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STUDIES OF THE EFFECT OF DEPTH OF FOCUS  
ON SEISMIC PULSES

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STUDIES OF THE EFFECT OF  
DEPTH OF FOCUS ON SEISMIC PULSES

I. Objectives

The principal objective of this research is to improve the accuracy of focal-depth determination as a means of distinguishing between natural earthquakes and explosions. The research has consisted mainly of evaluating a method of focal-depth determination which depends on recognition of the sequence of events which arise from the reflection of the initial P pulse at the surface, and evaluating the factors controlling the accuracy of this measurement.

A second objective is to study the effect of the nature of a boundary on seismic pulses refracted along it both in scale models and in the real earth.

II. Technical Status and Major Accomplishment.

A. Evaluation of the Watson-Merdler method of focal-depth determination

An earlier technical report (AFCRL-64-755) described the Watson-Merdler method of focal-depth determination in detail. A summary of this is in press in a VESIAC conference report. In brief, the method assumes that the seismogram consists of the sum of three signals:  $P(t)$ , the train of pulses emanating from the focus and travelling to a distant recorder;  $G(t)$ , a similar train of waves reflected from the earth's surface with a reflection coefficient  $R_H$  arriving a time  $\Delta t$  behind  $P(t)$ ; and  $n(t)$ , any other signals present, which are considered to be noise.

$$\begin{aligned} S(t) &= P(t) + G(t) + n(t) \\ &= P(t) + R_H G(t - \Delta t) + n(t) \end{aligned}$$

It is assumed that one of the effects of  $G(t)$  is to complicate the seismogram by changing the number and size of peaks and troughs which rise about the background noise level. As a means of identifying  $G(t)$  in the seismogram,  $S(t)$  is operated on by a series of inverse filters which find an approximation of  $P(t)$  for assumed values of  $R_H$ ,  $\Delta t$  and noise level ( $u$ ). A concentration ratio,  $C_R$ , is calculated for each  $P(t)$  found by deconvolution with the inverse filter using the formula

$$C_R = \frac{(\sum (|P(t)| - u)^2)_{\text{for all } |P(t)| > u}}{T \sum (P(t))^2} \quad (2)$$

where  $T$  is the time during which  $P(t)$  exceeds  $u$ . It is postulated that  $C_R$  for a range of  $\Delta t$ 's close to the true time delay of the surface reflection,  $pP$ , behind the direct compressional pulse,  $P$ , from any seismic event will produce a  $C_R$  which is greater than the concentration ratio of the original seismogram,  $C_{R0}$ .

Preliminary tests showed that for earthquakes and blasts and in scale models a  $C_R > C_{R0}$  was usually found at values of  $\Delta t$  and  $R_H$  close to what would be expected. It looked, therefore, as though the method might provide a simple means of measuring depth of focus, and, therefore, a simple means of separating blasts from all except the shallowest of earthquakes.

Further tests showed that the situation was not so simple as this. First, it was found that there are five different causes which can produce a value of  $C_R$  greater than  $C_{R0}$ :

1. Deconvolution removes  $pP$  sequence from the seismogram (the solution sought).
2. Deconvolution removes  $sP$  sequence or some other sequence than  $pP$ .

3. Deconvolution enlarges peaks on the seismogram producing a larger maximum amplitude in the deconvolved seismogram than in the original. ( $C_R$  is very sensitive to the height of the largest peak.)
4. Deconvolution cancels out a later half cycle or more of a long oscillatory original seismic pulse.
5. Deconvolution phases random noise so as to add to or subtract from the principal peaks of the seismic pulses.

As a result of this, for any seismogram there are many cases of large  $C_R$ , and the right value must be selected from the set. This works out to be a process of testing the deconvolved seismogram,  $P(t)$ , to determine the cause of each large value of  $C_R$ . The third cause in the above list appears to be the major source of false indications. Rules for simple identification are being sought.

The second problem encountered was that in some cases, no large value of  $C_R$  was found where the true solution was expected. There are several possible causes for this. First, if  $R_H$  is small, the ghost pulse will be lost in the noise. Figure 1 shows the expectable value of  $R_H$  as a function of distance from the epicenter for an assumed focal depth of 10 km and the indicated velocity structure. Experience with the method suggests that if  $|R_H| < 0.3$ , it is unlikely that the ghost can be regularly found in normal seismograms. This means that only seismograms recorded at distances of  $22^\circ$  and beyond will be dependable. This limits the method to events large enough to be recorded beyond  $22^\circ$ .

At the other end of the distance range, the principal seismic pulse recorded beyond  $103^\circ$  has been transmitted thru the earth's core. Wave paths thru the core are complicated, and for most core distances

more than one pulse is recorded. With more than one P pulse present there is danger of finding  $\Delta t$ 's due to these extra pulses. For this reason, little work has been done and none is planned on pulses penetrating into the core.

Another problem is that unless the length of the filter used in deconvolving the seismogram is several times as long as the seismogram itself, the deconvolution is inaccurate and the concentration ratios found may fail to indentify meaningful solutions. This was not realized until recently. As a result many of the tests made for  $\Delta t \leq 4$  seconds are undependable and will have to be redone.

A revealing series of tests of the accuracy of the method was made by testing pulses consisting of one or more cycles of a sine wave with and without a period of quiet following the sine waves (Table I). It was from these tests that it was first learned that deconvolution could give large values of  $C_R$  where there was peak-enhancement, and that when  $\Delta t$  was small, one had to be careful that the deconvolution filter, which is proportional in length to  $\Delta t$  in the computer program used, was long enough.

Table II summarizes the tests made to date on nuclear blasts. The tests made for recordings at less than 3,000 km were early tests, often unsystematic, and the results are of uncertain value. We have tested all values of  $\Delta t$  in the ranges given in the table in 0.1 sec intervals unless otherwise stated in the table. It is necessary to test at intervals which are short compared to the predominant frequency in the seismograms or cases where  $C_R$  is large may be missed. The digitizing interval used for the seismograms was 0.1 sec in all cases, though data at half this spacing is available.

The quantity,  $R$ , referred to in Table I, is the noise-to-signal power ratio assumed for the seismogram. This is a factor on which the inverse filter which does the deconvolution depends. The pulse length tested is shortened for short  $\Delta t$ 's to keep the inverse filter reasonably short. This was not done in the earliest experiments. As a result, there is overlap of the  $\Delta t$  ranges tested as summarized in Table II. It is believed that most of all of the cases of increased  $C_{R0}$  reported in Table II will be explainable by one of the reasons listed above. Which case corresponds to which cause is the subject of current study.

Fourier-integral frequency spectra for 24 of the seismograms of Table II have been calculated. The peak frequency and the range for which amplitude is within six decibels of the peak are given in Table III. It is reasonable to expect that testing and sampling intervals should be shorter than one-tenth the period of the peak frequency. No thorough test of how close the sampling interval should be has been made.

To evaluate the Watson-Merdler method it is necessary to compare its depth predictions for blasts with its predictions for earthquakes. To test a given earthquake record thoroughly for all possible amplitude ratios ( $R_H = pP/P$ ) and delay times ( $\Delta t$ ) within reasonable limits involves a considerable expenditure of time and money. Initial detailed analysis of the Ecuador earthquake of May 10, 1963, has been restricted to a reasonably small number of amplitude ratios and time delays by considering the following theoretical model. If one assumes that the earthquake can be represented by a point source with energy radiation equal in all

directions, then the theoretical amplitude ratio can be calculated. This assumption is not generally good as energy radiation is known to be dependent on azimuth. A knowledge of the initial radiation pattern (obtainable from fault-plane studies) would serve to improve the model but is not available during this stage of the work. Knowledge of the approximate depth of the disturbance can be used to restrict the range of delay times to be tested. Finally, a measure of the noise level of the seismogram allows one to pick the set of inverse filters designed for that particular noise-to-signal power ratio and to limit the number of noise-energy levels examined in the actual test.

To provide the necessary information for limiting the length of analysis, programs were written to give the following:

- (1) The angle of incidence of p at the free surface as a function of epicentral distance for 10 km focal depth (Figure 2). The velocity distribution assumed for this calculation is shown on the Figure.
- (2) The amplitude ratio,  $R_H$ , of pP/P as a function of the angle of incidence of p at the free surface for various values of Poisson's ratio. The curve for a Poisson's ratio of 0.25 is shown in Figure 3.
- (3) Finally, the amplitude ratio of pP/P as a function of epicentral distance was determined and is shown in Figure 1 for a focal depth of ten kilometers.

The pP wave is reversed in polarity compared with P for epicentral distances greater than about  $19^\circ$ , so negative filters are called for. It must be

recognized, however, that the focal mechanism may be such that both pP and P have the same polarity.

Preliminary tests have been carried out on twelve records for the 10 May 1963 Ecuador earthquake using the results from the theoretical calculations based on a point-source model, and some tests have been made on eight additional seismograms. Pertinent results are presented in Tables IV and V. The first five records listed in Table IV were tested for delay times between 2.5 and 12.4 sec corresponding to a depth of focus in the range of about 6 to 49 km. As no significant answers were developed for times greater than 6 sec, initial tests on the remaining seven records were only carried out to 8 sec (about 30 km). Depths less than 6 km have not been tested, as the present set of inverse filters are not designed properly for the small delay times. Table IV shows the theoretical amplitude ratio and measured noise-to-signal power ratio for each record and the filters used in the tests. In all except two cases there was more than one case where  $C_R$  exceeded  $C_{R0}$ . Only the solutions for the largest  $C_R$ 's are listed in Table IV. All solutions are shown in Figure 4.

No consistent depth persists throughout Table IV. Values range from 8 to 20 km. The average value is 12 km (compared to 30 km reported by the Coast and Geodetic Survey). In Figure 4, on the other hand, there is a solution between 8 and 12 km in every case except where no solution was found at any depth.

Additional test results using filters with a high noise-to-signal power ratio of 0.25 are included in Table V. The amplitude ratios giving significant answers are in general higher than those listed in



Table IV. The spread in answers is smaller and there appears to be a preferred depth of about 12 km. Causes of the numerous answers for each record are being sought as well as a means for picking the "best" answer.

In addition to those of the 10 May 1963 earthquake, nineteen other seismograms have been processed thru the Watson-Merdler program. These are listed in Table VI. The thoroughness of these tests varies from scattered trial solutions to systematic tests following the same systems used for the nuclear blasts. These tests have been run for a variety of purposes such as for comparison with nuclear blasts and as checks to see if any peculiar solutions would result from various features of the records. They have led to no conclusions not covered by the previous discussions of nuclear blasts and the 10 May 1963 Ecuador earthquake.

B. Factors controlling the frequency spectra of seismograms

In order to get a better understanding of the factors which control the frequency spectrum of a seismogram, a study has been made of the earthquakes of 13 April 1963 in Peru and 10 May 1963 in Ecuador. As many seismograms as possible of the beginning of this earthquake were obtained from the U. S. Coast and Geodetic Survey and the Dominion Observatory in Ottawa, Canada. As most of the effort was directed at the Peru earthquake it will be the only one of the two for which detailed results will be summarized here.

Of the paper seismograms obtained for the Peru earthquake, only ten (five from USCGS and five from

Dominion Observatory) were sufficiently, clearly and continuously recorded that they could be used (see Howell, 1965 for discussion of problems of digitizing paper seismogram). In each case the seismogram was digitized at tenth-second intervals for the first  $10.0 \pm 0.4$  sec of the seismogram. Twenty-seven additional digitized seismograms were obtained from the United Electrodynamics data center in Alexandria, Virginia. Fourier-integral frequency spectra were calculated and a correction for station sensitivity applied over the frequency range 0.4 to 2.5 cps for each of these 37 seismograms. The range of epicentral distances was from 4411 km to 11,326 km. Five other Vela stations located in the shadow zone or further away also gave excellent recordings but were not included in this study of the P-pulse.

Samples of the corrected frequency spectra are shown in Figure 5. Except for a general decrease in energy with increase in frequency, the spectra exhibit no systematic pattern. Maxima and minima occur in all cases, but their positions and heights are different in nearly every case.

A report by W. J. Hannon (1964A and B) led to a possible explanation of this extreme variability. Hannon developed a program for computing the effect of a layered crust on the interference pattern of continuous plane waves being passed thru it and reflected at the surface. The spectrum observed at the surface is the result of interference by the whole family of internally reflected multiples resulting from the layering. The effect of these layers on the spectrum is called the transfer function of the crust. The transfer function itself is a sequence of maxima

and minima (Figure 6).

Hannon's theory is developed for continuous waves. A real earthquake is a transient pulse. If only the first ten seconds of a seismic arrival is considered, many of the internal reflections contributing to Hannon's theoretical transfer function will generally not have had time to arrive. It was, therefore, necessary to develop a program for calculating the transfer function for the case of a finite length of pulse.

Truncation in the time domain corresponds to multiplication of the signal by a square window of unit amplitude during the time duration of the considered signal, and equal to zero outside this interval. The transform of such a square window is a sinc function whose zero-axis crossing will be at  $\frac{1}{T}$  cps, T being the duration in seconds.

Convolution in the frequency domain is equivalent to multiplication in the time domain. Let  $G(f)$  be the transform for infinite time with  $\theta(f)$  its related phase spectrum. The truncated spectrum

$$\begin{aligned} G_T(f) &= G(f) * \text{sinc}(f) \\ |G_T(f)| &= ((\text{Re}G(f) * \text{sinc}(f))^2 + \\ & (\text{Im}G(f) * \text{sinc}(f))^2)^{1/2} \end{aligned} \quad (4)$$

Proper caution must be taken during the convolution process to reduce as much as possible the error introduced by the truncation of the sinc function. This is done by extending the real and imaginary parts along the negative frequency axis before performing the convolution.

Computer programs were written to generate transfer functions corresponding to ten seconds in the time domain for angles of incidence at every  $1^\circ$  within the range of  $20^\circ$  to  $40^\circ$ . This range includes all expected angles of incidence for epicentral distances involved

in the study of the 37 spectra.

More than 20 crustal-structure models related to seven stations were studied. It was found that certain crustal models have a smooth transfer function for the whole range of angles of incidence, while other models, over the same range of angles, present great differences in the number, the position and the depth of the minima. Since the crustal effect acts as a filter on the incoming initial longitudinal wave, it modifies the frequency spectrum of the pulse greatly.

The variation of the truncated transfer function as a function of angle of incidence and of layer thicknesses was carefully studied by testing nine closely related models selected on the basis of published crustal-structure predictions. It was found that the transfer function is very sensitive to change of angle of incidence and layer thickness. The transfer functions can sometimes introduce minima of 20-30 db, very often of 10 db, thus offering an adequate explanation for similar minima found in earthquake spectra.

An attempt was made to find crustal models which would produce variations similar to those observed in the spectra at four stations. In two of these cases, namely Mountain Pine, Ark, and Alert, Canada, a structure was found whose transfer function, subtracted from the observed spectrum, produced a demonstrably smoother spectrum than the original. It is postulated that this model closely resembles the real crust. Failure to find a model which produced an improvement for the other two cases is presumably due to not having hit upon a model which closely

resembles the crust among the many models tested.

Finally, the average spectrum was obtained for the 37 stations (Figure 9). It shows a remarkable smoothness in comparison with individual spectra. This is interpreted as an indication that none of the minima is introduced by the source function. Otherwise it would persist and show up on the average spectrum.

It is concluded that the crustal transfer function is the dominant cause of variations in the spectrum from one observing station to another.

C. Scale-model studies of refractions along the Mohorovicic discontinuity.

Two scale models were designed and fabricated as shown in Figure 10. The upper model (A) corresponds to a transition layer underlying a uniform crust. The lower model (B) corresponds to an irregular boundary. Model A has been set up in the model laboratory and is under test.

In Model A an attempt is being made to measure the transfer characteristics of the two high-speed interfaces comprising an intermediate velocity layer, with the distance between these interfaces being of the same order of magnitude as the predominant wave length. The frequency band of the study is from 20 kc to 200 kc, which is approximately equivalent to 20 cm to 2 cm wave length in the model. The irregular boundary at the bottom of the model is an attempt to reduce reflections occurring at this surface, prevent the arrival of surface waves that may travel around the model by this path, and reduce the time that energy is contained in the model between pulses.

An electronics system capable of providing a short-duration input to the model was assembled. The system is able to put out square pulses of as short a duration as one microsecond and of 150 volts amplitude. Different preamplifiers and even the cascading of preamplifiers was tried to find out how much gain would be available when low-energy refractive arrivals are to be measured. A high signal-to-noise ratio is necessary, and precautions had to be taken to insure low pickup and interference. This will become critical at the lowest energy levels anticipated.

The velocities of compressional waves in the three layers were measured (Table VII). In addition, a calculation of the velocity,  $C_p$ , in the intermediate velocity layer (copper-steel lamination) was made using

$$C_p^2 = \frac{\rho_1 C_{p1}^2 T_1 + \rho_2 C_{p2}^2 T_2}{\rho_1 T_1 + \rho_2 T_2} \quad (5)$$

where  $\rho_1, C_{p1}, T_1$  are density, compressional wave velocity, and thickness of material number 1 and where  $\rho_2, C_{p2}, T_2$  are density, compressional wave velocity, and thickness of material number 2.

The shear-wave velocities were calculated several ways, and also roughly measured, with an approximate value being needed to identify fully the components present in the preliminary measurements.

Measurements of the absorptive and dispersive characteristics of the materials were made. This data is currently under study. Having measurements for the properties of the steel and the laminated material, the copper material characteristics can be

inferred. Preliminary evaluation of the data suggests that the three materials will be low absorptive and non-dispersive.

D. Attenuation of seismic waves under Lake Superior

Fourier-integral frequency spectra were calculated for the range 4-26.8 cps for first arrivals in two distance ranges: 35-82 km and 158-252 km for seismic pulses refracted under Lake Superior. The first case is interpreted as a direct pulse, the second as a refracted (head) wave in an intermediate (7.00 km/sec) layer. The absorption coefficient in the first case was found not to be significantly different from zero ( $\alpha = (-0.010151 - .00059F)/\text{km}$ , where F is frequency). In the second case, absorption was larger but not significantly dependent on frequency ( $\alpha = (0.006620 - 0.00011F)/\text{km}$ ). The refracted pulse was weaker in energy above 8.8 cps than the direct pulse. This is similar to the filtering effect observed in the Maine seismic experiment and is explainable, using Nakamura's theory, by a transition layer 0.16 km thick. (Nakamura, 1964; Nakamura and Howell, 1964). A report summarizing this is in press (Howell, 1966A).

E. Publications and oral reports

In addition to the reports required by this contract, during 1965 the following papers were presented orally or in writing thru the indicated media, thereby disseminating knowledge gained thru this research.

1. Robert J. Watson presented a paper describing the Watson-Merdler method of focal-depth analysis before a VESIAC conference in La Jolla on March 23. The proceedings of this conference have not yet been published, but are to be issued in 1966.

2. B. F. Howell, Jr. presented a paper before the Seismological Society of America discussing some of the problems of obtaining digitizable seismograms using paper recordings. This paper has been published in Earthquake Notes (Howell, 1965).
3. B. F. Howell, Jr. presented a paper before the Seismological Society of America describing the digitizing apparatus developed in the research and used for digitizing seismograms. This paper (Howell, 1966B) will be published shortly and distributed as a scientific report.
4. B. F. Howell, Jr. has prepared a report of his analysis of the frequency spectra of seismic refractions under Lake Superior. This is being submitted for publication in the Merle A. Tuve Testimonial Volume of the Carnegie Institution of Washington.

### III. PERSONNEL

The personnel engaged in this research during the past year consisted of Professors B. F. Howell, Jr., P. M. Lavin, and R. J. Watson and six graduate assistants: Y. Y. Cheng, G. Leblanc, J. L. Lin, T. W. Novotny, D. E. Siskind, and S. K. Yiu. Professor Howell has been guiding the studies of actual earthquakes by Leblanc, and Yiu and the scale-model work of Siskind. Professor Lavin has guided the scale model experiments of Novotny and an evaluation of the Watson-Merdler method as applied to the 10 May 1963 earthquake by Cheng. Professor Watson directed Mr. Lin in evaluating the Watson-Merdler method of depth-of-focus calculation for nuclear blasts until he resigned in July; Professor Howell has directed Lin since then. Professor Howell has been studying the spectra of pulses refracted thru the earth's crust under Lake Superior.



#### IV. Problems Encountered

We have been plagued throughout the work by slow delivery of parts and equipment. During part of the past month the University's computer has been closed. As a result, we are behind schedule and have had to obtain an extension of time to complete the proposed work.

#### V. Schedule of work and future plans

The research planned for the remainder of this project consists primarily of three experiments:

1. study of the cause of large values of  $C_R$  for deconvolved blast seismograms;
2. study of the 10 May 1963 earthquake;
- and 3. model studies of refraction along the Mohorovicic discontinuity.

Fourteen nuclear-blast seismograms recorded at large distances from the epicenter are on hand. All are being systematically tested using a standard procedure. In all cases where  $C_R$  exceeds  $C_{R0}$ , the deconvolved seismogram will be compared with the original seismogram to see exactly why the Watson-Merdler method picked this case as a potential solution. If all potential solutions have obvious explanations, the Watson-Merdler method can be used as a criterion to select blast records from a group of seismograms of unknown source nature.

The work on earthquake seismograms will follow similar lines. An explanation will be sought for all large values of  $C_R$  for the 10 May 1963 Ecuador earthquake and for a few other individual shocks. For the Watson-Merdler method to be successful, it will be necessary that natural earthquakes commonly produce large  $C_R$  values which cannot be easily

explained as being other than the result of combinations of pulses.

Data from the scale models simulating refractions along the Mohorovicic discontinuity will be taken during the coming quarter. Analysis of this data should be complete by June.

Several reports are under preparation. A Complete technical report and one or more scientific reports on the cause of variations in the frequency spectra of the 13 April 1963 Peru earthquake, including the program for deriving the truncated transfer function for a layered crust, is being written. Also, a scientific report on the spectra of refractions under Lake Superior is nearing completion. Some additional research on this latter problem continues, especially as it relates to absorption of seismic waves. This may lead to an additional report later.

#### VI. Actions desired of ARPA

A proposal to extend this research thru December, 1966, either with or without additional funds, was submitted a year ago and has never been acted on formally. It now looks as though funds already approved will be adequate to complete what needs to be done on this research. Although actual research should be completed by June of 1966, it is still desired the contract-terminated date should be postponed until 31 December 1966. This will permit the final reports to be prepared more carefully and thoroughly than will be possible if they must be in by June. Also, it will permit preparation and submission of a series of scientific reports for publication in journals where the information they contain will reach the largest number of scientists and will become a matter of convenient permanent record.

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Table I

Cases where Watson-Merdler program found  $C_R > C_{RO}$  for a sine wave of two seconds period

<u>Cycles</u>	<u>Length of pulse (sec)</u>	<u>Delays for which energy concentrations are larger than zero delay(sec)</u>	<u>Input delay (sec)</u>
1	2	0.6, 1.0	0.2-3.2 in steps of 0.2
2	4	0.2, 1.0, 1.4	" " " " "
3	6	0.2, 1.0, 3.0	" " " " "
4	8	1.0, 2.6, 1.6	" " " " "
5	10	1.0, 2.5, 3.3, 5.0	0.8-6.0 in irregular steps
6	12	0.2, 2.4, 3.0	0.6-6.0 in irregular steps
8	16	0.2, 2.6, 3.6, 4.6, 5.4	0.2-6.0 in irregular steps
10	20	0.2, 4.4, 5.0	" " " " "
12	24	0.2, 3.0, 4.4	" " " " "

TABLE II

Summary of Tests Made on Nuclear Blasts

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Event number	Station	Distance	Pulse Length sec.	Input Delay Time ( $\Delta t$ ) sec.	Input R + Input R <sub>H</sub>	Delay for which CR's are larger than CRQ's	RH
Bilby (29)	LZBV	8,000 km	40	0.1-8.0	R <sub>H</sub> = -0.4, -0.5, -0.7, -0.9 R = 0.25	0.9, 1.6, 2.3, 5.9, 7.4	-0.9
Bilby (29)	LZBV	8,000 km	28	8.0-14.5	R <sub>H</sub> = -0.4, -0.6, -0.8, R = 0.01	No solution	
Bilby (30)	OONW	8,122 km	40	0.1-5.0	R <sub>H</sub> = -0.4, -0.6, -0.8, -1.0 R = 0.25	0.7, 1.1, 2.2, 3.5	-1.0
Bilby (30)	OONW	8,122 km	28	4.1-14	R <sub>H</sub> = -0.5, -0.7, -0.9, R = 0.0625	9.1	-0.5
Bilby (30)	OONW	8,122 km	19.6	2.0-4.0	R <sub>H</sub> = -0.5, -0.7, -0.9 R = 0.0625	2.1, 2.2	-0.5
Bilby (30)	OONW	8,122 km	9.8	1.0-2.0	R <sub>H</sub> = -0.5, -0.7, -0.9 R = 0.0625	1.0, 1.3, 1.4	-0.9
Bilby (31)	SBGR	8,000 km	40	0.1-10	R <sub>H</sub> = -0.4, -0.6, -0.8, -1.0 R = 0.25	0.6, 1.0, 2.1, 2.4, 3.3, 8.3	-1.0
Bilby (31)	SBGR	8,000 km	28	8.0, 14	R <sub>H</sub> = -0.4, -0.6, -0.8 R = 0.0625	12.6	-0.4
-Bilby (31)	SBGR	8,000 km	19.6	2.0-4.0	R <sub>H</sub> = -0.5, -0.7, -0.9 R = 0.01	3, 3, 3, 4	-0.5

Table II - continued

Event number	Station	Distance	Pulse Length sec.	Input Delay Time ( $\Delta t$ ) sec	Input $R_H$ + Input R	Delay for which $C_R$ 's are larger than $C_{RO}$ 's	RH
Bilby (32)	HWIS	5,199 km	40	0.1-10	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	0.6, 1.2, 1.6, 4.7	-0.9
Bilby (32)	HWIS	5,199 km	28	8.0-14	$R_H = -0.4, -0.6, -0.8$ $R = 0.25$	No solution	
Bilby (32)	HWIS	5,199 km	19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	No solution	
Bilby (33)	CPO	2,725 km	40	0.1-8.0	$R_H = -0.4, -0.6$ $R = 0.25$	0.5, 0.9, 1.6, 4.3, 5.9	-0.4
Bilby (33)	CPO	2,725 km	28	8.0-14	$R_H = -0.4, -0.6, -0.8$ $R = 0.01$	12.6	-0.4
Bilby (33)	CPO	2,725 km	19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	2.0, 2.2	-0.5
Bilby (307)	EKA-2	7,967 km	28	4.1-14	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	4.1, 4.2	-0.5
Bilby (307)	EKA-2	7,967 km	19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	2.2, 2.3, 2.4, 2.5, 3.1, 3.7	-0.5
Bilby (307)	EKA-2	7,967 km	9.8	1.0-2.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	1.5, 1.6	-0.5
Shoal (34)	BMO	634 km	40	0.1-8.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	0.6, 1.6, 2.2, 3.2	-0.7

Table II - continued

-21

Event number	Station	Distance	Pulse Length sec.	Input Delay Time ( $\Delta t$ ) sec.	Input $R_H$ + Input R	Delay for which $C_R$ 's are larger than $C_{R0}$ 's	RH
Shoal (35)	CPO	2,915 km	40	0.1-10.0	$R_H = -0.5, -0.7$ $R = 0.25$	1.0, 1.1, 3.9	-0.7
Shoal (36)	WMO	1,826 km	40	0.1-10.0	$R_H = -0.5, -0.6, -0.8$ $R = 0.25$	0.9, 1.8, 2.6, 3.1	-0.6
Shoal (37)	LZBV	8,012 km	30	0.1-10	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	0.9, 5.2, 5.6, 7.6, 8.6	-0.1
Shoal (262)	DHNY	4,000 km	30	0.1-10	$R_H = -0.5, -0.7, R=0.25$	0.7, 0.9, 1.3, 6.5	-0.7
Shoal (268)	RYND	1,700 km	30	0.1-8.0	$R_H = -0.4, -0.6, -0.8$ $R = 0.25$	0.7, 1.4, 2.3, 3.1, 4.7, 6.4	-0.8
Shoal (261)	RKON	2,300 km	30	0.7-9.8	$R_H = -0.4, -0.5, -0.7, -0.9$ $R = 0.25$	0.8, 2.0, 2.8	-0.5
Shoal (325)	NPNT		28	4.1-14	$R_H = -0.5, -0.7-0.9$ $R = 0.0625$	7.2, 11.9	-0.5
Shoal (325)	NPNT		19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	No solution	
Shoal (325)	NT		9.8	1.0-2.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	1.2	-0.5
Aardvark (257)	LCNM	1,000 km	30	0.8-9.6	$R_H = -0.4, -0.5, -0.7, -0.9$ $R = 0.25$	1.6, 2.4, 4.0, 7.2	-0.7
Aardvark (266)	WNSD	1,500 km	30	0.7-7.7	$R_H = -0.4, -0.5, -0.7, -0.9$ $R = 0.25$	2.1, 4.2	-0.4

Table II - continued

<u>Event number</u>	<u>Station</u>	<u>Distance</u>	<u>Pulse Length</u> <u>sec.</u>	<u>Input Delay Time (<math>\Delta t</math>) sec.</u>	<u>Input R + Input R</u> <u>H</u>	<u>Delay for which CR's</u> <u>are larger than CR's</u>	<u>RH</u>
Aardvark (258)	MNW	500 km	30	0.8-9.6	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	1.6, 4.0	-0.4
Aardvark (270)	NLWS	2,500 km	30	0.5-13.0	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	0.5, 1.5, 3.0	-0.9
Hardhat (259)	BLWV	3,000 km	30	0.1-10	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	1.2, 1.7, 2.4, 4.9, 5.8, 8.6	-0.9
Hardhat (264)	RTUN	1,300 km	30	0.7-7.7	$R_H = -0.4, -0.5, -0.7$ $-0.9$ $R = 0.25$	1.4	-0.4
Haymaker (267)	WMO	1,600 km	30	0.7-8.4	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	1.4, 2.8, 4.9	-0.7
Salmon (260)	BMO	1,700 km	30	0.1-10	$R_H = -0.4, -0.5, -0.7$ $R = 0.25$	0.7, 1.8, 2.4, 5.3, 7.0, 7.6, 9.0	-0.5
Salmon (269)	DRCO	1,700 km	30	0.6, 1.3, 1.8, 2.4, 3.0, 3.6, 4.2, 4.8, 5.4, 6.0, 6.6, 7.2, 7.8, 8.4, 9.0	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	0.6, 3.0	-0.9
Salmon (263)	RMON	2,250 km	30	0.1-10	$R_H = -0.4, -0.5, -0.7$ $R = 0.25$	1.7, 2.3, 3.7, 4.5, 5.5	-0.7
Salmon (265)	UBO	2,100 km	30	0.8, 1.6, 2.4, 3.2, 4.0, 4.8, 5.6, 6.4, 7.3, 8.0, 8.8, 9.6, 10.4, 11.0	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	2.4	-0.7



Table II - continued

-23

Event number	Station	Distance	Pulse Length sec.	Input Delay Time ( t ) sec.	Input $R_H$ + Input R	Delay for which $C_R$ 's are larger than $C_{RO}$ 's	RH
Salmon (256)	BLWV	1,100 km	30	0.8-9.6 increment with 0.8 sec.	$R_H = -0.4, -0.5, -0.7,$ $-0.9$ $R = 0.25$	0.8, 2.4	-0.5
Mississippi (313)	HN-ME	4,070 km	28	4.1-14	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	4.2, 4.3, 4.4, 4.5, 4.6, 6.2, 6.3, 6.4, 12.9	-0.9
Mississippi (313)	HN-ME	4,070 km	19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	3.0, 3.1, 3.2	-0.9
Mississippi (313)	HN-ME	4,070 km	9.8	1.0-20	$R_H = -0.5, -0.7, -0.9$ $R = 0.25$	1.3	-0.9
Salmon (305)	NPNT	5,264 km	28	4.1-14	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	7.7, 7.8, 8.0 8.6, 9.0, 12.6	-0.9 -0.5
Salmon (305)	NPNT	5,264 km	19.6	2.0-4.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	2.7, 2.8, 3.5	-0.5
Salmon (305)	NPNT	5,264 km	9.8	1.0-2.0	$R_H = -0.5, -0.7, -0.9$ $R = 0.0625$	1.2, 1.3	-0.5

Table III

Peak of Frequency Spectrum of Seismograms of Blasts

Event and number	Station	Distance	6 DB down maximum at left side	F max	6 DB down maximum at right side
Bilby (29)	LZBV	8000 km	0.525	0.775	1.1
Bilby (30)	OONW	8122 km	0.525	0.625	0.75
Bilby (31)	SBGR	8000 km	0.775	0.825	0.85
Bilby (32)	HWIS	5199 km	0.70	0.725	0.825
Bilby (33)	CPO	2725 km	0.55	0.6	0.675
Shoal (34)	BMO	634 km	1.275	1.45	2.2
Shoal (35)	CPO	2915 km		0.225	0.325
Shoal (36)	WMO	1826 km	0.725	0.875	0.95
Shoal (37)	LZBV	8012 km		0.25	0.325
Shoal (262)	DHNY	4000 km	0.94	1.03	1.17
Shoal (268)	RYND	1700 km	1.12	1.17	1.42
Shoal (261)	RKON	2300 km	1.26	1.32	1.36
Salmon (256)	BLWV	1100 km	2.78	2.8	3.05
Salmon (260)	BMO	1700 km	0.21	0.3	0.56
Salmon (263)	RMON	2250 km	2.32	2.42	2.52
Salmon (265)	UBO	2100 km	0.46	0.56	0.71
Salmon (269)	DRCO	1700 km	0.44	0.6	1.18
Aardvark (257)	LCNM	1000 km	0.83	0.88	0.92
Aardvark (258)	MNW	500 km	1.05	1.12	1.19
Aardvark (266)	WSD	1500 km	0.84	0.87	0.9

Table III - continued

<u>Event and number</u>	<u>Station</u>	<u>Distance</u>	<u>6 DB down maximum at left side</u>	<u>F max</u>	<u>6 DB down maximum at right side</u>
Aardvark (270)	NLWS	2500 km	0.86	0.98	1.07
Ha. dhat (259)	BLWV	3000 km	2.13	2.19	2.4
Hardhat (264)	RTUN	1300 km	1.35	1.5	1.53
Haymaker (267)	WMO	1600 km	0.67	0.82	1.1

Focal depths indicated for the Ecuador Earthquake of 10 May 1963

Series	Sta.	$\Delta^\circ$	Expected Values		Filter Tested		Results				
			pP/P	Noise-signal ratio (R)	R	pP/P	$\Delta t$	pP/P	u	h	
7	AAM	44.63	-0.54	.072	.0625	-.5	.2, .3	3.5	-.5	.2	10.8
12	SCP	42.80	-0.53	.015	.01	-.7	.1, .2	5.6	-.5	.3	20.0
101	PHC	67.67	-0.71	.038	.0625	-.7	.2, .3	2.8	-.5	.1	8.2
113	RES	77.48	-0.81	.055	.0625	-.9	.1, .2	3.7	-.5	.2	11.8
102	VIC	64.24	-0.69	.005	.01	-.5	.1, .2	3.9	-.9	.3	11.5
9	CMC	74.59	-0.75	.012	.01	-.7	.1, .2	3.0	-.7	.2	8.3
5	STU	89.52	-0.82	.054	.0625	-.8	.2, .3	No significant solution			
8	PTO	75.79	-0.75	.055	.0625	-1.0	.2, .3	5.1	-.8	.3	15.3
13	WID	93.51	-0.83	.095	.125	-.7	.3, .4	3.8	-.8	.3	10.9
29	ALE	71.88	-0.81	.012	.0625	-.6	.1, .2	4.6	-.7	.2	14.2
						-.8		2.9	-.8	.3	7.7
								3.6	-.8	.4	9.9
								3.4	-.6	.2	9.4

Table IV - continued

Series	Sta.	$\Delta^\circ$	Expected Values		Filter Tested		Results				
			pP/P	Noise-signal ratio (R)	R	pP/P	u	$\Delta t$	pP/P	u	h
100	LDN	45.15	-0.54	.184	.25	-.5	.3, .4	4.2	-.6	.4	14.1
						-.6		2.7	-.5	.4	8.1
103	MBC	81.86	-0.79	.002	.01	-.6	.1, .2	3.0	-.6	.2	5.2
						-.8		3.9	-.6	.2	11.2

Additional depth predictions for the 10 May 1963  
Ecuador Earthquake:

No.	Station (code)	$\Delta$ (EM)	RH	U-level	Delay time (sec)	Focal depth (kri)
7	Ann rbor (AAM)	4,959	-1.0 -0.8	.3 .4	3 5.5	8 16.5
9	Copper Mine (CMC)	8,288	-0.6	.5	4	12
5	Stuttgart (STU)	9,947	-1.0	.4	6	18
8	Porto (PTO)	8,421	-0.8	.1	4	12.5
13	Windhook (WIN)	10,389	-0.8	.3	3	10
99	Alert (ALE)	--	--	--	--	--
100	London (LDN)	5,016	-1.0	.1	3.5	11
103	Mould Bay (MBC)	9,096	-0.8	.1	3.5	11
101	Port Hardy (PHC)	7,519	-1.0	.4	4	12
113	Resolute Bay (RES)	--	--	--	--	--
102	Victoria (VIC)	7,138	-0.8	.5	4	12
163	Manhattan (MHT)	9,418	-0.6	.2	2.7 3.1 3.5 4.0	7.2 8.4 9.8 11.4

TABLE V - continued

-29

No.	Station (code)	$\Delta$ (EM)	RH	U-level	Delay time (sec)	Focal depth (km)
162	Cape Girardeau (CGM)	9,769	-0.6	.2	2.8 3.9 5.6	7.4 11.1 17.1
14	Charles Tower (CTA)	14,625	-0.6 -0.6	.4 .5	3 5.5	9 14.5
10	Chieng Mai (CHG)	18,181	-0.6	.1	2.5	6.5
15	Baguio (BAG)	17,468	-0.8	.2	7	21
11	Mundaring (MUN)	15,952	-0.6	.4	3.5	1.0
6	New Dehli (NDI)	16,040	-0.6	.1	4.0	12

The following solutions are possibly paired core phases:

Table VI

Watson-Merdler Solutions for Earthquakes Other Than Ecuador 10 May 1963

number	Date	Location	at	Comp.	Rough distance (km)	USCGS depth (km)	"Best" solution		Rough Predicted depth (km)	
							$\Delta T$	$R_H$		u
1	14 JY 62	Kurile Is.	SCP	SPZ	-	60	12.7	-1.0	-	45
2	23 JY 62	Costa Rica	SCP	SPZ	3500	44	6.9 or 8.7	-0.8	-	23 or 32
3	23 AU 62	Alaska	SCP	SPZ	-	10	3.3	-0.8	-	10
4	17 NO 62	Mex.-Guat.	SCP	SPZ	-	12	4.9	-0.8	-	15
38	6 OC 62	Ecuador	WMO	SPZ	(4800)	149	25	-	-	(130)
39	6 OC 62	Ecuador	LCNM	SPZ	(4800)	149	25.5	-	-	(130)
40	5 OC 62	Ecuador	BMO	SFZ	(4800)	149	25.5	-	-	(130)
41	6 FE 64	Sumba	SCP	SPZ	-	43	11.5	-0.6	0.4	43
56	14 OC 63	Kurile Is.	SCP	SPZ	9351	60	No significant solutions	-	-	-
71	27 OC 63	Kamchatka	SCP	SPN	8000	-	0.5	-	-	-
141	2 JY 63	Ecuador	ARE	Z	-	33	4	-0.7	-	14
144	2 JY 63	Ecuador	CAR	Z	-	33	10.4	-0.4	-	37
237	9 JY 63	Costa Rica	ARE	Z	-	31	10.4	-0.9	-	40
156	1 SE 62	Rat Is.	SCP	SPZ	11500	-	1.6	-0.9	0.1	4
173	9 JY 63	Panama	SLM	Z	3500	31	1.8	-0.8	0.3	6
176	25 OC 62	Panama	MHT	SPZ	3800	51	14.4	-0.4	0.2	58
177	25 OC 62	Panama	BCU	SPZ	3200	51	12.8	-0.9	0.3	50
300	20 JY 62	Fallon	WMO	LI	1822	33	9.6	-0.5	0.3	50
317	10 JY 63	Georgian SSR	BMO	ZI	10037	17	5.7	-0.7	-	18



TABLE VII

<u>Material</u>	<u>Thickness</u>	<u>Measured Vel. of compr. waves</u>	<u>Calculated Vel. of compr. waves</u>	<u>Calculated Vel. of shear waves</u>
Copper plate	0.64"	3980 M/S	-----	1860-2200
Steel plate	0.32"	5450	-----	3000-3300
Copper-steel lamination	0.64" -0.32"	4510	4520	2500-2700

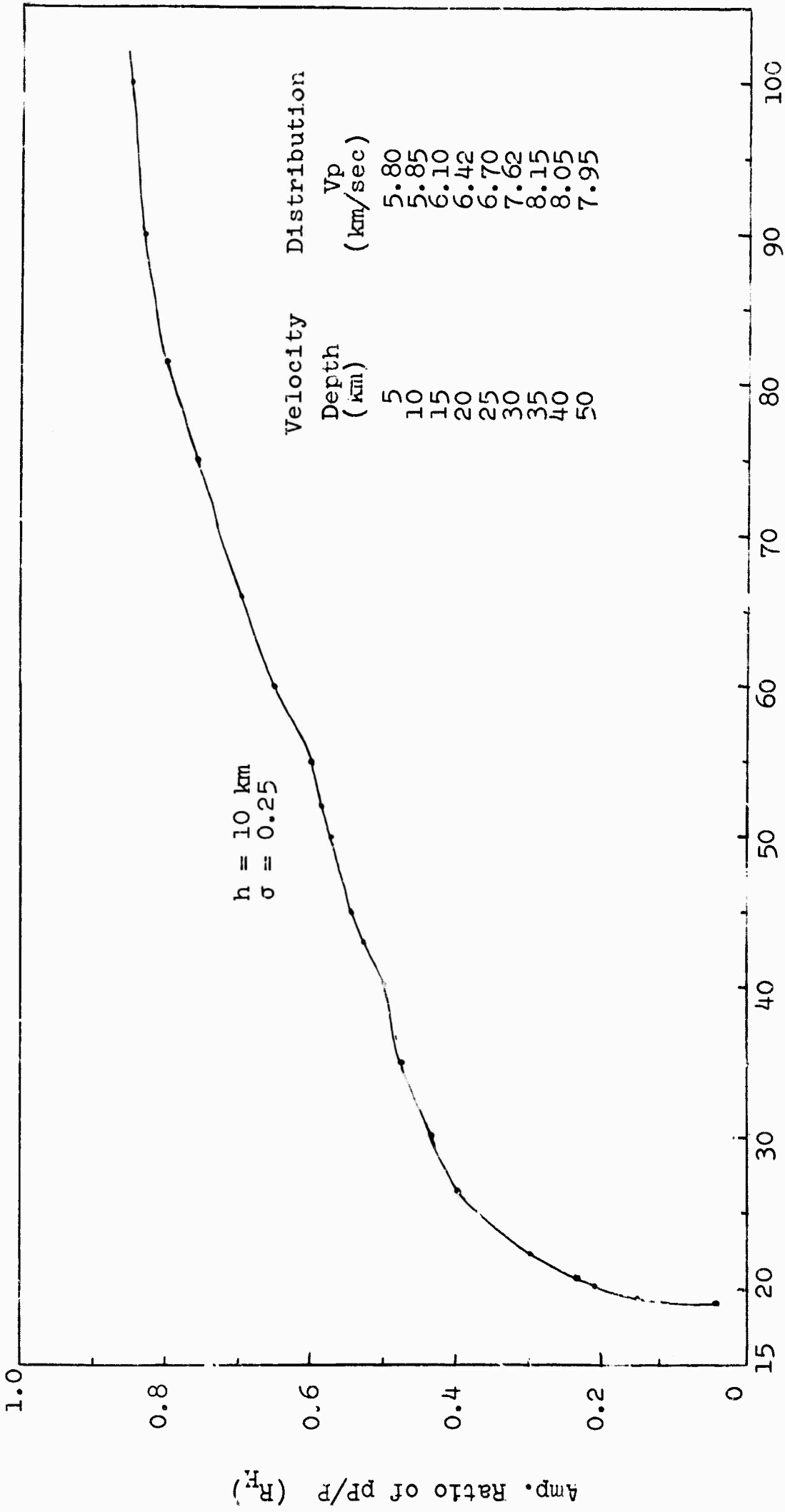


Figure 1 - Epicentral Distance (Degrees)

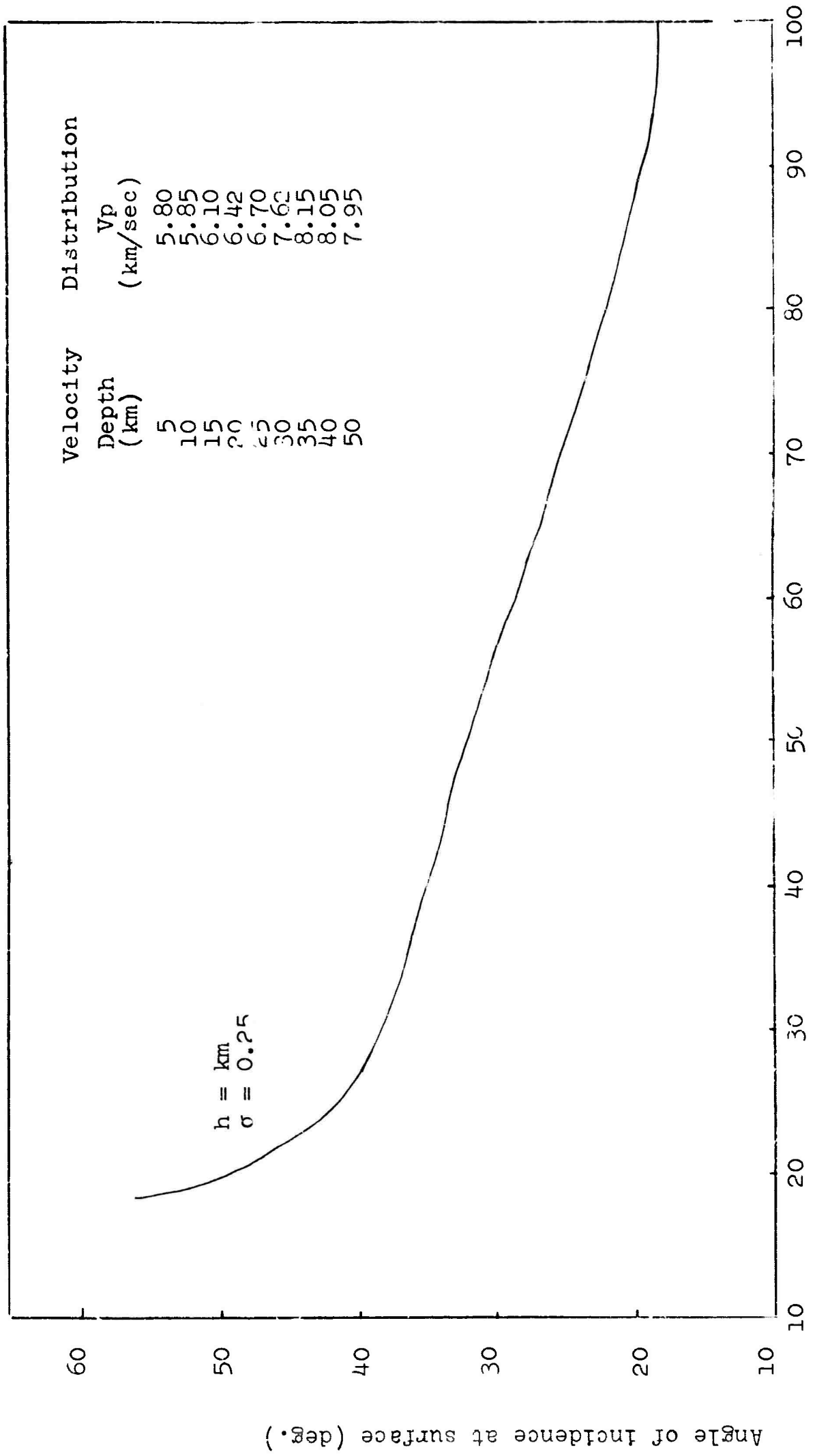


Figure 2. Angle of incidence of P vs. epicentral distance

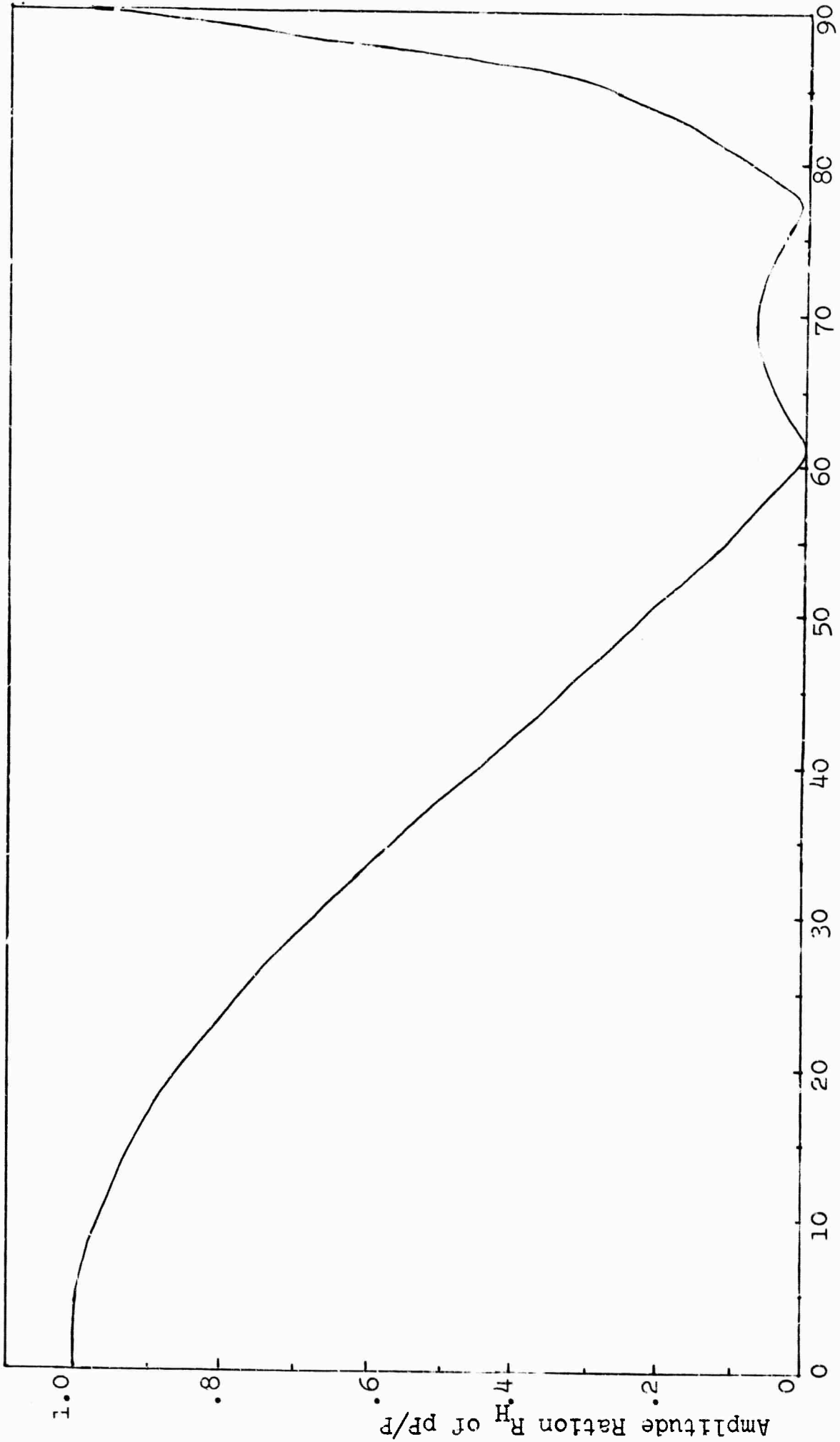
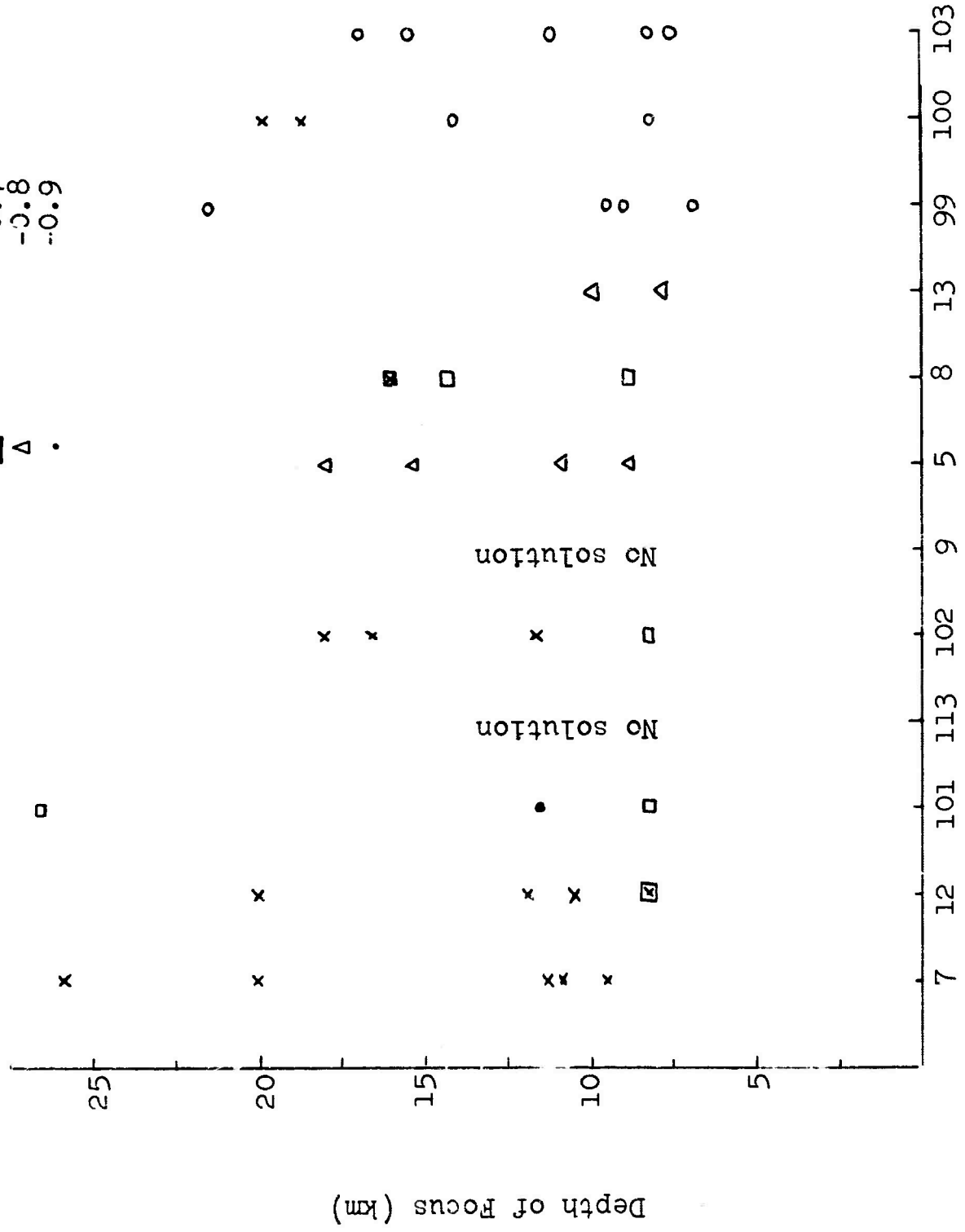


Figure 3. Angle of incidence at reflection point for  $\sigma = .25$

Legend

Symbol	Amplitude ratio
x	-0.5
o	-0.6
□	-0.7
△	-0.8
.	-0.9



Frequency in cps

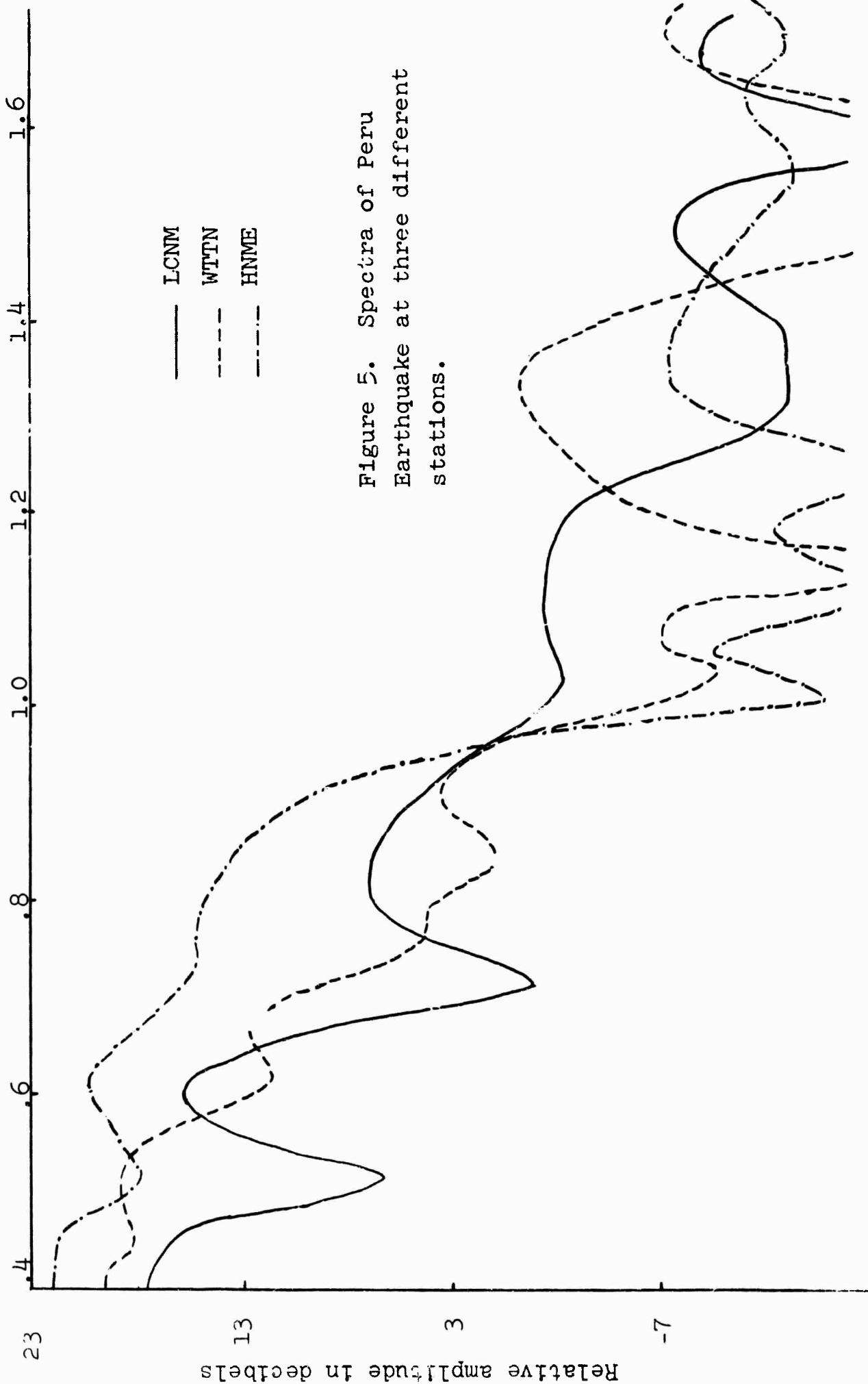


Figure 5. Spectra of Peru Earthquake at three different stations.

Relative amplitude in decibels

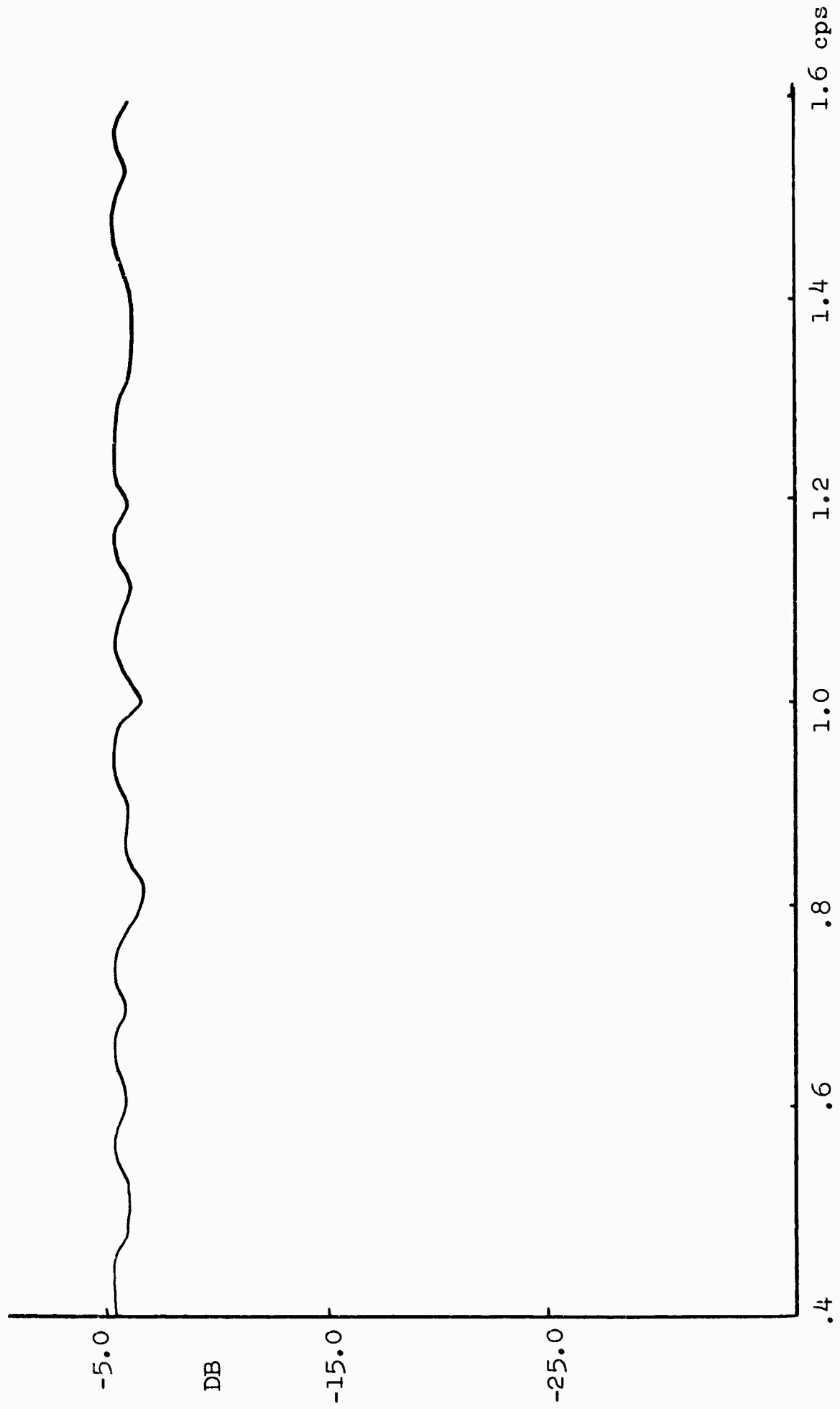


Figure 6. Truncated transfer function for Ontario, Angle  $1 = 30^\circ$ .

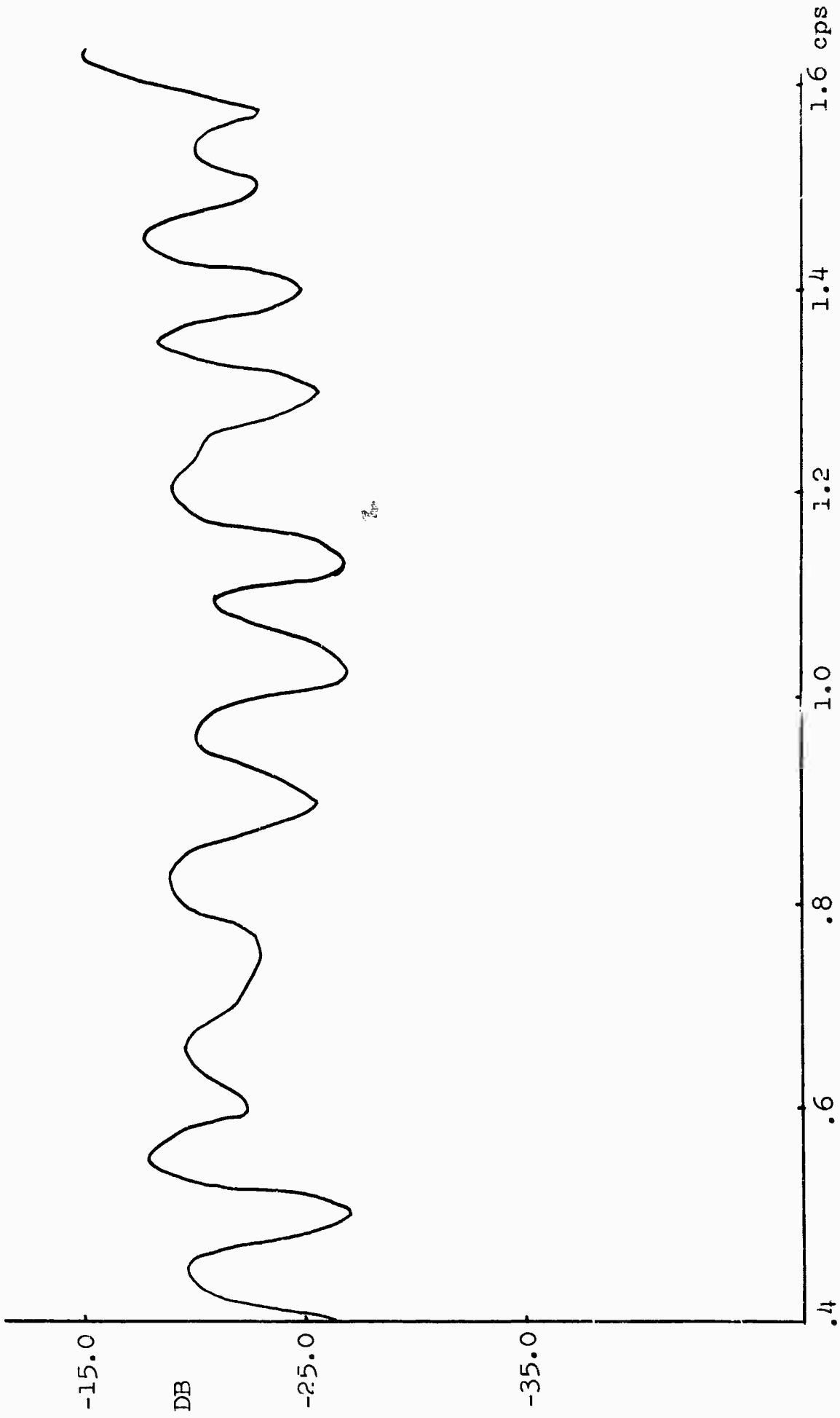


Figure 7. Truncated transfer function for Model 7.4, Angle 1 = 33°.



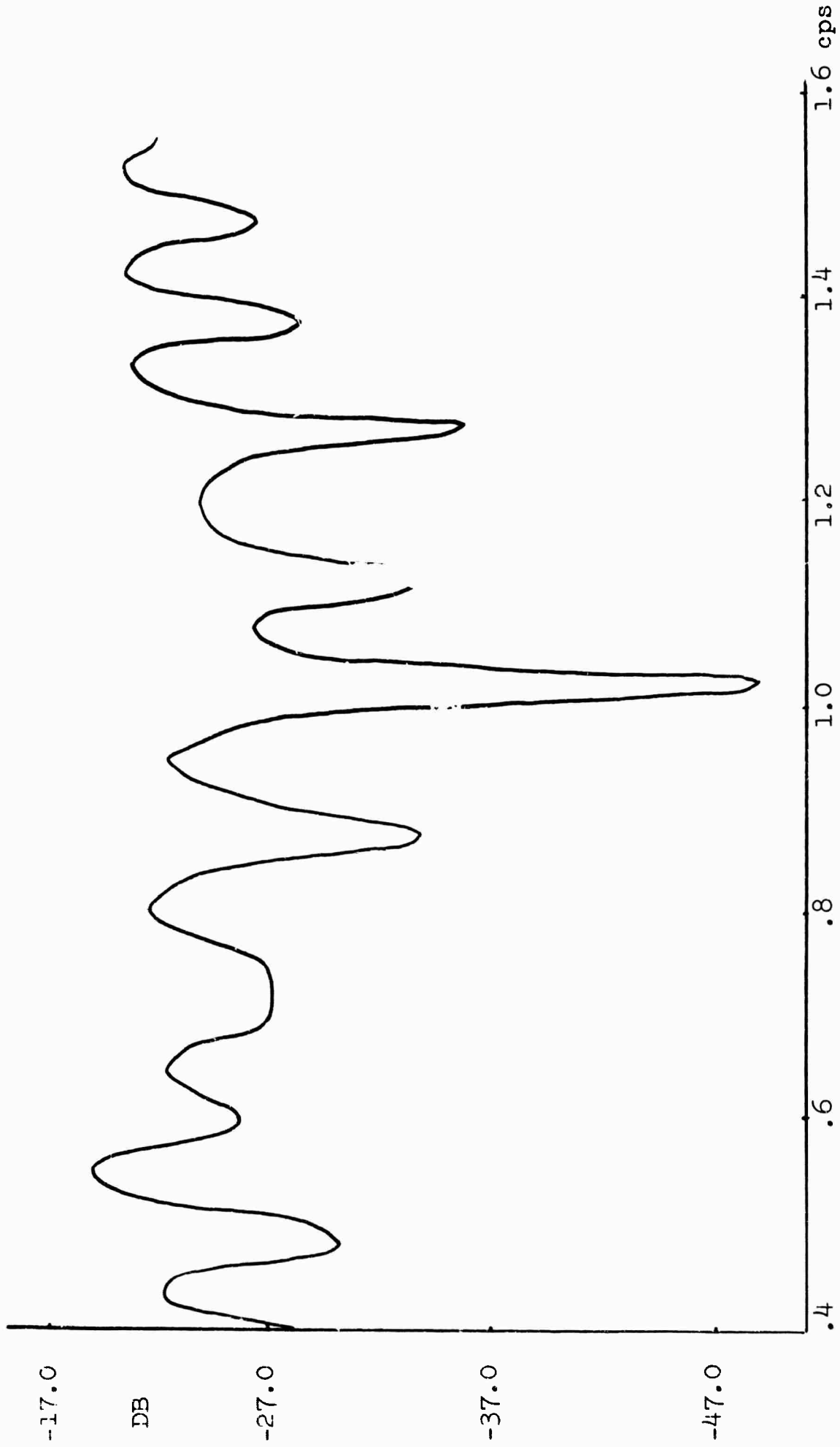


Figure 8. Truncated transfer function for Model 7.4, Angle 1 = 34°.

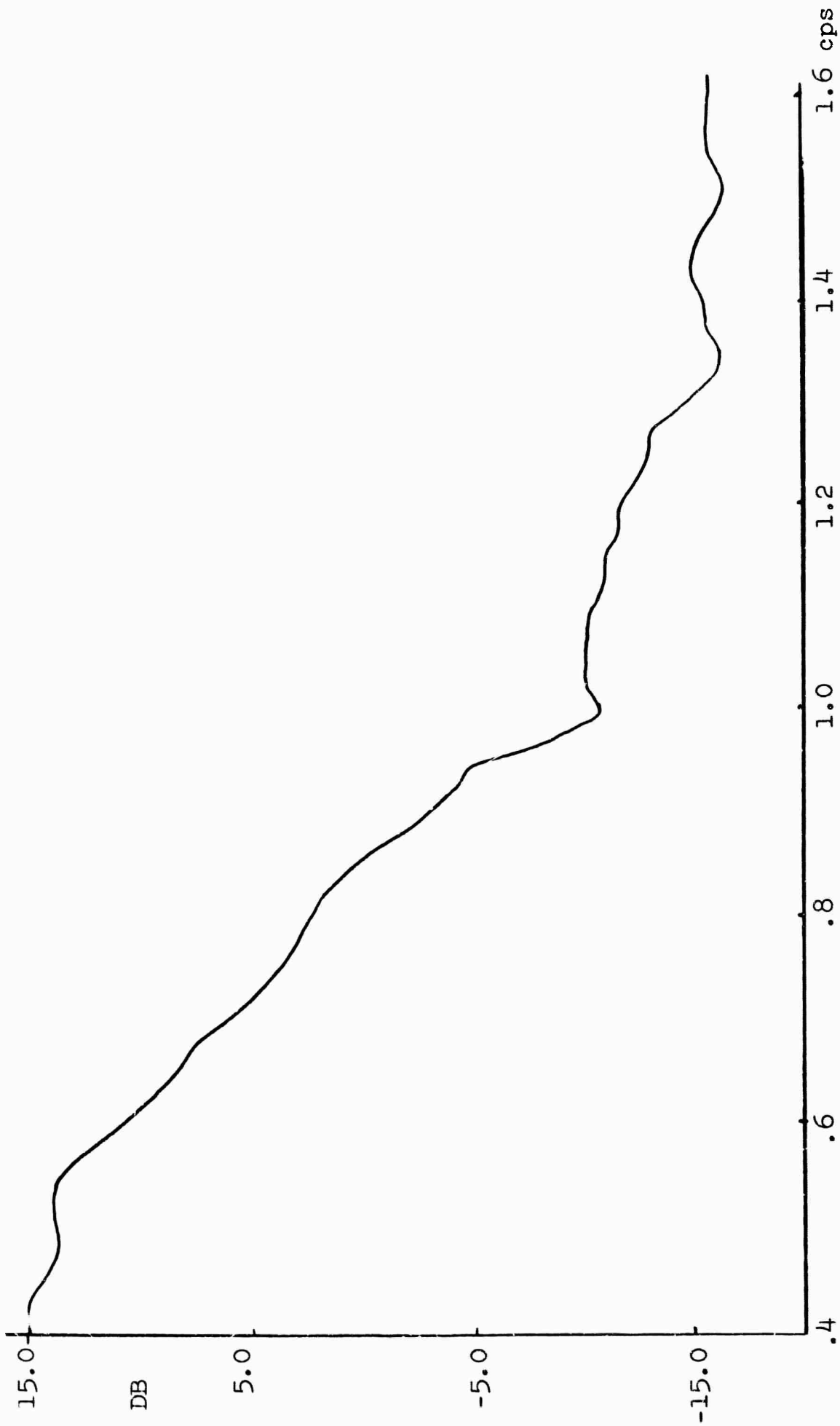


Figure 9. Average spectrum of all 37 stations

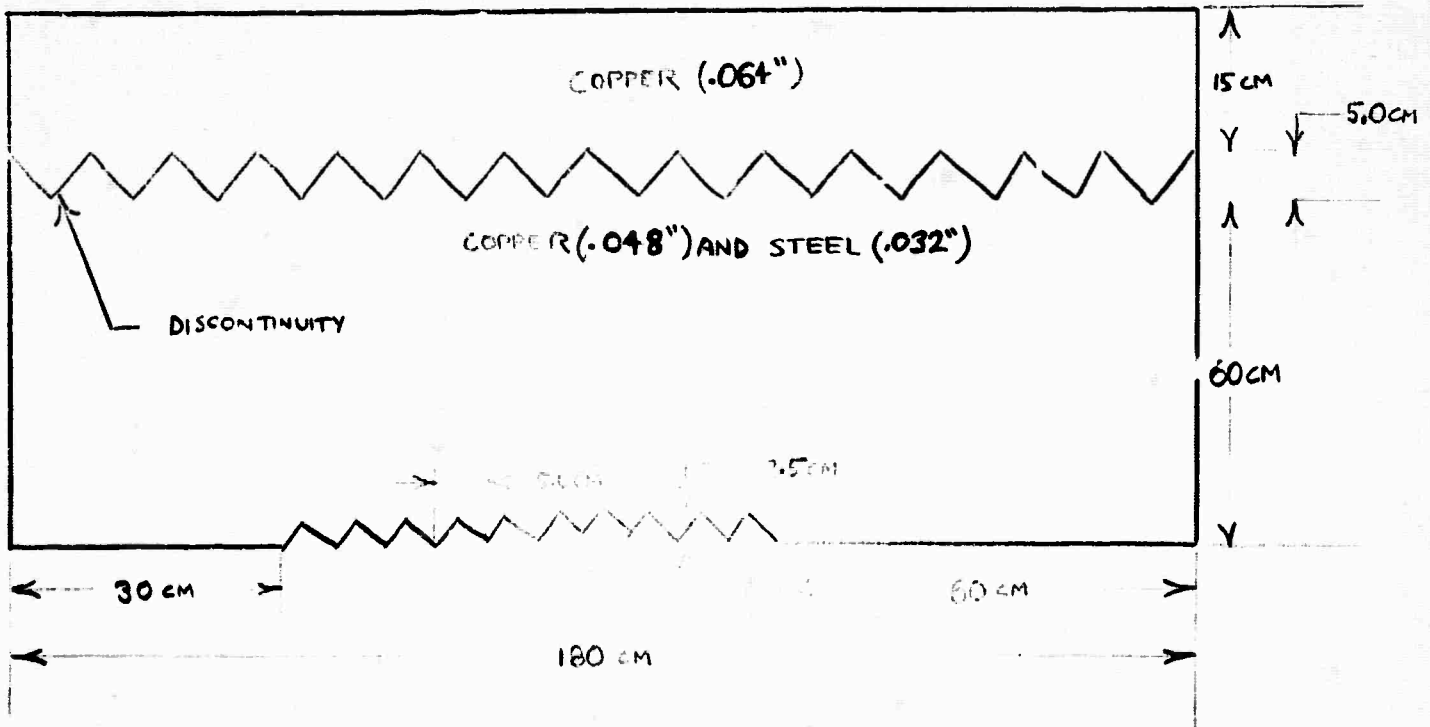
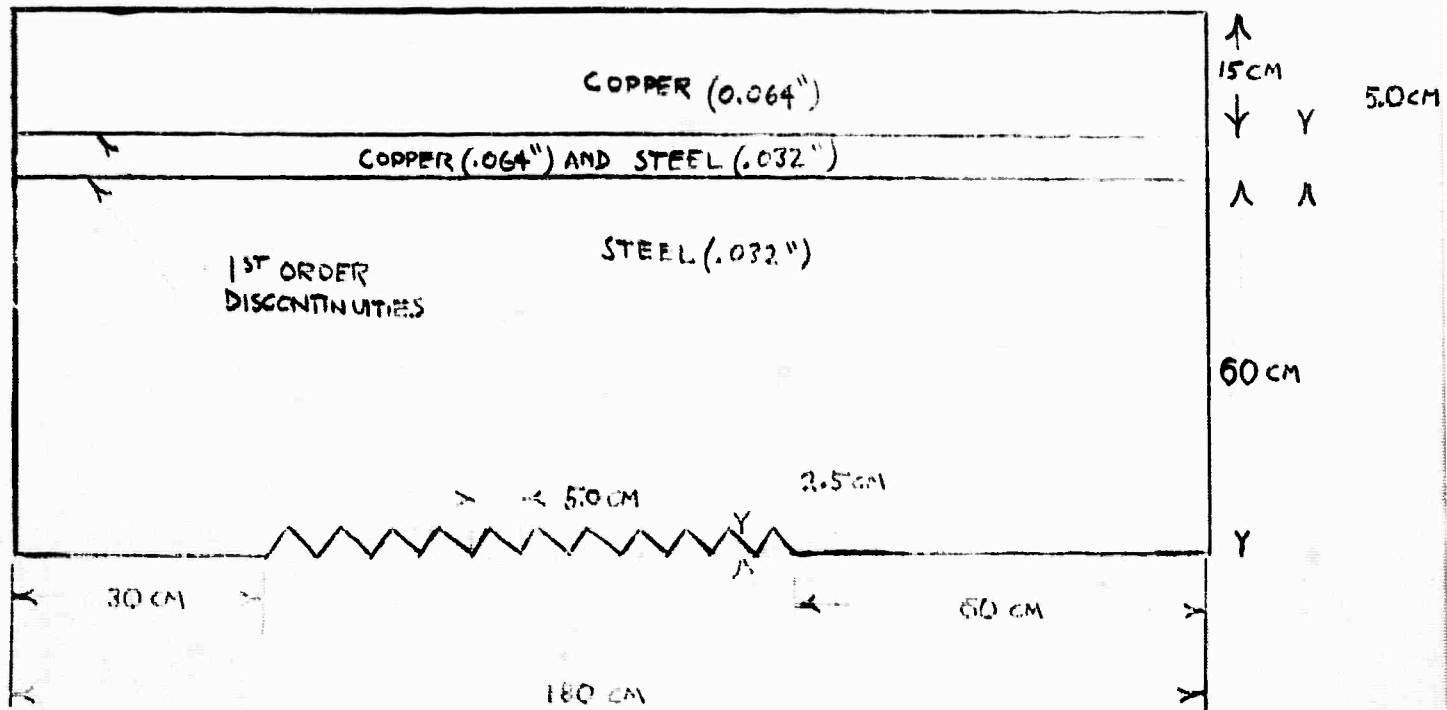


Figure 10. The two models being tested