UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



U.S. Geological Survey
OPEN FILE REPORT
This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

MENLO PARK, CALIFORNIA





20

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

National Center for Earthquake Research
345 Middlefield Road
Menlo Park, California 94025

TECHNICAL LETTER NCER-9

OPEN FILE REPORT

# $P_n$ SPECTRAL VARIATIONS OF THE GASBUGGY EXPLOSION AT INTERMEDIATE DISTANCE RANGES*

by

W. H. K. Lee and R. D. Borcherdt



1968

*Work done under ARPA Order No. 1094

# $P_n$ SPECTRAL VARIATIONS OF THE GASBUGGY EXPLOSION AT INTERMEDIATE DISTANCE RANGES

BY

W. H. K. Lee and R. D. Borcherdt

National Center for Earthquake Research

U.S. Geological Survey, Menlo Park, California

## INTRODUCTION

The Project GASBUGGY nuclear explosive of 26-kilotons design yield was detonated on Sunday, December 10, 1967, 1230:00.136 MST, at latitude 36°40'40.4" North and longitude 107°12'30.3" West, about 55 air miles east of Farmington, New Mexico. The U.S. Geological Survey recorded seismic waves generated by the explosion along five lines radiating from the shot site, using truck-mounted seismic-refraction recording systems described by Warrick, et al. (1961), plus other units. The unit impulse response for ground velocity of the recording systems is approximately flat from 2 cps to above 15 cps. A preliminary data report on traveltime and amplitude variations with azimuth and distance was prepared by Warren and Jackson (1968).

The present paper is submitted as a data-analysis report whose primary purpose is to study variations of $P_n$ spectra as a function of distance and azimuth. Seismic records were digitized from 19 stations in the distance range 300 to 500 kilometers from the shotpoint (Figure 1 and Table I). Time-series analysis was then applied to the portion of seismic records containing essentially the $P_n$ phase (the first 3 seconds after the first arrival). The results indicated significant variations of $P_n$ spectra from station to station. Following a brief summary of the method of data analysis, the results will be discussed in detail.

## DATA ANALYSIS

The first 3 seconds of the seismic records after the first arrival were digitized at a sampling rate of 50 per second, and calibrated such that the data represent absolute ground velocity in μ/sec normalized with zero mean value. The usual method of time-series analysis was then applied as described by Blackman and Tukey (1958). For a time series $X(t_1)$, $X(t_2)$, ..., $X(t_n)$ with zero mean, the autocovariance function at lag $\zeta$ is computed by

$$R(j) = \frac{1}{n - j} \sum_{i=1}^{n-j} X(t_i)\, X(t_{i+j}) \qquad (1)$$

for $j = 0, 1, 2, \ldots, m$; and $\zeta = j\Delta t$, where $\Delta t = t_i - t_{i-1}$.

The raw estimate of the spectral density at frequency $f_k$ is obtained by

$$\hat{P}(f_k) = \frac{2\, \Delta t}{\pi} \sum_{j=0}^{m} \epsilon(j)\, R(j) \cos(2\pi\, f_k\, j\Delta t) \qquad (2)$$

where

$$\epsilon(j) = \begin{cases} 1 & 0 < j < m \\ 1/2 & j = 0, m \end{cases}$$

for $f_k = \frac{k}{2m\Delta t}$, $k = 0, 1, \ldots, m$.

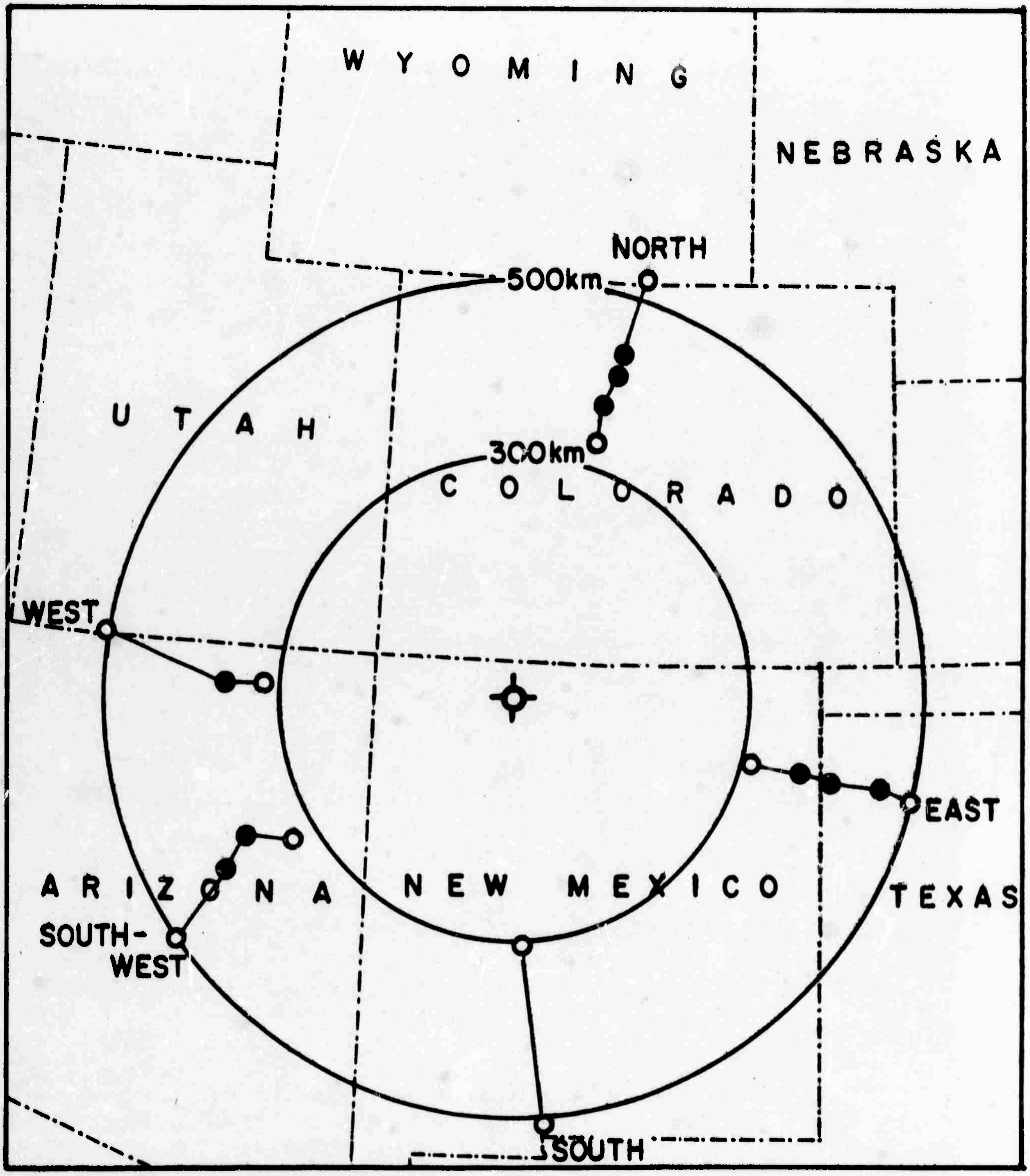


Figure 1. Location map for the GASBUGGY nuclear explosion and recording stations.

Table I

Station Locations and Distances, Spectral Energy for the $P_n$ Phase, and Q

| Direction | Name | Location Latitude, N | Location Longitude, W | Distance, km | Spectral Energy, $(\mu/sec)^2$ | Q |
|---|---|---|---|---|---|---|
| EAST | Roy, N. M. | 36°03' | 103°56' | 302 | 0.0320 | |
| | Rosebud, N. M. | 35°52' | 103°21' | 358 | 0.0081 | 160 |
| | Romero, Tex. | 35°43' | 102°56' | 399 | 0.0010 | 110 |
| | Channing, Tex. | 35°42' | 102°23' | 447 | 0.0023 | 220 |
| | Amarillo, Tex. | 35°31' | 101°49' | 502 | 0.0014 | 250 |
| SOUTH | Socorro, N. M. | 33°58' | 106°57' | 301 | 0.0280 | |
| | Mesquite, N. M. | 32°12' | 106°36' | 499 | 0.0012 | 250 |
| SOUTHWEST | Holbrook, Ariz. | 35°06' | 110°03' | 311 | 0.8400 | |
| | Winslow, Ariz. | 35°04' | 110°39' | 359 | 0.1100 | 90 |
| | Chevelon, Ariz. | 34°37' | 110°53' | 404 | 0.1100 | 170 |
| | Sunflower, Ariz. | 33°51' | 111°26' | 496 | 0.5100 | 1200 |
| WEST | Shonto, Ariz. | 36°36' | 110°36' | 304 | 0.3700 | |
| | Kaibito, Ariz. | 36°33' | 110°07' | 351 | 0.1400 | 190 |
| | Kanab, Utah | 37°01' | 112°49' | 502 | 0.0350 | 350 |
| NORTH | Climax, Colo. | 39°20' | 106°13' | 307 | 1.3000 | |
| | Dillon, Colo. | 39°44' | 106°08' | 351 | 0.2600 | 110 |
| | Granby, Colo. | 40°03' | 105°56' | 391 | 0.1200 | 140 |
| | Timber Creek, Colo. | 40°23' | 105°51' | 428 | 0.0013 | 70 |
| | Tie Siding, Wyo. | 41°02' | 105°33' | 505 | 0.0023 | 120 |

The raw spectral density estimates are then smoothed by "hamming":

$$P(f_0) = 0.54\,\hat{P}(f_0) + 0.46\,\hat{P}(f_1)$$

$$P(f_k) = 0.23\,\hat{P}(f_{k-1}) + 0.54\,\hat{P}(f_k) + 0.23\,\hat{P}(f_{k+1}),\ 0 < k < m$$

$$P(f_m) = 0.54\,\hat{P}(f_m) + 0.46\,\hat{P}(f_{m-1}). \qquad (3)$$

Spectra of ground velocity for the $P_n$ phase recorded along five lines of stations are shown in Figures 2 through 6. In each of these figures, the spectral density of ground velocity for the $P_n$ phase is plotted versus frequency. Stations in the same direction are plotted in the same figure to show the spectral variations as a function of distance. Dominant peaks in the spectra fall mostly between 3 to 5 cps. In general, the maximum spectral density decreases as the distance increases from the shotpoint. A notable exception is station Sunflower at 500 km where the maximum spectral density is almost the same as for station Holbrook at 300 km.

Spectra of ground velocity for the $P_n$ phase recorded at distances of 300 and 500 kilometers from the shotpoint are plotted in Figures 7 and 8 to show the spectral variations as a function of azimuth. At 300 km the maximum spectral density for the north, west, and southwest is larger by a factor of about 30 than that for the east and south. At 500 km the maximum spectral density is highest toward the southwest, decreases by a factor of about 20 toward the west, and decreases by an additional factor of about 10 toward the north, east, and south.

Spectra of all the stations show the spectral energy is concentrated between 2 and 8 cps and becomes insignificant beyond 10 cps.

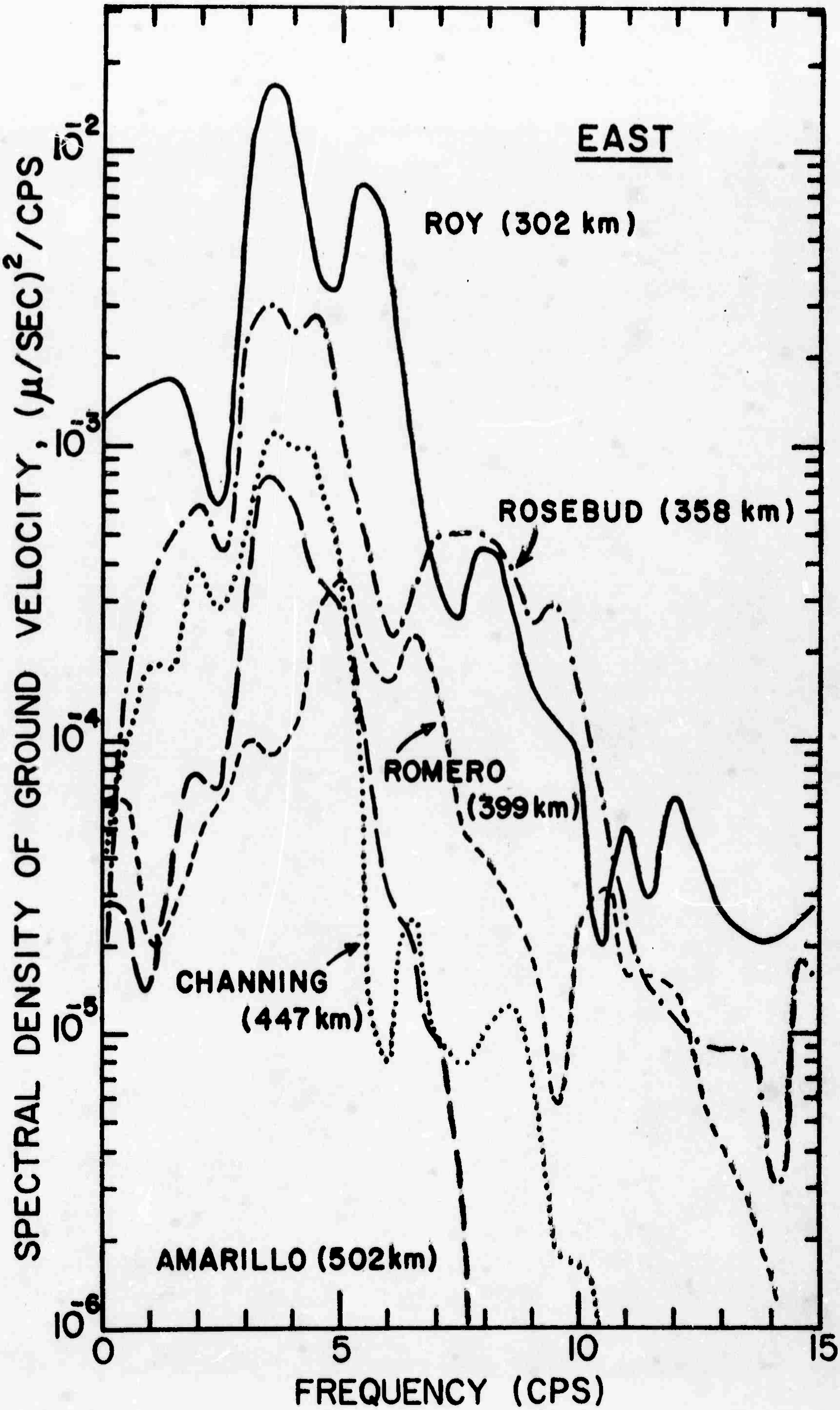


Figure 2. $P_n$ spectral variations along the east line.

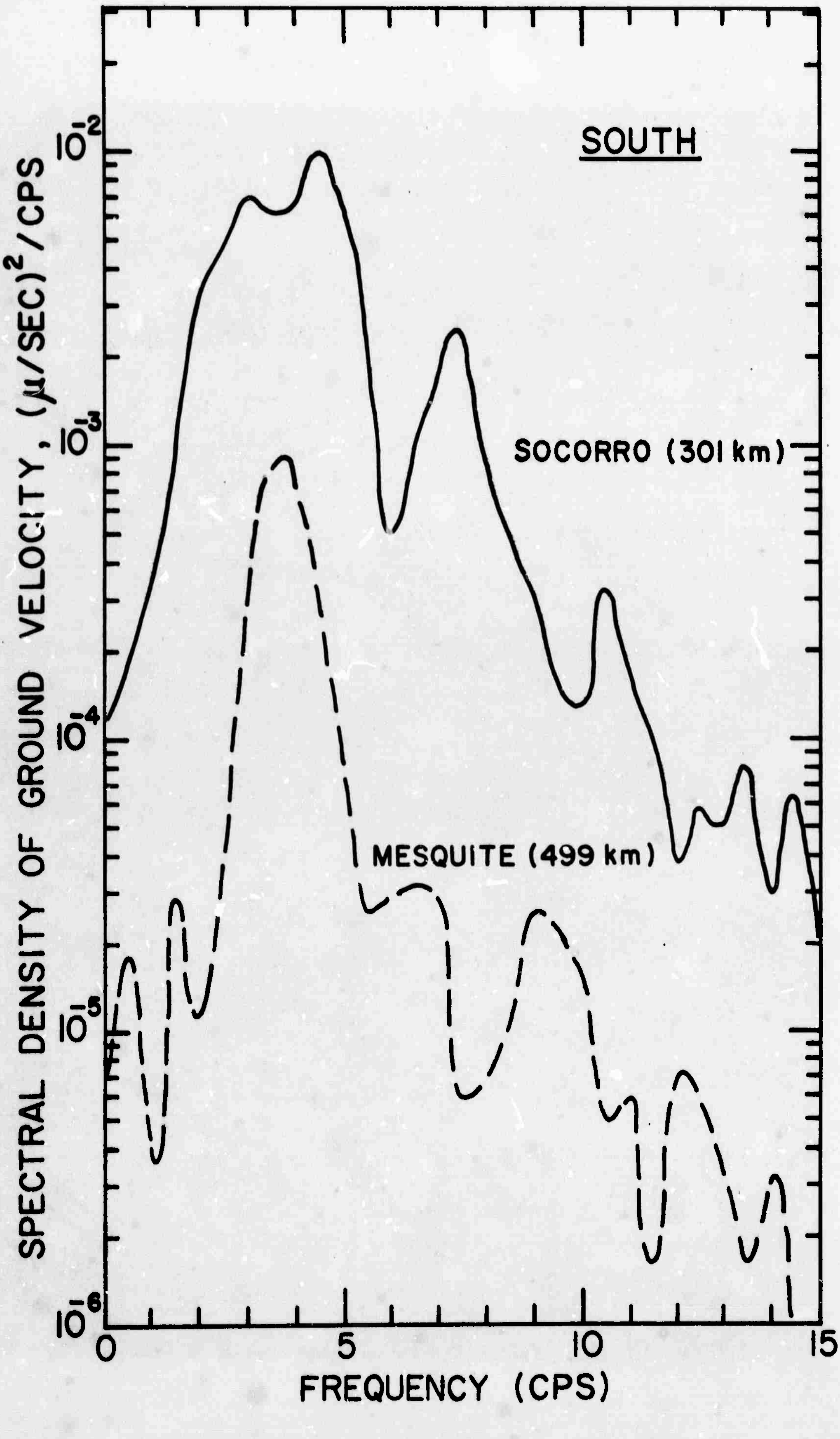


Figure 3. $P_n$ spectral variations along the south line.

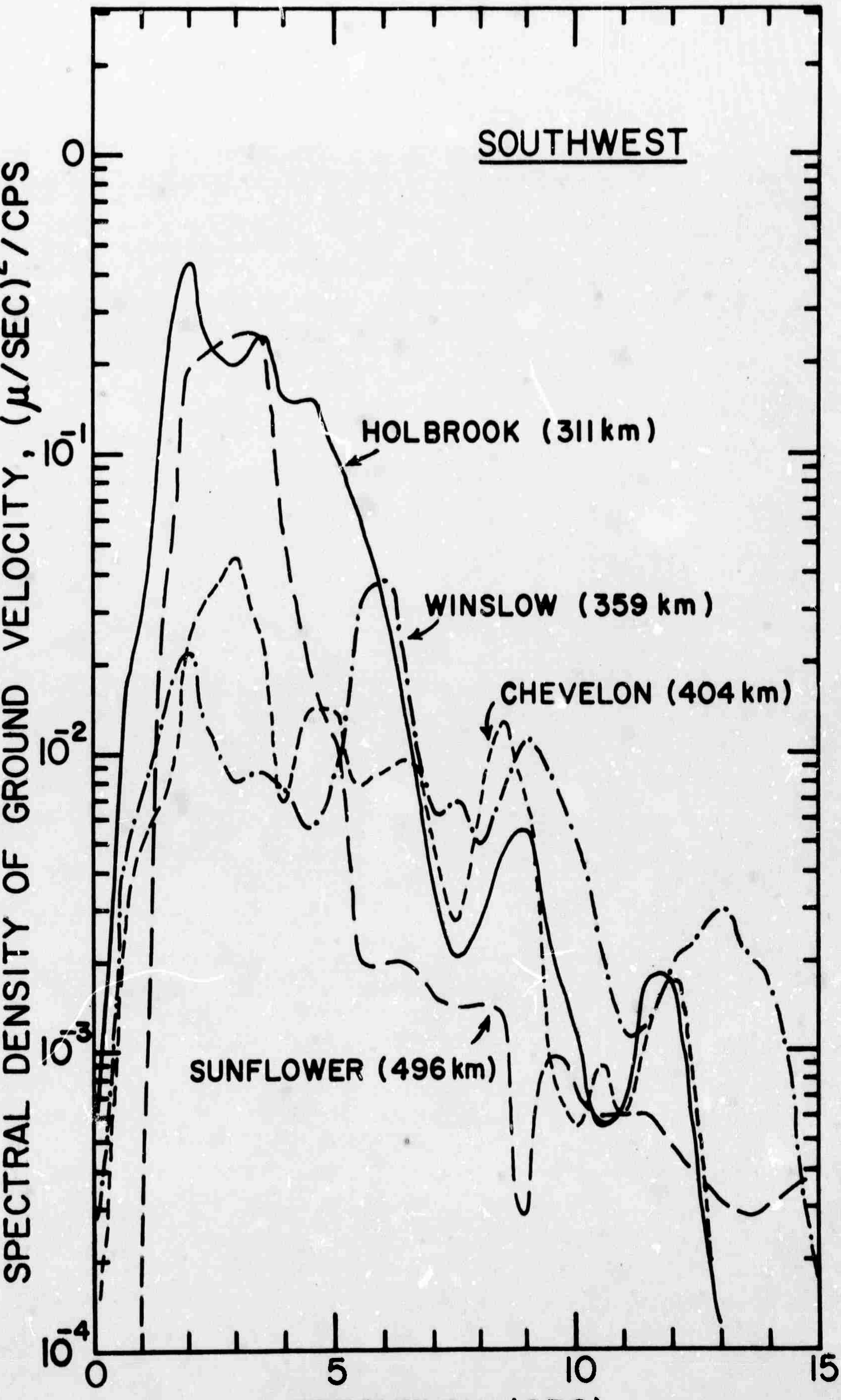


Figure 4. $P_n$ spectral variations along the southwest line.

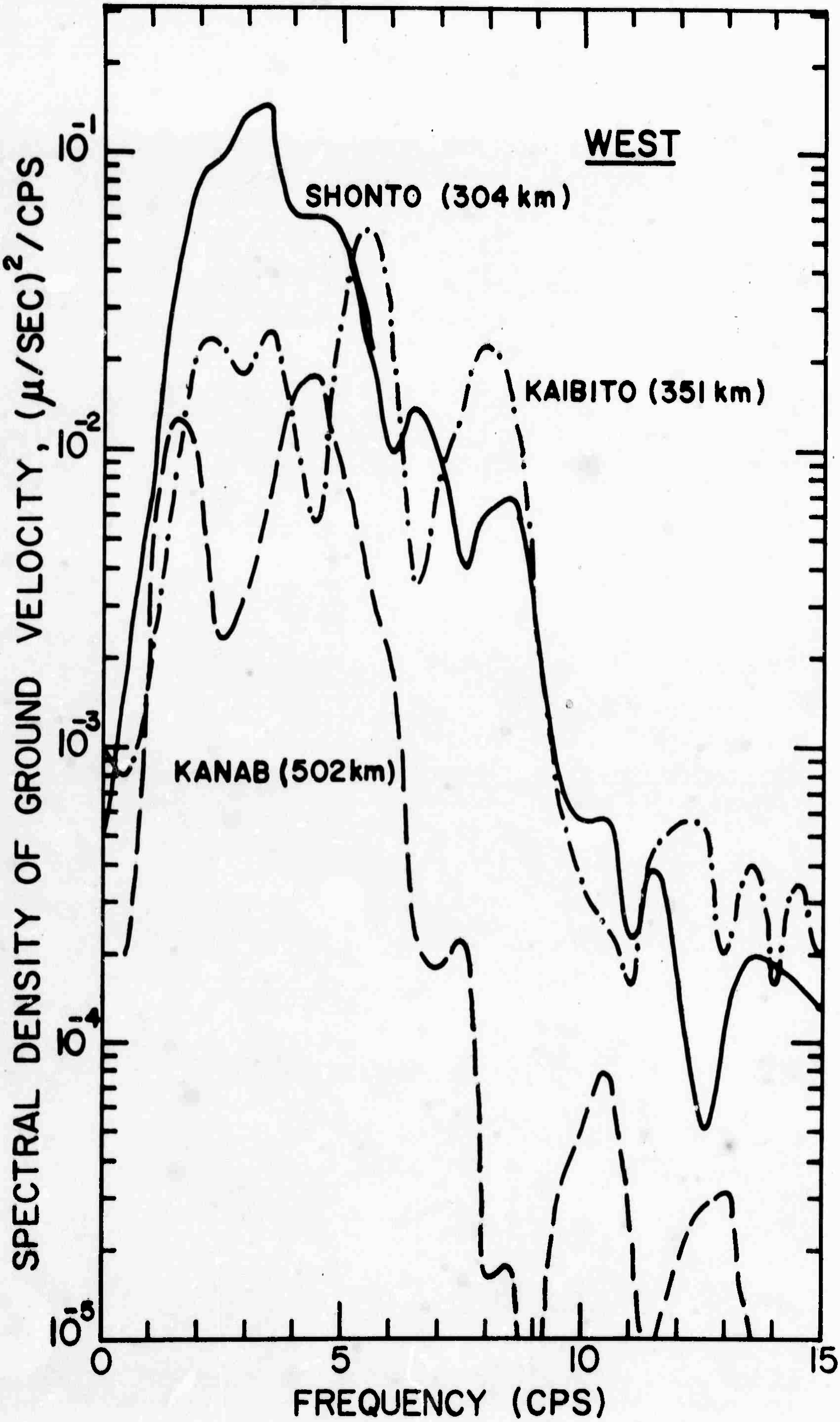


Figure 5. $P_n$ spectral variations along the west line.

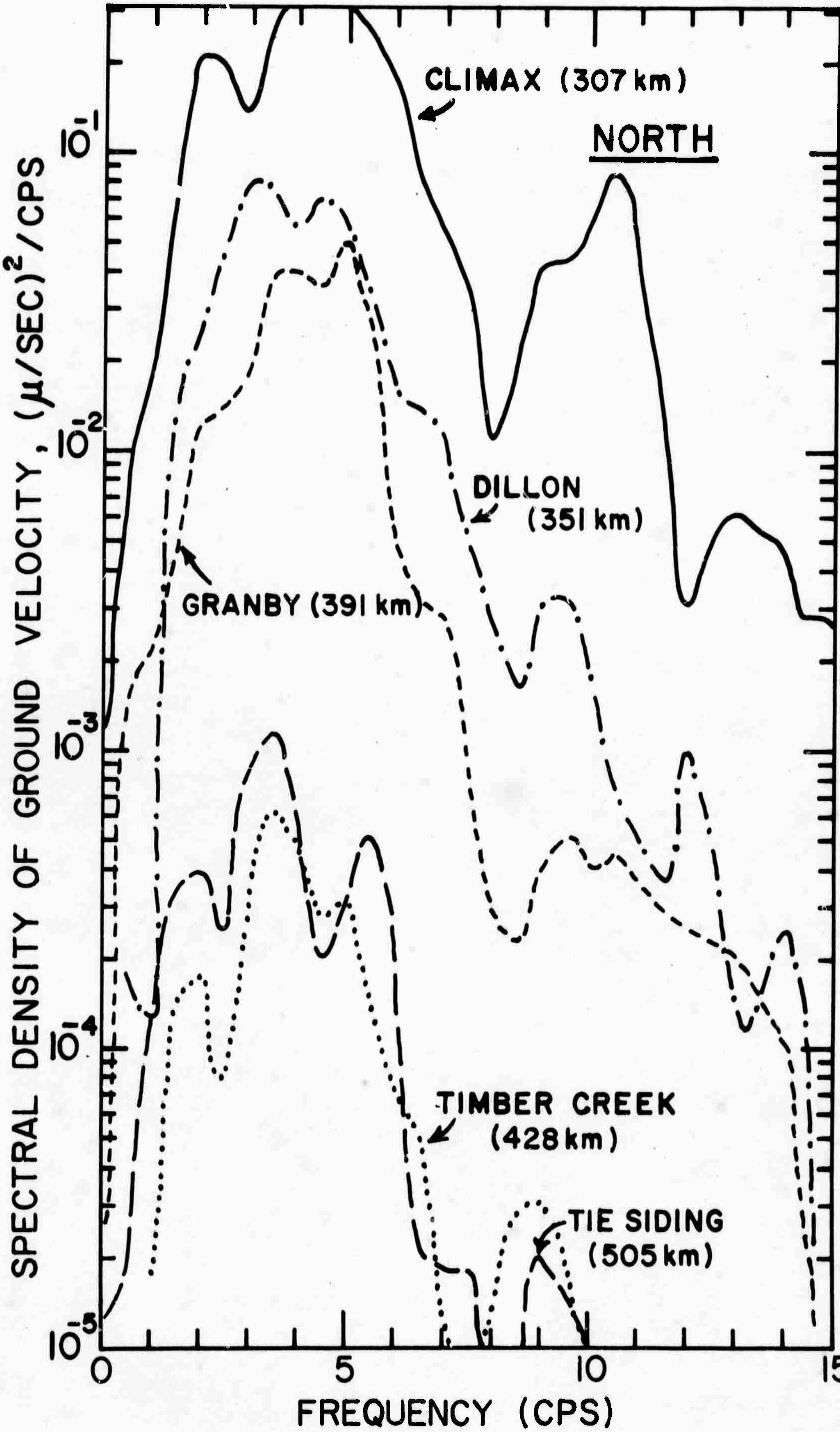


Figure 6. $P_n$ spectral variations along the north line.

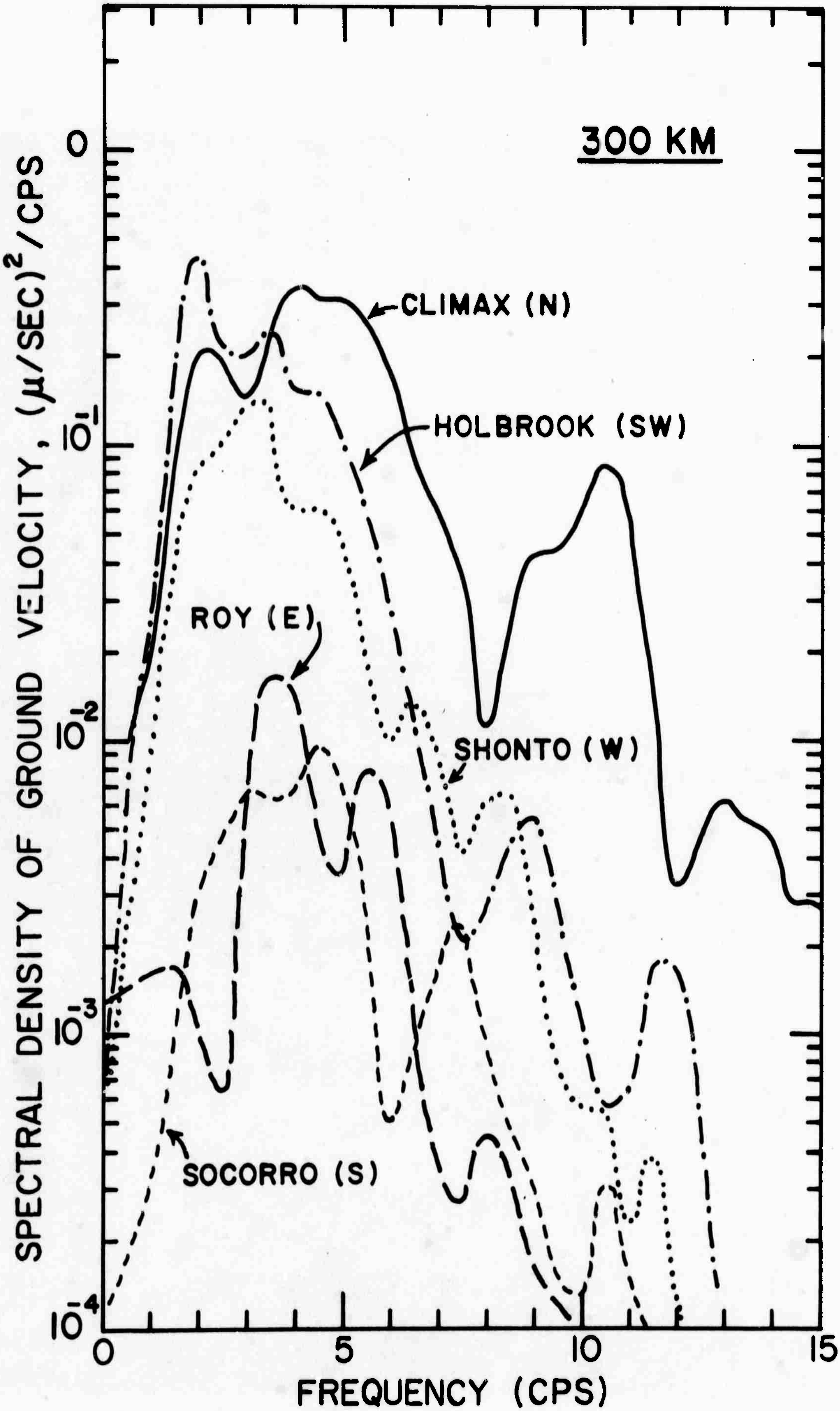


Figure 7. $P_n$ spectral variations at 300 km from the shotpoint.

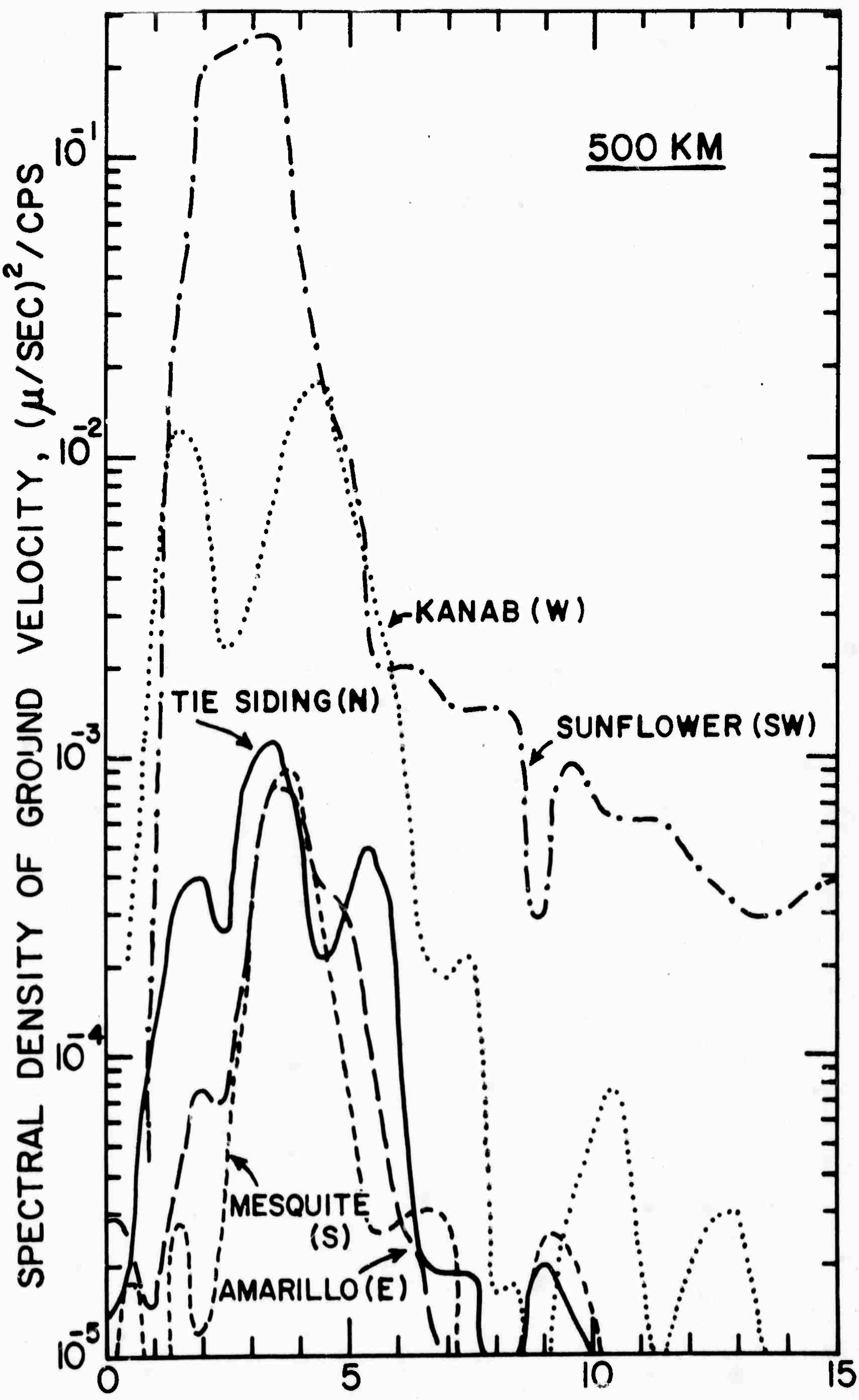


Figure 8. $P_n$ spectral variations at 500 km from the shotpoint.

The spectral energy of ground velocity can therefore be obtained by integrating the spectral density from 2 to 10 cps:

$$E = \int_{2}^{10} P\ (f)\ df \tag{4}$$

The results are tabulated in Table I. Spectral energy is plotted against distance in Figure 9, and a contour map of iso-spectral energy is shown in Figure 10. These figures show that the spectral energy is about 2 orders of magnitude higher for the southwest and west than for the east and south. The spectral energy along the north line is similar to the southwest and west lines for the distance interval 300 to 400 km, but is similar to the east and south lines from 400 to 500 km.

Attenuation of the $P_n$ phase can be studied by calculating the Q values between pairs of stations. The dimensionless quantity, Q, is the reciprocal of the specific attenuation factor (Knopoff, 1964) and is defined by Gutenberg (1958) as:

$$Q = \frac{\pi}{kTV}\ , \tag{5}$$

where

k = the coefficient of absorption

T = period of the seismic wave

V = seismic velocity.

The absorption coefficient k is defined by

$$\frac{A_1}{A_2} = e^{-k\ (D_1\ -\ D_2)}\ , \tag{6}$$

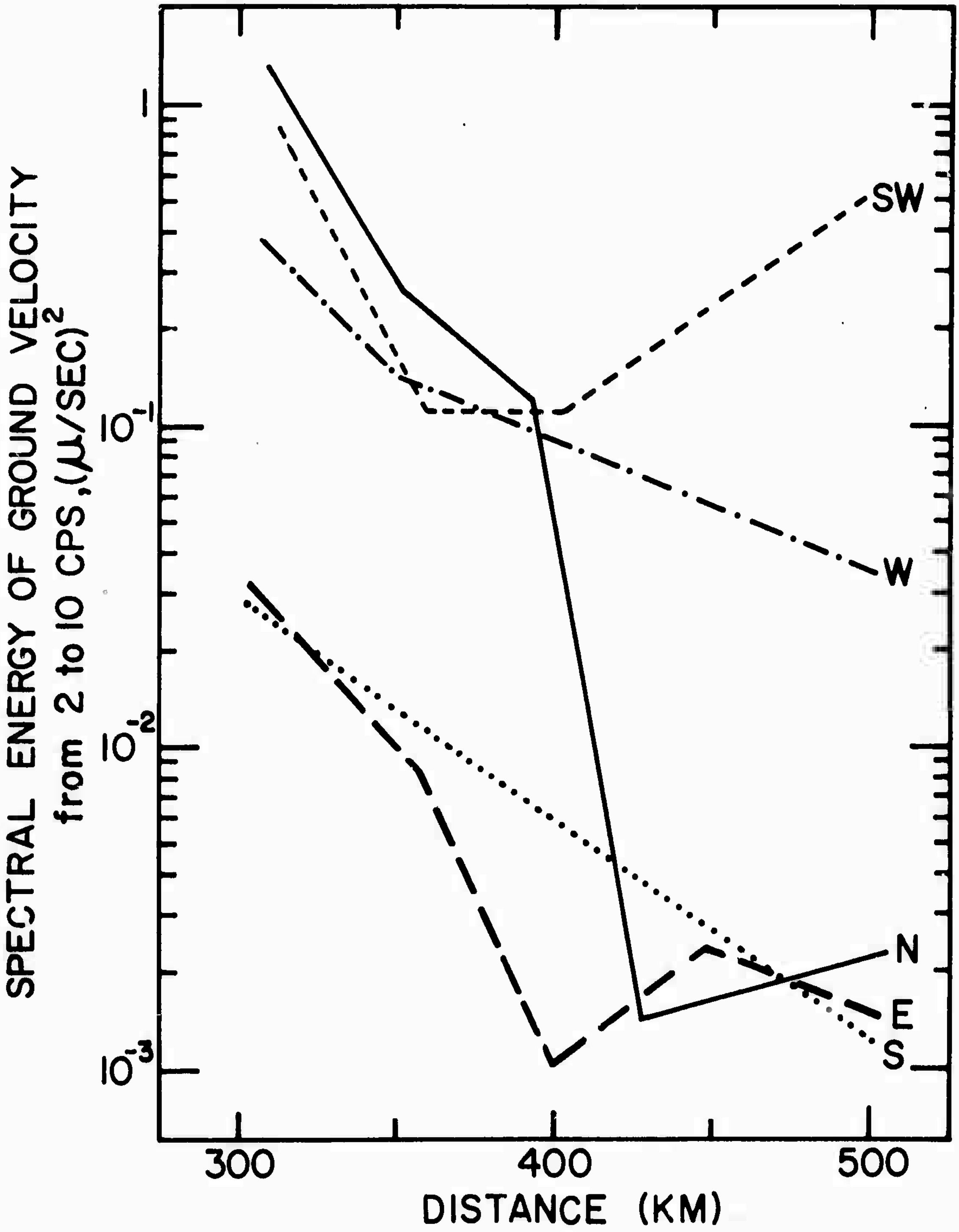


Figure 9. Spectral energy of ground velocity from 2 to 10 cps for the $P_n$ phase as a function of distance along the five lines of recording.

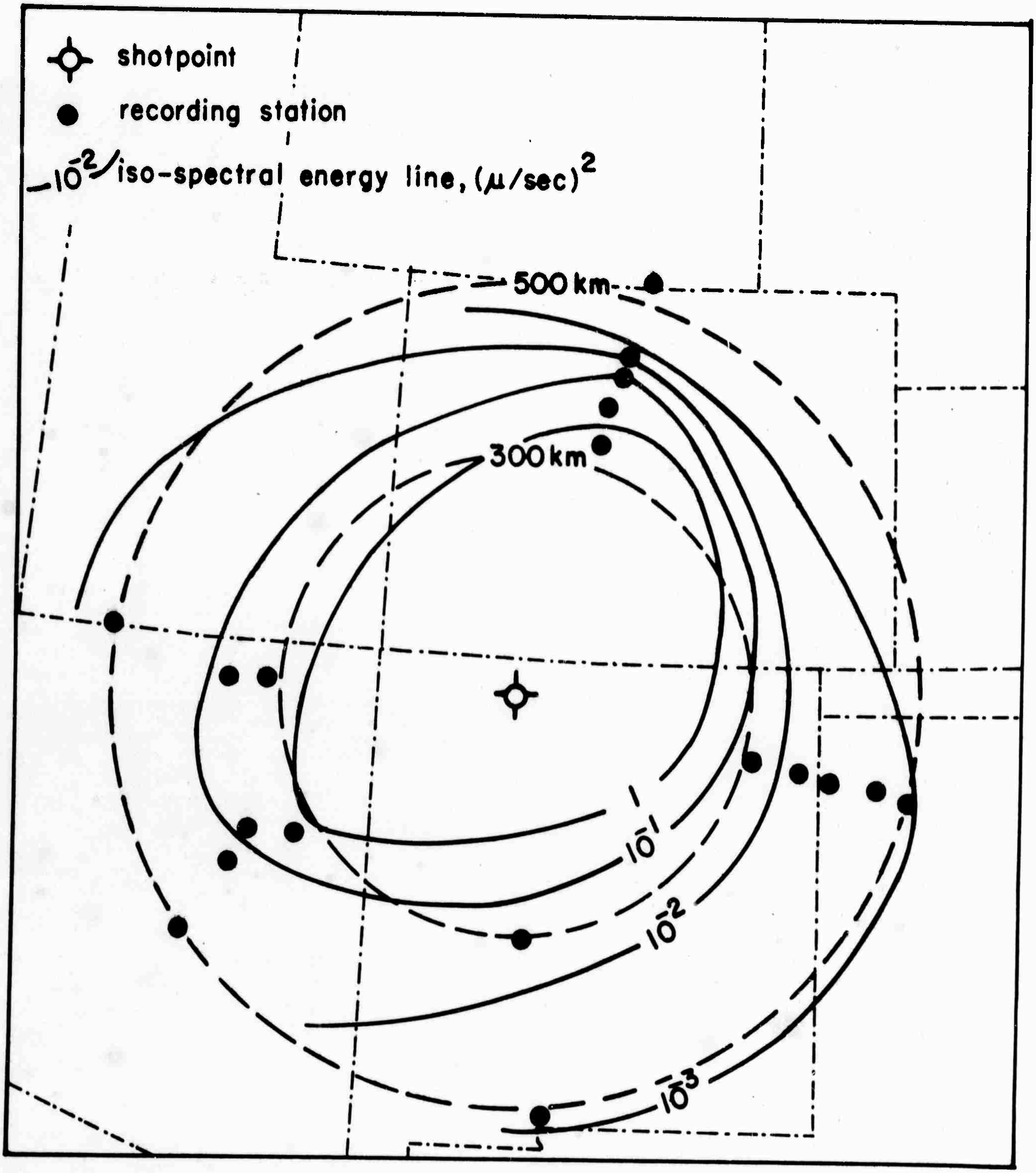


Figure 10. Contour map of spectral energy of ground velocity from 2 to 10 cps for the $P_n$ phase.

where

$A_1/A_2$ = ratio of amplitude of seismic wave at location I to location 2

$D_1 = D_2$ = distance between location I and location 2.

For rough estimates of Q, we use the spectral energy of ground velocity for the $P_n$ phase from 2 to 10 cps so that:

$$\frac{A_1}{A_2} = \sqrt{\frac{E_1}{E_2}} \, ,$$

$$T \approx \frac{1}{5 \text{ cps}} = 0.2 \text{ sec} \, ,$$

and

$$V \approx 8 \text{ km/sec} \qquad (7)$$

The results are tabulated in Table I. Values of Q range from about 70 to 350 and agree with the general estimate of 60 to 450 made by Anderson (1966) for the lower crust and upper mantle. The only exception is the Q value (1200) between Holbrook and Sunflower. This may be due to local conditions at Sunflower.

## CONCLUSIONS

Studies on the $P_n$ phase recorded at 19 stations for the GASBUGGY nuclear explosion show the following:

(1) Spectra of ground velocity differs from station to station. The gross characteristics are similar, but the maximum spectral density may differ by 3 orders of magnitude. Dominant peaks in the spectra are mostly between 3 and 5 cps.

(2) There is a general decrease in the spectral energy as distance increases from the shotpoint. Spectral energy is strongly dependent on the azimuth, being two orders of magnitude higher toward the southwest and north than toward the east and south.

(3) A contour map of iso-spectral energy indicates that attenuations of seismic waves is higher in the east and south than in the west and southwest. This result is consistent with the heat-flow measurements showing higher heat flow toward the southeast than toward the northwest (John Sass, personal communication).

(4) The reciprocal of specific attenuation factor, Q, was estimated from the spectral energy ratios between pairs of stations. Values of Q (70 to 350) are consistent with the general range estimated for the lower crust and upper mantle.

## REFERENCES

Anderson, D. L., 1966, Earth's viscosity: Science, v. 151, p. 321-322.

Blackman, R. B., and Tukey, J. W., 1958, The measurement of power spectra: New York, Dover Publications.

Gutenberg, B., 1958, Attenuation of seismic waves in the earth's mantle: Bull. Seis. Soc. America, v. 48, p. 269-282.

Knopoff, L., 1964, Q: Reviews of Geophys., v. 2, p. 625-660.

Warren, D. H., and Jackson, W. H., 1968, Surface seismic measurements of the project GASBUGGY explosion at intermediate distance ranges: U.S. Geol. Survey open-file report.

Warrick, R. E., Hoover, D. B., Jackson, W. H., Pakiser, L. C., and Roller, J. C., 1961, The specification and testing of a seismic-refraction system for crustal studies: Geophysics, v. 26, p. 820-824.