11/4-4-90 JS(1)

UCID-21870

Oklahoma Deep-Borehole Seismic-Noise Measurements: Characteristics as a Function of Depth in the Presence of High-Surface Noise

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January 25, 1990

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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ABSTRACT

We developed the Oklahoma borehole seismic experiment to determine deep-borehole signal and noise characteristics in a geologic analog to the Russian platforms. We recently upgraded the seismometers with internal preamps and recorded seismic noise as a function of depth in the presence of a large operating surface compressor located 100 m from the borehole. We calculated power-density spectra between 1 and 30 Hz for each station from the surface to 757 m. The results show no significant noise reduction in the 1- to 4-Hz band from the surface to 100 m, then indicate a gradual reduction in noise power with depth until 757 m where the noise power is reduced by 10 dB. Between 5 and 20 Hz there is significant noise reduction with depth that is especially pronounced at 757 m. We attribute this reduction to the high seismic-velocity Cambro-Ordovician sequence that acts to cut off low-velocity waveguide propagation of seismic noise because only the 757-m station penetrates the high seismic-velocity sequence. At 20 Hz the seismic noise is over 30 dB lower at 757 m compared to the surface. A prominent spectral peak centered at 25 Hz, caused by the compressor, reaches the lowest noise level at 473 m and is not significantly lowered at deeper stations. This is probably because the 25-Hz noise source has no significant energy below about 473 m. The noise power of the 25-Hz peak is reduced over 50 dB between the surface and 473 m. Signal levels were estimated from recorded events and found to be between 2 and 7.5 times lower at the 757-m station compared to the surface. This gives an average signal-to-noise ratio (SNR) improvement of about 3 at 1- to 4-Hz, 200 at 20 Hz, and 20,000 at the spectral peak centered at 25 Hz between the surface and the 757-m station. Locating verification seismometers in deep boreholes (below ~500 m) and nominally 100 m into a high seismic-velocity sequence (ideally Precambrian bedrock) will increase SNR across the entire 1- to 30-Hz band and provide significant seismic isolation from surface-noise sources.

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INTRODUCTION

We are examining ways of improving technologies for monitoring test ban treaties. One aspect of those studies is investigating ways of maximizing the seismic signal-to-noise ratio (SNR) from seismic treaty monitoring stations. To maximize SNR, the highest quality seismometers, data acquisition and data analysis capability must be obtained. The stations must also be located at sites with low seismic noise and/or in boreholes to reduce seismic noise.

Locating low seismic noise sites in a host country may be very expensive because low seismic noise sites are always far from cultural activity and, consequently, have poor access. These remote locations make development, fielding, and maintenance much more difficult.

Locating seismic instruments in boreholes is a means to lower the background seismic noise at a site, improve the SNR at most sites, and increase the number of acceptable sites. Furthermore, seismometers located in deep boreholes can better measure high-frequency components of a seismic-source signal because significant high-frequency attenuation occurs at the near-surface (Hauksson *et al.*, 1987). The amount of surface-noise rejection provided depends on the site geology and the characteristics of the seismic noise (Galperin *et al.*, 1986); so it cannot be assumed that a particular depth is acceptable at any given site. Experimental measurements of seismic noise in boreholes located in geology typical of the host country must be undertaken to assess borehole-noise suppression and SNR enhancement as a function of depth, geology, and surface-noise characteristics. This data can be related to in-country station specifications.

The Oklahoma borehole seismic experiment, located near Leonard, Oklahoma, is a joint research effort of the Lawrence Livermore National Laboratory and the Oklahoma Geophysical Observatory to determine deep-borehole seismic signal and noise characteristics in geology typical of large regions of the Soviet Union (Sweeney *et al.*, 1986). The borehole deployment began in December, 1988, in a 770-m deep borehole, water filled to a depth of 90-m (Harben *et al.*,1989). The borehole-deployed system has been collecting events for the past year. Recently with the addition of internal battery-operated seismometer preamps, we amplified the seismic noise above the system noise at deep-seismometer locations and obtained measurements of seismic noise the full depth of the borehole.

We obtained a data set of seismic-noise measurements at many depths in the borehole for the purpose of determining seismic-noise attenuation as a function of depth in platform geology typical of Soviet Union platforms. Seismic-noise data were measured while a large, natural-gas-powered compressor, located 100 m from the borehole, was operating. The compressor ran 24 hours a day as part of an enhanced oil-recovery operation. This situation provided an opportunity to measure the properties of seismic-noise levels with depth in the presence of very high surface-noise levels. From the standpoint of test ban treaty verification, high surface-noise levels at any site is a real possibility because the host country could always choose to locate heavy machinery, compressors, pumps, etc., near a verification station. Our paper presents the data and results obtained in measuring seismic noise as a function of depth in the Oklahoma borehole with a large nearby surface-noise source.

NOISE MEASUREMENTS

We measured seismic noise in the 770-m deep Oklahoma borehole using a single vertical-component Geotech 23900 model borehole-clamping seismometer. For noise measurements, the seismometer was positioned and clamped at the surface and the following depths: 20, 39, 67, 95, 190, 284, 379, 473, 568, 662, and 757 m. Clamping consisted of a spring-actuated cam that locks by using the seismometer and cable weight. After the seismometer was positioned and clamped, the cable was slacked an average of 2.5% of the depth. We allowed time for cable settling before noise recording. The cable-settling period was greater at the deeper locations where it often took over an hour before the cable settling events were infrequent enough for noise recordings.

The seismic noise was recorded using five-minute data files with a Kinemetrics PDR-2 digital gain-ranging recorder. The sampling rate was 200 samples/sec, and the total system gain was 40.9 dB. Preamps were installed in the downhole seismometers using differential-mode low-noise op-amps set at a fixed gain of 500. The preamps are powered by two D-cell lithium batteries mounted in the seismometers. The battery life is estimated at 100 days of continous operation. An uphole high-pass filter of 0.5 Hz was added to eliminate DC offset from the internal seismometer preamp to avoid exceeding the voltage range of the PDR-2. An uphole 4-pole low-pass filter at 31 Hz was used during these recordings. The filter was installed to eliminate 60-Hz pickup. The noise recordings were conducted over a three-day period when the weather was exceptionally calm. All recordings were on weekdays during the daylight hours.

NOISE SPECTRA

We have calculated noise spectra using the quietest contiguous three minutes of noise recorded at each depth. The mean was removed and the voltage output was converted to velocity in m/sec units by dividing the noise file by the system gain and by the measured effective generator constant of 127 V/m/sec. We calculated velocity power-density spectra by averaging 36 five-second data windows. Averaging provides a smoother, more stable spectral estimate. Velocity spectra were converted to acceleration spectra in the frequency domain. The power spectra presented for comparison are in the acceleration units of $(m/sec^2)^2/Hz$. Because the seismometer resonant period is 1.3 sec and the data were low-pass filtered at 31 Hz, we plotted spectra between 1 and 30 Hz, eliminating the need to correct for instrument response since seismometer velocity output is flat to within 1 dB in this frequency band. The background noise is assumed to be stationary. System noise was measured and power spectra estimated. The system noise was below 10^{-16} $(m/sec^2)^2/Hz$ throughout the 1- to 30-Hz band. Figures 1 through 5 and 7 through 10 plot the noise spectra in a variety of ways to focus attention on different features of the data. Figure 6 plots the geologic cross section and the seismic interval velocity. A discussion of these features follows.

Figure 1 shows very little seismic-noise attenuation in the 1- to 4-Hz band until the seismometer depth is 190 m. Below 190 m, the seismic-noise power diminishes with depth, reaching a minimum at 757 m. At this depth the spectral power between 1 and 4 Hz is over 10 dB below that measured on the surface. Above 4 Hz, seismic noise diminishes at shallower depth. This is apparent in the 0 and

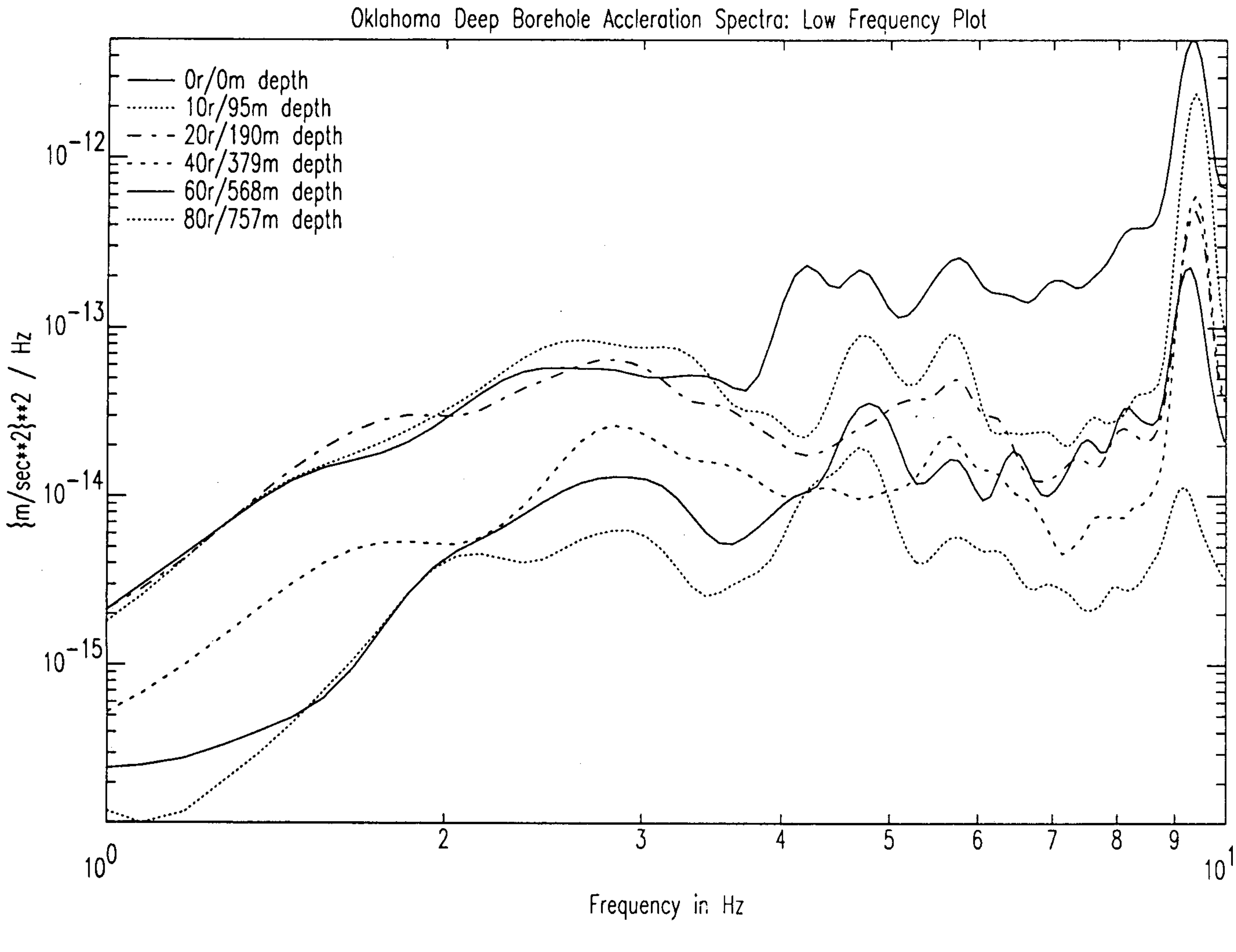

Figure 1. Seismic noise power density spectra are shown between 1 and 10 Hz for different depths in the borehole. The 1- to 4 -Hz noise does not significantly diminish through 190 m . Above 4 Hz, noise diminishes at shallow depth and continues to diminish through 757 m.

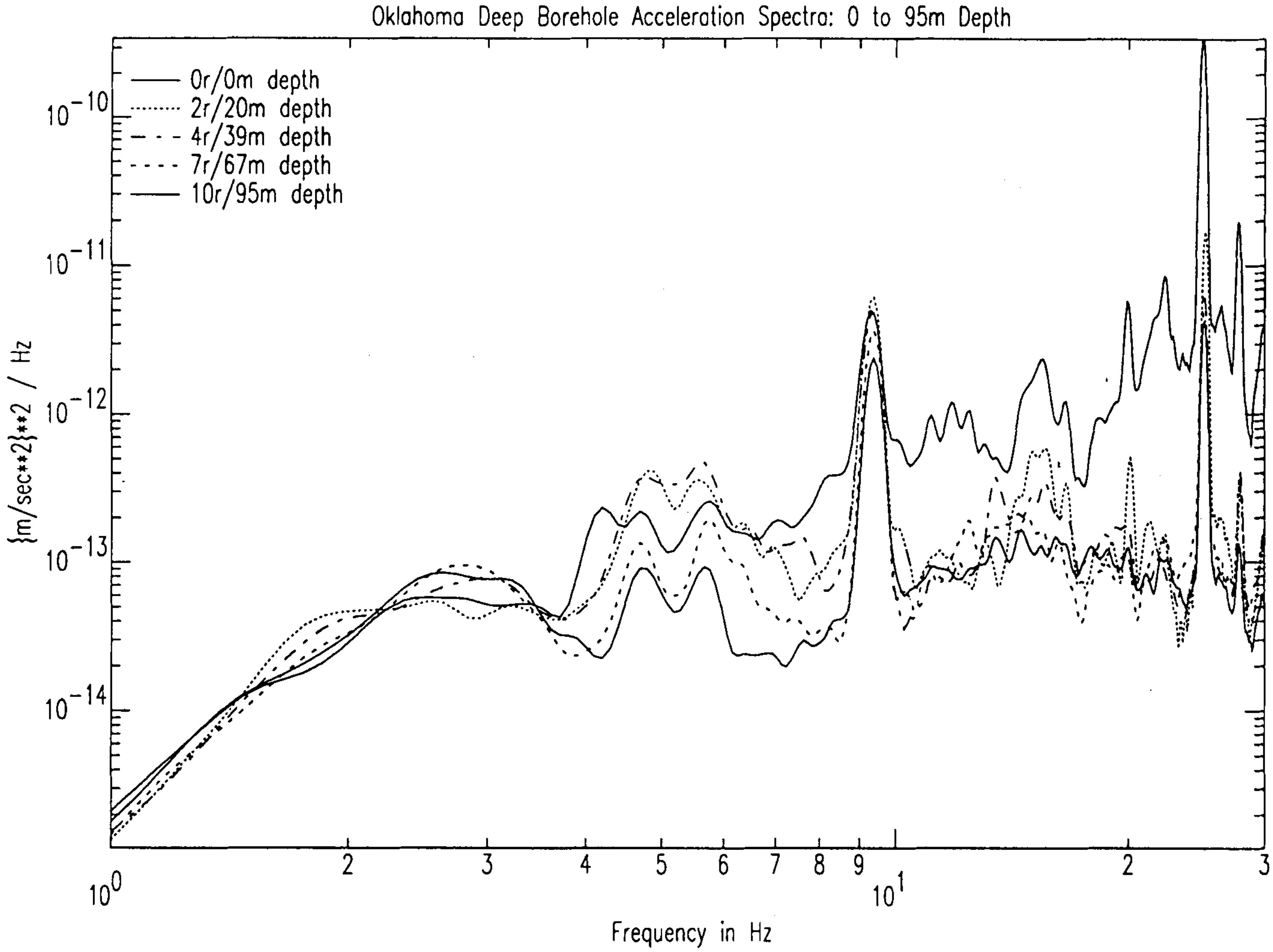

Figure 2. Seismic noise power density spectra are plotted between 1 and 30 Hz for borehole depths between 0 and 95 m. The largest incremental noise reduction occurs between the surface and 20-m depth.

95-m depth spectral plots, (Fig. 2) where, between 4 and 30 Hz, there is an overall decrease in seismic noise with depth that becomes more pronounced at the higher frequencies. The most dramatic noise reduction occurs between the surface and the first downhole measurement at 20 m. The recordings at deeper stations (39, 67, and 95 m) show slight reductions in noise power from the 20-m depth except at the prominent spectral peaks at 9.3 and 25 Hz. The seismometer reaches the water level at 90 m; consequently, the 95-m noise spectra is measured below the water level. There is no evidence from this spectra compared to other spectra that seismometer water submersion affects the seismic-noise levels.

The spectral plots in Fig. 3 show the seismic-noise power changes between the surface, 95-m depth, and the deepest location, 757 m, in the 1- to 30-Hz band. Above 4 Hz, the average noise level at 95 m is below the surface-noise level. The average

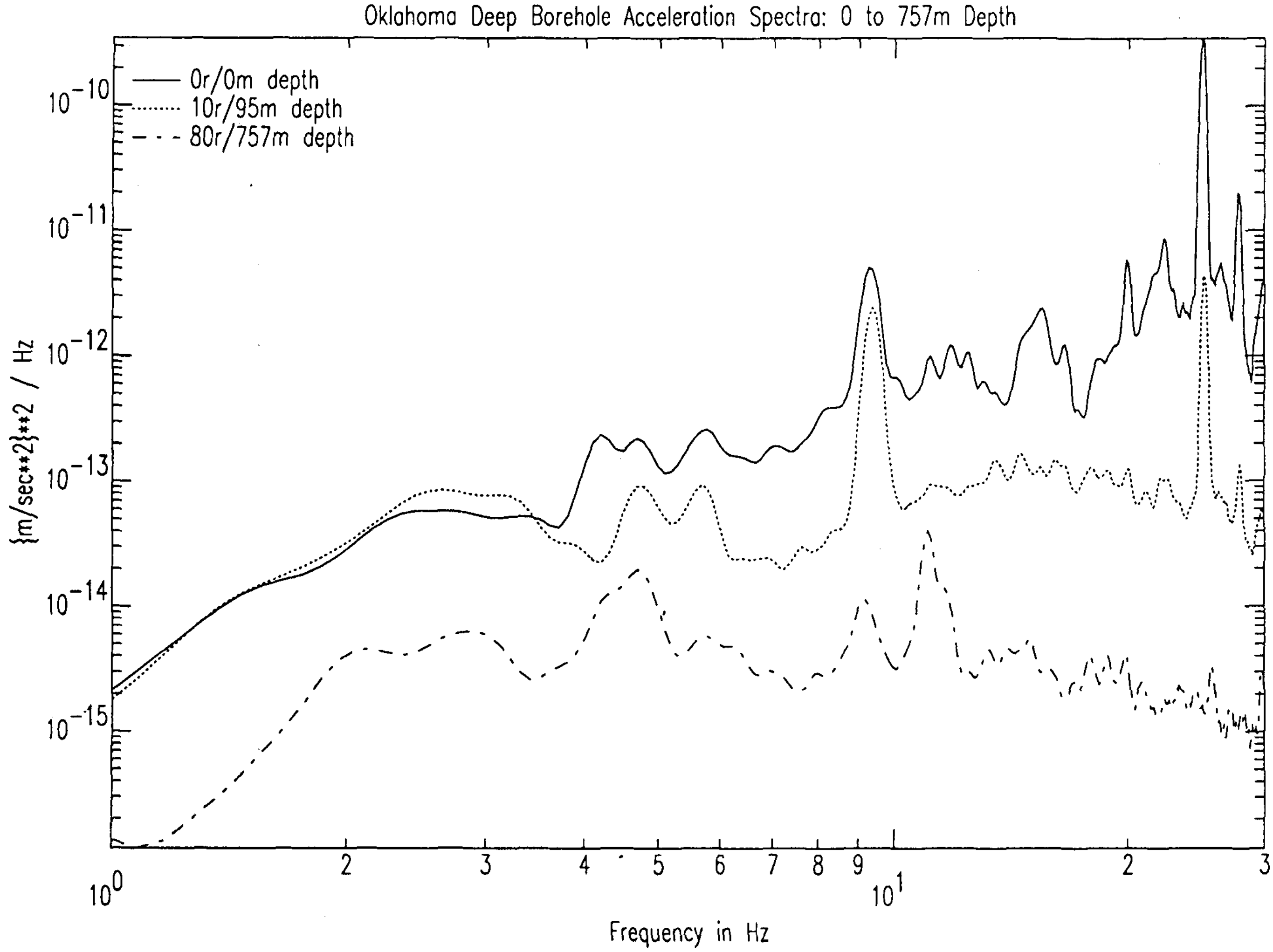

Figure 3. The noise power density spectra are shown plotted between 1 and 30 Hz for the surface, 95, and 757 m. Noise attenuation is more pronounced at higher frequencies. Notice the noise spectral peaks at 9.3 and 25 Hz.

95-m noise power at 10 Hz is nearly 10 dB below the surface noise at 10 Hz ; by 30 Hz, it is nearly 20 dB below the surface-noise power at 30 Hz. The average-noise power at 757 m remains about 10 dB below the 95-m noise power from 1- to 10-Hz; by 30 Hz, it is nearly two 20 dB below the 95-m noise power at 30 Hz. The exceptions occur at the spectral peaks centered at 9.3 and 25 Hz.

The spectral peak at 9.3 Hz is observed prominently at all recording depths shown in Fig. 3. The peak is largest relative to the average noise level at 95-m depth and slowly reduces in relative amplitude to a minimum at 757 m. This peak was observed in all noise recordings prior to the installation of the nearby compressor noise source. This peak is also recorded in an underground vault (TUL) located 400 m from the borehole. In the vault the power-density spectra of the peak does not vary over 1.5 dB with wind velocity between 0 and 25 km/hr, with day of the week,

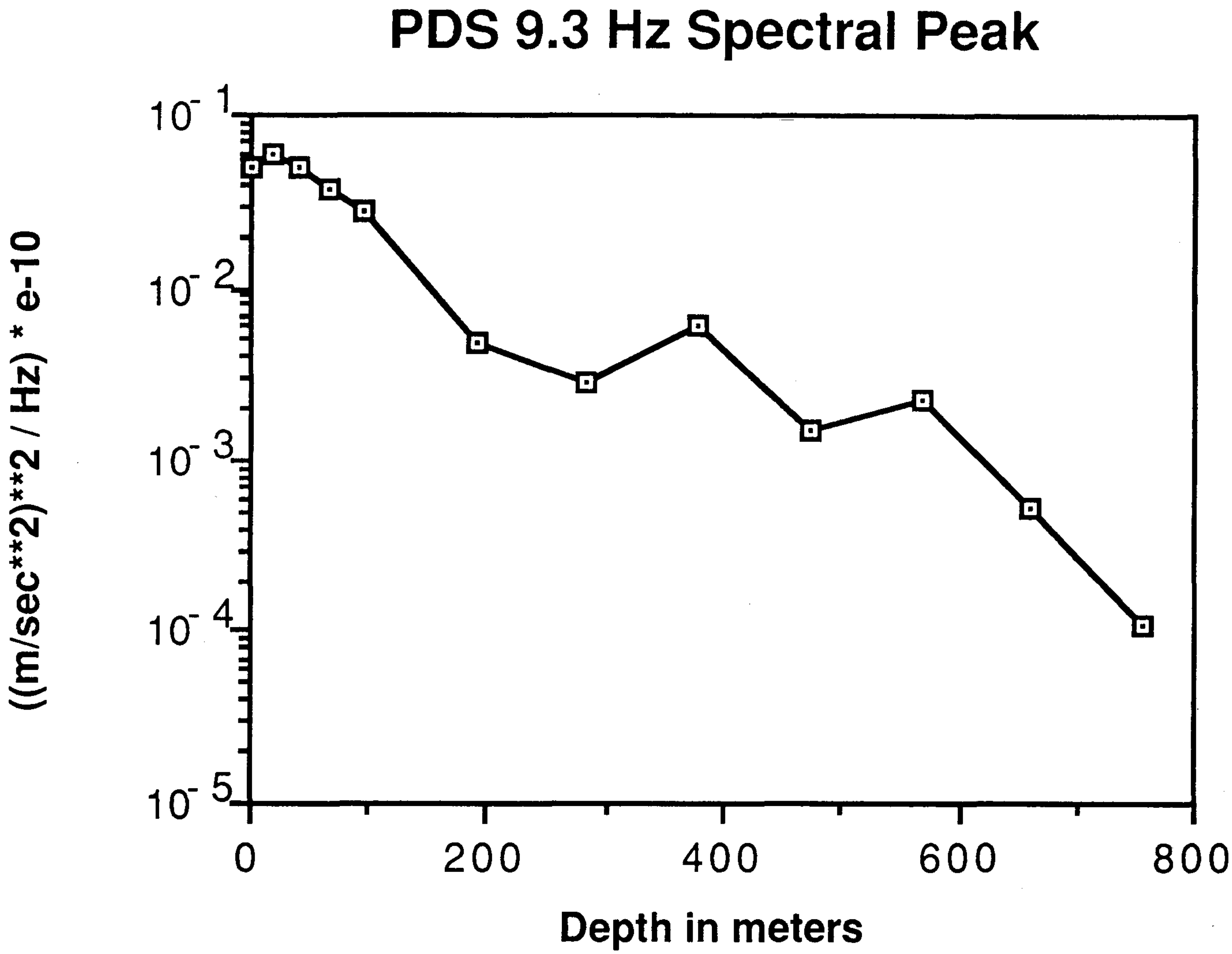

Figure 4. The 9.3-Hz noise power spectral amplitude is plotted as a function of depth in the borehole. The spectral peak amplitude diminishes with depth.

or with time of the day. The source of this noise has not been determined. Figure 4 plots the spectral peak as a function of depth.

Figure 5 plots the 25-Hz spectral peak as a function of depth. This spectral peak is caused by the surface compressor; prior to the installation of the generator surface-noise recordings showed no evidence of a 25-Hz spectral peak. The attenuation of this peak is most dramatic between the surface and the first down-hole location at 20 m. This corresponds primarily to the attenuation of a fundamental-mode 25-Hz compressor-generated Rayleigh wave. Since the surface-wave velocity in the region is on the order of 2 km/sec (as determined from recorded quarry shots), the wavelength is on the order of 80 m. We expect the maximum depth of penetration of fundamental-mode Rayleigh waves to be about 4/10 the wavelength, hence the 25-Hz Rayleigh wave should have little energy below about 30 m. This agrees well with the large power reduction observed at only

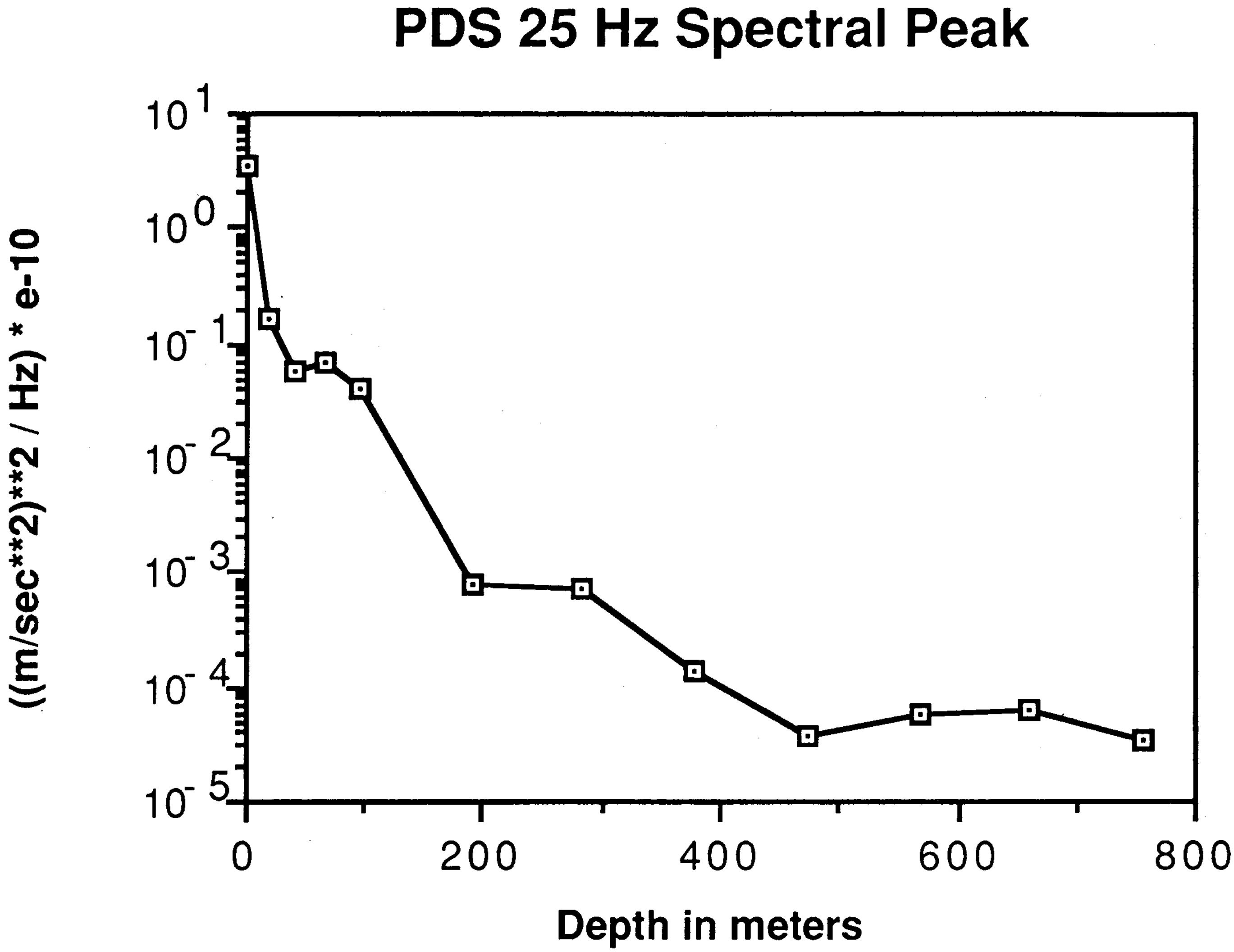

Figure 5. The 25-Hz compressor-generated noise power spectral peak is plotted as a function of depth in the borehole. The power reduction observed in the first 30 m is attributed to Rayleigh wave attenuation. Power reduction at deeper locations is attributed to the geometrical spreading of body waves.

20-m depth. Significant attenuation of the 25-Hz peak continues from 20 m until about 473 m where the 25-Hz compressor peak cannot be observed above the background 25-Hz seismic noise. The attenuation behavior observed from about 20 to 473 m is entirely consistent with the expected body-wave power loss because of geometrical spreading, assuming the compressor to be a point source. Consequently, the dominant body wave seismic-noise power from the compressor, under the geology and background seismic-noise conditions of this experiment, reaches the background-noise power somewhere between 379 and 473 m. This is the minimum seismometer emplacement depth to effectively reject the dominant frequency energy of the surface-noise source. Emplacing seismometers below this minimum

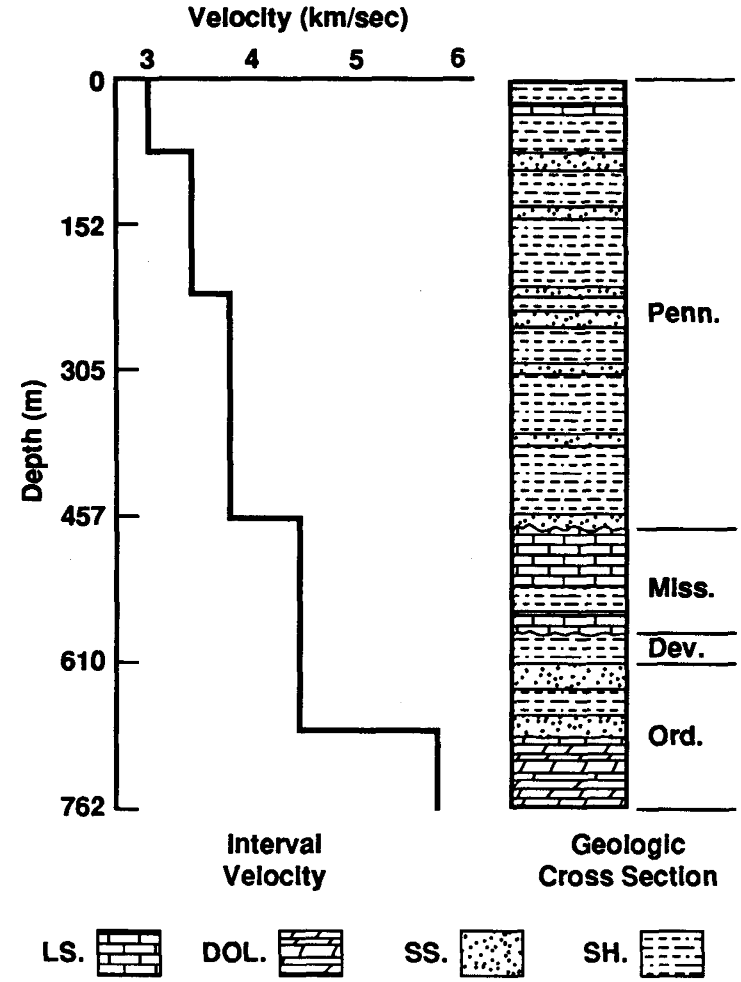

Figure 6. The geologic cross section and measured seismic interval velocity is shown for the Oklahoma borehole (VESIAC Special Report).

depth provides a reduction in seismic-noise spectral power at 25 Hz of over 50 dB compared to surface recordings.

The decrease in seismic background noise levels with depth is a strong function of the overall geologic strata of the region and the particular formation in which the seismometer is mounted. Figure 6 shows the changes in the interval velocity and geologic strata with depth (VESIAC, 1962), and also shows a large increase in the P-wave velocity to 6 km/sec at about 725 m. This corresponds to the top of the high-velocity lower Cambro-Ordivician dolomite sequence.

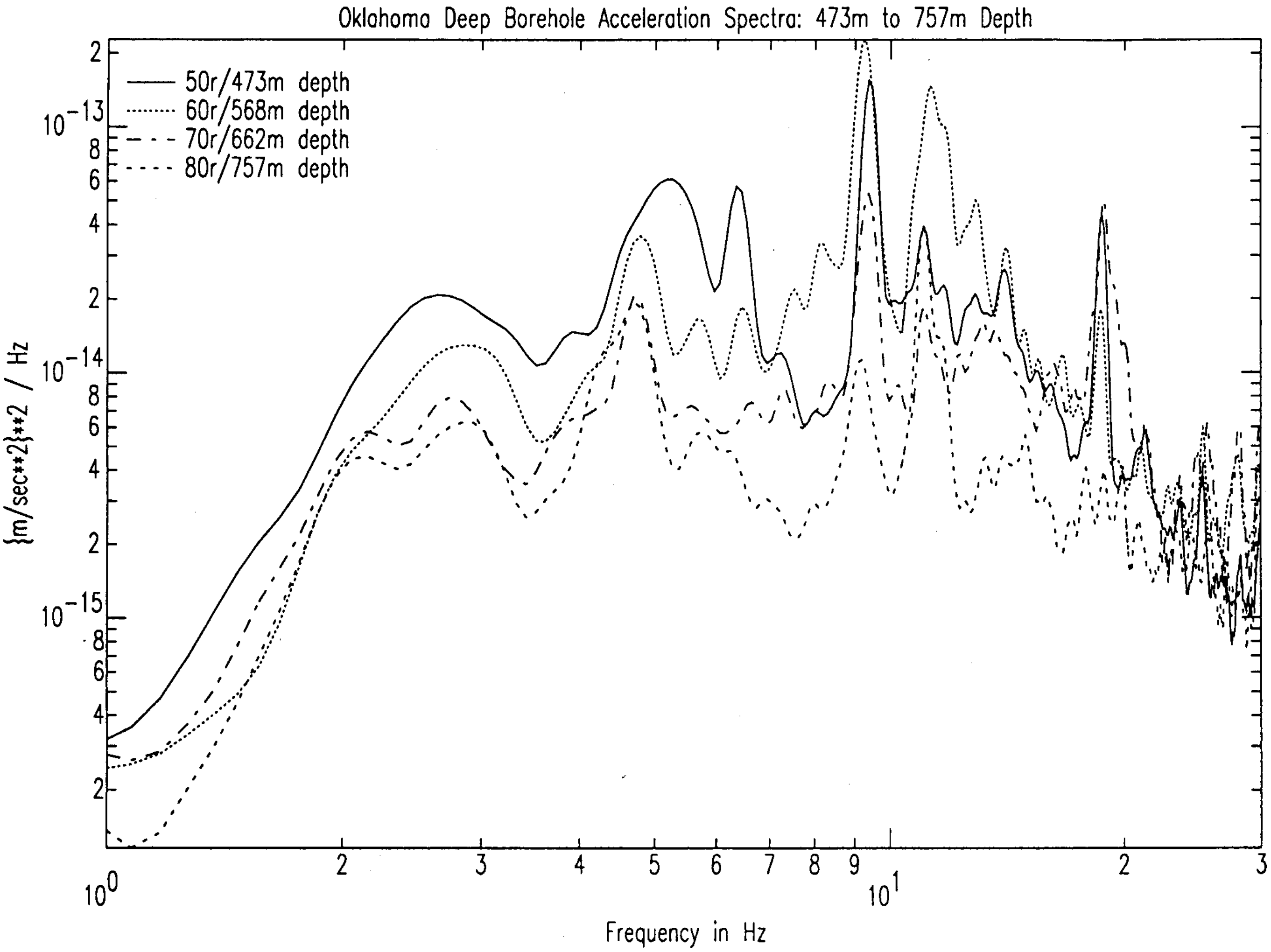

Figure 7. Seismic noise power density spectra are shown plotted between 1- and 30-Hz for borehole depths between 473 and 757 m. The greater incremental power reduction observed between 662 and 757 m is attributed to penetration of a high-velocity dolomite sequence.

Figure 7 plots the seismic noise acceleration spectra from 473 to 757 m at depths 95 m apart. The systematic overall decrease in seismic noise with depth is evident as noted earlier. The important point in this plot is the much larger reduction in noise level between about 6 and 20 Hz in going from 662 to 757m as compared to the noise reduction going from 473 to 568 m or from 568 to 662 m. This is probably because the 757-m measurement is within the high-velocity Cambro-Ordivician dolomite sequence. The 662-, 568-, and 473-m noise measurements are all above the dolomite sequence. Stations within the dolomite sequence can be expected to be partially isolated from seismic noise that exists in the waveguide defined by the surface and the dolomite sequence or between shallower sequences

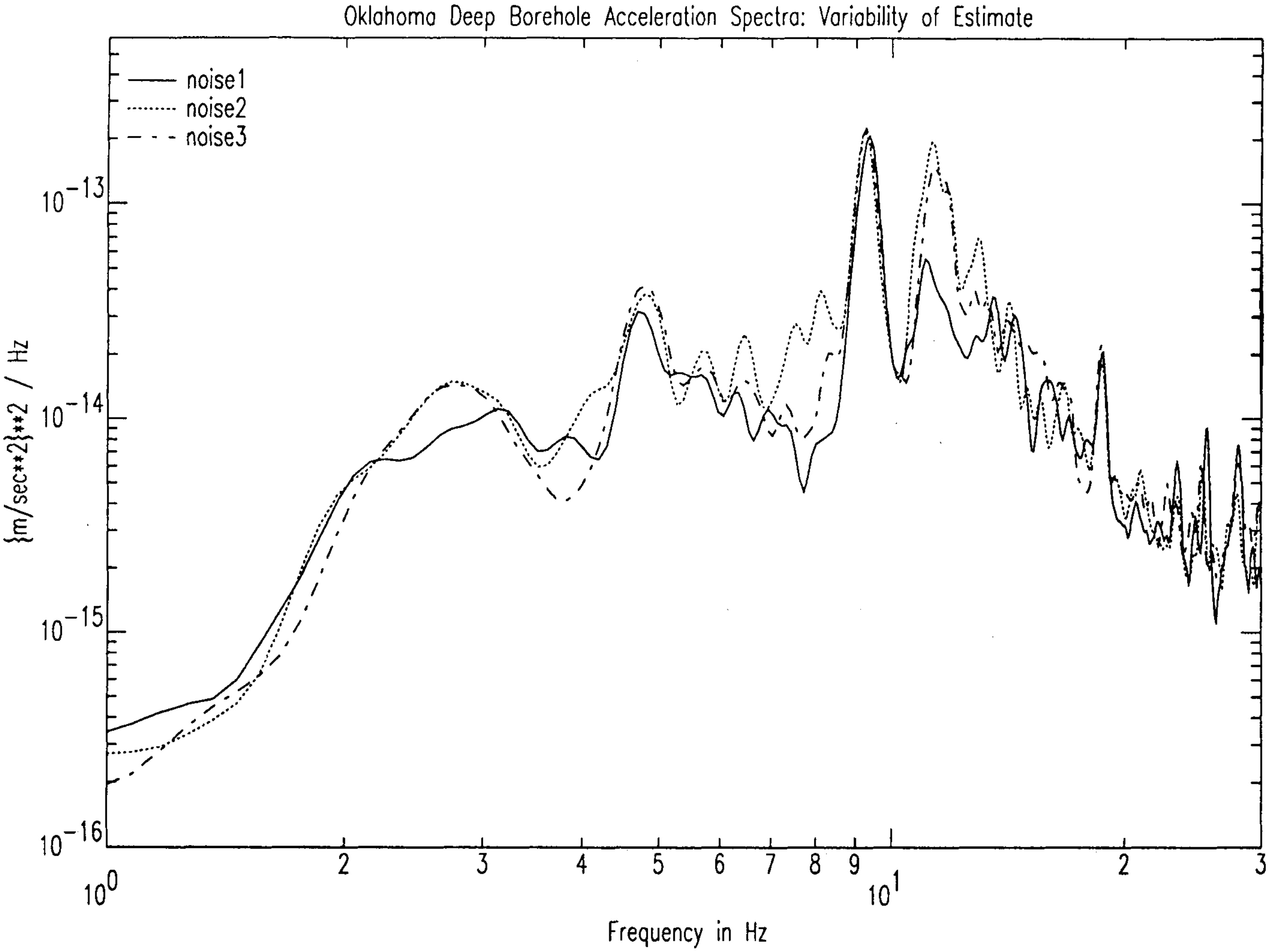

Figure 8. Noise power spectral density plots are shown for different times 568-m depth. The similarity of the spectra indicate the seismic background noise at this depth is stationary.

and the dolomite sequence. This means a substantial fraction of the seismic noise measured in the borehole below 450 m in the 6- to 20-Hz band is probably a wave-guided mode.

The relatively short five-minute time records taken at each depth make it difficult to assess the variability of the seismic-noise field. We consider this beyond the scope of the present data set. To provide some glimpse of the composite noise and estimator variability, we calculated spectra at 568 m using two non-overlapping two-minute noise windows from a single five-minute noise recording taken in the late afternoon and a third two-minute noise spectrum taken from a five-minute noise recording from the following morning at the same depth. The results are plotted in Fig. 8. The spectra show generally good agreement, to within a factor of two or so, except in the 7- to 9-Hz band and the 11- to 13-Hz band. The differences in

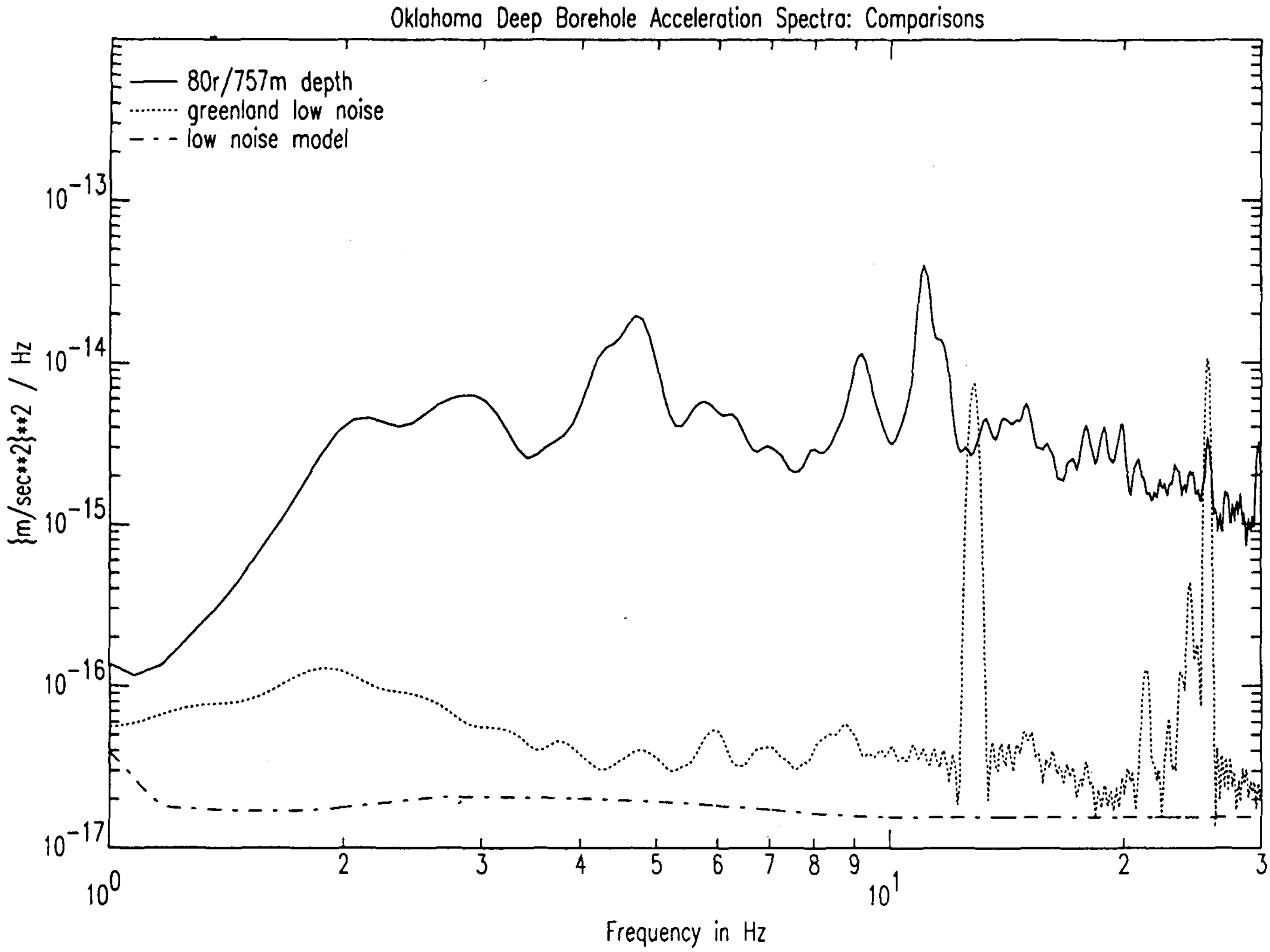

Figure 9. The lowest measured borehole noise power spectral density curve is compared to a low-noise Greenland surface site and the Peterson low-noise model.

the power spectra, particularly between the spectra calculated from the same five-minute noise record, at these frequencies are probably the result of transient local events like cable adjustment in the borehole. Spectral analysis using long noise (15 minutes or more) analysis windows would minimize the effect of occasional small local events. The fact that the spectra of the noise sample taken the next morning is within the envelope of the two other spectra indicates the noise field was stable in time.

In Fig. 9 we plotted the Oklahoma 757-m depth noise spectra, the Peterson low-noise model (Peterson, 1990), and a very low-noise site in northeastern Greenland. The comparison shows the Oklahoma borehole noise levels are about 20 dB higher than the Greenland low-noise site and about 23 to 25 dB higher than the low-noise model from about 2 to 30 Hz. The peaks in the Greenland noise are the result of a nearby power generator. Interestingly, one of the Greenland generator spectral peaks coincides with the 25-Hz spectral peak in the Oklahoma borehole caused by the surface compressor. We cannot determine with this data set if the overall broad-spectra noise in the deep borehole will be significantly reduced by the elimination of the surface compressor, or if the deep-borehole noise is exclusively caused by other local and regional sources.

SIGNAL SPECTRA

The events collected over the past year (1989) were configured with one seismometer located at 750-m depth and one seismometer at the surface, mounted 5 m below ground level in a shallow borehole. With this configuration we can estimate the differences in signal strength between the surface and the bottom of the borehole, but it does not allow us to determine it as a function of depth as we did with the seismic noise. Spectral power-density ratios calculated between the surface and downhole seismometers used the largest data time window containing only the P-wave phase and generally showed great variability across the full 1- to 30-Hz band. This is because such a ratio technique only applies at those frequencies where the uphole- and downhole-seismometer signal strengths are well above the background seismic-noise level. Consequently, the calculated ratios are only compared at the dominant-event signal frequencies. The following summarizes the signal-strength changes observed between the surface and the bottom of the borehole.

A teleseism recorded by the uphole and downhole seismometers was used to determine the difference in signal strength between the surface and the bottom of the borehole. A six-second analysis-window length was used to isolate the P-wave and spectral power-density ratios were calculated using a single six-second analysis window. The 1- to 5-Hz band contained the bulk of the teleseism energy and the dominant frequency was centered at 2 Hz. The spectral ratio at this frequency is 1.5, i.e., the uphole power spectra at 2 Hz is 1.5 times greater than the downhole power spectra at 2 Hz.

A nearby quarry shot (less than 50 km) showed a concentration of seismic energy in the higher frequencies (15 to 25 Hz). The dominant frequency was centered at 25 Hz, and the spectral power ratio at the dominant frequency was 7.5 Hz. A regional quarry shot (100 to 300 km) showed a concentration of energy in the 3 to 10 Hz band with bimodal dominant frequencies of 3.8 and 8.25 Hz. The spectral power ratios at these frequencies were 6.5 and 3.3 Hz, respectively. These crude measures show the signal at depth can be between 2 and 7.5 times lower than the surface records for the selection of signals discussed. Figure 10 plots the noise spectral power ratio between the surface and the 757-m station, 1/4 the noise ratio, and 1/8 the noise ratio. This is to bound the change in SNR for uphole and downhole measurements since the signal reduction between the surface and 757 m is between 1 and 8. Even the worst case (8 times signal reduction at depth) shows SNR is greater at 757 m than the surface.

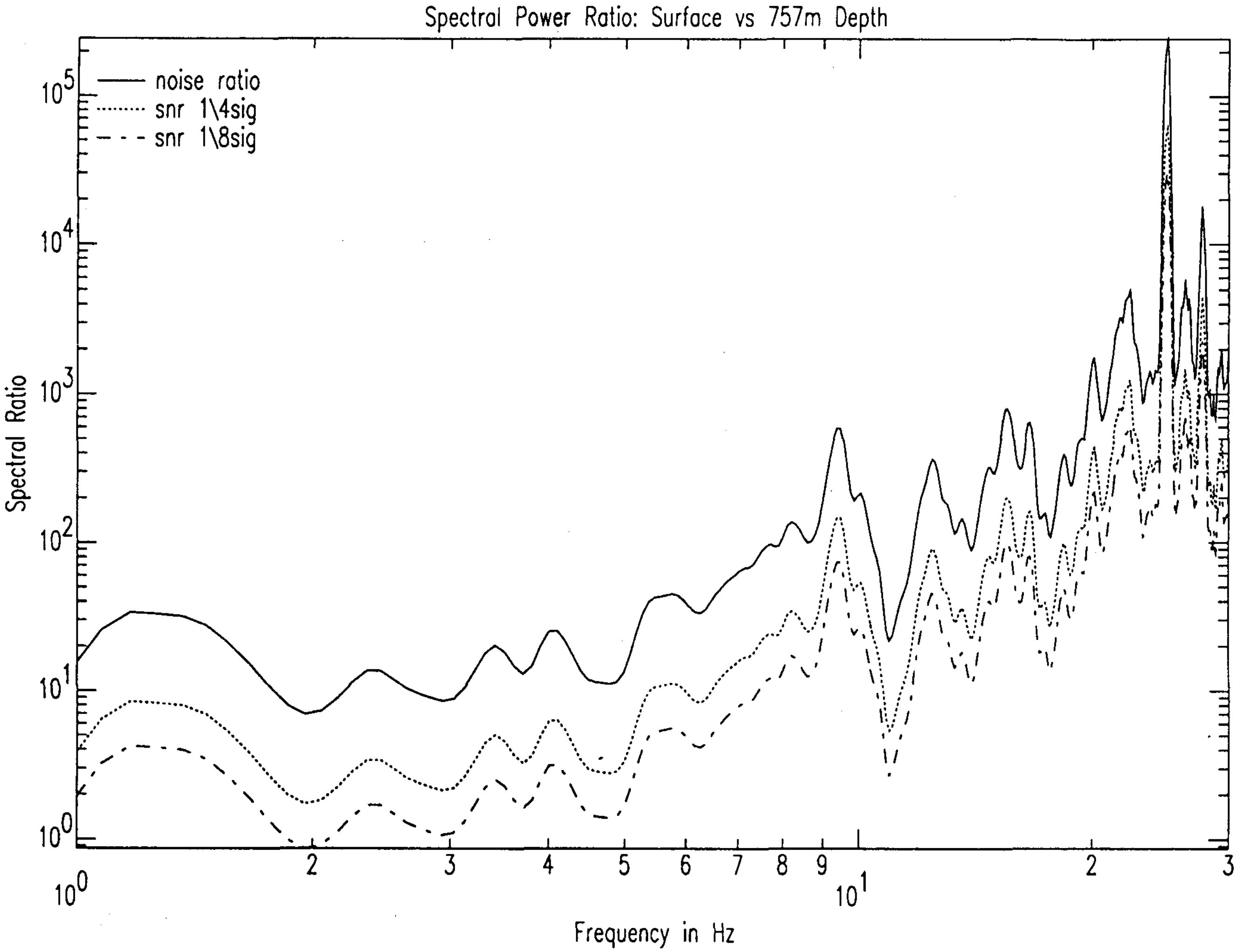

Figure 10. The noise spectral power density ratio between the 757-m station and the surface station is shown with 1/4 the noise ratio and 1/8 the noise ratio. The 1/8 noise curve is a lower bound on SNR assuming a maximum 8x reduction in signal at depth. The noise ratio is an upper bound on SNR assuming no signal reduction at depth.

The estimation of signal attenuation at depth shows great scatter. This is probably because: (1) the spectral-ratio method does not account for seismic attenuation between downhole and uphole seismometers, which becomes increasingly important at higher frequencies (see Malin *et al.*, 1988), (2) of the short time record required to isolate the P-phases, and (3) the downhole seismometer records a sum of the upcoming and surface-reflected downgoing waveform that may be constructively or destructively enhanced at the dominant signal frequency used in the spectral ratio.

Seismic-signal amplitudes are not the only property affected by deep-borehole measurement; the seismic waveform is too. Depending on the seismometer depth, surface and waveguided phases may not be detected. Furthermore, there is a reflection at the free surface that interferes with the upcoming waveform. At depth, the seismometer records the sum of the upcoming and reflected downgoing waveform producing a complex record. At 757-m depth in the Oklahoma borehole the P-wave travel time to the surface is 200 msec for teleseisms with vertical ray paths; consequently, only the first 400 msec (the two-way travel time) of the first P arrival recorded at depth is uncontaminated by surface reflections. Subsequent times represent the sum of two wavetrains, complicating identification and measurement of other wave phase properties. For verification research, these changes in signal properties caused by recording at depth are important to consider since they could degrade and/or complicate the application of some detection, discrimination, and yield-estimation algorithims to the recorded data.

Although examination of earthquakes and quarry shots indicate that Pg amplitude is smaller at depth than at the surface, the vertical component of Sg may be larger at depth. The SNR for vertical Sg has been measured in the Observatory vault and deep in the borehole, and was found to be higher at depth in the borehole. The SNR in the borehole at depth was similar to that measured at the vault on the horizontal components. For identification and timing of the Sg phase a deep-borehole vertical seismometer seems as effective as a vault-mounted three-component seismometer set.

CONCLUSIONS

For the specific geology and seismic-noise field of the Oklahoma borehole, shallow-depth (under 100 m) borehole-mounted seismometers show no significant noise reduction in the 1- to 4-Hz band. Consequently, any slight reduction of signal power expected at shallow depth will result in an SNR slightly less than that obtained with surface instruments. Above 4 Hz the SNR is higher than that obtained with surface seismometers because the noise is significantly suppressed. This enhancement is most pronounced at the higher frequencies; the noise reduction at the 25-Hz compressor peak is reduced by 20 dB at 95-m depth compared to the surface. From a verification viewpoint, shallow borehole seismometers do provide a means to reduce seismic noise at higher frequencies but at the expense of a possibly degraded SNR at low frequencies and a more complex and expensive deployment.

Deep (greater than 500 m) borehole-mounted seismometers show over ten times less surface noise than that measured by surface seismometers in the 1- to 4-Hz band. The signal is, however, reduced by a factor of around 4 giving an SNR improvement of about 3 times at 757 m compared to the surface in the 1- to 4-Hz band. In the 5- to 20-Hz band, significant further noise reduction occurred when the seismometer reached a high-velocity dolomite sequence. At 20 Hz the noise reduction at 757 m is nearly 30 dB less than the surface and the SNR is about 23 dB higher. At the 25-Hz compressor peak the noise level at 757 m is over 50 dB less than that measured on the surface. If deployment cost is secondary to maximizing the SNR of a seismic station, then deep-borehole deployment is warranted. In geologic and surface-noise conditions similar to the Oklahoma borehole, it is clear that a 500-m depth is adequate to eliminate most of the man-made high-power seismic-noise-source energy (evidenced by the 25-Hz compressor peak elimination). Another important consideration is to eliminate guided-mode noise. This can be accomplished by mounting seismometers nominally 100 m into the high seismic-velocity sequence(s) underlying low-velocity sediments. To determine the optimal depth of penetration into the high-velocity section would require deepening the Oklahoma Observatory borehole well into the underlying Spavinaw granite.

The conclusions of this report apply to the Oklahoma borehole in the presence of a particular high seismic-noise source. The results will probably differ significantly for a borehole in a low seismic-noise background region or in a different geologic setting. It is important to nuclear-test limitation verification to better understand noise attenuation, SNR enhancement, and seismic signals in boreholes; consequently, it is important that further noise measurements be conducted in other boreholes that are representative of geologic and seismic-noise conditions that may be encountered in a host country.

ACKNOWLEDGMENTS

We are indebted to Don Rock and Craig Johnston for their efforts in the design, building, and deployment of our seismic field system. Without their support this experiment would not have been possible. We also wish to thank the staff of the Oklahoma Geophysical Observatory for their efforts and cooperation over the course of this deployment. We are grateful to the Air Force Technical Applications Center for the loan of much of the seismic equipment used for this deployment. Finally, we thank Steve Taylor and Paul Kasameyer for review and criticism of this report.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1990 - 785-183/34012