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ABSTRACT

A total of nine portable broadband stations were deployed across the Arabian Shield from November 1995 to March 1997. The stations consisted of STS-2 seismometers recorded continuously at 40 samples per second on RetTek dataloggers.

Noise studies showed that most stations were exceptionally quiet with noise levels near the USGS low noise model for frequencies higher than 0.1 Hz. At lower frequencies, the horizontal components showed high noise levels, possibly due to instrumental characteristics. High frequency (>1 Hz) noise varied as much as 10 dB between day and night for some stations (RAYN and TAIF) while for more isolated stations (HALM) was constant. Seasonal noise levels also varied , with April to June being the quietest months. Slight changes in peak microseism frequency also occurred seasonally.

The quietest stations were HALM, RAYN, AFIF, and UQSK, all of which were located in central Saudi Arabia and show noise levels near the low noise model for frequencies between 0.1 and 4 Hz. The optimal site for a new quiet station would be near HALM which showed very little diurnal variations of cultural noise.

These stations appear to be among the best sites in the world for the properties of detection thresholds and ground noise levels. Events with mb > 3.5 could be detected at distances from 10 to 100 degrees.

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INTRODUCTION

A seismic deployment consisting of 6 seismographs arranged in two linear arrays was carried out in Saudi Arabia from November 1995 to March 1997 (Figure 1). One array consisting of the stations RAYN, HALM, and RANI was pointed in the direction of high seismicity in the Zagros. Earthquakes in this region occur along the eastern Arabian Plate boundary where it collides with the Persian Plate [1]. Seismic ray paths along this array from Zagros events should have entirely intraplate paths. The stations are between 900 and 1500 km from the nearest Zagros source.

The second linear array consists of stations AFIF, RANI, BISH, and SODA. It is aligned with events in the highly seismicly active area of the Afar triple junction in Africa and events in the Caucasus.

The array deployments allowed sampling of regional wave characteristics over a broad area, from numerous source regions. Ray paths traversing virtually all of the Arabian Shield were recorded, given the high seismicity rates characteristic of most active areas around the shield.

One important aspect of seismic characterizations is an estimate of the signal-to-noise properties at a particular site. The ambient noise spectra over a variety of conditions provides an estimate of the theoretical performance relative to other sites and to accepted noise models. A variety of near-site conditions which affect the ambient noise include cultural activities, weather and wind patterns, local seismicity, and proximity to oceans or seas. The teleseismic and regional signal reception levels are affected more by regional structure than the site characteristics.

This paper describes the power spectral density (PSD) at nine stations in the Arabian Shield and the Platform (Table 1). It also provides consistent variations in noise levels with time. The study is useful in identifying specific sites for future deployments, in calibrating detection thresholds, and in identifying instrumental problems.

SEISMOTECTONICS OF THE ARABIAN PENINSULA

The Arabian Plate is a relatively small lithospheric plate whose boundaries are representative of different types of plate boundaries. On the west, rifting in the Red Sea has split a large Precambrian shield into two distinct parts (Arabian and Nubian Shields). This tectonic boundary is characterized by complex faulting and Tertiary dike injections and volcanism. To the south, similar rifting running in a more east-west direction through the Gulf of Aden has separated the Arabian Peninsula from Africa. To the northwest, the Gulf of Aqabah is a continuation of the Dead Sea transform. The northern and northeastern boundaries of the Arabian Plate are areas of continental collision, with the Arabian Plate colliding with the Persian Plate.

Table 1. Geographic Coordinates and Geology of Nine Broadband Seismic Stations Deployed in the Arabian Shield and Platform.

Station	latitude	longitude	elevation (m)	geology
AFIF	23.9310	43.0400	1116	Gneiss
BISH	19.9228	42.6901	1379	Granitic
HALM	22.8454	44.3173	930	Granitic
RANI	21.3116	42.7761	1001	Granitic
RAYN	23.5220	45.5008	792	Granitic
RIYD	24.7220	46.6430	717	Limestone
SODA	18.2921	42.3769	2876	Metamorphic
TAIF	21.2810	40.3490	2050	Granitic
UQSK	25.7890	42.3600	950	Granitic

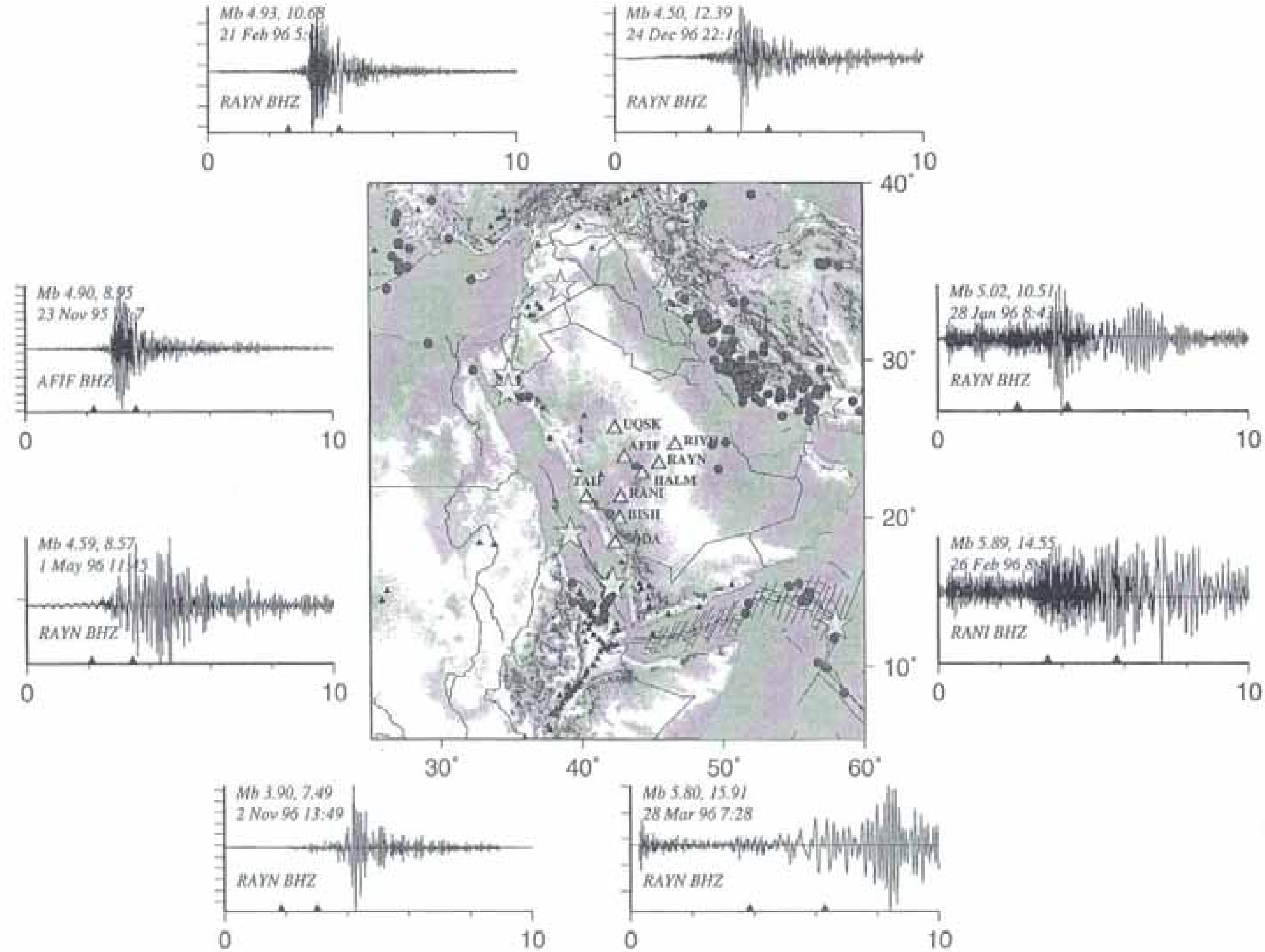


Figure 1. Location map of nine seismic stations deployed in the Arabian Shield, recorded earthquakes, and associated waveforms. Small filled triangles denote Holocene volcanics, small circles mark recorded events, open triangles mark station locations, and stars mark locations of waveforms shown on the Figure. Undersea faults and plate boundaries also shown.

Structurally, the Arabian Peninsula consists mainly of the Arabian Shield in the west and the Arabian Platform in the east. The Arabian Shield consists of a large outcrop of stratified volcanic and plutonic rocks of Precambrian age. Cenozoic basalts overly shield rocks in some areas. To the east, shield rocks are bordered by the sedimentary rocks of the Arabian Platform which makes up about two thirds of the Arabian Peninsula. It includes the interior homocline, the interior platform, and basins.

Mooney *et al. [2]* interpreted the boundary between the Arabian Shield and the Arabian Platform as a suture zone between crustal blocks of differing composition. They indicated that the Arabian Shield consists of two crustal layers, each about 20 km thick. Average P-wave velocities are 6.3 and 7.0 km/sec, respectively. The depth to the Moho is about 40 km, thinning slightly from northwest to southeast. The P-wave velocity in the upper mantle is 8.0-8.2 km/sec. Prodehl [3] noted that the upper crust of the eastern shield appears to be more uniform than that of the western shield. Al-Amri [4] shows a little higher P-velocity for the upper crust in the Shield than in the Platform and the crust in the western Platform seems to have a greater thickness than in the Shield by about 3 km.

The majority of earthquakes and other tectonic activities are concentrated along the Zagros fold belt, the Dead Sea transform, the Gulf of Aqabah, and the Red Sea belt, which extends from the central Red Sea region south to Afar and then east through the Gulf of Aden. The Arabian Plate is generally marked by very low levels of seismicity. This is not merely an effect of poor network coverage; local seismic networks indicates that microearthquake activity generally originates in the same areas as the teleseismically-located events. The causes of this intraplate seismicity are not well understood. The overall lack of seismicity in the interior of the Arabian Plate suggests that minor internal deformation of the plate is presently occurring.

METHODOLOGY

Each station has a Streckeisen STS-2 broadband seismometer which has a pass band between 0.008 Hz and 50 Hz. Each seismometer is heavily insulated to protect it from the daily changes in temperature and attached to bedrock outcrops whenever possible. The output of the STS-2 is recorded at a sample rate of 40 sps by a 24-bit RefTek RT72A-08 datalogger. The data are stored on a 2 Gbyte SCSI disk. Timing to the station is provided by a local GPS clock [5].

This paper follows the approach of Astiz [6] to estimate the power spectral density (PSD) of the noise. Single days of continuous data were selected pseudo-randomly from the complete recorded dataset. From each sampled day, 15 minute data segments were further randomly selected. Random sampling was used to ensure that periodic effects due to instruments (for example, hourly GPS locks or disk access) do not bias the data. Data segments which fell within 3 hours after large global earthquakes (above magnitude 5.5 in the Harvard CMT catalog) were rejected to avoid contamination of the long period data. Power spectral estimates were then calculated over windows with a length of 32768 samples (819.2 seconds). This window length was chosen to eliminate excessive biasing of the lowest frequencies (about 0.008 Hz for the STS-2) due to the tapering. A 4r prolate taper was applied to the data, and it was then transformed using Fast Fourier Transform (FFT). Windows 32768 points long were selected from the dataset, and the robust PSD was calculated using the weighted median estimate of Chave *et al. [7]*. This robust estimate ensures that isolated outliners do not adversely affect the resulting spectral estimate. The spectra were the averaged over bins of 4 frequencies and converted to acceleration spectra. Because the STS-2 has essentially flat response over the chosen frequency range, instrument response was not removed.

A desirable feature of this approach is that the data are not examined by eye prior to the power spectral estimate, so the analysis reliably estimates the noise levels at that station, rather than providing the quietest possible estimate. Small local and regional earthquakes were included in the estimate; however, the long windows and random estimate minimized their effects [8].

The processing scheme requires several steps: raw data retrieval followed by formatting, quality control, and event association. A Sun Sparc field computer is set up in Riyadh. The data conversion to CSS 3.0 format and quality control are performed. An automatic picking program is used to identify all arrivals. The initial event associations are based on predicted arrivals from a REB origin table using the IASPE191 travel time tables and the actual phase picks. Any recorded events not appearing in the REB catalog are located using just arrivals from the Saudi portable stations. The data are sectioned into an event oriented CSS 3.0 waveform database and distributed to interested users. Operating at 40 samples/second continuously, each station collects 41.5 Mbytes of waveform data per day. Thus, about 250 Mbytes per day for the 6 stations have to be processed.

RESULTS AND INTERPRETATION

Figures 2 through 7 show noise levels as a function of frequency by station and channel, and follow the format of Astiz [G]. The vertical axis is in decibels with respect to acceleration mZ/s^4lHz. In Figures 2, 3, and 4, the black curve shows the vertical (BHZ), east-west (BHE), and north-south (BHN) components. The dashed lines denote the USGS low and highnoise models of Peterson [9]. The low-and-high-noise models are based on a survey of seismic noise worldwide and on modeling of seismic noise. The low-noise-model [9] is a composite of station spectra obtained from many different seismic instruments, vaults, geologic environments, and geographic regions. It is a hypothetical background spectrum that is unlikely to be duplicated at any single location on Earth.

Plots showing duration and seasonal changes are appropriately presented in Figures 5, 6, and 7. Because the deployment was of limited duration, some stations did not record enough data to provide seasonal changes.

Not all stations had an equal number of data points, so some caution should be taken when comparing individual stations. The methodology of this noise study differs from that used to determine the USGS low- and high-noise models and consequently absolute power levels may differ slightly due to bias induced by different tapers and windows [8].

Some data which had known station and instrument problems were not used. This includes HALM data up to day 062 of 1996, which had a much reduced low frequency response.

The vertical components in particular lie near the USGS low noise model except at frequencies higher than 2 Hz. The high-frequency noise is generally due to cultural sources such as vehicles on nearby roads. This effect was especially pronounced for stations RIYD and TAIF, which were located in or near major cities. The horizontal components are significantly noisier at frequencies less than 0.1 Hz. This is most likely due to instrumental and site effects. Because these stations were temporary, the seismometers were not as well-insulated as a permanent station to thermal and other transient effects.

Figures 3 and 4 show the noise levels at each station. The number of observations at each station are shown in the upper right corner. HALM, RAYN, AFIF, AND UQSK are the quietest stations, as expected due to their remote locations and shield emplacement. RIYD, TAIF, and SODA show enhanced high frequency noise which is expected as all are relatively close to large cities.

In general, noise levels are similar for all channels for a given station for frequencies greater than 0.9 Hz. Between 0.9 Hz and roughly 0.1 Hz, the vertical is slightly noisier than the horizontals which is likely due to the characteristic G second (0.17 Hz) world-wide microseism peak. At frequencies less than 0.1 Hz, the horizontal components are much noisier and this creates an obvious discrepancy between the noise levels from the Saudi stations and the low-noise-model for the horizontal long periods. At frequencies greater than 0.1 Hz (10 seconds period), the noise levels between the verticals and the horizontals varies greatly (by up to 40 dB).

Figure 2 shows that the north-south components are slightly noisier than east-west components at frequencies <0.1 Hz. This could be due to the microseisms, which are generally considered to be Rayleigh waves coming from the southern direction (i.e. the Indian Ocean), but that would be expected to cause large amplitudes on the vertical also.

Examination of the data shows that longer period noise is clearly present in the data. This presents a problem for studies using longer period data such as surface wave studies and regional moment tensor inversions, which are forced to depend solely on vertical data for moderate sized events. The source of the noise is not clear. The long period noise often anticorrelates on the two horizontal channels (Figure 8) and consequently a simple rotation will eliminate the noise on one channel at least. The direction of rotation can be determined by polarization analysis or by a simple arctan (x/y) if it is assumed the motion is linear. The 57 degree angle for UQSK (Figure 9) suggests that the long period noise may be due to a single component on the STS-2 seismometer. The components on an STS-2 are 120 degrees from each other with one component pointing south. Therefore, the 57 degree vector is within 3 degrees of one component, which is within the range of an error of measurement or a possible misalignment of the seismometer [8].

An alternate possibility is that the long period noise may be due to small tilts which affect the horizontal more than the verticals because horizontal tilts greatly increase the effect of the local gravity vector. If the tilt is great enough, is quite large compared to the signals normally recorded. These tilts may be due also to prevailing wind direction and transient thermal effects caused by large temperature variations between night and day in the desert. This pattern is true of all stations

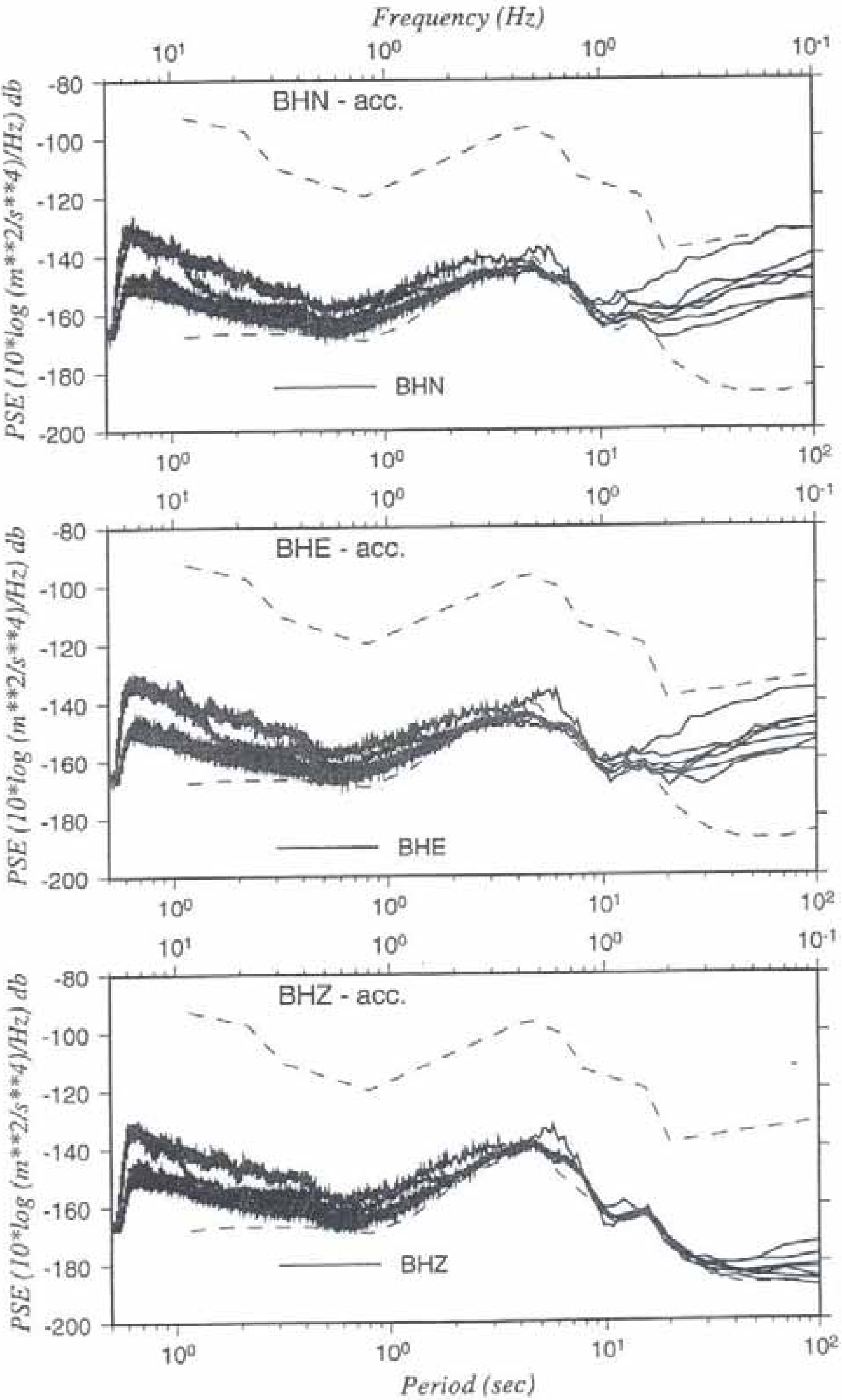


Figure 2. Noise levels at all stations. The black lines show the vertical (BHZ), east–west (BHE) and north–south (BHN) components. The dashed lines denote the USGS low- and high-noise models.

except RIYD, which shows a lower noise on the vertical at almost all frequencies (Figures 3 and 6). This may be due to an instrumental problem.

Based on visual comparison of the Saudi noise plots with the plots showing all Federation of Digital Seismograph Network (FDSN) stations, it appears that the Saudi stations are clearly among the quietest. This is not too surprising, given

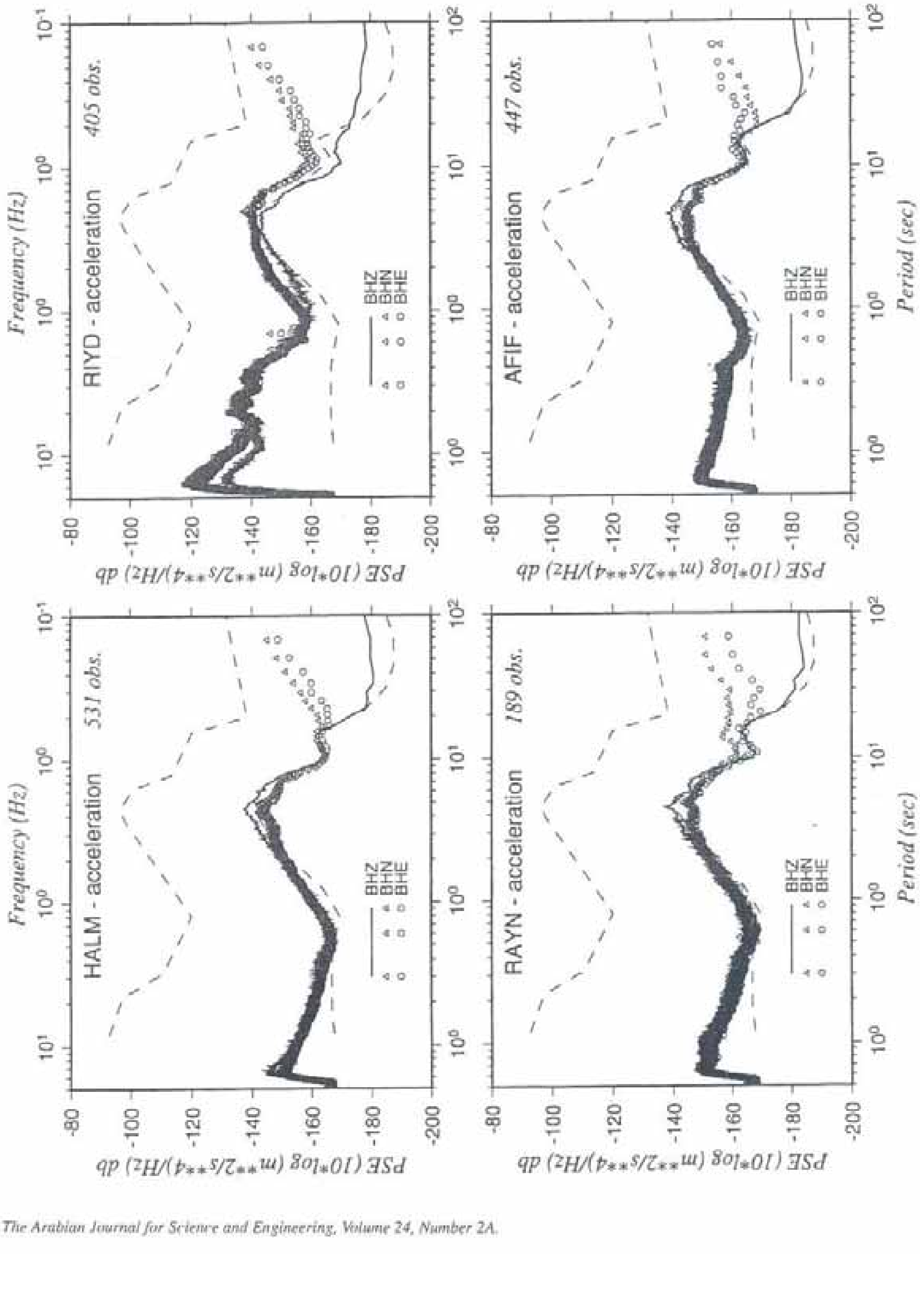


Figure 3. Noise levels at HALM, RIYD, RAYN, and AFIF stations. The black lines show the vertical (BHZ), open triangles mark the north-south (BHN), and open circles marks the east-west (BHE) components. The dashed lines denote the USGS low- and high-noise models. The number of observations at each station are shown in the upper right corner.

the isolated continental location, bedrock location, and distance from likely sources of microseism noise.. Astiz (pers.comm) suggests that the Saudi stations compare favorably with INK and MBC stations in Canada, AAK and WUS stations in central Asia, and KEG station in Egypt. Because the total station plot was not labeled by station in the FDSN, it is difficult to cite a particular quiet worldwide station.

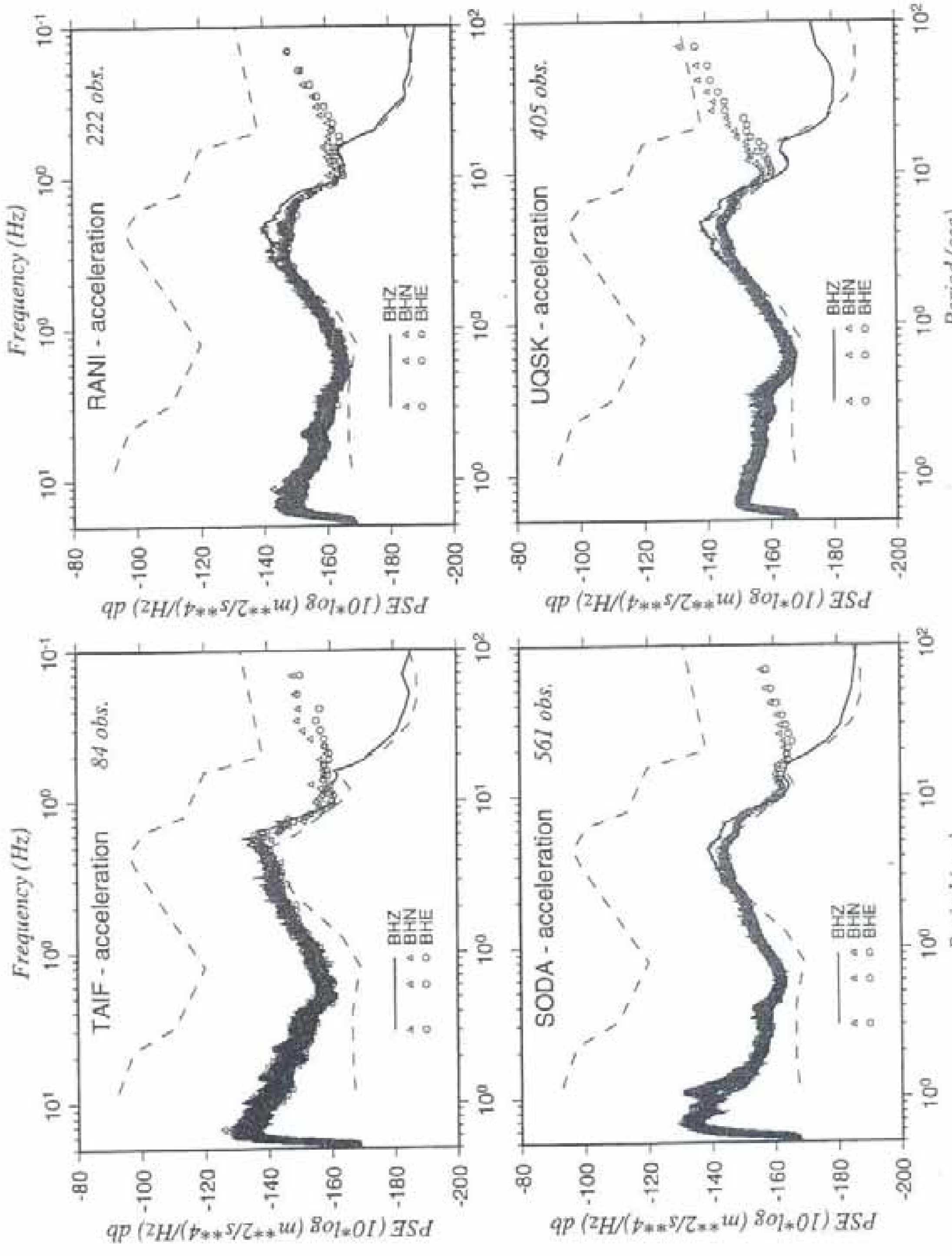


Figure 4. Noise levels at TAIF, RANI, SODA, and UQSK stations. Symbols as indicated in Figure 3.

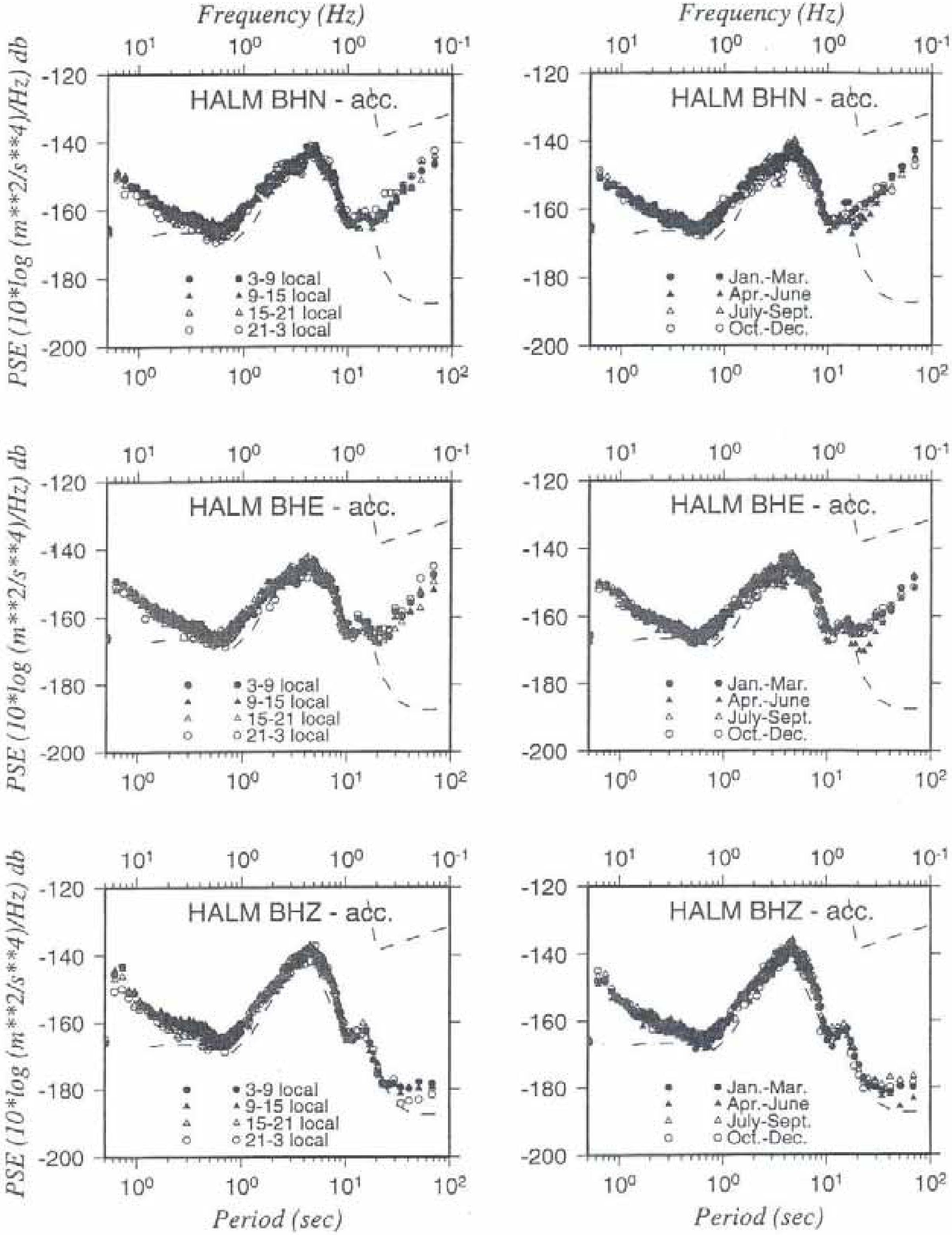


Figure 5. Diurnal and seasonal variations at HALM station. The lower axis shows period (seconds) while the upper axis shows frequency (Hz). The left axis is in decibels with respect to acceleration $m^2/s^4/Hz$.

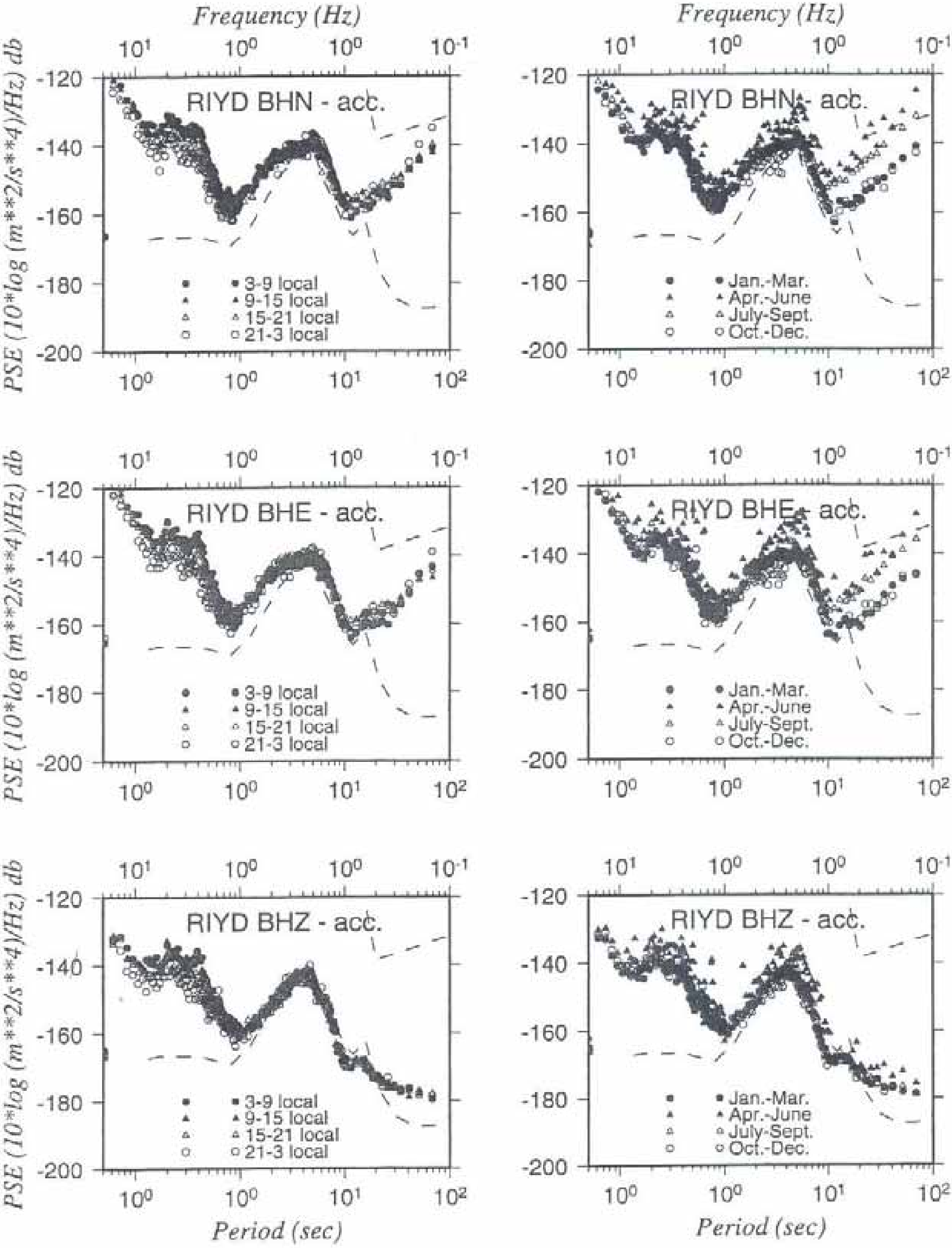


Figure 6. Diurnal and seasonal variations at RIYD station. Axes as indicated in Figure 5.

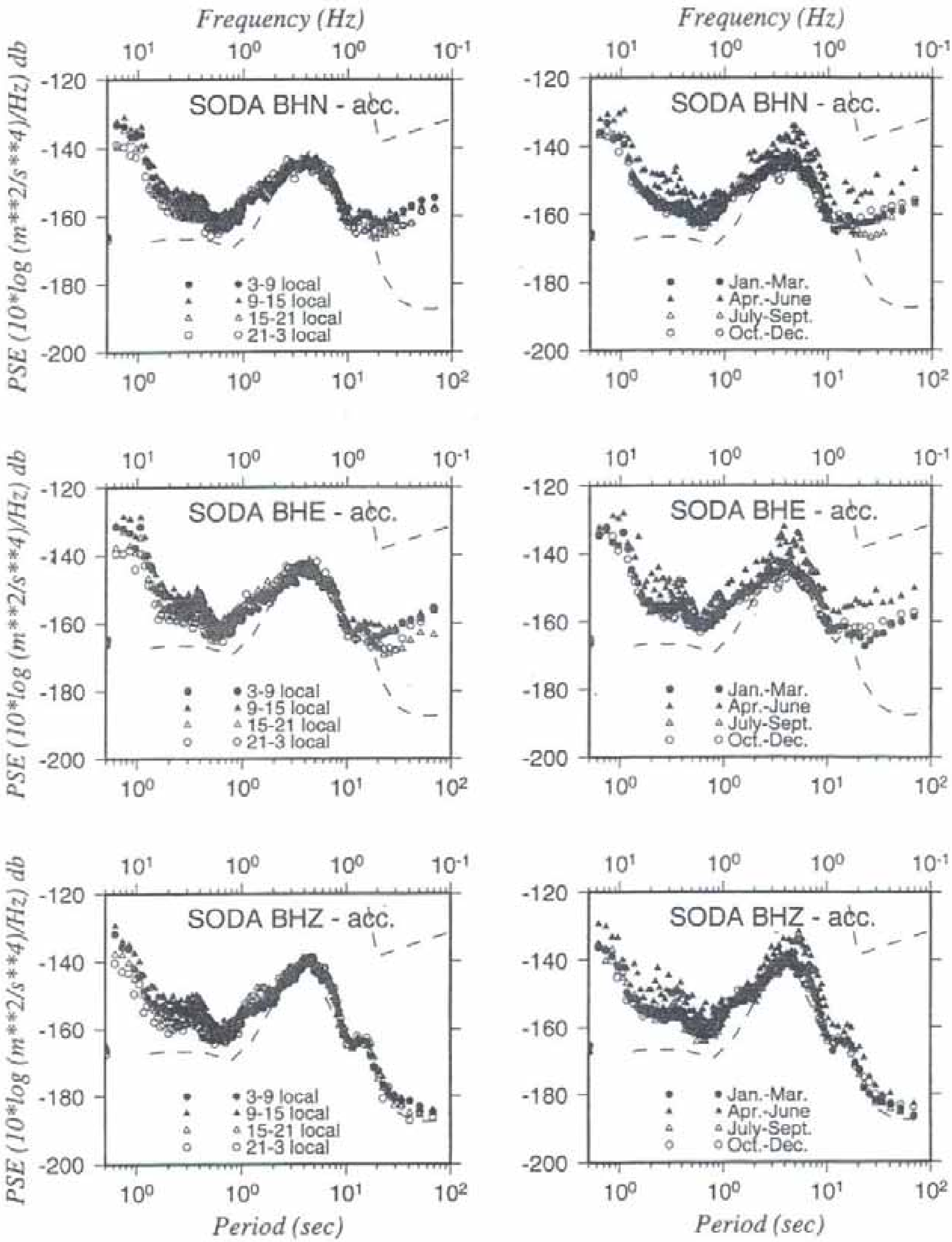
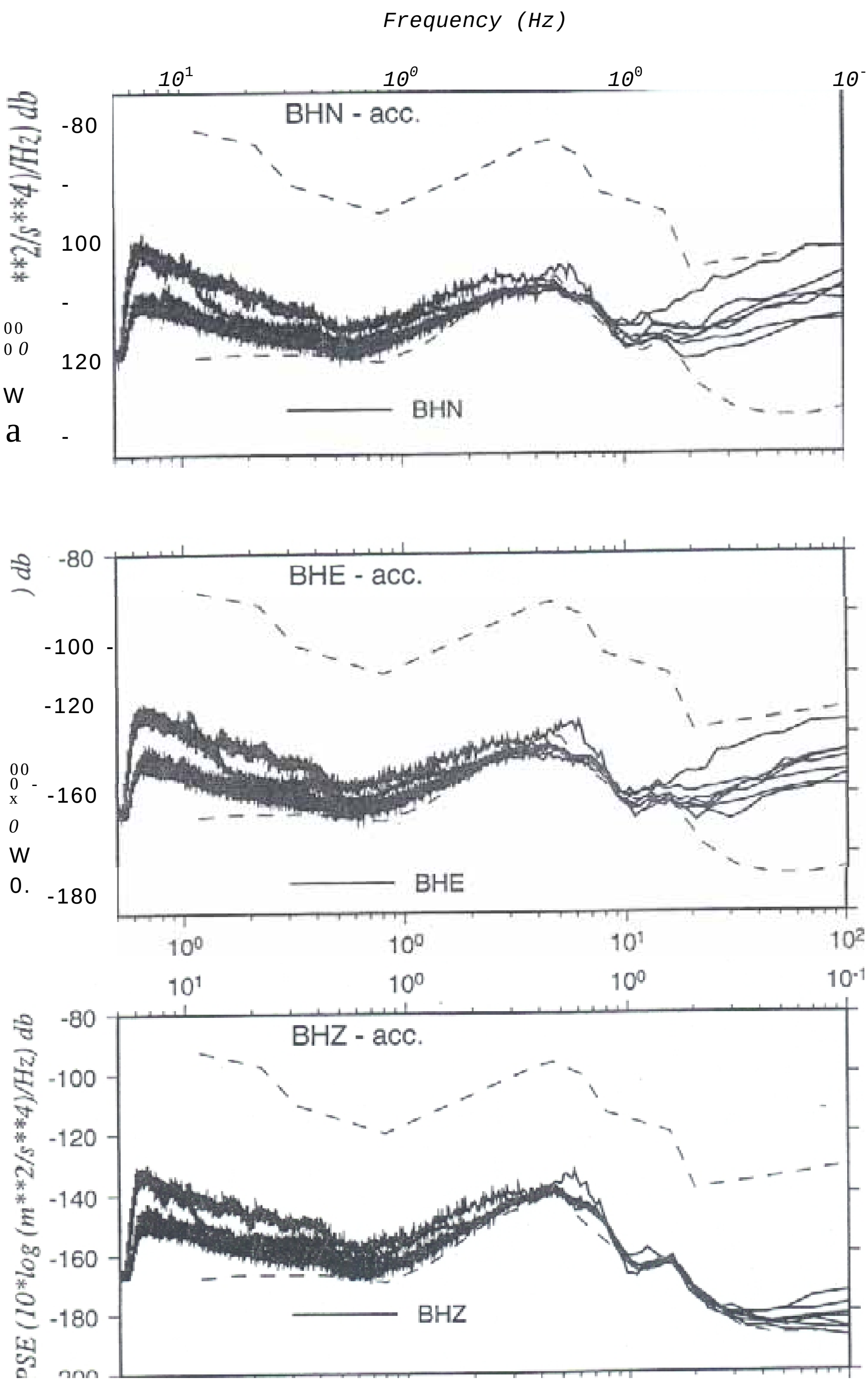


Figure 7. Diurnal and seasonal variations at SODA station. Axes as indicated in Figure 5.



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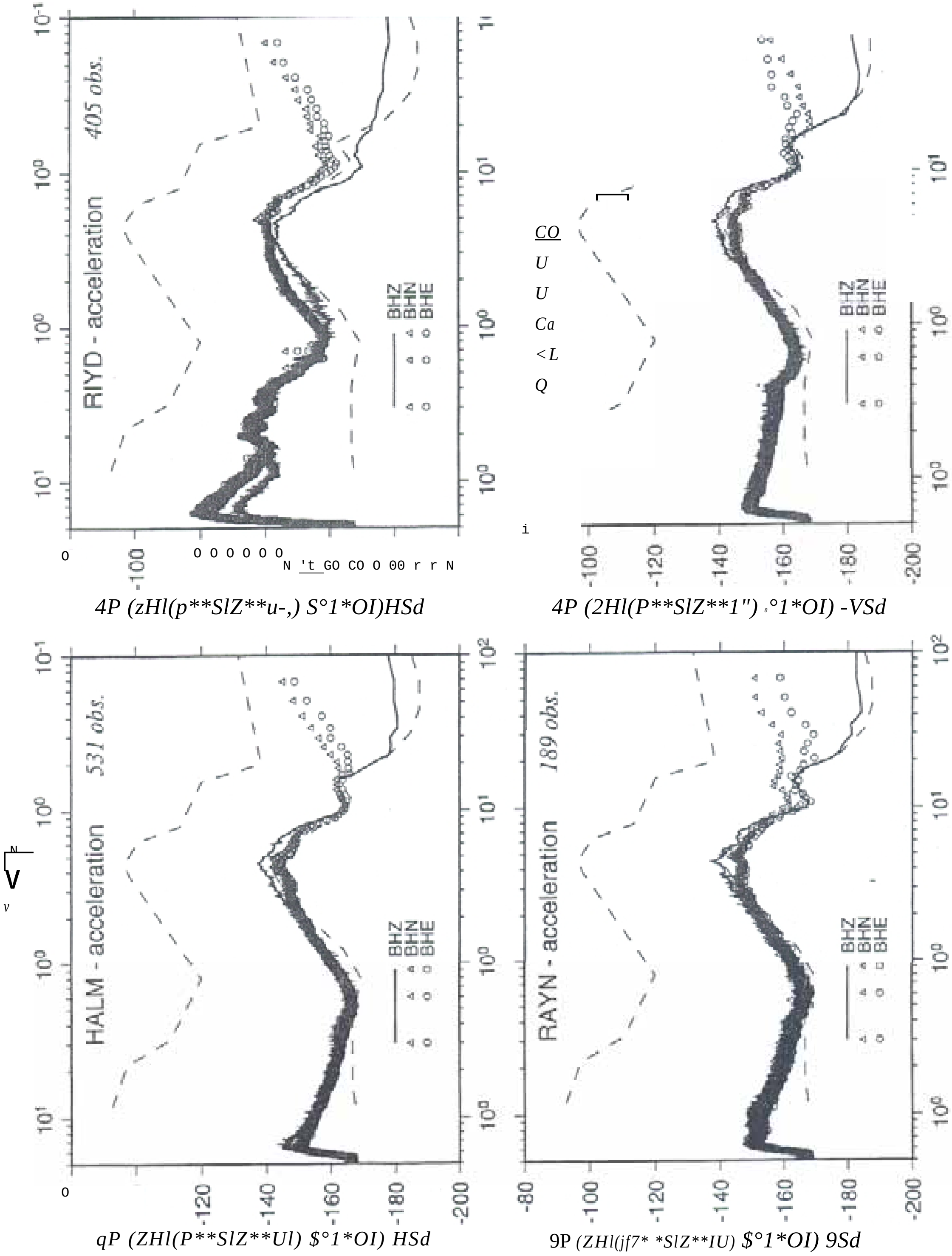

Figure ... RIYD, RAYN, and AFIF stations ... east (BHE) components. The dashe... station a... open ... how the vertical (BHZ), open triangles mark the USGS low- and high-noise models. The number ... per right corner.

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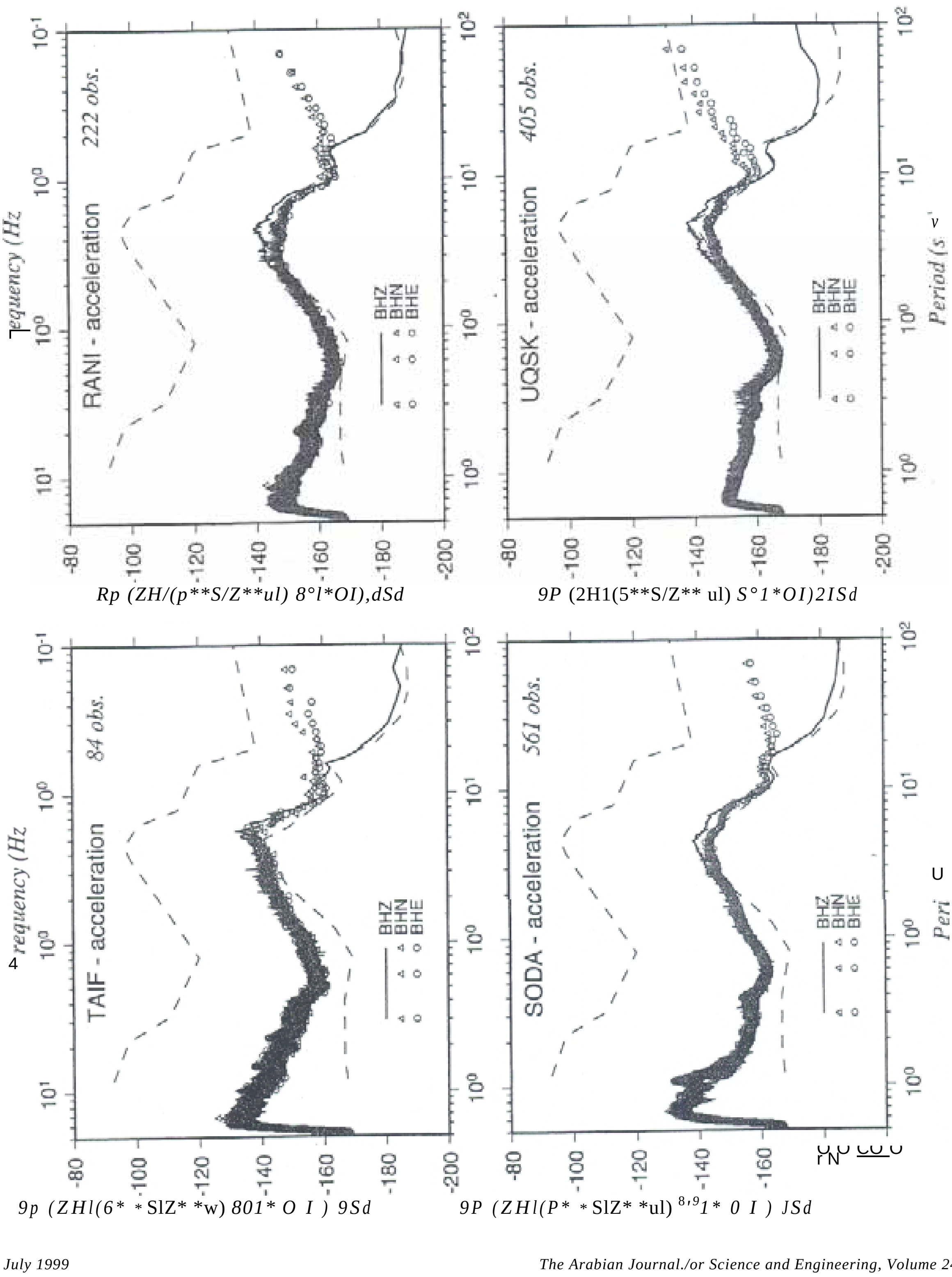

Figure 4. Noise levels at TA

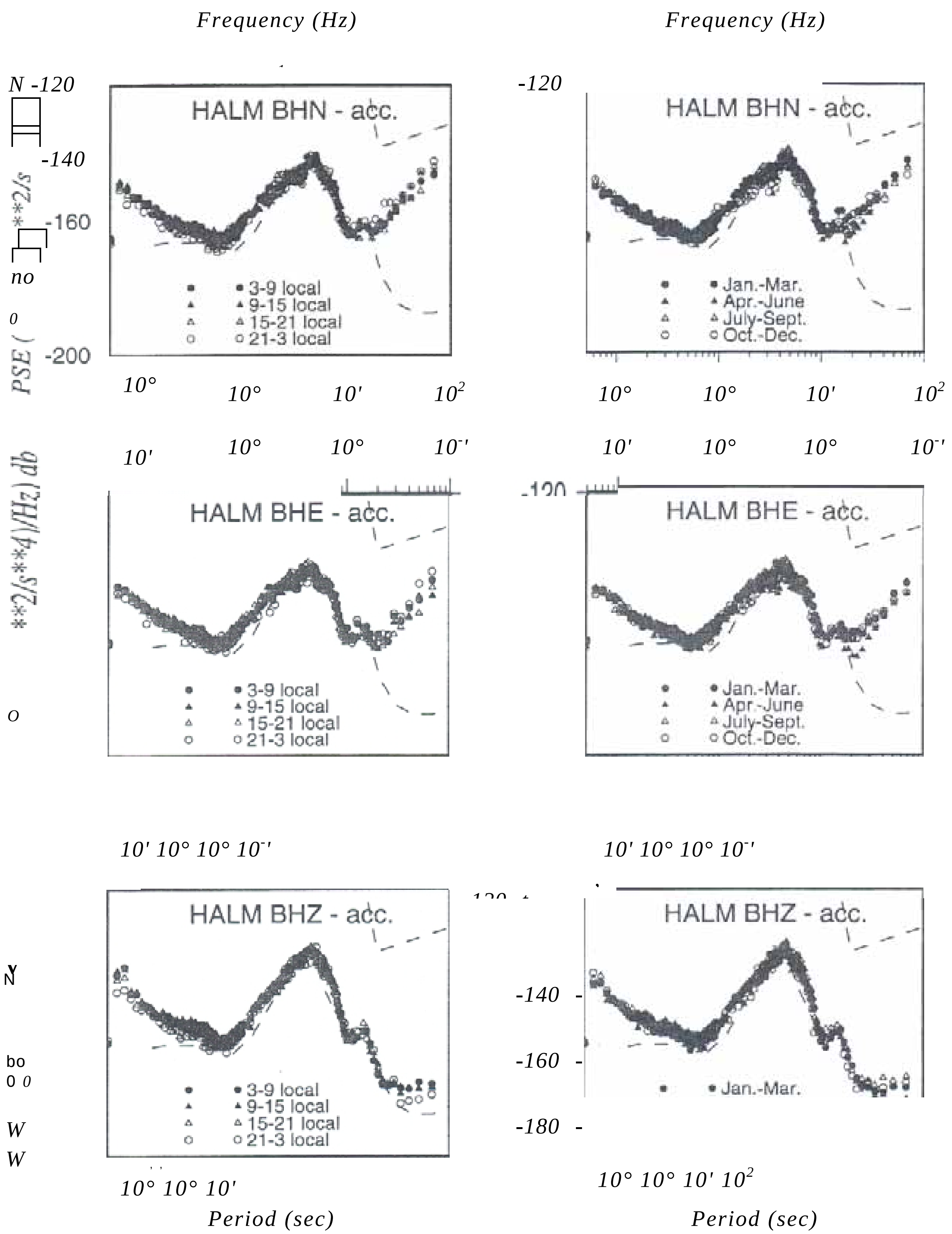

Figure S. Diurnal and seasonal variations at HALM station. The lower axis shows period (seconds) while the upper axis shows frequency (Hz). The left axis is in decibels with respect to acceleration m^z ls^r lHz.

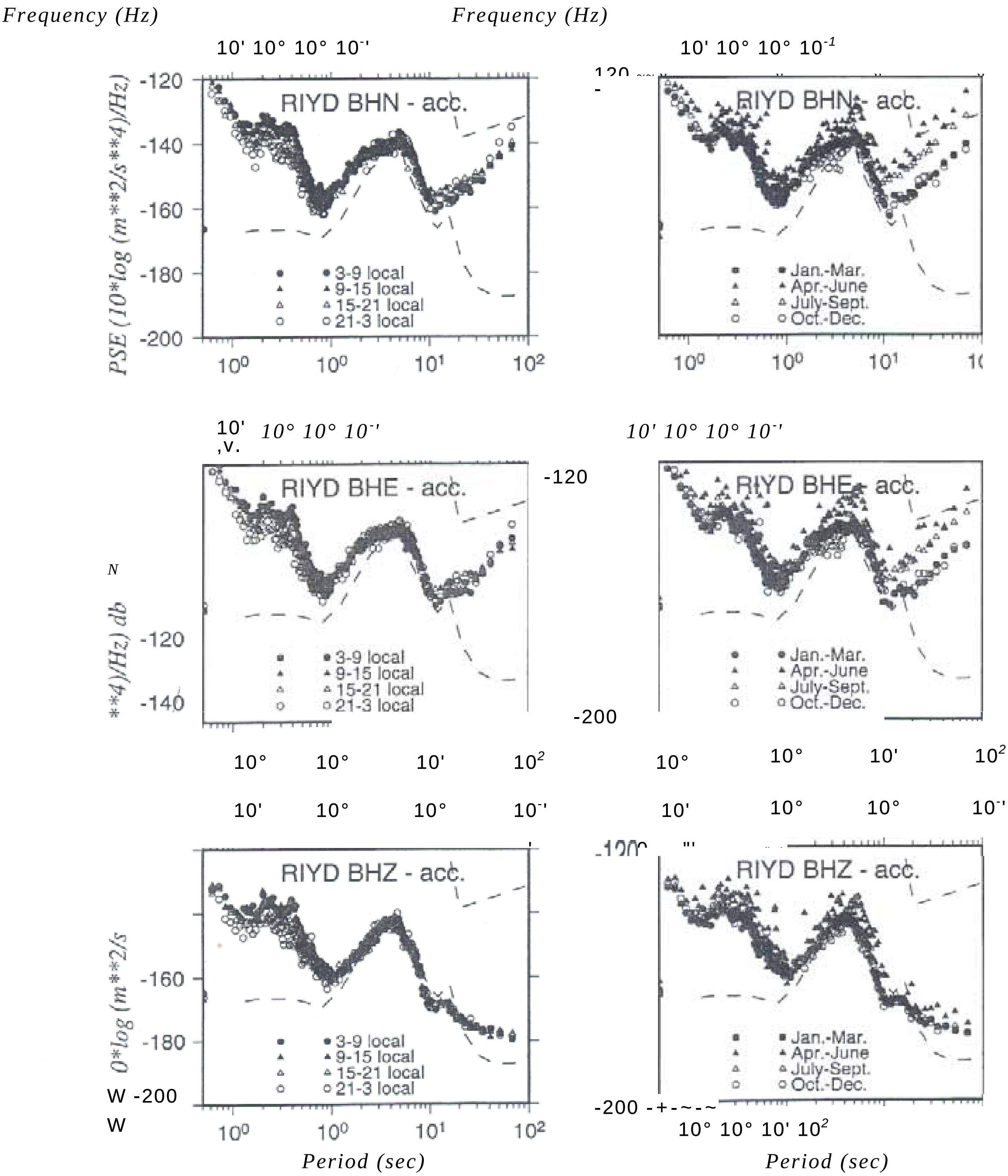

Figure 6. Diurnal and seasonal variations at RIYD station. Axes as indicated in Figure S.

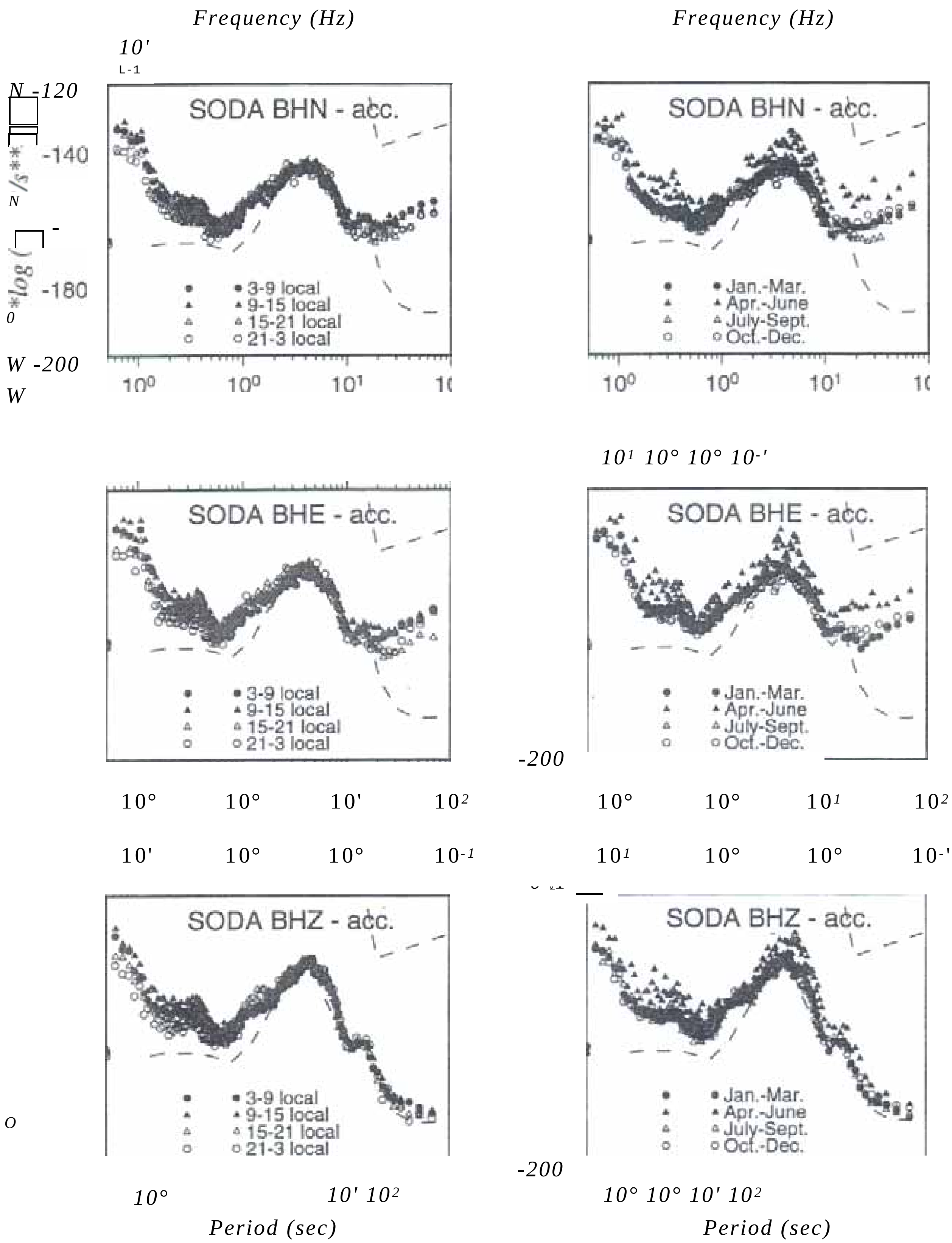

Figure 7. Diurnal and seasonal variations at SODA station. Axes as indicated in

Generally, regional seismograms (5 to 15 degrees) show unique characteristics which depend on the source region and azimuth of the event (Figure 1). Event in the Zagros show very good propagation of phases traveling through the crust and upper mantle (Pn and Sn) and an observable Lg surface wave. Shallow events in the Arabian Sea show clear body waves (P and S) but do not have an associated Lg phase. From the opposite direction, aftershocks from the Gulf of Aqabah have very weak upper mantle and crustal Pn and Sn but a very strong Lg phase. The cause of these differences may be related to anomalous upper mantle structure related to recent volcanism in the Western Arabian Shield [10, 11].

The body-wave magnitude (m_b) detection threshold for the distance range of 10-100 degrees is about Mb >3.5 [5]. Stations AFIF and HAML have nearly equivalent detection thresholds as the RAYN station. Minimum detectable magnitudes are estimated for RAYN station using the observed noise levels over 1 Hz. The Mb detection threshold for the distance range of 5-10 degrees is about Mb = 2.7-3.0 assuming the signal-to-noise ratio of 3 dB or better [12]. The western station SODA and RANI are less sensitive with detection thresholds of about Mb = 3.7.

Daily and Seasonal Variations

Figures 5 and 7 show diurnal and seasonal variations at the stations, as constrained by the available data. The most significant daily variations occurred at frequencies above 1 Hz and were strongest during the morning and early afternoon. Noise levels were quietest at night, which is the pattern expected for cultural noise (roads, etc.). TAIF, RIYD, and RAYN were most affected, as expected, because they were near cities or towns. RANI has a highly used road approximately 2 km away, which explains much of the noise. HALM, AFIF and UQSK were all in remote locations and show little variation between night and day (especially HALM in Figure 5).

Seasonally, the variations were less consistent. At high frequencies, RAYN, RIYD and SODA showed differences (TAIF was not functional for a long enough time to produce a reliable record). This may be due to cultural noise source that varies during the year. Wind noise may also play a role (trees and shrubs moving in the wind, especially at SODA in Figure 7). At low frequencies, the patterns were more scattered. It is likely that thermal variations are more pronounced during summer

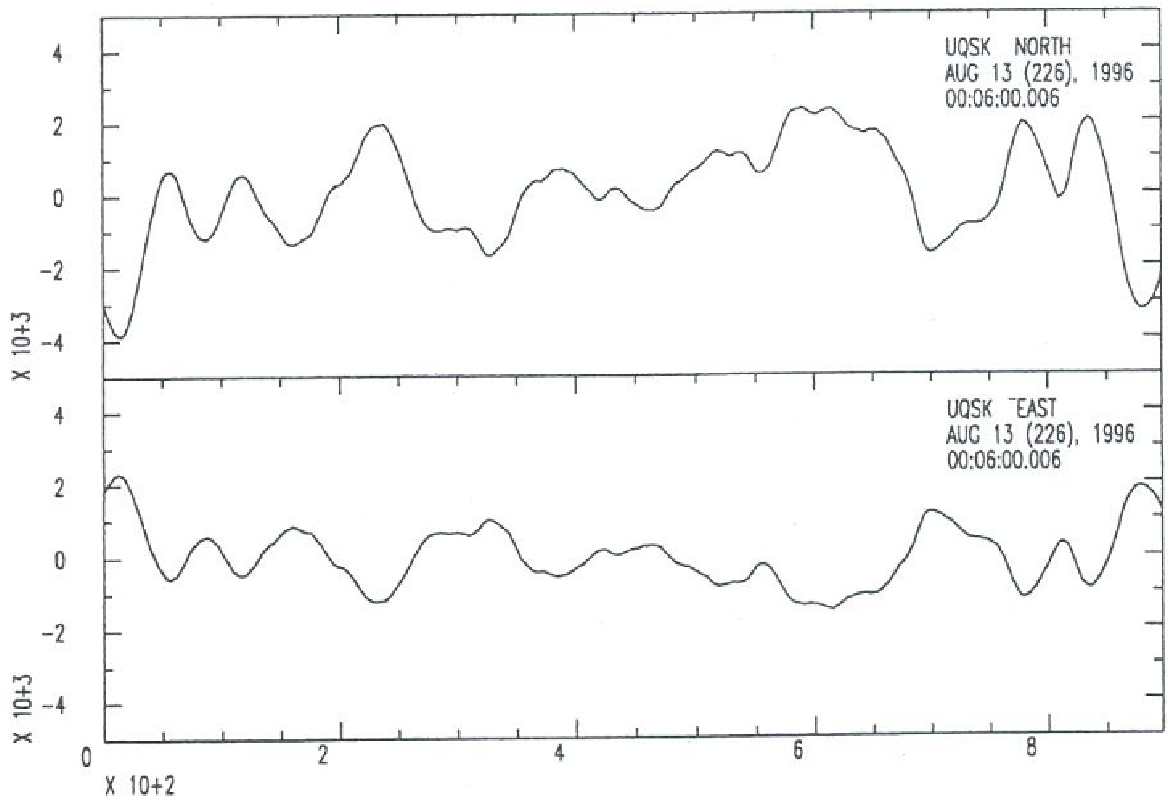

Figure 8. Horizontal channels showing anti-correlated long-period noise at UQSK station.

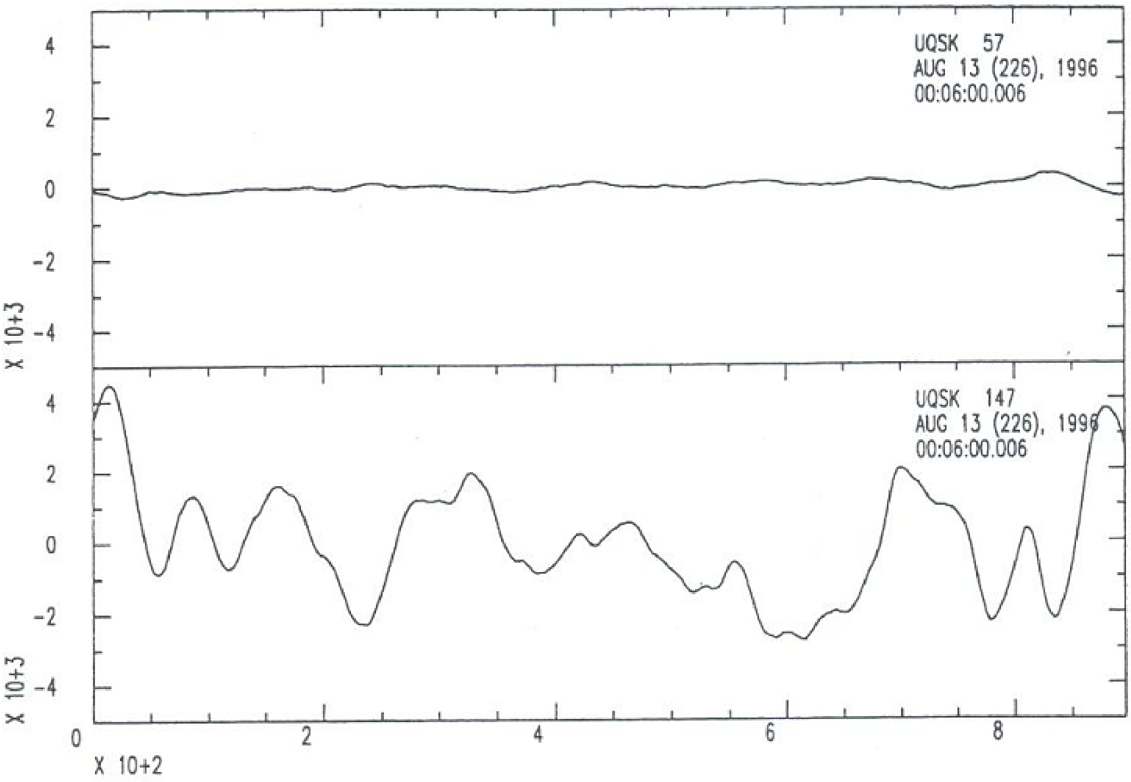

Figure 9. Horizontal channels showing anti-correlated long-period noise rotated 57 degrees for UQSK station to isolate the nois

than winter. The microseism peak (roughly at 0.17 Hz) showed seasonal variations and appeared stronger in July-September, suggesting that the nearest large oceanic storms are most active at this time.

Al-Amri *et al.* [12] indicated that seasonal noise levels varied at RAYN, with April to June being the quietest and with October to December being the nosiest months. Slight changes in peak microseism frequency also occurred seasonally. Absolute noise levels near the microseism frequency (0.1 to 0.2 Hz) were about equal for all seasons at -140 dB. Above 1 Hz, RAYN station shows an increase in seasonal variations from -140 dB in the summer to -160 dB in the winter.

Generally, the body-wave magnitude (m_b) detection threshold for the distance range of 10-100 degrees is about m_b >3.5 [5]. Stations AFIF and HALM have nearly equivalent detection thresholds as the RAYN station. Minimum detectable magnitudes are estimated for RAYN station using the observed noise levels over 1 Hz. The Mb defection threshold for the distance range of 5-10 degrees is about Mb = 2.7-3.0 assuming the signal-to-noise ratio of 3 dB or better [12]. The western station SODA and RANI are less sensitive with detection thresholds of about m_b= 3.7.

CONCLUSIONS

Most sites in the Arabian Shield are extremely quiet with ground noise near or equal to the low noise model in the frequency band from 1-10 Hz. The low noise contributes to the very low detection threshold of events with tn_b >3.5 at distances from 10 to 100 degrees. These stations appear to be among the best sites in the world for the properties of detection thresholds and ground noise levels.

Horizontal long-period components are significantly noisier than vertical at frequencies less than 0.1 Hz. At frequencies greater than 0.1 Hz, the noise level between the verticals and the horizontals varies greatly (by up to 40 dB). The source of the long-period noise is not clear and may be due to small tilts which affect the horizontal components more than the verticals.

Regional seismograms have very unique characteristics which can be used to identify the source regions. Zagros events have a clear Pn and Sn arrivals with an observable Lg. Shallow events from the Arabian Sea have clear P, S, and surface waves but no discernible Lg phases. Aftershocks from the Gulf of Aqabah have very weak P and S waves with very strong Lg phase.

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