LONG-PERIOD BACKGROUND EARTH NOISE AS MEASURED IN SHALLOW, HAND EXCAVATED HOLES

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(ABSTRACT)

To facilitate its objective of high resolution imaging of the Earth's crust and upper mantle, The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) has initiated studies into developing instrumentation capable of achieving that goal. The requirements include portable sensors capable of resolving seismic signals to 100 second periods.

To test the feasibility of obtaining useful long-period seismic data from a portable array, prototype instruments were installed in hand excavated shallow holes (postholes) at several sites in various geologic settings across the continental United States. Three of the sites were near established seismic vaults and comparisons between posthole installation and vault installation were made.

Results from this study indicate that posthole installation of long-period sensors may indeed be feasible: eight out of the 12 sites occupied had long-period background noise levels low enough to resolve 100 second surface waves generated from a magnitude 5.0 earthquake 30 degrees distant from the recording station. At periods less than 10 seconds, background noise recorded from postholes was no more than 3 dB. higher than that recorded in vaults. At 100 seconds, vertical noise was 11 to 16 dB. higher than that recorded in vaults and horizontal noise was 4 to 22 dB. higher. Across all posthole installations, as compared to Peterson's Low Noise Model, vertical and horizontal noise at 100 seconds averaged 27 and 45 dB. higher, respectively.

Sites should be located directly on bedrock, where possible. If this is not possible, they should be in well compacted inorganic soil with a low moisture content. Immediately after installation at a potential site, a noise sample should be analyzed in the field to test the suitability of the site.

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TABLE OF CONTENTS

ABSTRACT....................ii

ACKNOWLEDGMENTS....................iv

TABLE OF CONTENTS....................vi

I. INTRODUCTION....................1

II. METHODOLOGY....................6

III. PREVIOUS WORK....................8
- A. Determination of Noise Levels....................8
- B. Identification of Noise Sources....................10
- C. Installation Techniques....................14

IV. MATERIALS AND METHODS....................17
- A. Description of Field Hardware....................17
- B. Installation....................20
- C. Data Processing....................22
- D. Description of Field Sites....................24
  - 1. Vault Sites....................26
  - 2. Posthole only Sites....................29

V. RESULTS....................38

VI. RECOMMENDATIONS....................40
- A. Instrument Design Goals....................40
- B. Site Selection/Installation....................42

VII. CONCLUSIONS....................44

REFERENCES....................46

APPENDIX....................49
- A. Shake Table Facility....................49
- B. Instrument Response Curves....................50

VITA....................70

I. INTRODUCTION

The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) was formed to conduct and support projects aimed at high resolution imaging of the earth's structure (See 10 Year Plan, 1984). As a significant part of this project, the program intends to develop a new generation of seismic instrumentation and to maintain a set of 1000 of these instruments. The program's goal of a resolution of 1 km. to a depth of 670 km. will be realized, in one configuration, through the use of a dense array (spacing of 1 km.) of these instruments, some of which would have a passband of 100 - 0.02 second period. The broadband nature of the instruments used in this configuration is necessary to obtain the desired high resolution of structures as deep as the upper mantle. The array would not be permanent, but would be moved around to different locations on the continent for various projects. Considering the large size of the array and the requirement that it be portable, all instrumentation must be small, light, rugged and easily installed.

Although sensors capable of the desired operational specifications exist, they were not designed with the intent of rapid, field deployment. The currently available instruments are constructed to a high degree of precision and are generally quite delicate and sensitive to environmental perturbations. Variations in temperature will cause expansion and/or contraction of the materials making up the instrument thereby elevating the realizable noise floor. Pressure variations will change the buoyancy of the vertical seismic mass (Haubrich and MacKenzie, 1965). These pressure changes can be in the form of large-scale atmospheric pressure cells or as small as convection currents set up within the instrument's case itself (Savino and others, 1972). Horizontal instruments, in addition to being sensitive to horizontal motion, are also sensitive to tilts in the vertical plane, with the typical instrument's tilt sensitivity increasing with period (Rodgers, 1968).

The restrictive environmental requirements of the currently available "observatory" instrumentation has resulted in long-period seismic stations installed typically in vaults, deep mines or boreholes. Murphy and Savino (1975) recommend seismic station installation at depths of 150 m. or more to minimize atmospheric effects on horizontal instruments. Savino and others (1972) feel that instrumentation should be installed at a depth of "a few hundred meters" to attenuate wind noise. SRO stations were typically installed to a depth of 100 meters (Pers. comm. Jon Peterson, 1988). Such installations provide the required stable environment for long term reliable operation of observatory seismometers.

The above mentioned installations, however, carry a high price in money and time required for construction. The price especially tends to limit the number of sites deployed and maintained by a given research group. For example, the Geotech KS-36000 borehole package can cost in excess of $100,000 with an additional cost of installation in the neighborhood of $30,000. Installation time can be from several weeks to several months, depending on site accessibility, rock type, etc. (Pers. comm, O. D. Starkey, 1988). Furthermore, this class of instrumentation is necessarily eliminated from consideration for studies requiring rapid deployment of a large number of instruments, as would be needed for most studies conducted with a portable array.

With these characteristics in mind, this study was initiated by the Carnegie Institution of Washington, Department of Terrestrial Magnetism (DTM) to test the feasibility of obtaining broadband data from hand excavated shallow holes, typically less than 1 meter deep (henceforth referred to as "postholes"). It was realized at the outset that this type of installation could not replace the standard vault or borehole station. Rather, it is intended to supplement such sites and to provide an option for short- to medium-term studies requiring long-period data where time, money and/or logistics do not permit permanent installations. If resolvable long period signals can be recorded from installations of this type, the cost of installation time and money could be significantly reduced for many of the studies proposed by PASSCAL.

In this study, background earth noise in the period range of 1 to 100 seconds was sampled. The amplitude of this noise, recorded from shallow postholes, was used to determine, first, if it is possible to obtain meaningful seismic data in this period range from this type of installation and, secondly, an estimate of the maximum sensitivity for the instruments tested. Sites were chosen from a variety of geologic settings to provide some insight into difficulties that might be encountered during the installation process. Experience gained during field work was then used to develop guidelines for site selection and installation techniques. Sites were located mainly in National Parks because of their relative remoteness from cultural noise, the willing cooperation provided by Park personnel and the relative security for the field equipment. For comparison purposes, some sites were also located near established seismic vaults. At such sites, the field instruments were alternated between recording inside and outside of the vaults.

Field work began in the summer of 1986 and ended January 1987. The background noise was sampled using instruments installed in postholes that were sited at 12 locations across the continental United States (Fig. 1). All sites were occupied with the same set of instruments and recording equipment. Each site was typically occupied for about 24 hours, from which 12 hours of recordings were obtained.

II. METHODOLOGY

Criteria for evaluating noise samples obtained in this study were based on requirements of studies proposed in the PASSCAL Ten Year Plan (1984). Such studies would be limited to time frames of a few weeks to several months. The deployed instruments must be capable of detecting seismic signals of interest to the project at a level sufficiently above the background noise to permit analysis. Furthermore, an adequate number of detectable signals must be available during the period of the study. As an example, surface wave tomography and studies of large scale heterogeneities would require the recording of about two dozen teleseismic surface waves with periods as long as 100 seconds (PASSCAL 10 year plan, 1984). Background noise at the recording sites must be low enough so that this number of teleseisms may be recorded within a period of approximately six months. Examination of historical earthquake records indicates that this number (about 24) of magnitude 5.0 or greater earthquakes could be expected to occur within a six month period within a distance of about 30 degrees from a recording site located in the United States. We have, therefore, used these constraints to establish an upper limit on what would be considered acceptable levels of background noise. Curves representing surface wave magnitudes of 4.0 and 4.8 (The Design Goals for a New Global

Seismographic Network, IRIS, 1985) are reproduced on all spectral plots. A realistic upper limit which would allow a signal to noise ratio of 10 for an earthquake of surface wave magnitude 5.0 at a distance of 30 degrees from the recording site would fall between these two curves. Noise levels that fall in this range or lower are considered low enough to conduct experiments as proposed in the PASSCAL Ten Year Plan (1984).

III. PREVIOUS WORK

Most of the long-period background earth noise investigations have been directed toward three areas: (1) Determination of the lowest possible levels of earth noise attainable, (2) Identification of the sources of that noise, and, (3) Installation techniques that would minimize both instrumental and locally generated environmental noise sources. These three areas are discussed separately below.

A. Determination of noise levels

The maximum sensitivity and maximum system noise of practical interest in a seismometer is determined by the lowest level of ambient earth motion observed at a seismic station. Figure 2 shows a set of curves representing the lowest noise found by various authors. For purposes of comparison, these curves have been replotted in the units of meters squared per Hertz in order to be consistent with the units used in several of the later papers on earth noise. These units, which were used throughout this paper, can be converted to decibels relative to 1 meter squared per Hertz by multiplying all values by 10.

Brune and Oliver (1959) presented the first high-quality data on background noise for the period range from about 20 seconds to earth tides. Their paper presented curves estimating maximum, minimum and average earth noise in the subband of 10 to 40 second period. Savino and others (1972) studied background noise between 20 and 130 second periods and concluded that the noise minimum they identified in the 25 to 45 second period subband might be used as a "window" where seismic instruments' responses could be peaked. Fix (1972) presented a seismic noise model for periods 0.1 to 2560 seconds. His model was based on background noise recorded at the Queen Creek Seismological station in Arizona. Agnew and Berger (1978) reported noise levels from Project IDA sites in the period range of 100 to 1000 seconds. They noted that their results indicated noise levels at low frequencies are "much less than those reported by Fix (1972)". Peterson (1980) presented a Low Noise Model which was a composite of noise samples taken from 12 SRO and 5 ASRO stations. This Low Noise Model was generated by overlaying spectral plots from these 17 stations and selecting minimum points while ignoring narrow spectral peaks and valleys. Herrin (1982), using data from Peterson (1980), concluded that system noise for the SRO sensors is below that of ambient seismic background noise for periods above 1 second. Peterson and Tilgner (1985), using data from Agnew and Berger (1978), extended the Low Noise Model of Peterson (1980) to 1000 seconds. Agnew and others (1986) presented curves representing estimates of average minimum and maximum ground noise at typical sites. Holcomb (1987) presented curves comparing the ranges of background noise from 15 sites located around the world and that of four stations located in the interior of continents. He presented a curve which was a composite of data published by Herrin (1982), Peterson (1980) and Agnew and Berger (1978) and concluded that this was probably a good estimate of the lowest possible microseismic background over the period range of 0.025 to 1000 seconds.

In conclusion, the Low Noise Model presented by Peterson (1980) is considered a good estimate of the minimum levels of background seismic noise for the period range of 1 to 100 seconds obtainable anywhere on earth. This model is included as a reference on all spectral figures herein (dotted curves).

B. Identification of noise sources

Sources of noise have been identified as originating from (1) the ambient earth motion and (2) environmental factors such as temperature, atmospheric pressure and wind acting directly on the site or instrument.

Haubrich and others (1963) compared spectra from seismic and ocean wave recordings to periods as long as about 30 seconds. They identified the primary (about 14 second period) and secondary (about 6.7 second period) microseismic peaks and concluded that these two peaks were generated locally (within 100 to 200 miles of the recording site) by ocean wave activity.

Haubrich and MacKenzie (1965) looked at background noise in the period band of 2 to 200 seconds. Their studies uncovered "small blips" on seismic records from times near dawn and dusk. These "blips" were traced to temperature changes in the seismometer's case and mountings. They suggested a well insulated environment as a solution to this problem. Furthermore, they demonstrated dependence on pressure changes by evacuating a vertical sensor's enclosure and noted a reduction in the recorded noise by 10 to 16 dB. for periods greater than 25 seconds.

Capon (1969) identified two components making up seismic background noise in the 20 to 40 second period. By examining coherence of these two components across the large aperture seismic array (LASA), he determined that one component was propagating fundamental-mode Rayleigh waves generated by surf on coastlines and the other component was non-propagating noise generated by atmospheric fluctuations.

Sorrells and others (1971) found a strong correlation between wind induced atmospheric pressure changes and seismic signals recorded at the surface in the period range of 20 to 100 seconds. They showed that 100 second period wind induced noise was attenuated by 26 dB. at a depth of 183 m., but the effects of acoustic waves were only attenuated by 1.4 dB. for the same period and depth.

Savino and others (1972) determined that noise at periods greater than 30 seconds is predominantly nonpropagating ground motion induced by atmospheric pressure loading. Sorrells and Douze (1974) identified a possible source of seismic noise in the 20 to 100 second period band. They presented evidence that some of the background noise in this period range was caused by infrasonic waves generated by the jet stream blowing at a near normal angle to mountain ranges. Ringdal and Bungum (1977) reported that long-period noise at the NORSAR seismic array was dominated by fundamental-mode Rayleigh and Love waves related to large-scale weather disturbances in the North Atlantic. Rind and Donn (1978) studied microseisms recorded at Palisades, N.Y. They concluded the majority of the sources for these signals were ocean waves in the vicinity of the continental shelf to the east and northeast of their location. They were also able to correlate microseism amplitude with ocean wave amplitude.

Szelwis (1982) found fundamental-mode Rayleigh and Love waves that make up microseisms to both propagate in the same direction at a given time. Although he confirmed that the Rayleigh waves were generated by coastal reflection of ocean surface waves, source spectrum estimates contradicted a common origin for both Rayleigh and Love waves. He suggested that the Love waves might be due to partial conversion of the propagating Rayleigh waves.

To summarize, microseismic noise in the period range 6 to 20 seconds is dominated by Rayleigh and Love waves generated by surf along coastlines and storms at sea. The noise at periods longer than 30 seconds is dominated by relatively localized atmospheric pressure cells loading regions of the surface of the earth.

Instrumental noise in vertical instruments can be caused by changes in buoyancy of the seismic mass due to pressure changes. Another source of instrumental noise, the differential expansion and/or contraction of a seismometer's components and its mounting, is caused by temperature variation.

C. Installation techniques

Sorrells and others (1971) stated that earth motion due to the turbulent atmospheric pressure field in the period range of 20 to 100 seconds can be mostly eliminated by placing the sensor "several hundred meters below the surface". Haubrich and MacKenzie (1965) provided good evidence that noise generated by atmospheric pressure changes could be reduced significantly by installing the sensor in an evacuated case. They also recommended that instruments be well insulated to minimize effects of temperature changes. Ziolkowski (1973) claimed that a noise reduction of about 10 dB. may be achieved by either burying the seismometer at a depth of 150 m. or by deploying an array of at least 10 sensors installed at the surface with a spacing of no less than 1 km. With an array of this spacing the pressure induced noise would be incoherent across the array allowing the use of a stacking technique to increase signal/noise.

Sorrells and Douze (1974) observed that if noise in the period range of 20 to 100 seconds is mainly the result of atmospheric infrasonic waves, then installation to depths of 1 to 3 km. would be necessary to reduce its effect. Murphy and Savino (1975) studied earth noise between 20 and 200 second periods. They concluded that long-period noise generated by atmospheric pressure loading can be minimized by installing seismic sites at depths of 200 meters or greater.

Peterson and Tilgner (1985) compared vault and borehole records and concluded that records obtained from both the surface and borehole were both about 5 dB. above their Low Noise Model for periods of 50 to 100 seconds during non-windy periods. However, during windy periods, the borehole records were nearly the same as before, but the surface records increased by about 10 dB. for the period range of 50 to 100 seconds. They suggested that noise caused by atmospheric pressure loading may be worse at sites not located on rock as rigid as granite. Finally, they calculated coherence between two identical horizontal instruments using background noise in the period range of 10 to 700 seconds. Coherence at periods greater than 30 seconds was only about 0.25 when only one instrument was cemented to the pier. When the second instrument was also attached to the pier, coherence for periods greater than 30 seconds went up to values of 0.3 to 0.75.

To summarize, the sources of noise identified in section 2 above can be minimized by installing instruments in evacuated cases and then placing them in specially constructed vaults or down boreholes to a depth of at least 100 meters and imposing rigid environmental controls on the site.

The surf-generated microseismic noise, although usually the most dominant feature of the background noise, is fairly well confined to the 6 to 20 second period range. Traditionally, this noise was dealt with by peaking the instrument's response outside of this subband. However, with the dynamic range of modern systems, this is no longer necessary. The noise dominating periods greater than 30 seconds is more difficult to deal with, partly because of its broadband nature. The most effective solution to this problem has been to place the instruments at a depth of at least 100 meters below the surface. Instrumentally generated noise can, for the most part, be dealt with through installation techniques.

IV. MATERIALS AND METHODS

A. Description of field hardware

Long period background noise was detected by one vertical and one horizontal seismometer from each of two manufacturers: Guralp Systems, Reading, England and Teledyne Geotech located in Garland, Texas, and recorded digitally on magnetic tape. The two models obtained were the only two long period sensors available at the time of the study that could be modified for this kind of installation. Also, one goal of PASSCAL's sensor development was to evaluate available instruments for possible use by the program.

One set of sensors used was the seismometer element from the Geotech KS-36000 borehole system. This instrument is an active force feedback system and employs a coil-magnet transducer for applying the restoring force. The vertical sensor uses a horizontal pendulum and the horizontal sensor uses a "swinging gate" arrangement. Mass position is sensed with a capacitance bridge. Mass locking is accomplished by depressing a bellows mounted on the sensor's case. Depressing the bellows engages a mechanical linkage which pushes two locking pins into the seismic mass. The case containing the sensor is evacuated, and the mass locking mechanism used avoids the necessity of breaking this seal. Because these sensors were intended to go into a borehole package unsuitable for this field work, it was necessary to develop appropriate external packaging for the seismometers as well as their associated control electronics.

In the development of surface installation packaging for the KS modules, the first problem dealt with was instrument leveling. In the borehole package, the restrictive leveling requirement of +/- 0.1 degrees was met by a complex pneumatic system driving a gas bearing. With this arrangement, the bearing was pulsed with a gas which acted as the bearing's lubrication. During the duration of the pulse, the seismometer would swing free to a level position. This method was abandoned in favor of fine threaded leveling feet. The tolerance on the leveling specification was about one half turn on any one leveling foot. Leveling was verified first by a set of spirit levels mounted on the case and, finally, by the mass position output from the control electronics.

A suitable case had to be designed that would provide (non-pressurized) protection of the seismometer element from dirt and water. The seismometer element itself, as supplied from the factory, is in an evacuated vessel which is suspended from a gas bearing inside an aluminum cylinder. For field use, this cylinder was secured to an aluminum disk of a larger diameter. The resulting 0.5 inch flange was used to mount the leveling feet. The entire cylinder was then covered with a Lucite canister for waterproofing. In the Geotech borehole package, the mass locking mechanism is driven by a small motor controlled from the surface electronics package. For the surface installation configuration, the motor was removed and the locking mechanism was driven by hand with an allen wrench. Access to the locking mechanism is gained through a port in the top of the Lucite canister.

The other set of sensors were very early models of the Guralp CMG-3V and CMG-3H. The Guralp instrument is a small electrostatic feedback seismometer. The vertical sensor uses a horizontal pendulum and the horizontal sensor uses an inverted pendulum. The instrument provides outputs of acceleration, velocity and displacement. The acceleration output is D.C. coupled, which allows monitoring of the mass position. The instrument is installed in an airtight case which must be removed for mass clamping/unclamping. Leveling is done electrically with a small motor mounted in the seismometer case. Very little modification was done to these sensors other than waterproof packaging of the control electronics and cabling.

Analog output from the four sensors was recorded on an Earth Data EDR-8000 digital recorder which provided all anti-aliasing filters and A/D conversion. The data were recorded at a sampling rate of 40 samples per second per channel with 16 bits of precision on 3M DC-300-

XLP tape cartridges. For the sampling rate of 40/sec., all aliased components were guaranteed to be at least 96 dB. below the passband of D.C. to 16 Hz.

Control electronics, batteries and recording equipment were mounted inside waterproof fiberglass equipment cases. Because most sites were remote, a self-contained power source was required which provided a total of about 40 watts. Rechargeable, gelled electrolyte, lead-acid batteries were chosen for this purpose.

B. Installation

The field methods were designed around the concept of a low-cost installation that could be established by one or two persons using a minimum of support equipment. The equipment had to be small and light enough to allow, if needed, hand-carrying for as far as a few kilometers. Because man-made shelter for the equipment would not always be available, all equipment required protection from any natural conditions that might be encountered. Anticipated problems associated with an exposed site would be in the form of environmental perturbations (wind, rain, heat or cold) or biological disturbances (human vandalism and animal curiosity). The risk of vandalism was dealt with by choosing sites sufficiently remote that the chance of human detection would be minimized. Camouflage, where possible, was used to conceal the equipment from both vandals and animals.

A typical installation is schematically shown in Fig. 3. Each seismometer was installed in a shallow (about 0.6 m. deep) hole in the soil. The holes were excavated with a hand auger and a shovel to a 16 cm. diameter that would create about a 3 cm. space between the sides of the sensor and the hole walls.

It has been shown that a flat plate merely placed on a surface does not provide a good mounting surface for long-period instruments (Peterson and Tilgner, 1985, Pers. comm., O. D. Starkey, 1986). Therefore, to improve coupling and to provide a more stable installation surface, we developed the technique of driving three tapered brass spikes into the undisturbed soil at the bottom of each hole. Each leveling foot of the sensor was then placed on the flat top of a spike. With this arrangement, each instrument was coupled to the earth only through the leveling feet via the brass spikes. The leveling feet were accessible from the surface using a nut driver with a 0.6 m. extension.

To improve thermal isolation from the environment, the excavations were not back-filled around the instruments. Instead, the seismometers were wrapped with polyester fiberfill insulation to fill the space between the seismometer and the sides of the hole. The remaining space above the seismometer (about 0.3 m.) was also filled with fiberfill insulation up to the ground surface. The hole was capped with a rigid plastic disk which was then covered with a mound of soil.

Site selection usually began in the morning of an installation day by consulting with the study region's caretaker, usually the Park's superintendent. After specific site selection, the postholes were excavated, sensors placed in the holes, leveled, insulated and then the holes capped. The installation process was usually completed by midday, which would allow sufficient time for the sensors to stabilize for overnight recording. In the early evening, the recording equipment was brought to the site, any final leveling necessary was done and equipment was set up to record overnight. Temperature readings were taken at the beginning and at the end of each recording period using a Fisher digital thermometer. Wind speeds were visually estimated and noted. Temperature and wind speed were only taken at the posthole-only sites.

C. Data Processing

Analysis of the recordings was done after completion of all fieldwork. On most records made from instruments in postholes, short term localized disturbances were observed from time to time. These occurrences, which constituted, on average, about 5 percent of the seismic record, were dependent upon local conditions, such as proximity to trees, human and/or animal activity, etc. The 2 hour segments examined were visually chosen from the time series plot as the quietest segment out of the 12 hour recording. In this way, the selected segment would more closely represent true ambient background noise present at the site. Instrument corrected power spectral density plots were generated from the two hour segments (See the Appendix for instrument response curves). Each plot was checked for amplitudes exceeding the chosen upper limit, similarity to the Low Noise Model and differences between vertical and horizontal noise recorded at a given site.

Data were transferred from the Earth Data digital recorder over an RS-422 GPIB bus into an IBM-PC type computer for analysis. The computer communicated with the bus through a Metrabyte Corp. GPIB interface, which was provided with a set of FORTRAN callable driver routines. All output was plotted on a Hewlett Packard model 7475A plotter which was driven by a FORTRAN callable GKS graphics driver module. All communication, analysis and plotting routines were written in FORTRAN. Data processing, including transfer of the raw data segment out of the digital recorder and plotting, took about 1 hour per site.

Power spectral densities were calculated with a program adapted from Press and others (1986). These densities were obtained by averaging estimates obtained from 15 data segments of 409 seconds each. Plots are presented in units of meters squared per Hertz. The Low Noise Model curve, after Peterson (1980), is included in all plots for comparison purposes.

D. Description of field sites

The locations of the sites occupied during this study are given in Table 1 and Figure 1. The sites occupied are divided into two groups. The first group, consisting of three sites, was a set of permanent seismic stations where recordings were made simultaneously in the vault and in a nearby posthole. The second group of nine sites was a collection of posthole-only sites. The general characteristics of each site are presented in Table 2. A summary of the recorded noise levels can be found in Table 3. A common numbering system for the sites is used in Figure 1 and Tables 1, 2 and 3.

Due to the prototype nature of the Guralp instruments, it was not realized at the time the field work was done that these instruments required about 24 hours settling time before meaningful recordings could be made (The Geotech sensors required only a few minutes). At most field sites, this criterion was not met. Therefore, for most of the field sites, spectra generated from the CMG-3 instruments are not presented. At the vaults in Washington DC and Blacksburg, Virginia the instruments were left in place for several days before recording, which then produced suitable output. However, based on several months of observation in the DTM vault, it is suspected that the records obtained from the CMG-3 instruments at these sites may still include some instrumental and/or atmospheric pressure induced noise at the longer periods.

Due to the nature of this experiment, it was not possible to determine the seasonal dependence of microseisms or attenuation of microseisms with distance from coastlines (It would have been necessary to record simultaneously from several widely spaced sites). However, the microseismic background level may not be a factor for several PASSCAL studies because microseisms are sharply band-limited to the period range of 6 to 20 seconds.

In order to determine tilts due to atmospheric pressure cell loading, it would have been necessary to deploy several continuously recording microbargraphs in an array within a 1 km. radius around the recording site. Neither the equipment nor the manpower were available to do this.

1. Vault sites

DTM (Washington, D.C.) Cyclotron Tunnel (1)

The seismic vault here is in a room originally built to house a 60 inch cyclotron. The room, which is about 5 m. below grade, has been used as a seismic vault since 1967. The site is located in Washington, D.C. in a suburban environment. The surface postholes were located about 100 m. horizontally away from the vault under several widely spaced mature oak trees. Recordings were made simultaneously from the surface site and from the vault.

Power spectra from signals recorded at this site are presented in figure 4. At the posthole site, background noise levels were consistently higher by 3 to 15 dB. than those recorded in the vault at periods greater than 25 seconds. The vertical instruments had a difference between vault and posthole of 10 to 15 dB. while the horizontals had a difference of only 3 to 10 dB.

Blacksburg, VA. (2)

This seismic vault, established in 1962, is station BLA of the WWSSN network. It is located in a pasture with power line poles the only nearby objects. The pasture is frequented by dairy cattle. Again, at this site recordings were made simultaneously in the vault and from surface postholes located about 5 m. from the vault. The postholes were in Terra Rosa soil and were not excavated down to bedrock.

Results obtained from this site are presented in figures 5 and 6. The noise levels recorded from the postholes here were 5 to 25 dB. higher than those recorded in the vault for periods greater than 25 seconds. Here, the difference between vault and posthole records for the horizontal instruments was 10 to 25 dB. while the differences observed between the verticals was 7 to 15 dB.

USGS Albuquerque (3)

The seismic vault here is tunnelled about 10 m. into a granitic mountain. There are no man made structures within 1 km. of the vault. The surface site was installed almost directly above the access tunnel leading into the vault. While the field instruments were being recorded on the surface, simultaneous noise samples were taken from the observatory's Streckeisen instruments (Wielandt, 1982).

A comparison of spectra from the vault instruments with the surface installed instruments (Figure 7) shows a very good match with a difference of 1 to 10 dB. at periods greater than about 10 seconds. Both horizontal instruments recorded long-period noise levels 15 to 20 dB. higher than the vertical instruments for periods greater than 20 seconds. This elevated level was probably due to atmospheric disturbances from a thunderstorm that moved through the area during the recording period.

2. Posthole only sites

Petrified Forest / Painted Desert (4)

The Painted Desert is located in northeast Arizona on the Colorado Plateau. The selected seismic site was located on a broad flat plain of sparse grass and sagebrush within sight of the valley containing the Petrified Forest proper. The soil was a compacted dark reddish quartz sand virtually free of rocks. The surface ground temperature at the start of the recording was 94.1°F which dropped to 78.4°F by the end. During the recording the wind was about 20 km./hr.

The noise sample obtained from this site was overall the quietest of the surface sites (left-hand plot of Figure 8). The lack of any nearby man made structures, tall vegetation or topographic highs probably contributed to a lack of wind induced background noise recorded here. Atmospheric conditions were also quite calm during the recording. The horizontal was on average about 12 dB. higher than the vertical at periods greater than 25 seconds and on average 3 dB. higher at shorter periods.

Sunset Crater (5)

Sunset Crater is a cinder cone located in the San Francisco Mountains north of Flagstaff, Arizona. The instruments were installed in a small cave formed in a basaltic lava flow that issued from the base of the cinder cone. At this site, the sensors were placed directly on the rock floor of the cave. This lava flow, the Bonito Flow, is only 900 years old and is in a very well preserved state (Pewe and Updike, 1976). The ground temperature during the recording period was 48.7°F. The wind went from about 5 km./hr. to still during the same time.

The right-hand plot of Figure 8 shows power spectra of noise levels recorded at this site. Although the long-period vertical noise levels recorded here were similar to those recorded at Albuquerque, the horizontal was 20 to 40 dB. higher at periods greater than 12 seconds. The large difference between these two axes, particularly at periods greater than 12 seconds, implies a large tilt component present at this site. This postulation is reasonable in light of the fact that the lava flow, although rather thick and extensive, overlies a layer of cinder (Pewe and Updike, 1976) which may itself be fractured and/or be allowing the layer of basalt to flex.

Pinon Flat (6)

The Pinon Flat Observatory is a testing ground for geophysical instruments maintained by UCSD (Berger and others, 1972). It is located in southern California in the San Jacinto Mountains above Palm Springs. The surface site was installed in decomposed granite sandy soil. The ground temperature for the recording period was 76.2°F. The wind dropped from about 20 km./hr. at the start to less than 1 km./hr. by the end of the recording.

This is another site that had long-period background noise levels low enough to conduct meaningful seismic monitoring (left-hand plot of Figure 9). Results were quite similar to those obtained at the Petrified Forest except for the prominent secondary microseism peak at 8 seconds. The overall level of background noise was reasonably low with the horizontal 10 to 14 dB. above the vertical at periods greater than 25 seconds.

Kings Canyon (7)

Kings Canyon is located in southern California in the Sierra Nevada Mountains. The canyon was cut through a granitic pluton by the Kings River. This canyon is in excess of 1500 meters deep. The seismic site was located in the canyon at the base of the canyon's north wall. The instruments were placed in a crevice formed by large granitic blocks piled up at the base of the wall. The ground temperature during the recording period went from 59.5 to 58.6°F and the wind dropped from about 20 km./hr. to less than 1 km./hr.

This site also had noise levels low enough to conduct long-period seismic studies (right-hand plot of Figure 9). Again, horizontal noise levels were about 10 to 14 dB. higher than vertical at periods greater than 25 seconds. In addition, the overall noise level at periods greater than 25 seconds were about 10 dB. greater than those observed at Pinon Flat for both vertical and horizontal. The depth of the canyon and the competence of the rock were probably responsible for the relatively low noise levels, and could have been even lower had the instruments been installed directly on bedrock.

Lassen Peak (8)

Located at the extreme southern end of the Cascade Range in California, Lassen Volcanic National Park provided a suitably isolated spot for seismic noise investigations. The site chosen was approximately 10 km. from Lassen Peak itself. The instruments were placed in a hole located about 10 m. from a large basaltic lava flow. The instrumentation hole was in a field adjoining the lava flow. The soil was a light tan Diatomatious earth. During the recording period, the ground temperature went from 52.4 to 49.9°F and the wind dropped from about 30 to about 8 km./hr.

In spite of the remoteness of this site, the large difference between the horizontal and vertical noise levels seen in the left-hand plot of Figure 10 would make this site a poor choice for long-period recording. The horizontal noise was elevated 3 to 37 dB. over that of the vertical over the entire frequency band with the difference between the two curves increasing with period. The presence of a person walking in the field 10 meters from the site was readily observed on the instrument's low gain mass position monitors. As a result, relatively small local disturbances were recorded frequently enough so that a two hour segment without any such disturbances could not be located. The noise level was also probably elevated due to the relatively strong wind blowing on the nearby trees.

Crater Lake (9)

This 589 meter deep lake is located in the caldera of Mount Mazama, one of the Andesitic stratovolcanos of the Cascade Range in Oregon (Harris and Kiver, 1985). The seismic site was located near the rim of the caldera in a pine forest. At this site it was possible to dig completely through the layer of volcanic ash soil to place the instruments directly onto the underlying Andesite bedrock. The ground temperature during the recording period went from 50.9 to 50.8"F and the wind dropped from about 3 to less than 1 km./hr.

In spite of being able to place the instruments directly on bedrock, this site had considerably elevated levels of long-period horizontal noise over that recorded with the vertical (right-hand plot of Figure 10). Although lower than levels recorded at the site near Lassen Peak, the horizontal noise was 15 to 30 dB. higher than the vertical at periods greater than 10 seconds. The elevated levels of horizontal noise observed here are probably indicative of the incompetent nature of the layers making up this mountain (interspersed layers of Andesite, Pumice and ash (Harris and Kiver, 1985)). As with Sunset Crater, the incompetent layers were probably allowing the overlying layers to tilt.

John Day Fossil Beds (10)

This site is located in central Oregon on the Columbia Plateau. The John Day Formation, dominant at this site, consists of colorful layers of volcanic tuff (Baldwin, 1964). The seismic site, however, was installed near the base of an old basaltic neck in very hard, compacted pediment gravel. This site was quite remote. The nearest town, with a population of only about 250, was about 15 km. away. Between the town and site there were only a few ranches. During the recording period, the ground temperature dropped from 79.9 to 79.1"F and the wind was less than 1 km./hr. for the entire period.

Although this site was quite isolated from sources of environmental noise, experienced stable atmospheric conditions during the recording and achieved very good coupling to a presumed competent substrate (The coupling spikes were bent when driven into the undisturbed gravel), the long-period noise levels recorded here were not what was expected. Spectra are shown in the left-hand plot of Figure 11. Horizontal noise at periods greater than 25 seconds was only 3 to 10 dB. over the vertical, but the absolute level at those periods was elevated over that recorded at some of the other sites.

Yellowstone (11)

Located within the Yellowstone caldera, the selected seismic site was located on the flank of Bunsen Peak, a Tertiary basaltic mountain south of Mammoth Hot Springs. The site was in pine forest about 2 km. from the nearest occupied road. Installation was on a Quaternary basaltic flow that surrounds Bunsen Peak (Keefer, 1971). During the recording period, the ground temperature dropped from 52.9 to 52.8"F and the wind dropped from about 20 to about 10 km./hr.

This site had generally elevated levels of background noise at periods greater than 25 seconds in vertical and greater than about 10 seconds in horizontal (right-hand plot of Figure 11). Considering the instability of this area as a whole, it is surprising that the noise was not higher than it was. Horizontal noise was higher than vertical over the entire band with differences of 8 to 14 dB. observed at periods greater than 10 seconds. Because this site was located in forest, the wind blowing during the recording period probably contributed to the noise level.

Stickleyville, Va. (12)

This site was located in the Valley and Ridge province in the Appalachian Mountains of Southwest Virginia. Chosen for its relative remoteness from major population centers, the instruments were sited in a small clearing in a hardwood forest. Installation holes were dug in Terra Rosa soil derived from limestones of the Knox Group (Miller and Englund, 1975). During the recording period, the ground temperature was 68.2°F and the wind rose from less than 1 to about 3 km./hr.

The relative remoteness of this site by itself was not sufficient to achieve low noise levels. Not only were there higher noise levels at periods around 100 seconds, but noise levels around 1 second were also elevated (Figure 12). On the positive side, there was fairly good agreement between vertical and horizontal (1 to 10 dB. difference at periods greater than 10 seconds), indicating the site was not dominated by tilt.

V. RESULTS

A summary of the noise levels at 20 and 100 second periods recorded from each of the sites is presented in Table 3 and Figure 13. The decibel values in the table and figure are relative to the Low Noise Model presented in the figures. This reference was chosen to provide a tabular representation of the comparison made graphically in the figures. None of the sites studied, including the vaults, achieved the level of the Low Noise Model curve for the entire band. This discovery is not surprising, because the Low Noise Model represents a composite of minimum levels observed at several of the most quiet sites. It is encouraging, however, that noise levels at several sites came close to this curve in both amplitude and shape, especially for periods less than 10 seconds.

The background noise levels recorded in the vaults at periods less than 10 seconds were no more than 3 dB. below those recorded in the posthole sites. At periods longer than 10 seconds, the vaults were almost always quieter with a wider range of difference observed in the horizontal instruments.

At 100 seconds, compared to the seismic vaults used in this study, the vertical noise level was about 10 to 16 dB. higher and the horizontal was 4 to 20 dB. higher. A further complication comes from the observed local disturbances of the seismic record. Even though a quiet 2 hour segment could usually be found, any unprotected field site will be more susceptible to local, episodic disturbance than a seismic vault.

Low noise soil sites were typified by those at Albuquerque, Petrified Forest, Pinion Flat and John Day Fossil Beds. The sites at Washington, D.C., Stickleyville and Blacksburg, although also in inorganic, compacted soil, had somewhat higher noise levels.

The rock sites were located at Sunset Crater, Kings Canyon, Crater Lake and Yellowstone. The results from these sites varied quite a bit, but so did the rock type and competence of the underlying layers. Those sites located on or near lava flows appeared to have higher levels of tilt.

High wind velocities during recording periods did not, by itself, correlate to higher levels of long-period noise. It is probably more important to consider nearby topographic highs, man-made structures and tall vegetation. Such features will cause wind present at or near the site to have a more pronounced effect on the background noise.

VI. RECOMMENDATIONS

A. Instrument Design goals

This section is based on field experience with the set of seismometers used. It should be noted that although these comments are based on these particular instruments, they may not be applicable to what is presently available from either manufacturer. The Guralp instruments were pre-production models and the Geotech instruments are currently not available in a surface installation package.

Seismometers intended for field installation of the type employed in this study should be: (1) as small and lightweight as possible, (2) as rugged and as impervious to the environment as possible, and (3) as simple as possible to set up and operate.

The size and weight of the Guralp instruments was quite satisfactory and proved to be no problem in the field. The Geotech was acceptable, but was probably near the upper limit of the size and weight that would be desirable. It is not practical to excavate holes smaller than about 16 cm. diameter for depths of at least 60 cm. Therefore, for instruments of the size of the Geotech package and smaller, there would be no difference in the effort required to excavate the installation holes. Larger instruments, however, would require larger holes and accordingly a potentially significantly increased field effort.

An evacuated container with an externally operated mass lock proved to be very desirable in field use. It was necessary to open the pressure case of the Guralp instrument to lock/unlock the mass. This procedure exposed the instrument to potential contamination. The case was not evacuated, which made the instrument more sensitive to ambient thermal variations. Had this instrument been evacuated and provided with an externally controlled mass lock/unlock mechanism, it might not have taken 24 hours for it to stabilize, as was found to be the case.

The motor driven leveling mechanism on the Guralp was unsatisfactory. In fact, it was necessary to place the horizontal instrument on a platform with leveling feet similar to those used with the Geotech instruments to perform the leveling operation with the desired degree of repeatability. Furthermore, the addition of remote controlled leveling mechanism/circuitry adds complexity to the system, with the possibility of more things that can go wrong under field conditions. Simple leveling feet are quite adequate.

B. Site Selection/Installation

In addition to the avoidance of cultural noise, sites intended to produce records with signals of up to 100 second periods need to be located in a reasonably stable temperature and must be well coupled to the earth. The ideal installation is a spot that can be excavated through soil down to bedrock. Where this is not possible, the soil must be well compacted and free of organic material. Spikes driven into the undisturbed soil provide an adequately stable base to work from, especially for horizontal instruments.

One common feature of the four "low noise" soil sites was a lack of moisture. This is noted as an important condition on the observations made herein and requires further study. However, it seems reasonable that, in general, a well compacted soil with a low moisture content would provide a better coupling to the earth than the same soil with moisture added. Water content in soil will reduce the soil's shear strength which would increase the probability of a local disturbance causing small stick-slip movements (Personal communication, C. F. Watts, 1988). These movements, if detected by the sensor, would appear as small steps thereby contributing to the overall background noise.

It comes as no surprise that the quietest of the rock sites came from highly competent granitic rock. However, from this study it can be concluded that locating a site directly on bedrock in a remote location will not in itself assure good results. For example, basaltic lava flows, although quite competent and continuous, had relatively high levels of tilt.

Temperature stability within 3 degrees F may be obtained by using at least 0.3 m. of insulation between the top of the instrument and the ground surface. Instruments installed in evacuated housings are significantly less sensitive to temperature and pressure variations.

Rather than relying solely on a recipe of terrain, geology and rock type for site selection, it is recommended that such a recipe be used for initial selection, followed by analysis of a noise sample. All of this can be done in the field in about 1 day. The only additional equipment needed to do field analysis would be a portable computer with graphics capability, similar to that described above in the Data Processing section. With this additional capability, a potential site could be tested for suitability in as little as one 24 hour period and immediately relocated if necessary. In this way, a site may be selected with some confidence during one extended field visit.

VII. CONCLUSIONS

Instruments suitable for PASSCAL field operation should have noise performance no worse than 20 dB. below first class vault or deep borehole instruments at 100 second period. The added expense of obtaining performance better than this may not be cost effective. Instruments should be small, lightweight, rugged, simple to install and operate and should be as impervious to the environment as possible.

Of concern in posthole installations is the atmospheric induced noise at periods greater than 30 seconds. Surface installations in soil are quite susceptible to this long period noise which may be the biggest obstacle to successful field operation.

Operation to 100 second period with seismically meaningful results is possible under field conditions with rather simple posthole installations. However, as seen from the variable results obtained from the sites occupied, choice of a long period site does indeed require careful consideration. Long-period posthole sites with background noise levels below those of typical teleseismic signals can be found without much difficulty, but it is not possible to predict the suitability of a given site prior to actual installation. Therefore, after initial site selection and installation, a noise sample should be promptly analyzed while still in the field so that the site may be relocated immediately should it prove to be unsuitable.

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APPENDIX

A. Shake Table Facility

The shake table facility used for calibration of the instruments tested is an upgrade of the facility that existed at DTM and was used for calibration of the Sacks Broadband Seismometers (Sacks, 1966). It was necessary to redesign this facility to make it suitable for generalized sensor testing. The facility consists of two tables, one vertical and one horizontal. Figure A1 shows the system block diagram. Each table is driven by stacked Barium titanate wafers with a time varying high voltage applied. In the original configuration, the vertical table was not really a table, but merely three drive transducers mounted on a baseplate. The three transducers were positioned such that each would drive one foot on the Sacks seismometer. The device was upgraded to a general purpose shake table by adding an aluminum plate of the same dimensions as the base of the seismometer. This proved unsatisfactory, because the aluminum plate used as the table surface had resonances below 100 Hz. The solution was to use an aluminum honeycomb sandwich structure optical bench which was custom made for our application by Newport Research.

Drive voltage is derived from a Ploytec Optronics model P-260 three channel high voltage amplifier which supplies up to 1500 V. The amplifier is driven by a Hewlett Packard model 3325A function generator. Each of the drive transducers are driven by one channel of the amplifier. The output of the function generator is split three ways through three resistive pads. These pads allow independent adjustment of the applied voltage to the transducers. By using a Trans Tech LVDT, the input pads were adjusted so that all three transducers on the vertical table produced equal displacement, thereby allowing the table to generate pure vertical motion. The two transducers on the horizontal table were adjusted in a similar manner to eliminate any rotational motion. Output from the instruments is amplified and recorded digitally on an Earth Data EDR-8000 16 bit digital recorder. Frequency and amplitude parameters of the function generator as well as recording parameters of the digital recorder are programmable over an IEEE 488 bus which is controlled by a dedicated microcomputer. Subsequent to the recording of a frequency sweep on one of the tables, the raw data were transferred over the 488 bus to the microcomputer for analysis and plotting. Plotting was done on a Hewlett Packard model 7475A six pen plotter.

B. Instrument Response

Response curves for the instruments used in this study are presented in Figure A2. These curves, which were used for instrument correction, were obtained from the manufacturer's specifications in the case of the Guralp horizontal and from Farrel and Berger (1979) for the Geotech horizontal sensor. The Geotech vertical sensor's response curve should have been the sams as the horizontal, but it wasn't because an incorrect component value was in the instrument's feedback electronics as received from the manufacturer. Therefore, the Geotech vertical sensor response curve used for this study was obtained experimentally from shake table tests done at DTM. For completeness, the Guralp vertical sensor's response curve was also obtained experimentally, although it closely matched that stated by the manufacturer.

Table 1. A tabulation of each site and its location. Site numbers refer to numbers on Figure 1 and in tables 2 and 3. The site name is either the name of the National Park within which the site was located or, if not in a National Park, the name of the nearest town. Latitudes are in degrees north and longitudes are in degrees west. Elevations are in meters above sea level.

SITE LOCATIONS

SITE #	SITE	STATE	LATITUDE	LONGITUDE	ELEVATION
1	DTM Cyclotron Tunnel	Washington, DC	38.96	77.06	67
2	Blacksburg	Virginia	37.21	80.42	634
3	USGS Albuquerque	New Mexico	34.95	106.46	1740
4	Petrified Forest	Arizona	35.09	109.75	1730
5	Sunset Crater	Arizona	35.38	111.53	2100
6	Pinon Flat	California	33.61	116.46	1280
7	Kings Canyon	California	36.80	118.59	1555
8	Lassen Peak	California	40.56	121.30	1866
9	Crater Lake	Oregon	42.88	122.10	2012
10	John Day Fossil Beds	Oregon	44.56	120.22	622
11	Yellowstone	Wyoming	44.89	110.68	2171
12	Stickleyville	Virginia	36.74	82.83	680

Table 2. A tabulation of each site's basic characteristics. Site numbers refer to numbers on Figure 1 and in tables 1 and 3. Province refers to the physical province the site was located in. The rock type refers to the country rock of the site and substrate is the material on which the sensor was placed. The vegitation is that which was growing within about 0.5 km. of the site.

SITE CHARACTERISTICS

SITE #	SITE	PROVINCE	ROCK TYPE	SUBSTRATE	VEGETATION
1	DTM Cyclotron Tunnel	Piedmont	Gneiss	Clay soil	Sparse Oak
2	Blacksburg, Va.	Valley and Ridge	Limestone	Terra Rosa	Pasture
3	USGS Albuquerque	Basin and Range	Granite	Sandy soil	Sagebrush
4	Petrified Forest	Colorado Plateau	Siltstone	Sand	Grass, Sage
5	Sunset Crater	Colorado Plateau	Basalt	Basalt	None
6	Pinon Flat	Pacific Border	Granite	Sandy soil	Pinion Pine
7	Kings Canyon	Sierra Nevada	Granite	Granite	Pine forest
8	Lassen Peak	Cascade Range	Basalt	Diatomatious earth	Pine and field
9	Crater Lake	Cascade Range	Diorite	Diorite	Pine forest
10	John Day Fossil Beds	Columbia Plateau	Basalt	Pediment gravel	Grass, Cholla
11	Yellowstone	Middle Rocky Mts.	Basalt	Basalt	Mixed forest
12	Stickleyville, Va.	Valley and Ridge	Limestone	Terra Rosa	Oak forest

Table 3. A comparison of noise levels from all sites at 20 and 100 second periods. Values are in decibels relative to the low noise model of Peterson (1980). Site numbers refer to numbers on figure 1 and in tables 1 and 2.

		SITE RESULTS			
SITE #	SITE	V (20 s)	H (20 s)	V (100 s)	H (100 s)
1	DTM Cyclotron Tunnel (Vault)	13	17	21	41
	(Posthole)	16	17	35	45
2	Blacksburg, Jan 3 (Vault)	16	21	30	32
	Jan 3 (Posthole)	24	28	46	54
	Jan 7 (Vault)	2	8	16	32
	Jan 7 (Posthole)	-	22	-	50
3	USGS Albuquerque (Vault)	8	10	10	33
	(Posthole)	12	16	21	40
4	Petrified Forest	2	6	16	29
5	Sunset Crater	0	31	22	64
6	Pinon Flat	0	8	16	24
7	Kings Canyon	2	8	24	39
8	Lassen Peak	2	31	21	61
9	Crater Lake	1	21	16	46
10	John Day Fossil Beds	3	10	31	42
11	Yellowstone	6	20	34	43
12	Stickleyville, Va.	10	19	43	45

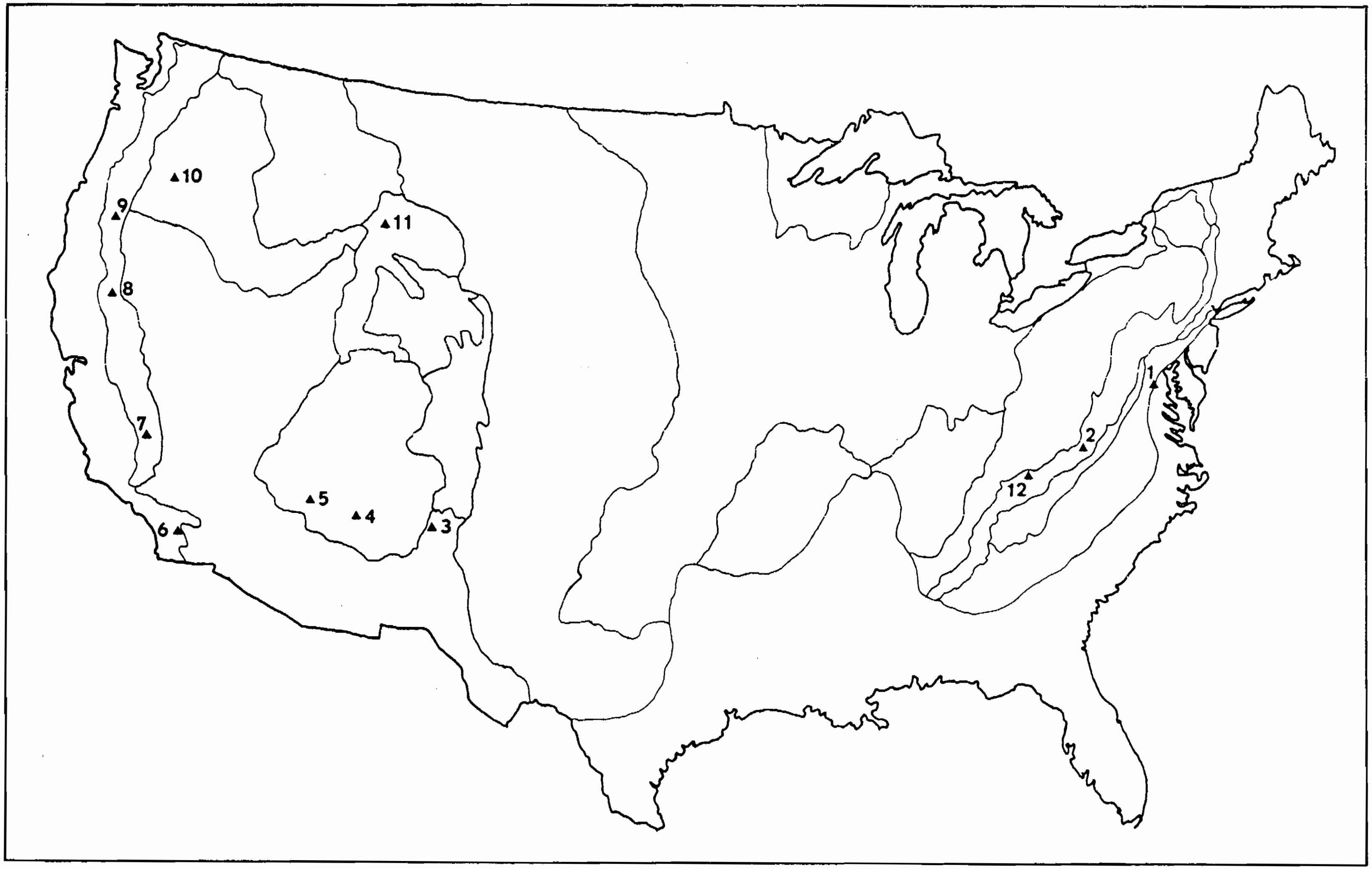


Figure 1. Geographic location of the 12 sites occupied during this study. Delineated areas are the geologic provinces (Harris and Kiver, 1985). The site numbers refer to numbers in tables 1, 2 and 3.

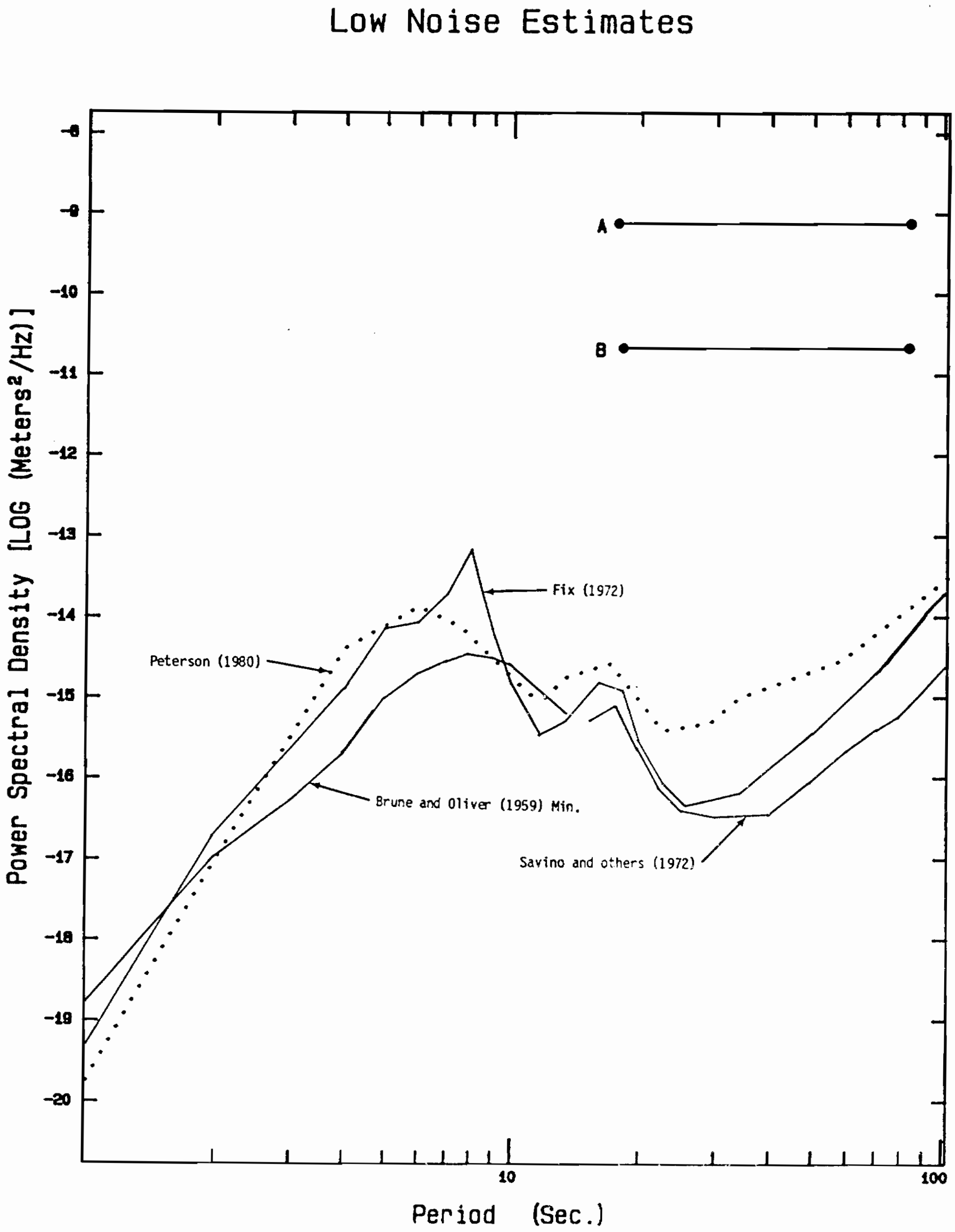


Figure 2. Estimates of earth noise made by various authors. The curves labelled A and B represent ground displacements that would be expected from earthquakes of surface wave magnitudes 4.8 and 4.0, respectively at a distance of 30 degrees. The Low Noise Model is from Peterson (1980) and appears in Figures 4 through 12. Multiplying the amplitude scale by 10 converts the units into decibels relative to 1 meter squared/Hz.

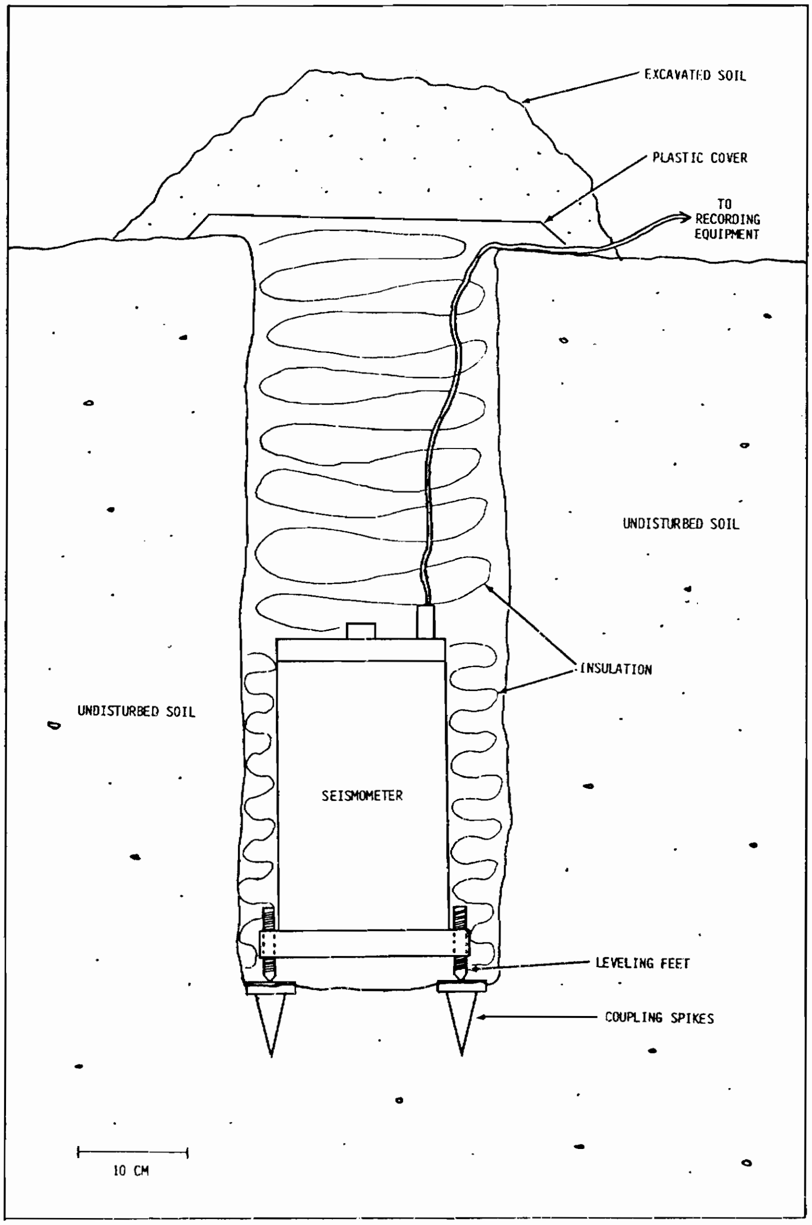


Figure 3. A typical field installation. Brass spikes are driven into the bottom of the hole to provide coupling and a firm foundation. Convection currents and rapid temperature changes are eliminated by filling the hole around and above the sensor with insulation. A rigid plastic cover was placed over the hole and covered with the excavated soil.

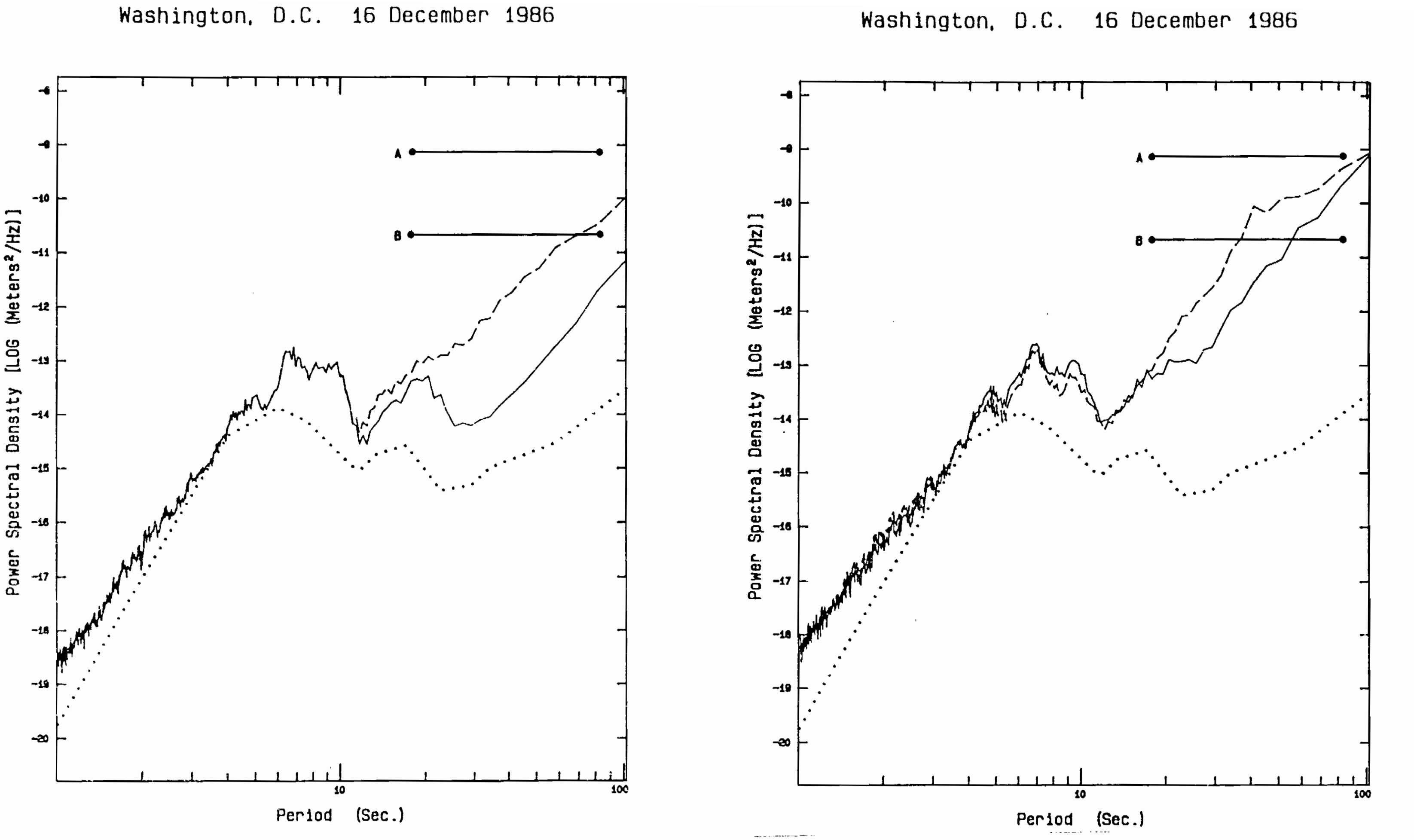


Figure 4. Spectra of noise recorded at DTM in Washington, D.C. Vertical is on the left and horizontal on the right. The Geotech instruments (solid lines) were placed in the vault near the Shake Table Facility. The Guralp instruments (dashed lines) were in postholes about 100 m. horizontal away from the vault. All else is the same as in Figure 2.

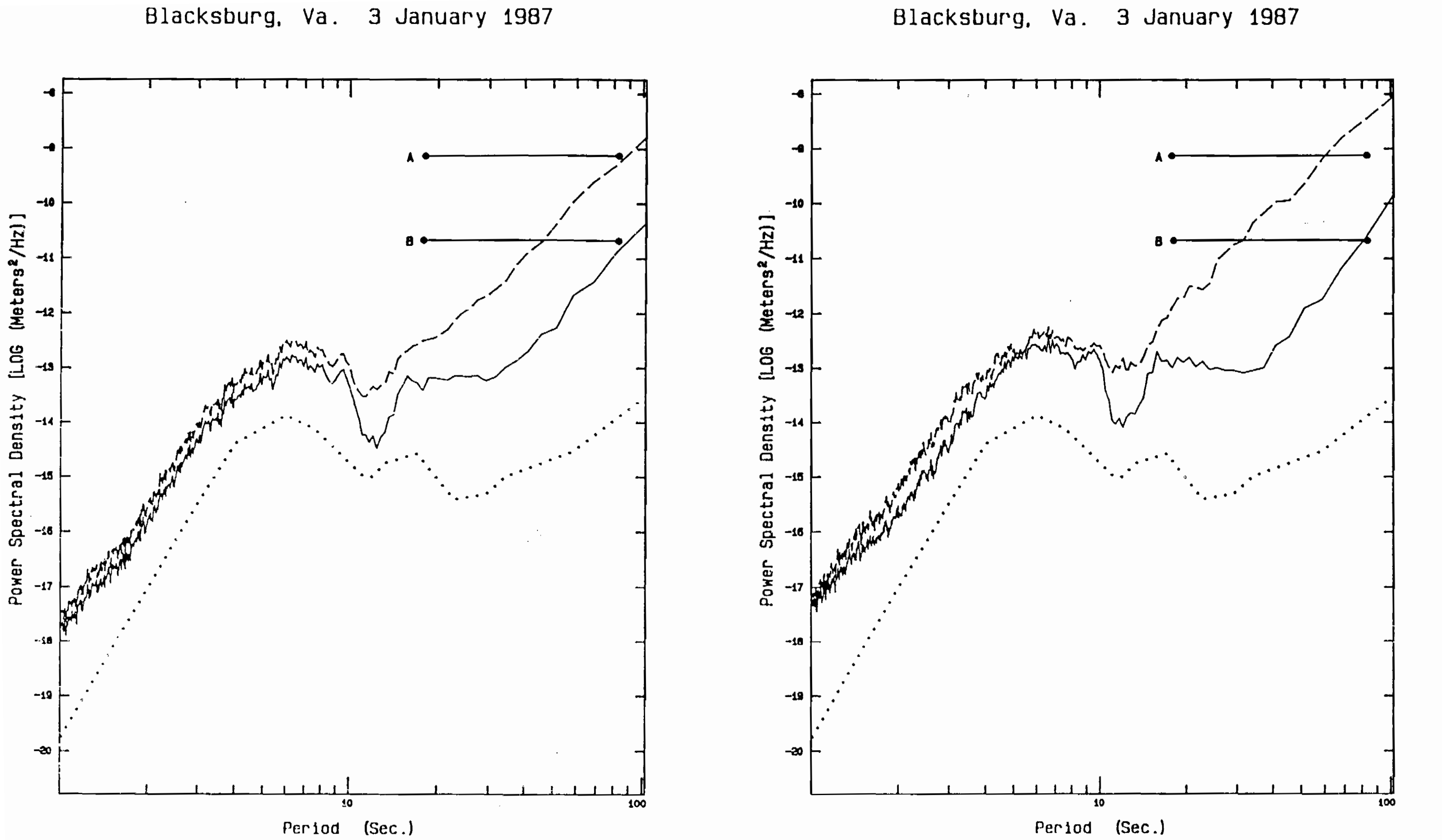


Figure 5. Spectra of noise recorded at the WWSSN vault in Blacksburg, Va. on 3 January 1987. The Geotech instruments (solid lines) were placed on the short period pier in the vault and the Guralp instruments (dashed lines) were in postholes outside of the vault. All else is the same as in Figure 4.

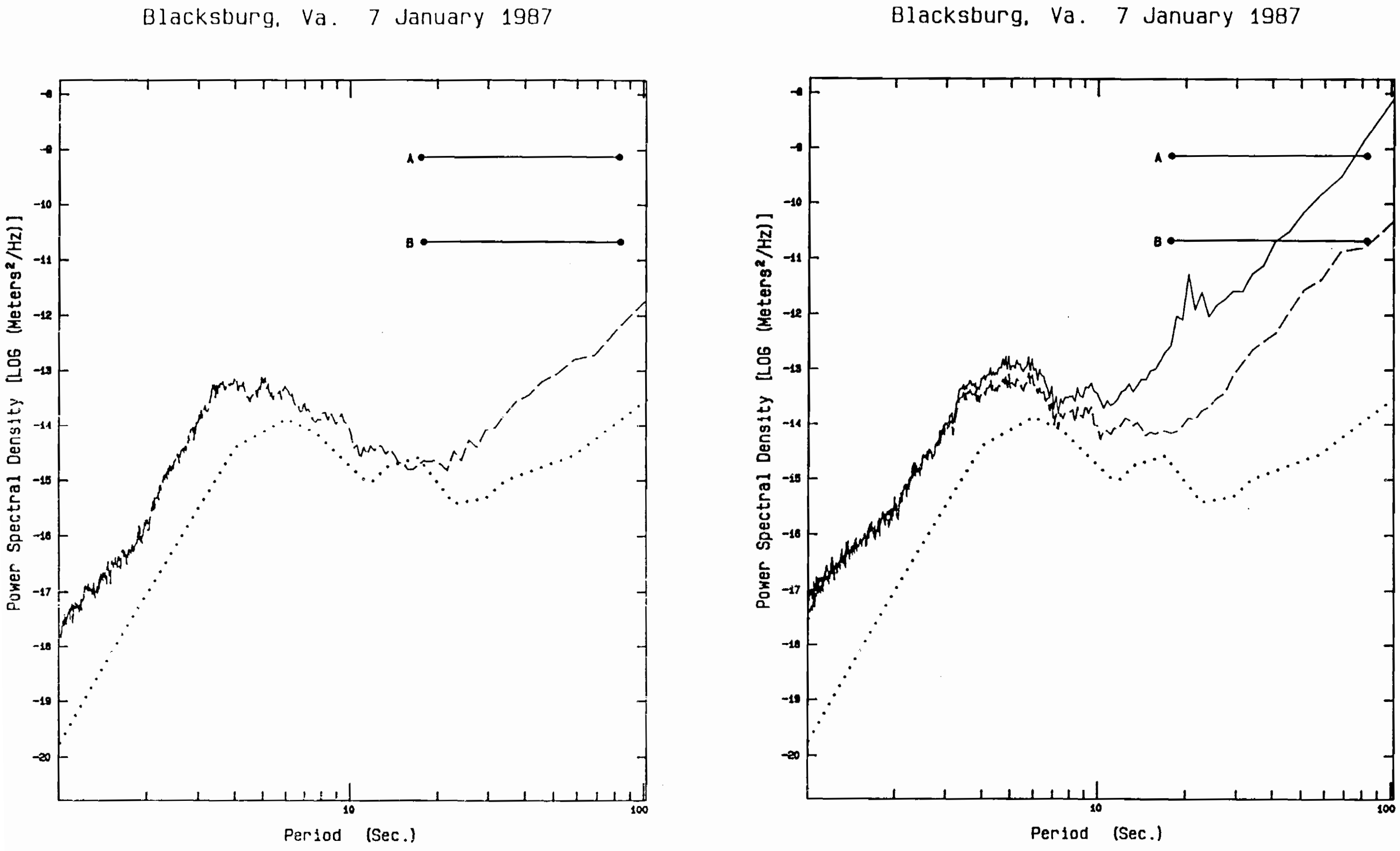


Figure 6. Spectra of noise recorded at the WWSSN vault in Blacksburg, Va. on 7 January 1987. The Guralp instruments (dashed lines) were placed on the short period pier and the Geotech instruments (solid lines) were in postholes. Equipment failure prevented recording of the Geotech vertical. All else is the same as in Figure 4.

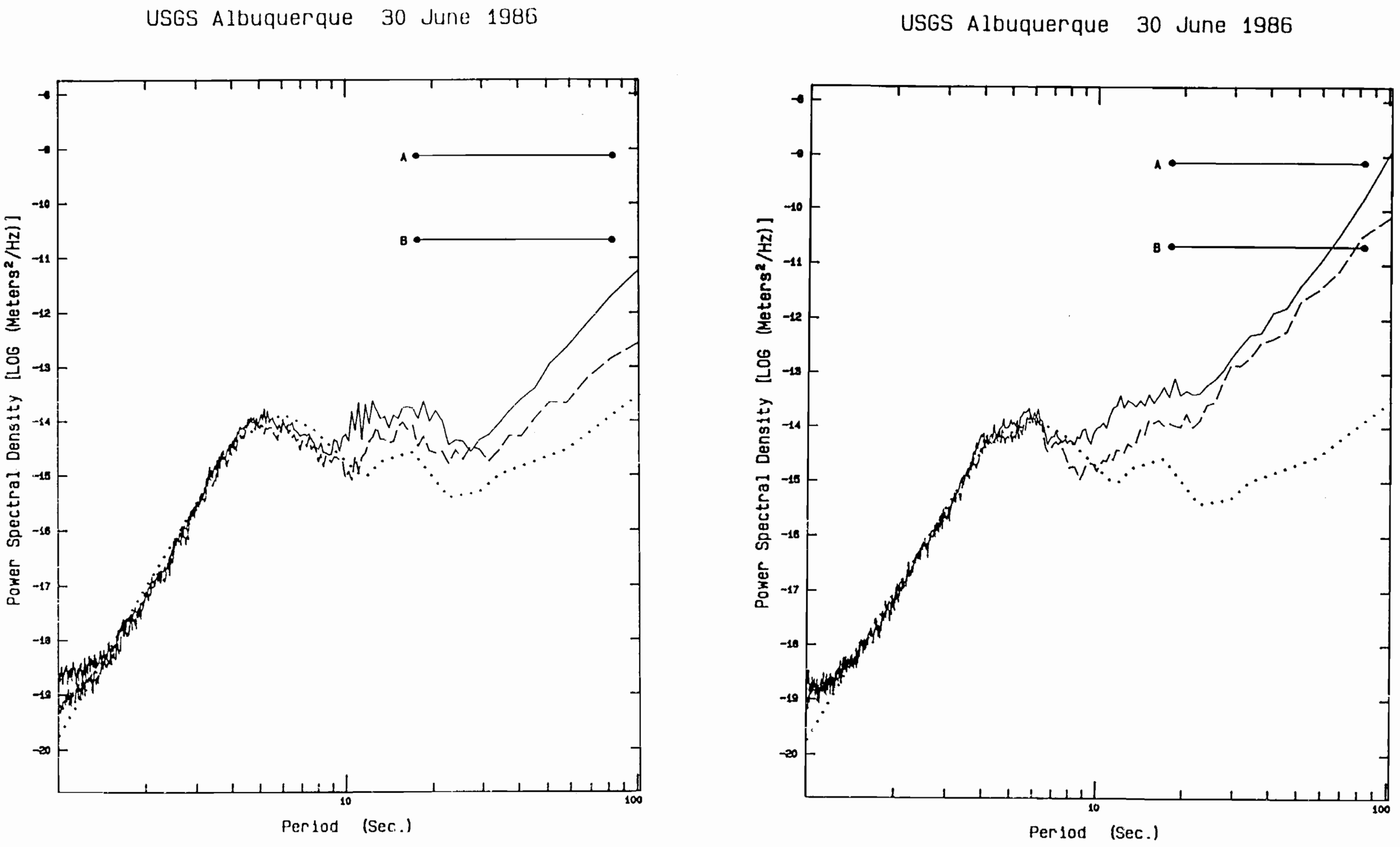
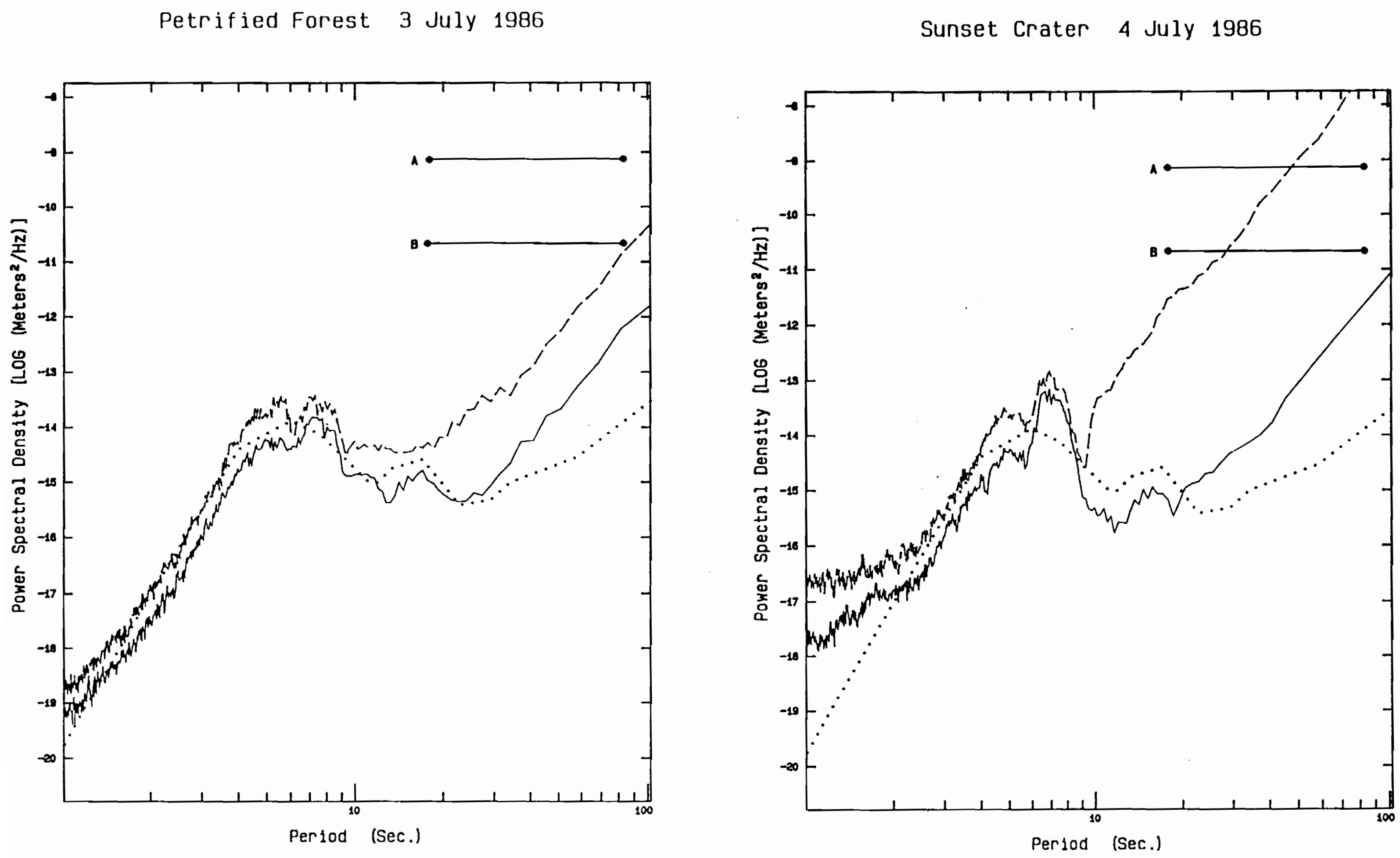


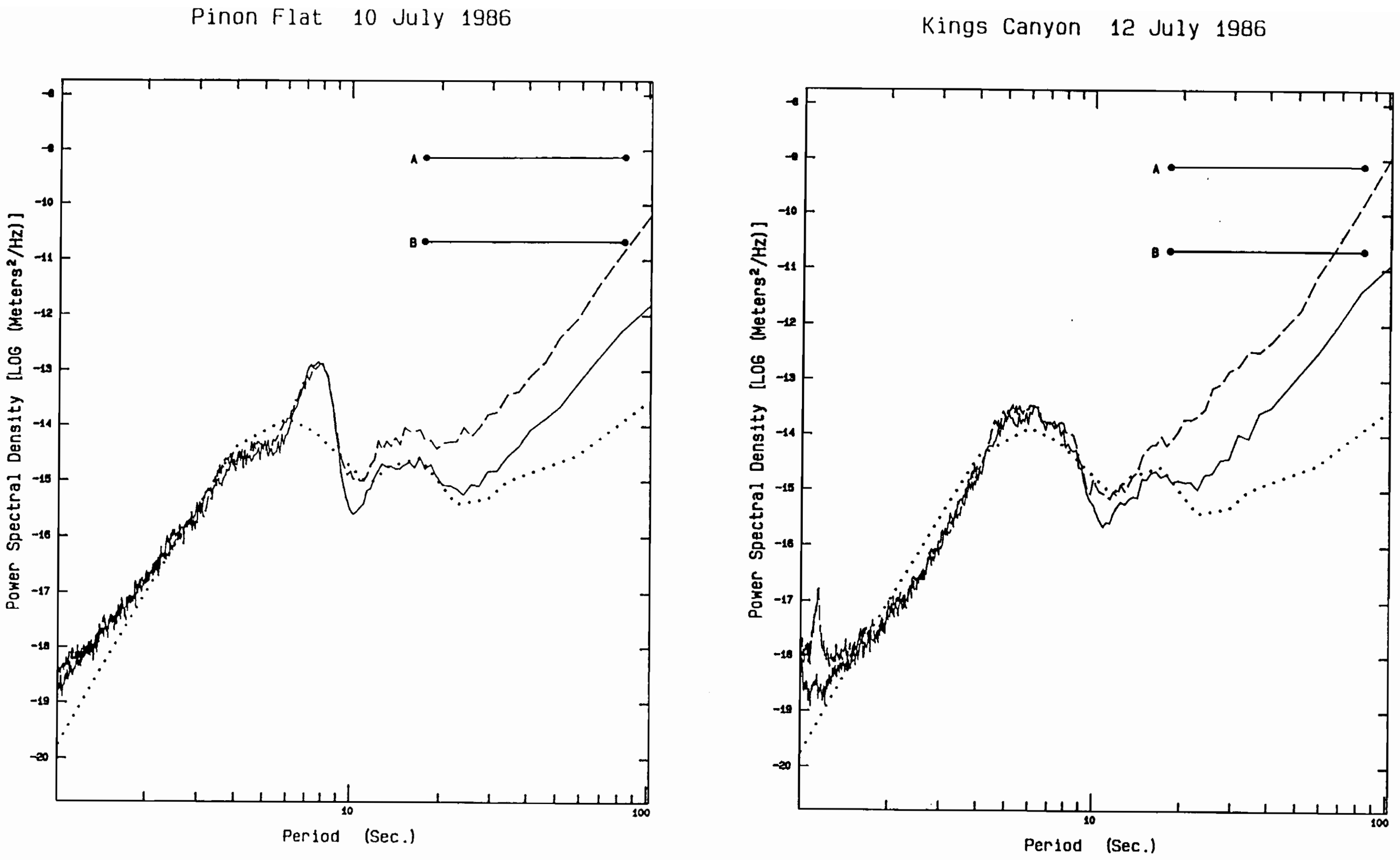
Figure 7. Spectra of noise recorded at the seismic vault of USGS at Albuquerque, New Mexico. The Streckeisen instruments (dashed lines) were permanently installed inside the vault. The Geotech instruments (solid lines) were in postholes above the vault. All else is the same as in Figure 4.



Petrified Forest 3 July 1986

Sunset Crater 4 July 1986

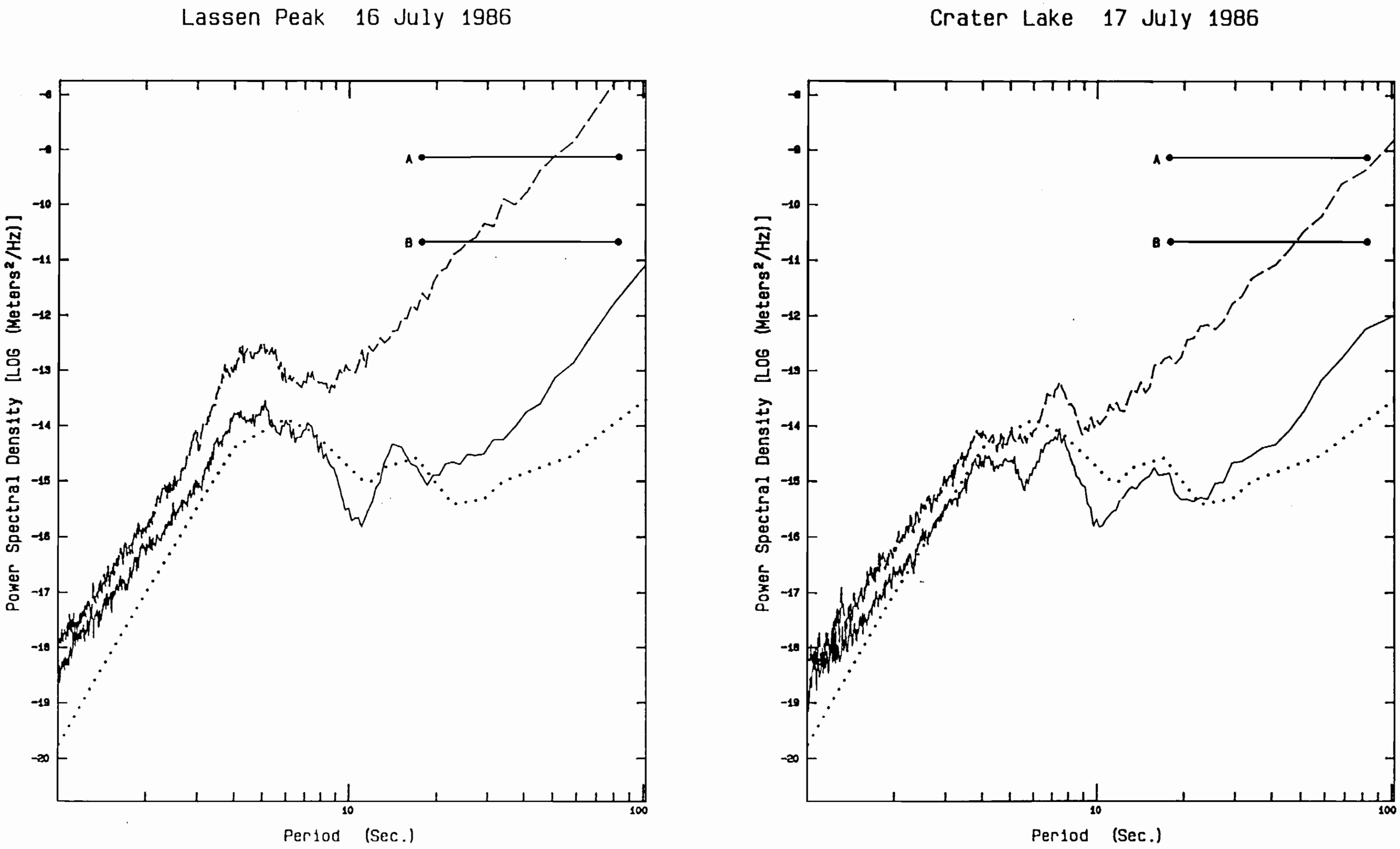
Figure 8. Spectra of noise recorded from sites located on the Colorado Plateau. One site was in the Painted Desert and the other was in the San Fransisco Mountains north of Flagstaff, Arizona. The solid lines are the Geotech vertical instrument and the dashed lines are the Geotech horizontal instrument. The dotted line is the Low Noise Model after Peterson (1980). Curves A and B are the same as in Figure 2.



Pinon Flat 10 July 1986

Kings Canyon 12 July 1986

Figure 9. Spectra of noise recorded at sites in southern California. Pinon Flat is a geophysical instrumentation testing station maintained by UCSD. Kings Canyon is in the Sierra Nevada Mountains. Both sites had noise levels low enough to permit meaningful seismic investigations. All else is the same as in Figure 8.


Lassen Peak 16 July 1986

Crater Lake 17 July 1986

Figure 10. Spectra of noise recorded at sites in the southern Cascade Mountains. Both sites appeared to have a significant tilt component because the horizontal long-period noise was considerably higher than the vertical. All else is the same as in Figure 8.

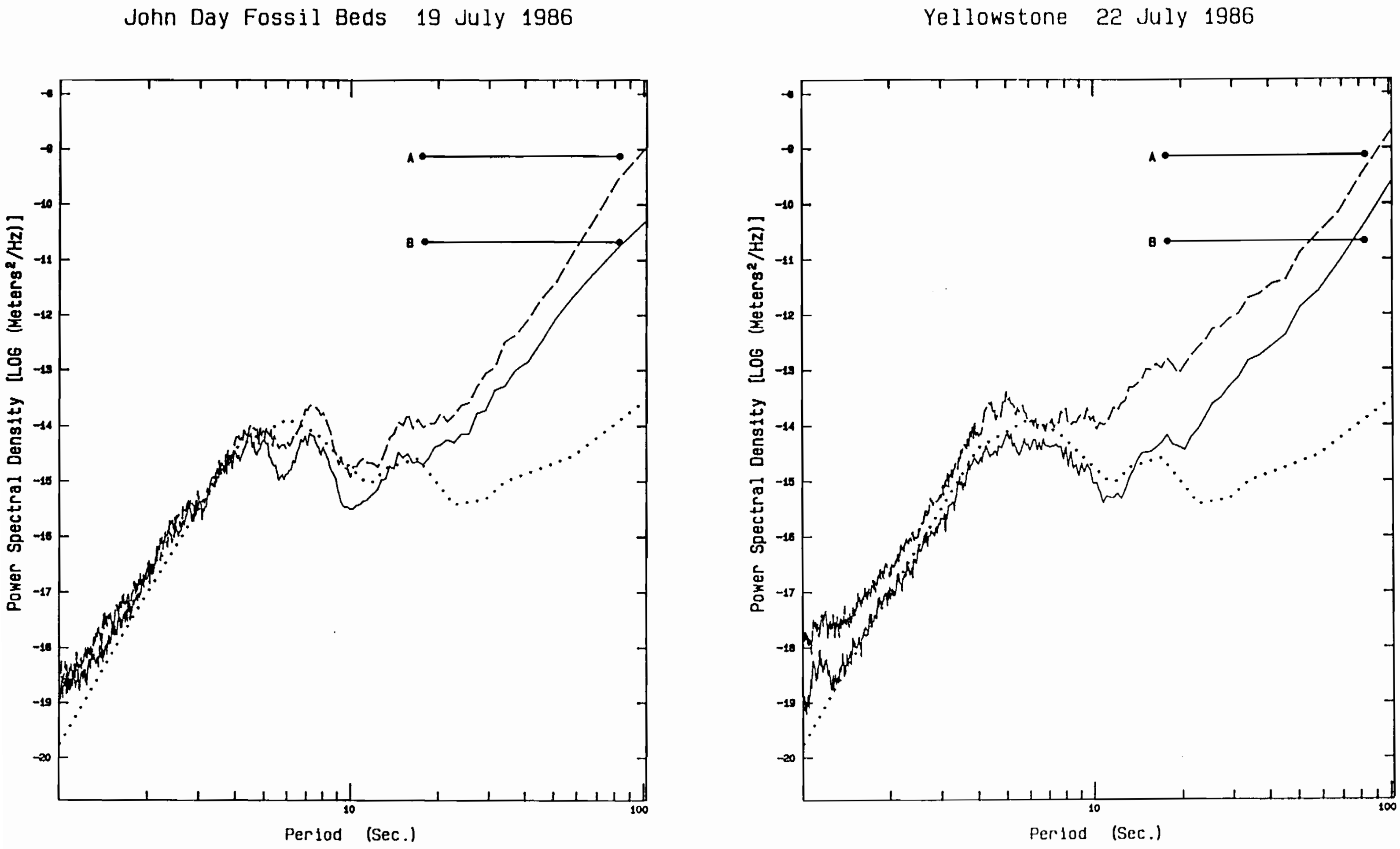


Figure 11. Spectra of noise recorded from a site on the Columbia Plateau (John Day Fossil Beds) and a site in the Yellowstone Caldera. Although from two quite different geologic settings, the noise levels from these tow sites are similar across the frequency band. All else is the same as in Figure 8.

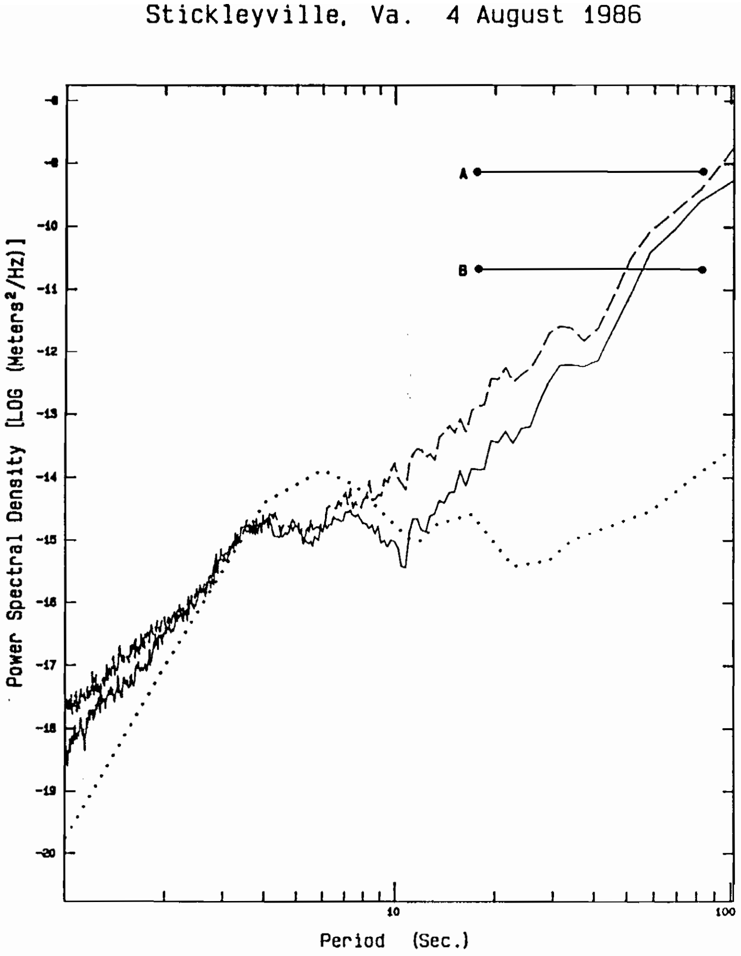


Figure 12. Spectra of noise recorded from the Valley and Ridge province in the central Appalachian Mountains. This site had elevated noise levels at both short and long periods. All else is the same as in Figure 8.

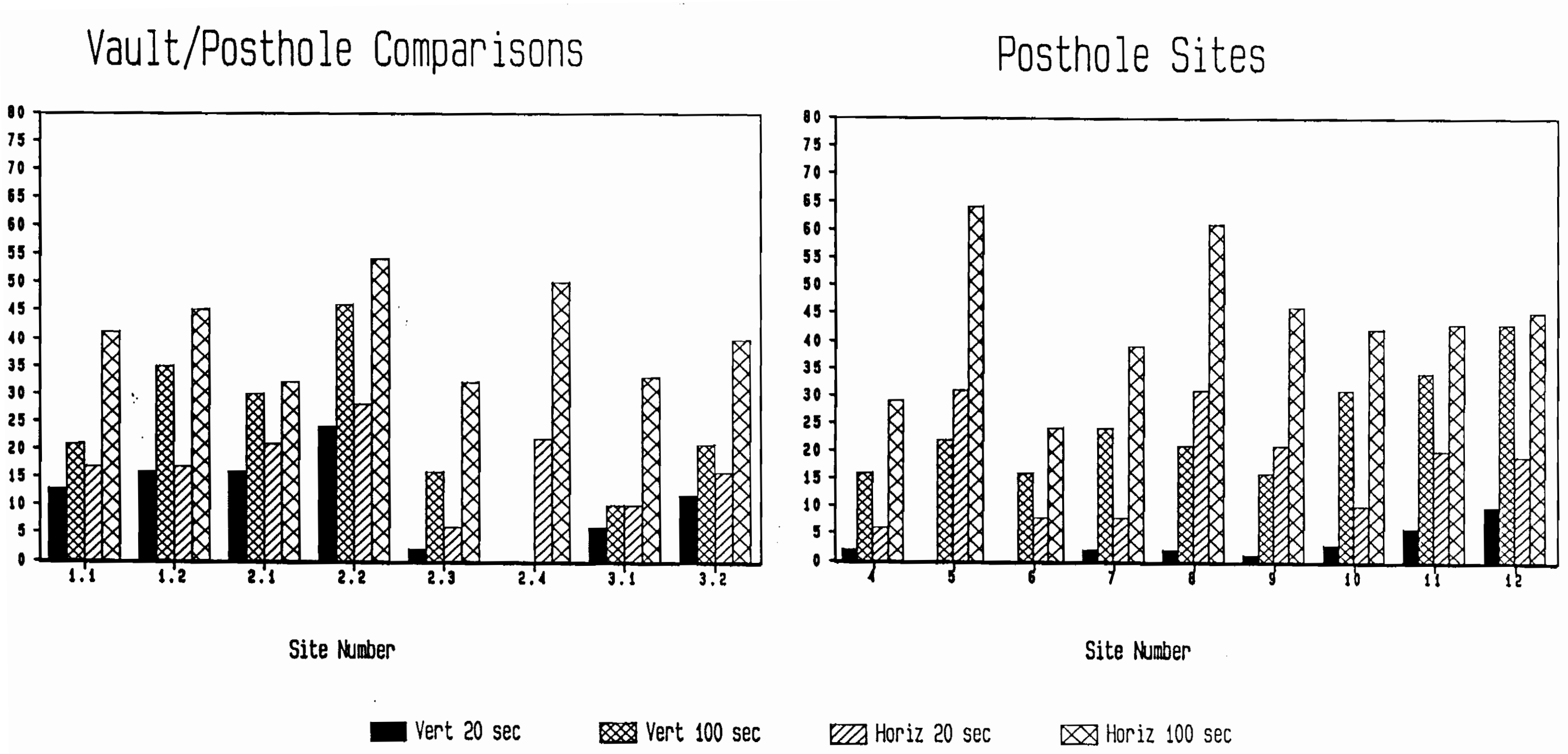


Figure 13. A comparison of noise levels at 20 and 100 seconds from all sites. Values (Y axis) are in decibels relative to the Low Noise Model by Peterson (1980). Site numbers refer to numbers given in Figure 1 and tables 1 - 3.

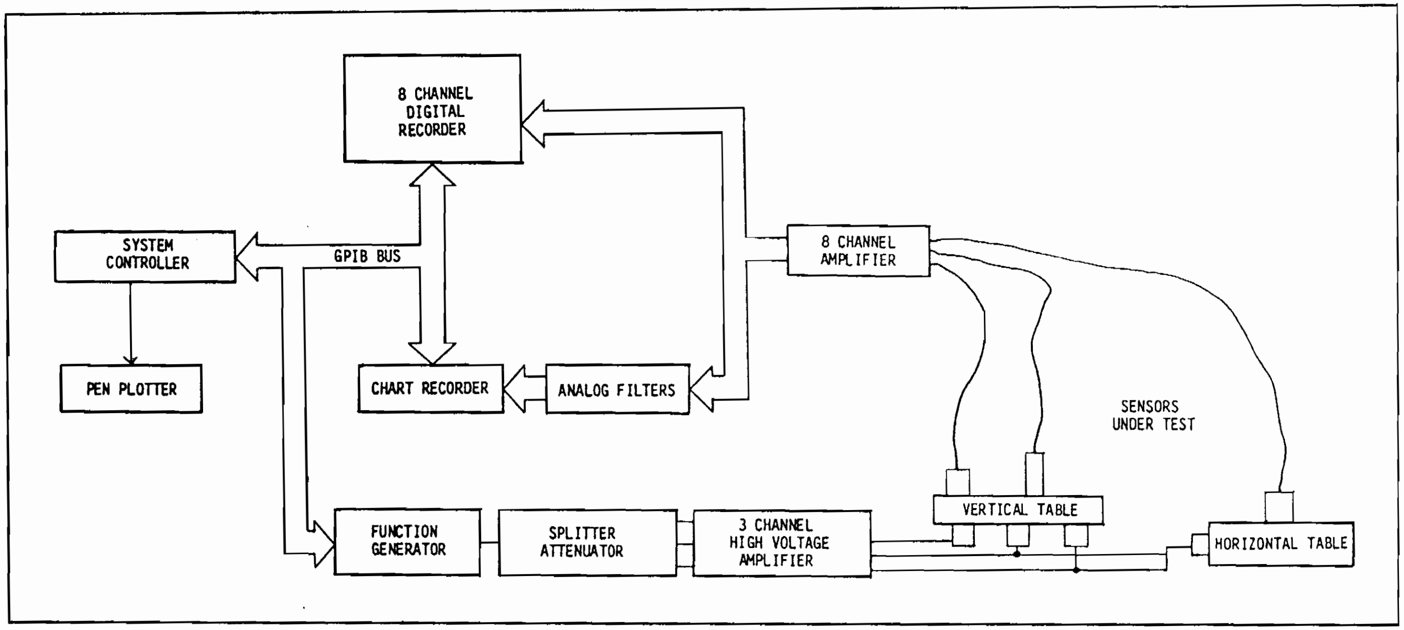


Figure A1. System block diagram of the DTM Shake Table facility showing the major components and their relationships. A sinusoid signal originates in the Function generator. This signal is split and amplitude trimmed before going to the 3 channel transducer driver amplifier. The three in-phase amplified signals are applied to the drive transducers to provide sinusoid table motion proportional to the applied voltage. Outputs from sensors under test are amplified, filtered and recorded in both analog digital formats. The digital data are transferred over the IEEE-488 (GPIB) to the system controller for processing.

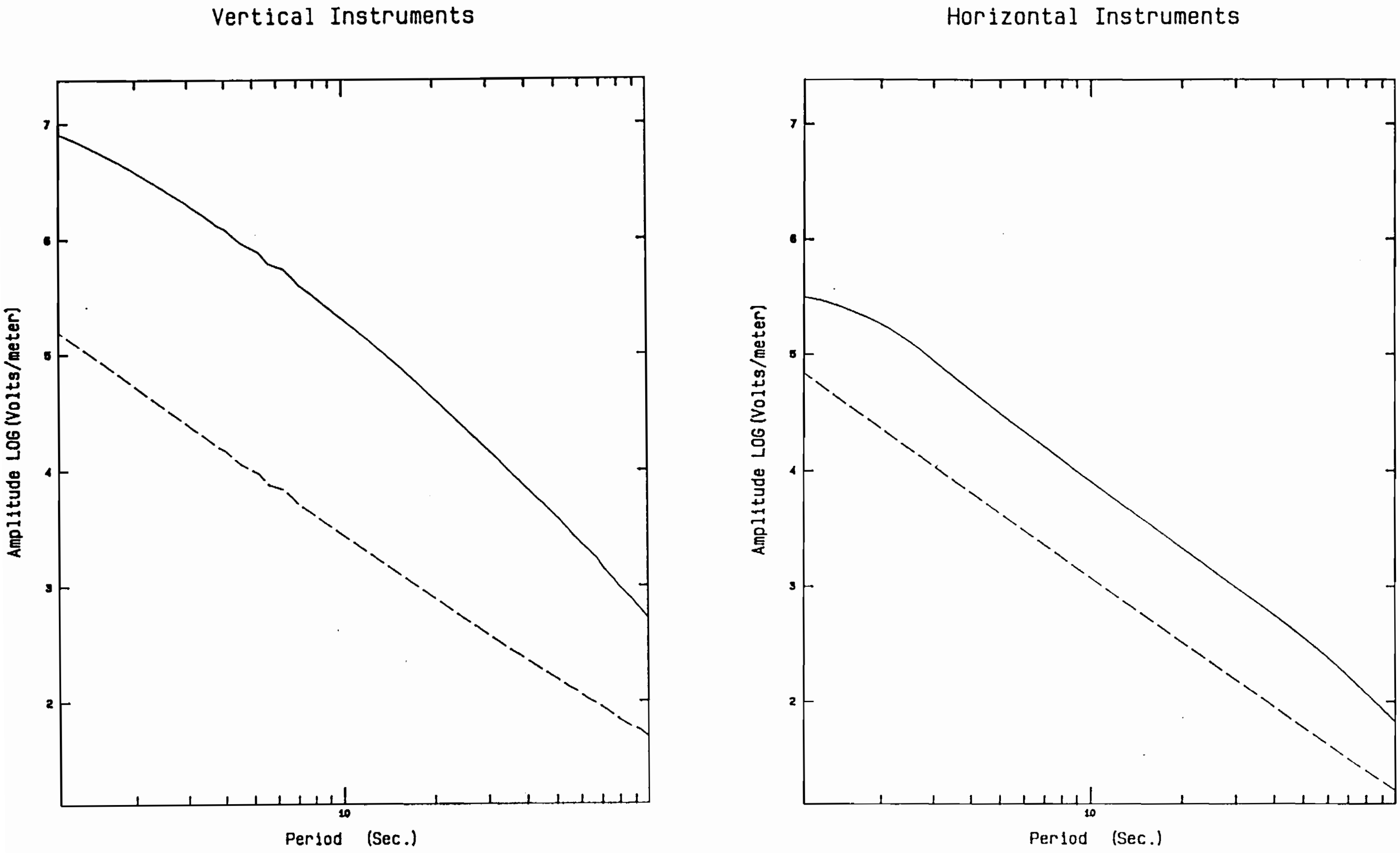


Figure A2. Response curves used for instrument correction during data processing. Curves for the vertical instruments were obtained from shake table tests and curves for the horizontal instruments came from the manufacturer's specifications. The solid lines are the Geotech instruments and the dashed lines are the Guralp instruments.

VITA

of

David Charles Dalton

Address: 40 Second Street
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Birth Date: 9 July, 1952

Marital status: Married, no children
Wife: Virginia M. Dalton, PhD
Assoc. Professor of Biology,
Radford University

Educational Background

Undergraduate: County College of Morris
Dover, New Jersey
Fall, 1970 through Spring, 1972
Major: Electronics
Degree: Associate of Applied Science

Radford University
Radford, Virginia
Fall, 1981 through Spring, 1984
Majors: Computer Science, Mathematics, Statistics
Minor: Geology
Degree: Bachelor of Science (Cum Laude)

Graduate: Virginia Polytechnic Institute
Blacksburg, Virginia
Fall, 1984 to present
Major: Geophysics
Degree: Master of Science

WORK EXPERIENCE

Bell Telephone Labrotories
Madison, New Jersey
June, 1972 through November, 1974
Title: Field Technican
Responsibilities: Off-line trouble analysis of all computer and radar hardware associated with the Safeguard Anti-ballistic missle system under development at that time. Also primary responsibility for maintenance of specific on-line equipment.

Universial Technology
Cedar Grove, New Jersey
November, 1974 through October, 1975
Title: Senior Technican
Responsibilities: Set up and implement a field return repair department for digital communications equipment manufactured by the company. Included the design of test equipment and development of testing procedures. Also design and implementation of low volume custom projects.

Digital Computer Controls
Fairfield, New Jersey
October, 1975 through October, 1976
Title: Engineering Technican
Responsibilities: Final stages of design of the minicomputers produced by the company. Development of test equipment and test procedures suitable for the manufacturing environment. Training of manufacturing technicans for testing and troubleshooting of new products.

Western Electric Company
Richmond, Virginia
October, 1976 through October, 1978
Title: Control Systems Technician
Responsibilities: Integration of new design electronic test sets into the production environment. Also electronic maintenence of numierical controlled equipment and dedicated minicomputers involved in the large scale manufacture of printed circuit boards.

Data General Corporation
Richmond, Virginia
October, 1978 through September, 1981
Title: Field Engineer
Responsibilities: Installation, maintenence, trouble analysis and repair of customer owned computer systems manufactured by the company.

Virginia Polytechnic Institute
Department of Geological Sciences
Blacksburg, Virginia
August, 1984 through December, 1985
Title: Research Assistant
Responsibilities: Development of video and hardcopy graphics modules and device drivers. Adapt, implement and maintain an earthquake monitoring and detection system. Maintain RMS and VAX/VMS operating systems and DECnet communications.

Carnegie Institution of Washington
Department of Terrestrial Magnetism
5241 Broad Branch Road
Washington, D.C. 20015
January, 1986 through April, 1987
Title: Research Fellow
Responsibilities: Investigations into long period seismic instrumentation. These investigations required hardware and software design and development of specialized calibration and field equipment. Duties included both field and laboratory work.

March, 1983 through present
Independent contract
Development of field equipment for biological research. Equipment includes infrared imaging and recording, ultrasound detection, insect collection and communication.

Private hardware/software consulting for small computer systems of individuals and local businesses. Types of consulting ranged from hardware/software systems integration to the development of inventory control and billing systems.
January, 1982 through present

David C. Dalton