AFRL-VS-HA-TR-98-0052

BROADBAND SEISMIC CHARACTERIZATION OF THE ARABIAN SHIELD

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07 October 1998

Final Report
10 August 1995 - 09 November 1997

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DEPARTMENT OF ENERGY
OFFICE OF NON-PROLIFERATION
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WASHINGTON, DC 20585

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SPONSORED BY
Department of Energy
Office of Non-Proliferation and National Security

MONITORED BY
Air Force Research Laboratory
CONTRACT No. F19628-95-K-0015

This technical report has been reviewed and is approved for publication.

JAMES C. BATTIS Contract Manager	CHARLES P. PIKE, Deputy Director Integration and Operations Division

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** ~~04/30/98~~	**3. REPORT TYPE AND DATES COVERED** Final Report 8/10/95-11/9/97

4. TITLE AND SUBTITLE
Broadband Seismic Characterization of the Arabian Shield

5. FUNDING NUMBERS
PE 69120H
PR DENN TA GM WU AF

Contract # F19628-95-K-0015

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Scripps Institution of Oceanography
IGPP 0225, 9500 Gilman Drive
La Jolla, California 92093-0225

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010
Contract Manager: James Battis / VSBI

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

AFRL-VS-HA-TR-98-0052

11. SUPPLEMENTARY NOTES
This research was sponsored by the Department of Energy,
Office of Non-Proliferation & National Security, Washington DC 20585

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

From November 1995 to March 1997 a total of nine broadband temporary stations were deployed across the Saudi Arabian shield. These stations consisted of STS-2 seismometers that recorded continuously at 40sps on Refraction Technology RT72A-07 dataloggers. All installations were at bedrock sites. The resuls from our field deployment of nine portable broadband stations suggest that 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 at the stations RAYN, AFIF, and HALM. All stations matched the low noise model for periods between 2 seconds and twenty second period. The low noise also contributes to the very low detection threshold at these stations of events with mb=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. Seismograms from sources 10 degrees from the center of the network have 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. From the opposite direction, aftershocks from the Gulf of Aquaba have very weak P and S waves with very strong Lg phases.

14. SUBJECT TERMS
Saudi Arabia, detection thresholds, ground noise, seismic regionalization

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18
298-102

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ACKNOWLEDGMENTS

We would like to thank Dr. Mohammed Al-Suwaiyel, the Vice President for Research of the King Abdul Aziz City for Science and Technology (KACST) who sponsored this joint project and Dr. Mohammed Al-Dail, Director of the Institute of Astronomical and Geophysical Research, the government agency responsible for seismological studies in the Kingdom for assistance with the field program. Prof. Abdullah Al-Amri from King Saud University and Dr. Jim Zollweg from Boise State University are co-investigators on this project. Adam Edelman, Dr. Robert Mellors, D. Glen Offield, and Brian McFeely from the Institute of Geophysics and Planetary Physics made major contributions this project. Essential in-country field work and data processing is provided by Dr. Ali Gharib from King Saud University. We also acknowledge the collaboration with Dr. Danny Harvey and Daniel Quinlan of the University of Colorado. They have developed and maintain the software package for the analysis of data collected.

SUMMARY

From November 1995 to March 1997 a total of nine broadband temporary stations were deployed across the Saudi Arabian shield. These stations consisted of STS-2 seismometers recorded continuously at 40 sps on REFTEK dataloggers. All installations were at bedrock sites. The results from our field deployment of nine portable broadband stations suggest that sites in the Arabian shield are extremely quiet. Using data sections selected randomly during the deployment, noise studies showed that most stations were exceptionally quiet with noise levels near the USGS *Peterson* (1993) low noise model for frequencies higher than 0.1 Hz. At lower frequencies, the horizontal components showed increased 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, TAIF) while more isolated stations (HALM) were 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 showed noise levels near the low noise model for frequencies between 0.1 and 4 HZ. The optimal site for a new station would be near HALM as it was both quiet and showed very little diurnal variation due to cultural noise.

The low noise at these stations also contributes to the very low detection threshold of events with mb = 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. Seismograms from sources 10 degrees from the center of the network have 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. From the opposite direction, aftershocks from the Gulf of Aqaba have very weak P and S waves with very strong Lg phases.

Keywords: Saudi Arabia, detection thresholds, ground noise, seismic regionalization

OBJECTIVES

This project consisted of a field program in the Kingdom of Saudi Arabia to collect broadband seismic waveform data and the associated parametric data describing the sources. We deployed nine portable broadband seismic stations on the Arabian Shield which recorded over a period of one year and three months. Most of the regional seismic sources are in the tectonically active areas of Iran and Turkey. Other areas of seismic activity include the Red Sea Rift bordering the

Shield to the southwest, the Dead Sea Transform fault zone to the north, and the Arabian Sea to the southeast.

The main research objectives of this program were:

1. to observe the propagation of regional phases across the Arabian Shield over a broad band of frequencies,
2. to study the seismicity recorded on the Arabian Shield,
3. to characterize potential sites for permanent seismic facility installation

RESEARCH ACCOMPLISHED

The first deployment in late 1995 consisted of six seismographs arranged in two linear arrays (Figure 1). One linear array consisted of the stations RAYN, HALM, RANI. This profile's long axis is pointed in the direction of high seismicity in the Zagros. These earthquakes are occurring in the Arabian Plate where it is colliding with Persian Plate (*Jackson and Fitch*, 1981). Seismic wave ray paths along this profile from Zagros events should therefore have entirely intra-plate paths. Stations were between 900 and 1500 km from the nearest Zagros sources. The second linear array consisted of the stations AFIF, RANI, BISH, SODA. Events in the highly active area of the Afar triple junction in Africa and events in the Caucasus are also generally aligned with this four station array.

Early in the experiment the station BISH was vandalized and the station was closed. Three new stations were installed in June 1996 at TAIF, UQSK, and RIYD. These stations provide a more areal distribution than the initial deployment. The station at RAYN was converted from a portable station to a permanent GSN station in June 1996.

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

Instrumentation

Each station was equipped with a Streckeisen STS-2 broadband seismometer which has a pass band between 0.008 Hz and 50 Hz. Each seismometer was heavily insulated to protect it from

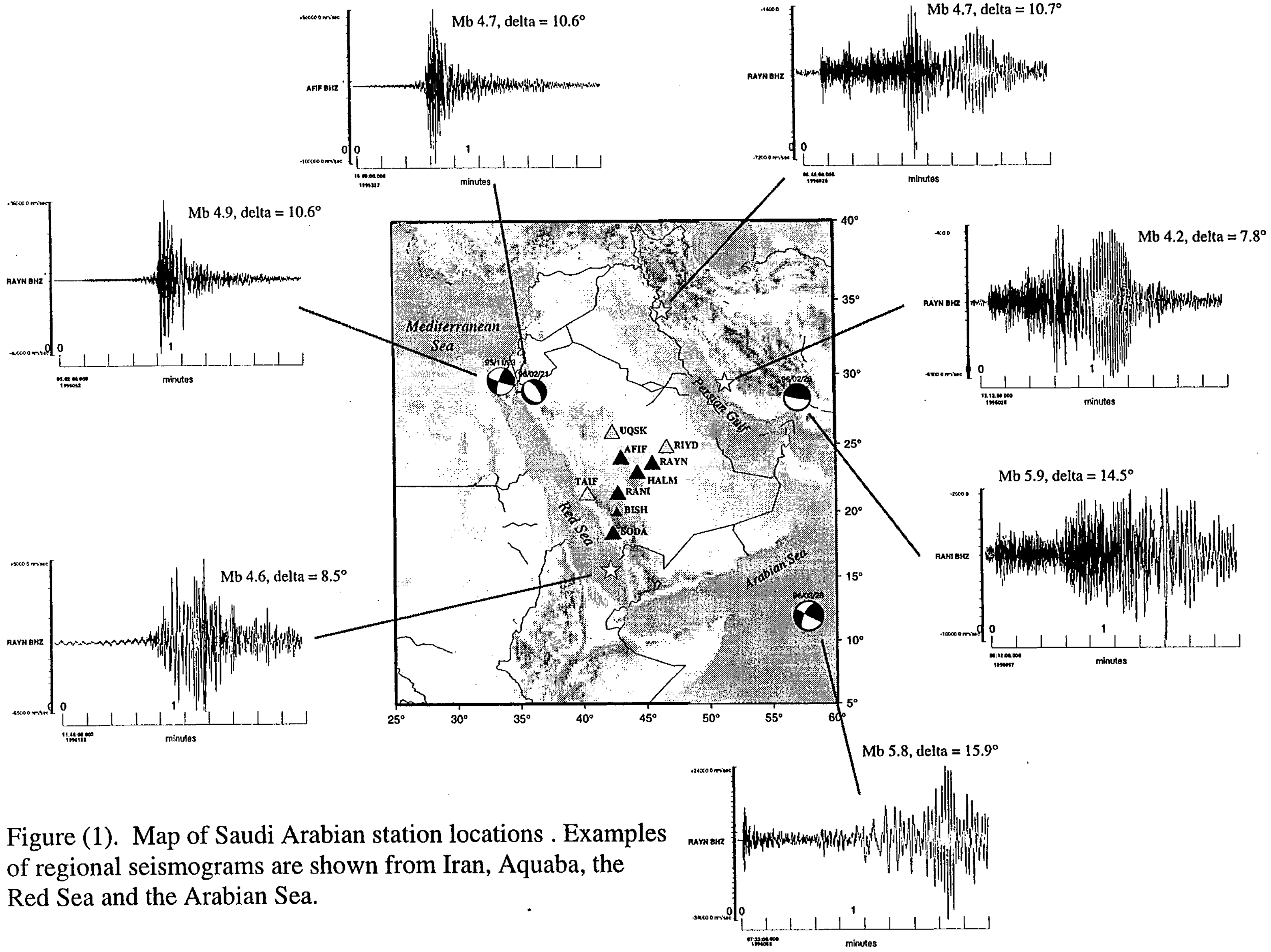

Figure (1). Map of Saudi Arabian station locations . Examples of regional seismograms are shown from Iran, Aquaba, the Red Sea and the Arabian Sea.

the diurnal changes in temperature. The sensors were attached to bedrock outcrops whenever possible.

The output of the STS-2 was recorded at a sample rate of 40 sps by a 24-bit REFTEK RT72A-08 datalogger. At the station the data were stored on a 2 Gbyte SCSI disk. To take advantage of the copious amounts of sunshine available in Saudi Arabia, we used solar panels to charge car batteries. Timing to the station was provided by a local GPS clock. Data were retrieved by exchanging disks at each site during service runs. Each site was visited every four to six weeks.

Station Descriptions

Station	Latitude	Longitude	Elevation (Km)	Location
AFIF	23.9310	43.0400	1.1160	Afif, Saudi Arabia
BISH	19.9228	42.6901	1.3790	Bisha, Saudi Arabia
HALM	22.8454	44.3173	0.9300	Hadabat Al-Mahri, Saudi Arabia
RANI	21.3116	42.7761	1.0010	Raniyah, Saudi Arabia
RAYN	23.5220	45.5008	0.7920	Ar-Rayn, Saudi Arabia
RIYD	24.7220	46.6430	0.7170	Riyadh, Saudi Arabia
SODA	18.2921	42.3769	2.8760	Al-Soda, Saudi Arabia
TAIF	21.2810	40.3490	2.0500	Taif, Saudi Arabia
UQSK	25.7890	42.3600	0.9500	Al-Soda, Saudi Arabia

Table 1. Station codes, coordinates, and names for the sites used in the Saudi Arabian broadband deployment.

AFIF - The station was on a low ridge of crystalline rock about 10 km from the town of AFIF and a few km from the nearest paved road. The vault was in a rectangular hole lined with cinder blocks. The top of the vault consists of a metal plate exposed to the sun. Solar panels were mounted on a steel pole set in concrete 3 meters from the vault.

BISH - Station was located under a large granite boulder at the edge of an outcrop in a well-built vault. The solar panel was mounted on a pole a few meters away.

HALM - Located in a well-built vault on a granite outcrop in a very isolated location. The nearest town was at least 50 km away, and the only other possible source of cultural noise was Bedouin encampments and shepherds in pickup trucks. Again, the vault was under a granite ledge. Solar panels were mounted on a steel pole set in concrete 3 meters from the vault.

RANI - Station was under a granite ledge about 3 km from a fairly heavily traveled paved road (one vehicle every few minutes during the day) in a well-built vault. Solar panels were mounted on a steel pole set in concrete 3 meters from the vault. There appears to have been some sort of earth-moving equipment visible (and audible) in the distance to the west about 10 km away (possible quarry ?).

RAYN - Located on a granite outcrop a few km from the town of Rayn. The vault was well-built, and under a overhanging ledge of granite. The site of the permanent IRIS/IDA station RAYN is approximately 200 m to the east. Solar panels were mounted on a steel pole set in concrete 3 meters from the vault.

RIYD - Station was on a pier in a large vault in the midst of the city of Riyadh. Basement rock was probably limestone.

SODA - Station was on the top of a mountain on metamorphosed sediments. The vault was in a large, cinder block lined hole covered by wooden boards. The KSU station SODA was also at this site. Solar panel was mounted low to the ground, 4 meters. The nearest paved road was about 5 km away. Some trees and bushes were nearby.

TAIF - Station was on the top of a mountain next to the city of Taif. The vault was a hole dug into the ground lined with cinder block, co-located with KSU station TAIF. Due to lack of space, the disk was placed on the seismometer mini-vault.

UQSK - Station was located on low granite outcrop, co-located with KSU station UQSK. The vault was placed in a hole lined with concrete.

Data Processing

The processing scheme required several steps: raw data retrieval followed by formatting, quality control, and event association. A Sun Sparc field computer was set up in Riyadh. The data conversion to CSS 3.0 format and quality control were performed on this field computer. The data were then sent to UCSD where an automatic picking program was used to identify all arrivals. These arrivals were reviewed by an analyst. The initial event associations were based on predicted arrivals from a REB origin table using the IASPEI91 travel time tables and the actual phase picks. Any recorded events not appearing in the REB catalog were located using arrivals from the Saudi portable stations. The data were sectioned into an event-oriented CSS 3.0 waveform database and have been distributed to interested users. A complete copy of all data is available through IRIS Data Management Center in Seattle, Washington.

Operating at 40 samples/second continuously, each station collected 41.5 Mbytes of waveform data per day. A total of 2300 station-days of data were recorded.

Instrument Problems

BISH	Station vandalized between November 1995 and March 1996, shortly after installation.
HALM	Seismometer problem - no long-period response from day 350 1995 to day 062 1996.
RANI	Leveling problems, seismometer changed day 063 1996. Intermittent cable problems due to rodents.
RIYD	Seismometer/DAS connection problem from day 069 1996 to day 156 1996 - no data. High-frequency intermittent noise (due to disk spin-up) - all data. Possible problem with seismometer gain on vertical component - see noise results above.
SODA	Loose vault (due to water softening plaster) caused leveling problems. Large offsets on data. Seismometer changed day 164 1996, host-box changed day 165 1996.
TAIF	High-frequency intermittent noise (due to disk spin-up) - all data.

Data Results

Data processing has been completed for all data recorded. A total of 1930 events have been processed and are shown in Figures 2(a), (b), (c). The epicenter map in Figure 2(a) shows the 338 events within 20° of the stations. The map in Figure 2(b) shows the 1528 recorded events within 90° of Saudi Arabia while Figure 2(c) shows the complete event catalog of 1930 events.

Most of the events within 20° of our stations are located in the Zagros region with almost all the remaining events concentrated as aftershocks to the 23 November 1995 Gulf of Aqaba earthquake or from the Arabian and Red Seas. Each of these four source regions were approximately 10° from the center of the network and had unique seismic characteristics as shown in Figure 1. Events from Iran had clear Pn and Sn arrivals with an observable Lg. Shallow events from the Arabian Sea had clear P, S, and surface waves but no Lg. From the opposite direction, aftershocks from the Gulf of Aqaba had very weak P and S waves with very strong Lg phases. Finally, from the Red Sea, all phases are difficult to distinguish since they were very emergent. P phases were the most distinctive, followed by weak to non-existent S phases followed by emergent Lg waveforms.

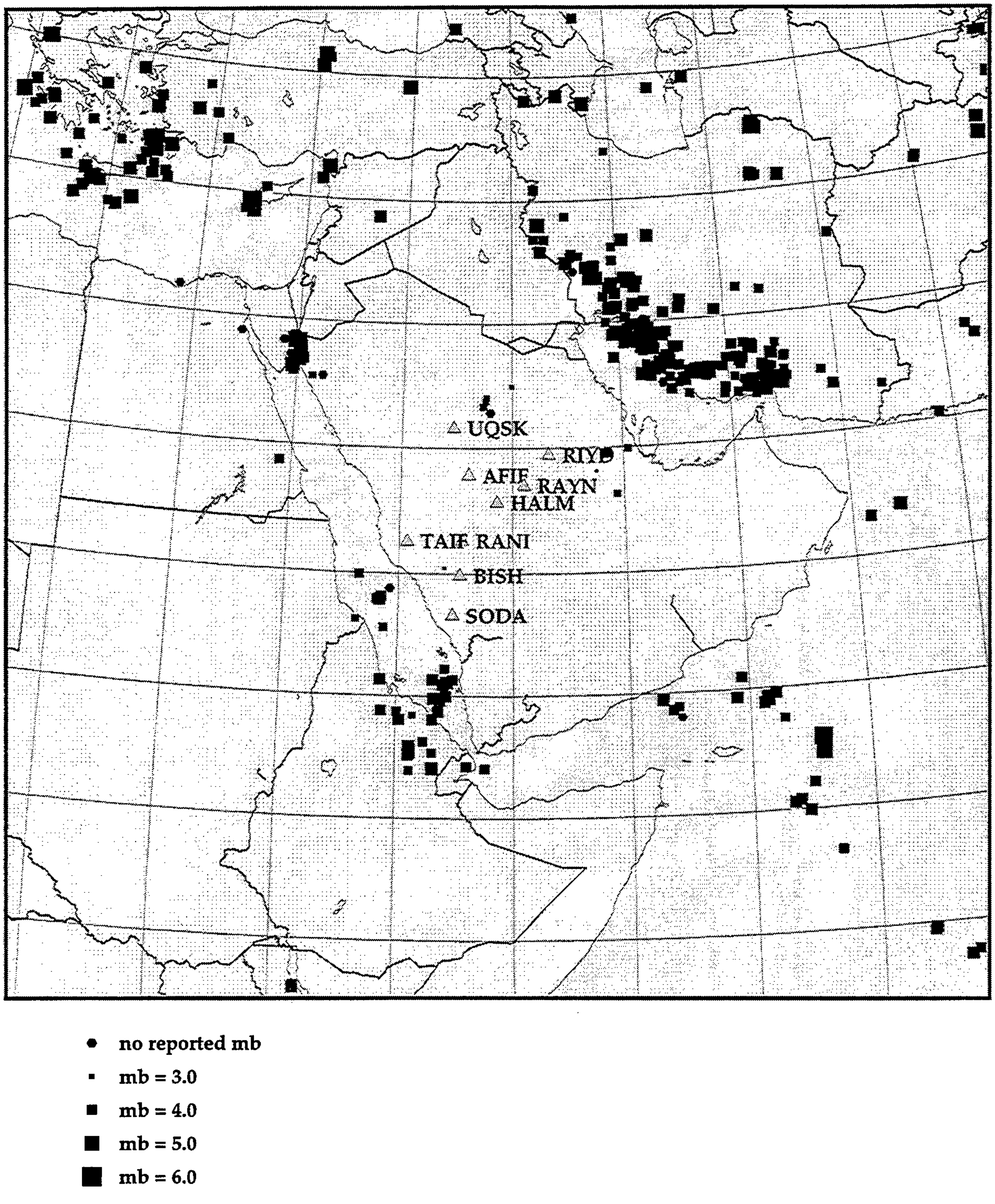

Figure 2(a). Epicenters of all earthquakes within 20 degrees of the station HALM recorded on the Saudi broadband stations.

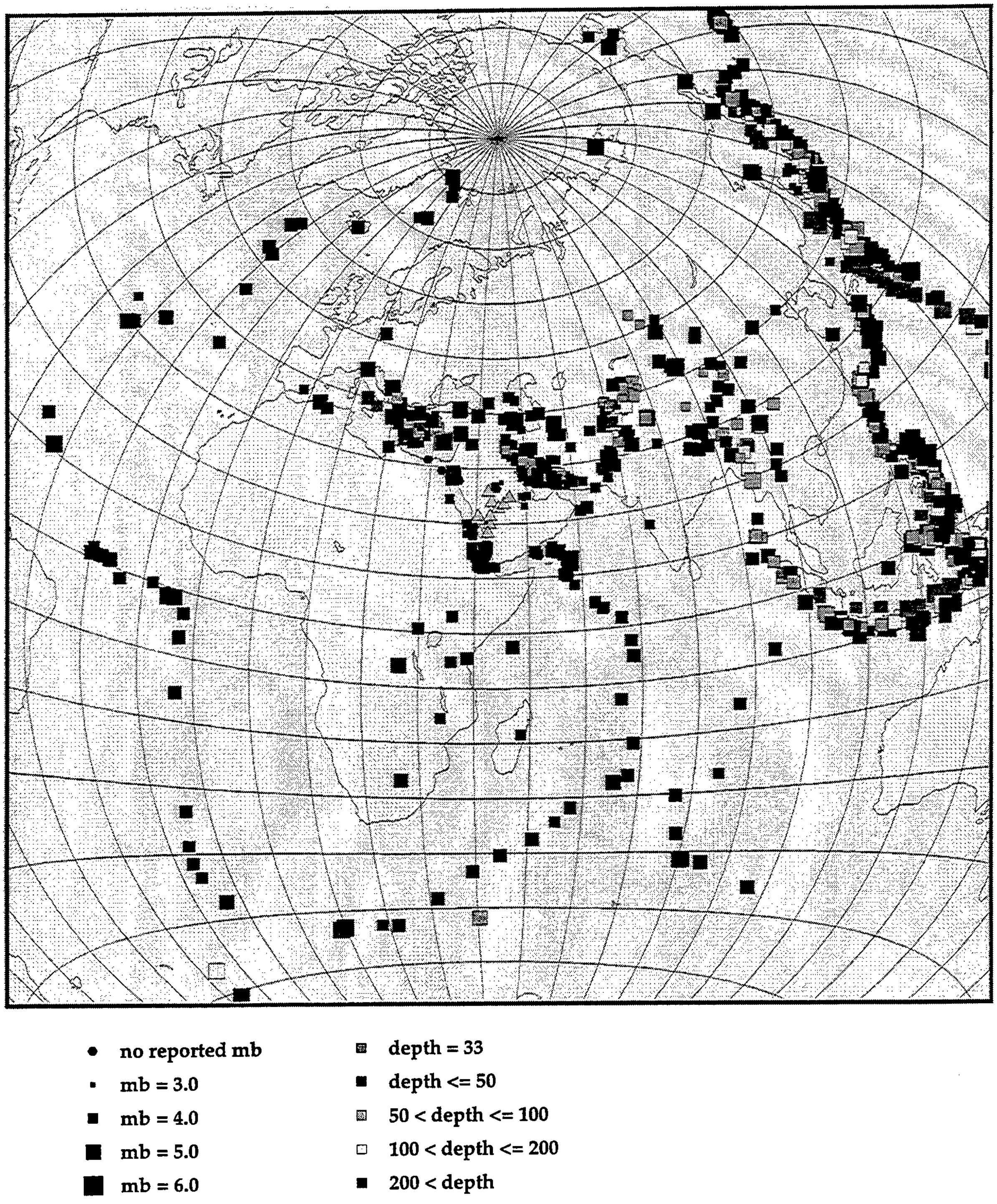

Figure 2(b). Epicenters of all earthquakes within 90 degrees of the station HALM recorded on the Saudi broadband stations.

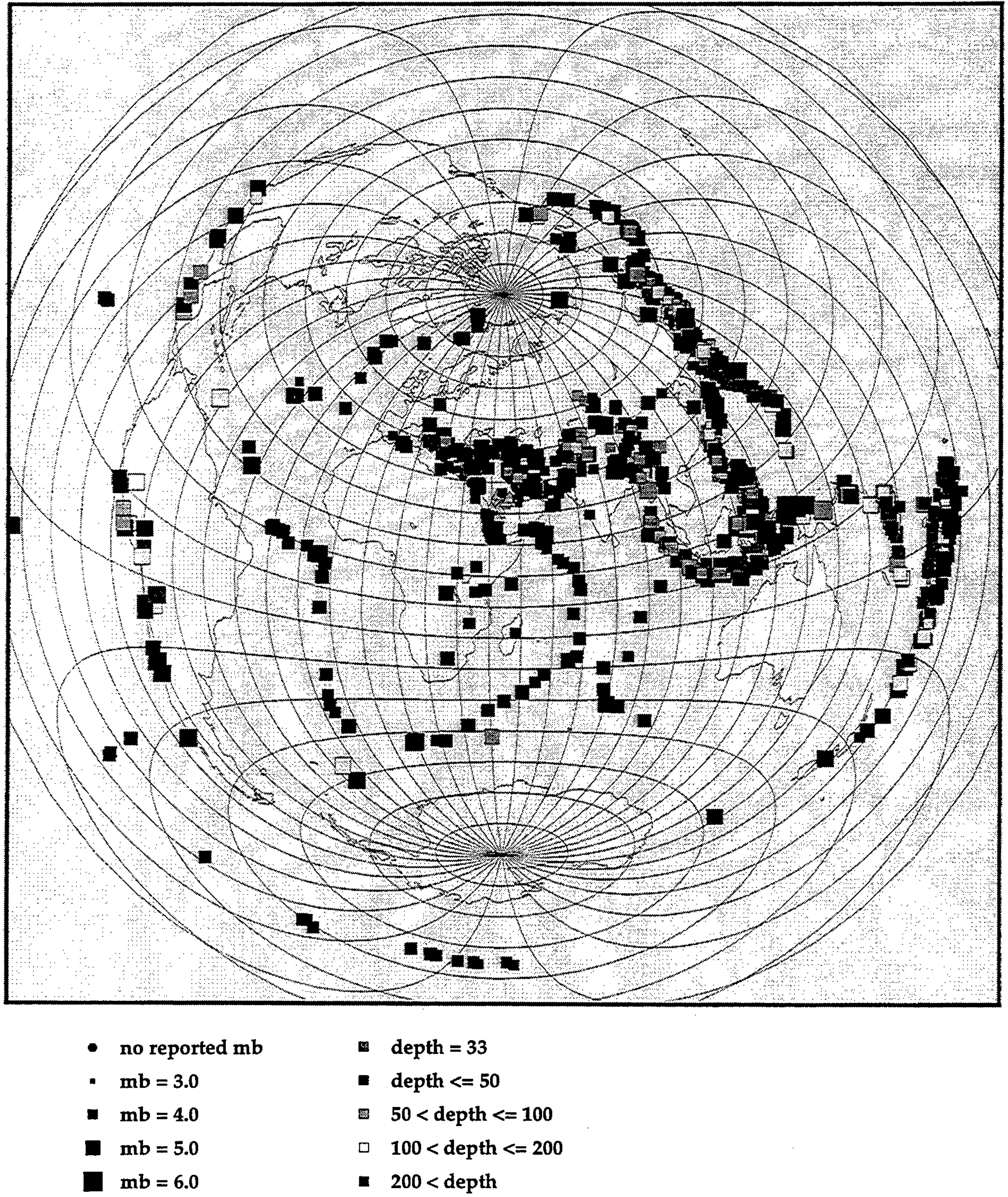

Figure 2(c). Epicenters of all earthquakes within 160 degrees of the station HALM recorded on the Saudi broadband stations.

Ground Noise Characteristics

One of the most important seismic characterizations for each site is an estimate of its ground noise properties. 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. This information is useful in identifying specific sites for future deployments, in calibrating detection thresholds, and in identifying instrumental problems.

We followed the approach of *Astiz* (1997) to estimate power spectra. 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 strongly. Data segments which fell 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 32,768 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 4 pi prolate taper was applied to the data, and it was then transformed using an FFT. Windows 32,768 points long were selected from the dataset, and the robust power spectra was calculated using the weighted median estimate of *Chave et al.* (1987). This robust estimate ensures that isolated outliers do not adversely affect the resulting spectral estimate. The spectra were then 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. The roll-off at 16 Hz of the anti-alias FIR filters on the digitizer remains however.

A feature of this approach is that the data are not examined by eye prior to the power spectral estimate, so the resulting estimate reliably estimates the noise levels at that station, rather than providing the quietest possible estimate. Small local and regional earthquakes will be included in the estimate; however, the long windows and robust estimate will minimize their effect.

The following plots show noise levels by station and channel, and follow the format of *Astiz* (1997). The lower axis shows period (seconds) while the upper axis shows frequency (Hz). The left axis is in decibels with respect to acceleration $m^2/s^4/Hz$. The black curve shows the vertical (BHZ), the red shows the east-west (BHE), and the blue marks the north-south (BHN). The dashed line denote the USGS low- and high-noise models (e.g. *Peterson*, 1993). Plots showing diurnal and seasonal changes are appropriately marked. Because the deployment was of limited duration, some stations did not record enough data to provide seasonal changes.

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. IDA RAYN data were also not included in this study, as the vault, instrument, and digitizer are different.

Figure 3 shows the noise levels for all stations for each channel (BHZ, BHN and BHE). In general, the stations were very quiet. The vertical components in particular lie very near the USGS low noise model except at higher (above 2 Hz) frequencies. This noise was generally due to cultural causes. It is clear that the horizontals were significantly noisier at frequencies less than 0.1 Hz. Not all stations had equal number of data points so some caution should be taken when comparing individual stations. The systematics 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.

Figures 4(a) and 4(b) show the noise levels at each station. The number of observations at each station are shown in the upper left corner. HALM, RAYN, AFIF and UQSK are the quietest stations. RIYD, TAIF and SODA show enhanced high frequency noise which is expected as all are relatively close to large cities. In general, noise levels were 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 was slightly noisier than the horizontals, and at frequencies less than 0.1 Hz, the horizontals were much noisier. This pattern is true of all stations except RIYD, which shows a lower noise on the vertical at almost all frequencies. The most likely explanation was an instrumental problem.

Figures 5(a) through 5(h) show diurnal and seasonal variations at the stations, as constrained by the available data. In general, noise levels were quietest at night and noisiest during morning and early afternoon, as expected for cultural noise. The most significant variations occurred at frequencies above 1 Hz.

Long period noise

The most obvious discrepancy between the noise levels from the Saudi stations and the low noise model is at the horizontal long periods. At frequencies greater than 0.1 Hz (10 second period), the noise levels between the verticals and the horizontals varied greatly (by up to 40 dB). Examination of the data showed 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 anti-correlates on the two horizontal channels (Figure 6(a)) and consequently a simple rotation will eliminate the noise on one channel at least (Figure 6(b)). 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 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 error of measurement or possible misalignment of the seismometer.

An alternate possibility is that the long period noise may be due to small tilts which affect the horizontal more than the verticals.

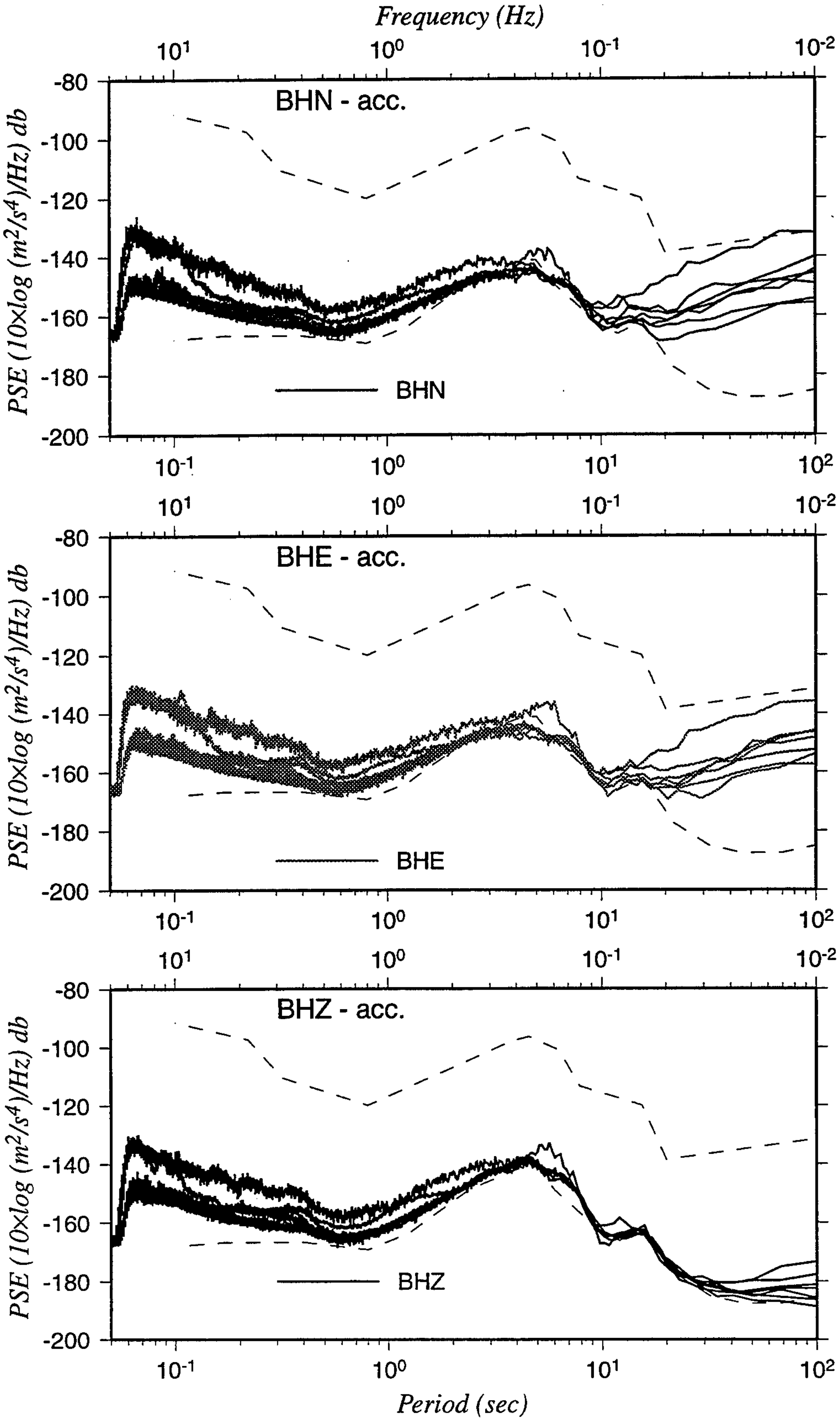

Figure 3. Noise levels at all stations.

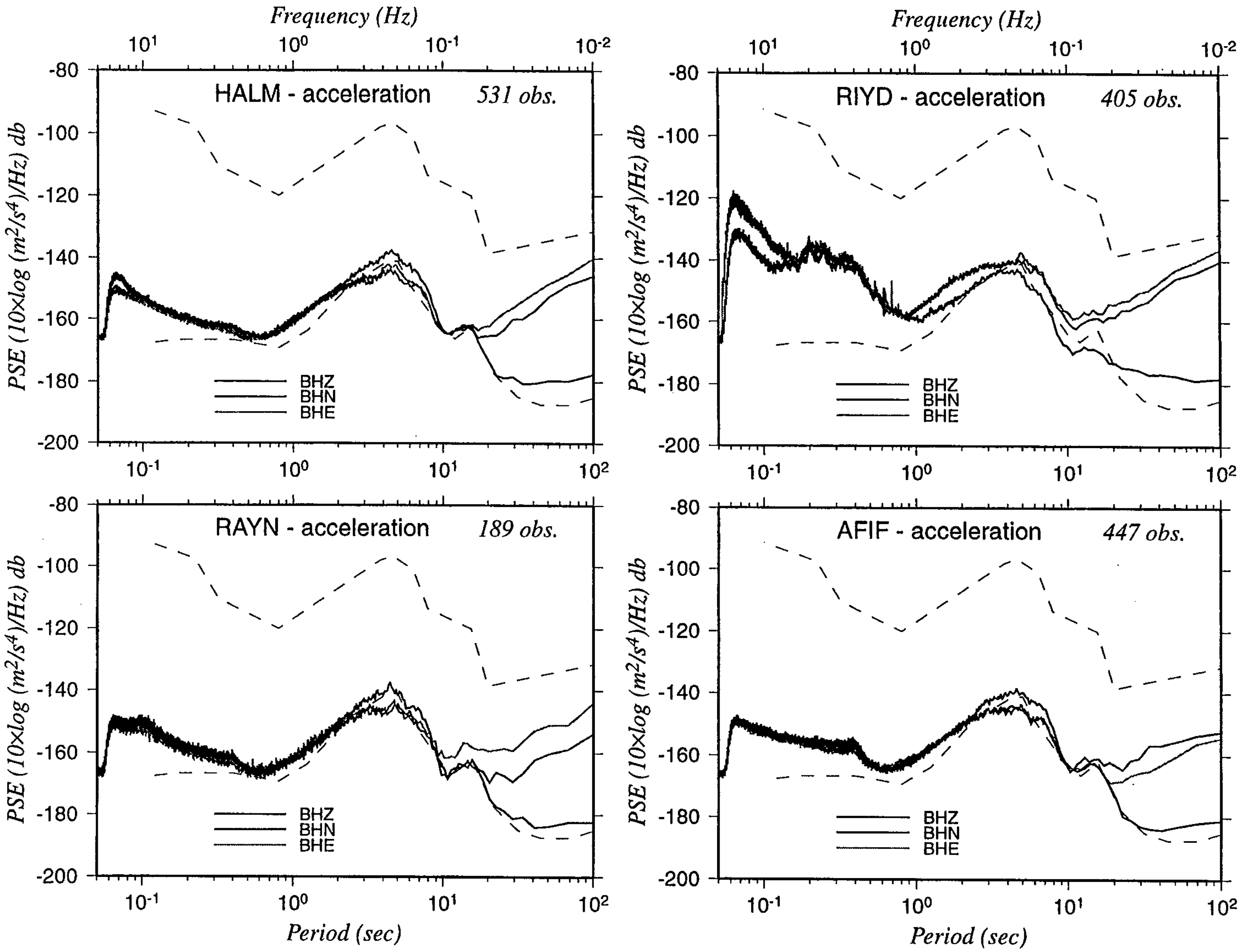

Figure 4(a). Noise levels at HALM, RIYD, RAYN, and AFIF.

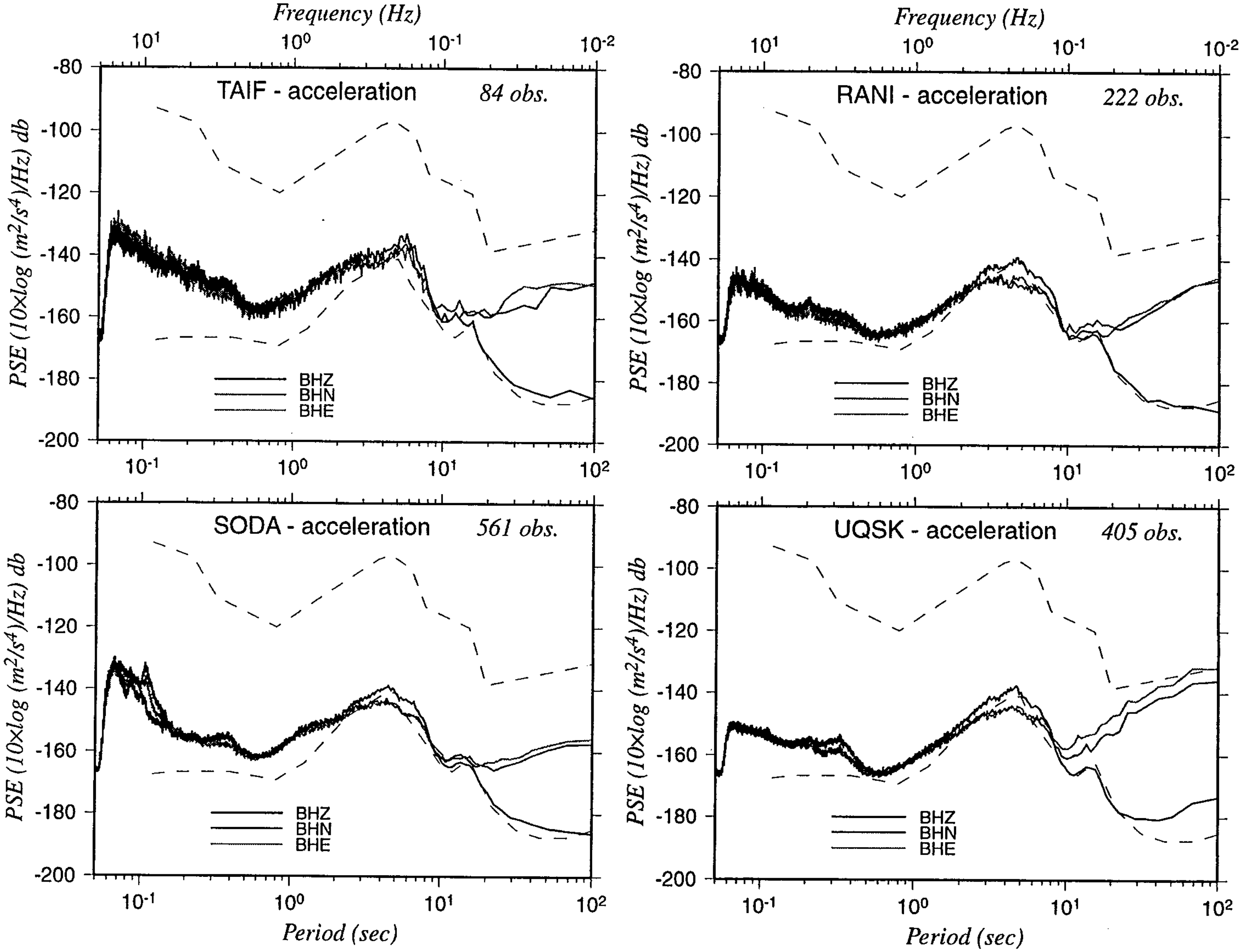

Figure 4(b). Noise levels at TAIF, RANI, SODA, and UQSK.

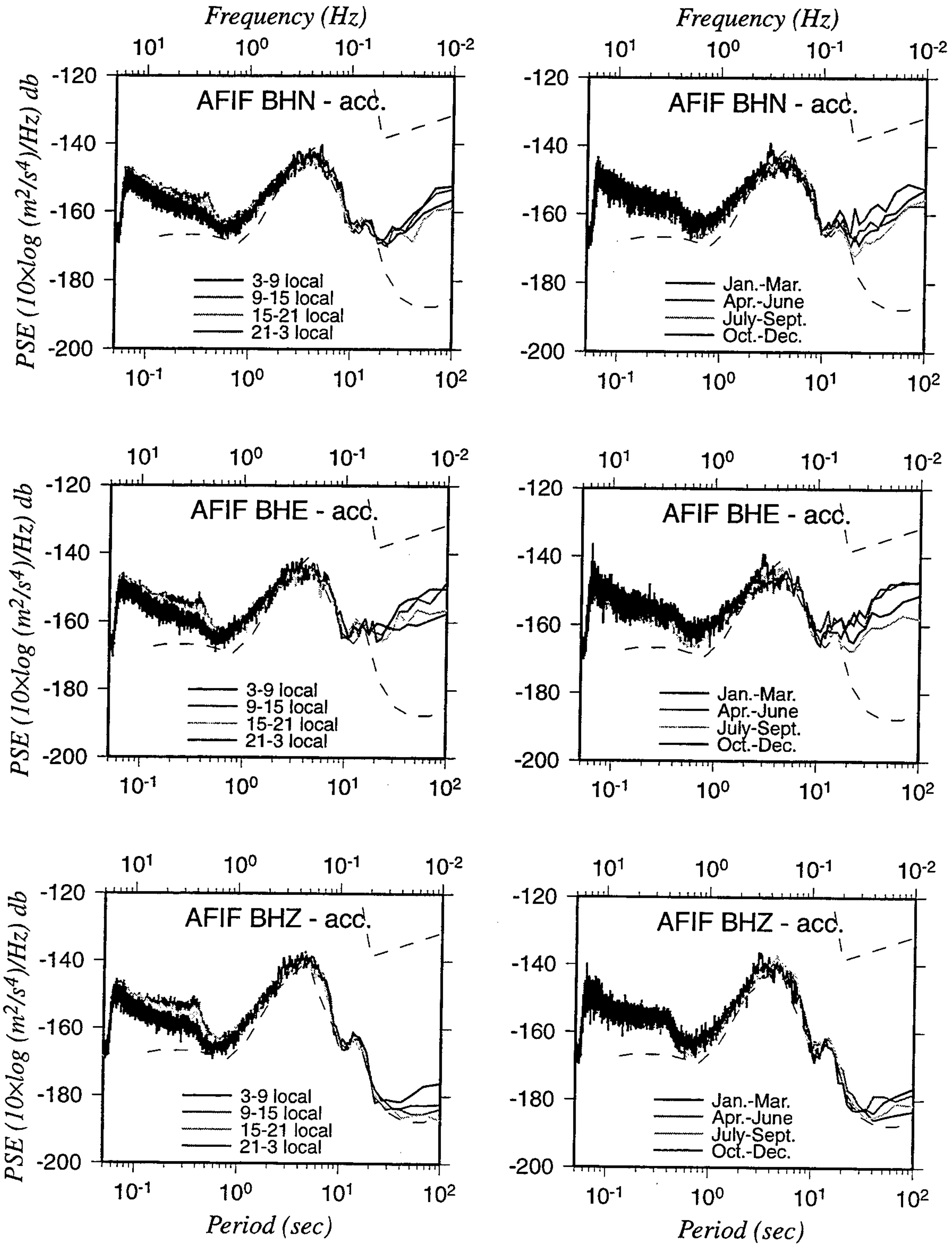

Figure 5(a). Diurnal and seasonal noise variations for station AFIF.

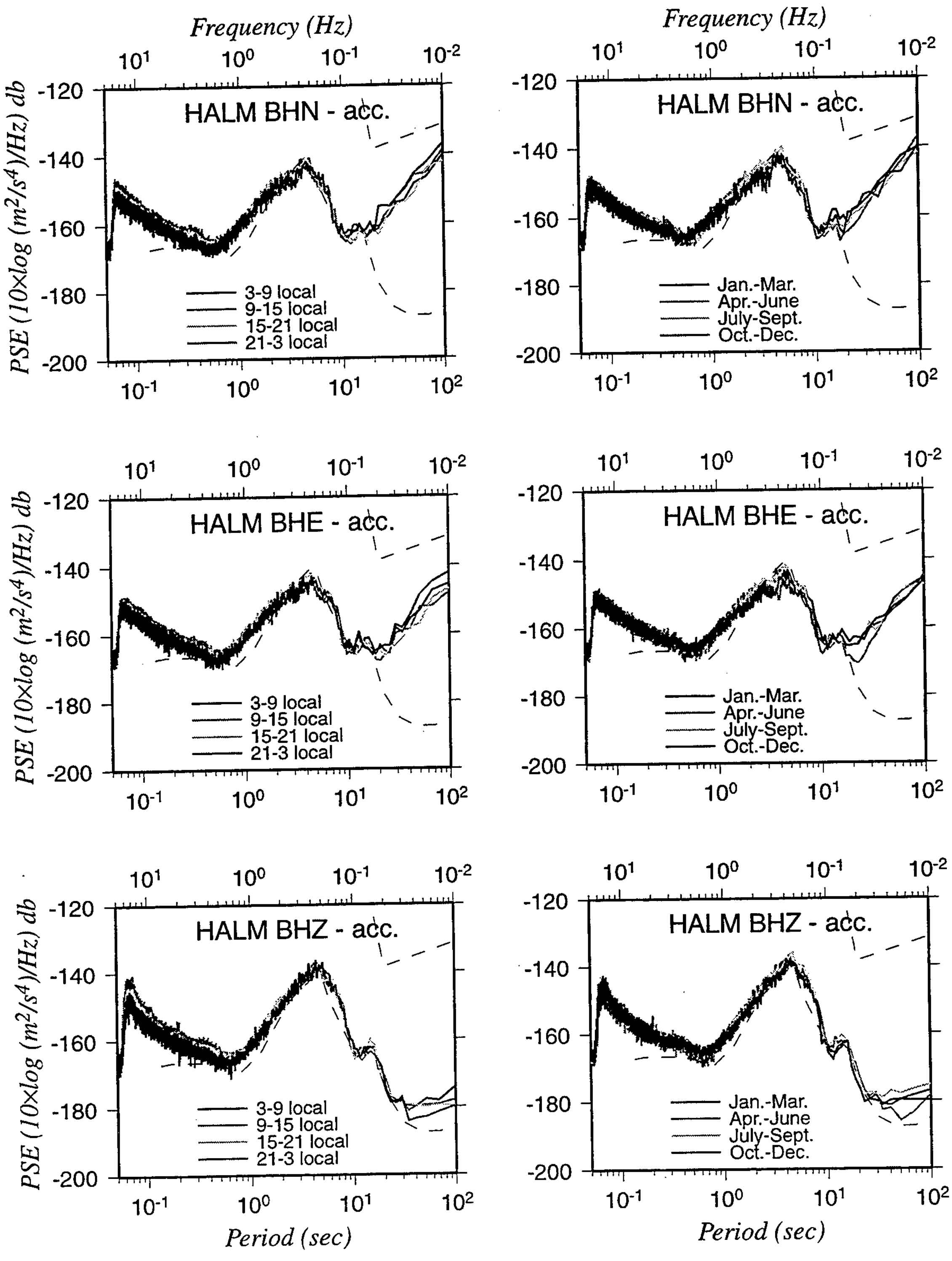

Figure 5(b). Diurnal and seasonal noise variations for station HALM.

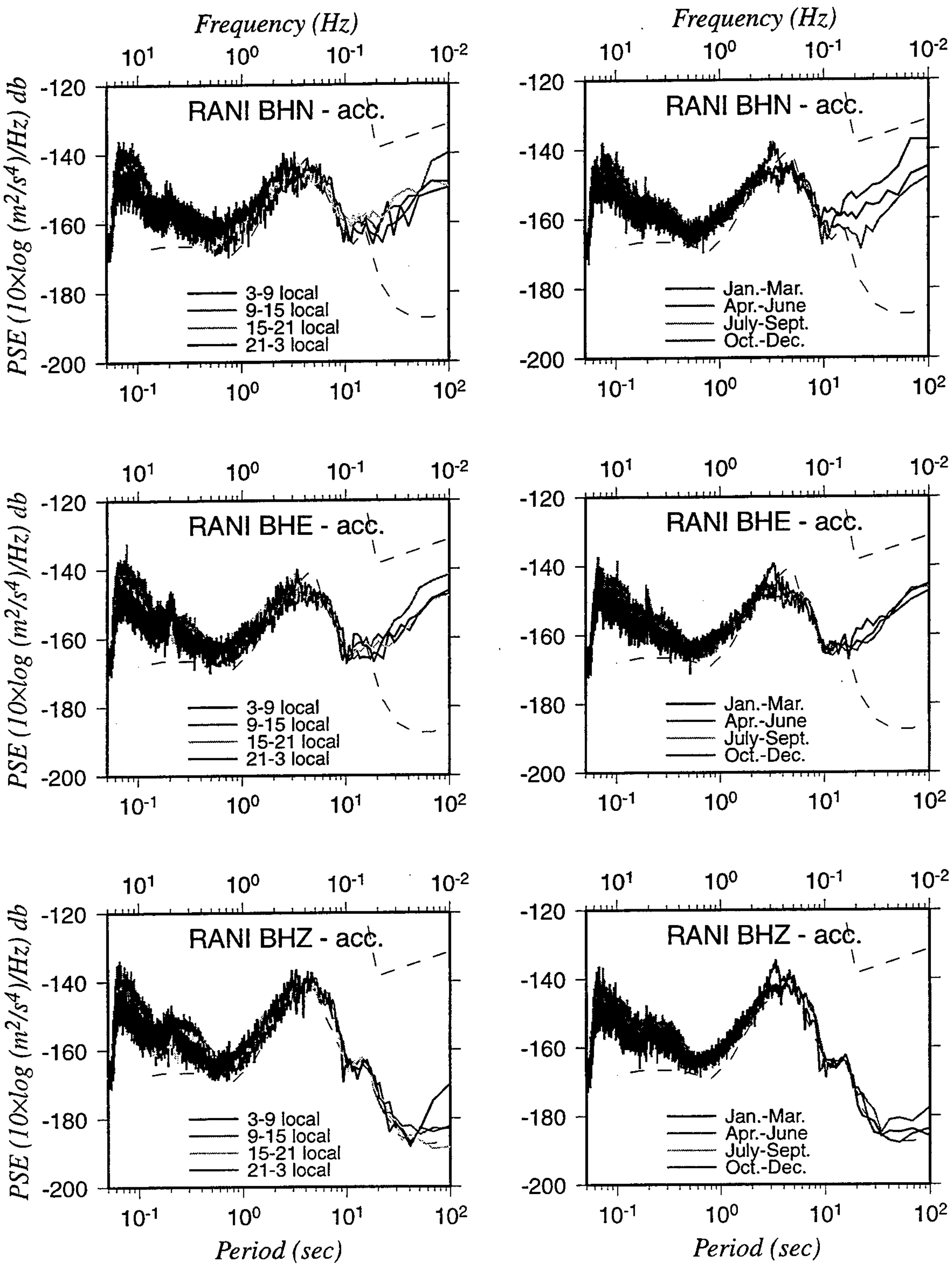

Figure 5(c). Diurnal and seasonal noise variations for station RANI.

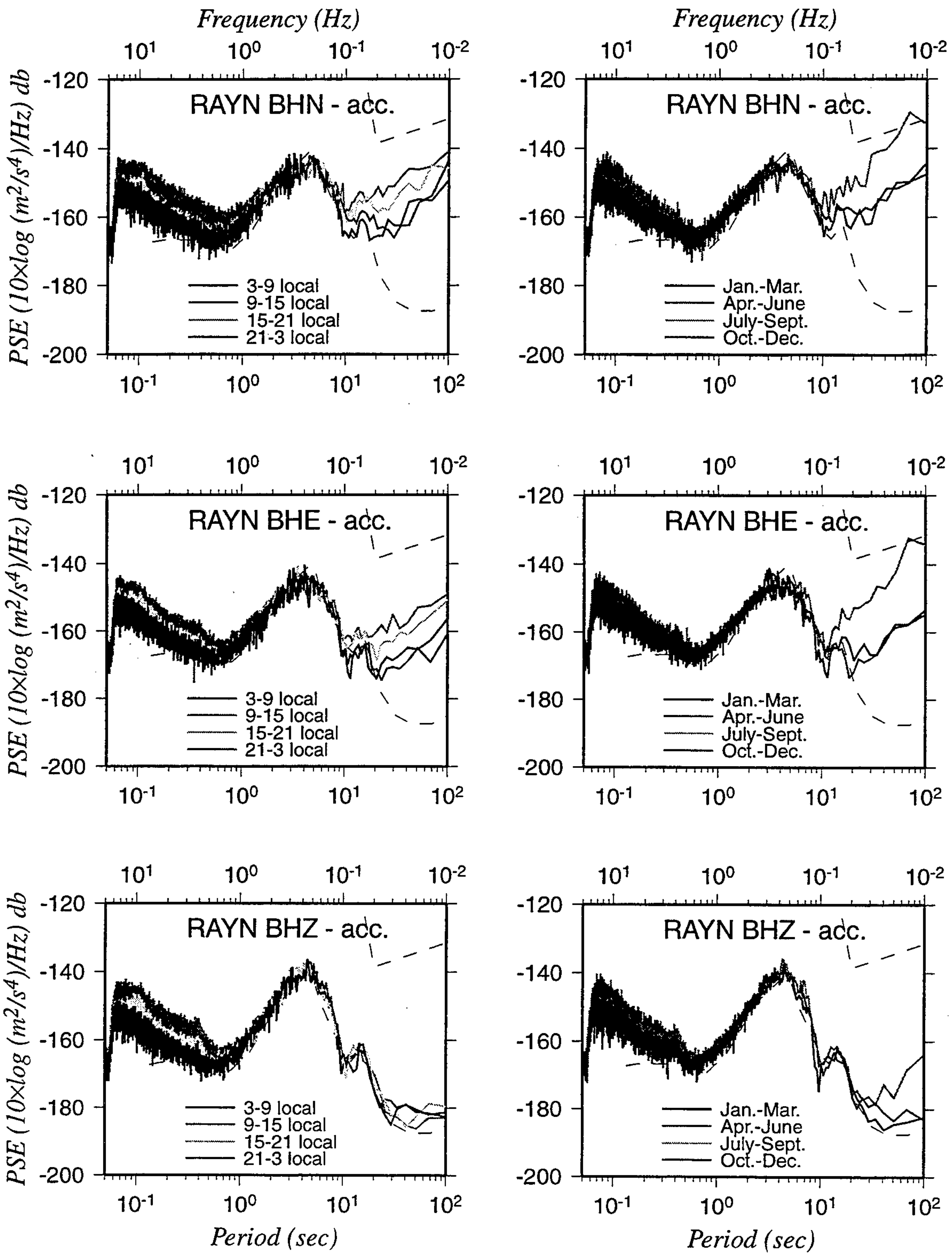

Figure 5(d). Diurnal and seasonal noise variations for station RAYN.

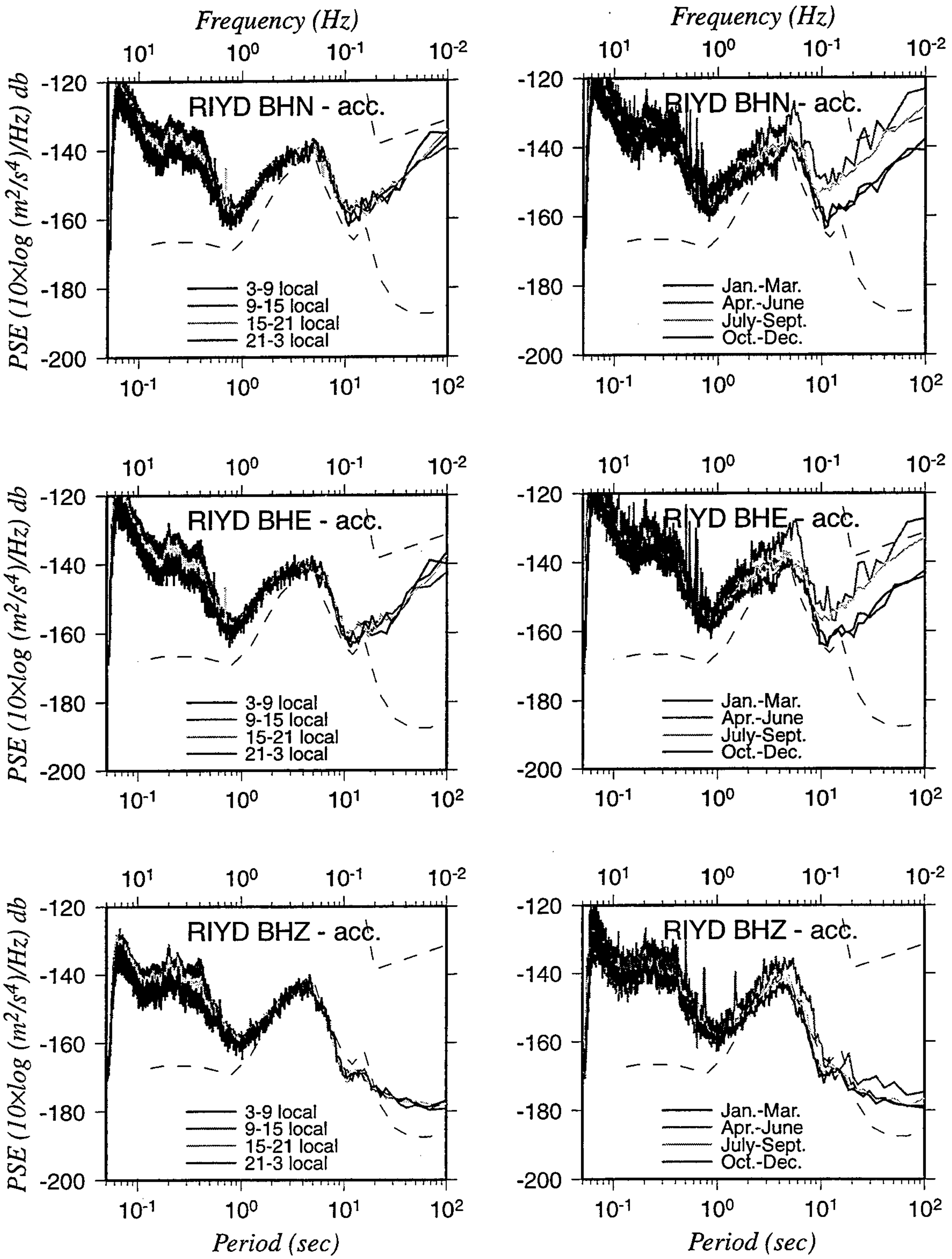

Figure 5(e). Diurnal and seasonal noise variations for station RIYD.

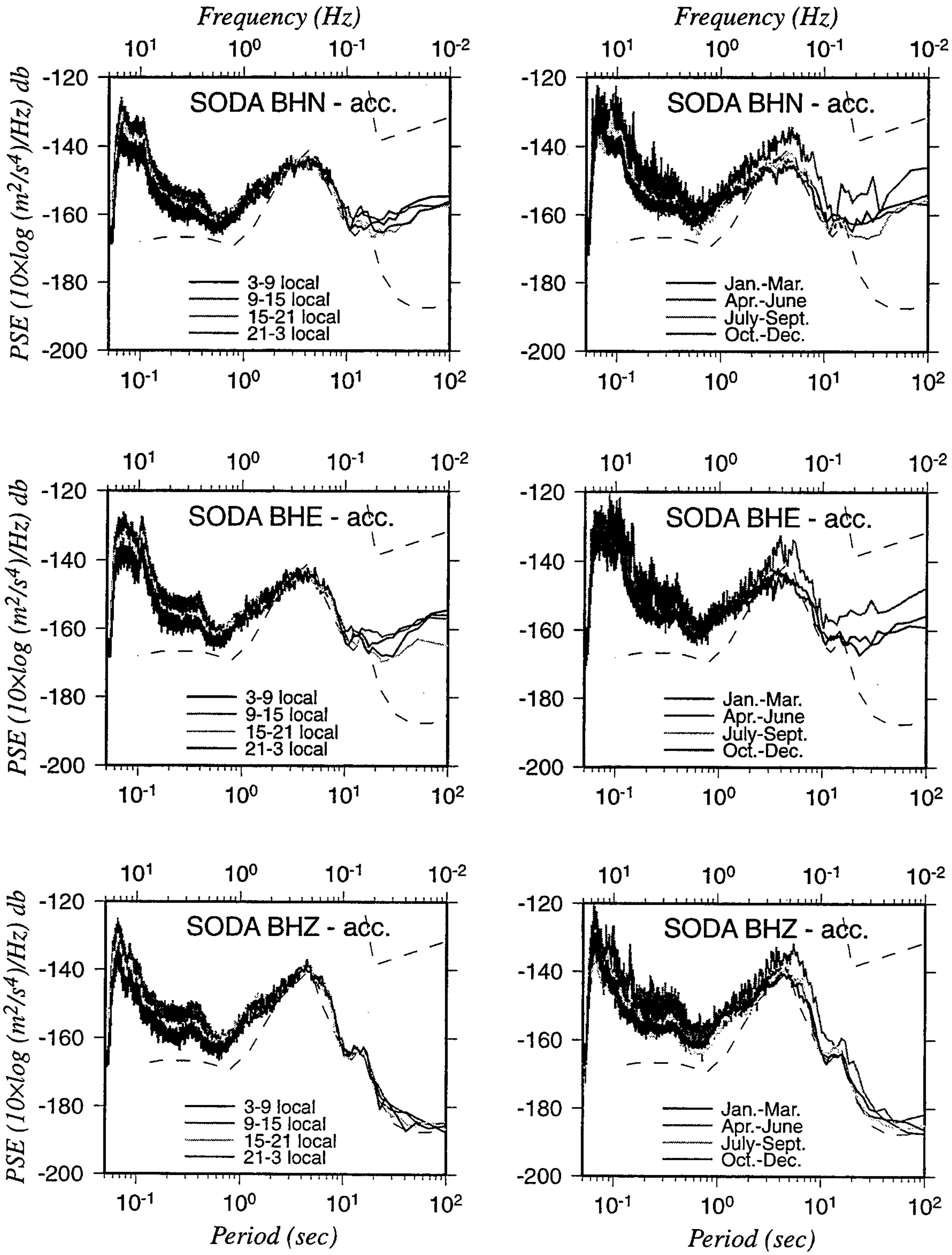

Figure 5(f). Diurnal and seasonal noise variations for station SODA.

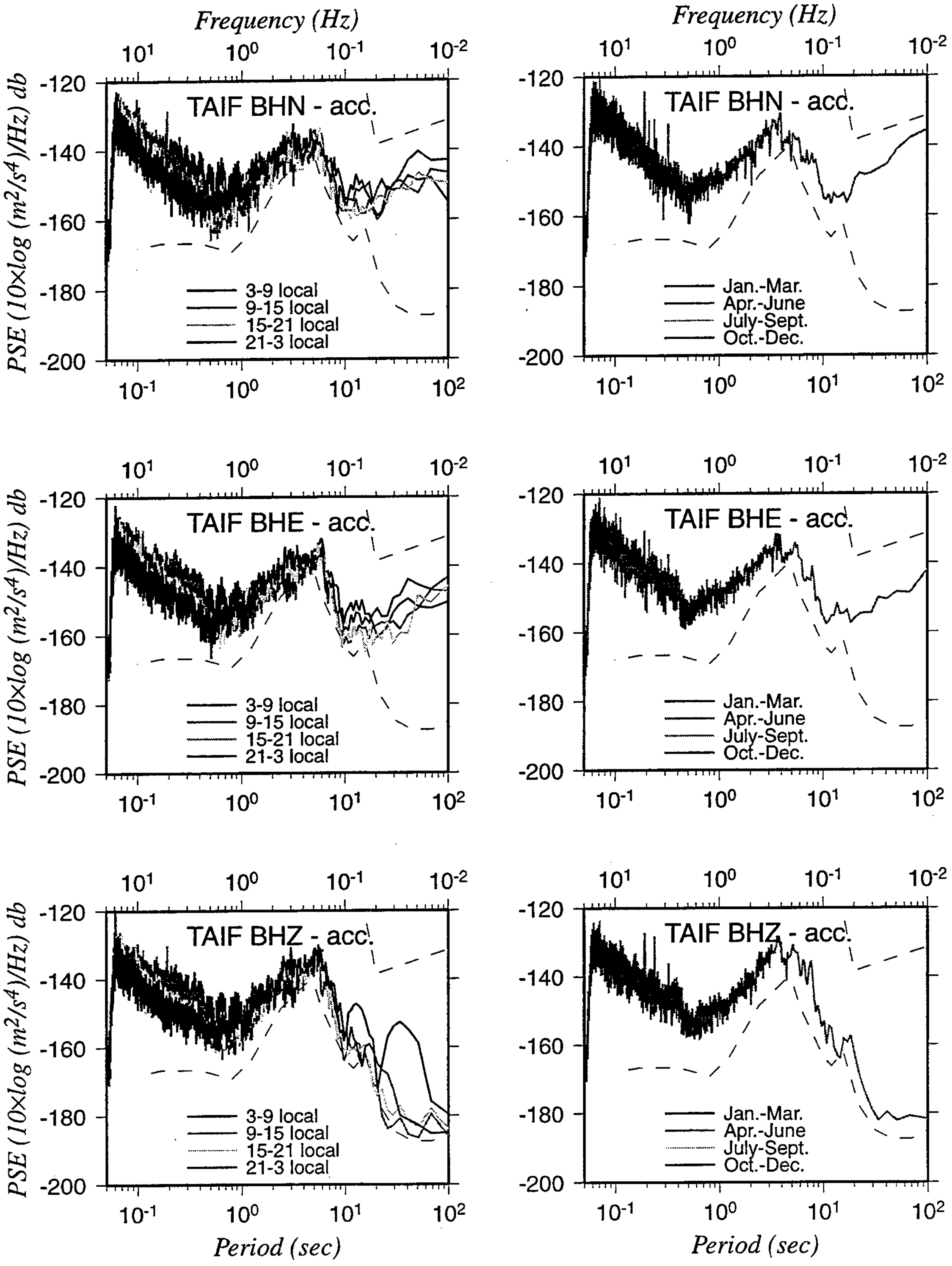

Figure 5(g). Diurnal and seasonal noise variations for station TAIF.

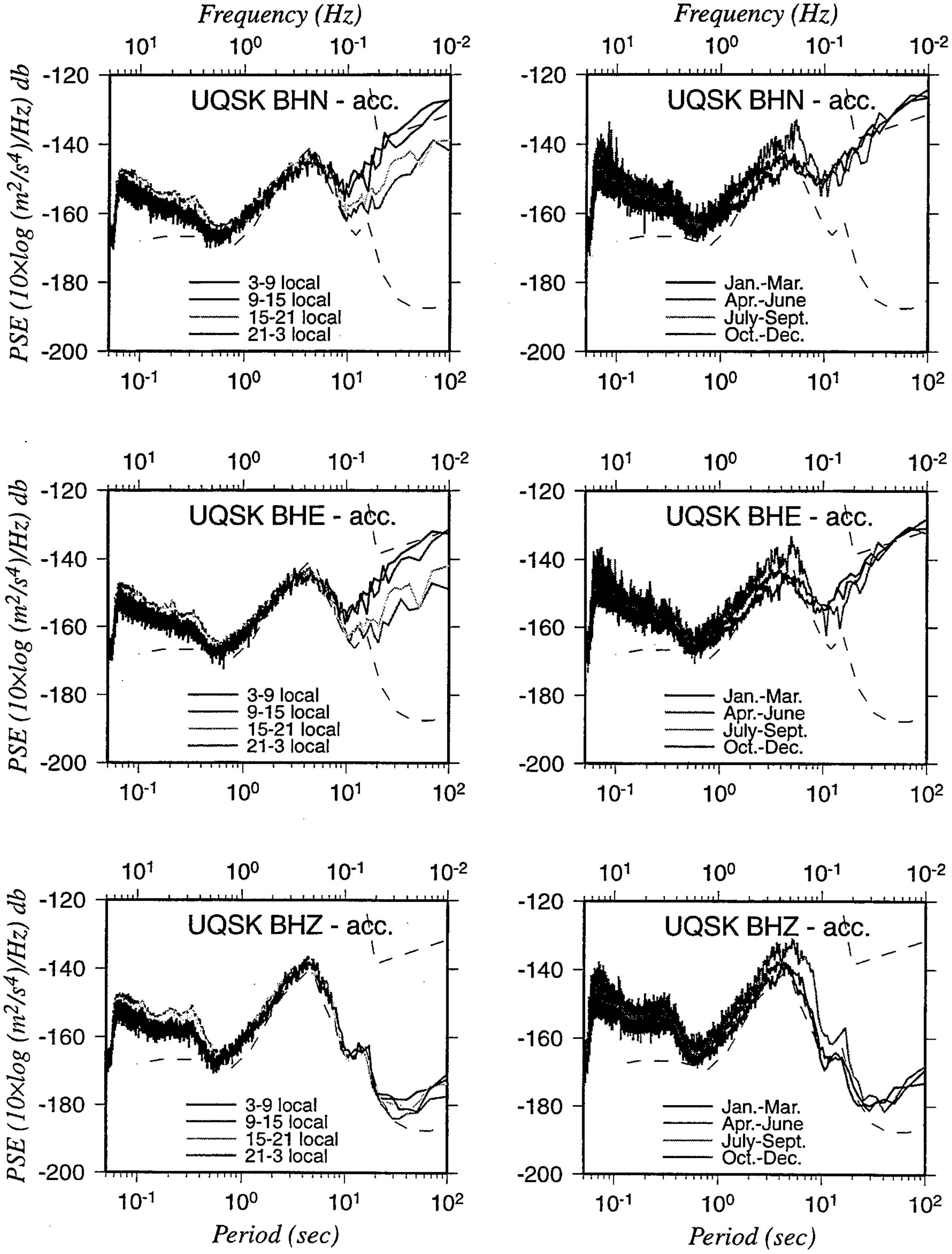

Figure 5(h). Diurnal and seasonal noise variations for station UQSK.

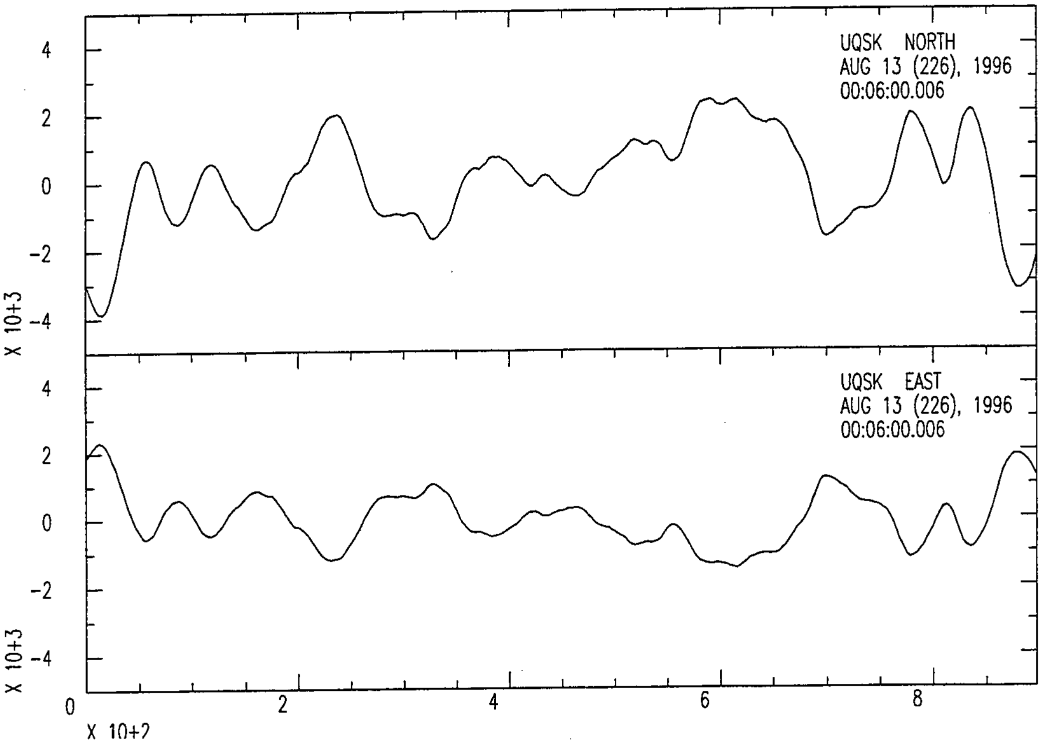

Figure 6(a). UQSK horizontal channels showing anti-correlated long-period noise.

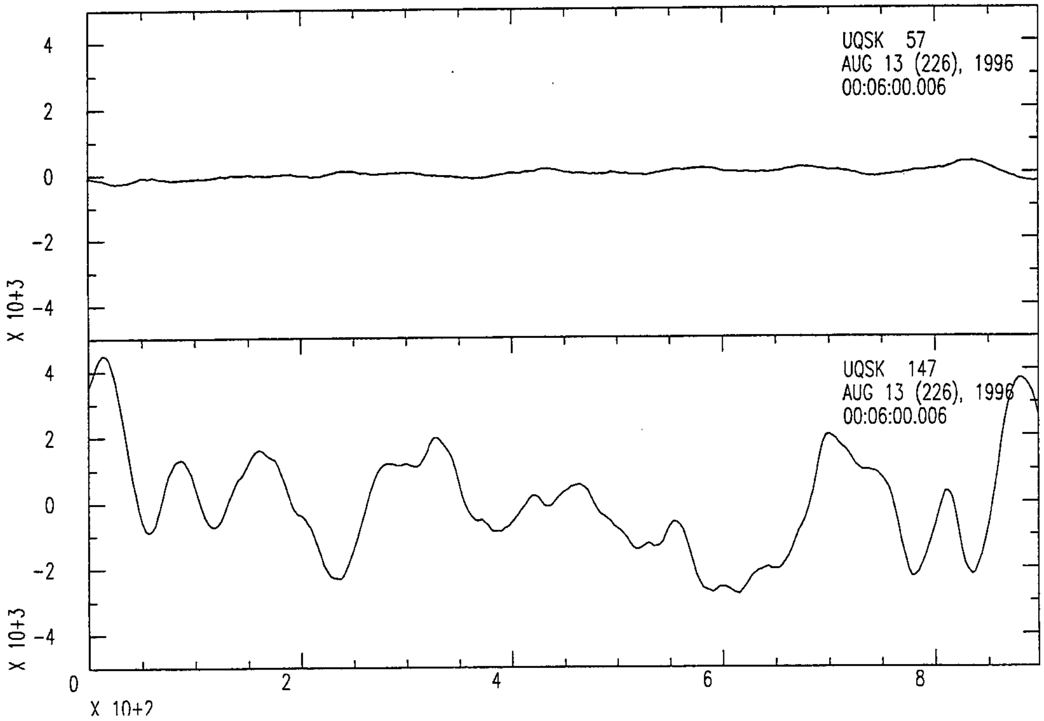

Figure 6(b). UQSK horizontal channels rotated 57 degrees to isolate the noise.

Detection Thresholds

Following the method of *Harvey and Hansen* (1994) we calculated for each station the single-site magnitude detection thresholds. Using event m_b magnitudes reported in the REB, the m_b estimates from our data in the 0.8 to 3 Hz pass band were corrected to produce zero mean statistics for the REB relative residuals. Single-site m_b vs. distance functions gave us the raw information for determining single-site detection magnitude thresholds. In a traditional analysis of single-site detection magnitude thresholds, one would create a map view, put events into regional bins, compute magnitude-frequency functions for each bin and set the magnitude threshold for each bin according to some roll-off criteria applied to the magnitude-frequency functions. However, this method requires more events than we had in our catalog.

There is an alternate method for determining single-site detection magnitude thresholds which yields reasonable results from relatively small catalogs. This method was based on using P wave signal-to-noise ratios observed at a given station to scale event magnitudes to equivalent threshold values for that station. This was done by adjusting the event magnitude by an amount equal to the logarithm of the ratio of the observed signal-to-noise level and a threshold signal-to-noise level representing the minimum level at which a signal would be detected. The assumption here was that the wave propagation is a linear process so that amplitudes can be scaled directly. This approach allowed us to scale down large magnitude events to equivalent smaller events that are at the detection limit for each particular source-receiver geometry.

The results of this method were applied to the events shown in Figures 7(a)-(f) for a specified detection threshold signal-to-noise level of two. Figure 7(e) shows such a function produced from events for the newly installed GSN station RAYN where squares represent events that were in the REB and the symbols are color coded according to event depth. We can see that the populations of shallow and deep events clearly separate as one would expect. Our results show that the mb detection threshold for the distance range of 10-100 degrees is about mb = 3.5. Stations AFIF (Figure 7(a)) and HALM (Figure 7(c)), UQSK (Figure 7(i)) have nearly equivalent detection thresholds as the RAYN station. The western stations SODA, RANI and TAIF are less sensitive, with detection thresholds of about mb = 3.7.

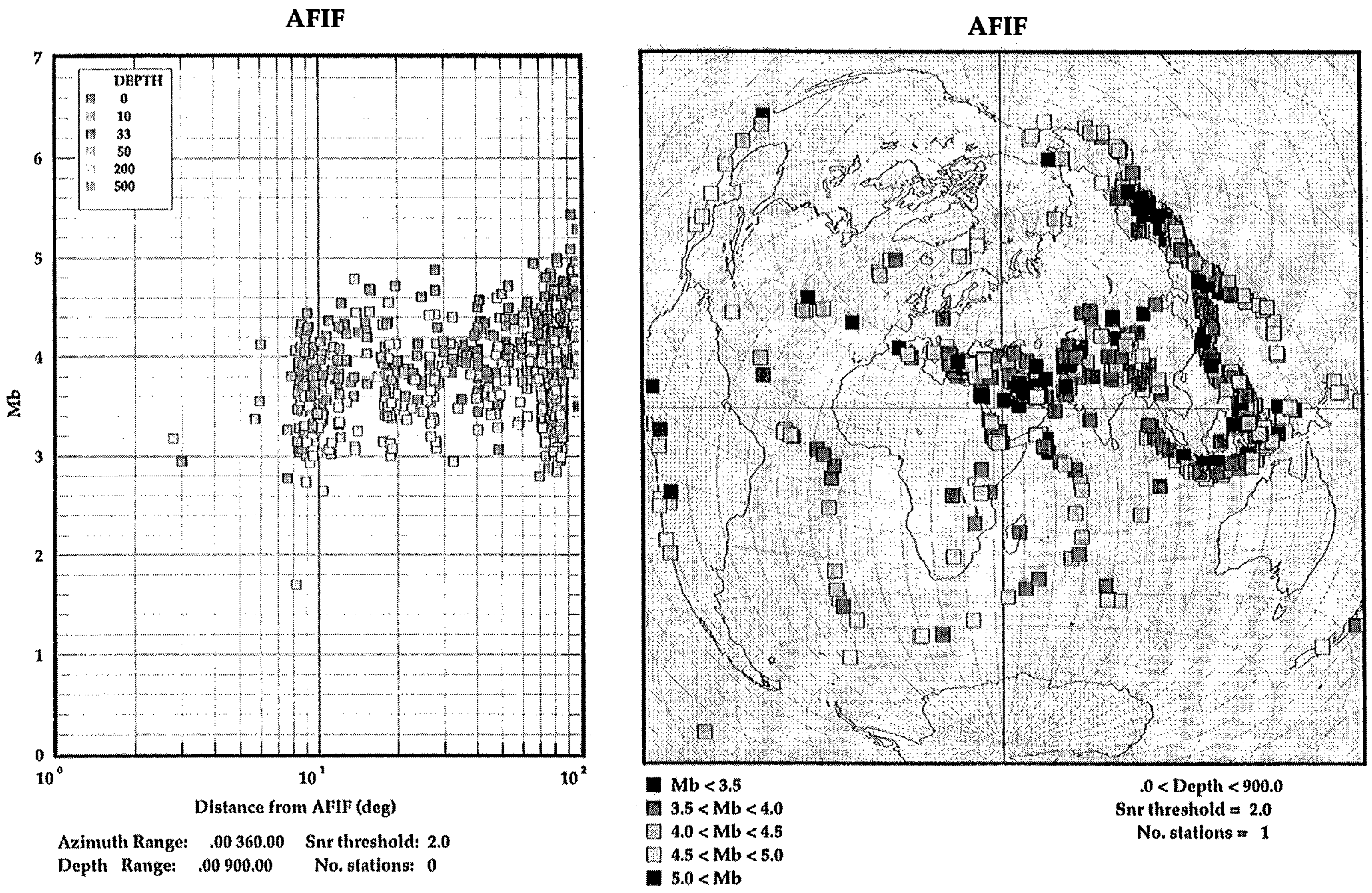

Figure 7(a). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station AFIF. Map view for the same events shown in the right panel.

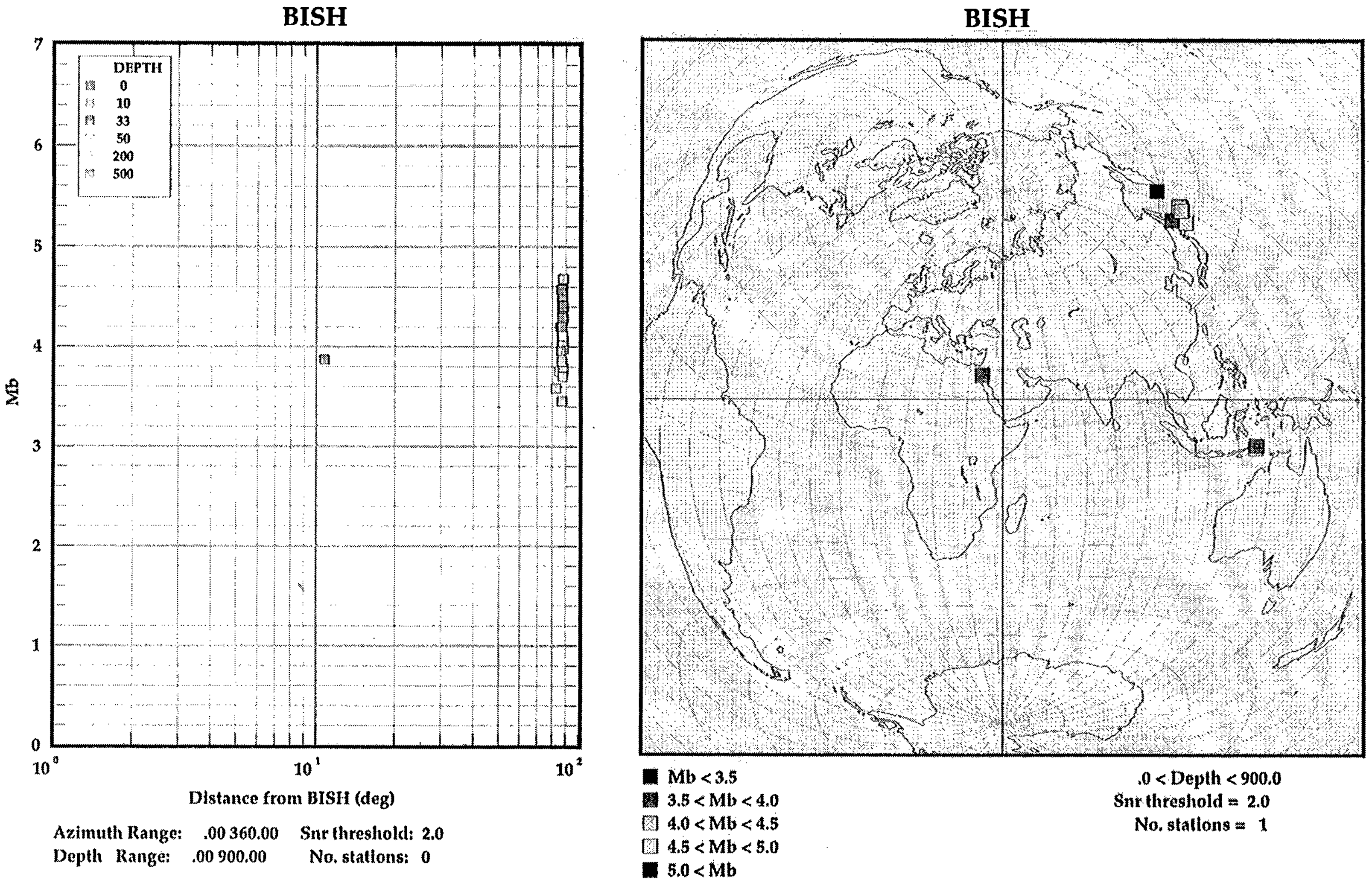

Figure 7(b). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station BISH. Map view for the same events shown in the right panel.

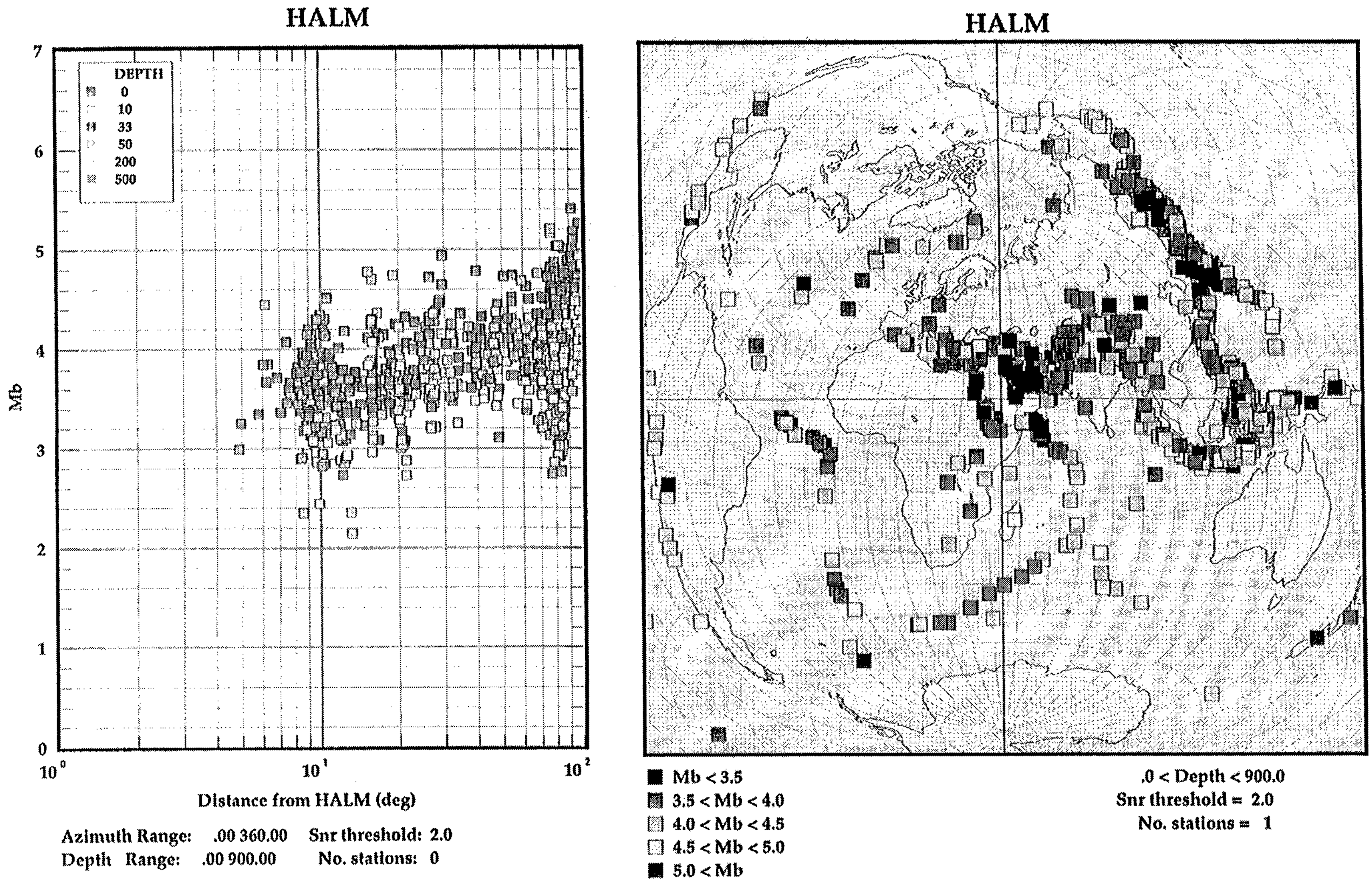

Figure 7(c). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station HALM. Map view for the same events shown in the right panel.

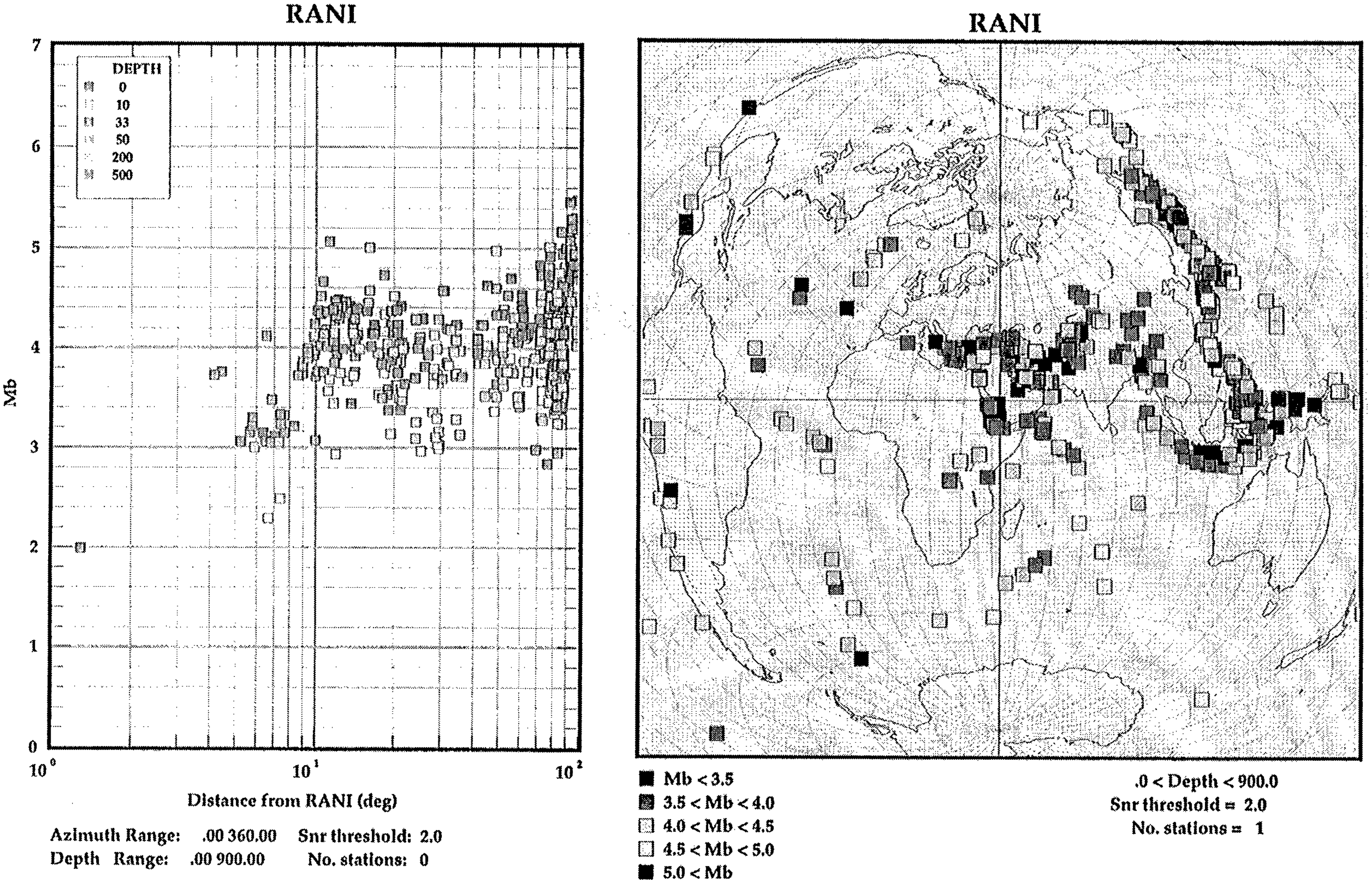

Figure 7(d). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station RANI. Map view for the same events shown in the right panel.

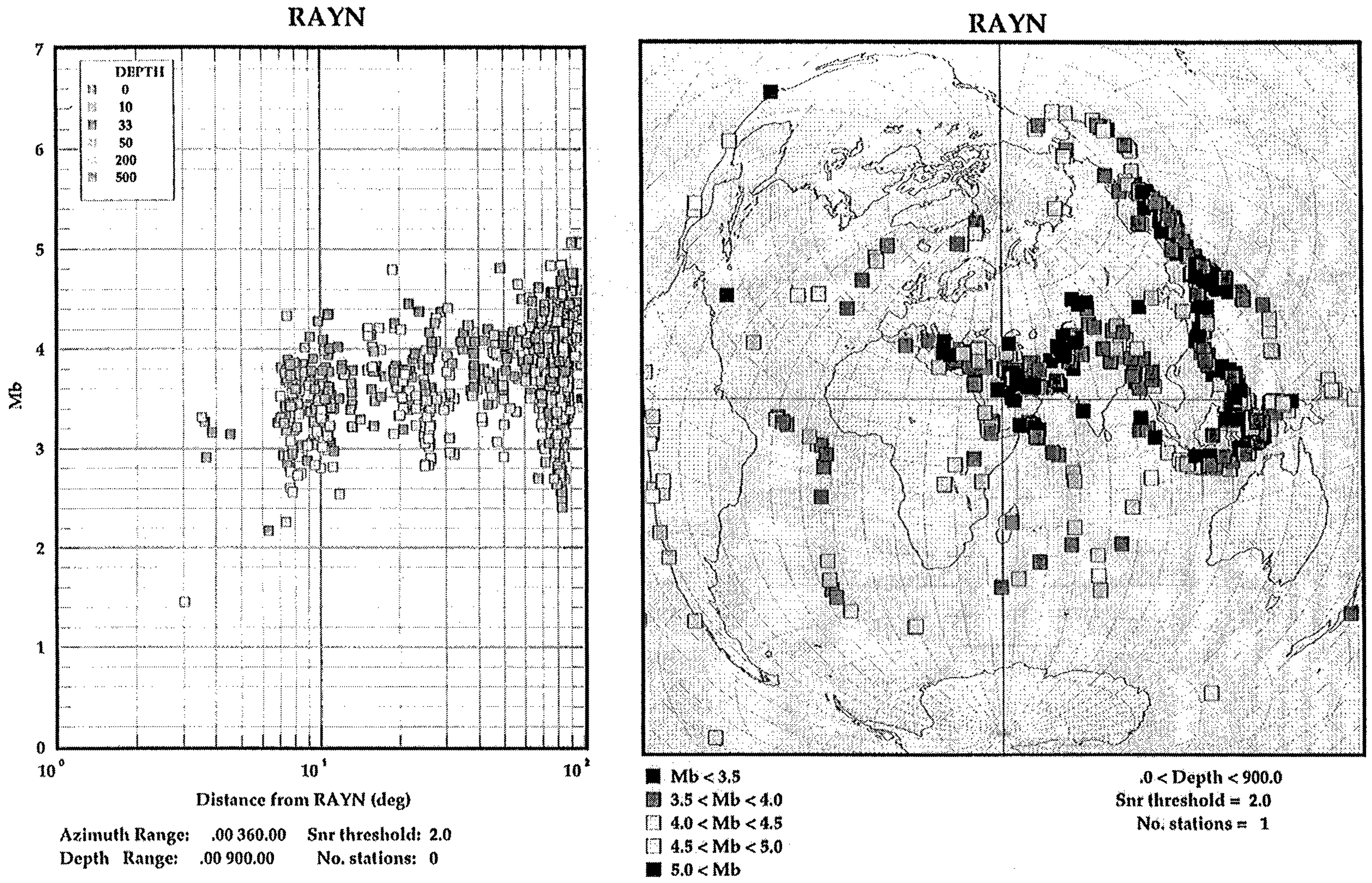

Figure 7(e). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station RAYN. Map view for the same events shown in the right panel.

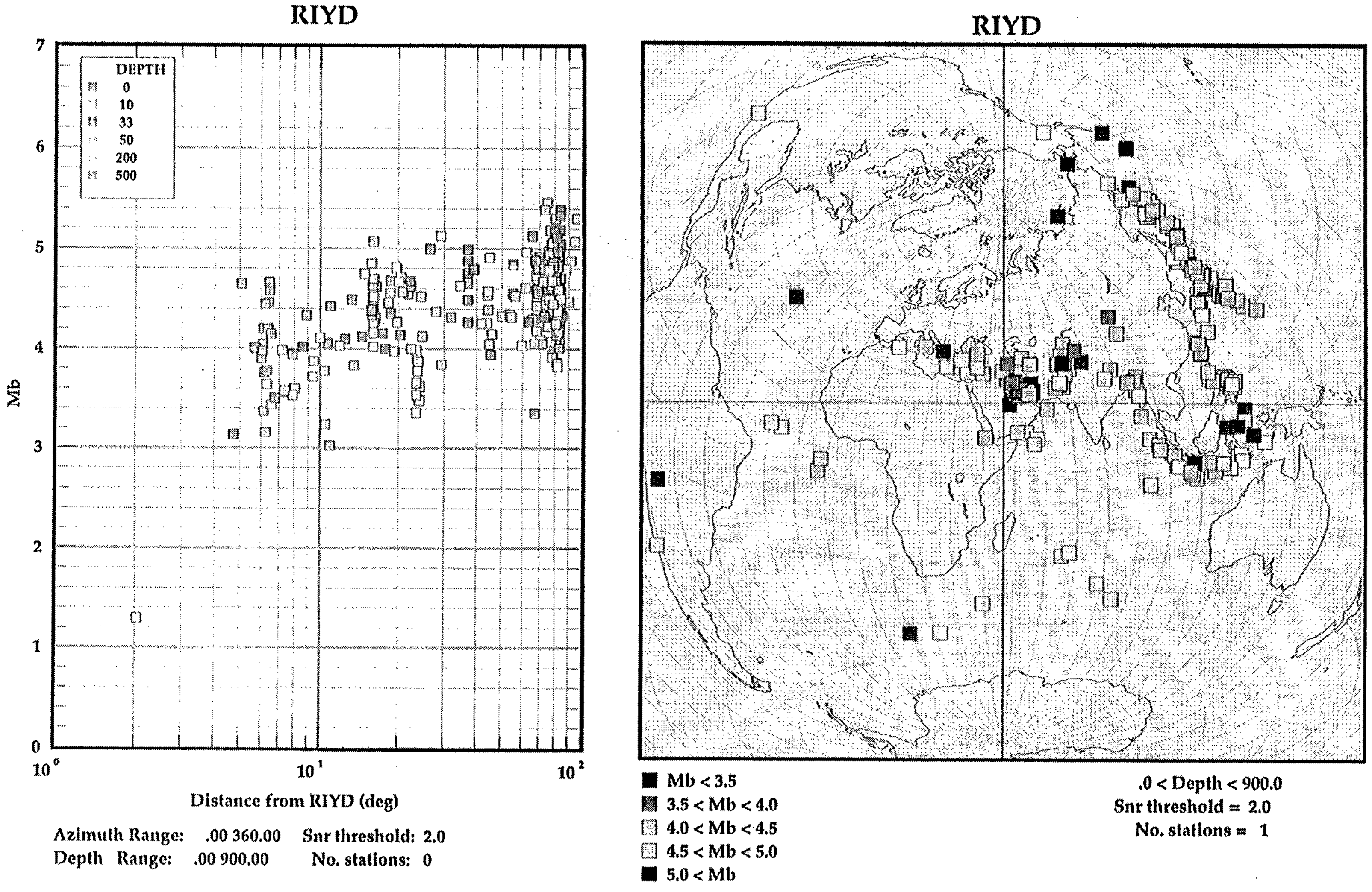

Figure 7(f). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station RIYD. Map view for the same events shown in the right panel.

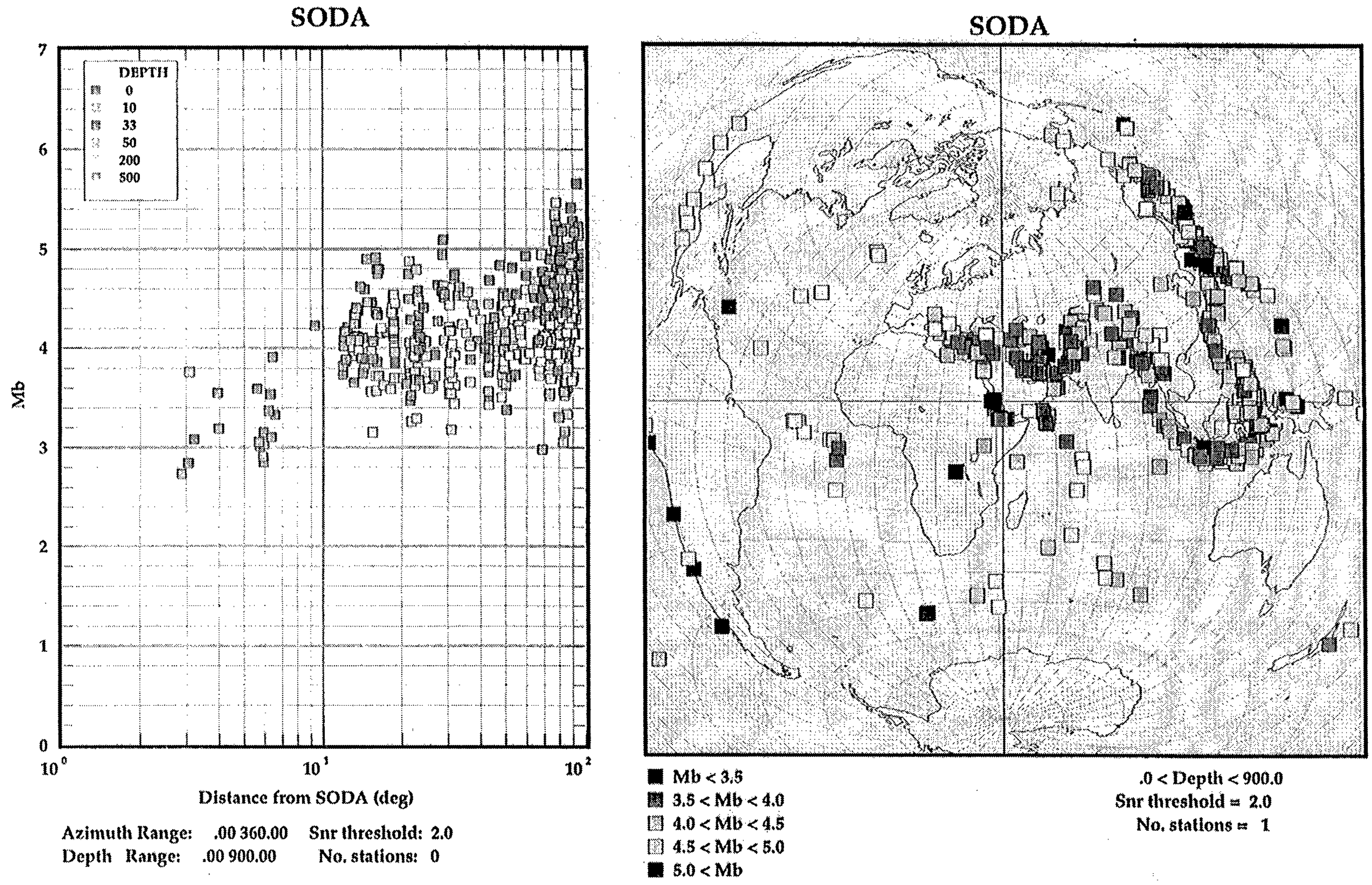

Figure 7(g). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station SODA. Map view for the same events shown in the right panel.

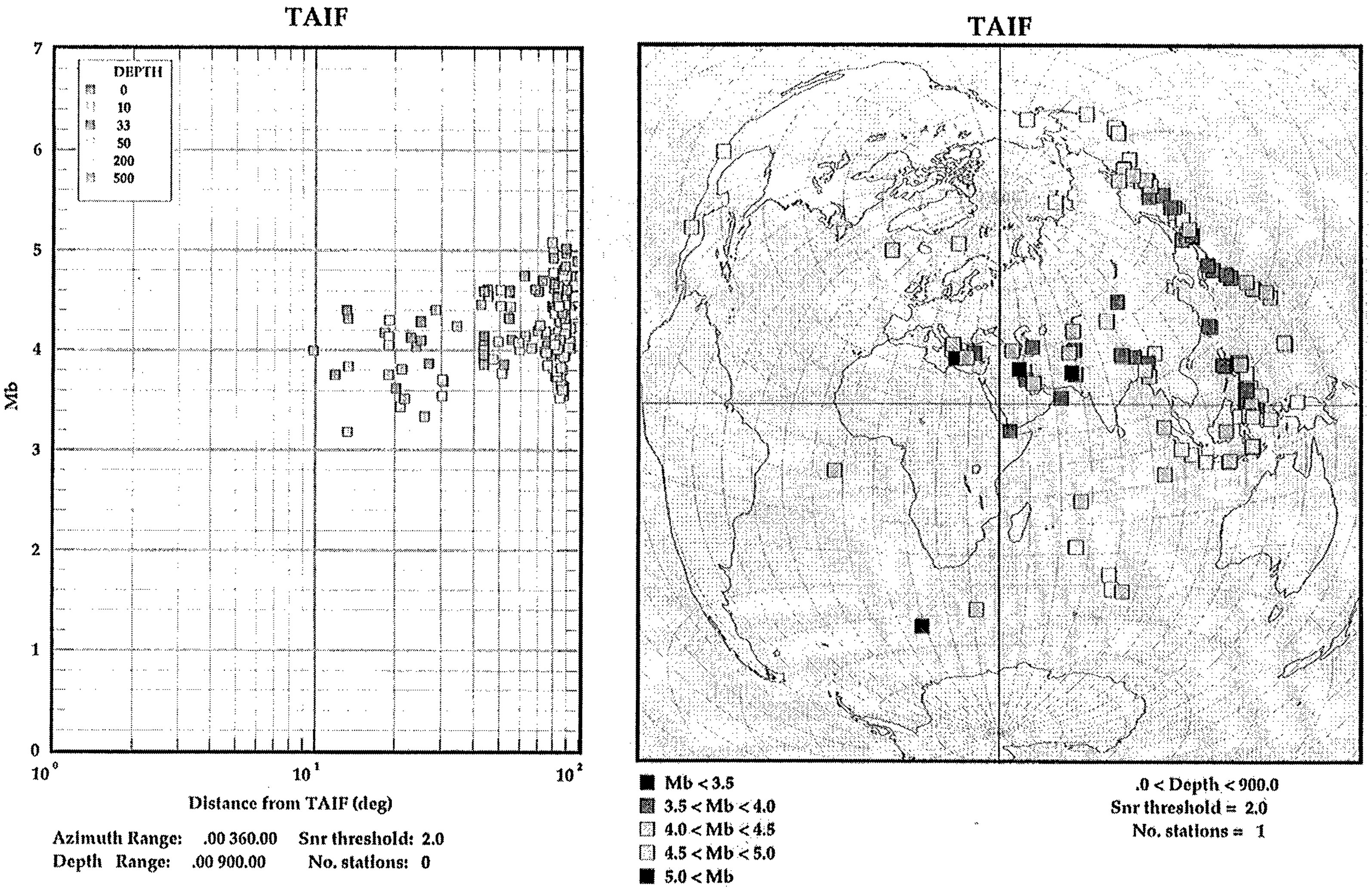

Figure 7(h). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station TAIF. Map view for the same events shown in the right panel.

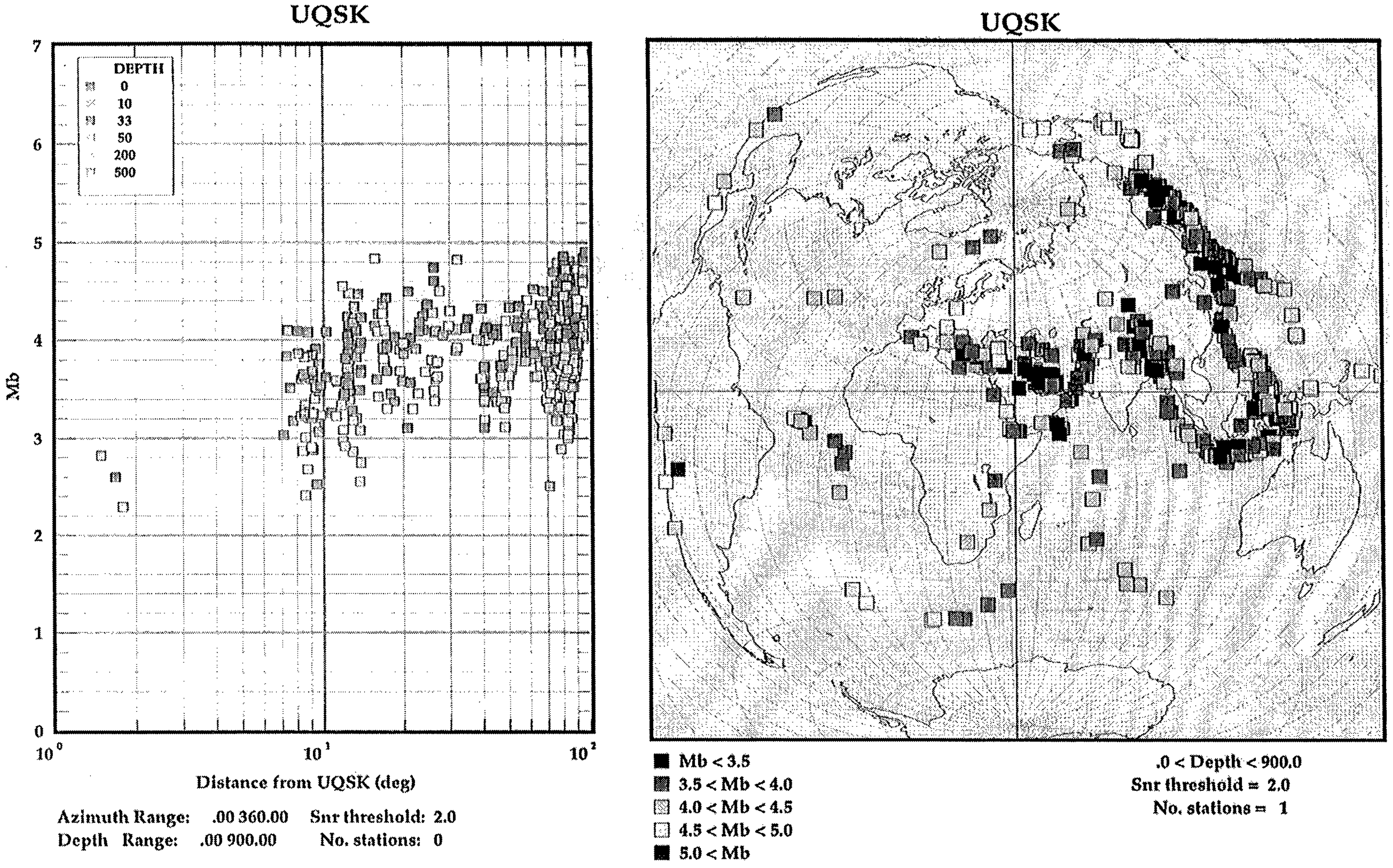

Figure 7(i). Detection threshold as a function of distance for a signal-to-noise ratio of 2 shown in the left panel for station UQSK. Map view for the same events shown in the right panel.

CONCLUSIONS AND RECOMMENDATIONS

The results of our field deployment suggest that many of our 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 also contributes to the very low detection threshold of events with mb >= 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. Seismograms from sources 10 degrees from the center of the network 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. From the opposite direction, aftershocks from the Gulf of Aqaba have very weak P and S waves with very strong Lg phases.

In the future, the understanding of the waveform propagation properties would be enhanced by placing stations further north in the Arabian shield areas. Based on our observations, there exist several excellent sites in the shield region of Saudi Arabia which could be used for potential seismic arrays.

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