File [illegible]
0087
cy

①

AFOSR-TR-71-2385

15 SEP 1970

Annual Report No. 2
for
Contract #F44620-68-C-0087

by

Brian T. R. Lewis, Joseph F. Gettrust, and
Robert P. Meyer

Annual no. 1 - no record

Sponsored by
Advanced Research Projects Agency
ARPA Order No. 292

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

ORIGINATING ACTIVITY (Corporate author)
University of Wisconsin
Madison, Wisconsin

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

REPORT TITLE
On the Comparison of Theoretical and Observed Truncated Ratio Spectra

DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific........Interim

AUTHOR(S) (First name, middle initial, last name)
Brian T. R. Lewis, Joseph F. Gettrust, and Robert P. Meyer

REPORT DATE
5 September 1970

7a. TOTAL NO. OF PAGES
38

7b. NO. OF REFS
11

CONTRACT OR GRANT NO
F44620-68-C-0087

PROJECT NO.
8652

62701D

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
AFOSR - TR - 71 - 2385

DISTRIBUTION STATEMENT
Approved for public release;
distribution unlimited.

SUPPLEMENTARY NOTES
TECH, OTHER

12. SPONSORING MILITARY ACTIVITY
AF Office of Scientific Research (NPG)
1400 Wilson Boulevard
Arlington, VA 22209

ABSTRACT

The purpose of this project is to i) improve our understanding of the crust and upper mantle structure near to and beneath the Montana LASA (Large Aperature Seismic Array) and ii) to remove the effects of this structure from seismic signals received there, in order that these signals more clearly show the effects of the source conditions (depth of focus, source function), and thus, hopefully, make more apparent the differences between explosions and earthquakes.

Contents

Summary

The purpose of this project is to i) improve our understanding of the crust and upper mantle structure near to and beneath the Montana LASA (Large Aperature Seismic Array) and ii) to remove the effects of this structure from seismic signals received there, in order that these signals more clearly show the effects of the source conditions (depth of focus, source function), and thus, hopefully, make more apparent the differences between explosions and earthquakes.

At this stage, it is necessary to discuss these two facets of the project separately; the main body of this report has been so divided.

A technical note on the method of truncated ratio spectra as a technique to remove the effects of crust and upper mantle structure on signals received at LASA has been completed. The achievements in this portion of the project have been:

1. Models which include layering in both the crust and upper mantle are necessary to produce ratios at least as complicated as the observations.

2. Although no model has been found which provides a satisfactory fit with the data, it is believed that variations in crustal thickness are responsible for the differences in ratio spectra between sites.

3. Simulation of variation in crustal thickness suggests that this effect will distort intolerably spectra averaged between stations. It would be preferable to average separate events recorded at one site.

4. The lack of an acceptable model precludes the deconvolution of seismograms with the receiver transfer function. Improvement in model fitting techniques will be necessary to accomplish this goal.

That part of this project aimed at directly developing a better understanding of the crust and upper mantle structure near LASA was based on project EDZOE, a series of five ton shots fired in Greenbush Lake, B.C., Canada. These shots were recorded by the University of Wisconsin along a line which roughly follows the axis of the Rocky Mountains and extends approximately 2300 km. on either side of the shot point. Data from the southern end of this line has been put in record section format over various reducing velocities and with a number of frequency filters. Accomplishments, to date, in the analysis of this data are:

1. A spherical earth ray-trace program has been used to find a velocity-depth function model which fits the data. So far, no model which satisfies both the arrival times and amplitudes of the data has been found. In particular, models for this region proposed by Johnson (1967) and Archambeau et al. (1969), have been found to be incompatible with the EDZOE data.

2. An offset in the arrivals from immediately beneath the M-discontinuity coupled with rapid attenuation of the amplitude of these arrivals is strongly suggestive of a lateral discontinuity in velocity at that depth. Greenfield and Sheppard (1969) report time residuals across LASA for sources NW of the array of the same order of magnitude (one-half second) over a comparable aperture. They attribute this delay to structure in the M-discontinuity; however, their model, a single layer crust with p-velocity of 6.0 km/sec over the mantle which has a p-velocity of 8.0 km/sec, fails to satisfy the observed Bouguer gravity anomoly (and, as shown in the truncated ratio spectra results, could not satisfy the complicated observed ratio). The EDZOE data supports a 6.0 km/sec crust overlying a "double M-discontinuity" with a relatively thin 7.9 km/sec refractor (on the order of a few tens of km. thick) overlying a refracting horizon with an apparent velocity of 8.1 km/sec (in which the time offset is seen). The inclusion of this 7.9 km/sec refractor may well allow us to fit not only the seismic and gravity data but better satisfy the complicated spectra ratio observed for this region as well

3. The region where a horizontal velocity discontinuity is suspected is related (at least spatially) with a protrusion of normal heat flow values (for the mid-continent) in the crust into the high heat flow province defined (in part) by the northern and southern Rockies, and the Basin and Range, Investigation of the correlation between the heat flow data, and upper mantle structure provides an independent constraint on acceptable crust-mantle models.

Both the truncated ratio spectra results, and the long range refraction data indicate a simplistic model of the crust and upper mantle structure is not viable for the LASA region. While horizontal layering in the crust and upper mantle have been shown to produce spectra ratios of sufficient complexity, the lack of an acceptable model from these criteria lends support to the more complex structure suggested by the refraction data.

Analysis of the EDZOE refraction data continues, with the aim of developing a crust- upper mantle model which satisfies not only the seismic data but the independent constraints of gravity and heat flow.

Dorman and Lewis (1970) developed, as part of this project, an analytic solution to the problem of isostasy. In their application of this technique (Lewis and Dorman, 1970), they derive the isostatic response function from actual data for the United States. This response function is of importance since it is possible to predict the gravity field for an area where only the topography is known (by convolving the response function with the topography). It would be of interest then, to use the crust upper mantle velocity depth function derived from the EDZOE data contrasted with that found for the mid-continent (e.g., Lewis and Meyer, 1968) to further test the density-contrast with depth they find reflects the isostatic process.

Publications

Dorman, LeRoy M., and Brian T. R. Lewis, "Experimental isostasy: part I, theory of the determination of the isostatic response of the earth to a concentrated load," J. Geophys. Res., 75, 17, 3357-3365, 1970.

Lewis, Brian T. R., and LeRoy M. Dorman, "Experimental isostasy: part II, an isostatic model for the United States derived from gravity and topographic data," J. Geophys. Res., 75, 17, 3367-3385, 1970.

Abstracts

Dorman, LeRoy M., R. P. Meyer, and L. C. Ocola, "Differential time terms and structure under arrays," AGU Transactions, 49, 4, 1968.

Gettrust, Joseph F., Brian T. R. Lewis, and R. P. Meyer, "Upper mantle studies along the axis of the Rocky Mountains," paper presented at the Sixty Fifth Annual Meeting of the SSA, March 1970 (in press).

Technical Note

On the Comparison of Theoretical and Observed Truncated Ratio Spectra

by

B. Lewis

Introduction:

It is well known that if the outer regions of the earth are viewed as a system of horizontal layers upon which is incident a P or S wave at an angle of incidence i, then the vertical and horizontal motions at the surface are given respectively by a convolution of the source function with the vertical and horizontal transfer function and the respective detector responses. Taking the ratio of the Fourier transforms of the truncated vertical and horizontal motions, one obtains a ratio spectrum which is independent of the source function if this function is of relatively small time duration (see Lablance, 1967) and depends only on the model if the assumptions in the theoretical case are adequate. Attempts to determine crustal structure using this method have been applied by Phinney, 1964; Lablance, 1967; McCamy, 1967 and others. However, since these studies, it has become evident that rapid changes in velocity occur at several depths in the mantle, notably near 600 km, 400 km and around 100 km. These discontinuities serve as generators of secondary P and S waves which are incident at the base of the crust shortly after the primary P or S wave and therefore violate the assumption of one incident wave.

In the present study we will apply this method to more complicated models which include discontinuities in the mantle, the data being obtained from long period LASA instruments.

Theory:

Given a system of N horizontal layers in each of which the P and S velocities, density and specific attenuation Q are variable and a plane P wave incident at angle i at the base of the system, the Fourier transforms of the vertical and horizontal motions are given by

$$V(f,i) = \left[S(f,i) \cdot Tz(f,i) \cdot Iz(f)\right] * W(f,i)$$

$$H(f,i) = \left[S(f,i) \cdot Th(f,i) \cdot Ih(f)\right] * W(f,i) \qquad (1)$$

where $V(f,i)$, $H(f,i)$, $S(f,i)$, $Tz(f,i)$, $Th(f,i)$, $Iz(f)$, $Ih(f)$ and $W(f,i)$ are the Transforms respectively of the vertical and horizontal motion, source function, vertical and horizontal transfer functions, vertical and horizontal instrument transfer functions and the time window used to truncate the time series.

From (1) we obtain the ratio spectrum $R(f,i)$

$$= \frac{\left[S(f,i) \cdot Tz(f,i) \cdot Iz(f)\right] * W(f,i)}{\left[S(f,i) \cdot Th(f,i) \cdot Ih(f)\right] * W(f,i)}$$

Lablance (1967) has shown that if the source time function $s(t)$ is short with respect to the window $w(t)$ then,

$$R(f,i) = \frac{S(f,i) \cdot \left[\left\{Tz(f,i) \cdot Iz(f)\right\} * W(f,i)\right]}{S(f,i) \cdot \left[\left\{Th(f,i) \cdot Ih(f)\right\} * W(f,i)\right]}$$

*denotes convolution

$$= \frac{\left[Tz(f,i) \cdot Iz(f)\right] * W(f,i)}{\left[Th(f,i) \cdot Ih(f)\right] * W(f,i)}$$

whereupon $R(f,i)$ is independent of the source function. It should be noted that $W(f,i)$ depends on the angle of incidence in that the window applied to the theoretical data must be the same as that applied to the observations and the length of this window must be such as to preclude waves of a different angle of incidence (or phase velocity) such as PP if we are using P. Thus, W(t) will depend on the separation of P and PP and hence on the distance. In this analysis we used the following steps in computing the theoretical R--

1. For a given model a spherical earth ray trace program was used to compute the angle of incidence at the base of the layered system at the ranges for which observations were available.

2. Tz(f,i) and Th(f,i) were computed for appropriate values of f using Haskell's (1962) method.

3. Tz(f,i) and Th(f,i) were multiplied by instrumental response functions which were believed to be smooth curve fits to the LASA long period instruments but involved zero phase shift since this was unknown.

4. The theoretical seismograms were then computed by taking the inverse transform of Tz(f,i). Iz(f) and Th(f,i) · Ih(f) and these were then multiplied by the same time window as applied to the observations.

5. The ratio spectrum was computed by taking the ratio of the transforms of the truncated seismograms.

6. Many models were then tried in order to judge the relative effect of varying layer thickness, velocity etc. and to find, if possible, a model which fitted the data best. Because of the difficulty in inverting this problem (see McCamy, 1967), we attempted in this study only to judge the relative merits of existing upper mantle-crust models and not to invert the problem.

In order to give the reader some idea of the accuracy of the plane wave and horizontal layer assumption a ray diagram for a typical crust mantle model is shown in Fig. 1 with an appropriate wave-front. It is seen that these assumptions are probably at least as accurate as other unknowns in the distance range 40 to 90 degrees.

The Data:

The raw data used in this research was obtained from the 63 long period LASA instruments arranged into three component sets at 21 sites. The events obtained on these instruments that were studied are tabulated below:

Table 1

Event No.	Date	Arrival Time			Location	Azimuth Degrees	Range Degrees
		hr.	min.	sec.			
1	122467	20	11	47.3	Leeward Island	112.1	46.8
2	101867	01	20	24.3	Greenland Sea	13.2	47.6
3	112367	13	50	40.9	Svalbard	13.2	49.2
4	120167	14	07	21.9	Kuril Island	313.2	62.5
5	012968	10	30	20.2	Kuril Island	312.3	69.0
6	122167	02	37	08.6	Chile	146.4	77.6
7	113067	07	36	06.9	Yugoslavia	37.1	80.0
8	021968	22	58	35.8	Turkey	35.2	85.1
9	102567	01	12	53.0	Taiwan	316.8	95.1

All these events are of magnitude $>$5.5 and all were reported as shallow focus.

Figure 2 shows in record section form the output of a single instrument from each event together with the expected times of P, PP, and PcP for a surface focus event as given by Herrin et al. (1968).

In selecting events for ratio spectrum determinations, we used only those that had arrival trains about 100 secs or greater resulting from a single incident wave.

We note that for events 6, 7, 8, and 9, P and PcP arrive within a few seconds of one another and calculations show that the difference in the angle of incidence between P and PcP is small enough that the ratio spectrum may be considered to be unchanged. That is, we are assuming we have two P waves incident at the same angle and separated by a short time.

For events 4 and 5, this assumption is not valid and these were not used. Events 1, 2, and 3 have a sufficiently long time separation between P and PcP and were used.

In all cases the horizontal motion along the azimuth to the event was synthesized from the N-S and E-W motion. In order to try to improve the estimate of the ratio spectrum averaging over all operational LASA sites was performed by averaging the amplitude spectra of the vertical and horizontal motion and then dividing. This is superior to averaging the ratio spectra at all sites since individual ratios may contain large peaks.

In order to judge the variability of the ratio spectra across the LASA array, we show in Fig. 3 ratios at 16 sites for event 9. For display purposes only the logarithm of the ratio has been plotted. Also shown is the square root of the power spectrum of the vertical motion at each site; Vz(f). Although Vz(f) does not exhibit large changes from site to site, the ratios are more variable. There are two possible causes:

a.) Variations in the instrumental response functions which may involve systematic differences between the vertical and horizontal and/or small differences between instruments. Unfortunately, sufficiently accurate calibrations of all the instrument were not available to make a statement about this, but it is thought that these differences may be small and throughout this study all instruments are assumed identical. However, for the accurate implementation of this method, this assumption should be checked and, if necessary, the data corrected for the instrumental response.

b.) Variations in the actual transfer function from site to site. From the results of Greenfield and Sheppard (1968) it would seem that substantial variations in crustal thickness exists under the LASA which would certainly contribute to the variability of the ratios in Fig. 2. A discussion of the averaging on the ratio spectra will be taken up in the next section.

Comparison of Observed and Theoretical Ratio Spectra:

In order to elucidate the effect on the ratio spectrum of truncating the seismogram we show in Fig. 4 the Fourier synthesized seismograms and corresponding ratio spectrum assuming a delta function input in a model which extends down to 600 km and has a low velocity zone. The ratio spectrum obtained after passing the seismogram through a band pass filter similar to the LASA instruments and truncating the filtered seismograms with a 230 second window is also shown. A comparisom of the two ratio spectra shows that in the 0.02 to 0.25 Hz range the position of the spectral peaks is not significantly changed although there are changes in the character of the peaks. This, of course, is because most of the energy has been included in the 230 second window and the filter cancels in the ratio. A much shorter window will naturally produce greater differences.

The relative importance of parameters in the crust and upper mantle has been tested by taking as a starting point a model somewhat like that of Green and Hales (1968) and perturbing the thickness of each layer. The ratio spectra and synthetic seismograms from this test are shown in Fig. 5 and the models used are given in Table 2.

Because large peaks occur in the ratio spectrum which introduce scaling problems, the logarithm of the ratio has been plotted. Also the ratios and seismograms in Fig. 5 are scaled to the maximum and minimum values and hence the vertical scales are variable. This is not considered detrimental since our interest lies in the relative position of peaks and troughs. From Fig. 5 it is clear that the most marked effect on the ratio spectra comes from changing the crustal thickness, represented by the differences between model L1 and L2 which are different by 10 km in the crustal thickness. From examing these differences, one can see that averaging over sites which have a variable crustal thickness or velocity will tend to cancel out the peaks and troughs and the average will not reflect an average crust, unless one thickness predominates. Thus, it appears that if we are to average spectra to decrease the effect of noise, it should not be done over different sites, but would be more justifiable over earthquakes having a constant distance and azimuth to one site. Because of the small data sample on hand this was not tried.

The effect of varying the thickness of the low velocity zone, shown in model 5, suggests that this method does have the resolution to remove from the travel time method the ambiguity in the thickness of a low velocity layer. Although the effect of changing the depth of deeper interfaces is not great, it is noticable.

Table 2

Model No.					L1 H km	L2 H km	L3 H km	L4 H km	L5 H km	L6 H km
Layer	V_p Km/sec	V_s km/s	ρ gm/cm^3	Q						
1	6.2	3.57	2.6	10^3	45	35	35	35	35	35
2	8.0	4.5	3.28	10^3	45	50	55	55	55	55
3	8.3	4.75	3.4	10^3	40	45	60	40	40	40
4	7.5	4.00	3.09	10^2	50	50	30	30	50	50
5	8.5	4.65	3.47	$8.x10^2$	220	220	220	240	270	270
6	9.7	5.4	3.93	$8.x10^2$	250	250	250	250	200	180
7	11.0	6.15	4.42	10^3	-	-	-	-	-	-

Comparison of Observed Ratios with Several Models:

Figures 6 through 12 show a comparison of ratio spectra for site E_3 for 7 events with different ranges. Also shown in these figures is the average ratio spectra, which as noted above probably has little physical significance, as well as the observed and theoretical seismograms and the vertical and horizontal amplitude spectra for site E_3. Naturally, it is agreement between the ratio spectra that we are seeking since the unknown source functions in the data should not affect the ratios. A description of the models used is given in Table 3.

As may be seen in Table 3, the hypothetical earth has been approximated by a rather small number of constant velocity layers. This is used as a first approximation on the assumption that the secondary portion of the seismogram will depend mostly on waves generated by the more abrupt and strong changes in velocity.

Model 1 is rather extreme in that a low velocity layer with very low velocities and Q values has been used. The high acoustic impedance of this low velocity zone generates secondary waves with significant amplitudes. Model 2 is different from Model 1 in that the velocities of the low velocity zone are not as severe. Model 3 is an approximation to Johnson's (1967) velocity depth function. Models 4 and 5 involve only a one layer and two layer crust to show the marked effect of layering in the mantle on the spectral ratios.

In general, S velocities were extropolated from or obtained from the results of Kovach and Robinson 1969. Densities were obtained using Birch's 1964 relationship between density and P velocity $\rho = 0.252 + 0.3788\ V_p$.

Table 3

Layer	V_p Km/sec	V_s Km/sec	ρ gm/cm^3	Q	Thickness Km
Model 1					
1	6.2	3.57	2.6	1000	35
2	8.0	4.5	3.28	1000	55
3	8.3	4.75	3.4	1000	40
4	5.0	3.0	2.15	10	30
5	8.5	4.65	3.47	800	240
6	9.7	5.4	3.93	800	250
7	11.0	6.15	4.42	1000	[illegible]
Model 2					
1	6.2	3.57	2.6	1000	35
2	8.0	4.5	3.28	1000	55
3	8.3	4.75	3.4	1000	40
4	7.5	4.0	3.09	100	50
5	8.5	4.65	3.47	800	220
6	9.7	5.4	3.93	800	250
7	11.0	6.15	4.4	1000	[illegible]
Model 3					
1	6.2	3.57	2.6	1000	35
2	8.05	4.54	3.3	1000	40
3	7.95	4.40	3.26	300	75
4	8.50	4.65	3.47	800	250
5	9.70	5.40	3.93	800	250
6	11.00	6.15	4.42	1000	[illegible]
Model 4					
1	4.0	2.5	1.77	500	4.0
2	6.2	3.57	2.60	1000	40.0
3	8.0	4.50	3.28	1000	[illegible]
Model 4					
1	6.2	3.57	2.6	1000	40.0
2	8.0	4.5	3.28	1000	[illegible]

In comparing the theoretical and observed spectral ratios one is reassured by the spectral ratios that the earth does not have velocity discontinuities only at the crust mantle boundary. This may be seen in Fig. 6 by comparing models 4 and 5 with the ratios for the E_3 site. Also in this figure, as in figures 7 through 12, one will note the strong difference between the average ratio, the average being over the LASA sites, and the E_3 site. As pointed out above, this is probably the result of averaging over sites with variable crustal thickness and there may also be a small contribution from instrumental differences.

As Phinney 1964 has pointed out, the crust, because of its small thickness compared to wavelengths in the 0.0 to 0.2 Hz range, produces relatively smoothly varying ratio spectra wheras the deeper thicker layers are responsible for the rapid oscillations in the ratio. This, of course, suggests that by smoothing the ratio spectra at each site one should be able to detect changes in crustal thickness over the LASA array. This has not been attempted in this study and, prior to such an analysis, it is suggested that simulation studies be performed to see how thin deeper layers in the mantle distort the contribution to the ratio from the crust alone.

As will be seen for Table 1, all the events except for No. 9 are incident in the mantle to the east of the Rocky Mountains. One might expect this to result in a different model fitting the data for event No. 9. In addition to this exception, one will note that the signal to noise ratio for events 1, 3 and 7 is rather poor and will distort the ratio spectrum. As was noted above that an improvement may be obtained by averaging over events at constant ranges and azimuths. This leaves only events 2, 6 and 8 for which a meaningful comparison between models and data can be made as a function of angle of incidence and frequency. As can be seen from the appropriate the data very satisfactorily. However, these models are still the better fitting ones of many others tried, but not shown.

From the experience gained in this analysis, the following improvements and techniques are offered as an aid to fitting the data.

1. Since part of the fitting problem is due to separating crust and upper mantle effects, if it can be shown that smoothing the ratio spectra does not distort the crustal effects, the crust may then be solved for first (as Phinney, 1964 has done). In the specific case of LASA this could be done for each sub-array. If a satisfactory fit to the smooth variations is obtained, the crustal effects could be removed leaving one with the rapid variation in the ratio which could be ascribed to layering in the mantle.

2. In the present study relatively few constant velocity layers have been used which approximation neglects the P to S conversions which will result from gradient effects as the wavelength becomes relatively short. This could be partially overcome by including more layers to approximate the gradients.

Conclusions:

It has been shown using the method of truncated ratio spectra that models which include layering in the crust and upper mantle produce ratios which are at least as complicated as the observations. Although no satisfactory fit of a particular model to the data has been obtained at this stage, it is the author's judgement, based on experience gained in this study, that further detailed work in which attempts are made to separate crust and mantle effects should allow one to more systematically approach a solution. In the case of LASA it is clear that variations in crustal thickness are probably mainly responsible for the differences in the ratio spectra from site to site. Simulations of this effect in models suggests that averaging ratios from different sites to improve signal to noise ratio distorts the data to an intolerable level. It would be better to average over several events recorded at one site. Since a satisfactory model has not yet been obtained one of the goals of this study, the deconvolution of the seismogram with the receiver transfer function, must await an improvement in model fitting techniques. In addition, adequate calibration of all instruments would no doubt also improve the results.

FIGURE CAPTIONS

Figure 1. Ray diagram for a crust-mantle model with a low velocity zone. Distances are in degrees and the dotted line marking the base of the layered system is at a depth of 650 km. The wave front shows that the plane wave assumption is reasonable at these distances.

Figure 2. Record section showing the events used and the time separation of P, PcP and PP as given by Herrin et al. (1968).

Figure 3. Ratio spectra at 16 LASA sites together with the corresponding spectrum of the vertical motion for event No. 9. Note how variable the ratios are in spite of the similarity in the vertical spectra.

Figure 4. Comparison of truncated and non-truncated theoretical ratio spectra. The truncated seismograms have also been filtered by multiplication in the frequency domain by a function similar to the LASA system response. Note that the position of the peaks and troughs in the ratios is litte changed by truncation although the amplitude of the ratio is.

Figure 5. Comparison of models which differ only in the thickness of one or two layers. The models are given in Table 2. Note the large difference between the ratios for L1 and L2 which differ mainly in crustal thickness.

Figure 6. Comparison of models with the ratio spectrum at the E_3 site for event No. 9. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 7. Comparison of models with the ratio spectrum at the E_3 site for event No. 8. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 8. Comparison of models with the ratio spectrum at the E_3 site for event No. 7. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 9. Comparison of models with the ratio spectrum at the E_3 site for event No. 6. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 10. Comparison of models with the ratio spectrum at the E_3 site for event No. 3. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 11. Comparison of models with the ratio spectrum at the E_3 site for event No. 2. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

Figure 12. Comparison of models with the ratio spectrum at the E_3 site for event No. 1. The vertical and horizontal spectrum at E_3 and the average ratio spectrum are also shown.

REFERENCES

Birch F., "Density and composition of the mantle and core," *J. Geophys. Res., 69*, 4377-4387, 1964.

Green, R. W. E. and A. L. Hales, "The travel times of P waves to 30° in the central United States and upper mantle structure," *Bull. Seism. Soc. Am., 58*, 267-290, 1968.

Haksell, Norman A., "Crustal reflection of plane P and SV waves," *J. Geophys. Res., 67*, 4751-4767, 1962.

Herrin, E., W. Tucker, J. N. Taggart, D. W. Gordon and J. L. Lobdell, "Estimation of surface focus P travel times," *Bull, Seism. Soc. Am., 58*, 1273-1325, 1968.

Johnson, L. R., "Array measurements of P velocities in the lower mantle," *Bull. Seis. Soc. Am., 59*, 973-1008, 1969.

Johnson, L. R., "Array measurements of P velocities in the upper mantle," *J. Geophys. Res. 72*, 6309-6325, 1967.

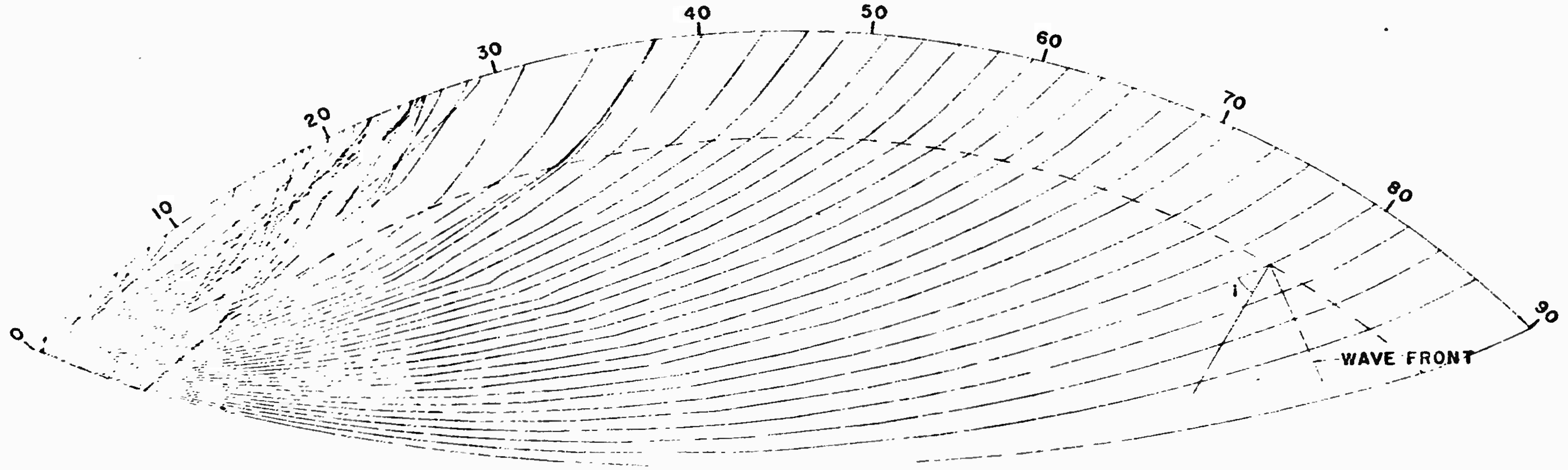
Kovach, Robert L. and Russel Robinson, "Upper mantle structure in the basin and range province, western North America, from the apparent velocities of S waves," *Bull. Seis. Soc. Am., 59*, No. 4., 1653-1666, 1969.

Leblanc, Gabriel, S. J., "Truncated crustal transfer functions and fine crustal structure determination, " *Bull. Seis. Soc. Am., 57*, 719-747, 1967.

McCamy, Keith, "An investigation and application of the crustal transfer ratio as a diagnostic for explosion seismology," *Bull. Seis. Soc. Am., 57*, 1409-1428, 1967.

Phinney, Robert A., "Structure of the earth's crust from spectral behavior of long period body waves," J. Geophys. Res. 69, 2997-3018, 1964.

Sheppard, R. M. and R. J. Greenfield, "The Mohorovicic depth variations under the LASA and their effect on dt/dΔ measurements," Bull. Seism. Soc. Am., 59, 409-420, 1969,


0
10
20
30
40
50
60
70
80
90
WAVE FRONT

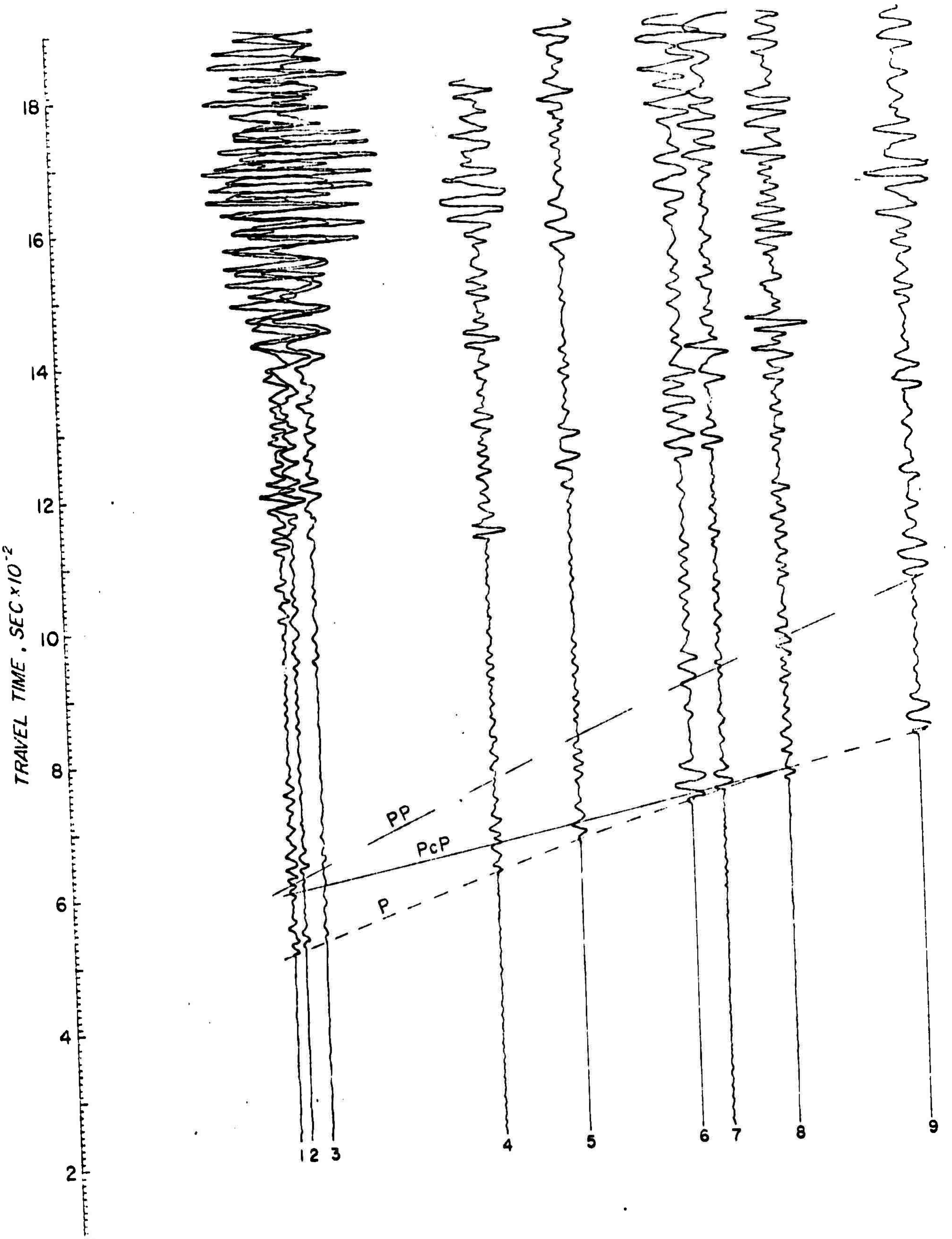

TRAVEL TIME, SEC ×10⁻²
0
2
4
6
8
10
12
14
16
18
30
40
50
60
70
80
90
DISTANCE, DEGREES
PP
PcP
P
1
2
3
4
5
6
7
8
9

Figure 2.

AMPLITUDE AND RATIO SPECTRA FOR 16 LASA SITES FROM EVENT NO. 9

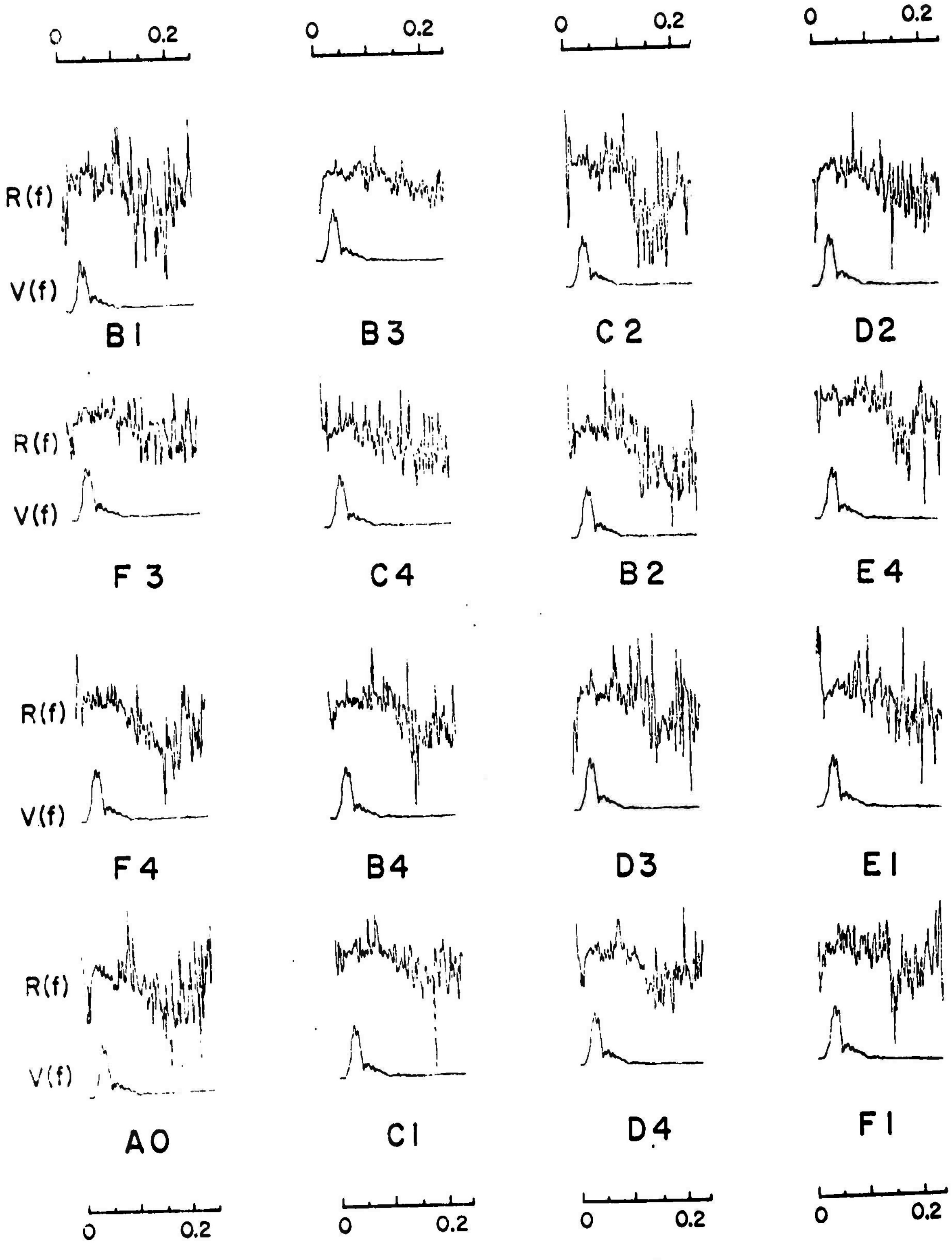


Figure 3.

COMPARISON OF SPECTRAL RATIOS FROM TRUNCATED AND NON-TRUNCATED THEORETICAL SEISMOGRAMS

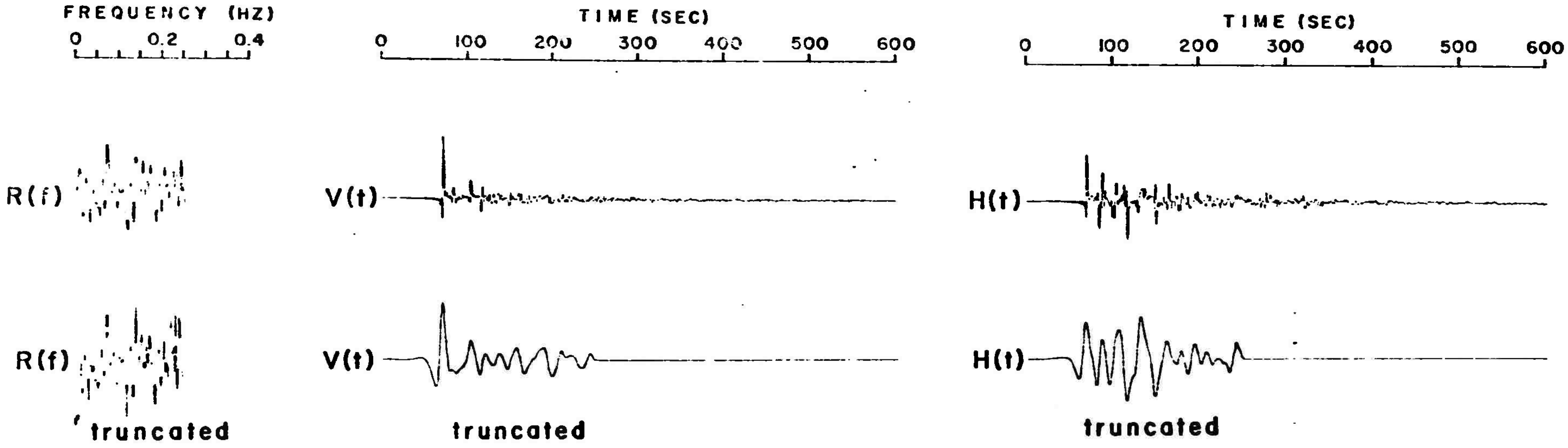


Figure 4.

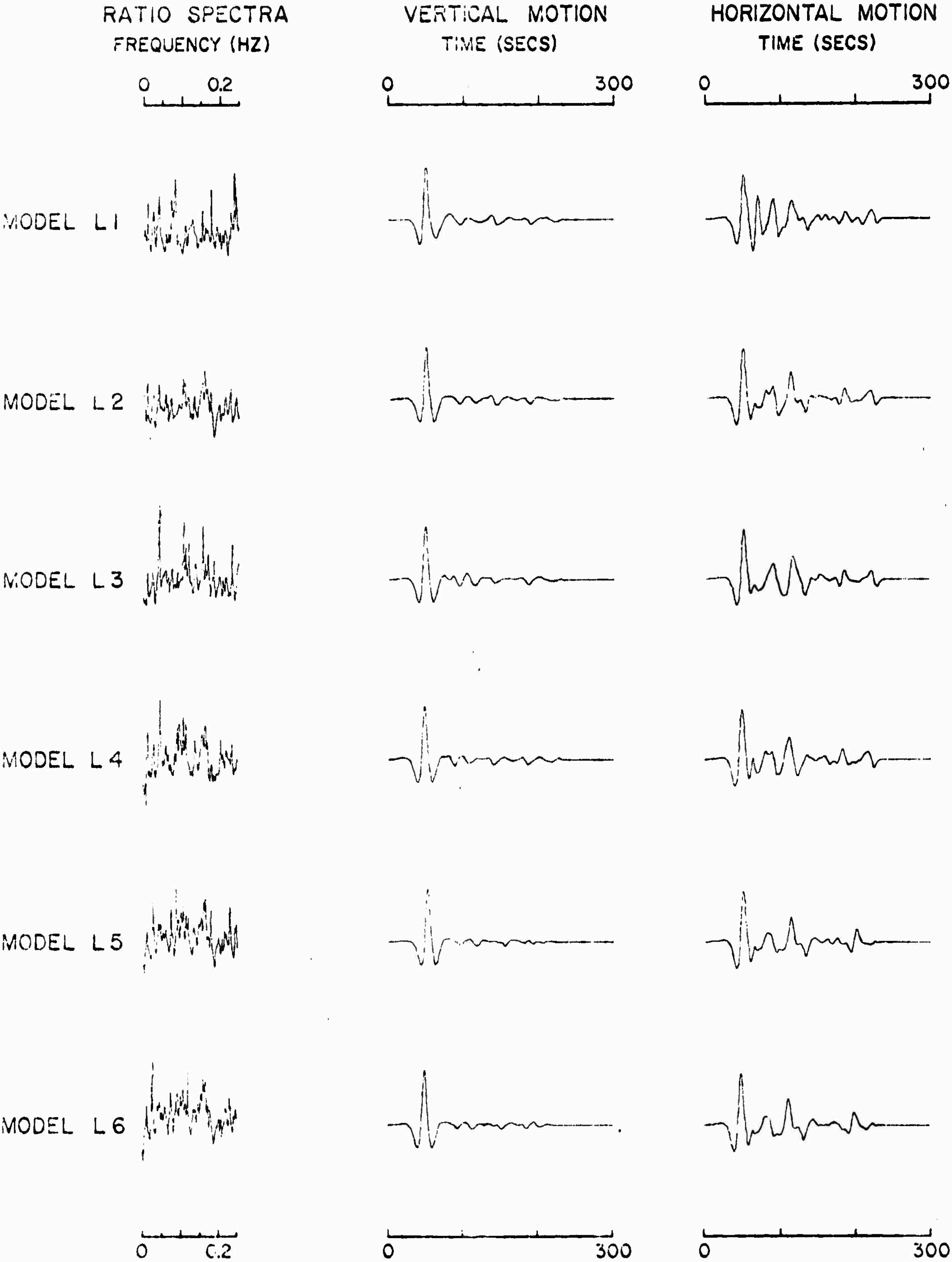

RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
VERTICAL MOTION
TIME (SECS)
0
300
HORIZONTAL MOTION
TIME (SECS)
0
300
MODEL L1
MODEL L2
MODEL L3
MODEL L4
MODEL L5
MODEL L6
0
0.2
0
300
0
300

Figure 5

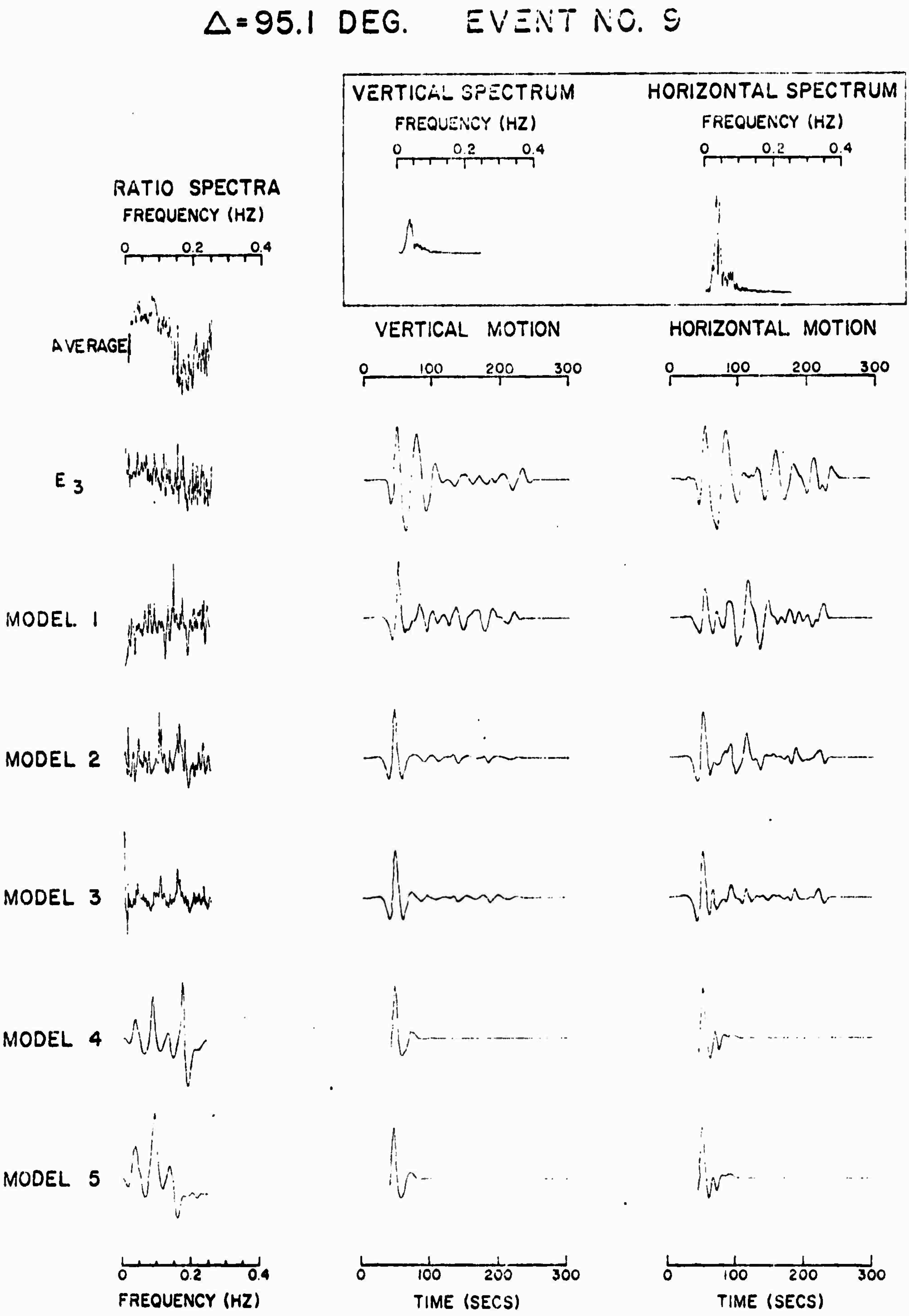

Δ=95.1 DEG. EVENT NO. 9
VERTICAL SPECTRUM
FREQUENCY (HZ)
0 0.2 0.4
HORIZONTAL SPECTRUM
FREQUENCY (HZ)
0 0.2 0.4
RATIO SPECTRA
FREQUENCY (HZ)
0 0.2 0.4
VERTICAL MOTION
0 100 200 300
HORIZONTAL MOTION
0 100 200 300
AVERAGE
E 3
MODEL 1
MODEL 2
MODEL 3
MODEL 4
MODEL 5
0 0.2 0.4
FREQUENCY (HZ)
0 100 200 300
TIME (SECS)
0 100 200 300
TIME (SECS)

Figure 6.

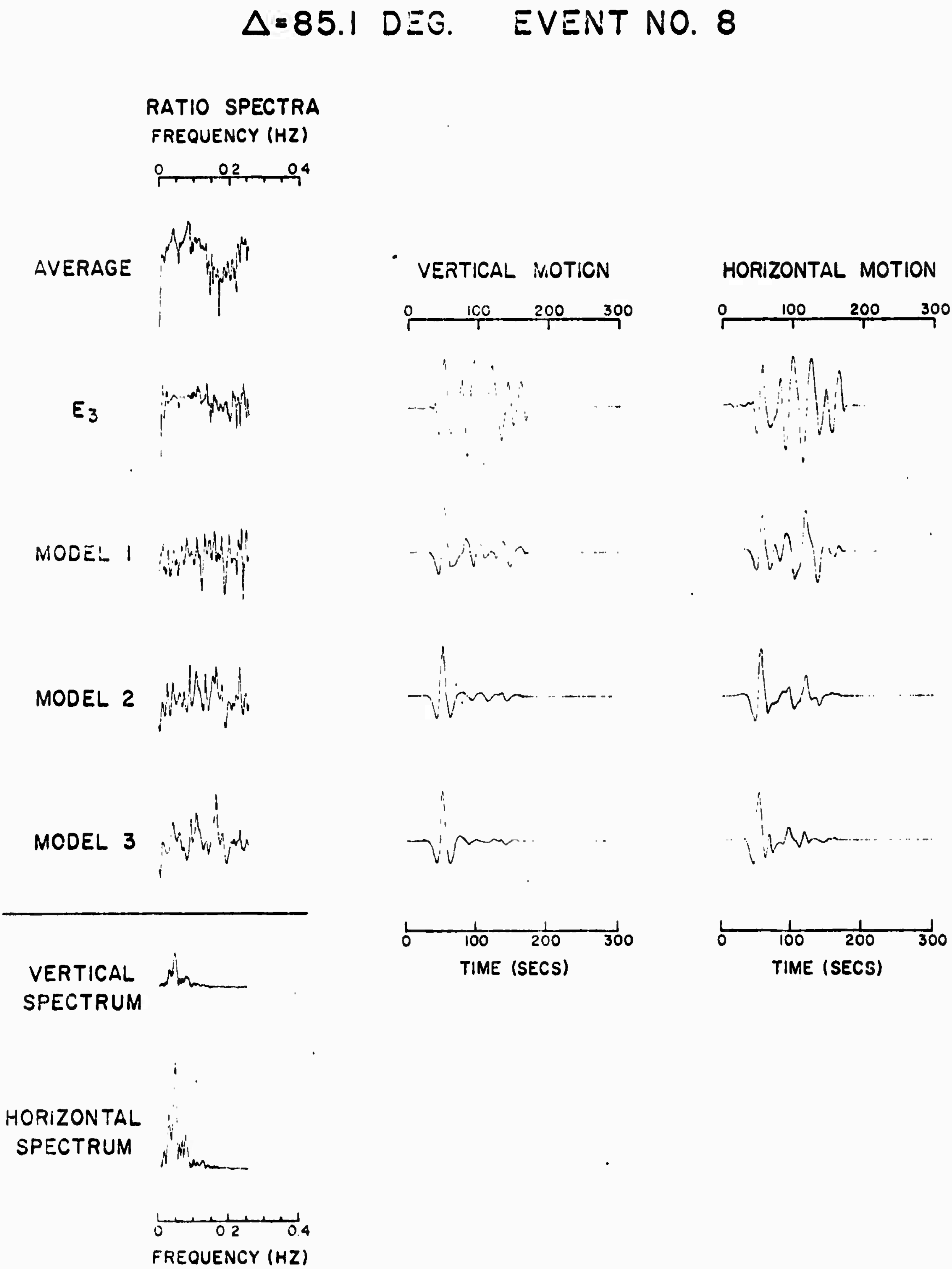

Δ=85.1 DEG. EVENT NO. 8
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E_3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
HORIZONTAL MOTION
0
100
200
300
0
100
200
300
TIME (SECS)
0
100
200
300
TIME (SECS)

Figure 7.

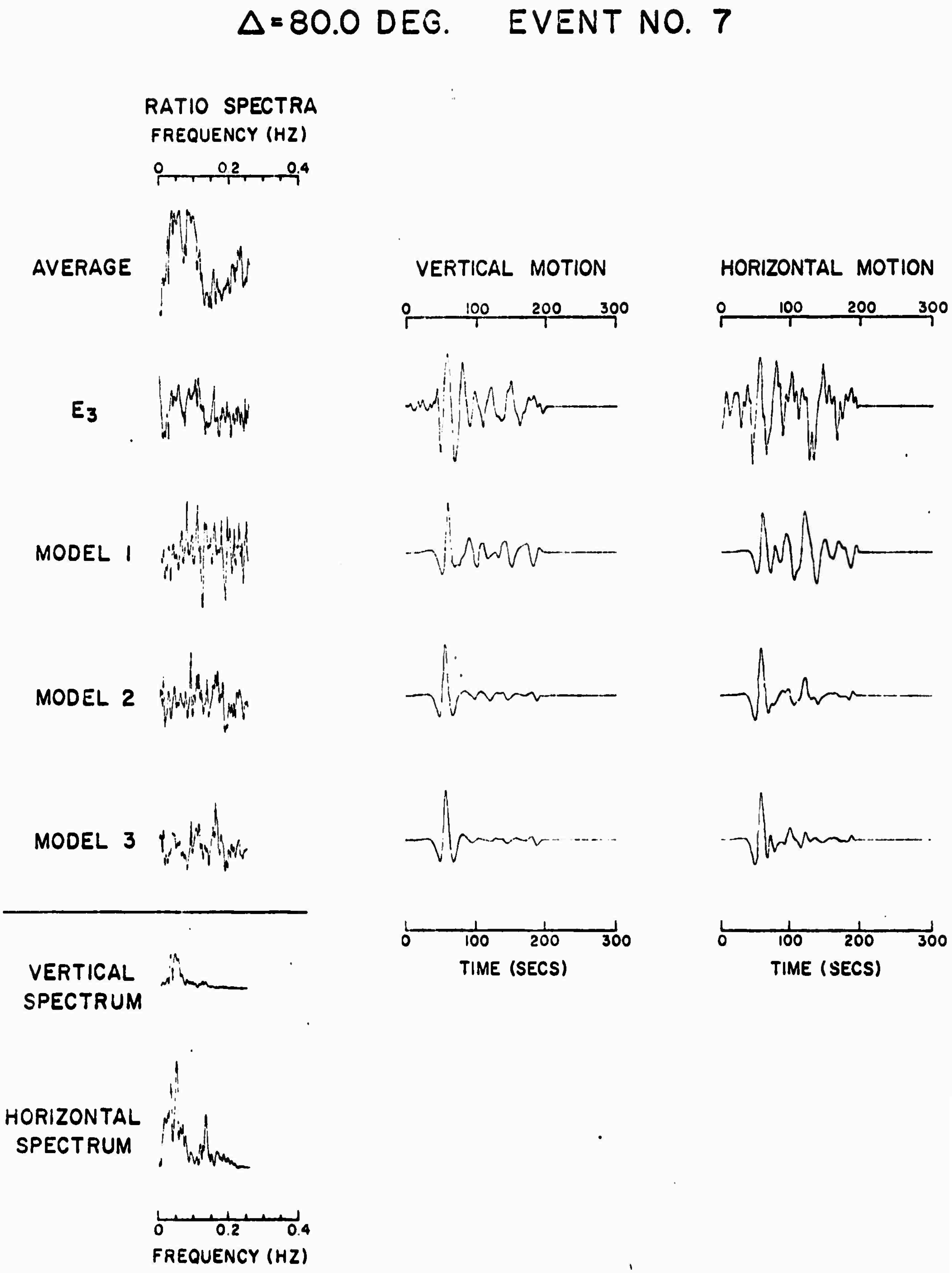

Δ=80.0 DEG.
EVENT NO. 7
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
0
100
200
300
TIME (SECS)
HORIZONTAL MOTION
0
100
200
300
0
100
200
300
TIME (SECS)

Figure 8.

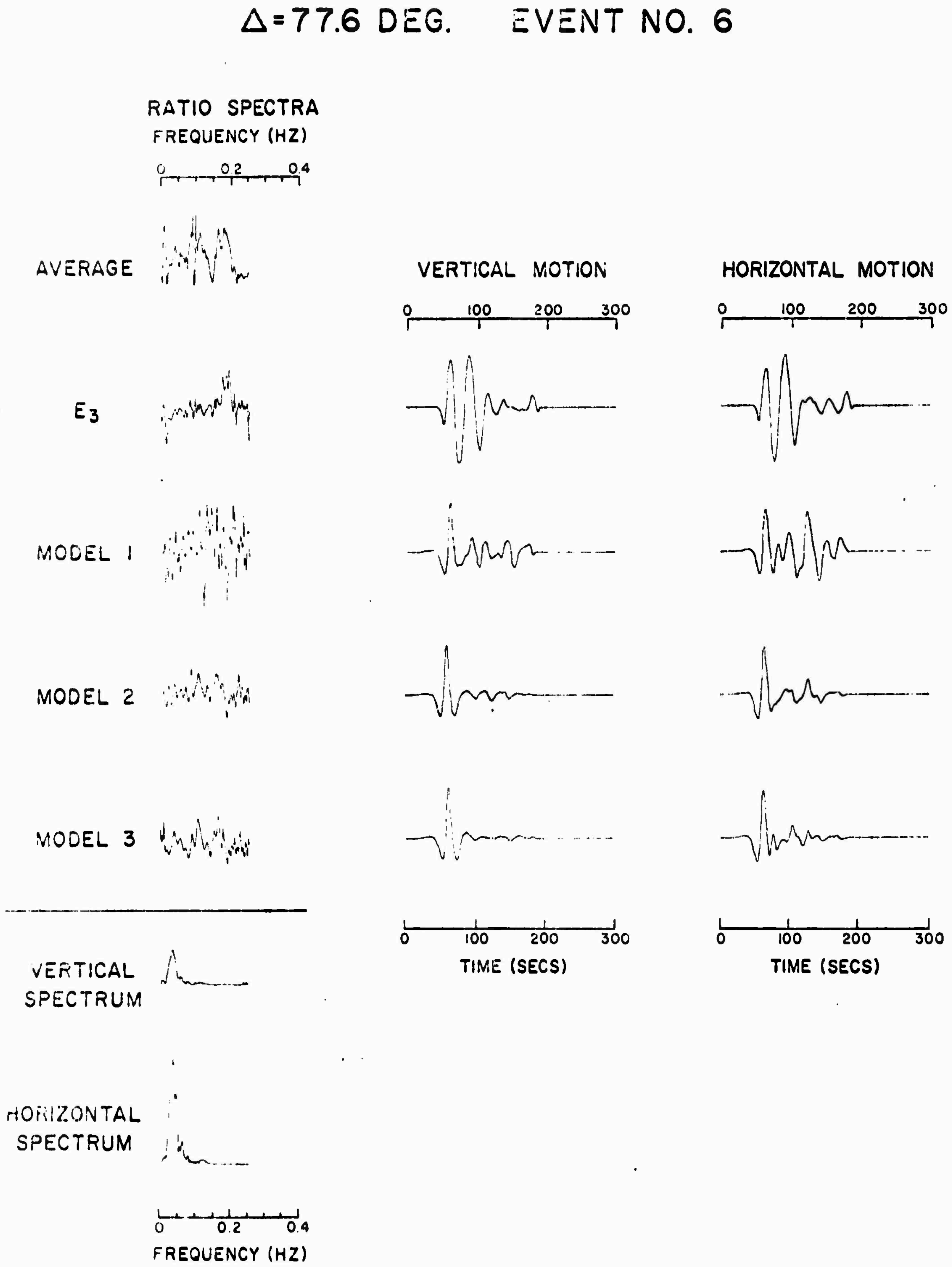

Δ=77.6 DEG. EVENT NO. 6
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
TIME (SECS)
HORIZONTAL MOTION
0
100
200
300
TIME (SECS)

Figure 9.

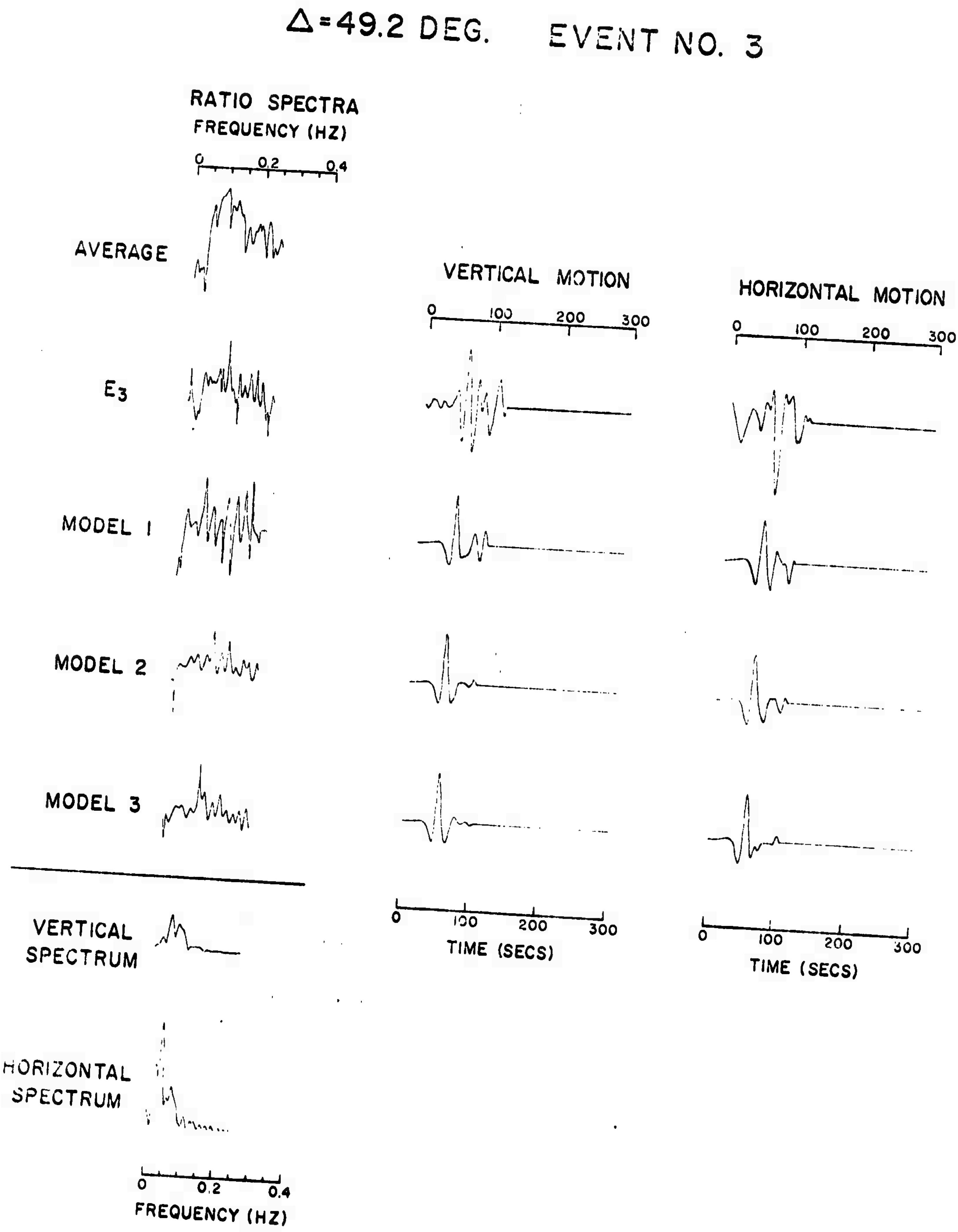

Δ=49.2 DEG.
EVENT NO. 3
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
0
100
200
300
TIME (SECS)
HORIZONTAL MOTION
0
100
200
300
0
100
200
300
TIME (SECS)

Figure 10.

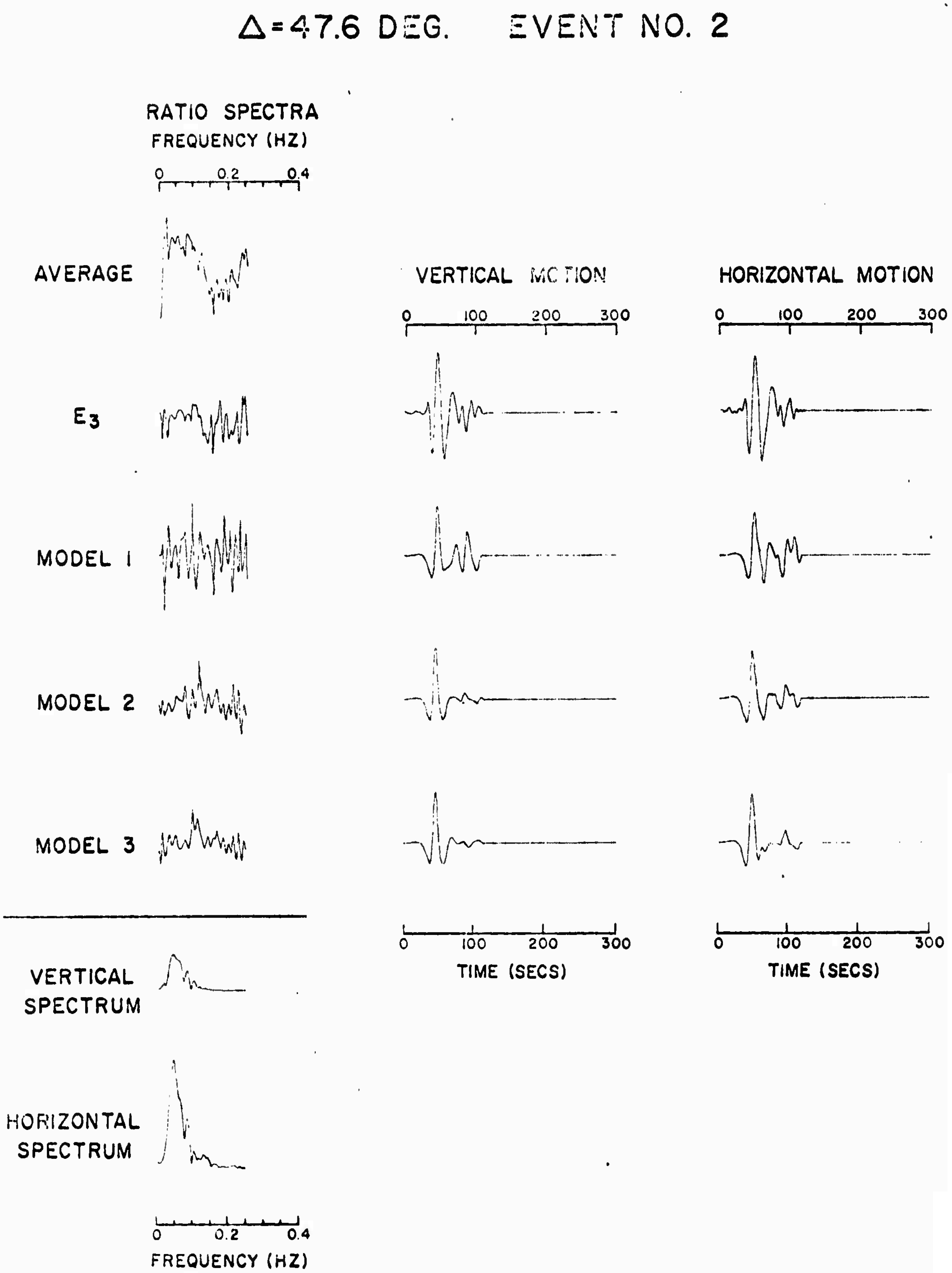

Δ=47.6 DEG.
EVENT NO. 2
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
TIME (SECS)
HORIZONTAL MOTION
0
100
200
300
TIME (SECS)

Figure 11.

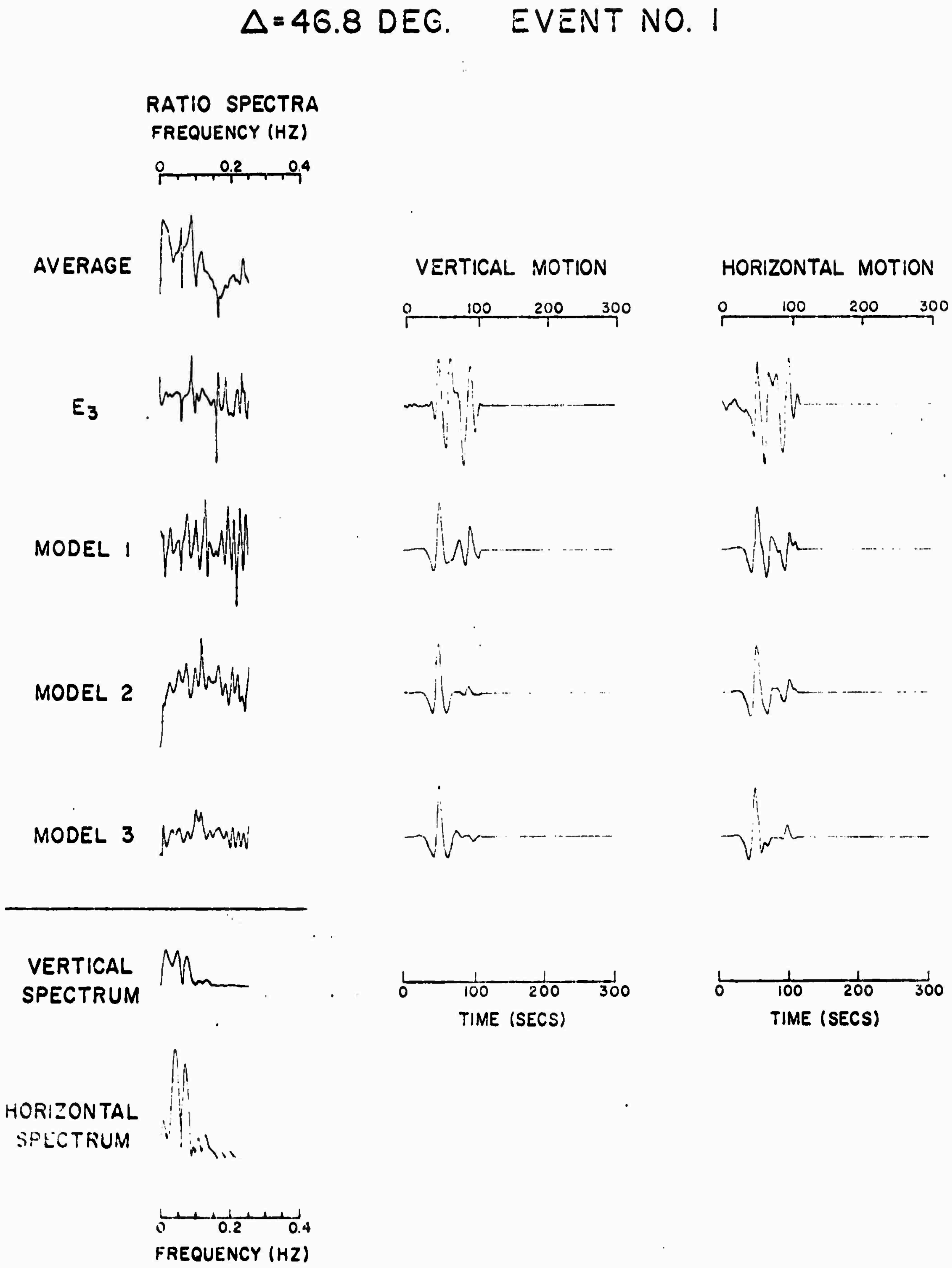

Δ=46.8 DEG.
EVENT NO. I
RATIO SPECTRA
FREQUENCY (HZ)
0
0.2
0.4
AVERAGE
E_3
MODEL 1
MODEL 2
MODEL 3
VERTICAL SPECTRUM
HORIZONTAL SPECTRUM
0
0.2
0.4
FREQUENCY (HZ)
VERTICAL MOTION
0
100
200
300
TIME (SECS)
HORIZONTAL MOTION
0
100
200
300
TIME (SECS)

Figure 12.

Report

Crust and Upper Mantle Structure near LASA

Introduction

During August, 1969, a series of shots fired in Greenbush Lake, British Columbia, Canada, were recorded by the University of Wisconsin along a line roughly following the axis of the Rocky Mountains from the United States-Mexico border in the south to Alaska in the north (Fig. 1).

Of the twenty shots scheduled for the experiment (code-named EDZOE), two were complete misfires, eleven were partial detonations, and the remainder fired successfully. Fortunately, the misfires and partial detonations occurred when our recording stations were closest to the shot point; seismic energy was recorded to approximately 2300 km. from Greenbush Lake, though a low signal/noise ratio was observed throughout the experiment.

Recordings of seismic data were made by three trucks equipped with seven element linear arrays (five vertical and two horizontal geophones) and five three-component portable stations (one vertical and two horizontal geophones) south of the shot point. North of Greenbush Lake, three three-component stations were used. All geophones have a nominal resonance of 1 hz.

Of the 198 possible records for EDZOE, approximately 120 were digitized for computer manipulation; this phase of the program has been completed. Record sections over various reducing velocities and with various frequency filters have been made for the southern end of our line (i.e., for data taken south of the shot point). The changeover from CDC-3600 to Univac 1108 computer programs to make record sections for data gathered north of the shot point is now being completed. (See request for no-cost extension.)

Crust Mantle Structure

A ray-trace computer program is being used to develop a crust-mantle model which fits data from the "southern line". To date, no model which fits both the arrival times and amplitudes of the data except for that from the crust and extreme upper mantle has been found; in particular, models proposed by Johnson (1967) and Archambeau et al. (1969) for this region are not satisfied by the data (Fig. 2). We must then restrict ourselves to preliminary observations of the structure.

For the single-ended southern profile (Fig. 2), the data support a mean apparent crustal velocity of 6.0 km/sec., with a thickness of approximately 32 km. The M-discontinuity is defined by an apparent velocity of 7.9 km/sec. at that depth. The record section indicates the 7.9 km/sec refractor is thin, (on the order of a few tenths of kilometers), and directly overlies a refracting horizon with an apparent velocity of 8.1 km/sec. Arrivals from the 8.1 km/sec refractor demonstrate an abrupt attenuation in amplitude at approximately 1000 km/ range, and immediately following an offset of one-half second in that branch of the travel-time curve defined by these arrivals; this behavior is suggestive of a lateral velocity discontinuity just below the M-discontinuity. (Fig. 3)

Greenfield and Sheppard (1969) report time residuals for sources NW of LASA of the same order of magnitude over a comparable aperature. They interprete these delays as the result of structure at the crust-mantle interface. Their model of the crust-mantle structure across LASA is simply a single layer crust with a compressional wave velocity of 6.0 km/sec overlying the mantle which has a p-wave velocity of 8.0 km/sec.

Though this two layer model does predict time residuals for sources NW of LASA, it fails on two counts. First, the predicted gravity anomoly for their structure does not fit the observed Bouguer anomoly values. Second, the truncated ratio spectra study (included in this report) shows that a single-layered crust and mantle cannot have a spectra ratio of sufficient complexity.

The 7.9 km/sec, 8.1 km/sec "double M-discontinuity" resolved by the EDZOE data would require a "larger" structure to explain the time delay, but the significant reduction in density contrast could be the key to satisfying the small gravity anomoly observed, while at the same time adding the complexity necessary to satisfy the observed ratio spectra.

The hypothesized correlation between the time residuals for LASA and the time shift in the EDZOE data, requires a westward lateral interpolation of structure over several hundred kilometers. Some support for this may be had from the heat flow data for this region. A protrusion of the heat flow values normal to the mid-continent into the high heat flow defined, in part, by the northern and southern Rocky Mountains and the Basin and Range is at least spatially correlated with the seismic anomoly. (Blackwell, 1970)

Continuation of the analysis of the EDZOE data is, of course, a necessary prelude to the more detailed picture of the crust upper mantle structure we wish to make. In terms of LASA, it can be seen that a simplified picture will not suffice to satisfy either the ratio spectra observations or the observed gravity. Data gathered north of the shot point will provide a partial reverse of seismic data, and must also be considered in this process.

As part of this project, Dorman and Lewis (1970), developed an analytic solution to the problem of isostasy. From data for the United States, they (Lewis and Dorman, 1970) have derived an isostasy response function; this function, when convolved with topography, predicts the gravity field (to the extent that the isostasy response function is an accurate predictor). The velocity-constrast with depth between the EDZOE data (for a tectonically-active region) and the mid-continent (e.g., Green and Hales, 1968; and Lewis and Meyer, 1968) can be used to check the density-contrast with depth which Lewis and Dorman find reflects the process of isostasy.

References

Archambeau, C. B., E. A. Flinn, and D. G. Lambert, Fine structure of the upper mantle, J. Geophys. Res., 74, 5825-5866, 1969.

Blackwell, D., The thermal structure of the crust (abstract), ONR-CIRES Conference 1970.

Dorman, L. M., and B. T. R. Lewis, Experimental isostasy, 1, Theory of the determination of the earth's isostatic response to a concentrated load, J. Geophys. Res., 75, 3357-3365, 1970.

Green, R. W. E., and A. L. Hales, The travel times of P waves to 30° in the central United States and upper mantle structures, Bull. Seismol. Soc. Amer., 58, 267-290, 1968.

Greenfield, R. J., and R. M. Sheppard, Mohorovičić depth variations under LASA and their effect on dT/dΔ measurements, Bull. Seismol. Soc. Amer., 59, 409-420, 1969.

Lewis, Brian T. R., and Leroy M. Dorman, Experimental isostasy, 2, An isostatic model for the U.S.A. derived from gravity and topographic data, J. Geophys. Res., 75, 3367-3385, 1970.

Lewis, B. T. R., and R. P. Meyer, A seismic investigation of the upper-mantle structure to the west of Lake Superior, Bull. Seismol. Soc. Amer., 58, 565-596, 1968.

Johnson, L. R., Array measurements of P velocities in the upper mantle, J. Geophys. Res., 72, 6309-6325, 1967.

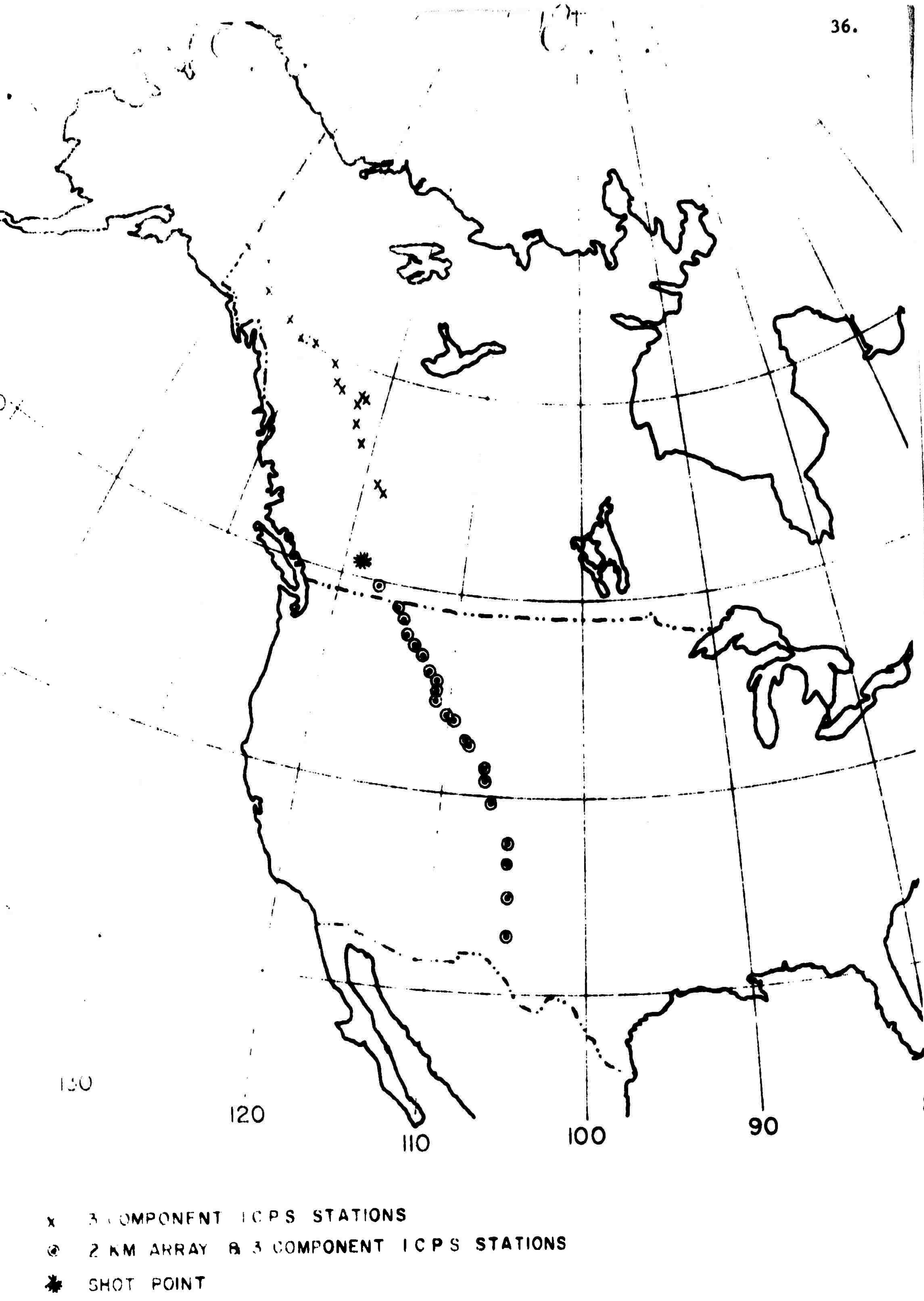

130
120
110
100
90
x 3 COMPONENT ICPS STATIONS
◎ 2 KM ARRAY & 3 COMPONENT ICPS STATIONS
✱ SHOT POINT

Figure 1.

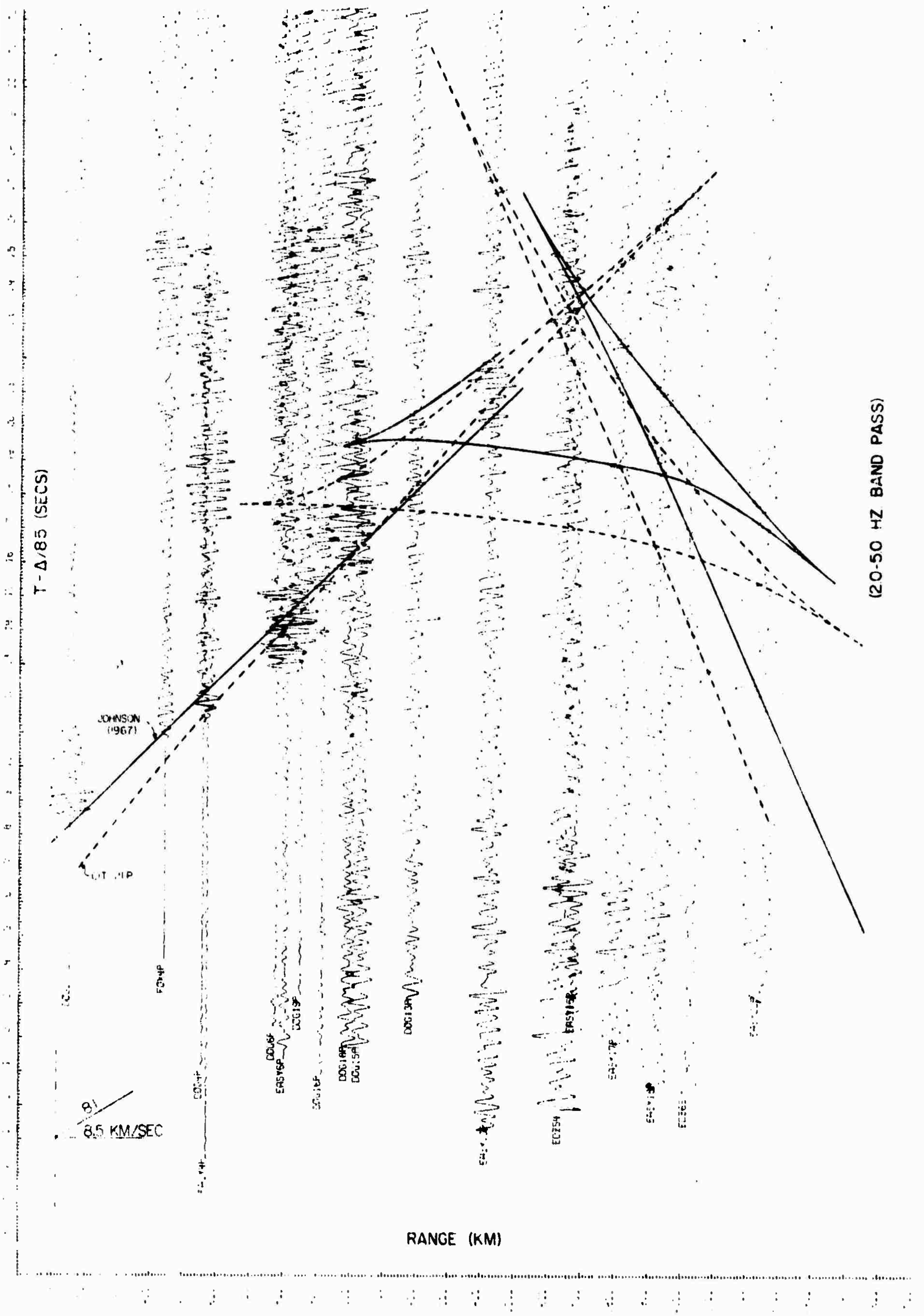

T-Δ/85 (SECS)
RANGE (KM)
(20-50 HZ BAND PASS)
JOHNSON (1967)
8.5 KM/SEC
8
DOG6P
EASY5P
DOG18P
DOG15P
DOG13P
EASY15P

Figure 2.

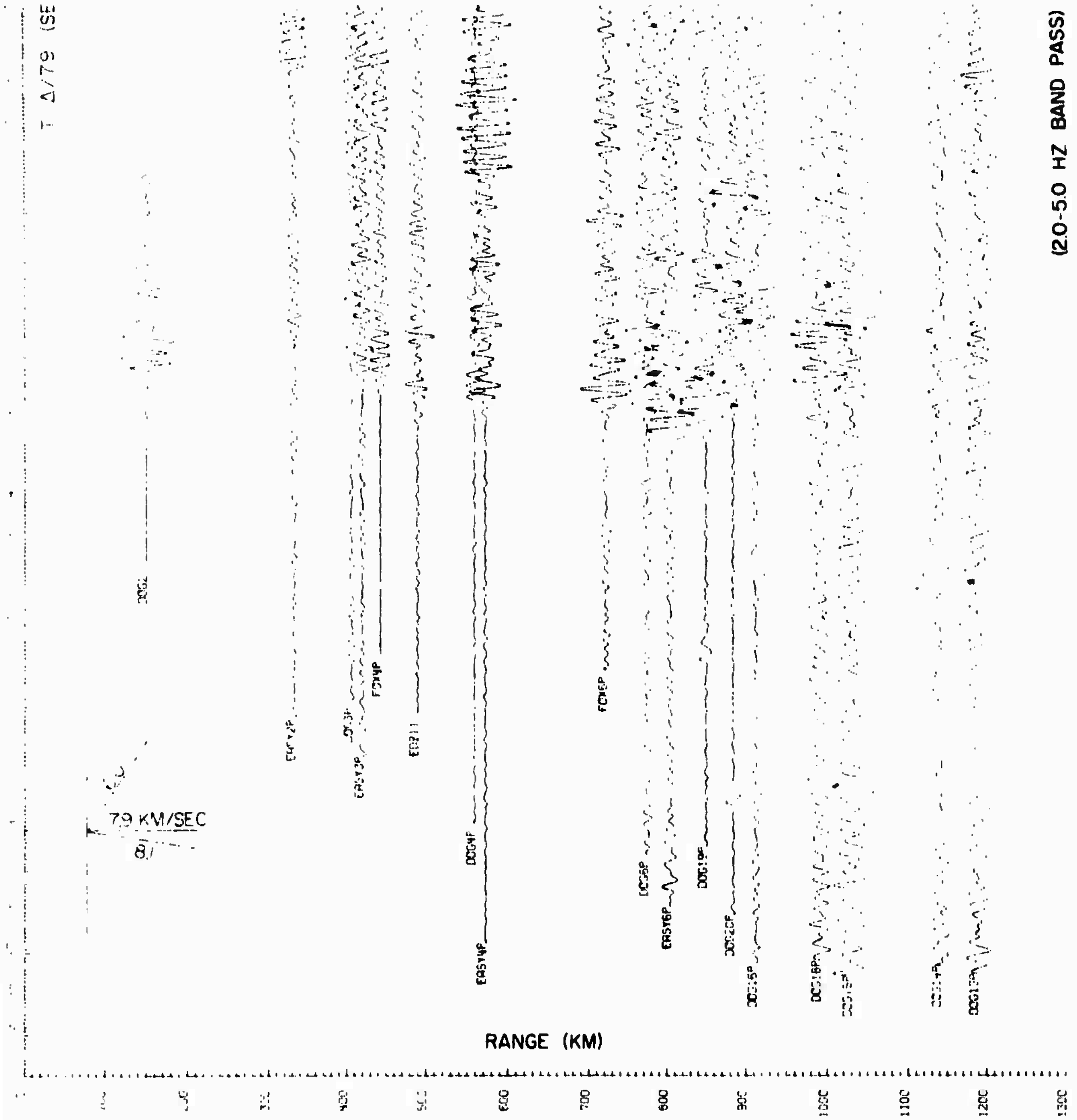

(2.0-5.0 HZ BAND PASS)
RANGE (KM)
7.9 KM/SEC
8.1
DCG2
FDY4P
DCG4P
ERSY4P
DCG5P
ERSY6P
DCG18P
DCG16PA
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300

Figure 3.