AN ARGUMENT FOR THE EXISTENCE OF A DECOLLEMENT BELOW STATION WTX

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SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR GEOPHYSICS 590
AND THE MASTER'S DEGREE PROGRAM

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY
SOCORRO, NEW MEXICO
MAY 1989

ACKNOWLEDGEMENTS

I would like to thank Dr. Sanford for providing the basic hypotheses and strategies required to bring this study to completion, and for sharing his excellent intuitive powers. I would like to thank the members of the Terminal Effects Research and Analysis Group, particularly David Emary, Senior Research Engineer, now with Battelle, for sponsering my research in 'Stress Distributions in Axisymmetric Projectiles with Applications to Lightweight Double Ramp Sabot/Penetrator Configurations', which indirectly funded my academic work. For his help and encouragement while I was an undergraduate, I would like to thank my undergraduate advisor, Dr. John Geissman, whose last and most sound bit of advice I failed to heed.

ABSTRACT

Several seismograms recorded at station WTX include an anomalous low frequency waveform which can reasonably be modeled as a product of constructive interference between multiples in a surface layer with flat, parallel boundaries and constant thickness. Because no simple compositional layer is known to exist under station WTX, it is suggested that the surface layer consists of various types of materials, pervasively fractured, which are separated from underlying, competent rock by a decollement. The approximate depth to the decollement is calculated using the time lag between the direct P wave and the direct S wave, the time lag between the direct P wave and the low frequency phase (assumed to be an S wave multiple), an approximate hypocenter location, and the velocities of the surface layer and underlying layer.

INTRODUCTION

An anomalous low frequency waveform occurs on the records of station WTX for each of twelve earthquakes occurring in a swarm that happened in August 1977. The arrival time of the low frequency waveform is typically three seconds after the first arrival and lasts about seven tenths of a second (see Figure 1 and Appendix I). The frequency content of the low frequency waveform is similar to that of the direct shear wave, except that the low frequency waveform lacks significant contributions from frequencies above seven hertz (see Figure 1). This suggests that the low frequency waveform may be the shear wave whose raypath includes a multiple reflection through a highly attenuative surface layer that is known to exist under station WTX (Carpenter and Sanford, 1985). Autocorrelation of the full seismogram gives a significant negative correlation approximately one tenth of a second after full correlation, but does not give a correlation with the low frequency wave, which follows the direct shear wave by about one second (see Figures 1 and 2). However, correlation of the direct shear wave with the seismogram, after both are filtered with a seven hertz low pass filter, does give a correlation with a one second lag time (see Figure 2). This further suggests that the low frequency waveform is a multiple.

The August 1977 swarm is a member of a group of swarms that occurred in 1977, each of which had approximately the same location. The location of the swarms are known to be approximately 34 01'N 107 03'W at focal depths of approximately 9.8 kilometers, which is about 14 kilometers from station WTX along a line approximately 45 degrees from horizontal and to the southwest.

The purpose of this study was to determine the surface layer thickness from the time lag between the direct P wave and the direct S wave, the time lag between the direct P wave and the low frequency phase (assumed to be an S wave multiple), an approximate hypocenter location, and the velocities of the surface layer and underlying layer.

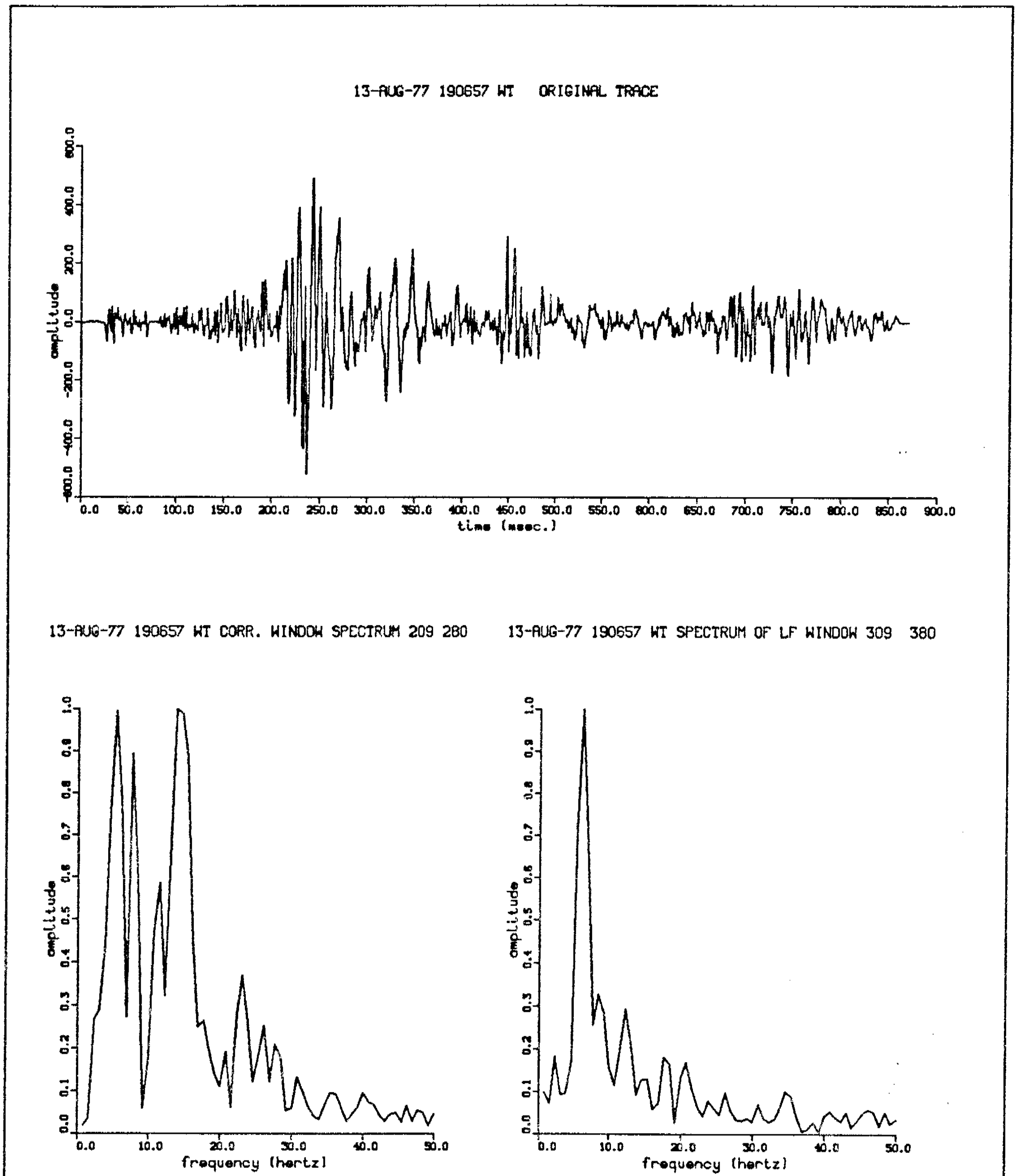


Figure 1: Original seismogram (top). Amplitude spectrum of direct shear wave (lower left). Amplitude spectrum of low frequency waveform (lower right).

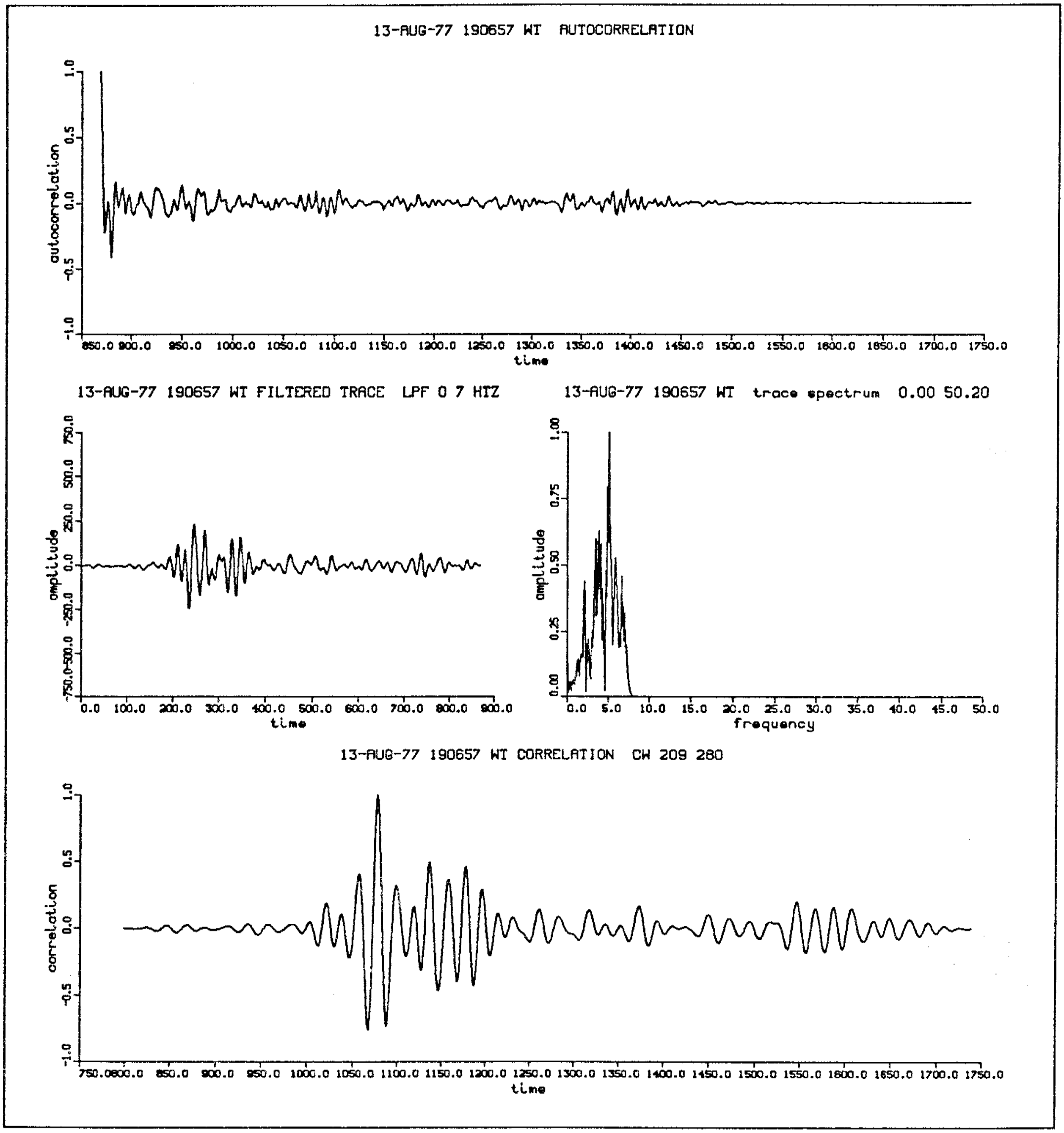


Figure 2: Autocorrelation of original seismogram (top). Seismogram filtered with seven hertz low pass filter (middle left). Frequency spectrum of filtered seismogram (middle right). Correlation of filtered shear wave with filtered seismogram (bottom).

BASIS OF TECHNIQUE

The distance from the recording station to the hypocenter is given by the law of cosines (see Figure 3 and Figure 4).

$$R^2 = R_1^2 + R_2^2 - 2R_1R_2\cos\{\pi + \theta_1 - \theta_2\} . \quad (1)$$

The angles of refraction at the lower boundary of the layer are related by Snell's Law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{V_1}{V_2} , \quad (2)$$

If the shear wave velocity is related to the P wave velocity by ,
the difference between the travel times of the P and S waves is

$$\Delta T_{SP} = \frac{\sqrt{3}}{V_2}R_2 + \frac{\sqrt{3}}{V_1}R_1 - \left\{\frac{R_2}{V_2} + \frac{R_1}{V_1}\right\} . \quad (3)$$

From equation (3)

$$R_2 = V_2\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1} - \frac{R_1}{V_1}\right\} . \quad (4)$$

From equation (2)

$$\theta_2 = \sin^{-1}\left\{\frac{V_2}{V_1}\sin\theta_1\right\} \quad (5)$$

Substitution of equations (4) and (5) into equation (1) gives the distance to the hypocenter as a function of R1 and theta 1, the S–P interval, and the velocities V1 and V2,

$$R^2 = R_1^2 + \left\{\frac{\Delta T_{SP}}{\sqrt{3}-1} - \frac{R_1}{V_1}\right\}^2 V_2^2 + 2R_1V_2\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1} - \frac{R_1}{V_1}\right\}\cos\left\{\theta_1 - \sin^{-1}\left\{\frac{V_2}{V_1}\sin\theta_1\right\}\right\} . \quad (6)$$

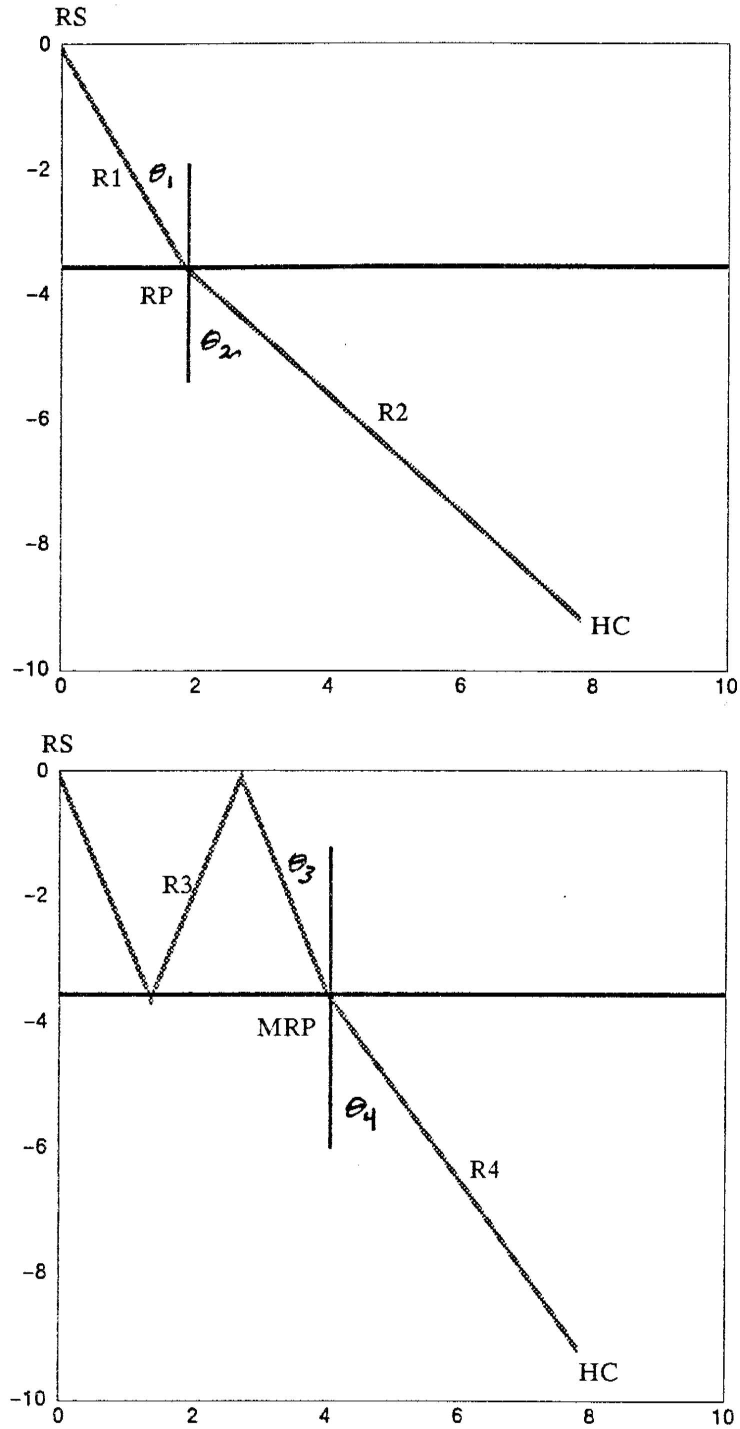


Figure 3: Typical raypaths. Bold horizontal line represents bottom of surface layer. RP signifies the refraction point of the direct ray. MRP signifies the refraction point of the multiple ray. RS signifies the recording station. HC signifies the hypocenter. Top: Direct raypath. R1 is the distance from the recording station to the refraction point. R2 is the distance from the refraction point to the hypocenter. Theta 1 is the angle of R1 from vertical. Theta 2 is the angle of R2 from vertical. Bottom: Multiple raypath. R3 is the total length of the three segments of the multiple path between the recording station and the refraction point. R4 is the distance between the refraction point and the hypocenter. Theta 3 is the angle of R3 from vertical. Theta 4 is the angle of R4 from the vertical. V1, V2, V3, and V4 are the velocities along segments R1, R2, R3, and R4 respectively.

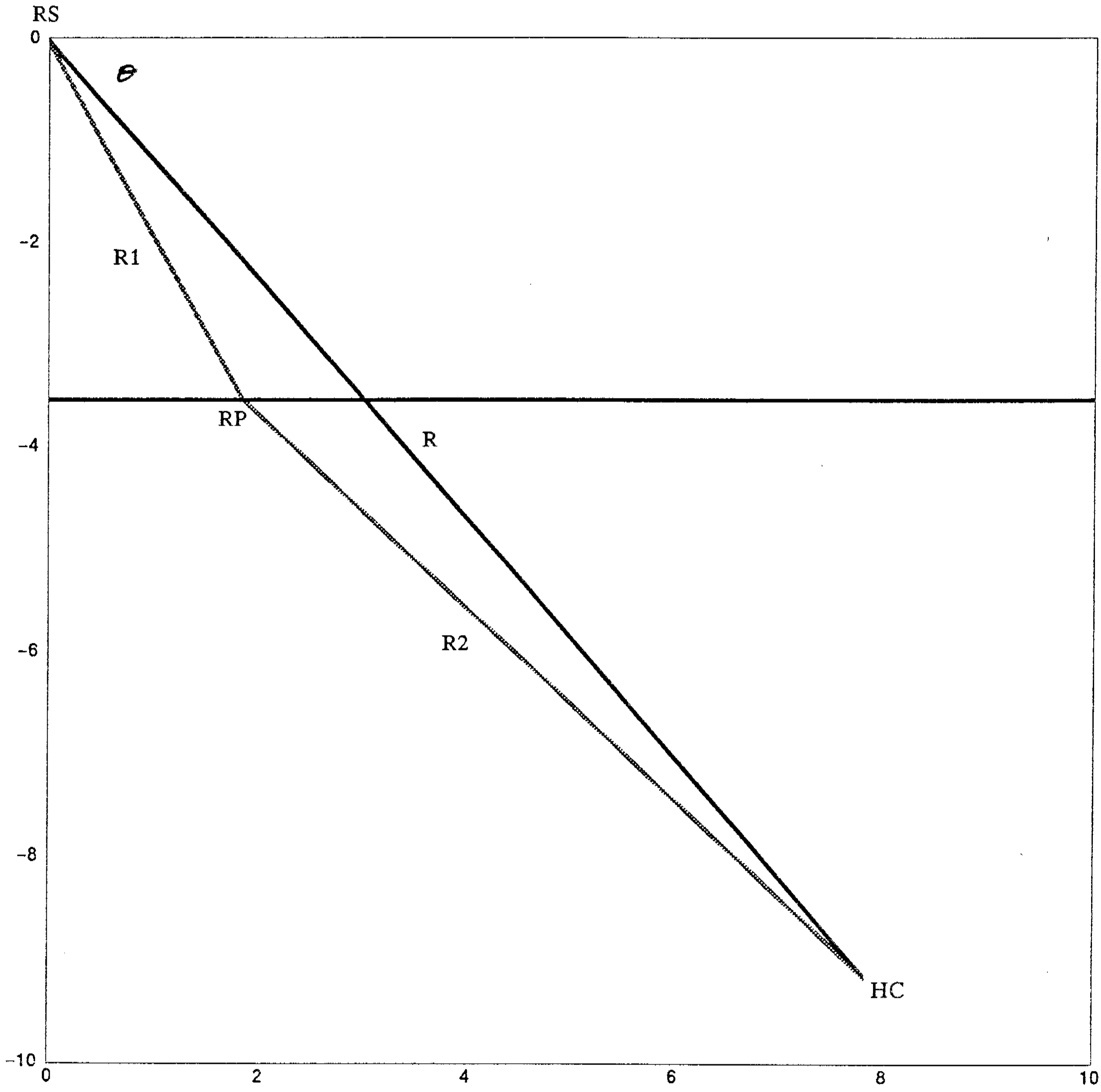


Figure 4: Hypocenter location vector. R signifies the hypocenter location vector. The magnitude of R is the distance along a straight line between the recording station and the hypocenter. The direction of R, theta, is the acute angle between R and the horizontal axis. The magnitude of R is related to R1, R2, theta 1, and theta 2 by the Law of Cosines.

The angle of the hypocenter from the horizontal axis is given by

$$\theta = \tan^{-1}\left\{\frac{R_1\cos\theta_1 + R_2\cos\theta_2}{R_1\sin\theta_1 + R_2\sin\theta_2}\right\} . \tag{7}$$

Therefore, a hypocenter location is associated with each refraction point, if the lag time between the direct P wave and the direct S wave is known. The surface layer thickness is

$$x_i = R_1\cos\theta_1 , \tag{8}$$

For each refraction point and associated hypocenter, a theoretical time lag between the P wave and the multiple can be calculated and compared with the time lag between the direct P wave and the low frequency waveform which is observed on the seismogram. To calculate the lag time between the direct P wave and the multiple, the projections of the multiple and direct ray paths onto the horizontal and vertical axes are considered, and imply

$$R_3\sin\theta_3 + R_4\sin\theta_4 = R_1\sin\theta_1 + R_2\sin\theta_2 , \tag{9}$$

$$R_3\cos\theta_3 = 3R_1\cos\theta_1 , \tag{10}$$

and $$R_4\cos\theta_4 = R_2\cos\theta_2 . \tag{11}$$

The angles of refraction for the multiple obey Snell's Law

$$\frac{\sin\theta_4}{\sin\theta_3} = \frac{V_4}{V_3} . \tag{12}$$

From equation (12)

$$\theta_4 = \sin^{-1}\left\{\frac{V_4}{V_3}\sin\theta_3\right\} \quad . \tag{13}$$

From equations (11) and (12)

$$R_4 = \frac{R_2\cos\theta_2}{\sqrt{1-\left(\frac{V_4}{V_3}\sin\theta_3\right)^2}} \quad . \tag{14}$$

From equation (10)

$$R_3 = \frac{3R_1\cos\theta_1}{\cos\theta_3} \quad . \tag{15}$$

Substitution of equations (13), (14), and (15) into equation (9) gives

$$\sin\theta_3\left\{\frac{3R_1\cos\theta_1}{\cos\theta_3} + \frac{V_4 R_2\cos\theta_2}{V_3\sqrt{1-\left(\frac{V_4}{V_3}\sin\theta_3\right)^2}}\right\} = R_1\sin\theta_1 + R_2\sin\theta_2 \quad . \tag{16}$$

After equation (16) is solved numerically for theta 3, the ray path of the multiple is known because

$$\theta_4 = \sin^{-1}\left\{\frac{V_4}{V_3}\sin\theta_3\right\} \quad , \tag{17}$$

$$R_4 = \frac{R_2\cos\theta_2}{\cos\theta_4} \quad , \tag{18}$$

and $$R_3 = \frac{3R_1\cos\theta_1}{\cos\theta_3} \quad . \tag{19}$$

Then, the lag time between the multiple ray and the direct P wave is

$$\Delta T_{MP} = \frac{R_3}{V_3} + \frac{R_4}{V_4} - \left\{\frac{R_1}{V_1} + \frac{R_2}{V_2}\right\} \quad . \tag{20}$$

RANGE OF R

The distance to the hypocenter is bounded within a certain range, the boundaries of which are determined as follows. If there is no surface layer, R1 is zero and equation (4) implies that R2 is $V_2\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1}\right\}$, in which case R2 equals R. If there is no lower layer, R2 is zero and equation (4) implies that R1 is $V_1\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1}\right\}$, in which case R1 equals R. The maximum value of theta 1 is determined by evaluating equation (5) with theta 2 equal to 90 degrees which implies

$$\theta_{1MAX} = \sin^{-1}\left\{\frac{V_1}{V_2}\right\} \quad . \tag{21}$$

Substituting θ_{1MAX} into equation (1) gives

$$R^2 = R_1^2 + R_2^2 + 2R_1 R_2 \frac{V_1}{V_2} \quad , \tag{22}$$

Therefore, the following boundaries exist for the range of R

$$V_1\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1}\right\} \leq R \leq V_2\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1}\right\} \quad , \tag{23}$$

for $\frac{\pi}{2} - \theta_{1MAX} \leq \theta \leq \frac{\pi}{2}$; (24)

and $\sqrt{R_1^2 + R_2^2 + 2R_1 R_2 \frac{V_1}{V_2}} \leq R \leq V_2\left\{\frac{\Delta T_{SP}}{\sqrt{3}-1}\right\}$, (25)

for $0.0 \leq \theta \leq \frac{\pi}{2} - \theta_{1MAX}$. (26)

SUMMARY OF TECHNIQUE

The difference between the arrival times of the direct P wave and the surface multiple, given by equation (20), is a function of R1 and theta 1, the position of the refraction point. The domain of equation (20) is defined by the limits of R1 and theta 1, which are

$$0.0 \leq R_1 \leq V_1 \left\{ \frac{\Delta T_{SP}}{\sqrt{3}-1} \right\} , \tag{27}$$

and

$$0.0 \leq \theta_1 \leq \sin^{-1} \left\{ \frac{V_1}{V_2} \right\} . \tag{28}$$

The difference between the theoritical time lag (equation (20)), and the observed time lag expressed as

$$\Delta T = \frac{R_{V3}}{V_3} + \frac{R_{V4}}{V_4} - \left\{ \frac{R_1}{V_1} + \frac{R_{V2}}{V_2} \right\} - (\Delta T_{MP})_{OBSERVED} , \tag{29}$$

defines a surface over the domain of equation (20) such as the surface shown in Figure 5. The combinations of R1 and theta 1 associated with the intersection of the surface with the zero time difference plane constitute the set of refraction points and associated hypocenters that give lag times that are consistent with the data. In this analysis , equation (29) was solved with the bisection algorithm for R1, while theta 1 was held constant at regular increments within its limits.

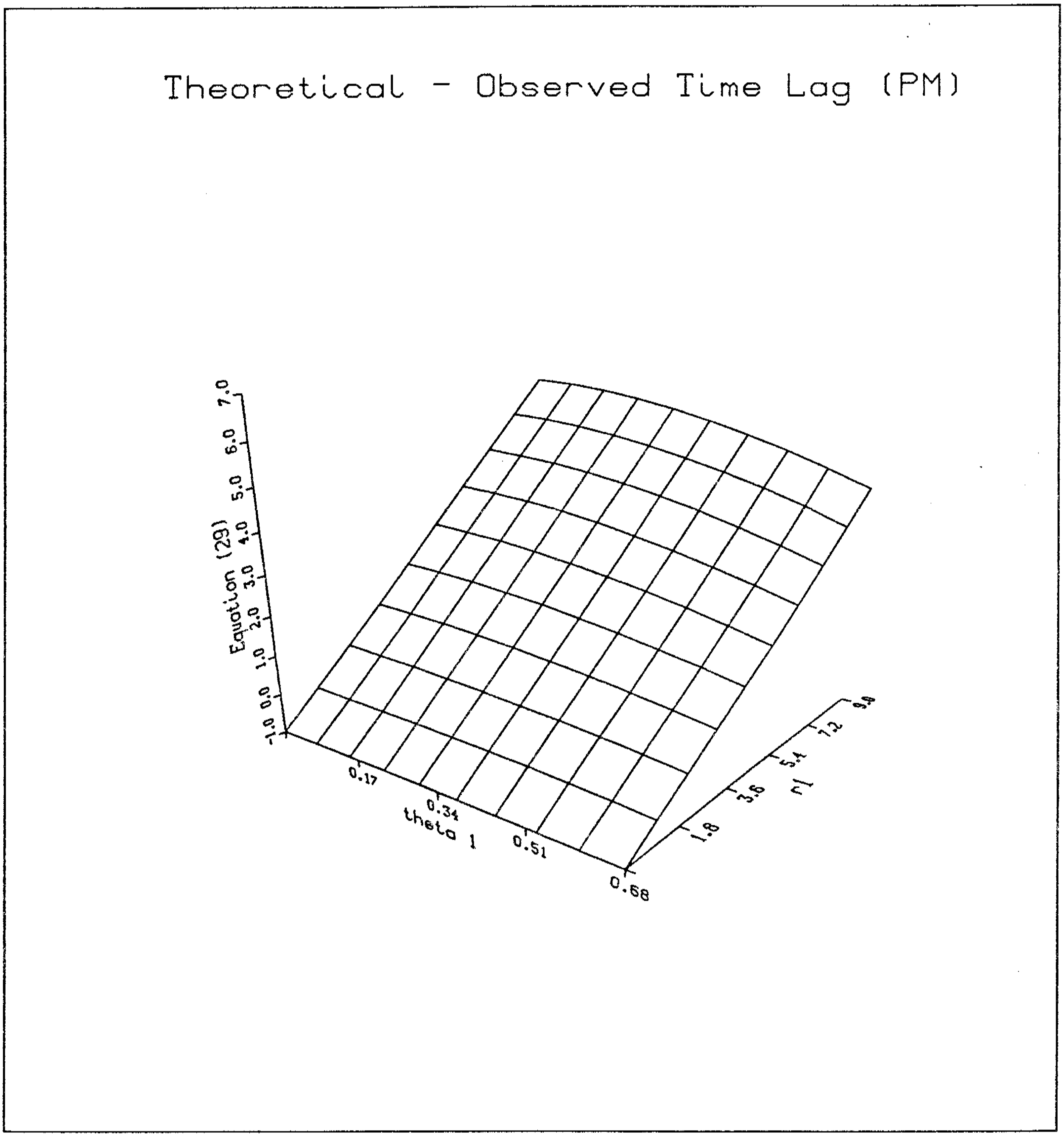


Figure 5: Equation (29) evaluated over the allowable ranges of theta 1 and R1.

HYPOTHESIS ONE

In the seismogram of Figure 1, the direct shear wave follows the direct P wave by approximately 1.8 seconds, and according to the correlogram of Figure 2 the low frequency wave follows the direct shear wave by one second. The raypath parameters of twenty models consistent with these lag times are shown in Table 1. Note, the angles given in the tables are in radians. The surface layer thickness (xi) ranges between approximately 1.07 kilometers, for a hypocenter directly below the recording station, to approximately 1.34 kilometers, for a relatively shallow hypocenter laterally removed from the recording station. The hypocenters of the twenty models lie along a line shown in Figure 6. The raypaths for one model, whose hypocenter exists on a line approximately 45 degrees from horizontal and passing through the recording station is shown in Figure 7.

v1......	3.70
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.00
lf......	0.00
th1max..	0.68
th3max..	0.69
r1max...	9.15
r2max...	14.46

x	y	r	theta	xi
0.00	-13.84	13.84	1.57	1.07
0.73	-13.82	13.84	1.52	1.07
1.45	-13.76	13.84	1.47	1.07
2.18	-13.66	13.83	1.41	1.08
2.90	-13.52	13.83	1.36	1.08
3.61	-13.34	13.82	1.31	1.09
4.32	-13.11	13.81	1.25	1.09
5.03	-12.85	13.80	1.20	1.10
5.72	-12.54	13.78	1.14	1.11
6.40	-12.18	13.76	1.09	1.12
7.07	-11.78	13.74	1.03	1.13
7.73	-11.33	13.72	0.97	1.14
8.38	-10.82	13.69	0.91	1.16
9.00	-10.26	13.65	0.85	1.18
9.61	-9.64	13.61	0.79	1.20
10.20	-8.93	13.56	0.72	1.22
10.77	-8.14	13.50	0.65	1.24
11.32	-7.23	13.43	0.57	1.27
11.83	-6.15	13.34	0.48	1.30
12.32	-4.74	13.20	0.37	1.34

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	1.07	12.77	3.21	12.77	0.00	0.00
0.73	0.03	0.05	0.03	0.05	1.07	12.77	3.22	12.77	0.04	0.10
1.45	0.07	0.11	0.06	0.10	1.07	12.77	3.22	12.75	0.07	0.20
2.18	0.10	0.16	0.09	0.15	1.08	12.76	3.24	12.73	0.11	0.30
2.90	0.14	0.22	0.12	0.20	1.09	12.74	3.26	12.69	0.15	0.41
3.61	0.17	0.27	0.16	0.25	1.10	12.72	3.30	12.64	0.19	0.51
4.32	0.21	0.33	0.19	0.30	1.11	12.70	3.33	12.58	0.23	0.62
5.03	0.24	0.38	0.22	0.35	1.13	12.67	3.38	12.51	0.27	0.74
5.72	0.27	0.44	0.25	0.40	1.15	12.64	3.44	12.42	0.31	0.85
6.40	0.31	0.50	0.28	0.46	1.17	12.61	3.50	12.32	0.36	0.98
7.07	0.34	0.56	0.31	0.51	1.20	12.56	3.57	12.21	0.40	1.11
7.73	0.38	0.62	0.35	0.57	1.23	12.52	3.65	12.08	0.45	1.24
8.38	0.41	0.68	0.38	0.63	1.27	12.46	3.75	11.92	0.51	1.39
9.00	0.45	0.75	0.41	0.69	1.30	12.40	3.86	11.75	0.56	1.55
9.61	0.48	0.82	0.45	0.75	1.35	12.33	3.98	11.55	0.62	1.72
10.20	0.51	0.89	0.48	0.82	1.40	12.25	4.13	11.32	0.69	1.92
10.77	0.55	0.97	0.52	0.90	1.46	12.16	4.29	11.06	0.76	2.13
11.32	0.58	1.05	0.56	0.98	1.52	12.06	4.49	10.75	0.84	2.37
11.83	0.62	1.15	0.59	1.09	1.60	11.94	4.72	10.39	0.92	2.65
12.32	0.65	1.28	0.64	1.22	1.68	11.80	5.00	9.94	1.02	2.98

Table 1: Raypath parameters for 20 cases which would give a 2.81 second lag time between the direct P wave and an assumed S wave multiple. Velocities, lag times, and other parameters (upper right). Hypocenter locations (x,y or r,theta), and layer thicknesses (upper right). Raypath parameters (bottom). Note, all angles are in radians, all distances are in kilometers.

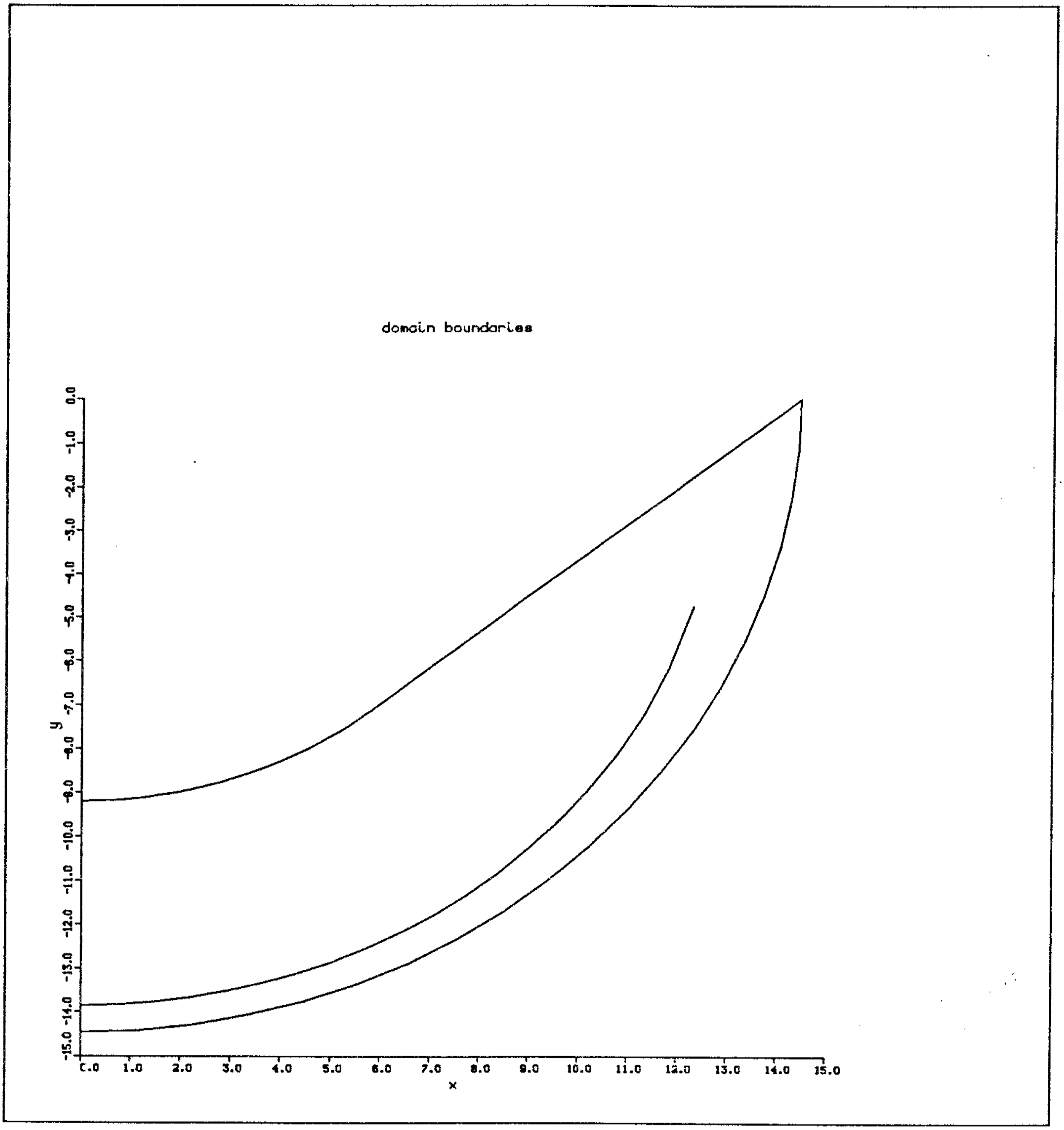


Figure 6: For the velocities chosen for hypothesis 1, hypocenters cannot occur outside of the above sector. The hypocenters from Table 1, which are consistent with the seismogram in Figure 1, lie along the line shown within the sector. The raypaths for the hypocenter occurring with coordinates at 9.62, −9.64 kilometers are shown in Figure 7.

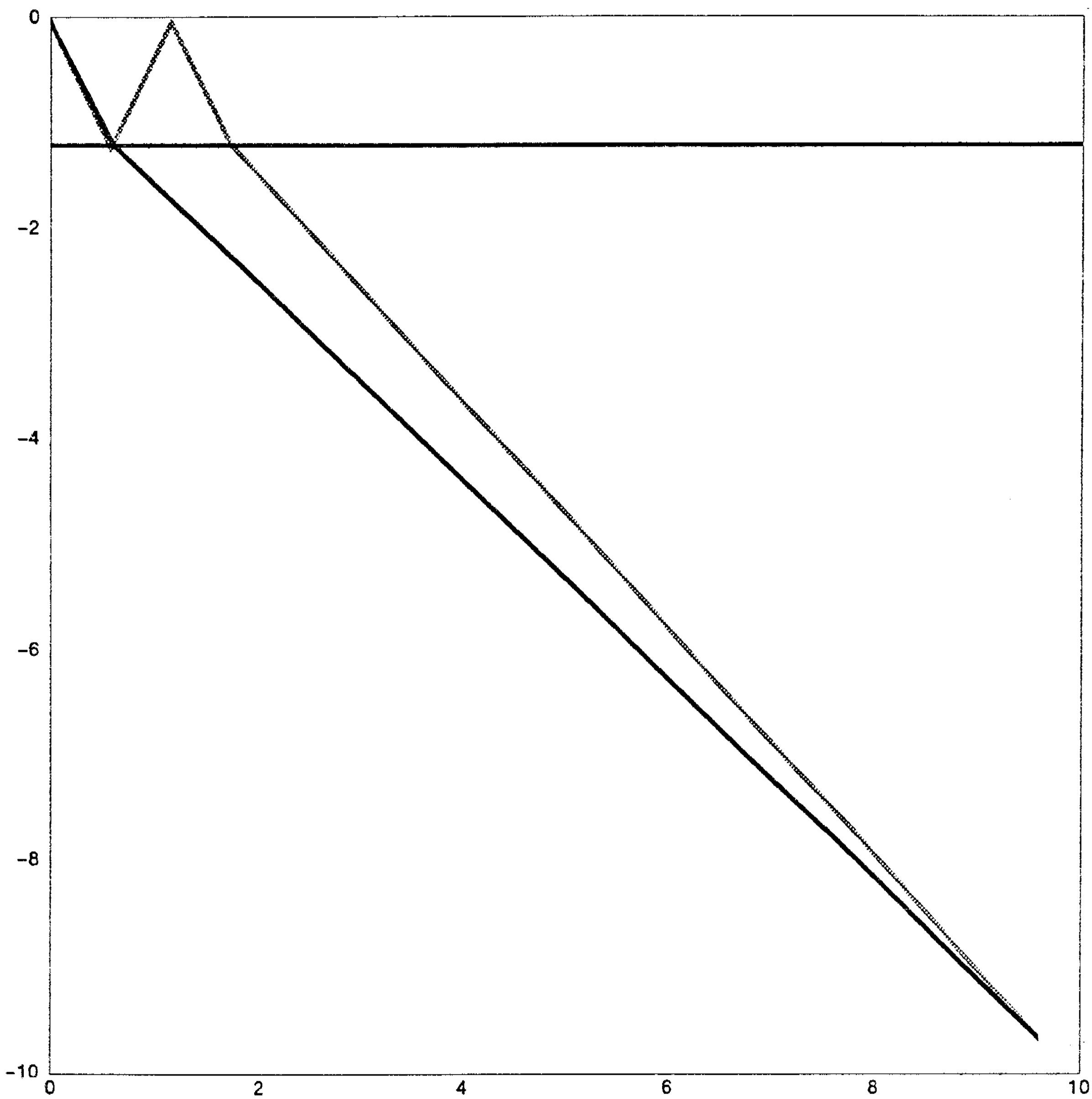


Figure 7: Raypaths for the case of a hypocenter with coordinates of 9.62 and -9.64 kilometers (see Table 1).

HYPOTHESIS TWO

The correlation of the filtered shear wave with the filtered seismogram gives several correlation peaks other than the one associated with the low frequency waveform, that is, the one occurring one second after full correlation. This suggests additional multiples arrive at the recording station. The recording station is in a mine, so the observed correlation peaks could be caused by two types of multiples; one whose last reflection was from the free surface, and another whose last reflection was from the base of the surface layer (see Figure 8). To account for a buried recording station, equation (10) must be changed to

$$R_3 \cos\theta_3 = 3R_1 \cos\theta_1 + 4l \quad , \tag{30}$$

for the multiple whose last reflection is from the free surface in Figure 8, and to

$$R_3 \cos\theta_3 = 3R_1 \cos\theta_1 + 2l \quad , \tag{31}$$

for the multiple whose last reflection is fom the base of the surface layer in Figure 8. "l" is the depth to the station. The negative correlation peak occurring 0.7 seconds after full correlation in Figure 2 is assumed to be the correlation of the shear wave with the multiple whose last reflection was from the base of the surface layer. Table 2 shows 20 models consistent with this case assuming "l" is 0.35 kilometers. The positive correlation peak occurring 1.0 second after full correlation in Figure 2 is assumed to be the correlation of the shear wave with the multiple whose last reflection was from the free surface. Table 3 shows 20 models consistent with this case, also assuming "l" is 0.35 kilometers. Notice that both Table 2 and Table 3 include the case of a hypocenter with coordinates at approximately 10.17 and -9.79, and an associated layer thickness below station (xi) of approx–

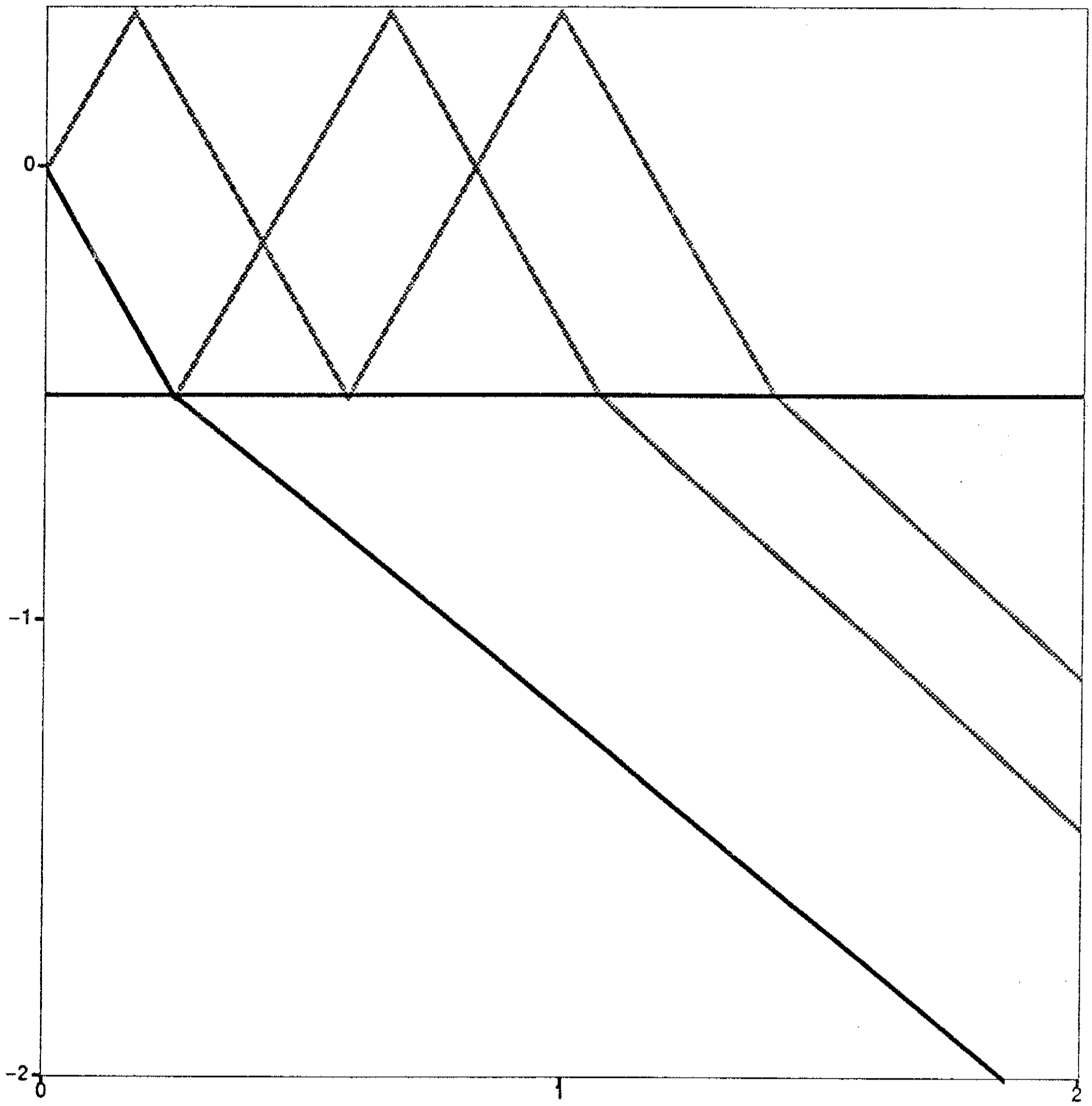


Figure 8: Close up view of direct ray and surface layer multiples for Hypothesis 2 (see also Tables 2 and 3).

v1......	3.70
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.51
l.......	0.35
lf......	2.00
th1max..	0.68
th3max..	0.69
r1max...	9.15
r2max...	14.46

x	y	r	theta	xi
0.00	-14.23	14.23	1.57	0.40
0.76	-14.21	14.23	1.52	0.40
1.52	-14.15	14.23	1.46	0.40
2.28	-14.04	14.23	1.41	0.40
3.04	-13.90	14.23	1.36	0.40
3.79	-13.71	14.22	1.30	0.41
4.54	-13.47	14.22	1.25	0.41
5.28	-13.19	14.21	1.19	0.42
6.01	-12.87	14.20	1.13	0.43
6.73	-12.49	14.19	1.08	0.43
7.44	-12.07	14.18	1.02	0.44
8.14	-11.59	14.17	0.96	0.45
8.83	-11.06	14.15	0.90	0.46
9.51	-10.46	14.13	0.83	0.48
10.17	-9.79	14.11	0.77	0.49
10.81	-9.04	14.09	0.70	0.51
11.43	-8.18	14.06	0.62	0.52
12.04	-7.19	14.02	0.54	0.54
12.62	-5.99	13.97	0.44	0.57
13.18	-4.42	13.90	0.32	0.59

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.40	13.83	1.90	13.83	0.00	0.00
0.76	0.03	0.05	0.03	0.05	0.40	13.83	1.90	13.83	0.01	0.06
1.52	0.07	0.11	0.06	0.10	0.40	13.83	1.91	13.82	0.03	0.12
2.28	0.10	0.16	0.10	0.15	0.40	13.82	1.92	13.80	0.04	0.18
3.04	0.14	0.22	0.13	0.20	0.41	13.82	1.93	13.78	0.06	0.25
3.79	0.17	0.27	0.16	0.26	0.42	13.81	1.95	13.74	0.07	0.31
4.54	0.21	0.33	0.19	0.31	0.42	13.80	1.98	13.70	0.09	0.38
5.28	0.24	0.38	0.23	0.36	0.43	13.78	2.01	13.66	0.10	0.45
6.01	0.27	0.44	0.26	0.42	0.44	13.76	2.05	13.60	0.12	0.52
6.73	0.31	0.50	0.29	0.47	0.46	13.74	2.09	13.53	0.14	0.60
7.44	0.34	0.56	0.32	0.53	0.47	13.72	2.14	13.45	0.16	0.68
8.14	0.38	0.62	0.36	0.58	0.49	13.69	2.20	13.36	0.18	0.77
8.83	0.41	0.68	0.39	0.64	0.50	13.67	2.26	13.26	0.20	0.86
9.51	0.45	0.75	0.42	0.71	0.53	13.63	2.33	13.14	0.23	0.96
10.17	0.48	0.82	0.46	0.77	0.55	13.59	2.42	13.01	0.25	1.07
10.81	0.51	0.89	0.49	0.84	0.58	13.55	2.52	12.85	0.29	1.19
11.43	0.55	0.97	0.53	0.92	0.61	13.50	2.63	12.68	0.32	1.33
12.04	0.58	1.05	0.57	1.01	0.65	13.44	2.76	12.47	0.36	1.48
12.62	0.62	1.15	0.60	1.11	0.69	13.37	2.91	12.23	0.40	1.65
13.18	0.65	1.28	0.64	1.24	0.74	13.29	3.09	11.96	0.45	1.85

Table 2: Raypath parameters for 20 cases which would give a 2.51 second lag time between the direct P wave and a multiple whose last reflection is of the bottom of the surface layer (see Figure 8). Velocities, time lags, and other parameters (upper right). Hypocenter locations (x,y or r,theta), and layer thicknesses (upper right). Raypath parameters (bottom).

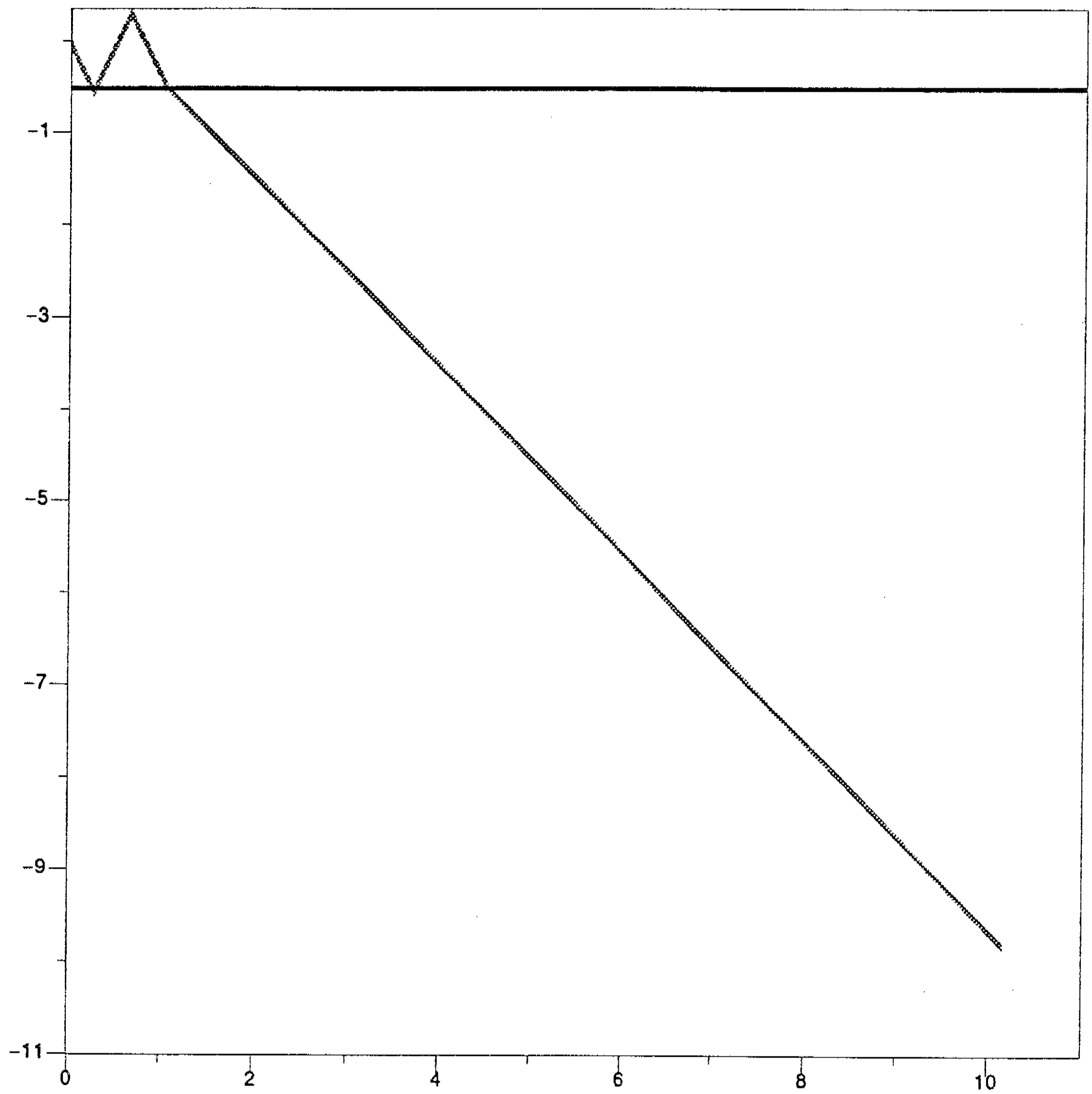


Figure 9: Raypath for the case of a multiple whose last reflection is from the base of the surface layer with hypocentral coordinates of 10.17 and -9.79 (see Table 2).

v1......	3.70
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.35
lf......	4.00
th1max..	0.68
th3max..	0.69
r1max...	9.15
r2max...	14.46

x	y	r	theta	xi
0.00	-14.25	14.25	1.57	0.37
0.76	-14.23	14.25	1.52	0.37
1.53	-14.17	14.25	1.46	0.37
2.29	-14.06	14.24	1.41	0.38
3.04	-13.91	14.24	1.36	0.38
3.80	-13.72	14.24	1.30	0.39
4.54	-13.48	14.23	1.25	0.39
5.28	-13.20	14.22	1.19	0.40
6.01	-12.88	14.21	1.13	0.41
6.74	-12.50	14.20	1.08	0.42
7.45	-12.08	14.19	1.02	0.43
8.15	-11.60	14.17	0.96	0.44
8.83	-11.06	14.15	0.90	0.46
9.50	-10.46	14.13	0.83	0.48
10.16	-9.79	14.11	0.77	0.50
10.80	-9.04	14.08	0.70	0.52
11.41	-8.18	14.04	0.62	0.54
12.01	-7.19	14.00	0.54	0.57
12.58	-6.00	13.94	0.45	0.60
13.12	-4.45	13.85	0.33	0.64

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.37	13.88	2.51	13.88	0.00	0.00
0.76	0.03	0.05	0.03	0.05	0.37	13.88	2.51	13.87	0.01	0.08
1.53	0.07	0.11	0.06	0.10	0.37	13.87	2.52	13.86	0.03	0.16
2.29	0.10	0.16	0.09	0.15	0.38	13.87	2.54	13.84	0.04	0.24
3.04	0.14	0.22	0.13	0.20	0.38	13.86	2.56	13.81	0.05	0.32
3.80	0.17	0.27	0.16	0.25	0.39	13.85	2.59	13.76	0.07	0.40
4.54	0.21	0.33	0.19	0.30	0.40	13.83	2.62	13.71	0.08	0.49
5.28	0.24	0.38	0.22	0.35	0.41	13.81	2.66	13.64	0.10	0.58
6.01	0.27	0.44	0.25	0.40	0.42	13.79	2.71	13.56	0.11	0.68
6.74	0.31	0.50	0.28	0.46	0.44	13.77	2.77	13.47	0.13	0.78
7.45	0.34	0.56	0.32	0.51	0.46	13.74	2.83	13.37	0.15	0.88
8.15	0.38	0.62	0.35	0.57	0.48	13.71	2.91	13.25	0.18	1.00
8.83	0.41	0.68	0.38	0.63	0.50	13.67	3.00	13.11	0.20	1.12
9.50	0.45	0.75	0.42	0.69	0.53	13.63	3.10	12.95	0.23	1.25
10.16	0.48	0.82	0.45	0.76	0.56	13.58	3.21	12.77	0.26	1.40
10.80	0.51	0.89	0.48	0.83	0.60	13.52	3.34	12.56	0.29	1.56
11.41	0.55	0.97	0.52	0.90	0.64	13.46	3.49	12.33	0.33	1.74
12.01	0.58	1.05	0.56	0.99	0.68	13.38	3.67	12.05	0.38	1.94
12.58	0.62	1.15	0.60	1.09	0.74	13.30	3.88	11.71	0.43	2.18
13.12	0.65	1.28	0.64	1.23	0.80	13.19	4.14	11.31	0.49	2.47

Table 3: Raypath parameters for 20 cases which would give a 2.81 second lag time between the direct P wave and a multiple whose last reflection is from the free surface (see Figure 8). Velocities, lag times, and other parameters (upper right). Hypocenter locations (x,y or r,theta), and layer thicknesses (upper right). Raypath parameters (bottom).

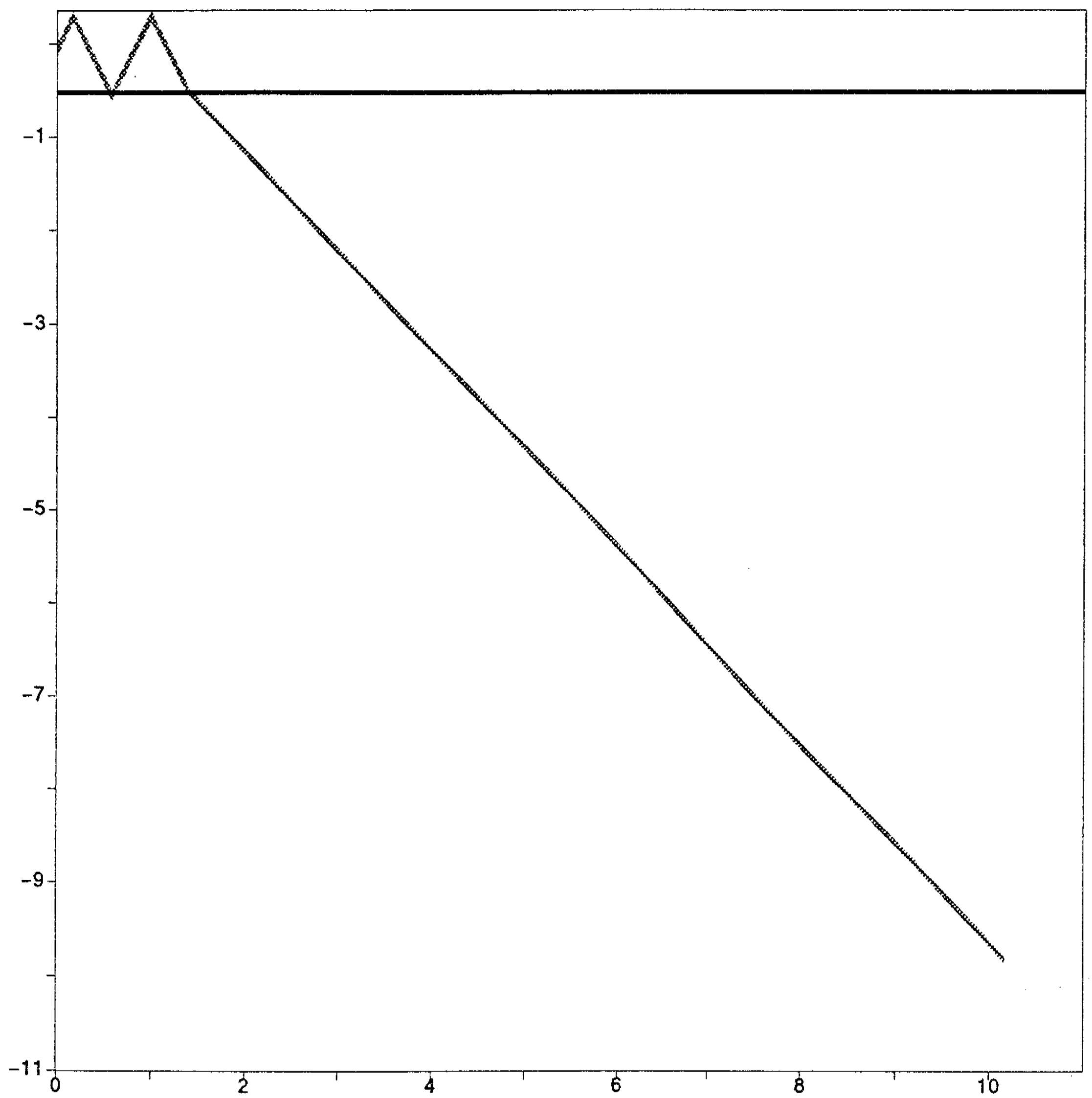


Figure 10: Raypath for the case of a multiple whose last reflection is from the free surface and a hypocenter with coordinates of 10.16 and -9.79 (see Table 3).

imately 0.5 kilometers. So, for this case, the multiples would arrive 0.7 and 1.0 seconds after the arrival of the direct shear wave, consistent with the correlogram of Figure 1. The raypaths for the two multiples with hypocentral coordinates of 10.17 and -9.79 are shown in Figures 9 and 10. If a depth to station other than 0.35 kilometers were chosen, there would not be a simultaneous solution for this hypocenter (see Appendix II). Note, that a 180 degree phase shift is required for the first multiple, but not the second, in order to agree with the correlogram.

A comparison of the frequency content of the multiple that follows the direct shear wave by 0.7 seconds with that of the low frequency phase suggests that the 6.1 hertz component in the low frequency phase has been amplified relative to other components (see Figure 11), which suggests constructive interference between the two multiples of the 6.1 hertz component. Constructive interference is also suggested in the original seismogram, since the window preceding the onset of the low frequency phase by 0.3 seconds seems to have less energy content than the low frequency phase.

The filtered seismogram suggests that part of the direct shear wave has been amplified by a multiple whose only reflection was from the free surface (see Figure 12), since the amplitude increases abruptly shortly after onset. Constructive interference is also suggested by a comparison of the frequency contents of the unfiltered direct shear wave with the frequency content of a window of equal length lagging the onset of the direct shear wave by 0.2 seconds (see Figure 11). The negative correlation in the autocorrelogram at the top of Figure 2 may correspond with the multiple whose only reflection was from the free surface.

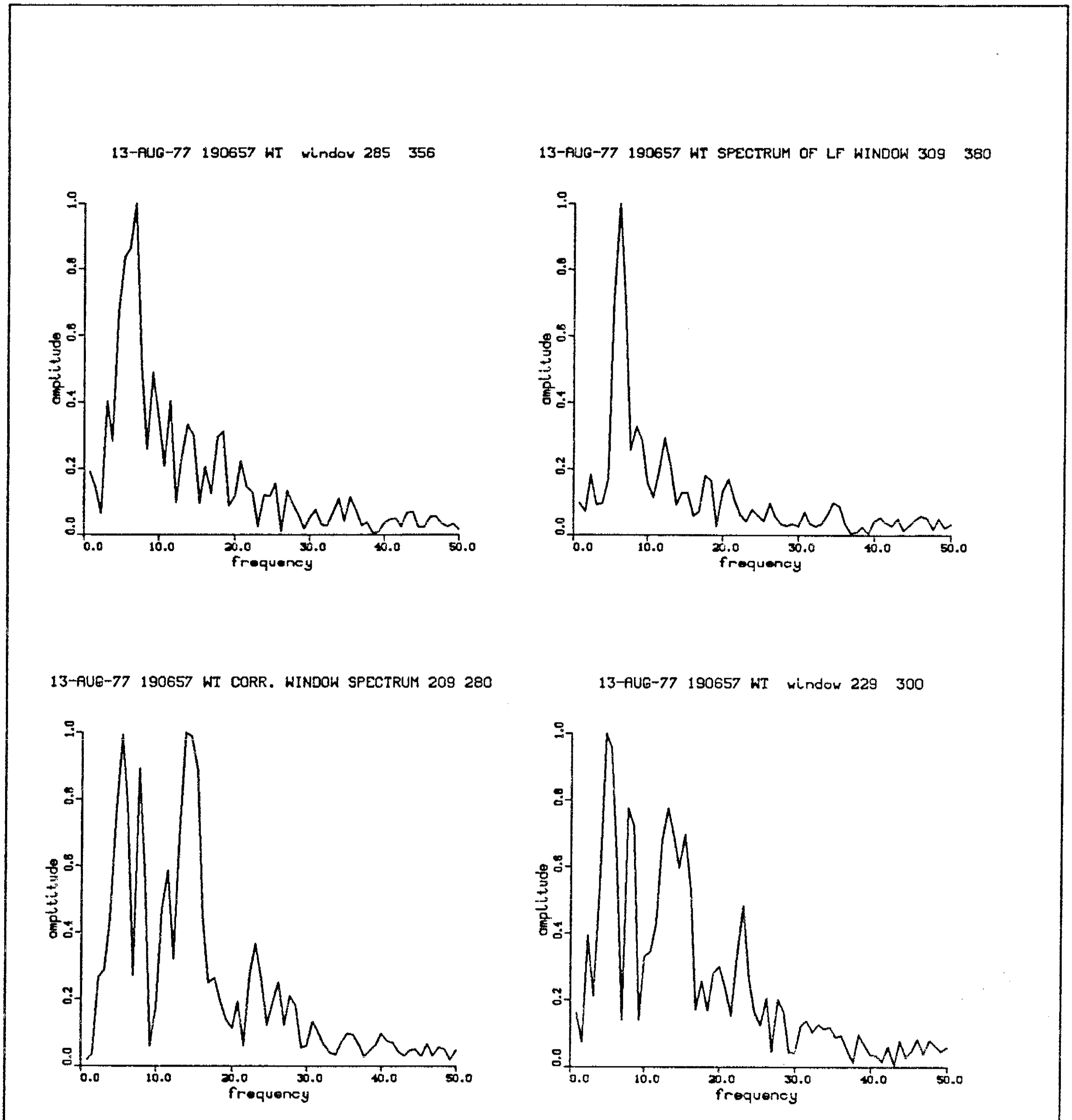


Figure 11: Relative frequency content of various windows from the seismogram of Figure 1. Bottom: Direct shear (left). Window beginning 0.2 seconds after onset of direct shear (right). Top: Low frequency phase (right). Window beginning 0.24 seconds before onset of low frequency phase (left). Top and Bottom: note that the change between left and right sides can be explained by an amplification of the 6.1 hertz component on the right side.

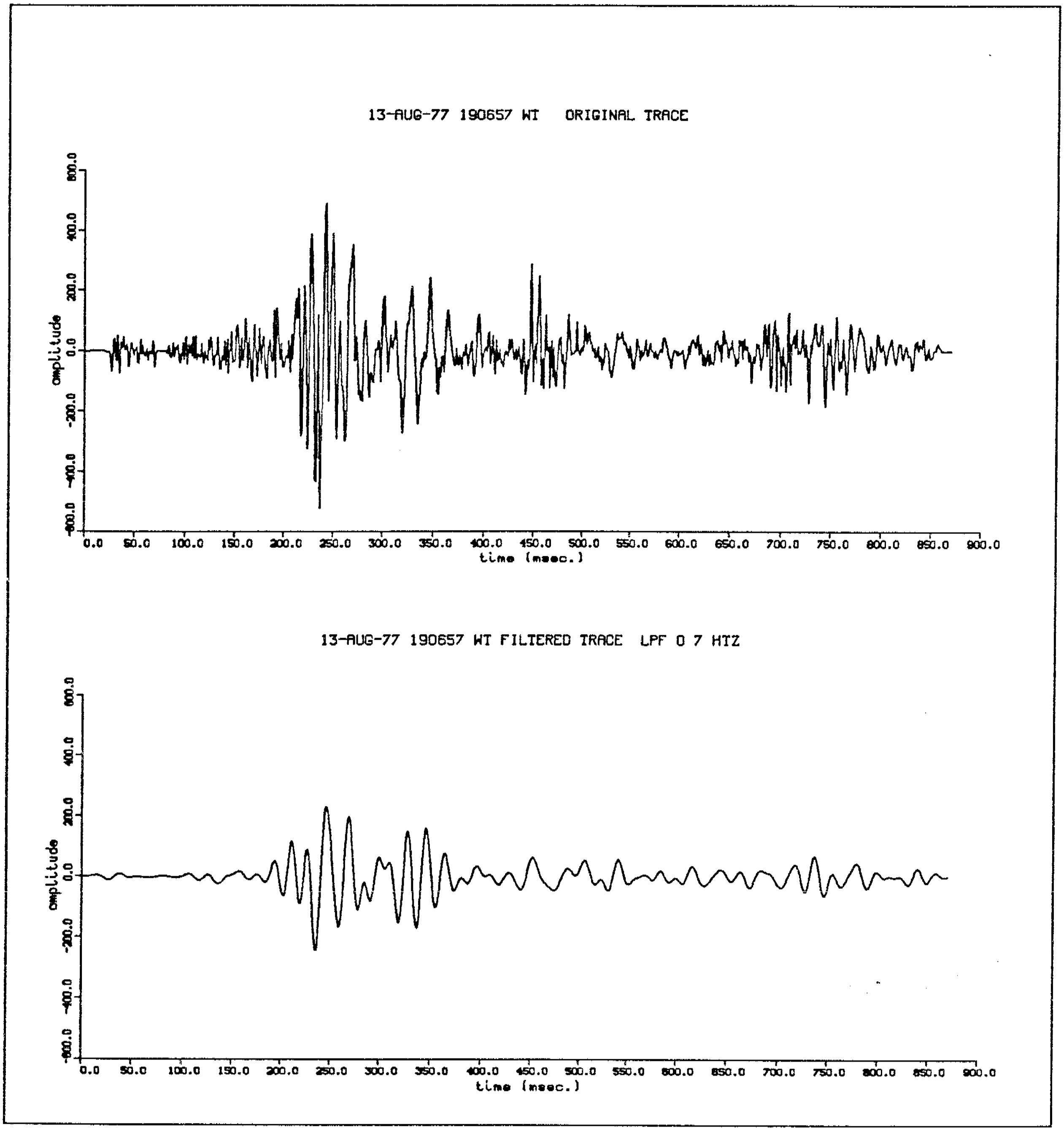


Figure 12: HOLY MACKEREL!

DISCUSSION

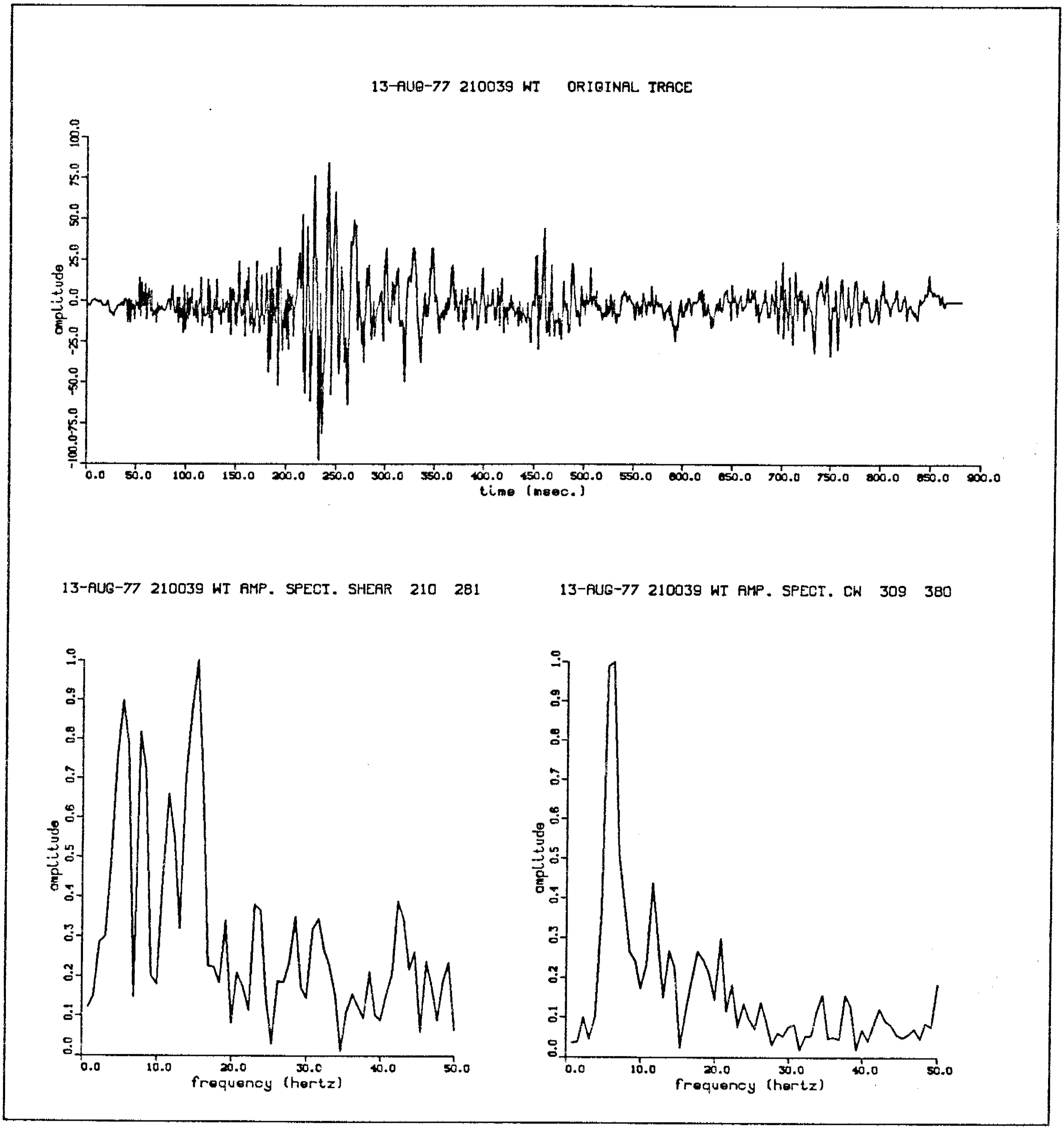
The known geology under station WTX does not include a simple compositional surface layer. Instead, the geology consists of many different types of materials, separated by faults, dipping boundaries, or intrusive contacts (Chamberlin, 1980). It is suggested that the surface layer is a group of highly fractured materials of various sorts separated from underlying, competent rock by a nearly flat decollement.

The depth to station WTX is not exactly 0.35 kilometers, nor is the surface flat and horizontal, as hypothesis 2 requires. But this analysis is only meant to deliver first order approximations to complicated problems.

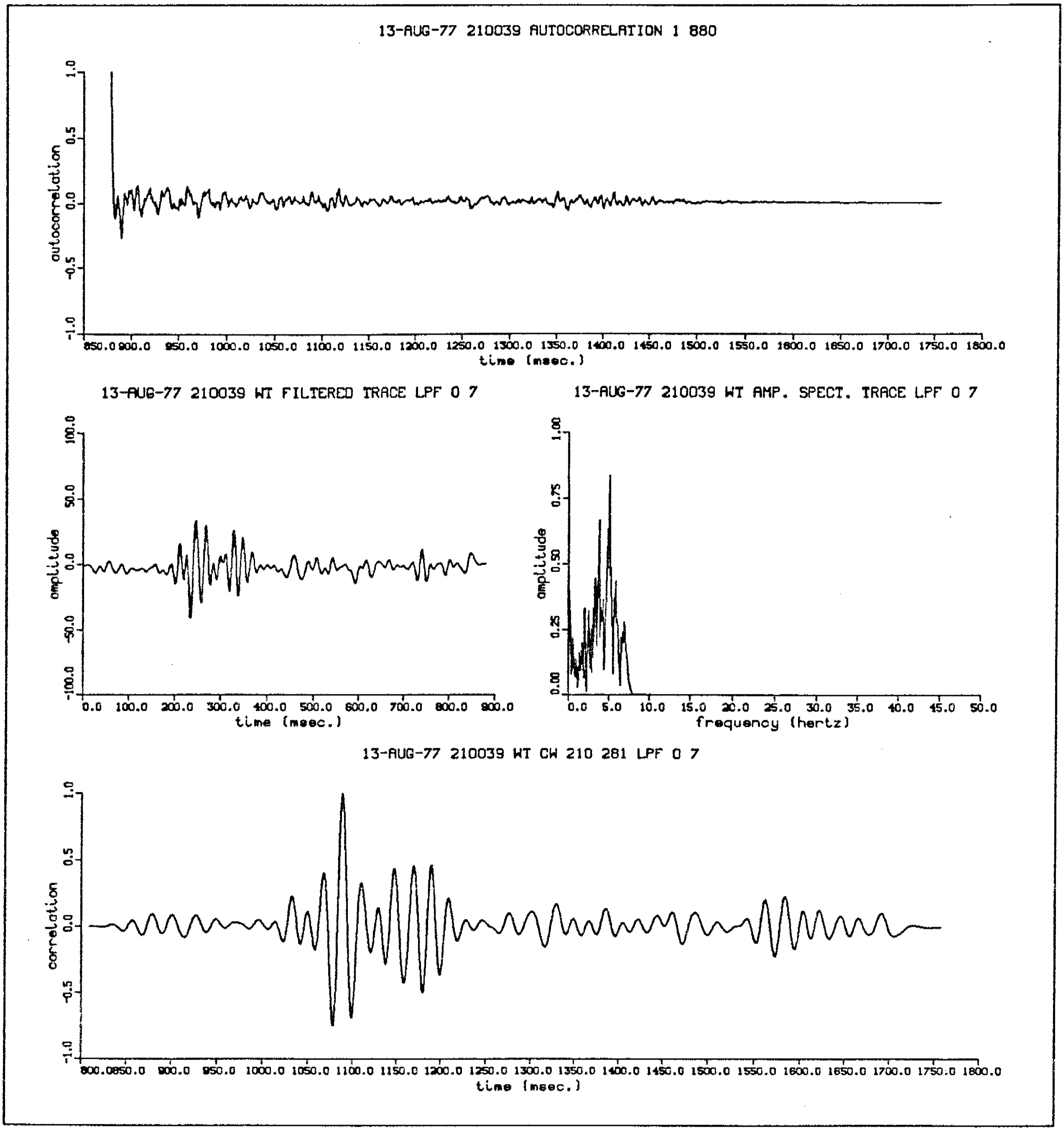
In summary, the low frequency waveform occurring on the seismograms of the August 1977 swarm can be reasonably explained as the product of constructive interference between multiples in a surface layer made highly attenuative by severe fracturing.

APPENDIX I
OTHER SEISMOGRAMS

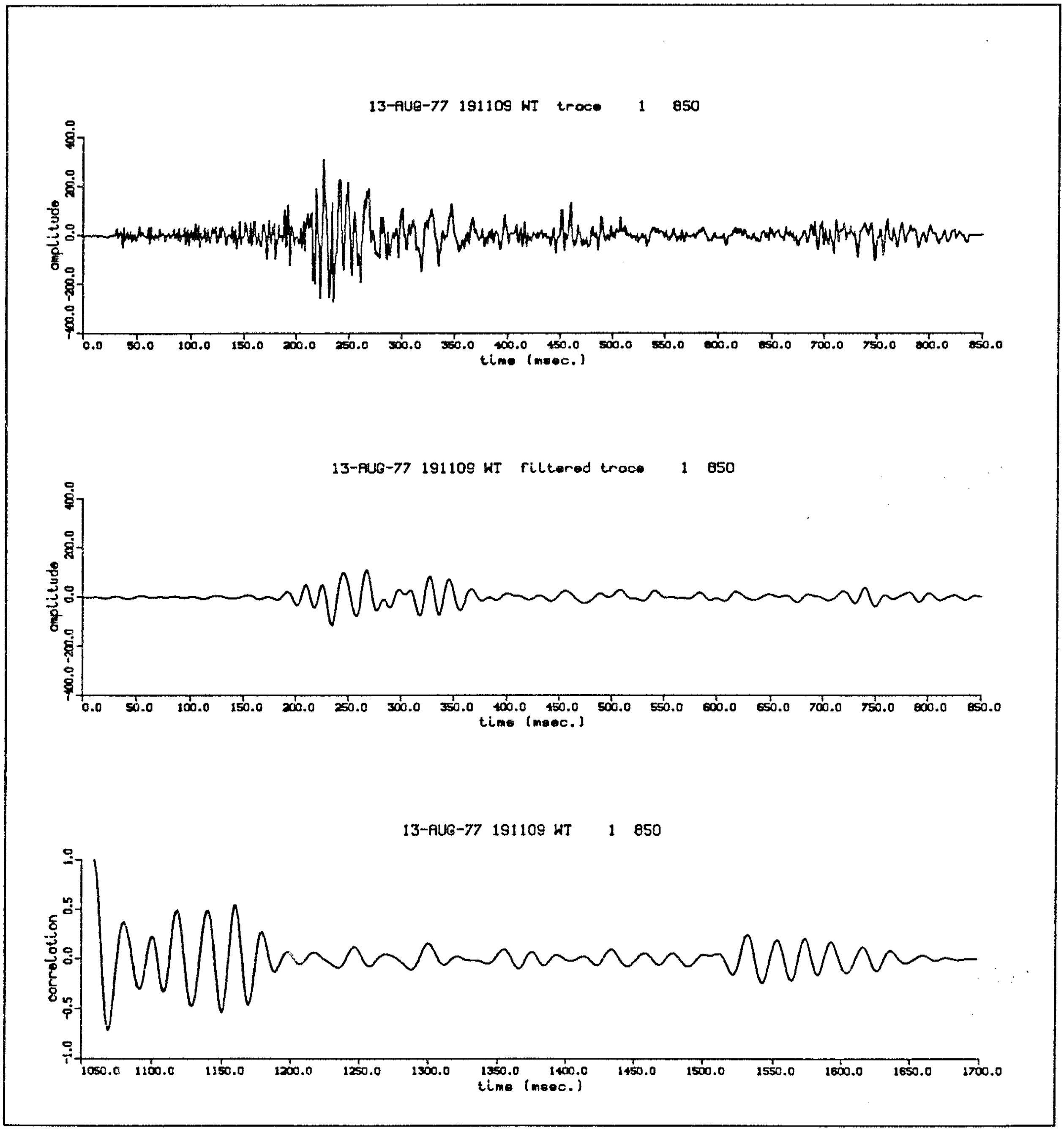
In this appendix, seismograms and correlograms of 11 other events from the August 1977 swarm are presented. The event on pages AI–2 and AI–3 is presented in the same format as the event presented in Figures 1 and 2 of the main text. For the others, only the original seismograms (top), the seven hertz filtered seismogram (middle), and the correlogram of the filtered shear wave with the filtered trace (bottom) are shown. Except for the seismograms and correlogram on page AI–12, note the similarity between the events.



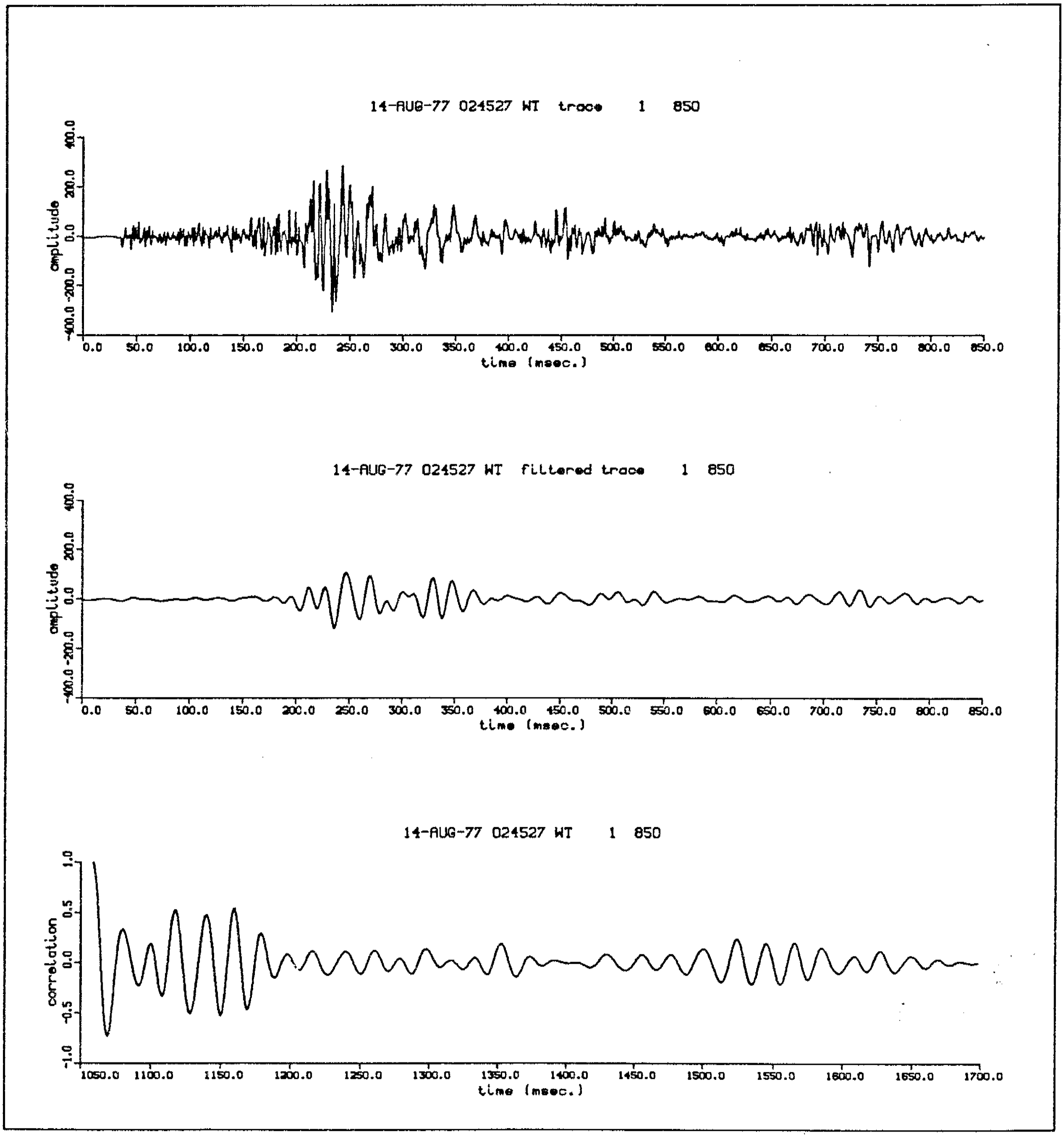
13–AUG–77 210039



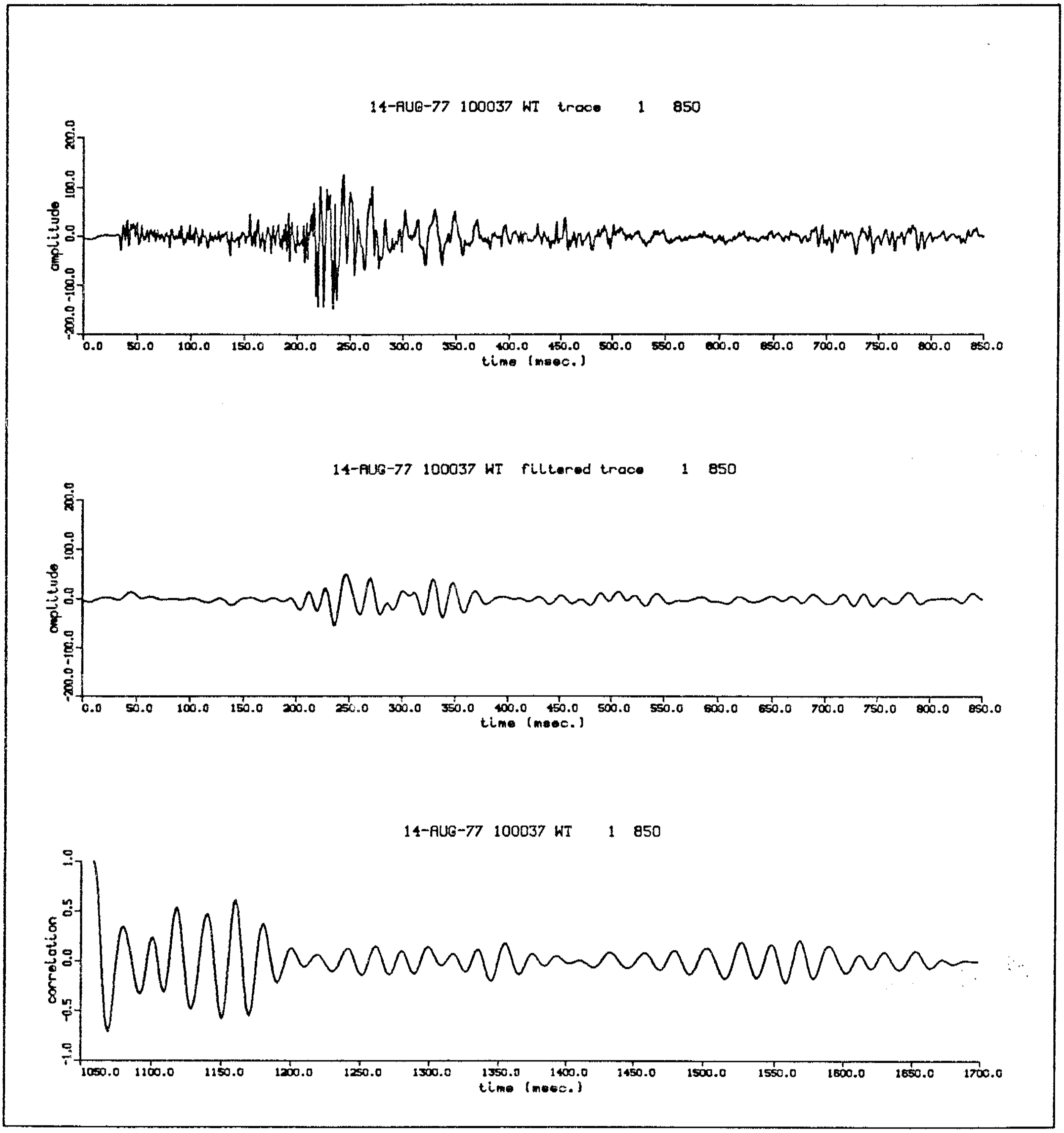
13–AUG–77 210039



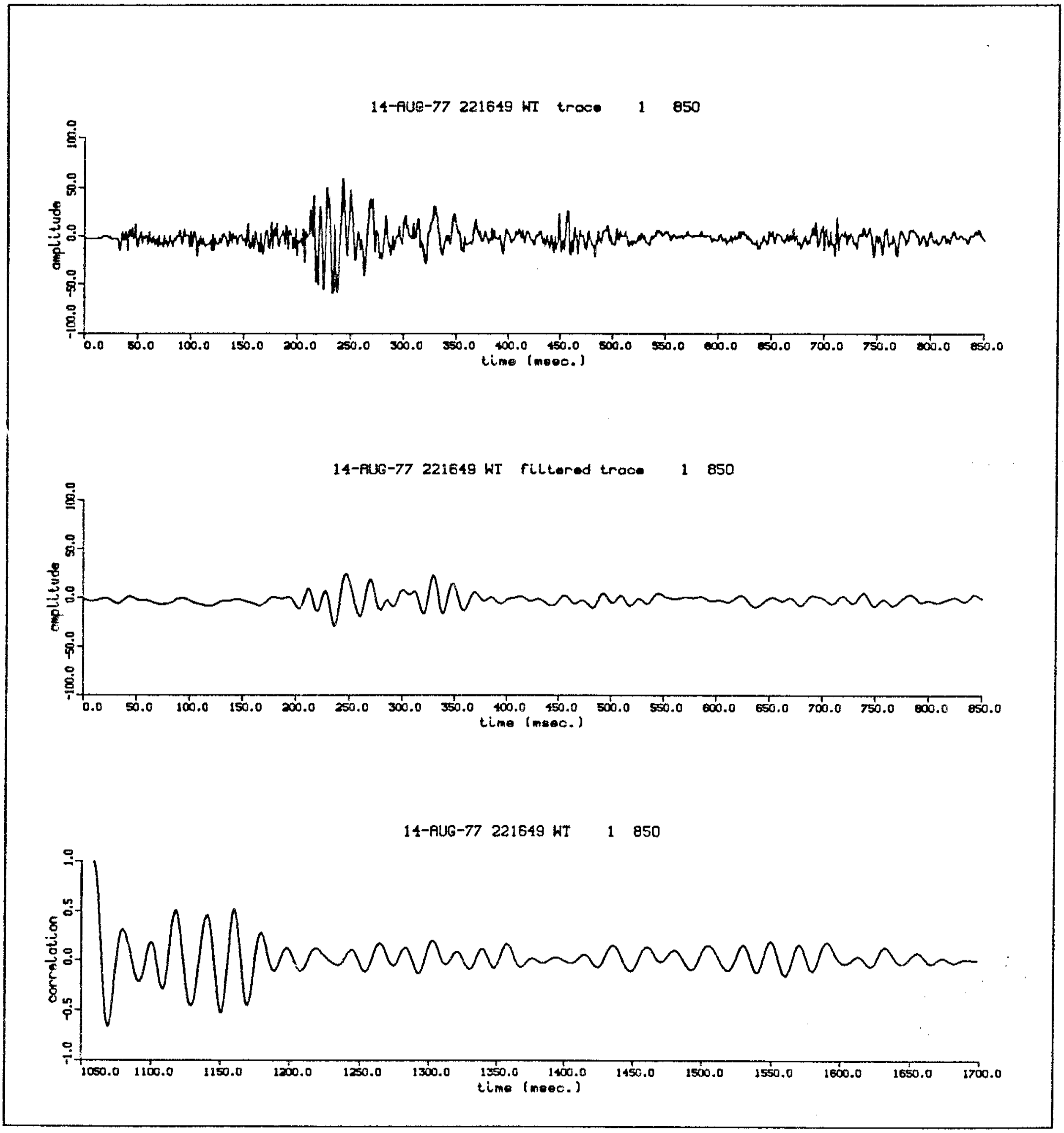
13–AUG–77 191109



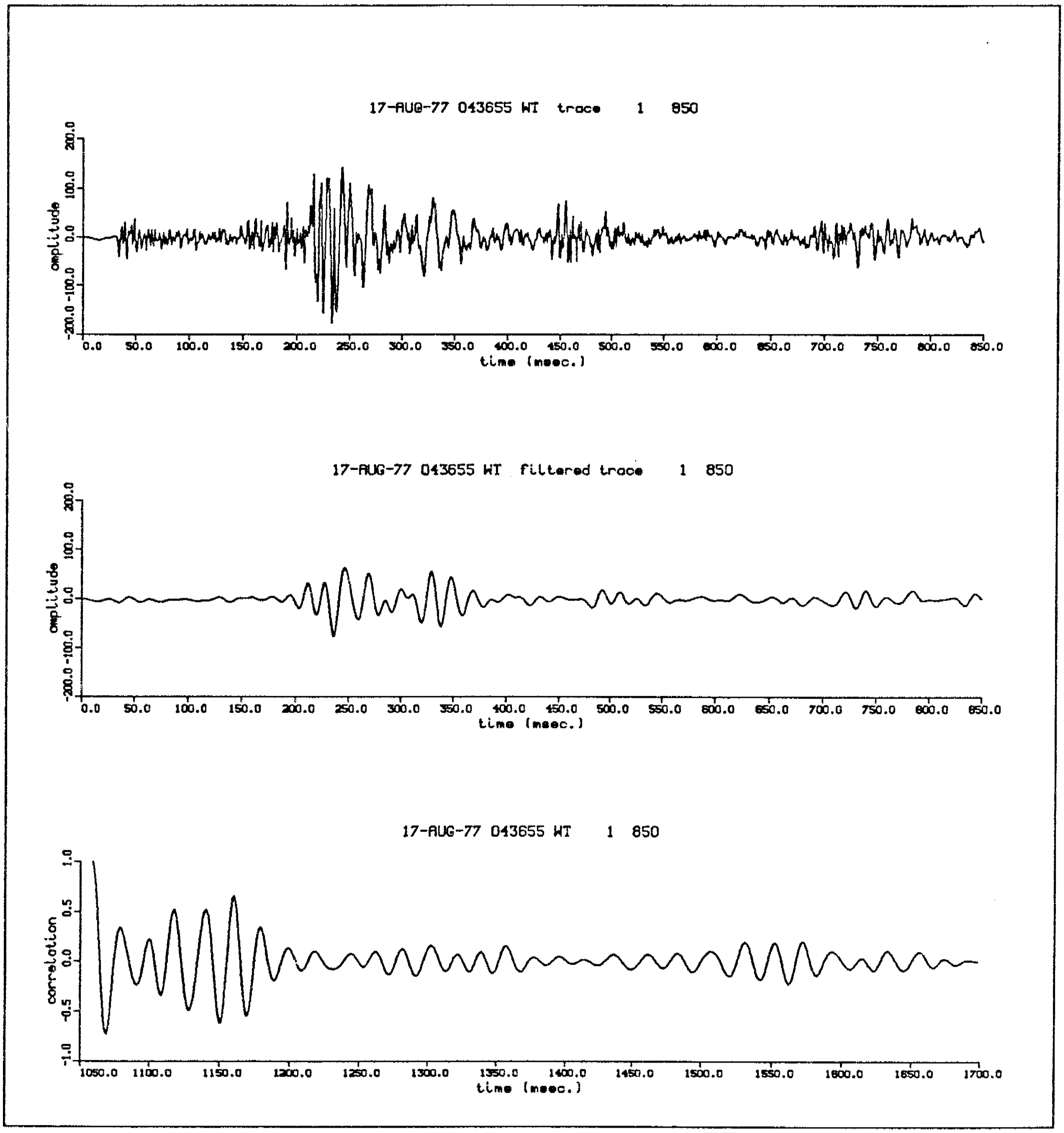
14–AUG–77 024527



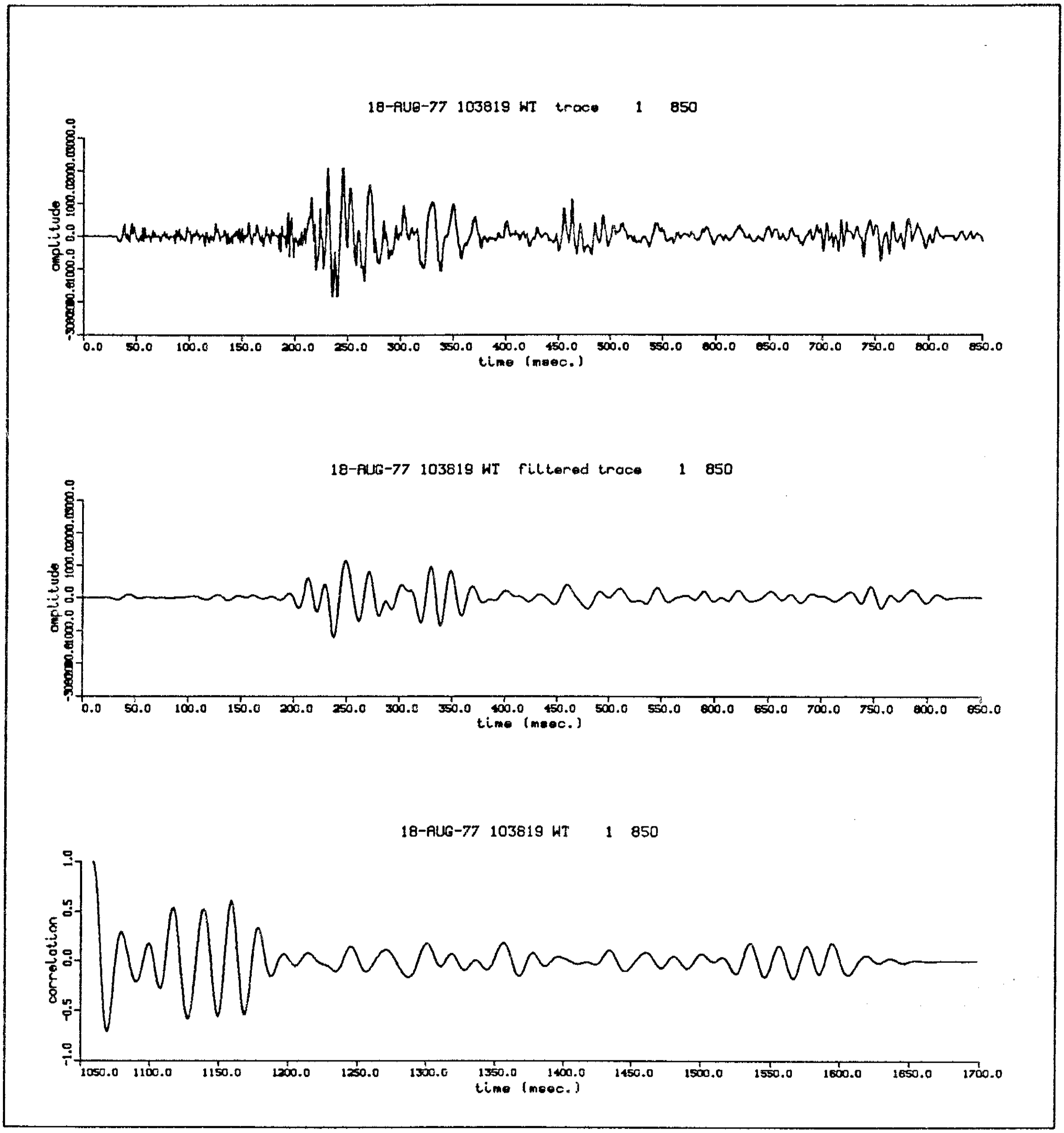
14–AUG–77 100037



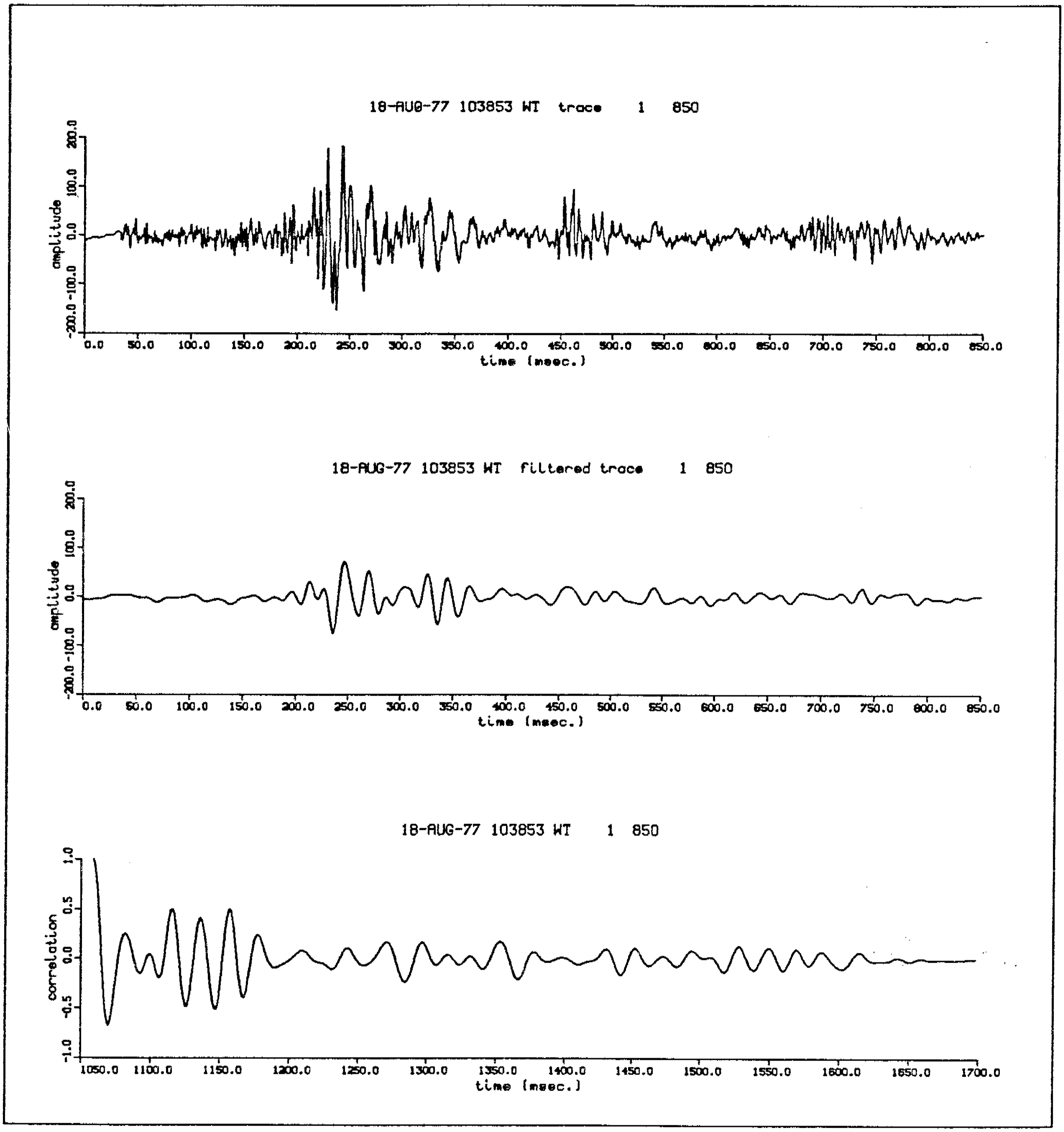
14-AUG-77 221649



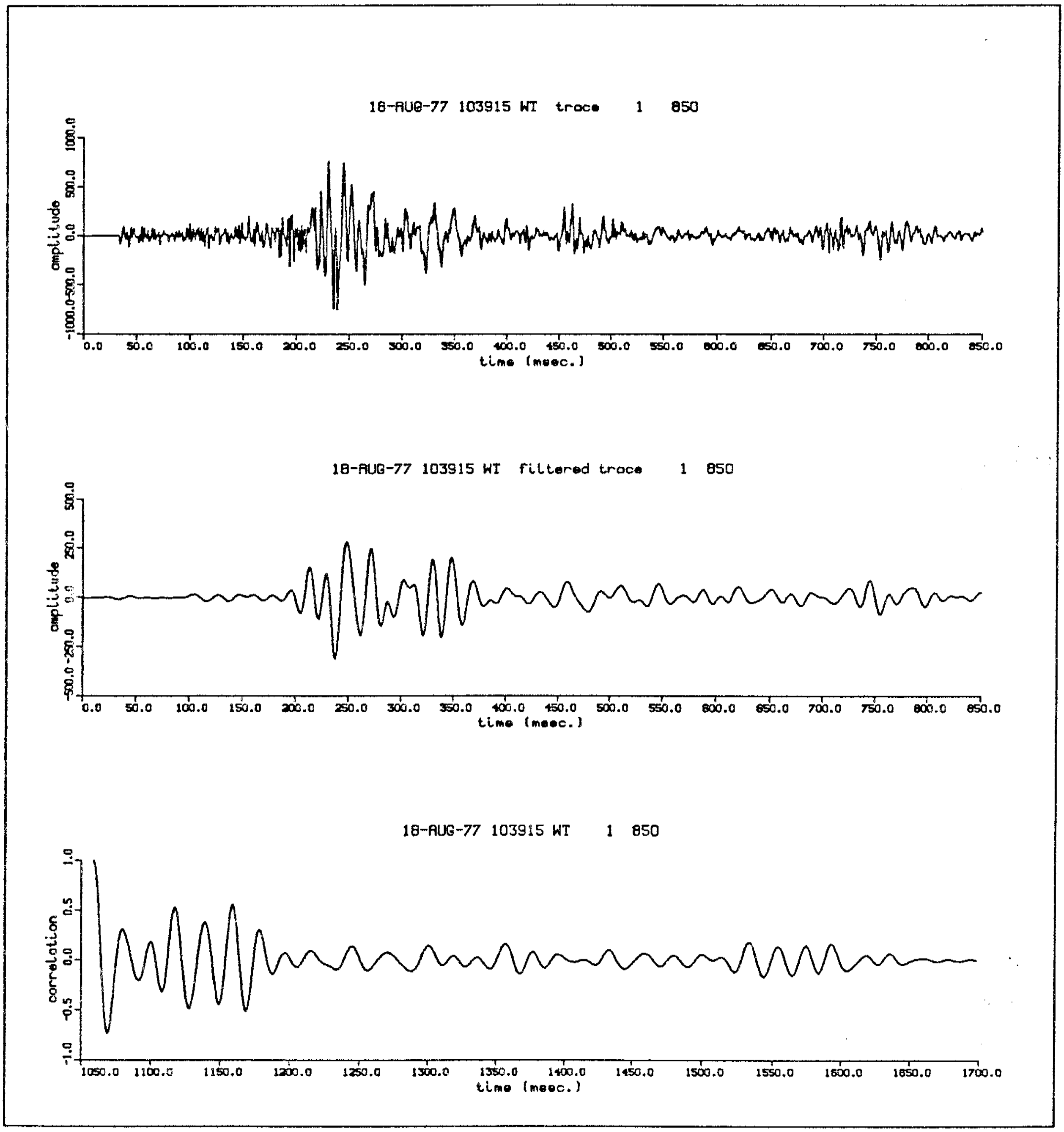
17–AUG–77 043655



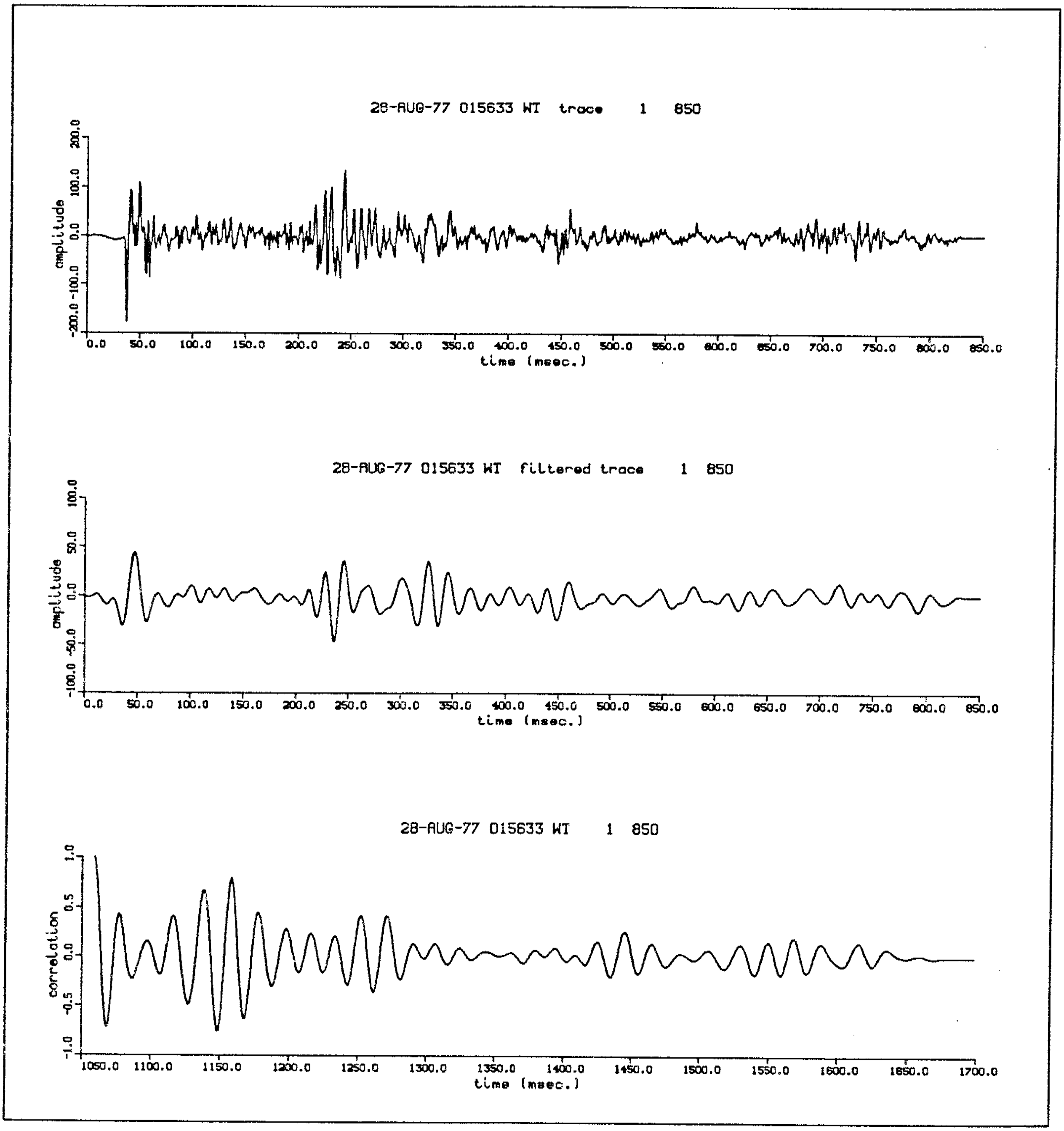
18–AUG–77 103819



18-AUG-77 103853



18–AUG–77 103915



28-AUG-77 015633

APPENDIX II
THE EFFECT OF CHANGING INPUT PARAMETERS ON THE SOLUTION

In this appendix, the consequence of changing input parameters is demonstrated. In the following examples, the hypocenter location closest to a line 45 degrees from horizontal is used. Concerning hypothesis 1, a change of the surface layer velocity to 3.4 kilometers/second from 3.71 kilometers/second causes a change in the surface layer thickness to 1.09 kilometers from 1.2 kilometers (see Table AII1). A change in the time lag, between the direct P wave and the low frequency phase, from 2.81 seconds to 2.71 seconds causes a change in the surface layer thickness to 1.10 kilometers from 1.20 kilometers (see Table AII2).

Concerning hypothesis 2, a change in depth to the station to 0.30 kilometers from 0.35 kilometers causes the sets of surface layer thicknesses of the multiples to not intersect, which means there is no simultaneous solution (see Tables AII3 and AII4). A change in the choice of the correlation peak, associated with the multiple whose last reflection was from the base of the surface layer, to lag the direct S wave by 0.58 seconds instead of 0.70 seconds causes a change in depth to station to 0.50 kilometers from 0.35 kilometers, and a change in layer thickness below station to 0.2 kilometers from 0.5 kilometers (see Tables AII5 and AII6). Finally, a change in surface layer velocity to 3.4 kilometers/second from 3.71 kilometers/second causes a change in depth to station to 0.32 kilometers from 0.35 kilometers, and a change in layer thickness below station to 0.43 kilometers from 0.5 kilometers (see Tables AII7 and AII8).

v1......	3.40
v2......	5.85
v3......	1.96
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.00
lf......	0.00
th1max..	0.62
th3max..	0.62
r1max...	8.41
r2max...	14.46

x	y	r	theta	xi
0.00	-13.76	13.76	1.57	0.98
0.71	-13.74	13.76	1.52	0.98
1.42	-13.68	13.75	1.47	0.98
2.13	-13.58	13.75	1.42	0.98
2.84	-13.45	13.74	1.36	0.99
3.54	-13.27	13.74	1.31	0.99
4.24	-13.06	13.73	1.26	0.99
4.93	-12.80	13.71	1.20	1.00
5.61	-12.50	13.70	1.15	1.01
6.29	-12.15	13.68	1.09	1.01
6.95	-11.76	13.66	1.04	1.02
7.61	-11.32	13.64	0.98	1.03
8.25	-10.82	13.61	0.92	1.05
8.88	-10.27	13.57	0.86	1.06
9.49	-9.65	13.54	0.79	1.07
10.09	-8.95	13.49	0.73	1.09
10.67	-8.16	13.44	0.65	1.11
11.23	-7.25	13.37	0.57	1.13
11.78	-6.14	13.28	0.48	1.15
12.29	-4.70	13.16	0.37	1.17

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.98	12.78	2.94	12.78	0.00	0.00
0.71	0.03	0.05	0.03	0.05	0.98	12.78	2.94	12.78	0.03	0.08
1.42	0.06	0.11	0.06	0.10	0.98	12.77	2.95	12.76	0.06	0.17
2.13	0.09	0.16	0.09	0.15	0.99	12.77	2.96	12.74	0.09	0.25
2.84	0.12	0.21	0.11	0.20	0.99	12.76	2.98	12.71	0.12	0.34
3.54	0.16	0.27	0.14	0.25	1.00	12.74	3.00	12.67	0.15	0.43
4.24	0.19	0.32	0.17	0.30	1.01	12.72	3.03	12.62	0.19	0.52
4.93	0.22	0.38	0.20	0.35	1.02	12.70	3.06	12.56	0.22	0.61
5.61	0.25	0.44	0.23	0.40	1.04	12.68	3.10	12.49	0.25	0.71
6.29	0.28	0.49	0.26	0.46	1.05	12.65	3.15	12.41	0.29	0.81
6.95	0.31	0.55	0.29	0.51	1.08	12.61	3.20	12.32	0.33	0.91
7.61	0.34	0.61	0.32	0.57	1.10	12.57	3.27	12.21	0.37	1.02
8.25	0.37	0.68	0.35	0.63	1.12	12.53	3.34	12.09	0.41	1.14
8.88	0.40	0.74	0.38	0.69	1.15	12.48	3.42	11.95	0.45	1.26
9.49	0.43	0.81	0.41	0.76	1.18	12.43	3.51	11.80	0.50	1.40
10.09	0.47	0.88	0.44	0.83	1.22	12.37	3.62	11.61	0.55	1.54
10.67	0.50	0.96	0.47	0.90	1.26	12.30	3.73	11.41	0.60	1.70
11.23	0.53	1.05	0.51	0.99	1.30	12.22	3.87	11.18	0.66	1.88
11.78	0.56	1.15	0.54	1.10	1.35	12.14	4.02	10.91	0.72	2.07
12.29	0.59	1.27	0.58	1.23	1.41	12.03	4.21	10.59	0.78	2.30

Table AII1: Raypath parameters for a recording station at the surface, a lag time between the P and multiple phases of 2.81 seconds, and a surface layer velocity of 3.4 kilometers/second. Notice that in comparison with the similar case with a surface layer velocity of 3.7 kilometers/second (see Table 1 of main text), the surface layer thickness has changed from 1.2 kilometers to 1.07 kilometers for the case of hypocentral coordinates on a line approximately 45 degrees from horizontal.

v1......	3.71
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.71
l.......	0.00
lf......	0.00
th1max..	0.69
th3max..	0.69
r1max...	9.17
r2max...	14.46

x	y	r	theta	xi
0.00	-13.91	13.91	1.57	0.96
0.73	-13.89	13.91	1.52	0.96
1.47	-13.83	13.91	1.47	0.96
2.20	-13.73	13.90	1.41	0.97
2.92	-13.59	13.90	1.36	0.97
3.65	-13.40	13.89	1.31	0.98
4.36	-13.18	13.88	1.25	0.98
5.07	-12.91	13.87	1.20	0.99
5.77	-12.59	13.85	1.14	1.00
6.46	-12.24	13.84	1.08	1.01
7.14	-11.83	13.82	1.03	1.02
7.81	-11.37	13.80	0.97	1.03
8.46	-10.86	13.77	0.91	1.04
9.10	-10.30	13.74	0.85	1.06
9.72	-9.66	13.70	0.78	1.08
10.31	-8.95	13.66	0.71	1.10
10.89	-8.15	13.60	0.64	1.12
11.45	-7.22	13.54	0.56	1.14
11.98	-6.12	13.45	0.47	1.17
12.48	-4.69	13.33	0.36	1.20

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.96	12.95	2.89	12.95	0.00	0.00
0.73	0.03	0.05	0.03	0.05	0.96	12.95	2.89	12.94	0.03	0.09
1.47	0.07	0.11	0.06	0.10	0.97	12.94	2.90	12.93	0.07	0.18
2.20	0.10	0.16	0.09	0.15	0.97	12.93	2.91	12.90	0.10	0.27
2.92	0.14	0.22	0.13	0.20	0.98	12.92	2.93	12.87	0.13	0.37
3.65	0.17	0.27	0.16	0.25	0.99	12.90	2.96	12.83	0.17	0.47
4.36	0.21	0.33	0.19	0.30	1.00	12.88	3.00	12.77	0.21	0.57
5.07	0.24	0.38	0.22	0.35	1.02	12.86	3.04	12.71	0.24	0.67
5.77	0.27	0.44	0.25	0.41	1.03	12.83	3.09	12.63	0.28	0.77
6.46	0.31	0.50	0.29	0.46	1.06	12.80	3.15	12.54	0.32	0.89
7.14	0.34	0.56	0.32	0.52	1.08	12.76	3.21	12.43	0.36	1.00
7.81	0.38	0.62	0.35	0.57	1.11	12.72	3.29	12.31	0.41	1.13
8.46	0.41	0.68	0.38	0.63	1.14	12.67	3.37	12.18	0.46	1.26
9.10	0.45	0.75	0.42	0.69	1.17	12.61	3.47	12.02	0.51	1.41
9.72	0.48	0.82	0.45	0.76	1.21	12.55	3.59	11.84	0.56	1.57
10.31	0.52	0.89	0.49	0.83	1.26	12.48	3.72	11.63	0.62	1.74
10.89	0.55	0.97	0.52	0.91	1.31	12.39	3.87	11.39	0.69	1.93
11.45	0.58	1.05	0.56	0.99	1.37	12.30	4.05	11.11	0.76	2.15
11.98	0.62	1.15	0.60	1.09	1.44	12.20	4.25	10.79	0.83	2.39
12.48	0.65	1.28	0.64	1.23	1.52	12.07	4.50	10.39	0.92	2.69

Table AII2: Raypath parameters for a recording station at the surface, a lag time between the P and multiple phases of 2.71 seconds, and a surface layer velocity of 3.71 kilometers/second. Notice that in comparison with the similar case with a time lag between the P and low frequency phases of 2.81 (see Table 1 of main text), the surface layer thickness has changed from 1.2 kilometers to 1.08 kilometers for the case of hypocentral coordinates on a line approximately 45 degrees from horizontal.

v1......	3.71
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.51
l.......	0.30
lf......	2.00
th1max..	0.69
th3max..	0.69
r1max...	9.17
r2max...	14.46

x	y	r	theta	xi
0.00	-14.21	14.21	1.57	0.45
0.76	-14.19	14.21	1.52	0.45
1.52	-14.12	14.20	1.46	0.45
2.28	-14.02	14.20	1.41	0.45
3.03	-13.87	14.20	1.36	0.45
3.78	-13.68	14.19	1.30	0.46
4.52	-13.45	14.19	1.25	0.46
5.26	-13.17	14.18	1.19	0.47
5.99	-12.84	14.17	1.13	0.48
6.71	-12.47	14.16	1.08	0.48
7.42	-12.05	14.15	1.02	0.49
8.12	-11.57	14.14	0.96	0.50
8.80	-11.04	14.12	0.90	0.51
9.48	-10.45	14.10	0.83	0.53
10.13	-9.78	14.08	0.77	0.54
10.77	-9.03	14.06	0.70	0.55
11.39	-8.18	14.02	0.62	0.57
11.99	-7.19	13.98	0.54	0.59
12.57	-6.00	13.93	0.45	0.61
13.13	-4.44	13.86	0.33	0.64

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.45	13.76	1.94	13.76	0.00	0.00
0.76	0.03	0.05	0.03	0.05	0.45	13.76	1.94	13.76	0.02	0.06
1.52	0.07	0.11	0.06	0.10	0.45	13.75	1.95	13.74	0.03	0.13
2.28	0.10	0.16	0.10	0.15	0.45	13.75	1.97	13.72	0.05	0.19
3.03	0.14	0.22	0.13	0.20	0.46	13.74	1.98	13.70	0.06	0.25
3.78	0.17	0.27	0.16	0.26	0.47	13.73	2.00	13.67	0.08	0.32
4.52	0.21	0.33	0.19	0.31	0.47	13.72	2.03	13.63	0.10	0.39
5.26	0.24	0.38	0.23	0.36	0.48	13.70	2.06	13.57	0.12	0.46
5.99	0.27	0.44	0.26	0.42	0.49	13.68	2.10	13.52	0.13	0.54
6.71	0.31	0.50	0.29	0.47	0.51	13.67	2.14	13.45	0.15	0.61
7.42	0.34	0.56	0.32	0.53	0.52	13.64	2.19	13.37	0.18	0.70
8.12	0.38	0.62	0.36	0.58	0.54	13.61	2.25	13.28	0.20	0.79
8.80	0.41	0.68	0.39	0.65	0.56	13.58	2.31	13.18	0.22	0.88
9.48	0.45	0.75	0.42	0.71	0.58	13.55	2.39	13.06	0.25	0.98
10.13	0.48	0.82	0.46	0.77	0.61	13.50	2.48	12.92	0.28	1.10
10.77	0.52	0.89	0.49	0.85	0.64	13.46	2.57	12.77	0.31	1.22
11.39	0.55	0.97	0.53	0.92	0.67	13.40	2.69	12.59	0.35	1.36
11.99	0.58	1.05	0.57	1.01	0.71	13.35	2.81	12.39	0.39	1.51
12.57	0.62	1.15	0.60	1.11	0.75	13.28	2.96	12.15	0.44	1.68
13.13	0.65	1.28	0.64	1.24	0.80	13.20	3.14	11.87	0.49	1.88

Table AII3: Change of depth to station for the raypath whose last reflection was from the base of the surface layer (hypothesis 2). Notice that when the depth to station is changed from 0.35 to 0.3, the set of hypocenters and the set of layer thicknesses do not intersect with those of the raypath whose last reflection was from the free boundary (Table AII4).

v1......	3.71
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.30
lf......	4.00
th1max..	0.69
th3max..	0.69
r1max...	9.17
r2max...	14.46

x	y	r	theta	xi
0.00	-14.19	14.19	1.57	0.47
0.76	-14.17	14.19	1.52	0.47
1.52	-14.11	14.19	1.46	0.47
2.27	-14.00	14.19	1.41	0.47
3.03	-13.86	14.18	1.36	0.48
3.77	-13.67	14.18	1.30	0.48
4.51	-13.43	14.17	1.25	0.49
5.25	-13.15	14.16	1.19	0.50
5.98	-12.83	14.15	1.13	0.51
6.69	-12.46	14.14	1.08	0.52
7.40	-12.03	14.13	1.02	0.53
8.09	-11.56	14.11	0.96	0.54
8.77	-11.03	14.09	0.90	0.56
9.44	-10.43	14.07	0.84	0.58
10.09	-9.77	14.04	0.77	0.60
10.72	-9.02	14.01	0.70	0.62
11.33	-8.17	13.97	0.62	0.64
11.91	-7.19	13.92	0.54	0.67
12.48	-6.02	13.86	0.45	0.70
13.01	-4.49	13.76	0.33	0.74

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.47	13.72	2.61	13.72	0.00	0.00
0.76	0.03	0.05	0.03	0.05	0.47	13.72	2.61	13.72	0.02	0.08
1.52	0.07	0.11	0.06	0.10	0.47	13.72	2.62	13.71	0.03	0.16
2.27	0.10	0.16	0.09	0.15	0.48	13.71	2.64	13.68	0.05	0.25
3.03	0.14	0.22	0.13	0.20	0.48	13.70	2.66	13.65	0.07	0.33
3.77	0.17	0.27	0.16	0.25	0.49	13.69	2.68	13.60	0.08	0.42
4.51	0.21	0.33	0.19	0.30	0.50	13.67	2.72	13.55	0.10	0.51
5.25	0.24	0.38	0.22	0.35	0.51	13.66	2.76	13.48	0.12	0.60
5.98	0.27	0.44	0.25	0.40	0.53	13.63	2.81	13.41	0.14	0.70
6.69	0.31	0.50	0.28	0.46	0.54	13.61	2.87	13.31	0.17	0.80
7.40	0.34	0.56	0.32	0.51	0.56	13.58	2.93	13.21	0.19	0.91
8.09	0.38	0.62	0.35	0.57	0.58	13.54	3.01	13.09	0.22	1.03
8.77	0.41	0.68	0.38	0.63	0.61	13.50	3.10	12.95	0.24	1.16
9.44	0.45	0.75	0.42	0.69	0.64	13.45	3.21	12.78	0.28	1.29
10.09	0.48	0.82	0.45	0.76	0.67	13.40	3.32	12.60	0.31	1.44
10.72	0.52	0.89	0.48	0.83	0.71	13.34	3.45	12.39	0.35	1.61
11.33	0.55	0.97	0.52	0.90	0.75	13.28	3.60	12.15	0.39	1.79
11.91	0.58	1.05	0.56	0.99	0.80	13.20	3.79	11.86	0.44	2.00
12.48	0.62	1.15	0.60	1.09	0.86	13.11	3.99	11.53	0.50	2.25
13.01	0.65	1.28	0.64	1.23	0.93	13.00	4.26	11.12	0.56	2.54

Table AII4: Change of depth to station for the raypath whose last reflection was from the free boundary (hypothesis 2).
Notice that when the depth to station is changed from 0.35 to 0.3, the set of hypocenters and the set of layer thicknesses do not intersect with those of the raypath whose last reflection was from base of the surface layer (see Table AII3).

v1......	3.71
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.39
l.......	0.50
lf......	2.00
th1max..	0.69
th3max..	0.69
r1max...	9.17
r2max...	14.46

x	y	r	theta	xi
0.00	-14.40	14.40	1.57	0.12
0.78	-14.37	14.39	1.52	0.12
1.55	-14.31	14.39	1.46	0.12
2.33	-14.20	14.39	1.41	0.12
3.10	-14.05	14.39	1.35	0.13
3.86	-13.86	14.39	1.30	0.13
4.63	-13.62	14.39	1.24	0.13
5.38	-13.34	14.38	1.19	0.14
6.13	-13.01	14.38	1.13	0.14
6.87	-12.62	14.37	1.07	0.15
7.60	-12.19	14.36	1.01	0.16
8.32	-11.70	14.36	0.95	0.16
9.02	-11.15	14.35	0.89	0.17
9.72	-10.54	14.34	0.83	0.18
10.40	-9.85	14.32	0.76	0.20
11.06	-9.08	14.31	0.69	0.21
11.71	-8.19	14.29	0.61	0.22
12.34	-7.17	14.27	0.53	0.24
12.95	-5.93	14.24	0.43	0.26
13.53	-4.29	14.20	0.31	0.28

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.12	14.28	1.36	14.28	0.00	0.00
0.78	0.03	0.05	0.03	0.05	0.12	14.27	1.36	14.27	0.00	0.04
1.55	0.07	0.11	0.07	0.10	0.12	14.27	1.36	14.26	0.01	0.09
2.33	0.10	0.16	0.10	0.15	0.12	14.27	1.37	14.25	0.01	0.13
3.10	0.14	0.22	0.13	0.21	0.13	14.26	1.39	14.23	0.02	0.18
3.86	0.17	0.27	0.16	0.26	0.13	14.26	1.40	14.21	0.02	0.23
4.63	0.21	0.33	0.20	0.31	0.13	14.25	1.42	14.17	0.03	0.28
5.38	0.24	0.38	0.23	0.37	0.14	14.24	1.45	14.13	0.03	0.33
6.13	0.27	0.44	0.26	0.42	0.15	14.23	1.48	14.09	0.04	0.38
6.87	0.31	0.50	0.29	0.48	0.16	14.22	1.51	14.03	0.05	0.44
7.60	0.34	0.56	0.33	0.53	0.17	14.20	1.55	13.97	0.06	0.50
8.32	0.38	0.62	0.36	0.59	0.18	14.19	1.60	13.90	0.07	0.56
9.02	0.41	0.68	0.39	0.65	0.19	14.16	1.65	13.82	0.08	0.63
9.72	0.45	0.75	0.43	0.72	0.20	14.14	1.71	13.73	0.09	0.71
10.40	0.48	0.82	0.46	0.78	0.22	14.11	1.78	13.62	0.10	0.79
11.06	0.52	0.89	0.50	0.85	0.24	14.09	1.85	13.50	0.12	0.88
11.71	0.55	0.97	0.53	0.93	0.26	14.05	1.94	13.36	0.14	0.99
12.34	0.58	1.05	0.57	1.02	0.29	14.01	2.04	13.20	0.16	1.10
12.95	0.62	1.15	0.61	1.12	0.32	13.97	2.16	13.02	0.18	1.23
13.53	0.65	1.28	0.65	1.25	0.35	13.91	2.29	12.80	0.21	1.38

Table AII5: Choice of the positive correlation peak following the direct shear wave by 0.58 seconds (instead of the negative correlation peak which follows by 0.7 seconds) to be the correlation with the multiple whose last reflection is from the base of the surface layer. Note that the layer station is now only 0.2 kilometers above the base of the layer, 0.5 kilometers below the surface (compare with Table 2 and 3 of text, and AII6 of this appendix).

v1......	3.71
v2......	5.85
v3......	2.14
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.50
lf......	4.00
th1max..	0.69
th3max..	0.69
r1max...	9.17
r2max...	14.46

x	y	r	theta	xi
0.00	-14.42	14.42	1.57	0.07
0.78	-14.40	14.42	1.52	0.07
1.56	-14.34	14.42	1.46	0.07
2.33	-14.23	14.42	1.41	0.07
3.11	-14.08	14.42	1.35	0.08
3.88	-13.88	14.41	1.30	0.08
4.64	-13.64	14.41	1.24	0.09
5.40	-13.36	14.40	1.19	0.10
6.14	-13.02	14.40	1.13	0.11
6.88	-12.64	14.39	1.07	0.12
7.61	-12.20	14.38	1.01	0.13
8.33	-11.71	14.37	0.95	0.14
9.03	-11.16	14.36	0.89	0.16
9.72	-10.54	14.34	0.83	0.18
10.40	-9.85	14.32	0.76	0.20
11.05	-9.08	14.30	0.69	0.22
11.69	-8.19	14.27	0.61	0.24
12.31	-7.17	14.24	0.53	0.27
12.90	-5.93	14.20	0.43	0.30
13.47	-4.31	14.14	0.31	0.34

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.07	14.35	2.21	14.35	0.00	0.00
0.78	0.03	0.05	0.03	0.05	0.07	14.35	2.21	14.35	0.00	0.07
1.56	0.07	0.11	0.06	0.10	0.07	14.35	2.22	14.34	0.00	0.14
2.33	0.10	0.16	0.09	0.15	0.07	14.35	2.23	14.32	0.01	0.21
3.11	0.14	0.22	0.13	0.20	0.08	14.34	2.25	14.28	0.01	0.28
3.88	0.17	0.27	0.16	0.25	0.09	14.33	2.28	14.24	0.01	0.36
4.64	0.21	0.33	0.19	0.30	0.09	14.32	2.31	14.19	0.02	0.43
5.40	0.24	0.38	0.22	0.35	0.10	14.31	2.35	14.13	0.02	0.51
6.14	0.27	0.44	0.25	0.41	0.11	14.29	2.40	14.05	0.03	0.60
6.88	0.31	0.50	0.28	0.46	0.12	14.27	2.45	13.97	0.04	0.69
7.61	0.34	0.56	0.32	0.51	0.14	14.25	2.52	13.87	0.05	0.79
8.33	0.38	0.62	0.35	0.57	0.15	14.22	2.59	13.75	0.06	0.89
9.03	0.41	0.68	0.38	0.63	0.17	14.19	2.67	13.62	0.07	1.00
9.72	0.45	0.75	0.42	0.69	0.20	14.15	2.77	13.47	0.09	1.12
10.40	0.48	0.82	0.45	0.76	0.22	14.11	2.88	13.30	0.10	1.25
11.05	0.52	0.89	0.49	0.83	0.25	14.07	3.00	13.10	0.12	1.40
11.69	0.55	0.97	0.52	0.90	0.29	14.01	3.15	12.87	0.15	1.57
12.31	0.58	1.05	0.56	0.99	0.32	13.95	3.32	12.60	0.18	1.76
12.90	0.62	1.15	0.60	1.09	0.37	13.88	3.52	12.28	0.22	1.98
13.47	0.65	1.28	0.64	1.23	0.43	13.79	3.76	11.91	0.26	2.24

Table AII6: Choice of the positive correlation peak following the direct shear wave by 0.58 seconds (instead of the negative correlation peak which follows by 0.7 seconds) to be the correlation with the multiple whose last reflection is from the base of the surface layer. Note that the layer station is now only 0.2 kilometers above the base of the layer, 0.5 kilometers below the surface (compare with Table 2 and 3 of text, and AII5 of this appendix).

v1......	3.40
v2......	5.85
v3......	1.96
v4......	3.38
dsp.....	1.81
dmp.....	2.51
l.......	0.32
lf......	2.00
th1max..	0.62
th3max..	0.62
r1max...	8.41
r2max...	14.46

x	y	r	theta	xi
0.00	-14.20	14.20	1.57	0.37
0.75	-14.18	14.20	1.52	0.37
1.50	-14.12	14.20	1.47	0.37
2.24	-14.02	14.20	1.41	0.37
2.99	-13.88	14.19	1.36	0.37
3.73	-13.69	14.19	1.30	0.37
4.46	-13.46	14.18	1.25	0.38
5.20	-13.19	14.18	1.20	0.38
5.92	-12.87	14.17	1.14	0.39
6.64	-12.51	14.16	1.08	0.39
7.34	-12.10	14.15	1.03	0.40
8.04	-11.63	14.14	0.97	0.40
8.73	-11.10	14.13	0.90	0.41
9.41	-10.51	14.11	0.84	0.42
10.08	-9.85	14.09	0.77	0.43
10.73	-9.10	14.07	0.70	0.44
11.36	-8.24	14.04	0.63	0.46
11.98	-7.24	14.00	0.54	0.47
12.59	-6.04	13.96	0.45	0.48
13.17	-4.44	13.90	0.32	0.50

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.37	13.84	1.74	13.84	0.00	0.00
0.75	0.03	0.05	0.03	0.05	0.37	13.84	1.74	13.83	0.01	0.05
1.50	0.06	0.11	0.06	0.10	0.37	13.83	1.74	13.82	0.02	0.10
2.24	0.09	0.16	0.09	0.15	0.37	13.83	1.75	13.81	0.03	0.15
2.99	0.12	0.21	0.12	0.20	0.37	13.82	1.76	13.79	0.05	0.21
3.73	0.16	0.27	0.15	0.25	0.38	13.81	1.78	13.76	0.06	0.26
4.46	0.19	0.32	0.18	0.31	0.38	13.80	1.80	13.73	0.07	0.32
5.20	0.22	0.38	0.21	0.36	0.39	13.79	1.82	13.69	0.08	0.37
5.92	0.25	0.44	0.24	0.41	0.40	13.78	1.85	13.64	0.10	0.43
6.64	0.28	0.49	0.27	0.47	0.41	13.76	1.88	13.59	0.11	0.49
7.34	0.31	0.55	0.30	0.53	0.42	13.74	1.92	13.52	0.13	0.56
8.04	0.34	0.61	0.33	0.58	0.43	13.73	1.96	13.45	0.14	0.63
8.73	0.37	0.68	0.36	0.64	0.44	13.70	2.00	13.37	0.16	0.70
9.41	0.40	0.74	0.39	0.71	0.46	13.67	2.06	13.28	0.18	0.78
10.08	0.43	0.81	0.42	0.77	0.48	13.64	2.12	13.18	0.20	0.86
10.73	0.47	0.88	0.45	0.85	0.50	13.61	2.19	13.06	0.22	0.95
11.36	0.50	0.96	0.48	0.92	0.52	13.57	2.27	12.92	0.25	1.05
11.98	0.53	1.05	0.51	1.01	0.54	13.53	2.35	12.77	0.27	1.16
12.59	0.56	1.15	0.55	1.11	0.57	13.48	2.45	12.60	0.30	1.28
13.17	0.59	1.27	0.58	1.25	0.60	13.43	2.57	12.40	0.34	1.41

Table AII7: Raypath parameters for hypothesis 2 but with a surface layer velocity of 3.4 kilometers/second. Notice that the depth to station has changed to 0.32 kilometers (from 0.35 kilometers), and the surface layer thickness below the station has changed to 0.43 kilometers (from 0.5 kilometers). These parameters are for the multiple whose last reflection is from the base of the surface layer (compare with Table AII8).

v1......	3.40
v2......	5.85
v3......	1.96
v4......	3.38
dsp.....	1.81
dmp.....	2.81
l.......	0.32
lf......	4.00
th1max..	0.62
th3max..	0.62
r1max...	8.41
r2max...	14.46

x	y	r	theta	xi
0.00	-14.22	14.22	1.57	0.34
0.75	-14.20	14.22	1.52	0.34
1.50	-14.14	14.22	1.47	0.34
2.25	-14.04	14.21	1.41	0.34
2.99	-13.89	14.21	1.36	0.35
3.74	-13.71	14.21	1.30	0.35
4.47	-13.48	14.20	1.25	0.35
5.20	-13.20	14.19	1.20	0.36
5.93	-12.89	14.18	1.14	0.37
6.65	-12.52	14.17	1.08	0.37
7.35	-12.10	14.16	1.02	0.39
8.05	-11.63	14.15	0.97	0.39
8.74	-11.10	14.13	0.90	0.41
9.41	-10.51	14.11	0.84	0.42
10.07	-9.85	14.09	0.77	0.43
10.72	-9.10	14.06	0.70	0.45
11.35	-8.24	14.03	0.63	0.47
11.97	-7.24	13.99	0.54	0.49
12.56	-6.04	13.94	0.45	0.51
13.13	-4.45	13.86	0.33	0.53

x	th1	th2	th3	th4	r1	r2	r3	r4	rp	mrp
0.00	0.00	0.00	0.00	0.00	0.34	13.88	2.30	13.88	0.00	0.00
0.75	0.03	0.05	0.03	0.05	0.34	13.88	2.30	13.88	0.01	0.07
1.50	0.06	0.11	0.06	0.10	0.34	13.88	2.30	13.87	0.02	0.13
2.25	0.09	0.16	0.09	0.15	0.34	13.87	2.32	13.85	0.03	0.20
2.99	0.12	0.21	0.11	0.20	0.35	13.86	2.33	13.82	0.04	0.27
3.74	0.16	0.27	0.14	0.25	0.36	13.85	2.36	13.78	0.05	0.34
4.47	0.19	0.32	0.17	0.30	0.36	13.84	2.38	13.74	0.07	0.41
5.20	0.22	0.38	0.20	0.35	0.37	13.83	2.41	13.68	0.08	0.48
5.93	0.25	0.44	0.23	0.41	0.38	13.81	2.45	13.62	0.09	0.56
6.65	0.28	0.49	0.26	0.46	0.39	13.79	2.49	13.55	0.11	0.64
7.35	0.31	0.55	0.29	0.51	0.40	13.77	2.54	13.46	0.12	0.73
8.05	0.34	0.61	0.32	0.57	0.42	13.74	2.60	13.37	0.14	0.82
8.74	0.37	0.68	0.35	0.63	0.44	13.71	2.66	13.25	0.16	0.91
9.41	0.40	0.74	0.38	0.69	0.46	13.68	2.73	13.13	0.18	1.01
10.07	0.43	0.81	0.41	0.76	0.48	13.64	2.82	12.99	0.20	1.13
10.72	0.47	0.88	0.44	0.83	0.50	13.60	2.91	12.83	0.23	1.25
11.35	0.50	0.96	0.48	0.91	0.53	13.55	3.02	12.64	0.25	1.38
11.97	0.53	1.05	0.51	1.00	0.56	13.50	3.14	12.44	0.28	1.53
12.56	0.56	1.15	0.54	1.10	0.60	13.43	3.28	12.19	0.32	1.70
13.13	0.59	1.27	0.58	1.24	0.64	13.36	3.45	11.90	0.36	1.89

Table AII8: Raypath parameters for hypothesis 2 but with a surface layer velocity of 3.4 kilometers/second. Notice that the depth to station has changed to 0.32 kilometers (from 0.35 kilometers), and the surface layer thickness below the station has changed to 0.43 kilometers (from 0.5 kilometers). These parameters are for the multiple whose last reflection is from the free surface (compare with table AII7).

APPENDIX III
COMPUTER CODE

```
      dimension r(50),th(50),xi(50),x(50),y(50)
      dimension ath1(50),ath2(50),ath3(50),ath4(50)
      dimension ar1(50),ar2(50),ar3(50),ar4(50)
      dimension rp(50),rpm(50),char(12),var(50)
      character*10 char
      open(unit=50,file='pol0')
      open(unit=51,file='pol1')
      open(unit=52,file='pol2')
      open(unit=53,file='pol3')

c     read input from file
      read(50,*)v1
      read(50,*)v2
      read(50,*)dsp
      read(50,*)v3
      read(50,*)v4
      read(50,*)dpsob
      read(50,*)el
      read(50,*)elf
      read(50,*)tm

c     calculate initial constants
      pi=2.0*asin(1.0)
      th3max=asin(v3/v4)
      th1max=asin(v1/v2)
      c1=dsp/(sqrt(3.0)-1.0)
      r1max=v1*c1
      r2max=v2*c1
      tinc=asin(v1/v2)/20.0
      rinc=r1max/10.0
      k=0

c     initialize variables
      th1=0.0
      th(1)=pi/2.0
      x(1)=0.0
      rpm(1)=0.0
      rp(1)=0.0

c     begin main loop (which increments theta 1)
      do 1000 i=1,20
          th2=asin( (v2/v1)*sin(th1) )
          k=k+1

c     determine initial guess for numerical method
          r1=0.0
          r2=r2max
          por=0.0
          if(i .eq. 1)then
          th3=0.0
          else
          po=0.0
          p1=asin(v3/v4)
          qo=r1*sin(th1)+r2*sin(th2)
          q1=-r2*cos(th2)
          t1=qo*q1
          if (t1 .gt. 0.0) then
```

```
           write(6,*)'no zero,  k= ',k
           endif
           do 6000 ii=1,15
           th3=po+(pl-po)/2.0
           tl=sqrt(1.0-  ( (v4/v3)*sin(th3) )**2.0  )
           ql=
     +        -(tm*rl*cos(thl)+el*elf)*tan(th3)-
     +         (v4/(tl*v3))*r2*cos(th2)*sin(th3)+
     +         ( rl*sin(thl)+ r2*sin(th2) )
           t20=abs(ql)
           if(t20.lt.0.001)then
              go to 6500
              endif
           tl=qo*ql
           if (tl .gt. 0.0)then
            po=th3
           else
            pl=th3
           endif
 6000     continue
          endif
 6500     r3=(tm*rl*cos(thl)+el*elf)/cos(th3)
          th4=asin(v4*sin(th3)/v3)
          r4=r2*cos(th2)/cos(th4)
          qor=-dpsob+( r3/v3 + r4/v4 -(rl/vl +r2/v2))
       plr=rlmax
       rl=rlmax
       r2=0.0
       r4=0.0
       th3=atan(rlmax*sin(thl)/(tm*rlmax*cos(thl)+el*elf))
       r3=(tm*rlmax*cos(thl)+el*elf)/cos(th3)
       qlr=-dpsob+( r3/v3 + r4/v4 -(rl/vl +r2/v2))
       tl=qor*qlr
       if(tl .gt. 0.0)then
          write(6,*)'no zero for thl ',thl
          endif

C      begin numerical search for Rl (constant theta l)
       do 2000 j=1,20
         rl=por+(plr-por)/2.0
         r2=( dsp/(sqrt(3.0)-1.0) -rl/vl )*v2

C      solve simple equations if theta l is zero
       if(i .eq. l)then
           qlr=-dpsob+r2/v4 +tm*rl/v3 -(rl/vl +r2/v2)+ el*elf/v3
           r3=tm*rl+el*elf
           r4=r2

C      find theta 3 if theta l is not zero
       else
           po=0.0
           pl=asin(v3/v4)
           qo=rl*sin(thl)+r2*sin(th2)
           ql=-r2*cos(th2)
           tl=qo*ql
           if (tl .gt. 0.0) then
            write(6,*)'no zero,  k= ',k
           endif
           do 6001 ii=1,15
           th3=po+(pl-po)/2.0
```

```
          tl=sqrt(1.0-  ( (v4/v3)*sin(th3) )**2.0   )
          ql=
     +       -(tm*rl*cos(thl)+el*elf)*tan(th3)-
     +        (v4/(tl*v3))*r2*cos(th2)*sin(th3)+
     +        ( rl*sin(thl)+ r2*sin(th2) )
          t20=abs(ql)
          if(t20.lt.0.001)then
             go to 6501
             endif
          tl=qo*ql
          if (tl .gt. 0.0)then
           po=th3
          else
           pl=th3
          endif
 6001  continue

C      calculate quantities which depend on theta 3
 6501  r3=(tm*rl*cos(thl)+el*elf)/cos(th3)
          th4=asin(v4*sin(th3)/v3)
          r4=r2*cos(th2)/cos(th4)
          qlr=-dpsob+( r3/v3 + r4/v4 -(rl/vl +r2/v2))
          tl=abs(qlr)
          if(tl .lt. 0.001)go to 6510
       endif
       tl=qor*qlr
       if(tl.gt.0.0)then
          por=rl
          else
             plr=rl
       endif
 2000 continue

C     store variables in the RAM for later printout
 6510 athl(k)=thl
      ath2(k)=th2
      ath3(k)=th3
      ath4(k)=th4
      arl(k)=rl
      ar2(k)=r2
      ar3(k)=r3
      ar4(k)=r4
      r(k)=sqrt(rl**2.0 +r2**2.0+ 2.0*rl*r2*cos(thl-th2))
      if(k .gt. 1)then
      th(k)=atan( (rl*cos(thl)+r2*cos(th2))/
     +          ( rl*sin(thl)+r2*sin(th2) ))
      x(k)=r(k)*cos(th(k))
      rpm(k)=r3*sin(th3)
      rp(k)=rl*sin(thl)
      endif
      y(k)=r(k)*sin(th(k))
      xi(k)=rl*cos(thl)
 1001 thl=thl+tinc
 1000 continue

C     write results to file poll, ect...
      char(1)='vl......'
      char(2)='v2......'
      char(3)='v3......'
      char(4)='v4......'
```

```
      char(5)='dsp.....'
      char(6)='dmp.....'
      char(7)='l.......'
      char(8)='lf......'
      char(9)='thlmax..'
      char(10)='th3max..'
      char(11)='rlmax...'
      char(12)='r2max...'
      var(1)=vl
      var(2)=v2
      var(3)=v3
      var(4)=v4
      var(5)=dsp
      var(6)=dpsob
      var(7)=el
      var(8)=elf
      var(9)=thlmax
      var(10)=th3max
      var(11)=rlmax
      var(12)=r2max
      write(51,8900)
 8900 format(36x,6x,'x',6x,'y',6x,'r',2x,'theta',5x,'xi')
      do 8000 i=l,k
         if(i .lt. 13)then
         write(51,9000)char(i),var(i),x(i),-y(i),r(i),th(i),xi(i)
 9000    format(9x,a,f7.2,l0x,5f7.2)
         else
         write(51,10000)x(i),-y(i),r(i),th(i),xi(i)
10000    format(36x,5f7.2)
         endif
         write(52,*)x(i),-y(i)
 8000    continue
         write(51,11500)
11500    format(//,10x,'x',3x,'thl',3x,'th2',3x,'th3',3x,'th4',
     +           4x,'rl',4x,'r2',4x,'r3',4x,'r4',4x,'rp',3x,'mrp')
         do 11000 i=l,k
            write(51,12000)x(i),athl(i),ath2(i),ath3(i),ath4(i),
     +                  arl(i),ar2(i),ar3(i),ar4(i),rp(i),rpm(i)
12000       format(5x,llf6.2)
11000       continue

C     receive diploma
      stop
      end
```

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