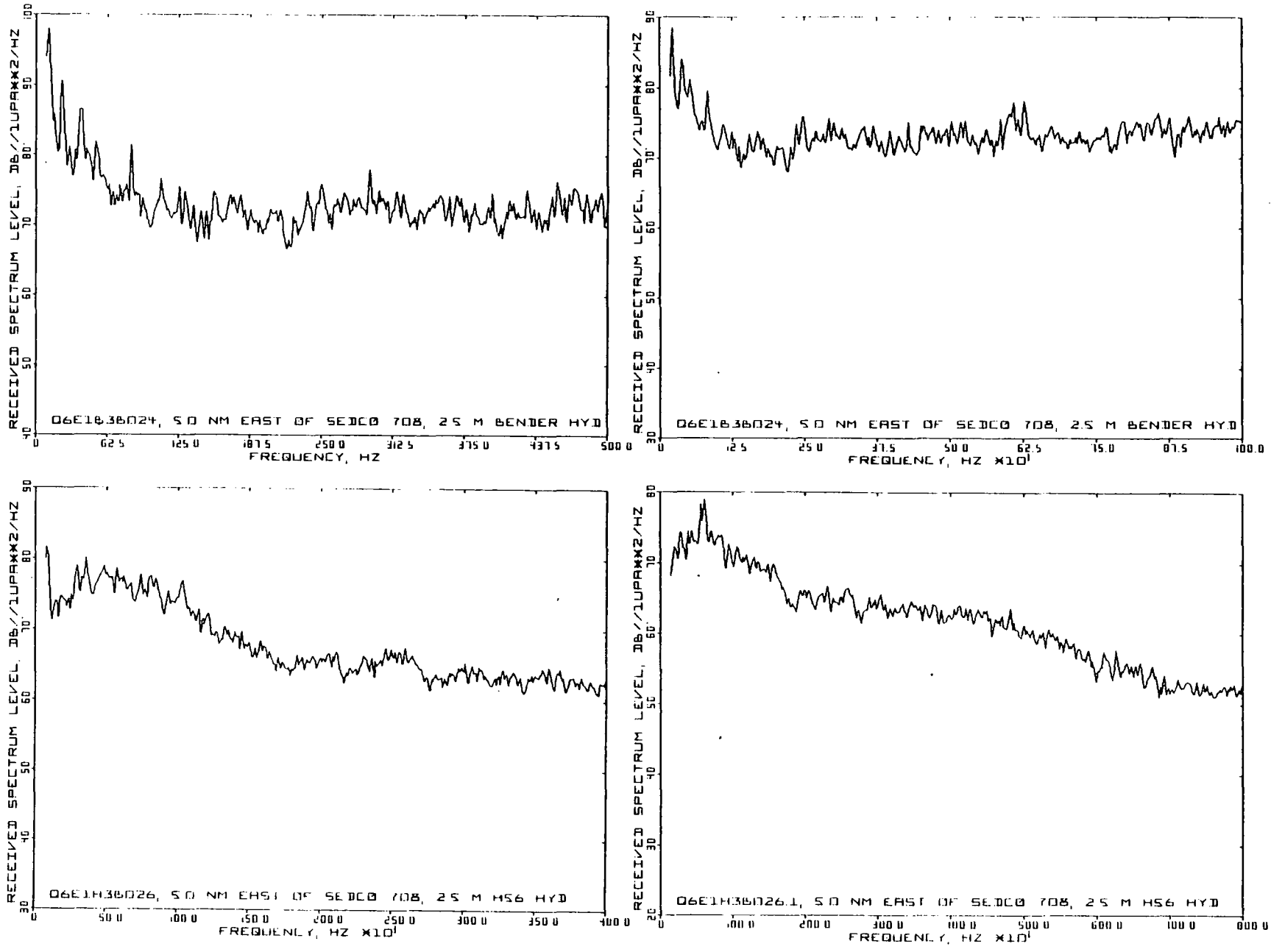

Fig A-6. Sound pressure spectra 5.0 nm east of SEDCO 708, 2.5 m depth.

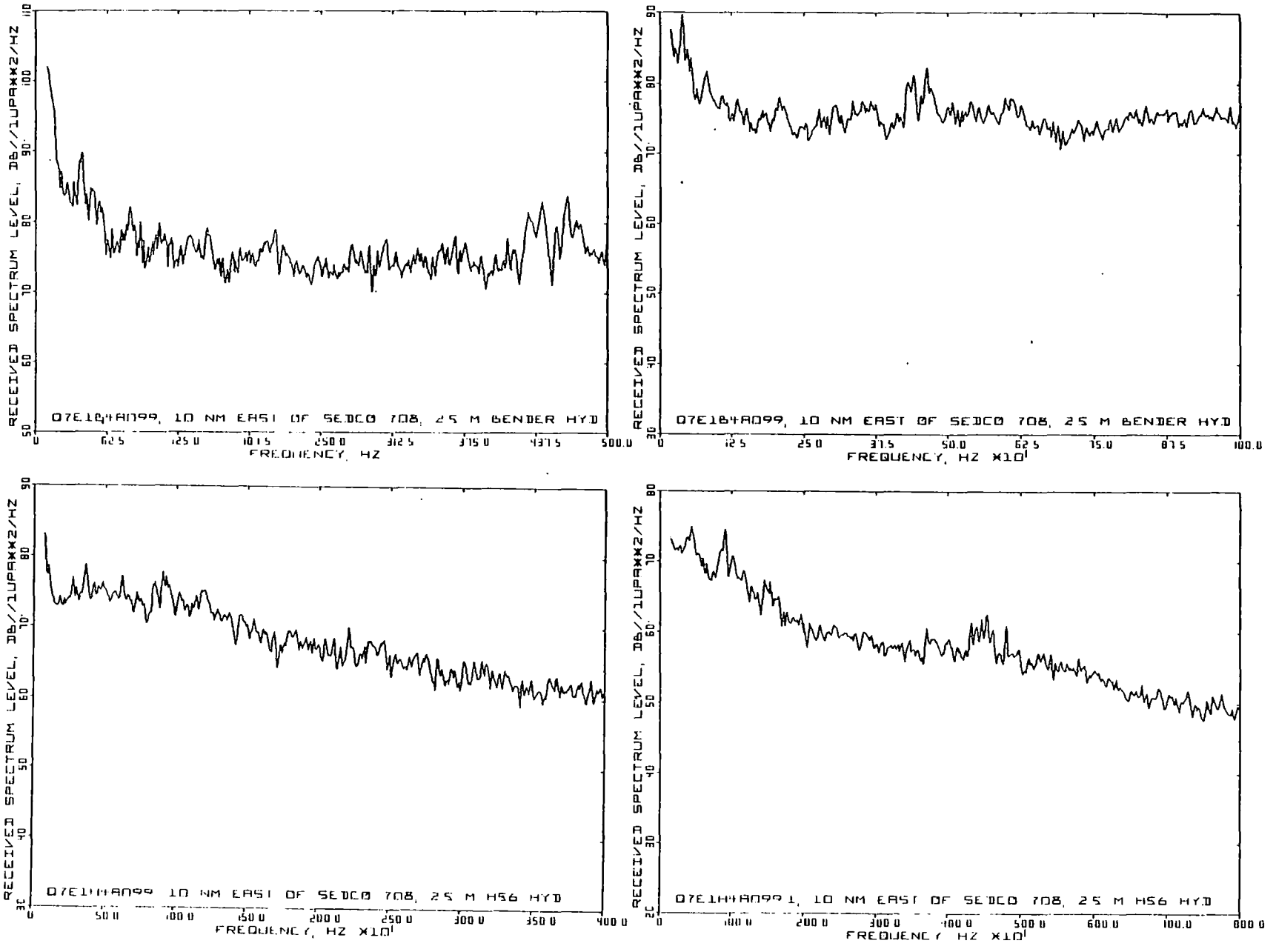

Fig A-7. Sound pressure spectra 10.0 nm east of SEDCO 708, 2.5 m depth.

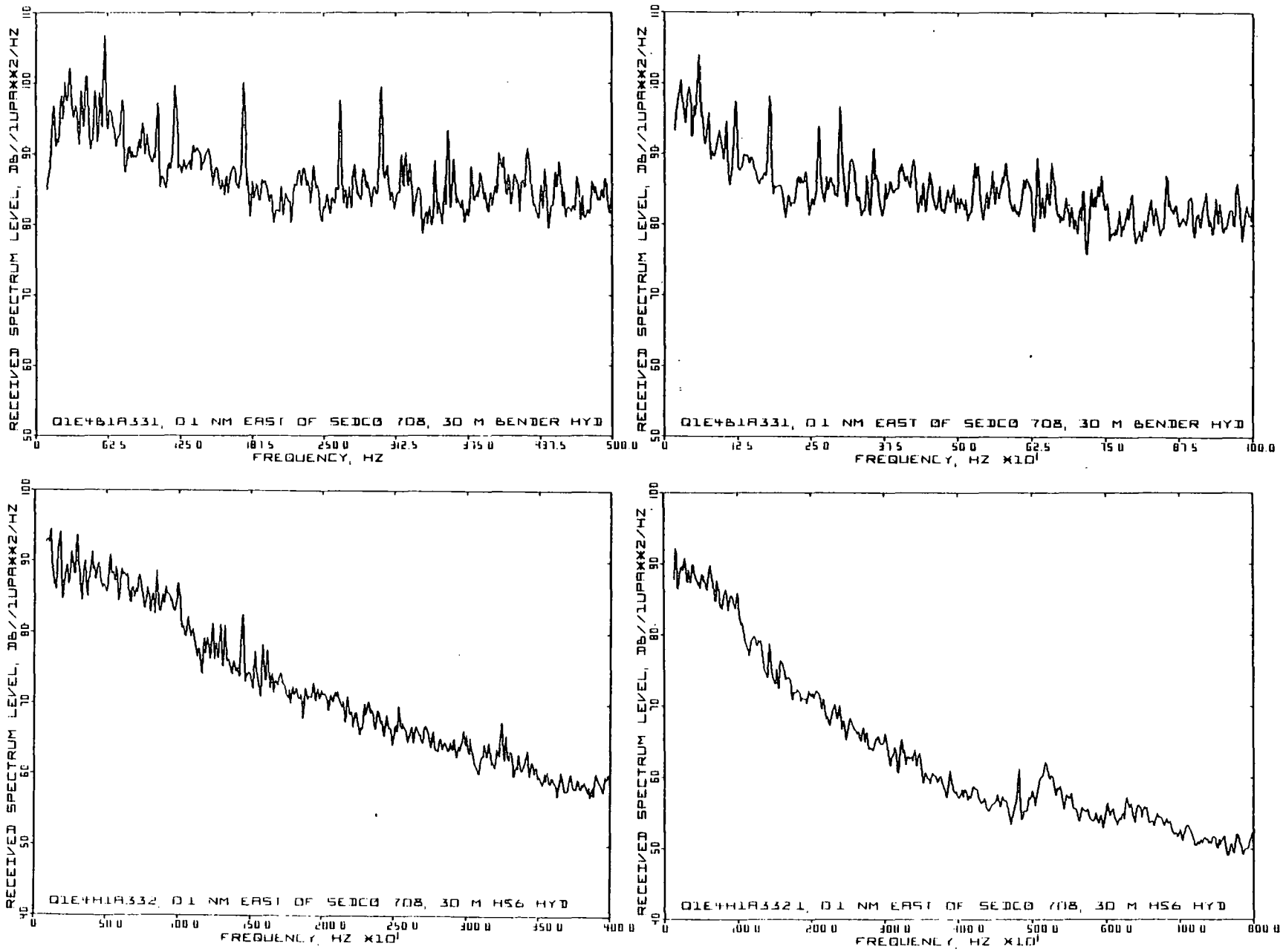

Fig A-8. Sound pressure spectra 0.1 nm east of SEDCO 708, 30 m depth.

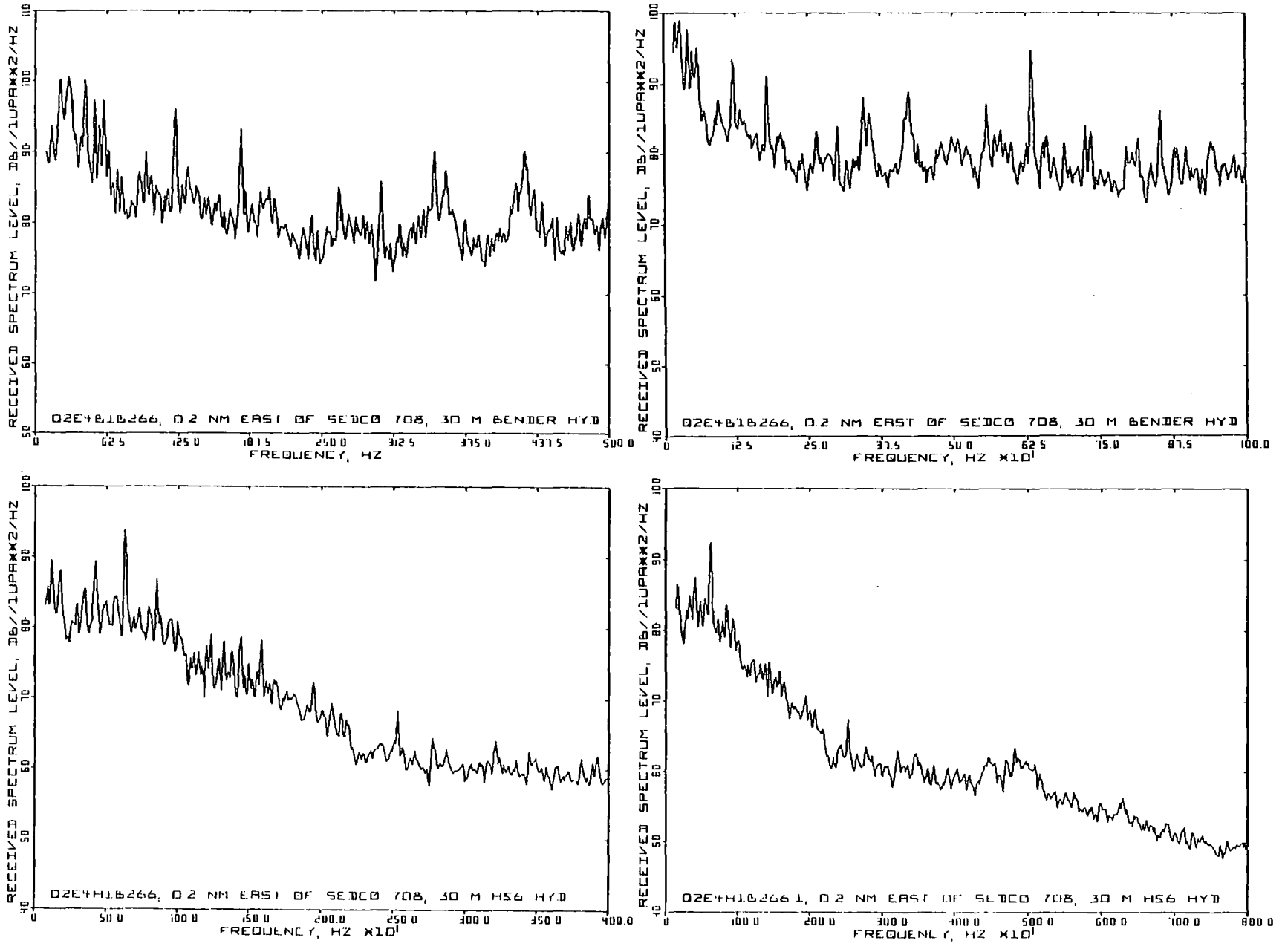

Fig A-9. Sound pressure spectra 0.2 nm east of SEDCO 708, 30 m depth.

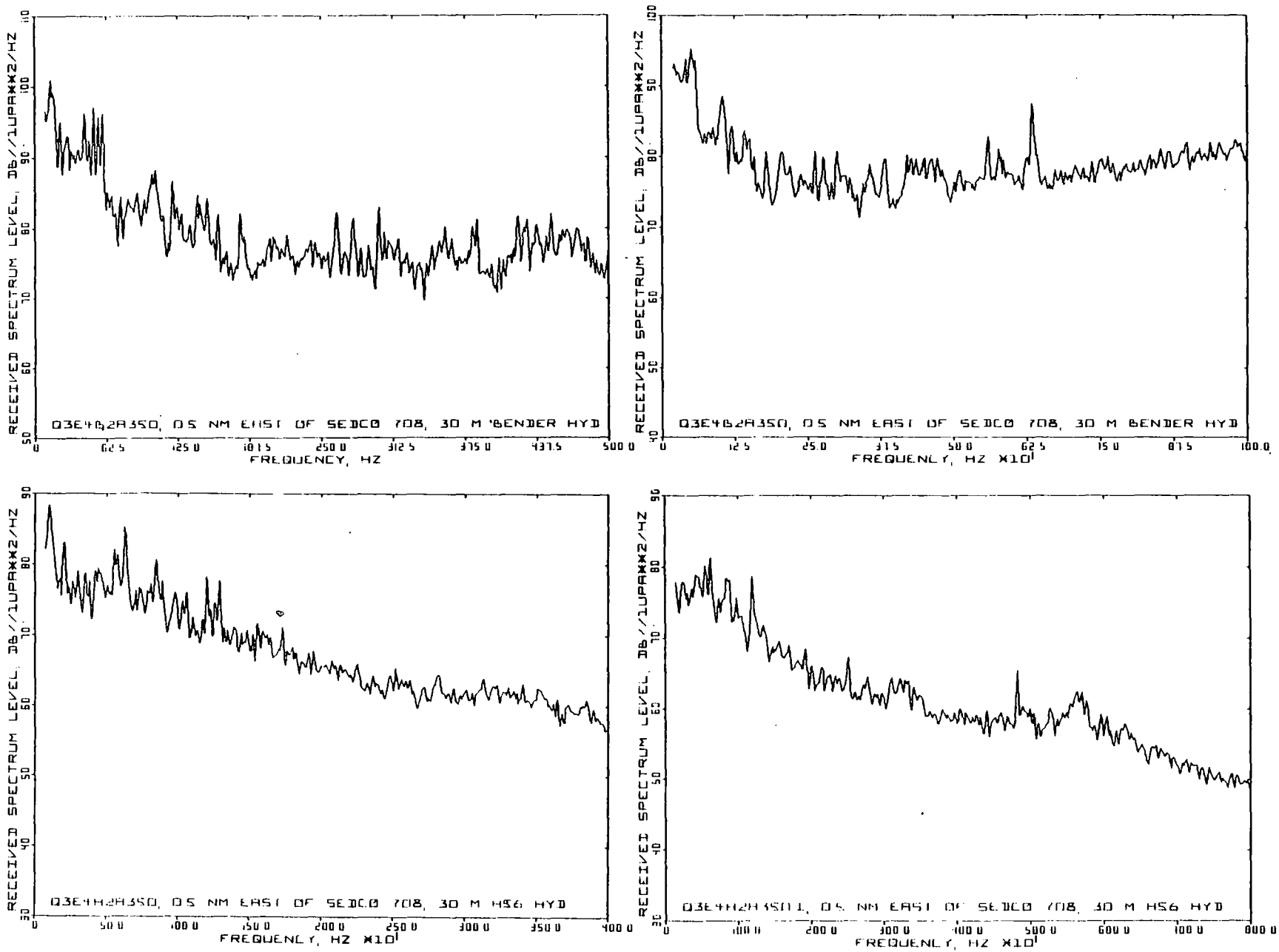

Fig A-10. Sound pressure spectra 0.5 nm east of SEDCO 708, 30 m depth.

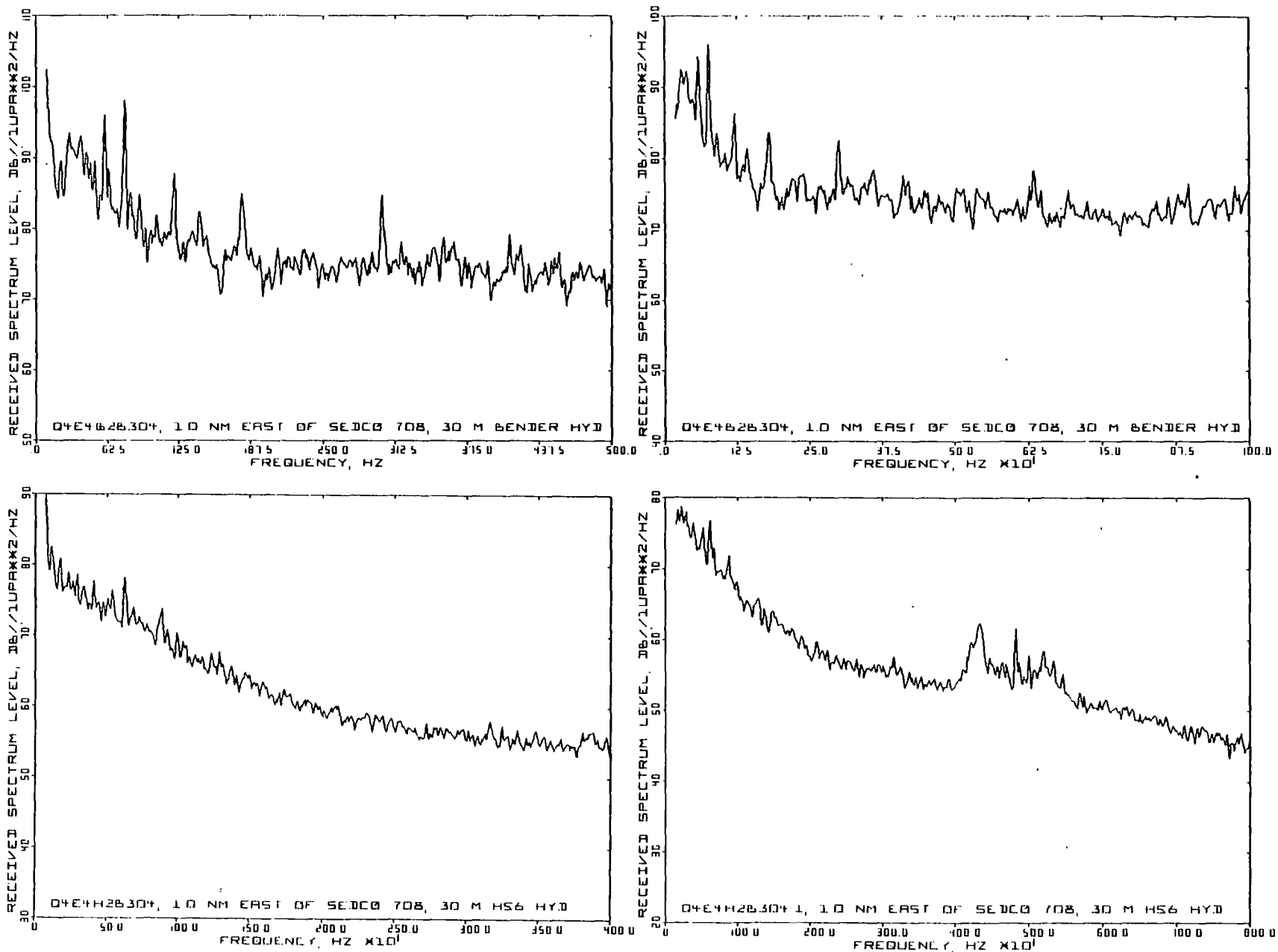

Fig A-11. Sound pressure spectra 1.0 nm east of SEDCO 708, 30 m depth.

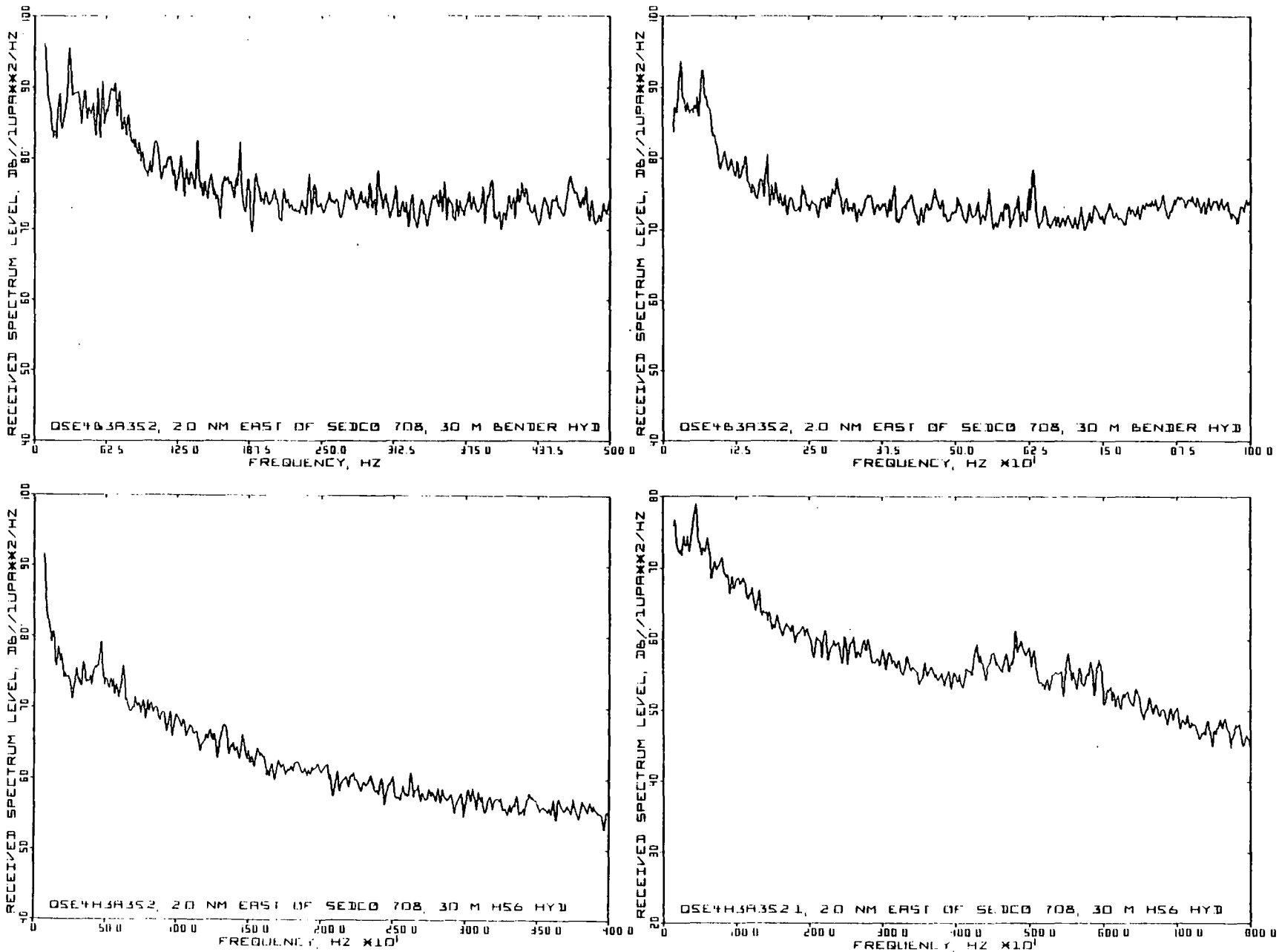

Fig A-12. Sound pressure spectra 2.0 nm east of SEDCO 708, 30 m depth.

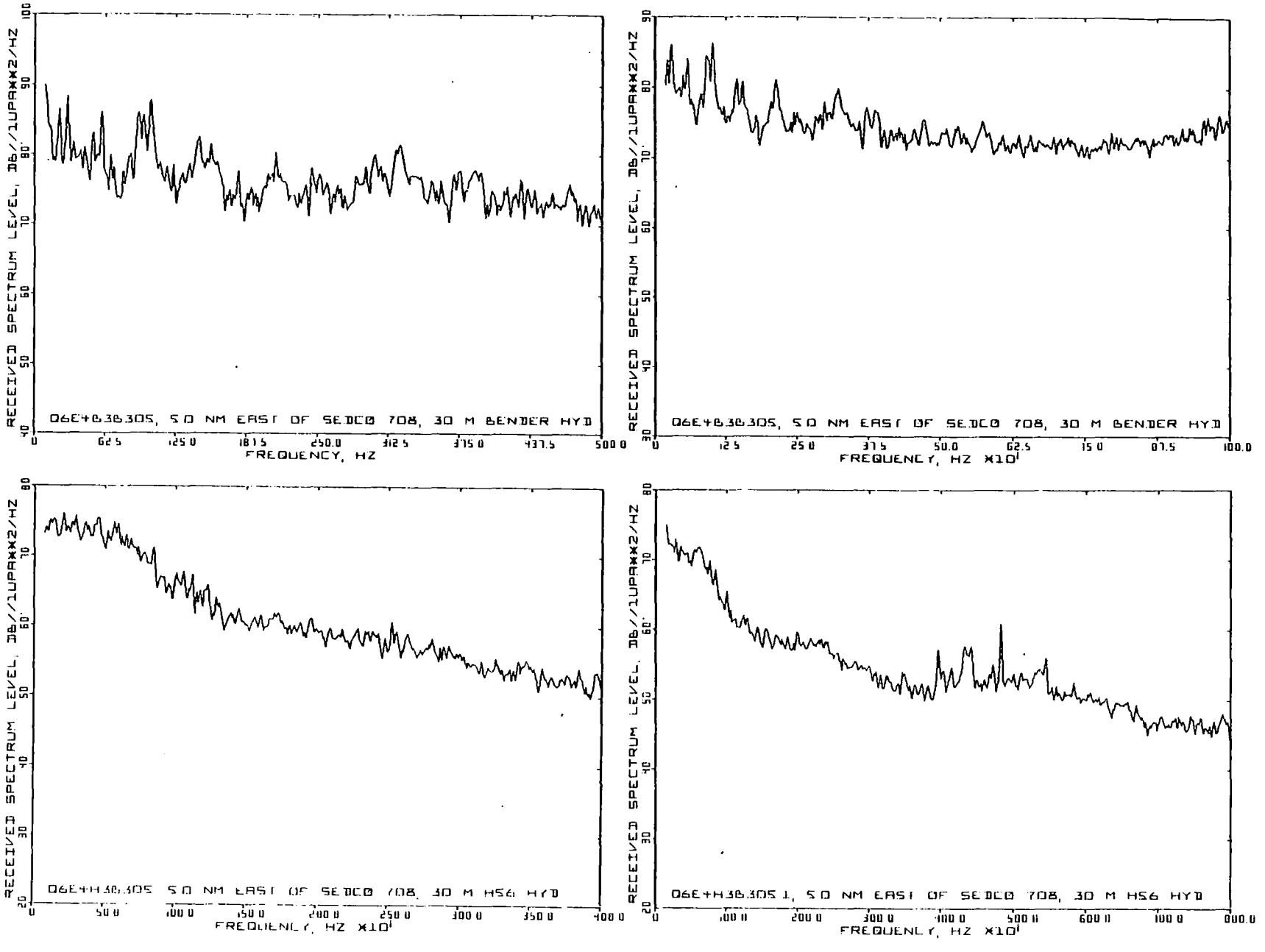

Fig A-13. Sound pressure spectra 5.0 nm east of SEDCO 708, 30 m depth.

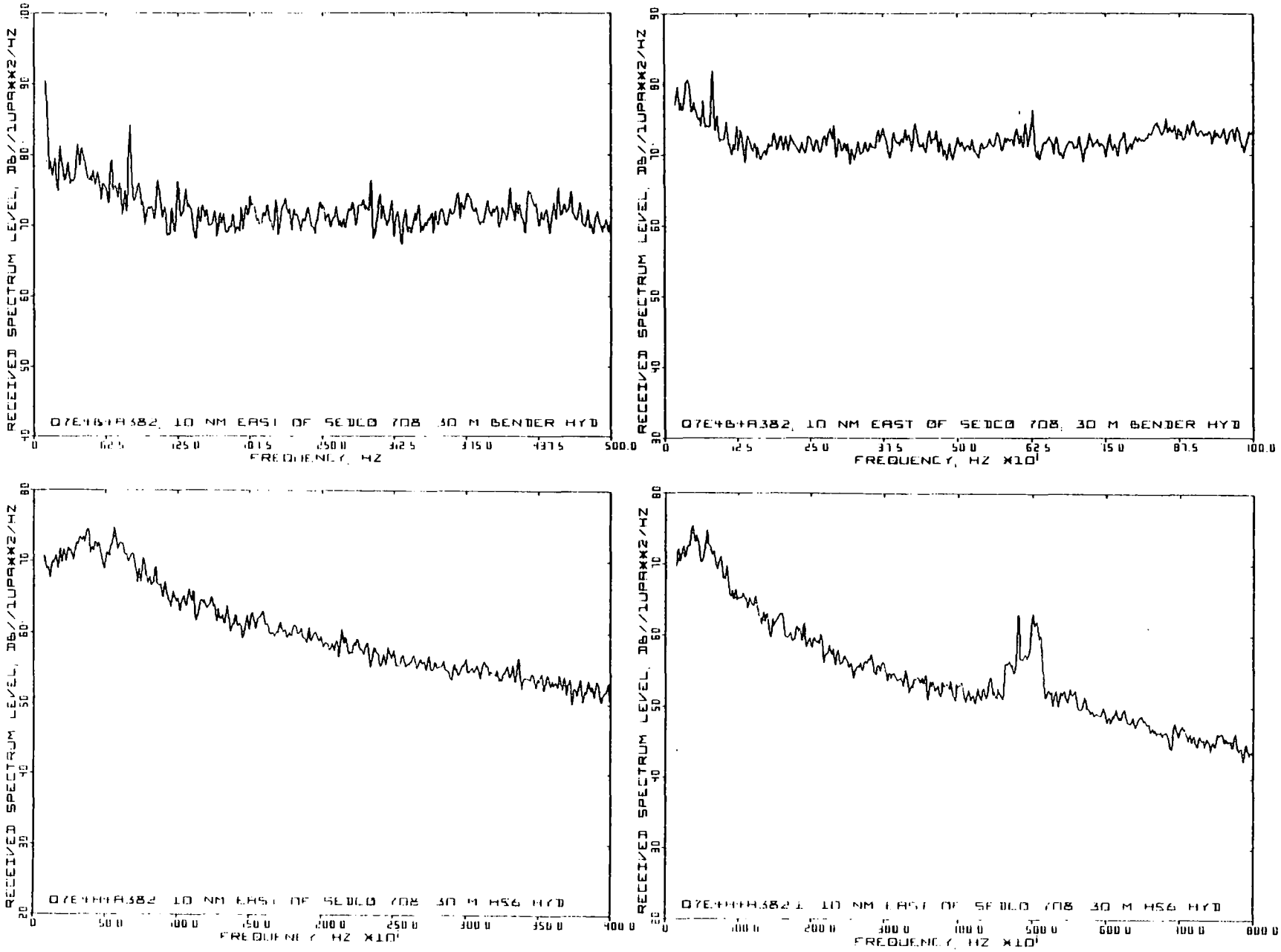

Fig A-14. Sound pressure spectra 10.0 nm east of SEDCO 708, 30 m depth.

APPENDIX B

Sound pressure spectra vs depth

at ranges of 0.5 and 10 nm.

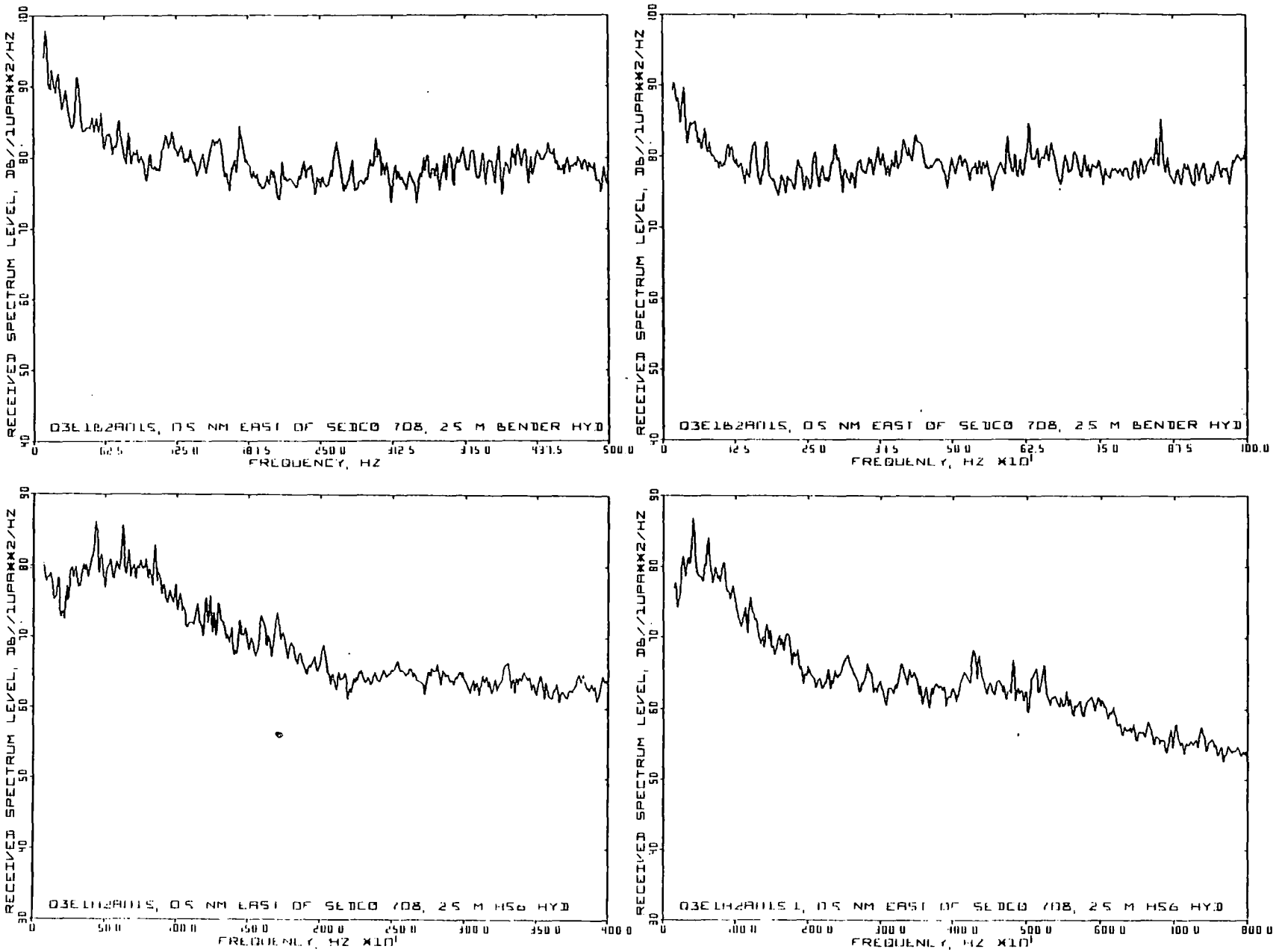

Fig B-1. Sound pressure spectra 0.5 nm east of SEDCO 708, 2.5 m depth.

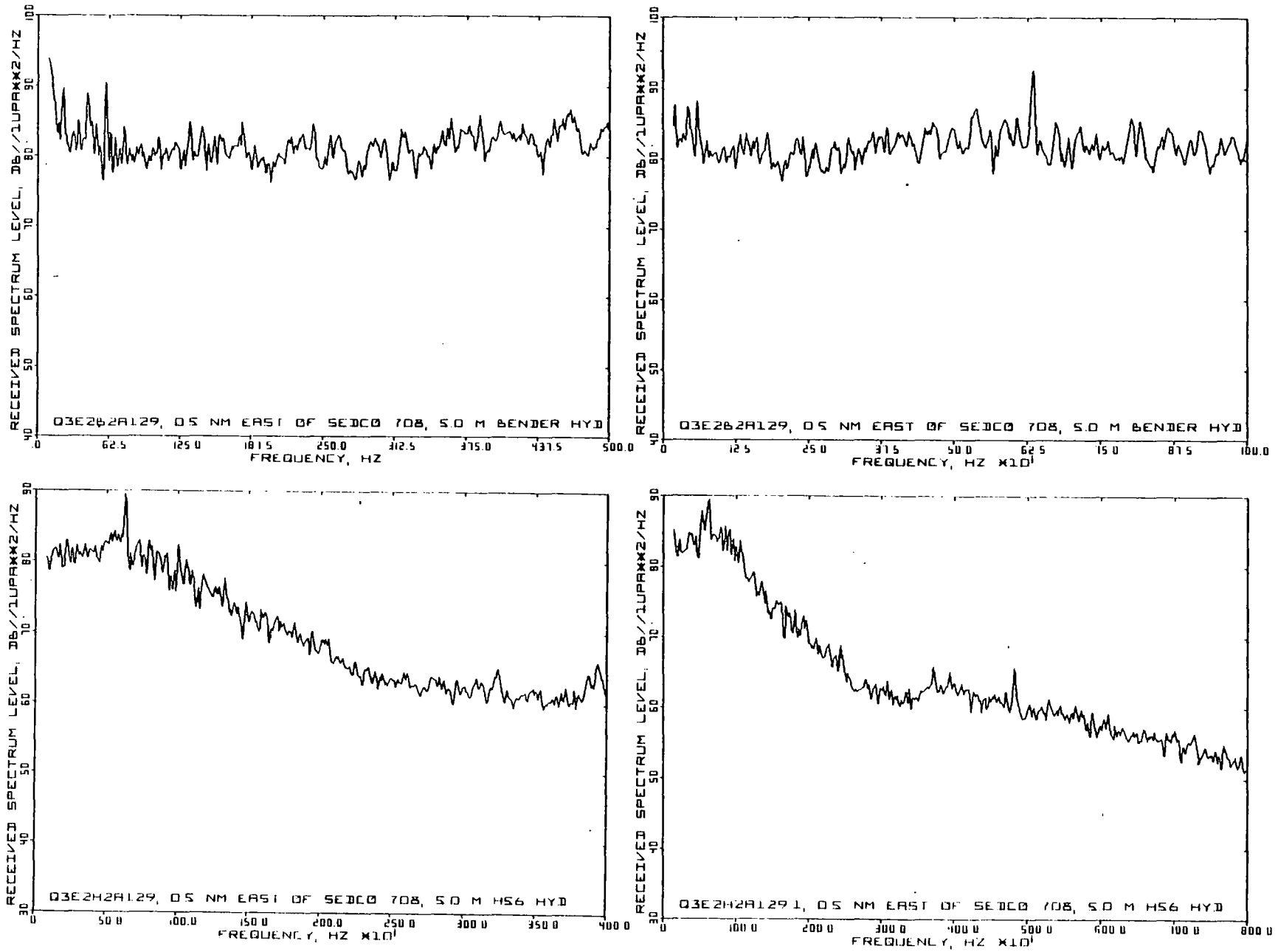

Fig B-2. Sound pressure spectra 0.5 nm east of SEDCO 708, 5 m depth.

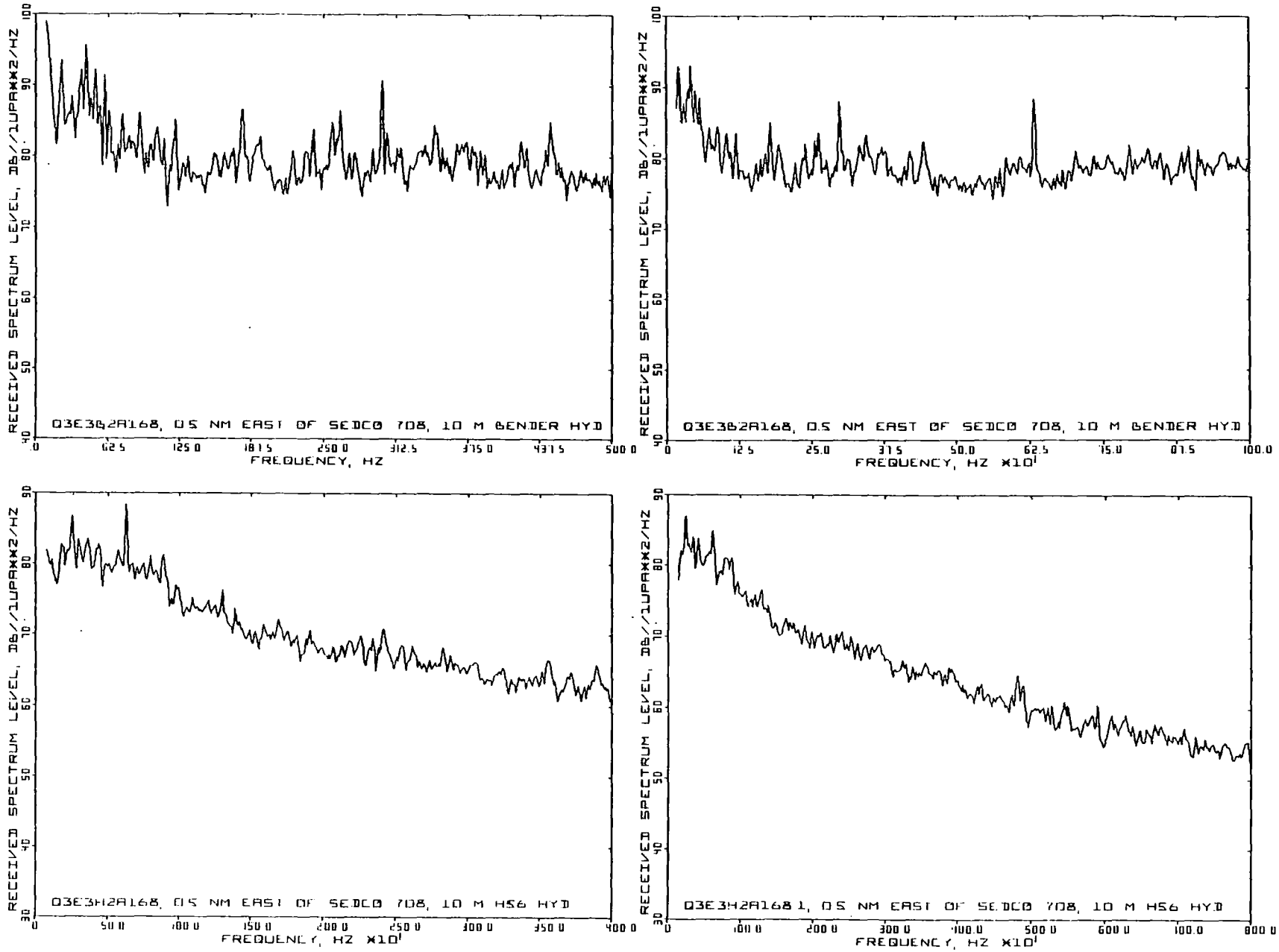

Fig B-3. Sound pressure spectra 0.5 nm east of SEDCO 708, 10 m depth.

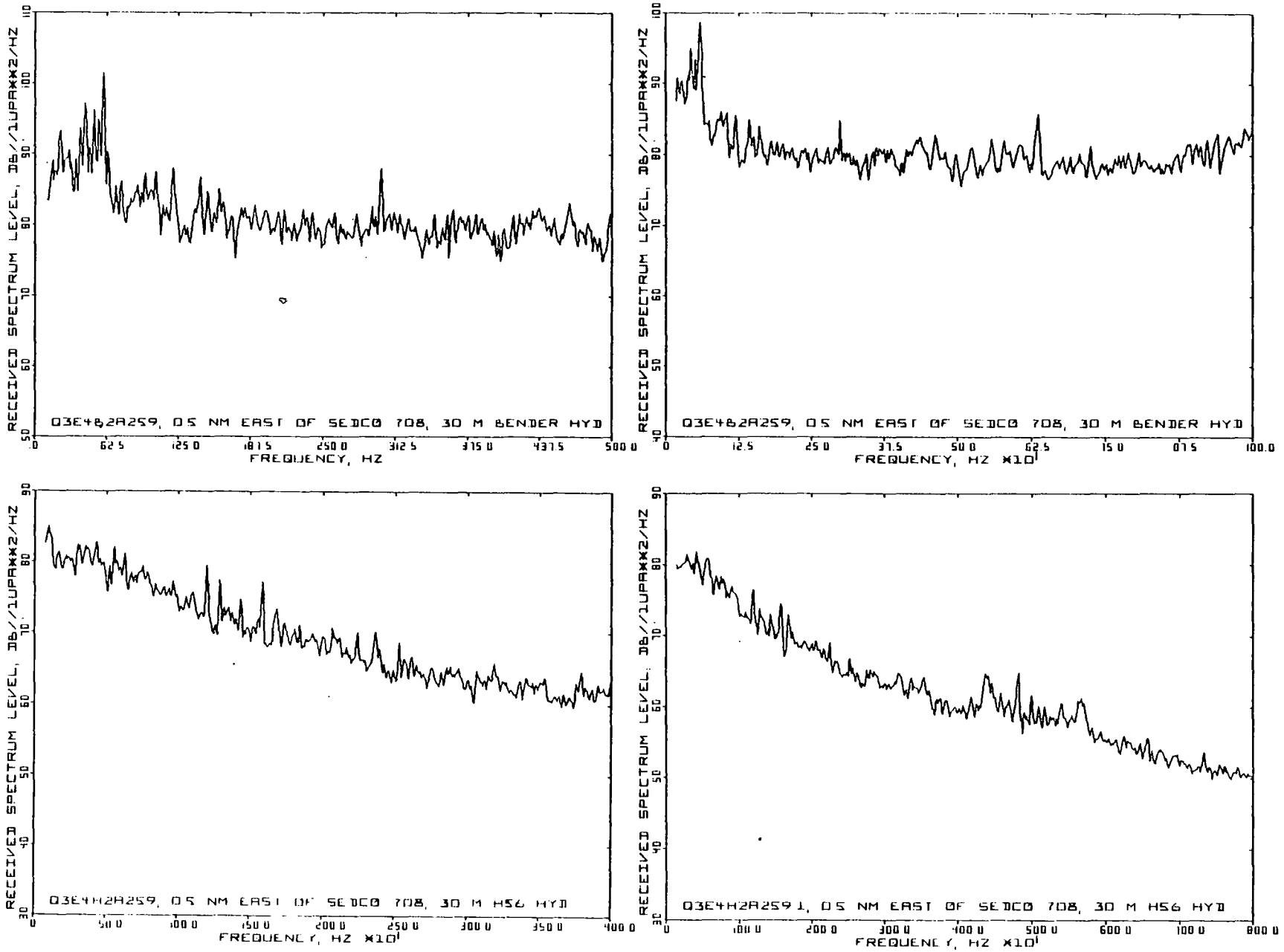

Fig B-4. Sound pressure spectra 0.5 nm east of SEDCO 708, 30 m depth.

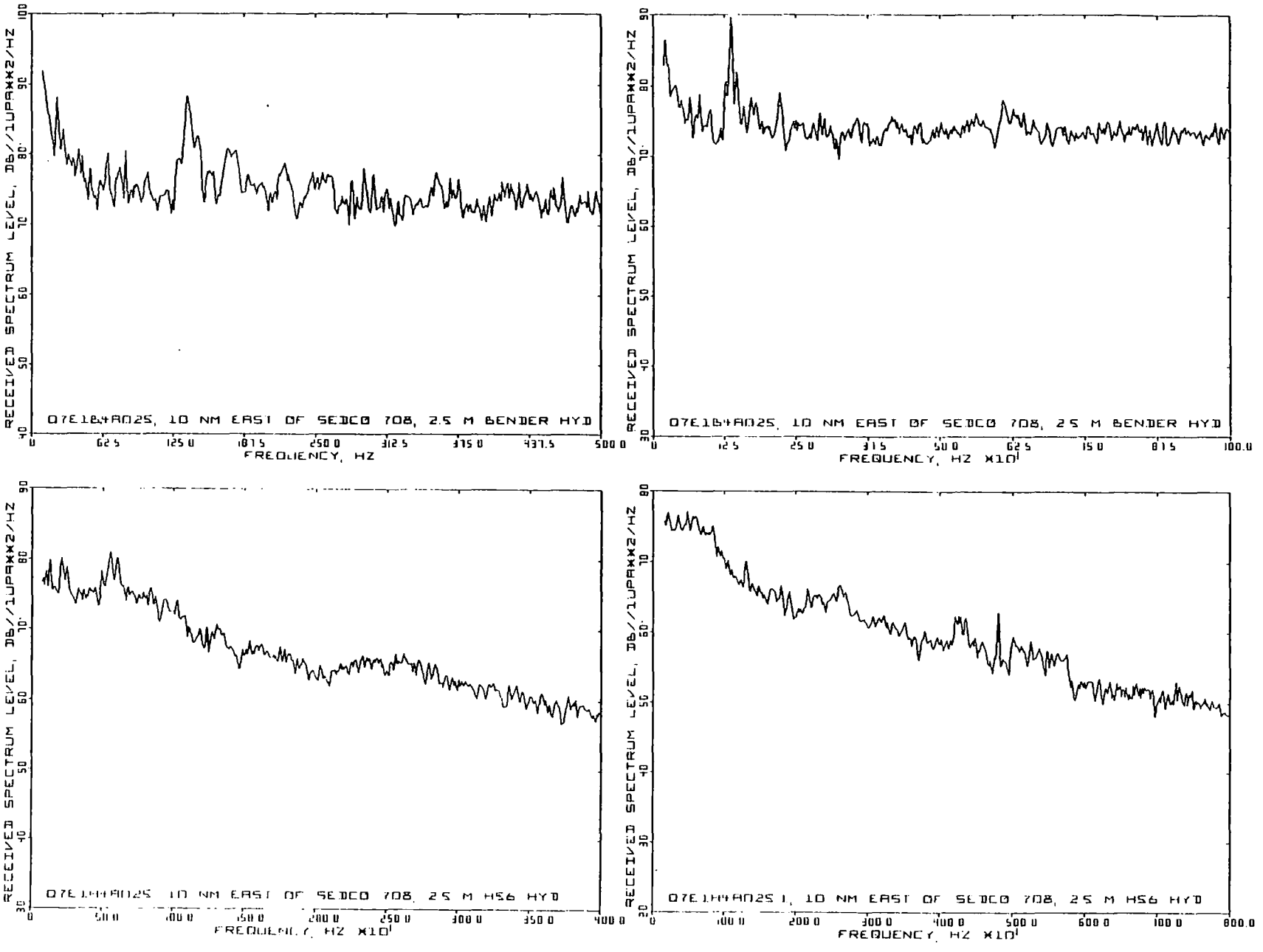

Fig B-5. Sound pressure spectra 10 nm east of SEDCO 708, 2.5 m depth.

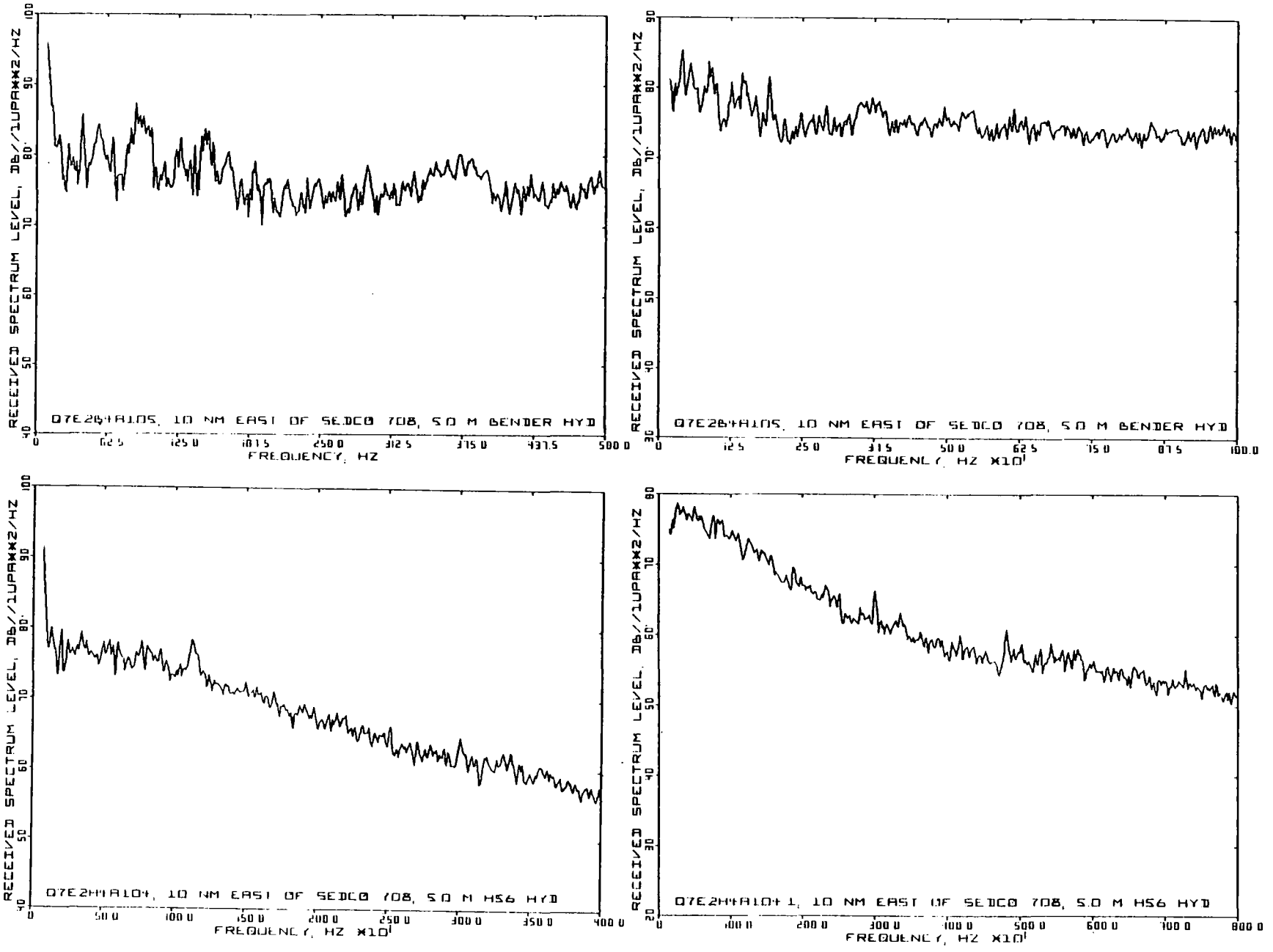

Fig B-6. Sound pressure spectra 10 nm east of SEDCO 708, 5 m depth.

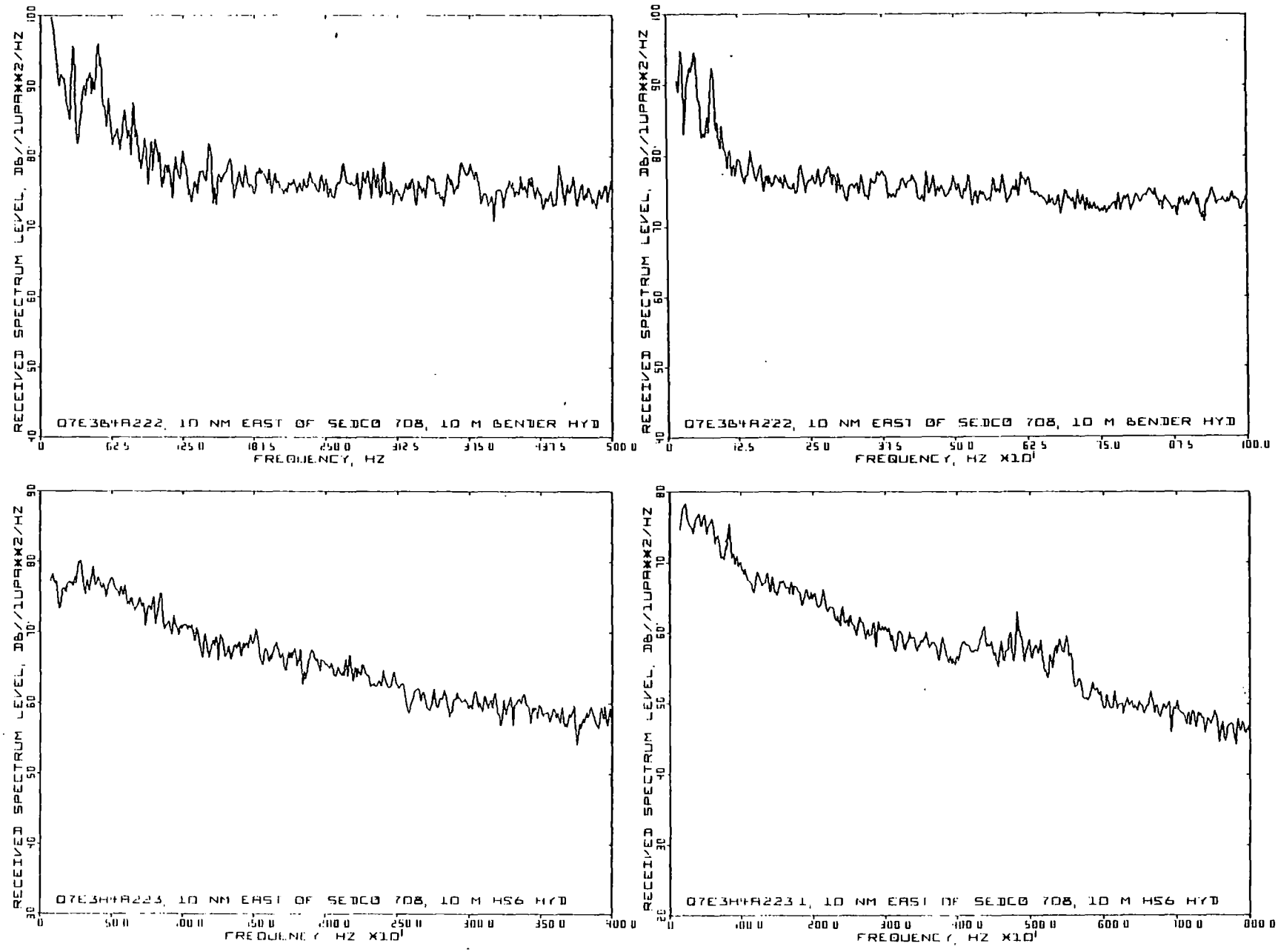

Fig B-7. Sound pressure spectra 10 nm east of SEDCO 708, 10 m depth.

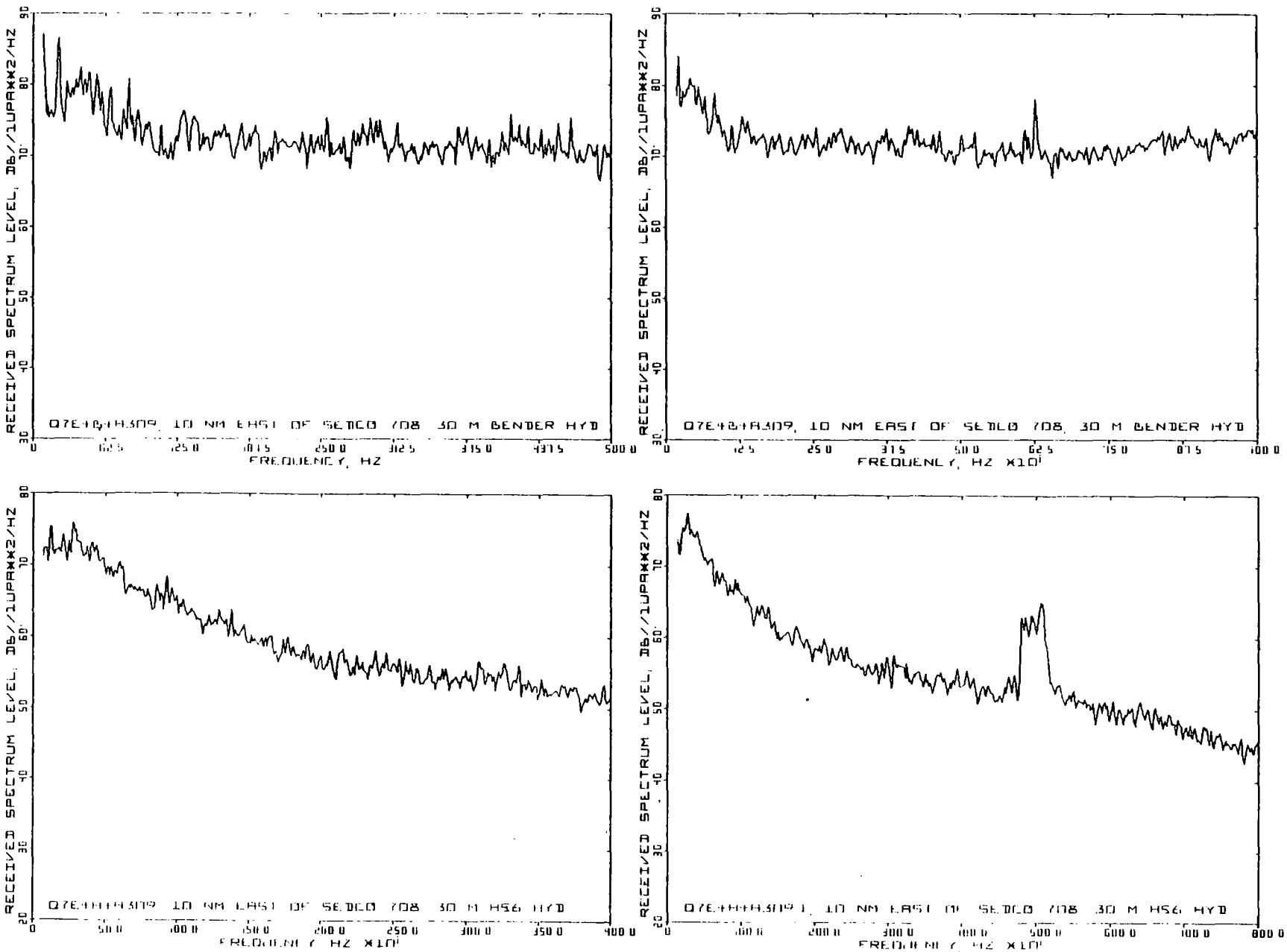

Fig B-8. Sound pressure spectra 10 nm east of SEDCO 708, 30 m depth.

APPENDIX C

Sound pressure spectra vs azimuth

at a range of 0.5 nm and a depth of 30 m.

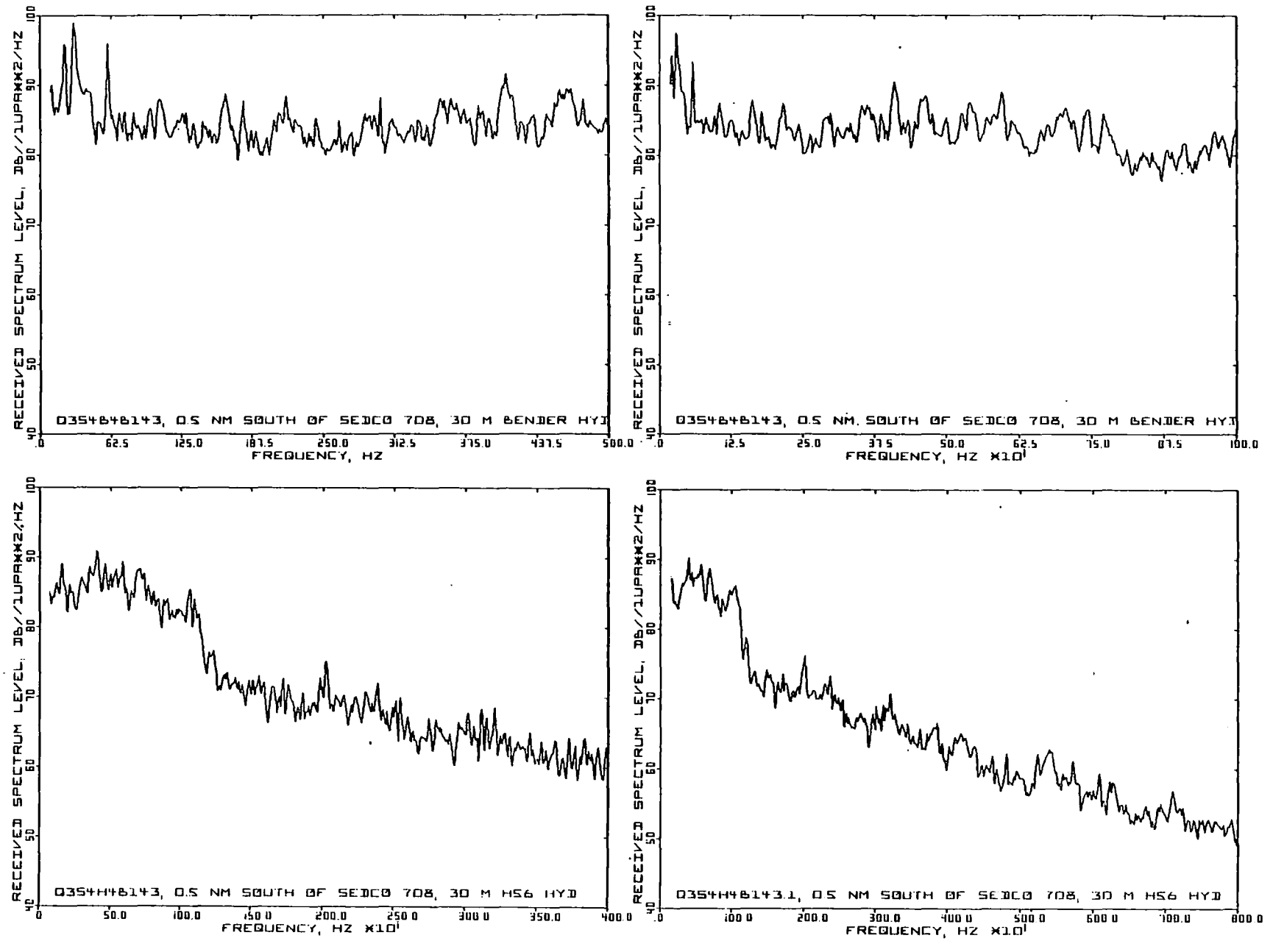

Fig C-1. Sound pressure spectra 0.5 nm south of SEDCO 708, 30 m depth.

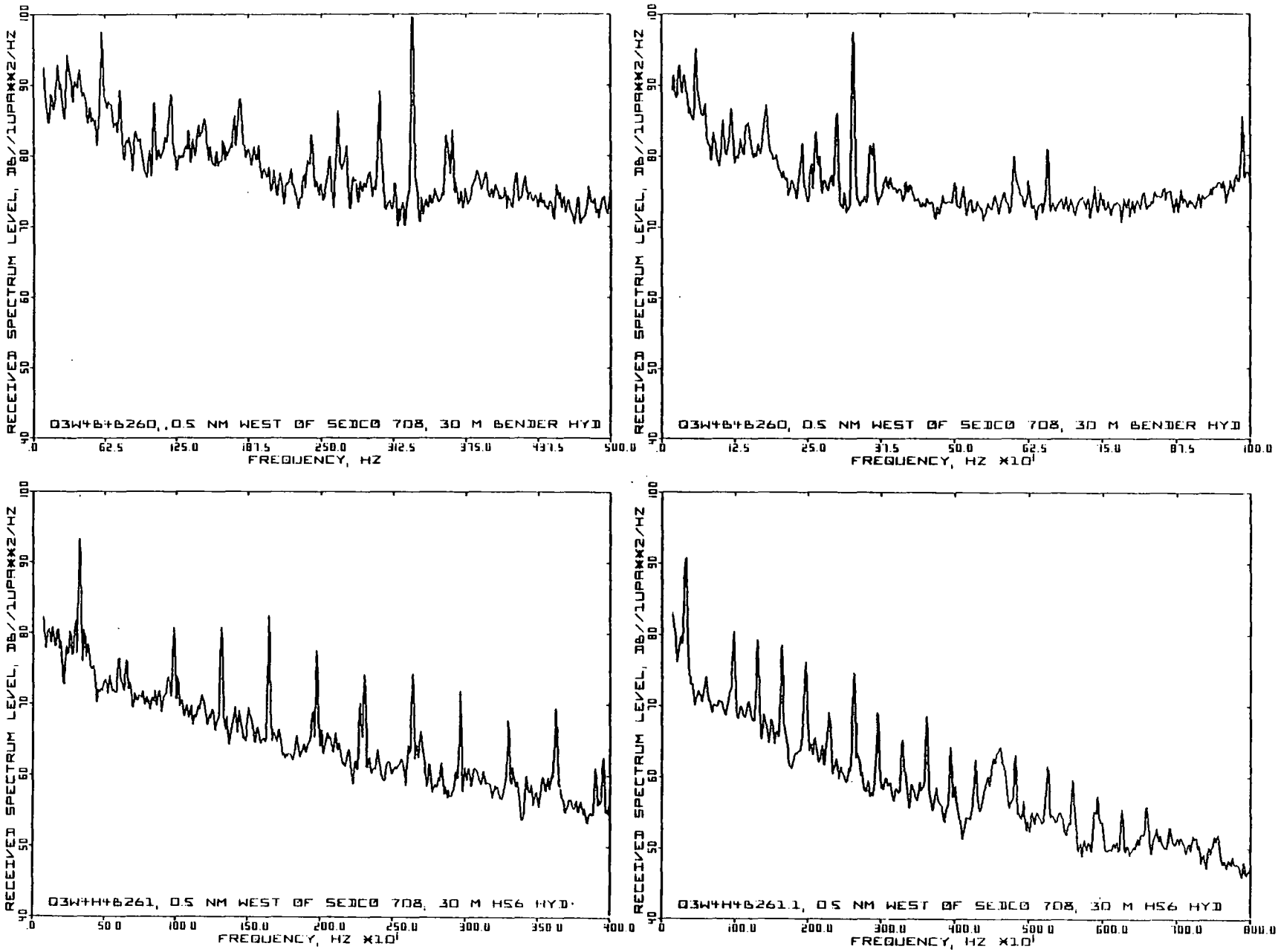

Fig C-2. Sound pressure spectra 0.5 nm west of SEDCO 708, 30 m depth.

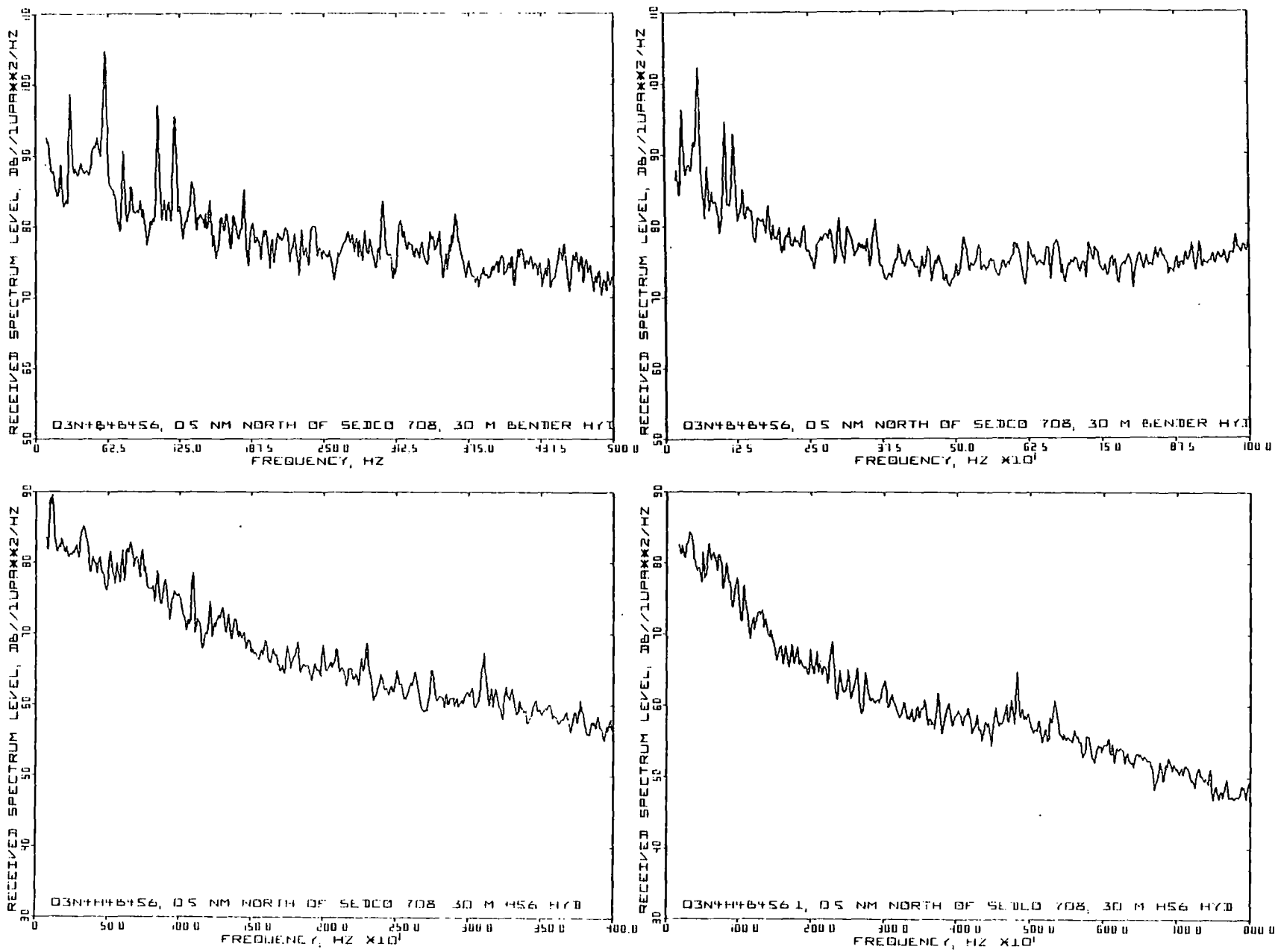

Fig C-3. Sound pressure spectra 0.5 nm north of SEDCO 708, 30 m depth.

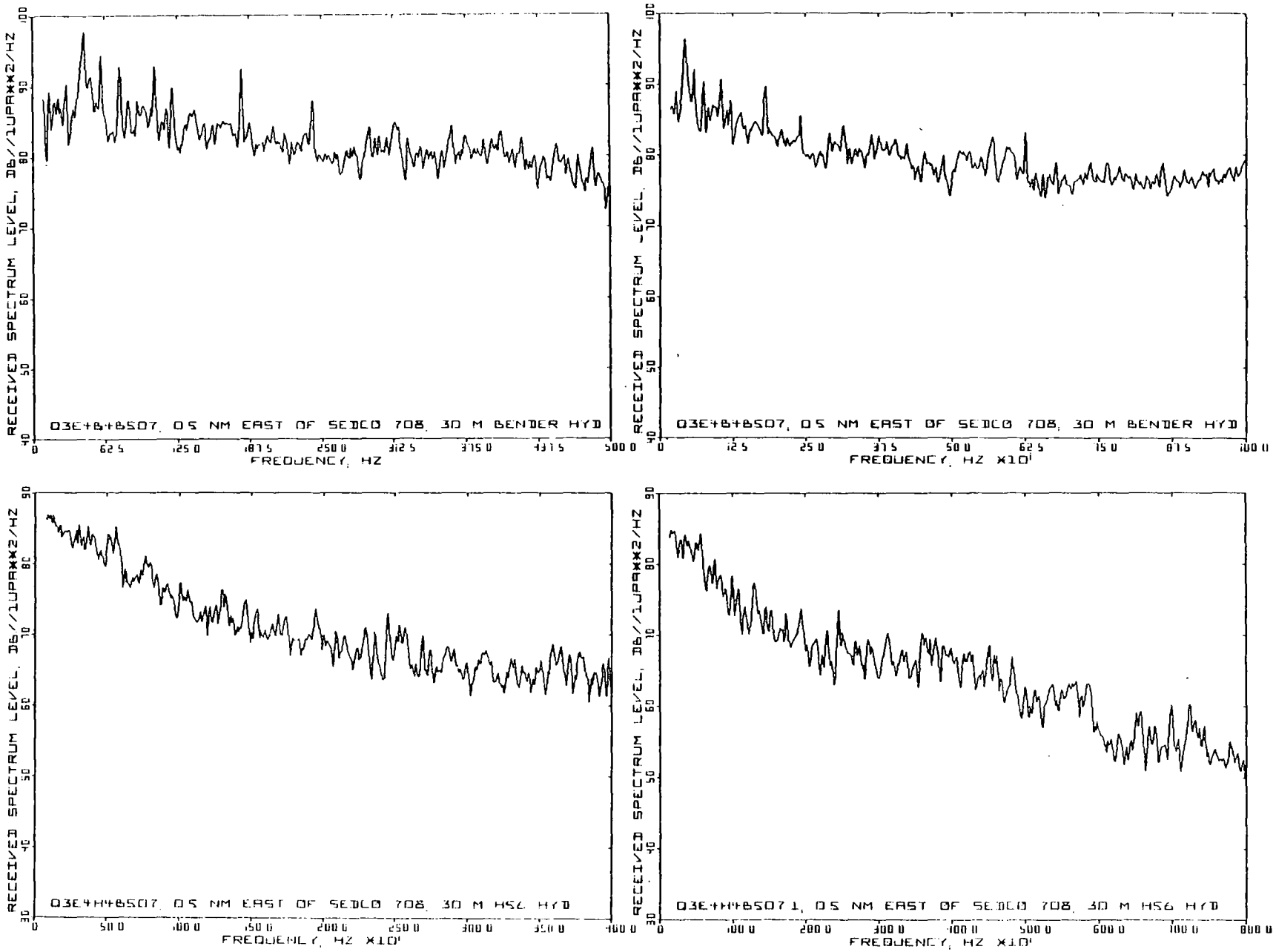

Fig C-4. Sound pressure spectra 0.5 nm east of SEDCO 708, 30 m depth.

APPENDIX D

Band levels of noise vs range at four depths,

vs depth at seven ranges

and vs depth, 0.5 nm range, four azimuths.

Table D-1. Band levels (in dB//1uPa) vs range, 2.5 m depth.

	RANGE, nm						
BAND, Hz	0.1	0.2	0.5	1.0	2.0	5.0	10.0
Bender:							
10- 500	115	110	111	104	105	105	108
100- 500	113	107	107	101	102	99	102
200- 500	112	106	104	100	101	98	100
10- 20	101	107	105	98	101	103	106
20- 40	103	102	104	93	95	97	97
40- 80	105	99	104	95	94	94	96
80- 160	106	100	104	92	94	92	98
160- 320	111	103	102	96	97	95	97
25- 50	104	100	104	93	95	96	97
50- 100	106	99	104	95	93	92	95
100- 200	108	102	104	93	95	92	98
200- 400	111	103	102	98	99	96	98
56:							
200- 400	114	107	102	99	97	101	99
400- 800	111	111	106	106	101	103	102
800-1600	107	107	104	103	100	102	101
1600-3200	100	100	99	97	97	98	98
80-4000	117	114	110	109	106	109	107

Table D-2. Band levels (in dB//1uPa) vs range, 5 m depth.

	RANGE, nm						
BAND, Hz	0.1	0.2	0.5	1.0	2.0	5.0	10.0
Bender:							
500	115	113	110	107	109	109	106
100- 500	112	111	108	105	103	106	103
200- 500	110	108	106	102	101	104	101
10- 20	108	101	102	99	105	100	98
20- 40	106	102	99	98	100	101	94
40- 80	108	107	101	98	99	98	96
80- 160	107	107	100	101	98	104	101
160- 320	108	108	104	100	99	102	98
25- 50	106	103	99	98	100	100	95
50- 100	108	106	100	99	98	102	99
100- 200	107	108	101	101	98	102	100
200- 400	108	107	105	101	100	103	99
H56:							
200- 400	112	110	105	101	98	104	103
400- 800	111	111	108	104	101	104	103
800-1600	108	109	106	102	99	103	103
1600-3200	102	102	99	96	93	99	97
80-4000	117	116	112	108	106	110	109

Table D-3. Band levels (in dB//1uPa) vs range, 10 m depth.

	RANGE, nm						
BAND, Hz	0.1	0.2	0.5	1.0	2.0	5.0	10.0
Bender:							
10- 500	116	116	110	111	109	108	111
100- 500	112	113	106	106	106	106	105
200- 500	111	111	105	104	104	104	101
10- 20	102	104	104	107	104	101	107
20- 40	108	104	101	101	98	98	104
40- 80	110	110	104	105	100	97	102
80- 160	105	107	101	101	101	100	102
160- 320	111	109	103	102	103	103	100
25- 50	109	107	103	101	98	98	102
50- 100	109	110	102	104	100	97	102
100- 200	106	108	102	102	102	101	102
200- 400	111	110	104	102	103	103	100
H56:							
200- 400	114	111	106	106	103	102	101
400- 800	109	112	106	106	103	103	103
800-1600	106	109	104	104	100	100	100
1600-3200	99	102	100	98	96	96	96
80-4000	117	117	111	112	108	108	108

Table D-4. Band levels (in dB//1uPa) vs range, 2.5 m depth.

	RANGE, nm						
BAND, Hz	0.1	0.2	0.5	1.0	2.0	5.0	10.0
Bender:							
10- 500	118	115	112	110	108	104	101
100- 500	113	111	106	102	104	101	98
200- 500	110	109	103	99	101	99	97
10- 20	102	101	106	106	99	96	92
20- 40	111	110	105	104	101	96	93
40- 80	114	109	108	105	103	96	94
80- 160	110	106	102	99	102	98	92
160- 320	109	107	101	98	100	96	94
25- 50	112	110	106	105	102	95	93
50- 100	113	107	107	104	103	97	93
100- 200	110	107	102	99	101	97	92
200- 400	108	107	102	98	100	98	95
H56:							
200- 400	111	108	102	99	97	95	95
400- 800	114	111	105	100	99	97	95
800-1600	110	107	103	97	96	92	92
1600-3200	102	99	98	91	91	90	89
80-4000	118	115	110	106	105	101	100

Table D-5. Band levels (in dB//1uPa) vs depth, 0.1 nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	115	115	116	118
100- 500	113	112	112	119
200- 500	112	110	111	110
10- 20	101	108	102	102
20- 40	103	106	108	111
40- 80	105	108	110	114
80- 160	106	107	105	110
160- 320	111	108	111	108
25- 50	104	106	109	112
50- 100	106	108	109	113
100- 200	108	107	106	110
200- 400	111	108	111	108
H56:				
200- 400	114	112	114	111
400- 800	111	111	109	114
800-1600	107	108	106	110
1600-3200	100	102	99	102
80-4000	117	117	117	118

Table D-6. Band levels (in dB//1uPa) vs depth, 0.2 nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	110	113	116	115
100- 500	107	111	113	111
200- 500	106	108	111	109
10- 20	107	101	104	101
20- 40	102	102	104	110
40- 80	99	107	110	109
80- 160	100	107	107	106
160- 320	103	108	109	107
25- 50	100	103	107	110
50- 100	99	106	110	107
100- 200	102	108	108	107
200- 400	103	107	110	107
H56:				
200- 400	107	110	111	108
400- 800	111	111	111	111
800-1600	107	109	109	107
1600-3200	100	102	102	99
80-4000	114	116	117	115

Table D-7. Band levels (in dB//1uPa) vs depth, 0.5 nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	111	108	110	113
100- 500	107	108	106	106
200- 500	104	106	105	103
10- 20	105	102	104	106
20- 40	104	99	101	105
40- 80	104	101	104	108
80- 160	104	100	101	102
160- 320	102	104	103	101
25- 50	104	99	103	106
50- 100	104	100	102	107
100- 200	104	101	102	102
200- 400	102	105	104	102
H56:				
200- 400	102	105	106	102
400- 800	106	108	106	105
800-1600	104	106	104	103
1600-3200	99	99	100	98
80-4000	110	112	111	110

Table D-8. Band levels (in dB//1uPa) vs depth, 1.0nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	104	107	111	110
100- 500	101	105	106	102
200- 500	100	102	104	99
10- 20	98	99	107	106
20- 40	93	98	101	104
40- 80	95	98	105	105
80- 160	92	101	101	99
160- 320	96	100	102	98
25- 50	93	98	101	105
50- 100	95	99	104	104
100- 200	93	101	102	99
200- 400	98	101	102	98
H56:				
200- 400	99	101	106	99
400- 800	106	104	106	100
800-1600	103	102	104	97
1600-3200	97	96	98	91
80-4000	109	108	112	106

Table D-9. Band levels (in dB//1uPa) vs depth, 2.0 nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	105	109	109	108
100- 500	102	103	106	104
200- 500	101	101	104	101
10- 20	101	105	104	99
20- 40	95	100	98	101
40- 80	94	99	100	103
80- 160	94	98	101	102
160- 320	97	99	103	100
25- 50	95	100	98	102
50- 100	93	98	100	103
100- 200	95	98	102	101
200- 400	99	100	103	100
H56:				
200- 400	97	98	103	97
400- 800	101	101	103	99
800-1600	100	99	100	96
1600-3200	97	93	96	91
80-4000	106	106	108	105

Table D-10 Band levels (in dB//1uPa) vs depth, 5.0nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	105	109	108	104
100- 500	99	106	106	101
200- 500	98	104	104	99
10- 20	103	100	101	96
20- 40	97	101	98	96
40- 80	94	98	97	96
80- 160	92	104	100	98
160- 320	95	102	103	96
25- 50	96	100	98	95
50- 100	92	102	97	97
100- 200	92	102	101	97
200- 400	96	103	103	98
H56:				
200- 400	101	104	102	95
400- 800	103	104	103	97
800-1600	102	103	100	92
1600-3200	98	99	96	90
80-4000	109	110	108	101

Table D-11. Band levels (in dB//1uPa) vs depth, 10.0nm range.

	DEPTH, meters			
BAND, Hz	2.5	5.0	10	30
Bender:				
10- 500	108	106	111	101
100- 500	102	103	105	98
200- 500	100	101	101	97
10- 20	106	98	107	92
20- 40	97	94	101	93
40- 80	96	96	102	94
80- 160	98	101	102	92
160- 320	97	98	100	94
25- 50	97	95	102	93
50- 100	95	99	102	93
100- 200	98	100	102	92
200- 400	98	99	100	95
H56:				
200- 400	99	103	101	95
400- 800	102	103	103	95
800-1600	101	103	100	92
1600-3200	98	97	96	89
80-4000	107	109	108	100

Table D-12. Band levels vs depth, 0.5 nm range, south and west.

		0.5 nm South		0.5 nm West	
BAND, Hz	5m	10m	30m	10m	30m
Bender:					
10- 500	106	111	112	115	110
100- 500	104	107	109	113	106
200- 500	101	104	108	110	104
10- 20	96	103	97	105	97
20- 40	96	102	106	104	104
40- 80	99	104	103	106	104
80- 160	99	103	102	110	100
160- 320	100	103	104	108	101
25- 50	97	102	106	105	104
50- 100	98	104	102	106	103
100- 200	100	104	103	110	101
200- 400	100	103	106	108	104
H56:					
200- 400	102	104	108	109	105
400- 800	103	104	113	110	100
800-1600	100	101	109	105	101
1600-3200	96	98	105	102	99
80-4000	108	110	116	115	109

Table D-13. Band levels vs depth, 0.5 nm range, north and east.

	0.5 NM NORTH		0.5 NM EAST	
BAND, Hz	10m	30m	10m	30m
Bender:				
10- 500	115	113	110	111
100- 500	111	110	108	108
200- 500	108	108	104	106
10- 20	108	98	97	97
20- 40	106	103	99	100
40- 80	107	109	104	106
80- 160	108	106	105	104
160- 320	107	103	104	104
25- 50	105	104	101	105
50- 100	108	109	104	104
100- 200	108	106	105	104
200- 400	106	106	103	104
H56:				
200- 400	108	107	104	106
400- 800	109	110	104	106
800-1600	105	108	101	104
1600-3200	100	104	98	100
80-4000	115	115	110	112

HEARING THRESHOLD MEASUREMENTS AND RESPONSES OF BELUKHA WHALES TO PLAYBACKS OF UNDERWATER DRILLING NOISE

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EXECUTIVE SUMMARY

Exploration for and production of offshore oil generates underwater noise. Belukha whales, Delphinapterus leucas, are common in arctic and subarctic continental shelf areas with known or suspected oil reserves. Because these whales depend heavily upon acoustics for orientation and communication, this man-made noise could conceivably have adverse effects upon them. Underwater noise could disrupt communication, interfere with mating, affect prey capture, cause avoidance of traditional feeding areas or migration routes, or even damage hearing permanently. Measuring the properties of an underwater noise source and extrapolating them to other distances is a fairly straightforward problem in physics, but controlled experiments using marine mammals were needed to determine how the noise affects live animals. We performed such controlled experiments at Hubbs Marine Research Institute with captive belukha whales, thus providing data that were not confounded by the many variables present in a field situation.

The purposes of our investigation were to 1) document behavioral responses of captive belukha whales to high level underwater playbacks of drilling noise, 2) determine whether that noise caused stress as measured by changes in blood hormone levels, and 3) measure the whales' hearing sensitivity and relate it to Gales' (1982) postulated zones of influence around drilling structures.

We compared social interactions, swimming and respiration/dive patterns, and blood levels of stress-related hormones in four captive belukha whales before and during a series of high level playbacks of noise recorded from a semi- submersible drilling platform, SEDCO 708. Using audiometric procedures, we then measured hearing sensitivities of three whales to pure tones between 125 Hz and 128 kHz.

We found no change in swimming pattern, social structure, or respiration/dive pattern, except for dive interval, of captive belukha whales during playbacks of drilling noise. Blood catecholamine levels, measured immediately after the playbacks as an indicator of stress, were not elevated. The hearing sensitivity of these whales declines rapidly below 4 kHz, so it is much less sensitive at the lower frequencies predominant in drilling noise than at higher frequencies used for their communication and echolocation.

We conclude that playbacks of underwater sound from a semi-submersible drilling platform at levels comparable to that at the source had no significant short-term behavioral or physiological effects on captive belukha whales.

INTRODUCTION

Exploration, production, and transportation of continental shelf oil generates underwater noise. There is concern that such noise may have detrimental effects on marine mammals.

In general, the concerns are that whales might react to noise by leaving or refusing to enter an area, which could be serious if the area was critical for breeding or feeding. Whales, especially the more gregarious toothed whales, may respond to sudden disturbances by sounding, aggregating, or by dispersing. High noise levels could interfere with navigation or feeding by masking echolocation signals. Or, the noise might disrupt social bonds or activity by masking communication signals. Very high level sounds might even cause permanent hearing loss by destroying sound-sensitive hair cells in the inner ear. Even at lower levels, noise could cause physiological stress, with variable effects ranging from interference with feeding to altered reproductive behavior and increased spontaneous abortions. This study addresses some of these concerns by measuring the effects of one type of noise (i.e. noise from a semi-submersible drilling platform) on belukha whales Delphinapterus leucas.

Odontocetes have a well developed underwater acoustic system. All odontocetes that have been examined, including belukha whales, use sound to gather spatial information about their environment and for intraspecific communication. Belukha whales would be expected to rely very heavily on acoustics for orientation and communication, particularly when they are in murky water that is common in many places where petroleum is found.

The environment of marine mammals normally contains many noise sources, (Figure 1). Ambient sound levels in the ocean vary daily, seasonally, and geographically (Wenz 1962; Urick 1975). They are lowest in calm, deep water, without shipping or industrial noise. Shallow bays, harbors, and coastal areas generally have higher ambient levels, especially at frequencies above 500 Hz. Sound energy is greatest between 20 and 500 Hz. Above 500 Hz, it decreases at about 5 dB per octave (Ross 1976). Energy below 1000 Hz comes predominantly from vessel traffic, wind, and marine animals. Increasing wind speed and sea state raises ambient noise levels across the spectrum. In the odontocetes that have been examined, hearing is most sensitive between 8 kHz and 145 kHz, well above the predominant frequency range of industrial noise. Industrial noise is probably less important as a potential masking source in this frequency range than rain or the sounds produced by animals. Cetaceans almost certainly use behaviors such as changing orientation, increasing signal level or emphasizing different frequencies to minimize masking effects (Grinnell 1967; Evans 1967; Au et al. 1985).

Even though behavior of cetaceans in their natural environment is difficult to observe, there are some reports on responses of at least ten cetacean species, including both odontocetes and mysticetes, to man-made underwater noise (Gambell 1968; Nishiwaki and Sasao 1976;

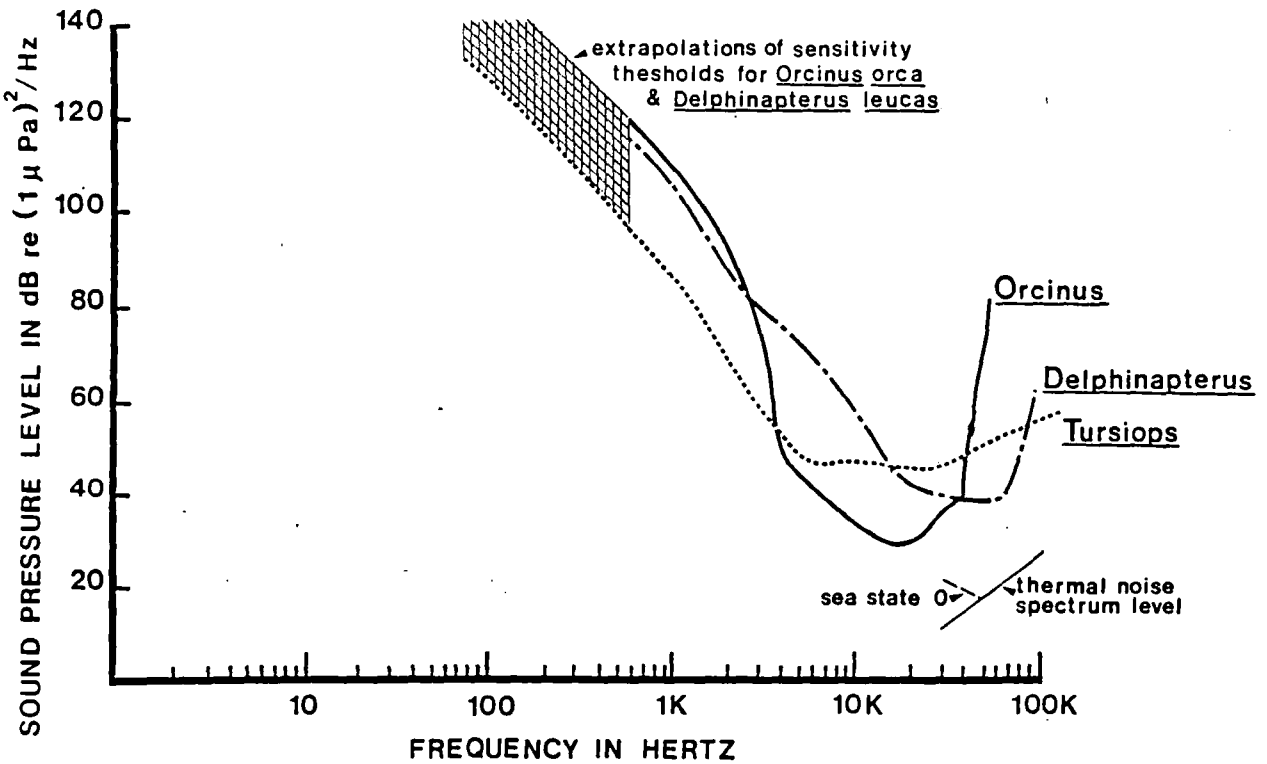

Figure 1. Ambient noise levels (after Urick 1975) and hearing sensitivity curves between 500 Hz and 150 kHz of selected marine mammals (Johnson 1966, Mohl 1986; Schusterman et al. 1972). Stippled areas show ambient noise level ranges under various conditions.

Faker 1977 a,b; Schallenberger 1977; Norris et al. 1978; Swartz and Jones 1979; Davis and Koski 1980; Ljungblad et al. 1980; Dahlheim et al. 1981; Fraker et al. 1981; Stewart et al. 1982, 1984). Direct comparison is difficult because important information either is not available or differs among reports (e.g., spectrum, level, distance to sound source, season, time of day, ambient sound levels, and pre-disturbance behaviors of the animals). Also, odontocete and mysticete hearing characteristics probably are quite different (Norris and Leatherwood 1981).

Although exposure to sustained high amplitude noise can cause discomfort, stress, and even physical damage to humans and animals, the actual effect(s) on whales of noise made by a drilling platform are still uncertain. Gales (1982) approached this question by measuring sound spectral levels near a semi-submersible drilling platform (SEDCO 708) in the Aleutian Islands and then, using sound propagation theory and hearing sensitivity curves for marine mammals (Figure 2), modeled a potential zone of influence around such structures. He estimated distances where sound could be detected, where it might mask hearing, and where hearing damage might occur.

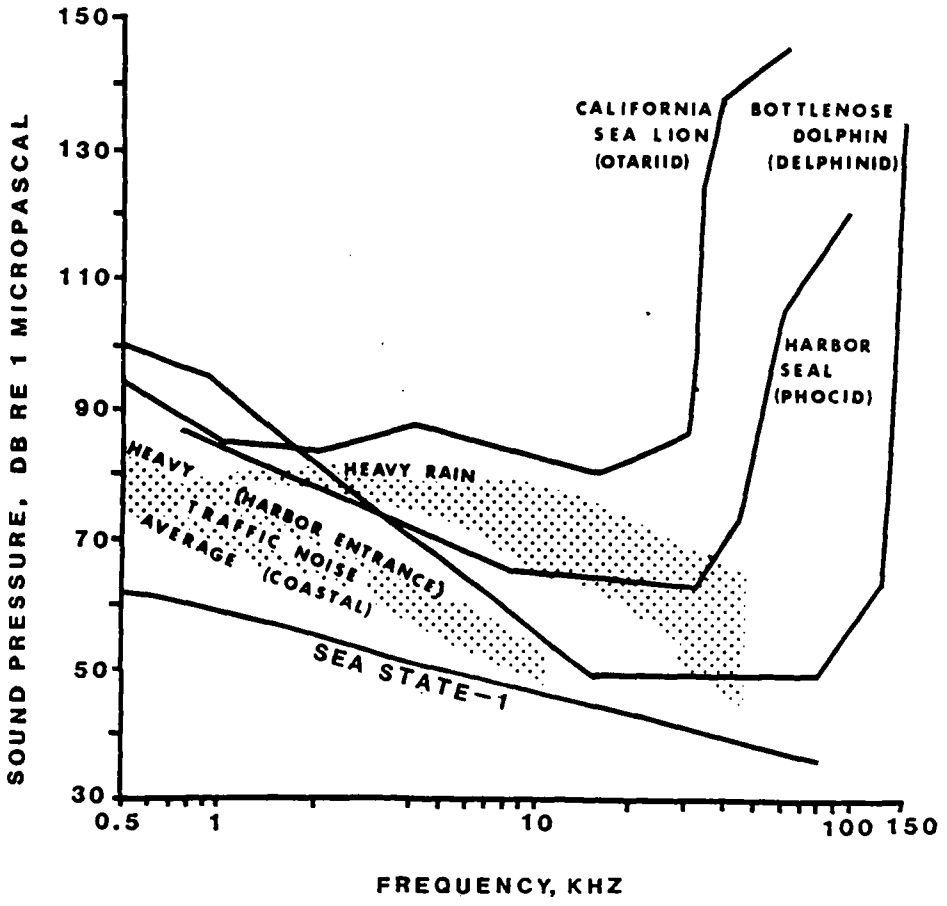

Figure 2. Hearing thresholds between 100 Hz and 100 kHz for killer whales, bottlenose dolphins, and belukha whales. Data from Johnson (1966), Hall and Johnson (1971) and White et al. (1978).

This type of model is a good "first-approach" to the question, but it needs testing. Among the questions are: Do whales hear the sounds produced by drilling structures and other equipment? If so, is it stressful? Will these sounds cause whales to avoid certain areas?

These questions can best be answered by experiments with captive animals. For example, changes in normal behavior associated with perturbations are much easier to quantify with captive animals than with free-ranging cetaceans. Also, acclimation is easier to detect, if it occurs. Quantifying stress, using catecholamine levels in the blood-stream, requires taking blood samples soon after a potentially stressful event (Durrett and Ziegler 1980). Catching a wild animal for a blood sample could well be more stressful than the event in question. Finally, behavioral techniques for measuring hearing in marine mammals require trained animals.

Accordingly, we used captive animals to investigate the following three topics concerning noise effects on belukha whales: 1) behavioral responses to high level underwater playbacks of noise from the semi-submersible drilling platform, SEDCO 708; 2) an increase in blood catecholamine levels after these playbacks as a stress indicator; and 3) hearing thresholds of pure tones in octave steps between 125 Hz and 128 kHz.

The belukha whale was chosen for this investigation because it is a good model for studying the effects of noise from petroleum-related activity on small odontocetes. It is widely distributed in arctic and subarctic waters. It is a highly vocal species that relies heavily on sound for orientation and communication (Ford 1977; Gurevich and Evans 1976; Kamminga and Wiersma 1981). Its activities in the vicinity of petroleum exploration and production have been monitored for over a decade in the Mackenzie River estuary in the Canadian Beaufort Sea (Fraker 1977b; Fraker et al. 1978; Fraker and Fraker 1979). Experimental field studies on its responses to man-made noise, including the sound from SEDCO 708, have been conducted (Stewart et al. 1982, 1984). Captive, trained animals were available for study at Sea World, San Diego. Two of these animals had participated in an earlier hearing study (White et al. 1978), allowing us to determine whether their hearing had changed.

MATERIALS AND METHODS

Behavioral and Physiological Measurements

Four belukha whales were used in the playback and hormone experiments; a young male, an adult male, a young female and an adult female. Before, during and after the testing period, these animals participated in regularly scheduled shows.

The whales were housed in a pool complex at Sea World, Inc. in San Diego, California. The complex consists of a main pool (13 m x 13 m x 4.5 m) and an adjacent holding enclosure (8.5 m x 4.5 m x 1.5 m) separated by gates (Figure 3). The animals normally move freely between the pools.

Baseline Measurements As a baseline, data under undisturbed acoustic conditions were collected four times a day (0000, 0600, 1200 and 1800) during 40-min sampling periods for 30 days. During each period, "focal animal" behavioral samples (Altman 1974) were collected for the four animals in four consecutive 10-min periods. The order of animals to be studied was decided from a random numbers table. Animals could move freely between the main pool and the holding enclosure. Lights were on 24 hr a day. Observers were out of sight of the whales, 3.5 m above the water (location O in Figure 3). There were potential visual disturbances only during the 1200 period, when the whales could see the public in an underwater viewing area.

Observers narrated the following activities on cassette recorders during both baseline and playback sessions:

a) blow (respiration)
b) surface, without a blow
c) dive
d) "head up" (external ear opening and jaw bone out of the water)
e) "head down" (animal puts its head back in the water after a "head up")
f) movement within the ten areas of the pool complex (Figure 3)
g) change in social combination (i.e., alone or in one of 13 potential social groups)

Playback Tests Playbacks were conducted nine times in a 13-day period. Because this study used animals that performed in daily shows at Sea World, our experimental design had to fit the animals' schedule. This necessitated conducting playbacks at 0730. At this hour the animals' normal workday had not yet begun and they had not been fed (a requirement for obtaining accurate catecholamine measurements). Because the park was not yet open, no spectators were in the underwater viewing area to distract the animals. As in the baseline testing, the whales were free to swim between the main pool and the holding pool. Beginning at 0720, each observer recorded a randomly assigned whale's activities during a 10-min pretest period. At 0730,

underwater sound playback began. During the 30-min exposure, the activities of each whale were recorded in three consecutive 10-min "focal animal" samples.

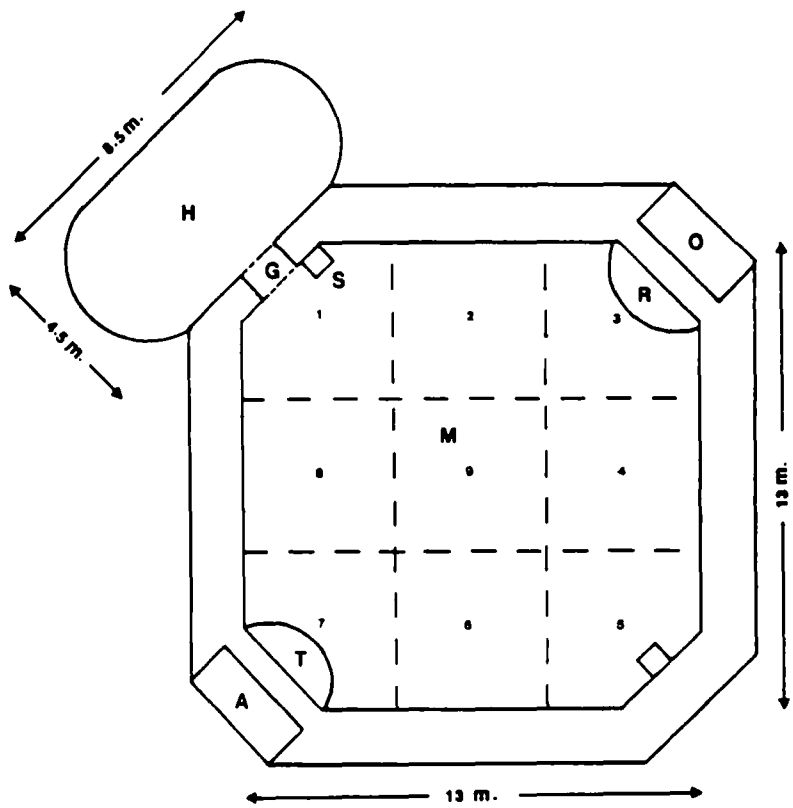

Figure 3. Diagram of pool complex where experiments were conducted on captive belukha whales. A = playback and audiogram equipment. G = gates. H = holding pool, area 10. M = main pool. O = behavior observers and monitoring equipment. R = hydrophone. S = target T = transducer. Numbers 1 to 9 = an imaginary grid that divides the main pool into nine areas.

The playback electronics (Figure 4) consisted of a Marantz PMD 360 stereo cassette recorder and an ASI TS107A amplifier. The output level was checked by a Heathkit voltmeter and the meter in the TS107A. A J9 transducer was suspended 2.5 m under water and behind a 1 cm thick curved fiberglass wall (location T in Figure 3).

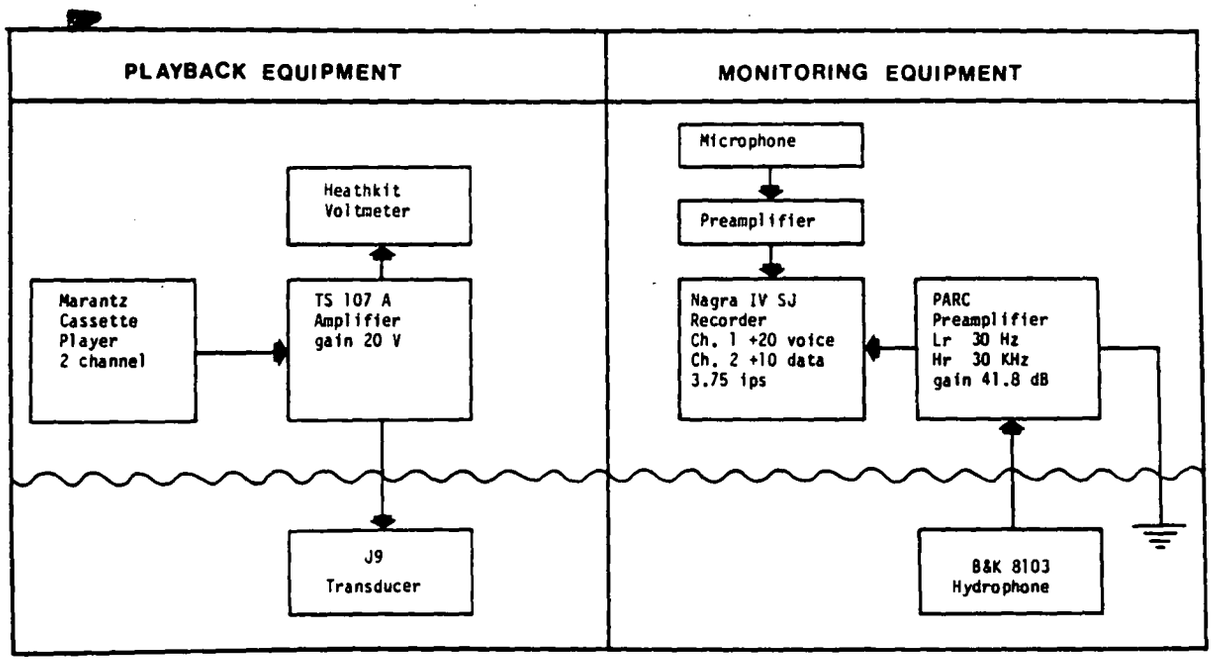

Figure 4. Diagram of the playback and monitoring equipment.

For the first five playback experiments, a cassette recording of the noise of SEDCO 708 was used. Polar Research Laboratory (Greene 1983), supplied a cassette tape containing a 5-min segment recorded 185 m from the platform at a 30 m hydrophone depth. This recording

had many interruptions caused by blocking of the hydrophone preamplifier. It was duplicated onto a reel to reel tape, and the interruptions and some poor quality sections were removed. The working cassette tapes were then made from this edited tape. The tapes all contained a low-level, 5 kHz FM carrier signal that had leaked through from the second track of the field tape recorder. Because we were concerned that the whales might misconstrue this slowly oscillating tone as a nonspecific whistle, we synthesized a version of the drilling noise by using filters to shape the output of a white noise generator (Wavetek 132) mixed with a 650 Hz tone. The synthesized version lacked the feedthrough tone and various transients present on the original SEDCO 708 recording. It was used in the last four playback experiments. Figures 5 and 6 show the close resemblance of the two versions.

In this report all sound levels are in decibels relative to the standard underwater reference pressure of one micropascal.

A calibrated system composed of a Bruel & Kjaer 8103 hydrophone, PARC 113 preamplifier and Nagra IV SJS tape recorder (Figure 4) were used to measure and record ambient and playback levels. The hydrophone was 2.5 m under water behind the fiberglass barrier on the opposite side of the pool from the transducer (transducer to hydrophone distance was 14 m). The average underwater ambient sound pressure level was 106 dB before and after the experiments. Consequently, the sound level at the hydrophone ranged from 135 to 140 dB during those SEDCO 708 playbacks. The sound level at the hydrophone ranged from 134 to 137 dB during those four playbacks of the synthesized version. The projected level of a synthesized SEDCO noise measured 1 m from the J9 transducer was 153 dB. This level is equivalent to the source level of the sound of the SEDCO 708 (Greene 1983). Propagation characteristics of the pool complex housing the whales were measured with the same underwater speaker and amplifier system.

After each behavior session (baseline and playback), all activities and the times they occurred were determined from the commentary on observer's tapes. These data were entered into a computer, which calculated the following statistics for each animal in each period:

a) number of blows per min
c) number of dives per min
d) number of "head ups" per min
e) number of "head downs" per min
f) proportion of time spent in each of the 14 possible social combinations
g) proportion of time spent in each of the 10 areas of the pool
h) blow interval (time between consecutive blows)
i) dive interval (time between consecutive dives)

Summary statistics were generated using the Statistical Package for the Social Sciences (SPSSX) in conjunction with some special programs written in Fortran. These were checked with an artificial data set.

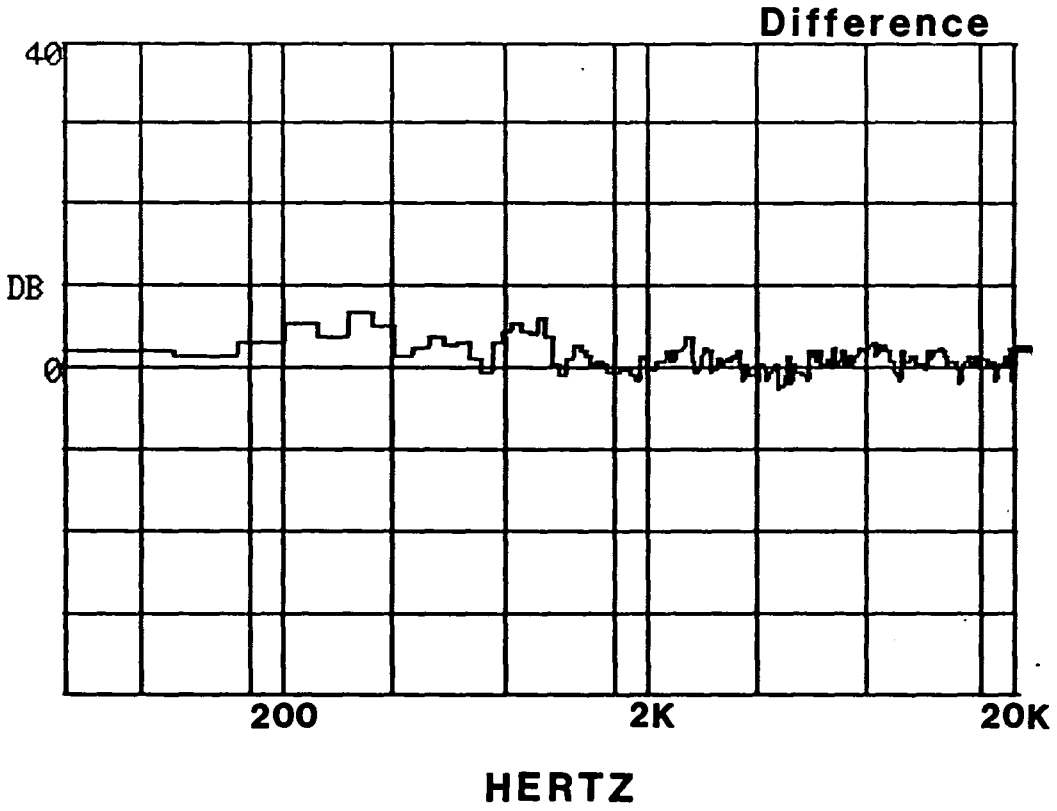

Figure 5. Spectra of synthesized sound and of the actual noise from SEDCO 708. Levels shown are arbitrary, for comparison of recorded levels.

We tested for diel differences in these variables to separate "normal" behavior variation from changes caused by a playback. If playback behaviors were outside the 95% confidence interval of the baseline value, we considered it "abnormal" and thus, a response. For respiration/dive pattern variables (e.g., mean number of blows per min, mean number of dives per min, mean dive interval, and mean blow interval), a Student's t-test was employed. For swimming patterns (proportion of time in each area in the pool) and social combinations (proportion of time in each social grouping), a Spearman's rank correlation test was used. We chose the 5% level of significance for all statistical tests.

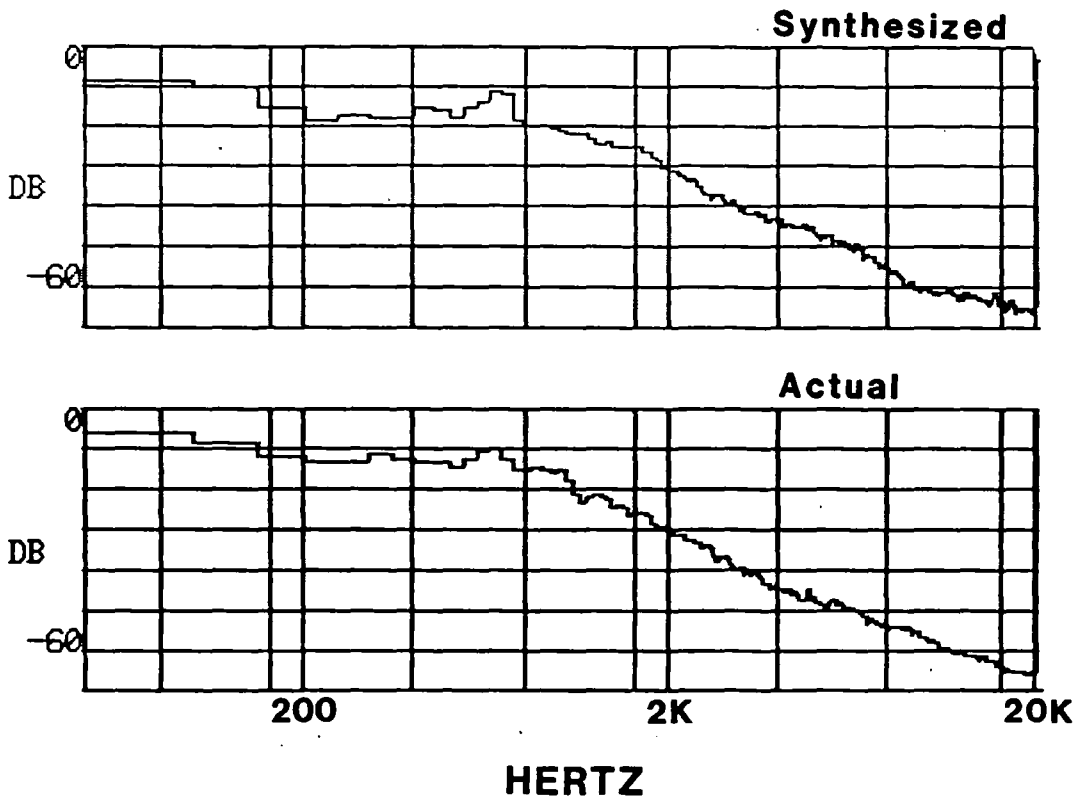

Figure 6. Difference between synthesized and actual noise spectra.

Catecholamine Measurements Baseline blood samples were collected under normal conditions over a two-month period, beginning approximately three months before the playback experiments. Each sample was collected after a 15 to 18-hr fast. The four "clinically normal" whales were trained to present their tail flukes above the waterline and drape them over the edge of the pool for sampling. Two trainers steadied the fluke in this position while a third drew blood (Figure 7). Because this behavior is part of their normal training program, the animals participated readily. A disposable syringe with a 2.5 cm, 18-gauge, plastic needle was employed for venipuncture on the ventral side of the tail fluke.

Blood samples were collected on four of the nine playback days. Immediately after the playback, the whales swam into the holding pool and were released one at a time to present their tail fluke. All blood samples were collected within 8 to 40 min after the noise stopped. According to Ziegler (personal communication), these times are sufficient to detect elevated catecholamine levels.

Immediately after collection, the blood was placed in Vacutainer tubes with sodium heparin added as an anticoagulant. These tubes were immediately set in ice water. Within 1 hr, samples were centrifuged for 10 min (2500 rpm) to separate the plasma from the cells. Plasma was stored at -70 degrees C until all samples (i.e., baseline samples and samples collected after the playback experiments) had been collected. The samples were taken to University Hospital in San Diego, where catecholamine levels were measured. Catecholamine levels in plasma stored at -70 degrees C remain stable for up to a year (Lake et al. 1976). The plasma catecholamines levels were determined by a sensitive radio-enzyme assay (Durrett and Ziegler 1980).

Figure 7. Drawing of a blood sample from the ventral side of the tail fluke.

Hearing Threshold Measurements

For logistical reasons and time considerations, the young female's hearing was not tested. Each of the other three belukhas was trained to station with its rostrum on a target (Figure 8), which was 0.5 m below the water surface (S in Figure 3), and to remain there until either it heard a test tone or was called back by the trainer's

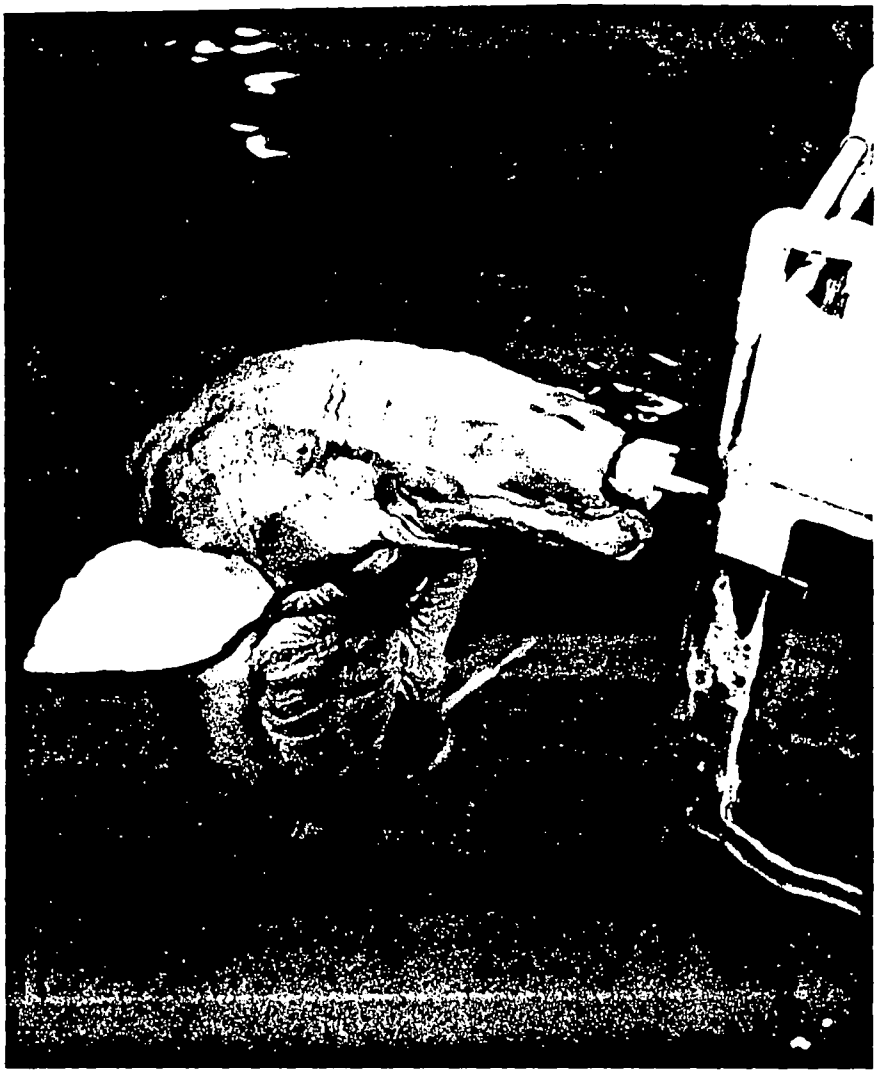

Figure 8. Belukha whale during hearing test.

whistle. The whales were trained initially to respond to either a 10 kHz (117 dB at the subject's head) or a 3 kHz (97 dB) tone transmitted from a hydrophone located 1 m from the target. Upon hearing the tone, the subject swam to the trainer, about 4 m away, for food reinforcement. Initial training took about 3 months. A computer-controlled audiogram testing system then was used to train subjects to generalize their response to a wide range of frequencies, which took less than one week. The animals' hearing sensitivity was tested at the 11 octave intervals between 125 Hz and 128 kHz. The first seven frequencies (125 Hz to 8 kHz) were projected into the water from a loudspeaker suspended in the air 1.9 m directly above the station (Figure 9). Loudspeakers were used because they produce high levels with low distortion at low frequencies, where hydrophones are very inefficient. Airborne sound is transmitted efficiently into water as long as the angle of incidence is small. A Rogersound Labs "Outsider" loudspeaker was used to project frequencies between 500 and 8000 Hz. An RCA LC1-A loudspeaker in a vented enclosure was used to project frequencies from 125 Hz to 1000 Hz. These loudspeakers were driven by one channel of a 17 Watt stereo amplifier (Kenwood KA-3700), which was driven directly by a modified function generator (Wavetek 148). The six frequencies from 4 kHz to 128 kHz were projected underwater from a Bruel and Kjaer 8104 hydrophone located 0.5 m from the target (Figure 10). This hydrophone was driven by the function generator through a Hewlett Packard 350D 1-dB step- attenuator. Projected sound levels were measured with the ITC 6050-C hydrophone or an ASI 307A acoustic monitor set with an ITC 8095 hydrophone. The ITC 6050-C hydrophone was used to measure ambient noise in the pool.

An Apple II+ computer served as the central controlling and data recording device for hearing sensitivity tests. A Wavetek 148 function generator was modified so the frequency and amplitude of its shaped 0.5 sec sinewave tone-burst could be controlled by special circuitry installed in the computer.

A session, lasting 30 to 45 min, usually consisted of a ten trial set with each of three subjects. In one month we ran 41 sessions (nearly 1200 trials). In each trial set, the computer randomly ordered two replicates of four different octave multiples of 125 Hz and two silent control trials for presentation to a subject. The trainer started the trial and scored the responses by pushing switches on a remote control panel. The computer program determined whether the subject responded correctly or cheated during a trial and indicated this with lights on the control panel. Cheating was defined as leaving the station at any time other than immediately after the tone presentation or as remaining at station when the trainers' whistle indicated a callback.

Audiometric thresholds were determined using the ascending form of the psychophysical technique "method of limits" (Voroba 1978). In a trial, a 1/2 sec pure tone was presented at a level supposedly below the subject's threshold. If the animal did not respond by leaving the station within the next five sec, the tone was presented again with its level raised 2 dB. This was repeated until the subject responded or six levels (12 dB) had been presented. Trials with a response to

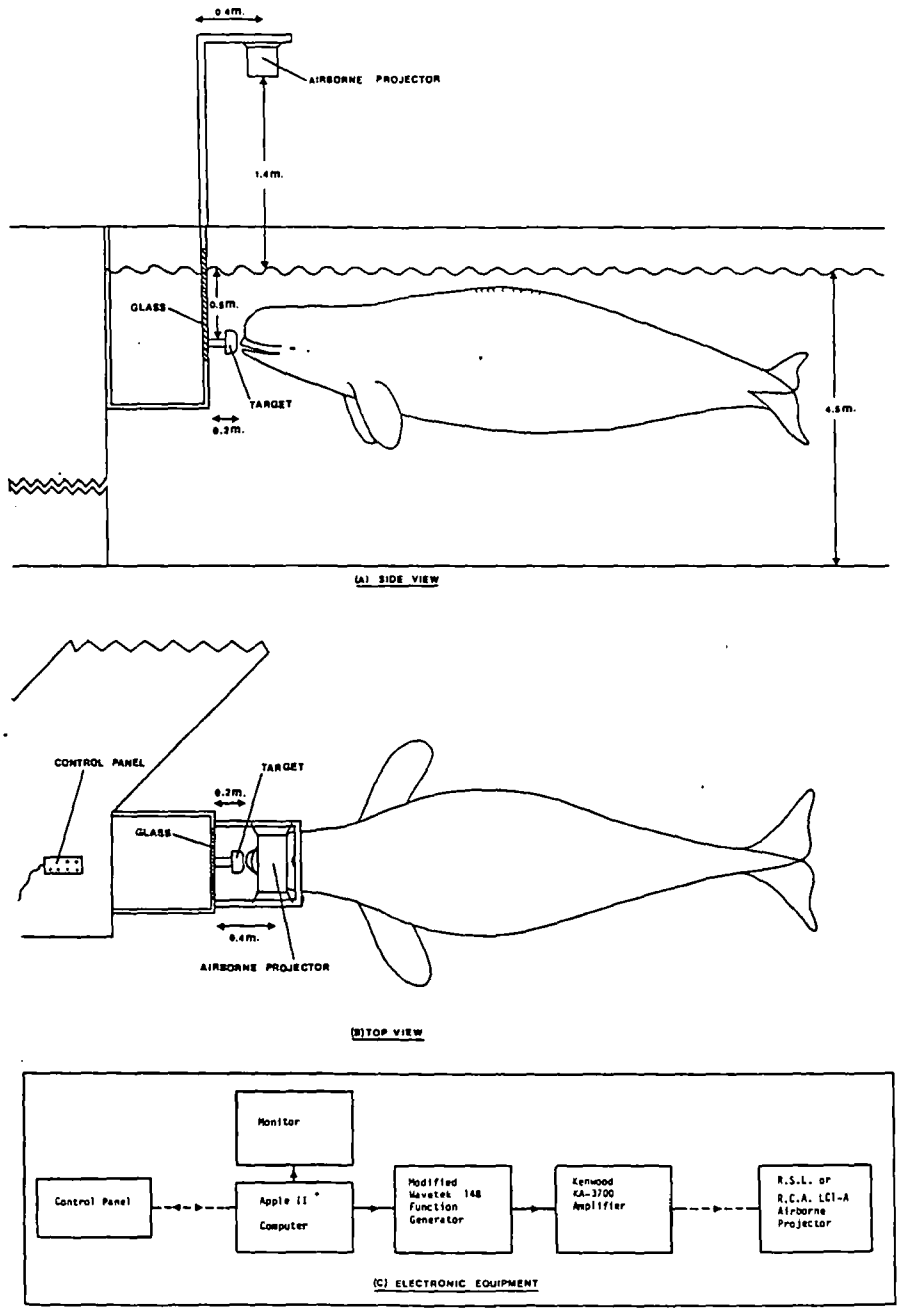

Figure 9. Diagram showing relation between whale station and equipment used to project low frequencies (125 Hz to 8 kHz) in hearing tests.

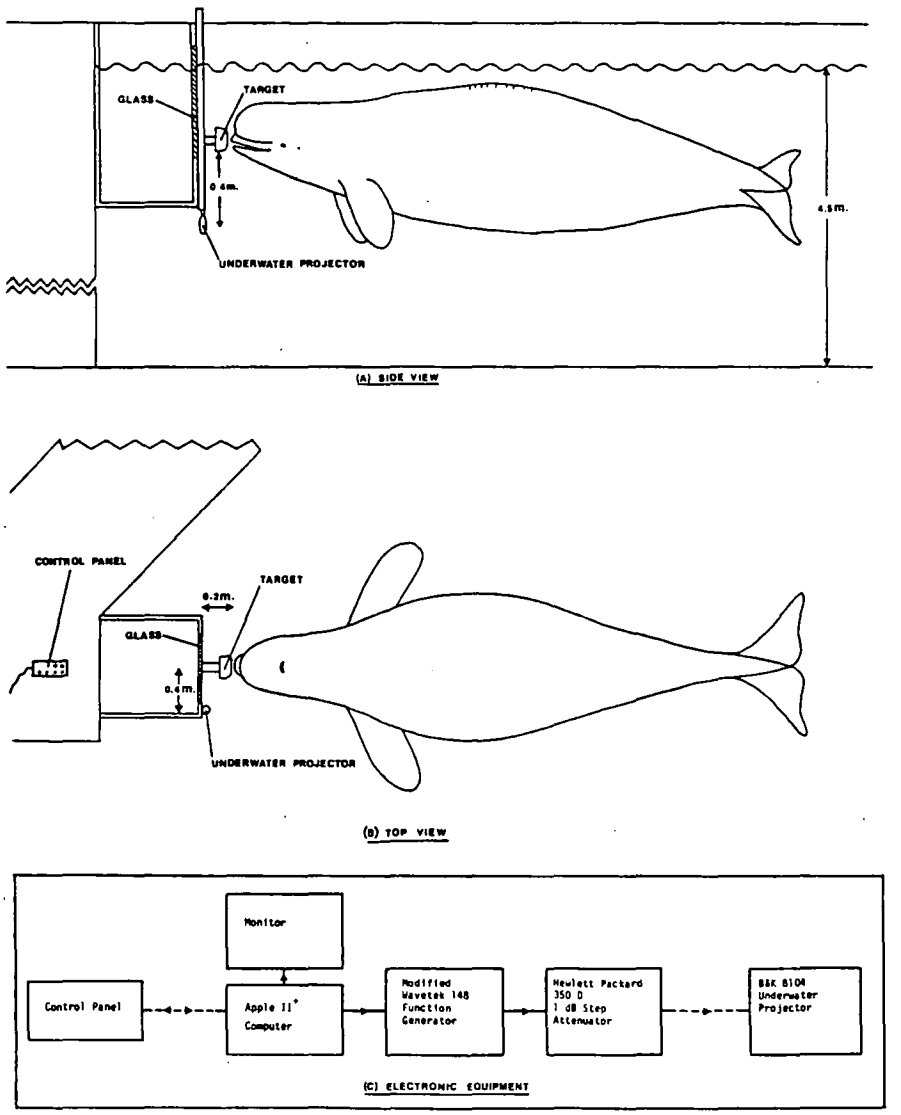

Figure 10. Diagram showing relation between whale station and equipment used to project high frequencies (4 kHz to 128 kHz) in hearing tests.

the first presentation were not counted, nor were those that appeared questionable to the trainers or experimenters. Responses generally were unmistakable. The animal immediately broke away from the station and swam to the trainer. If it hesitated or made a false start, the response was questionable. The effect was to make threshold estimates conservative. Leaving the station during silent control trials or during the 0 to 10 sec delay before the first presentation was uncommon. The hearing threshold in each trial was assumed to be midway between the level when the subject responded and the previous level. The average of all the threshold levels for a given frequency estimates the audiometric threshold, defined as the sound level that the subject had a 50% probability of detecting.

RESULTS

Behavioral Responses to Playback Experiments

Baseline data showed no differences in the swimming patterns at different times of the day. However, individual swimming patterns differed. Therefore, for each whale we calculated the mean proportion of time spent in each of the ten areas of the pool (Figure 11). That the whales appeared to spend less time in the odd-numbered cells than in even-numbered cells is explained by the circular swimming pattern.

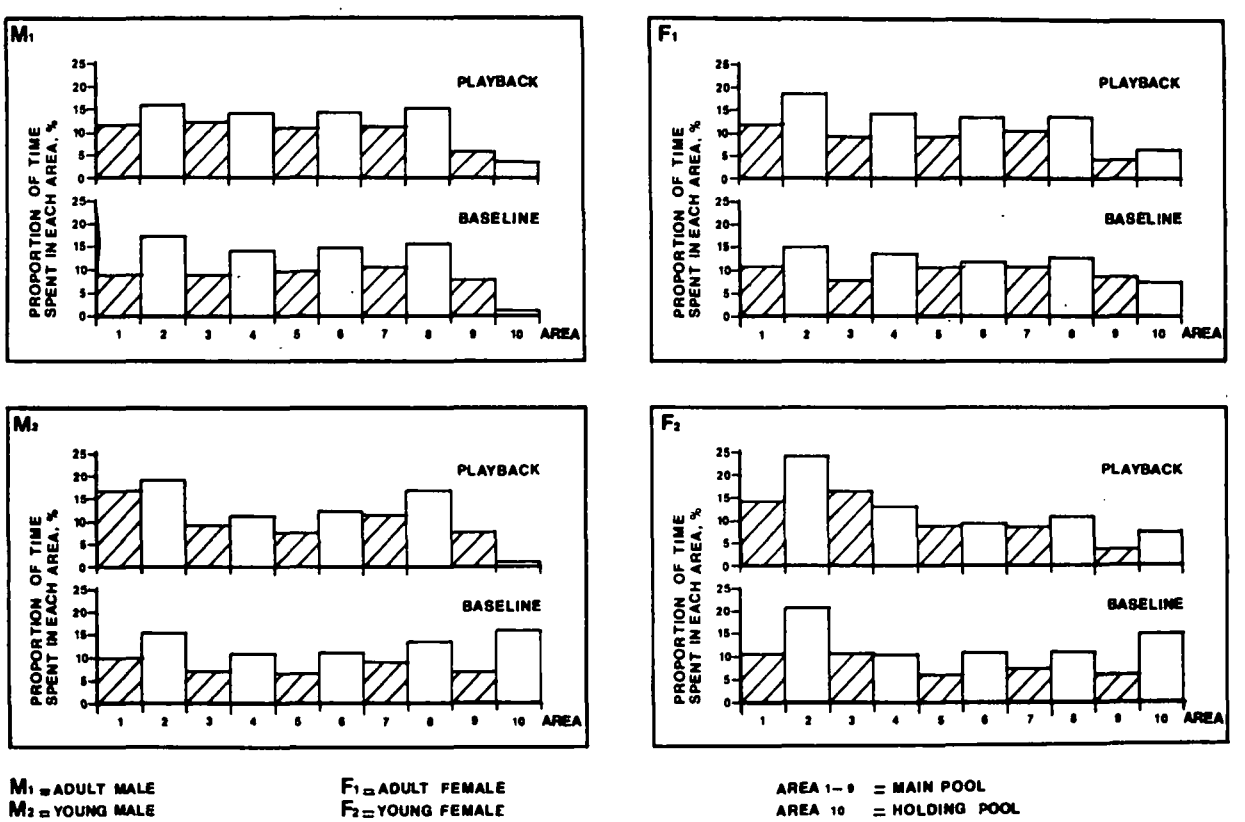

Figure 11. Proportion of time spent in ten areas of the pool during the baseline period and during the playbacks. Areas are numbered as in Figure 3 except that the holding pool is area 10. The whales appear to spend less time in the numbered cells because they normally swam clockwise around the pool, so time spent in even-numbered areas was effectively longer than in the odd-numbered corners.

The whales usually swam clockwise around the perimeter of the pool, as is common among captive cetaceans. Only the young female broke this pattern by frequently "spy-hopping" (i.e. orienting vertically with the head out of water) in areas 2 and 3. The odd-numbered corners have effectively smaller areas than the even-numbered side cells. The circular swimming pattern causes little time to be spent in the pool's center.

During five of the nine playback experiments, an initial flight response was observed immediately after the onset of the SEDCO 708 sound from the loudspeaker. When the noise started, all animals moved to and sometimes entered the holding pool for about 30 sec. This initial response did not significantly change the swimming pattern during the first 10-min interval compared to the second and third intervals, allowing us to combine data from all three intervals.

Differences between baseline and playback swimming patterns in three of four whales were not statistically significant. There was a difference in usage pattern by the young male, who spent a large proportion of time in the holding pool during the 1200 baseline period, using it as a refuge from the dominant adult male, who often threatened him by chasing and jaw clapping. (We don't know why this difference showed up only during the 1200 baseline period.) The whales frequently swam within 1 m of the transducer (area 7) and therefore, were exposed to sound pressure levels of 153 dB, without showing any apparent aversion, as is obvious in Figure 11.

To see whether the whales might change their social structure in the presence of noise, we compared social structure data during the 0730 playbacks with those from the 0600 baseline sample (Figure 12). All whales spent a proportion of time alone (asocial). The young male spent the largest proportion of time alone (51%). In contrast, the adult male spent a relatively small proportion of time alone (12%). The combination of young male + young female or young male + adult female rarely occurred (<5%), presumably because of social inhibition by the adult male. The combination of young male + both females never occurred, but that of adult male + both females existed for a large proportion of time (38%). The combination of both males occurred at about the same rate as any other combination where the two males were with one or two females. These data indicate that a distinct social structure existed in this group of captive belukha whales and that the adult male was dominant over the young male. We found no statistical difference in any social combination between the 0600 base-line sample and the mean of the combined playback data.

During the baseline period, the four captive belukha whales generally had a series of rapid surfacings with blows, followed by a longer dive. Sometimes a surfacing whale would blow several times before diving. Thus, the mean number of blows was larger than the mean number of dives (Figure 13) and the blow interval (i.e. time between successive exhalations during a surfacing) is smaller than the dive interval (i.e., time between successive dives).

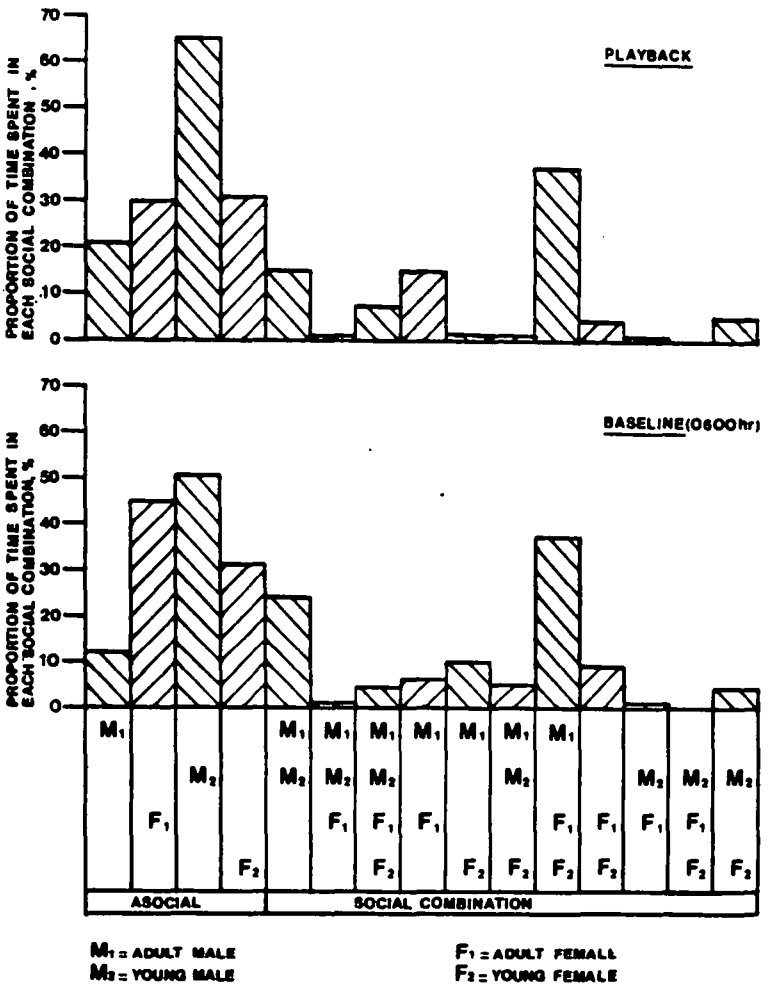

Figure 12. Social structure during the 0600 hr baseline and the playbacks.

Baseline respiration patterns for the whales, except the adult male, varied during the day (Table 1 and Figure 13). These differences are unlike the daily cycle of belukha whales in the wild because these captive whales' daily activities are tied to feeding times and training sessions.

Table 1. Baseline and playback data on respiration/dive patterns for four belukha whales.
Ranges between means are reported where individuals had statistically different mean rates at different times of the day.
* B = baseline - mean of 120 values.
**P = Playback - mean of 27 values.

	Dives/min		Blows/min		Blow Interval (seconds)		Dive Interval (seconds)	
	B*	P**	B	P	B	P	B	P
Adult Male	1.5	1.8	1.9	1.9	27.0	24.0	33.4	26.0
Young Male	1.2-1.9	1.6	1.8	1.8	23.8-	28.0 31.6	27.1-	31.7 40.5
Adult female	1.2-1.8	1.7	1.5-2.2	2.0	26.1	27.0	28.5-37.1	25.0-38.8
Young Female	1.0-1.9	2.0	1.3-2.3	2.4	24.6-34.6	21.1	28.5-44.1	20-28.7

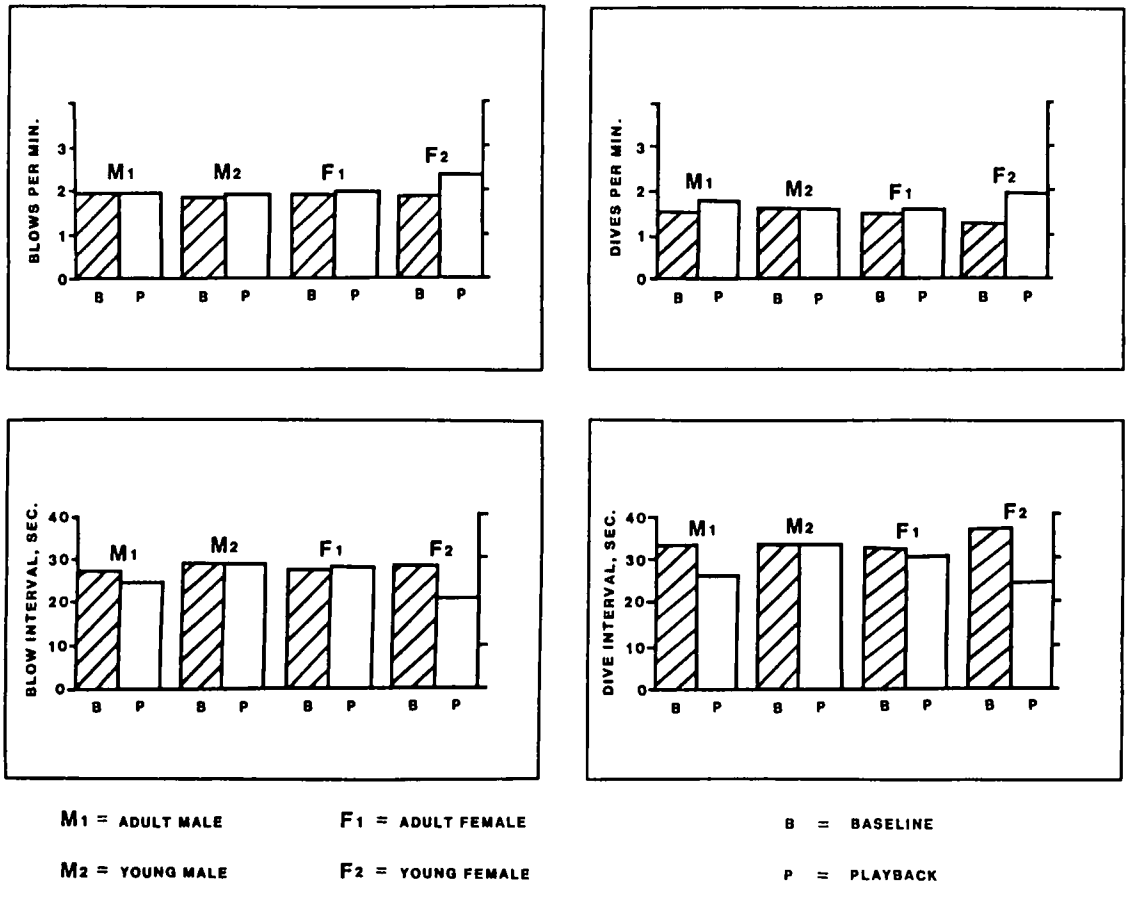

Figure 13. Mean number of blows and dives per min and mean blow and dive intervals during 0600 baseline and playbacks.

If the whales were affected by playbacks of SEDCO 708 noise, we would expect changes in their respiration patterns. To determine whether changes occurred during a playback session, we tested for differences between the three con- secutive "focal animal" samples. Both males had stable respiration patterns, but the females tended to make longer dives in the third 10-min sample than in the first (Figure 14).

ADULT MALE

MEAN NO. OF DIVES

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN NO. OF BLOWS

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN BLOW INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN DIVE INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	↓	↓	↓
12.00			–	–	–	–
18.00				↓	↓	↓
1					–	–
2						–

YOUNG MALE

MEAN NO. OF DIVES

	0600	1200	1800	1	2	3
00.00	–	↵	↵	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN NO. OF BLOWS

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN BLOW INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	↓	–	–	–
06.00		–	↓	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN DIVE INTERVAL

	0600	1200	1800	1	2	3
00.00	–	↓	↓	↓	↓	↓
06.00		↓	↓	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

ADULT FEMALE

MEAN NO. OF DIVES

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		↵	–	↵	↵	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN NO. OF BLOWS

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		↵	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN BLOW INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	–	–	–	–
06.00		–	–	–	–	–
12.00			–	–	–	–
18.00				–	–	–
1					–	–
2						–

MEAN DIVE INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	–	↓	–	–
06.00		↓	–	↓	↓	–
12.00			↵	–	–	↵
18.00				↓	↓	–
1					–	↵
2						↵

YOUNG FEMALE

MEAN NO. OF DIVES

	0600	1200	1800	1	2	3
00.00	–	↵	–	↵	↵	–
06.00		↵	–	↵	↵	–
12.00			↓	–	–	–
18.00				↵	↵	–
1					–	–
2						–

MEAN NO. OF BLOWS

	0600	1200	1800	1	2	3
00.00	–	–	–	↵	–	–
06.00		↵	–	↵	↵	↵
12.00			↓	–	–	–
18.00				↵	↵	–
1					–	–
2						–

MEAN BLOW INTERVAL

	0600	1200	1800	1	2	3
00.00	–	–	–	↓	↓	–
06.00		↓	–	↓	↓	↓
12.00			↵	↓	–	–
18.00				↓	↓	↓
1					–	–
2						–

MEAN DIVE INTERVAL

	0600	1200	1800	1	2	3
00.00	–	↓	–	↓	↓	↓
06.00		↓	–	↓	↓	↓
12.00			↵	↓	–	–
18.00				↓	↓	↓
1					–	↵
2						–

Figure 14. Results of paired t-tests, comparing differences in baseline by time of day (0000 to 1800) and playback intervals (1 to 3). Separate comparisons were made for the mean no. of dives and blows and mean dive and blow interval of each animal. – = no statistical difference ($p < 0.05$) * = a statistical difference. The arrow points to the smaller value.

Comparing baseline and playback respiration behavior (Figures 13 and 14), the adult male showed no statistical difference in mean number of dives, mean number of blows, and mean blow interval. His mean dive interval during the playback period was shorter than the interval during the 0600 and 1800 baseline periods, but was within the daily variation of his baseline. The young male's mean dive interval was shorter during playbacks than during the 0000 baseline. Otherwise, there were no significant differences between his baseline and playback respiration patterns (Figure 14).

The adult female showed no statistical differences in mean number of blows and mean blow interval between any baseline samples and playbacks. The mean number of dives during the 0600 baseline sample was smaller than during the first two "focal animal" samples of the playback. Her mean dive interval during the playback generally was shorter than during the baseline period (Figure 14).

The respiration/dive patterns for the young female during baseline and playbacks are difficult to compare, because her behavior was so variable in both the base-line and the playback sessions. Generally, she made more blows and dives during the playbacks. Consequently, her mean blow and dive intervals were shorter during the playbacks.

Overall, we detected no biologically significant adverse effects due to the noise playback. There was an initial flight response immediately after the start of the noise playback and some tendency for the dive interval to be shortened, but this effect was not consistent.

Physiological Responses to Playback Experiments

Plasma norepinephrine levels in humans (Lake et al. 1976), rats and monkeys (Kopin et al. 1978), and dogs (Nechay et al. 1981) range from about 200-400 pg/ml during basal resting state. Initial blood samples taken from the belukha whales uniformly had higher norepinephrine levels, but with repeated sampling, norepinephrine levels decreased in all whales (Figure 15). All blood samples were obtained on the first venipuncture, except for one sample from the adult female. In this instance, she resisted initially, but then returned and presented her tail fluke for blood drawing. Her norepinephrine level on that one occasion was above 1,000 pg/ml. The sample was excluded from the regression. Over the course of testing, norepinephrine levels declined until they returned to or below normal basal levels for other species.

Plasma epinephrine levels ranged from 0-101 pg/ml in these whales and were not increased by repeated sampling or exposure to noise (Table 2). Epinephrine levels were frequently so low that the normal variance of the assay ($\pm$20 pg/ml) might have obscured level changes. In humans, stresses such as insulin-induced hypoglycemia can increase epinephrine levels above 1,000 pg/ml. Change in epinephrine levels in these animals was small compared to the overall capacity of the adrenal medulla to secrete epinephrine.

Number of samples was limited to prevent scar tissue formation and to keep the blood sampling procedure from becoming too aversive. Also,

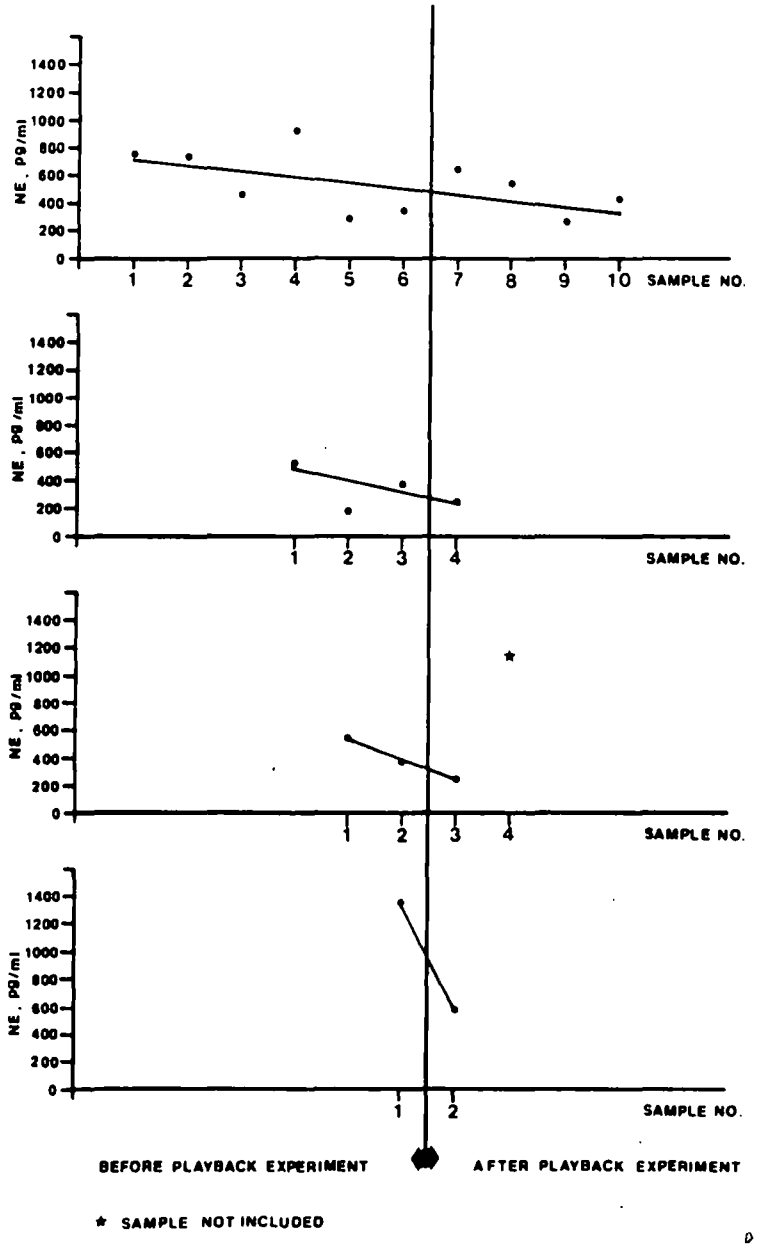

Figure 15. Norepinephrine levels in the blood of four belukha whales before playback experiments were begun and immediately after each of several playback experiments. The one sample was excluded because the subject resisted venipuncture and had to return for a second try. Data from table 2.

Table 2. Blood levels of epinephrine and norepinephrine during control period and after exposures to playback of drilling sound.

Whale	Sample #	Date	E (pg/ml)	NE (pg/ml)
Adult Male	1	17/2/83	69	763
	2	11/3/83	47	730
	3	15/3/83	35	430
	4	18/3/83	72	908
	5	22/3/83	21	281
	6	25/3/83	15	307
	7*	18/5/83	20	604
	8*	23/5/83	44	517
	9*	25/5/83	10	261
	10*	27/5/83	29	405
Young Male	1	17/2/83	44	506
	2	11/3/83	9	180
	3	19/4/83	46	389
	4*	25/5/83	10	224
Adult Female	1	15/3/83	0	535
	2	18/3/83	21	391
	3*	25/5/83	23	238
	4*	27/5/83	56**	160**
Young Female	1	17/2/83	101	1348
	2*	18/5/83	5	584

E = epinephrine, NE = norepinephrine.
* = samples taken immediately after playback of drilling rig sound.
** = sample collected in a second attempt.

because blood sampling required cooperation of the animals and had to be done quickly it usually was not possible to get a sample from every individual every time. Hence, the number of samples per animal ranged from two to ten. As a result, the number of samples was too small for meaningful statistical analysis. However, exposure to playbacks of the underwater sounds from the semi-submersible drill platform SEDCO 708 clearly did not increase norepinephrine or epinephrine levels.

Hearing Threshold Measurements

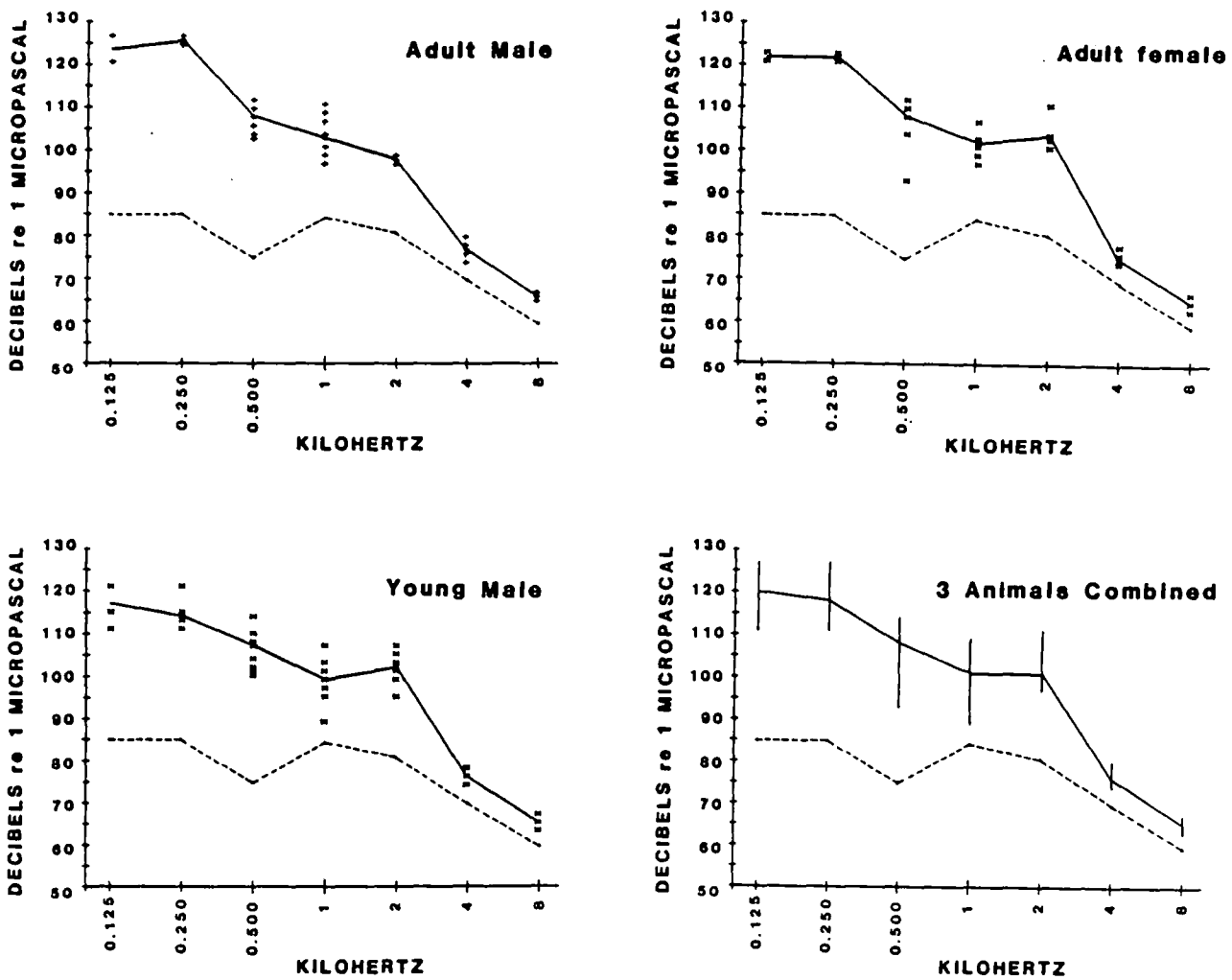

Figure 16. Individual and combined hearing sensitivity curves of three belukha whales measured by the in-air transducer for the frequency range 125 Hz to 8 kHz. The broken line shows the ambient sound level. Symbols indicate individual readings.

The results of the hearing threshold measurements using the in-air transducer (125 Hz to 8 kHz) are shown in Figure 16. These measurements are combined with underwater levels to show the overall range of hearing of belukhas in Figure 17. The sensitivities we measured with the in-air transducer (Figure 16) match the sensitivities between 1 and 8 kHz reported for belukhas by White et al. (1978). The only exception was at 2 kHz, where the average threshold we measured was around 12 dB higher. Whether the lowered sensitivity at 2 kHz is anomalous is unknown. Ambient noise level in the tank was highest at 1 and 2 kHz, but not high enough at 2 kHz for masking to account for the higher threshold. Sound level fluctuations measured at various places in the vicinity of the subject's head did not exceed 5 dB at frequencies produced by the loudspeaker.

The hearing thresholds that we measured at frequencies above 4 kHz with the underwater sound projector (Figure 17) were as much as 20 to 25 dB higher than those previously measured for belukhas (White et al. 1978) and for bottlenose dolphins (Johnson 1966). The threshold we measured with the underwater projector was within 3 dB of that measured with the in-air projector at 4 kHz, but was 8 dB lower at 8 kHz. These differences almost certainly were due to differences in test conditions. The projector was located within 10 cm of the trainer's booth wall, so interference effects were possible. More importantly, the transducer had to be located to one side and slightly below the subject. Odontocete hearing sensitivity at high frequencies can be 20 dB or more lower to sound coming from the side or below than to sound coming from directly in front of an animal (Au and Moore 1984). Nevertheless, the "shape" of the curve agrees well with curves obtained by other investigators for belukhas and other odontocetes (see Figures 1 and 2).

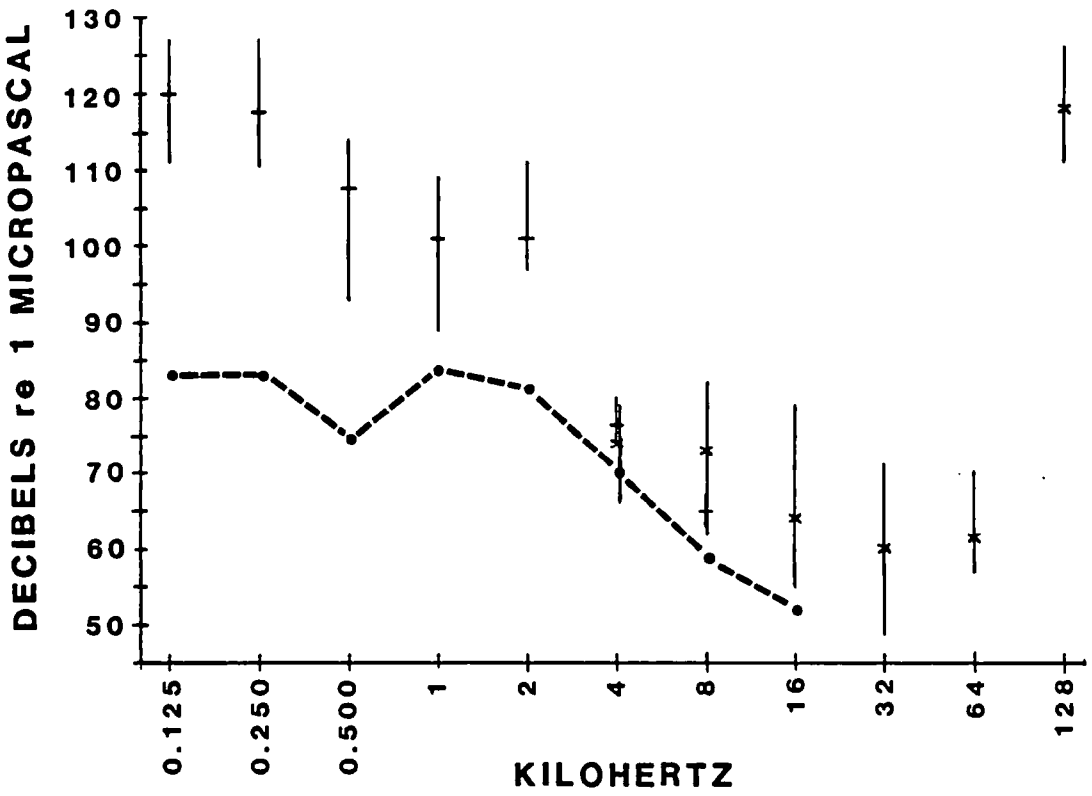

Figure 17. Combined hearing sensitivity curves of three belukha whales for octave-interval frequencies between 125 Hz and 128 kHz.
x = mean thresholds measured with the underwater projector.
+ = mean thresholds measured with in-air projector.
Vertical bars indicate range of responses at each frequency.
--- = ambient sound level.

DISCUSSION

Gales (1982) estimated zones around oil platforms where sound could be expected to influence toothed whale behavior. He calculated that belukha whales are unlikely to be able to detect noise from a platform like SEDCO 708 at distances greater than 8 km, even under optimum listening conditions, and that actual detection distances are probably considerably less. Greene (1983) measured actual spreading loss around SEDCO 708 and concluded that the sound had essentially faded into the ambient at distances of 3 or 4 km from the platform.

Sound levels of low frequency tonal components produced by SEDCO 708 (Greene 1983) tend to be near or below the hearing sensitivity of belukha whales. For example, 185 m from the platform the 300 Hz tonal from the platform varied between 110 and 115 dB. The belukhas used in our hearing tests responded to 250 Hz tones at levels ranging from 110 to 125 dB (mean = 120 dB). Even at higher frequencies, where belukha hearing is more sensitive, sounds from the drilling platform, especially broadband sounds, tend to fade into the ambient within 2 or 3 km. Detection would depend upon sea state and other factors that affect ambient noise levels, and whether the thresholds we measured are masked measurements. Thus, belukha whales probably cannot hear the sound from a typical drilling platform that is more than 3 or 4 km away. This agrees with the observations of Ford (1977) and Mansfield (1983) that high level shipping and dredging noise are unlikely to disturb belukha whales at distances of 5 km or more.

Even at closer distances belukha whales are not likely to show strong aversion to drilling noise because their hearing is insensitive to low frequencies, where most drilling noise energy is concentrated. Furthermore, drilling noise is essentially a steady signal that animals would be expected to accommodate to readily. That whales do accommodate to petroleum-related noise is now evident. Belukha whales near offshore petroleum facilities in the Mackenzie estuary have been studied for over a decade (Fraker 1977a, b; Fraker and Fraker 1979). Sorensen et al. (1984) found no difference in the distribution and abundance of fish-eating cetaceans in the presence or absence of oil drilling platforms, surface oil, or boat traffic along the northwestern Atlantic continental shelf. Stewart et al. (1984) saw wild belukha whales pass within 15 m of an underwater loudspeaker projecting recorded SEDCO 708 sound with a source level of 158 to 163 dB.

Our results are consistent with these observations. The captive belukha whales soon accommodated to high level playbacks of recorded sound at source level from a typical drilling platform. They showed no change in social structure and even evinced some curiosity about the sound source. Respiration and diving patterns for three whales with a consistent baseline pattern did not change during playback sessions. Patterns of the fourth whale were too variable to assess whether they changed. Blood catecholamine levels were not elevated by the noise playback, indicating that the tests were not stressful to the whales.

Mammals can accommodate to very high noise levels. Mechanisms exist to compensate for masking effects of noise. Odontocetes usually

can overcome masking problems simply by producing louder sounds. Tursiops, for example, produces sounds with peak amplitudes up to 200 dB (Fish and Turl 1976). Other ways they can resolve masking problems are to change orientation or to alter frequencies and bandwidths of their echolocation pulses (Au, et al. 1985) to make them more directional. Belukha whales probably use all these mechanisms. Directional sound production and directional hearing, prerequisites of echolocation, have been well documented in many odontocetes. Gurevich and Evans (1976) reported directional sound production in belukha whales. Gales' (1982) calculations took into account the odontocetes' high directivity index (DI), which is the ratio of the size of the animal's receiving system to the wavelength of the sound. He reported a DI of 5 dB at 5 kHz for belukha whales. Because the DI increases with frequency, whales can use it to help compensate for very high levels of noise.

The effect of drilling noise on whales should be functions of the characteristics of the drilling platform's sound relative to the whales' hearing and of the animal's ability to adapt. Our study showed no obvious behavioral or physiological responses of captive belukha whales to playbacks of drilling noise. Given the ability of the animals to adapt to noise in captivity, they probably could adapt to drilling noise even when it falls within their hearing range. Nevertheless, all this does not imply that mammals are immune to harm from noise. Our study did not address long-term or subtle effects that may be caused by chronic noise levels well below those we examined. Whether living under those conditions would be harmful to the populations can only be determined by further research.

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