ANALYSIS OF THE RELATIONSHIP BETWEEN ASSOCIATED VOLCANIC AND SEISMIC EVENTS

EDWARD J. WALTER
DIRECTOR SEISMOLOGICAL OBSERVATORY
JOHN CARROLL UNIVERSITY
CLEVELAND OHIO

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PROJECT 8652

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
BEDFORD, MASSACHUSETTS

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENGY

PROJECT VELA-UNIFORM

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ABSTRACT

This project was undertaken to study earthquakes that occur in volcanic regions and which result from volcanic processes. The purpose was to determine whether or not these volcanic quakes are the same as ordinary earthquakes, and if not, just how they differ and what seismic parameters can be used to identify them.

Three areas were selected for investigation: Italy, Hawaii and Japan. Volcanoes in Italy and Japan are explosive while those in Hawaii are not. The Italian volcanoes have been under investigation for many years and under observation for centuries. Hawaiian Volcanology and Japanese Volcanology are more recent but both have contributed greatly to the application of modern geophysical techniques to Volcanology.

Seismic data from all three areas were analyzed. Crustal models and seismic wave velocities, where available, were used as a basis for locating epicenters. Graphical methods such as the Δ P-H Arc-Distance Method and the Hyperbolic Method were used to locate epicenters. A computer program was set up for the same purpose. Several techniques were developed to augment the use of data in the computer program. One of these was the technique of supplying a fictitious arrival time at a seismic station and varying this arrival time value until all the input data converged to a solution. Results of the graphical solutions and those from the computer program were in excellent agreement.

Epicentral locations gave distances, azimuths and focal depths which were important in analyzing various seismic parameters. Hawaiian volcanic quakes show distinct tectonic characteristics. Quadrantal patterns of first motion can be delineated and related to tectonic features. Japanese quakes show a mixed set of characteristics. Some patterns are quadrantal, indicating a tectonic relationship, while others show push or compressional motion at all stations indicating an explosive mechanism. Vesuvius shows both compressional and dilatational first motion.

Amplitude distance relationships fail to show statistical significance at Vesuvius because the observations are all from a single station. In Hawaii there is a significant relationship. Magnitude curves based on log A versus log Δ show that the earthquakes are of low energy with magnitudes from plus one, down to negative values and quakes are usually not recorded at any great distance. Attenuation is high in the caldera region.

Volcanic quakes occur in swarms and an analysis of the frequency of occurrence was made. Tectonic and explosion quakes have characteristic values for m in the equation $NA^m = c$. This parameter or coefficient may depend on a number of factors - such as focal mechanism, focal depth, and stress application. Stress application certainly is part of the focal mechanism but, in the sense of an externally applied surface stress, it is vastly different from any of the usual earthquake mechanisms. It seems possible that such a stress application might have a characteristic m value.

ANALYSIS OF THE RELATIONSHIP BETWEEN ASSOCIATED VOLCANIC AND SEISMIC EVENTS

1

INTRODUCTION

Perhaps one of the oldest associations of natural phenomena is that of volcanoes and earthquakes. In the many regions of the earth in which these phenomena occur, man has puzzled as to their relationship. In more modern times geophysicists have come to a recognition of tectonic earthquakes as distinct from volcanic earthquakes but even here the distinction becomes vague in many cases.

Volcanic earthquakes could be loosely described as earthquakes associated with a volcanic eruption, leaving unanswered many questions as to the seismic events in both the pre-eruptive and post-eruptive periods. One set of notable characteristics of volcanic earthquakes is that they are very low in intensity and occur in swarms.

The nature of these seismic events can be better perceived when the fundamental volcanic process is known and understood. The cause and mechanics of a volcanic eruption represent a very complex subject which the author prefers to leave to those who are better qualified. However, all eruptions involve certain basic processes which can be delineated here and which will throw some light on the resulting seismic events. First, there is the pre-eruptive stage during which there is the movement of magmatic material from depth toward the surface of the earth. Associated with the vertical rise of the magma there may be significant horizontal movements as well. Second, there is the actual eruptive stage in which volcanic material is discharged at the surface. The eruptive stage may vary from a quiescent outpouring of fluid lava at the one extreme to the violently explosive eruption at the other extreme. Volcanologists have developed an impressive classification of eruptive types and resulting eruptive materials. Finally, there is the post-eruptive stage during which the processes that have been active in producing the eruption are seeking an equilibrium condition.

During these various stages, seismic activity manifests itself as an increasing swarm of very small earthquakes. These are probably associated with the transport of magma either vertically or horizontally, resulting in the splitting and rupture of the crustal rock layers and with the general distention of the area. Closely associated with the actual eruptive stage is the development of volcanic tremor which is a continuous vibration of the crust.

2

AREAS INVESTIGATED

The present project has as its immediate purpose the investigation of seismic signals originating in volcanic areas to delineate if possible unique identifying characteristics which will distinguish them from seismic signals associated with other types of earthquakes whether natural or artificial. Originally two volcanic areas, Italy and Hawaii, were selected for investigation, and then a third area, Japan, was added.

MOUNT VESUVIUS

The Italian investigation began with a visit to Professor Pietro Caloi, Director of the National Institute of Geophysics. Here data and information on the local crustal structure and seismicity were gathered as background information for the investigations of Mount Vesuvius and Mount Etna which were to follow.

3.1 THE VESUVIAN OBSERVATORY

At Mount Vesuvius, Professor Guiseppe Imbo, Director of the Vesuvian Observatory and also Director of the Institute of Physics of the Earth, University of Naples, put the facilities of the Observatory at my disposal. Due to the lack of instrumental constants only data after 1944 were useful for the investigation. The instruments consisted of two horizontal component 200 kg Wiechert Seismographs and a vertical component 80 kg Wiechert Seismograph.

Free period and static magnification for the instruments are as follows:

Component	T_o	V_o
NS	4.1	158
EW	4.1	158
Z	2.25	118

Magnification curves were available for each instrument. The approximate distance from the Vesuvian Observatory to the center of the crater of Mount Vesuvius is 2.5 kilometers. The elevation of the Observatory is 609 meters, that of the crater floor is 951 meters, and the rim of the crater is some 200 meters higher. This presents the interesting situation that seismic foci could be either above or below the Observatory level.

3.2 VESUVIAN EARTHQUAKES

In the following table, time is Central European Mean Time, Amplitude A is in millimeters as read from the record, period T is in seconds, and direction of motion is N-north, S-south, E-east, W-west, c-compression, and d-dilatation.

TABLE I VESUVIAN QUAKES

No.	Date	Phase	Time	Direction	Amplitude	Period
1	11-3-61	iP	18-28-25.0	S	0.2	-
		iP	25.0	-	-	-
		iP	25.6	d	0.1	-
		eS	25.9	N	0.7	-
		eS	26.0	E	0.2	0.2
2	8-4-61	iP	01-50-27.7	S	0.4	0.4
		iP	28.1	E	0.3	0.4
3	7-27-61	eP	13-01-36.3	N	0.2	0.4
		iP	37.1	W	0.4	0.6
4	7-6-61	iP	11-22-23.6	S	0.4	0.4
		eP	23.6	E	0.4	0.6
		eS	25.2	E	0.7	0.8
		iS	25.4	S	1.0	0.5
5	6-27-61	iP	05-02-08.3	S	0.2	0.3
		eP	08.3	E	0.3	0.6
6	5-19-61	iP	23-05-42.5	d	-	-
		iP	42.6	N	0.2	0.6
		eP	43.0	W	0.4	0.6
7	5-11-61	iP	23-53-28.[illegible]	S	0.3	0.5
		iP	28.5	E	0.4	0.5
		iS	29.0	N	0.8	0.7
		iS	30.0	E	0.8	0.5
8	5-10-61	iP	17-16-38.8	E	0.3	0.1
		e	41.7	W	0.7	0.4
		i	42.6	S	1.0	0.6

No.	Date	Phase	Time	Direction	Amplitude	Period
9	9-29-60	iP	10-32-11.8	N	0.2	0.2
		iP	11.9	d	0.2	0.2
		iP	12.0	W	0.4	0.2
		iS	12.6	S	1.0	0.4
		iS	12.8	E	0.8	0.2
10	8-30-60	iP	07-34-33.7	W	0.3	0.4
		iP	34.4	d	0.3	0.2
		iS	34.7	N	0.8	0.3
		iS	34.7	E	0.8	0.6
11	7-14-60	iP	04-00-35.1	S	0.1	-
		iP	35.1	W	0.2	0.2
		iP	35.4	d	0.1	-
12	7- 7-60	eP	01-16-32.1	S	0.1	0.8
		eP	32.1	-	0.1	0.2
13	7- 7-60	iP	01-16-33.5	N	0.2	0.6
		iP	33.9	W	0.2	0.5
		iP	34.0	d	0.2	0.4
		iS	37.8	S	0.5	0.7
		i	39.1	E	0.5	0.5
14	12- 2-56	eP	02-54-55.2	d	0.3	0.8
		iP	56.4	c	0.5	0.8
		iP	56.4	N	0.8	0.8
		iP	56.4	W	0.4	0.8
		iS	58.0	W	2.2	0.8
		iS	58.3	S	2.6	0.9
		iS	58.8	c	0.7	0.8
		i	55-00.2	E	2.7	0.9
15	12- 2-56	iP	02-42-55.2	W	0.3	0.6
		eP	55.4	c	0.3	0.6
		iP	55.5	N	0.3	0.4
		iS	58.3	d	0.4	0.6
		iS	58.6	N	0.6	-
		i	43-01.1	S	0.8	1.0
16	11-30-56	iP	22-33-41.7	E	0.7	0.8
		iP	42.4	d	0.5	0.8
		iP	42.4	N	1.6	0.8
		iS	44.5	c	0.7	0.4
		iS	44.6	E	2.8	0.6
		iS	45.2	N	3.3	0.6
		i	46.4	S	5.4	0.6

No.	Date	Phase	Time	Direction	Amplitude	Period
17	11-30-56	iP	23-33-09.8	S	0.5	0.8
		iP	09.9	W	0.5	0.6
		iP	10.4	d	0.2	0.5
		iS	13.8	d	0.5	0.6
		iS	13.8	N	0.5	0.6
		iS	14.2	W	0.8	0.6
18	9-24-56	iP	22-40-45.7	d	0.3	0.4
		iP	45.9	S	0.8	0.6
		eP	45.9	E	0.6	0.6
		iS	46.9	S	0.2	1.6
		iS	47.1	W	0.7	0.8
		eS	47.6	d	0.8	0.4
19	7-26-56	eP	03-03-42.5	d	0.2	-
		iP	42.6	S	0.4	-
		iP	42.6	E	0.4	-
20	3-22-56	iP	18-06-39.6	W	0.3	0.2
		iP	39.8	d	0.1	0.4
		iP	39.8	S	0.4	0.4
		iS	40.2	W	0.3	-
		iS	40.7	d	0.7	0.4
		iS	40.7	N	0.3	0.4
		i	41.3	S	0.8	1.6
21	2-2-56	eP	16-53-23.2	W	0.4	-
		iP	23.5	c	0.2	0.2
		iP	25.0	c	0.2	0.2
		eP	25.7	N	0.5	-
		eP	25.7	E	0.5	0.6
		iS	26.2	c	0.3	0.8
		iS	27.5	E	0.4	0.6
		iS	28.3	N	0.8	0.4
22	1-15-56	eP	05-04-05.3	N	0.2	-
		eP	05.8	S	0.3	0.6
		eP	05.8	E	0.2	0.4
		iS	07.0	S	0.7	0.6
		iS	07.4	W	0.7	0.4
23	1-15-56	eP	05-03-05.9	c	0.2	-
		iP	05.9	S	0.3	0.4
		eP	05.9	E	0.4	-
		iS	06.8	N	0.6	0.4
		iS	06.8	W	0.5	0.4
		i	07.2	S	0.9	0.4

No.	Date	Phase	Time	Direction	Amplitude	Period
24	11-23-55	iP	09-59-28.9	S	0.3	0.4
		iP	28.9	W	0.4	0.4
		iS	29.9	S	0.7	0.4
		iS	30.4	W	1.0	0.4
25	10-15-55	iP	04-22-41.1	d	0.1	0.4
		eP	41.9	W	0.2	0.4
		eP	42.1	S	0.2	-
		iS	42.7	E	0.5	0.2
26	10-15-55	eP	04-21-21.4	E	0.1	0.2
		eP	21.5	c	0.1	0.4
		iP	21.7	N	0.1	0.3
		iS	22.7	E	0.4	0.2
		iS	23.2	N	0.5	0.6
27	9-17-55	eP	20-19-45.4	d	0.1	0.2
		eP	45.9	N	0.1	-
		eP	45.9	W	0.05	-
		eS	46.2	d	0.3	0.2
		iS	46.6	S	0.7	0.6
		eS	46.6	E	0.4	0.6
28	9-2-55	eP	08-17-53.4	c	0.2	0.6
		eP	53.9	E	0.1	0.4
		iP	54.2	S	0.3	0.6
		iP	54.5	c	0.7	0.5
		iP	54.8	N	0.5	1.0
		iP	55.2	E	0.7	0.6
		iP	55.2	d	0.8	0.4
		iS	56.1	c	0.7	-
		iS	56.1	S	1.1	0.6
		iS	56.5	E	1.0	0.4
29	8-30-55	eP	02-19-26.7	c	0.1	0.6
		iP	26.7	N	0.3	0.6
		eP	26.7	W	0.05	-
		iS	29.5	N	0.8	0.6
		eS	30.2	E	0.6	0.5
		eS	30.2	d	0.3	0.8
		i	32.4	W	0.9	0.4
30	7-29-55	iP	12-48-15.3	d	0.8	0.4
		iP	15.9	S	0.7	-
		iP	15.9	W	1.2	0.4

No.	Date	Phase	Time	Direction	Amplitude	Period
31	3-31-55	iP	06-01-19.9	d	0.3	-
		iP	20.1	S	0.6	0.4
		iP	20.1	E	0.5	0.5
		iS	20.5	W	1.0	0.6
		iS	20.9	N	0.6	0.4
32	2-11-55	eP	20-59-25.6	d	0.05	-
		eP	25.6	S	0.2	0.3
		eP	25.6	E	0.2	-
		iS	27.9	W	0.4	-
		eS	28.3	N	0.4	0.3
		eS	28.4	c	0.2	0.6
		e	29.1	N	0.5	0.6
33	12-22-54	eP	00-35-28.6	c	0.05	-
		eP	29.1	S	0.1	0.4
		iP	29.4	W	0.1	0.2
		iS	29.8	N	0.4	0.4
		iS	30.5	N	0.4	0.4
		eS	30.6	d	0.2	0.4
		iS	31.0	E	0.1	0.4
		i	32.0	S	0.5	0.6
34	9-14-54	iP	19-57-59.5	d	0.1	-
		eP	59.7	N	0.2	-
		eP	59.7	E	0.2	0.6
		iS	58-00.9	d	0.2	0.4
		iS	01.4	c	0.3	0.4
		eS	01.6	N	0.3	1.0
		eS	02.2	E	0.4	1.0
35	6-30-54	eP	12-38-03.3	E	0.1	-
		iP	03.7	d	0.2	-
		iP	03.7	N	0.4	-
		iS	04.5	c	0.4	-
		iS	04.5	S	1.2	0.4
		iS	04.6	W	0.8	0.4
36	8-27-53	eP	10-00-03.6	S	0.2	0.6
		eP	03.6	W	0.1	0.6
		eP	04.3	c	0.05	0.2
		eS	05.7	W	0.2	1.0
		iS	06.3	S	0.7	0.5
		eS	06.4	c	0.2	0.6
37	5-2-53	iP	15-37-48.7	S	0.2	-
		iP	48.8	c	0.2	0.1
		iP	48.9	E	0.2	-
		iS	49.4	S	0.9	0.4
		iS	49.5	d	0.8	-
		iS	49.6	E	0.8	-

No.	Date	Phase	Time	Direction	Amplitude	Period
38	3-13-53	eP	13-58-31.9	S	0.3	1.0
		eP	31.9	W	0.1	0.2
		eP	32.3	c	0.2	0.2
		iS	32.9	W	0.8	0.6
		iS	33.5	c	0.3	0.3
		iS	33.5	S	0.7	0.4
39	11-24-52	iP	15-56-19.5	d	0.1	0.2
		eP	19.5	E	0.4	1.0
		iP	19.6	N	0.2	0.4
		iS	20.3	N	0.3	0.4
		iS	20.3	W	1.2	0.8
		iS	20.6	d	0.5	0.2
40	11-3-52	eP	05-48-09.8	N	0.05	0.8
		iP	10.3	E	0.2	0.4
		eP	11.1	d	0.1	0.6
		iS	11.0	N	0.2	0.6
		iS	11.4	W	0.4	0.4
		iS	11.9	d	0.8	1.4
41	8-7-52	eP	18-00-02.9	c	0.05	0.3
		iP	03.1	d	0.1	0.4
		iP	04.0	N	0.2	-
		iP	04.5	W	0.5	0.6
		iS	04.1	c	0.4	0.2
		iS	04.7	N	0.3	0.2
		iS	05.4	E	0.6	0.6
42	2-12-52	eP	15-34-57.2	d	0.05	-
		eP	57.9	W	0.3	0.6
		eP	58.3	N	0.2	0.6
		eP	58.7	c	0.3	-
		iS	35-00.4	W	0.7	0.6
		iS	01.4	S	1.2	0.6
		i	04.3	W	0.8	1.4
43	4-7-51	eP	07-32-59.5	N	0.1	0.6
		eP	59.7	W	0.1	0.6
		iP	33-00.0	E	0.2	1.0
		eP	00.2	c	0.05	0.4
		iS	01.4	N	0.3	0.8
		iS	01.4	E	0.5	0.4
		eS	01.7	c	0.1	0.3
		i	02.4	W	0.7	0.6

No.	Date	Phase	Time	Direction	Amplitude	Period
44	3-2-51	eP	17-20-19.6	c	0.1	0.6
		iP	20.7	S	0.3	0.7
		eP	20.8	E	0.3	0.6
		eS	21.9	d	-	-
		iS	22.0	E	0.5	0.6
		iS	22.4	S	0.5	0.7
		i	26.5	E	2.0	0.5
45	1-29-49	iP	22-28-23.5	S	0.1	0.3
		iP	23.5	W	0.1	0.2
		iP	23.6	c	0.1	0.2
		iS	24.1	N	0.5	0.4
		eS	24.1	E	0.6	-
		iS	24.1	c	0.5	0.2
46	12-8-48	e	20-37-35.5	S	0.05	-
		i	46.8	N	0.2	0.4
		i	47.2	W	0.2	0.4
		e	47.4	d	0.1	-
47	12-8-48	eP	16-18-20.9	N	0.5	0.4
		eS	22.9	S	0.4	0.6
		eS	22.9	c	0.05	-
48	10-7-48	iP	11-43-22.8	W	0.2	-
		iP	22.9	d	0.2	0.1
		iP	23.0	N	0.2	0.2
49	8-21-48	eP	15-26-41.2	E	0.1	-
		eP	41.5	d	-	-
		iP	41.6	S	0.5	0.8
		iS	43.0	d	-	-
		eS	43.2	E	0.5	0.5
		iS	3.6	S	0.5	0.4
		i	45.3	W	0.9	0.3
50	5-23-48	eP	07-14-15.8	c	0.2	0.5
51	4-20-48	eP	02-03-48.2	d	0.05	-
		iP	48.4	E	0.1	0.5
		eS	50.0	E	0.1	0.4
		iS	50.6	S	0.3	0.4
52	4-20-48	iP	04-06-23.9	W	0.1	0.4
		eP	25.0	S	0.3	0.5
		iP	25.5	W	0.2	0.7
		iP	25.7	d	0.1	0.2
		iS	26.3	S	0.9	0.6
		iS	27.2	E	0.7	0.6
		iS	27.5	c	0.3	0.4
		i	29.7	E	1.0	0.6

No.	Date	Phase	Time	Direction	Amplitude	Period
53	4-16-48	eP	17-05-06.0	E	0.5	-
		iP	06.3	c	0.4	0.4
		iP	06.4	N	1.0	0.2

3.3 ANALYSIS OF FIRST MOTION

An examination of the above data reveals that out of the fifty-three events there were forty-two observations of vertical component first motion. These were distributed as eighteen compressions and twenty-four dilatations. In those cases where no vertical component was recorded but where horizontal components indicated an azimuth direction, the sense of the motion is ambiguous so that no conclusion could be drawn.

Combining the direction of motion and the compression-dilatation nature of the first motion, there were thirty-four cases for which these characteristics were known. Arranging these in the general quadrants, northwest, northeast, southeast, and southwest, as indicated by the motions above gives a picture of the relative frequency of dilatations and compressions arriving at the observatory from each quadrant. This data is given in the following table:

Quadrant	NW	NE	SE	SW
Compression	3	4	3	3
Dilatation	5	5	5	6

The table shows that for eight earthquakes lying in the quadrant northwest of the observatory, three of these had compressional first motion and five had dilatational first motion. Similar results are seen for the other quadrants. This shows that for this type of low intensity volcanic quake in the non-eruptive period, the first motion is not uniformly compressional.

In fact, it shows for the limited number of quakes which occurred a slight statistical preference for dilatational first motion.

Distance based on the (S-P) interval and a longitudinal wave velocity of 1.79 km/second were computed and plotted on a graph with the observatory as the center. No apparent relationship between distance, direction, and compression-dilatation nature of the first motion is apparent. The results are shown in Figure 1.

3.4 AMPLITUDE-DISTANCE RELATIONSHIP

With the distance values it is possible to inquire whether a significant relationship exists between the observed amplitude of motion and distance from the epicenter. The medial test was used to determine if such a relationship exists. This test consists of plotting the amplitude values as ordinates versus the distance values as abscissae. A horizontal medial line is drawn so that half the points fall above the line and the other half below the line. Next a vertical medial line is drawn so that half of the points lie to the left of the line and the other half lie to the right of the line. Theoretically equal numbers of points should fall in opposite quadrants such as quadrants one and three, and quadrants two and four. If no significant relationship exists between the parameters the points will be equally distributed in the four quadrants or approximately so. If there are too few points in any quadrant then a relationship between the parameters is inferred. Points falling on a medial line are disregarded.

Amplitude-distance values for 28 events were taken from Table I using the maximum amplitude value. Referring to Quenoilles table of significant levels for numbers of points falling in any quadrant, the number depends on

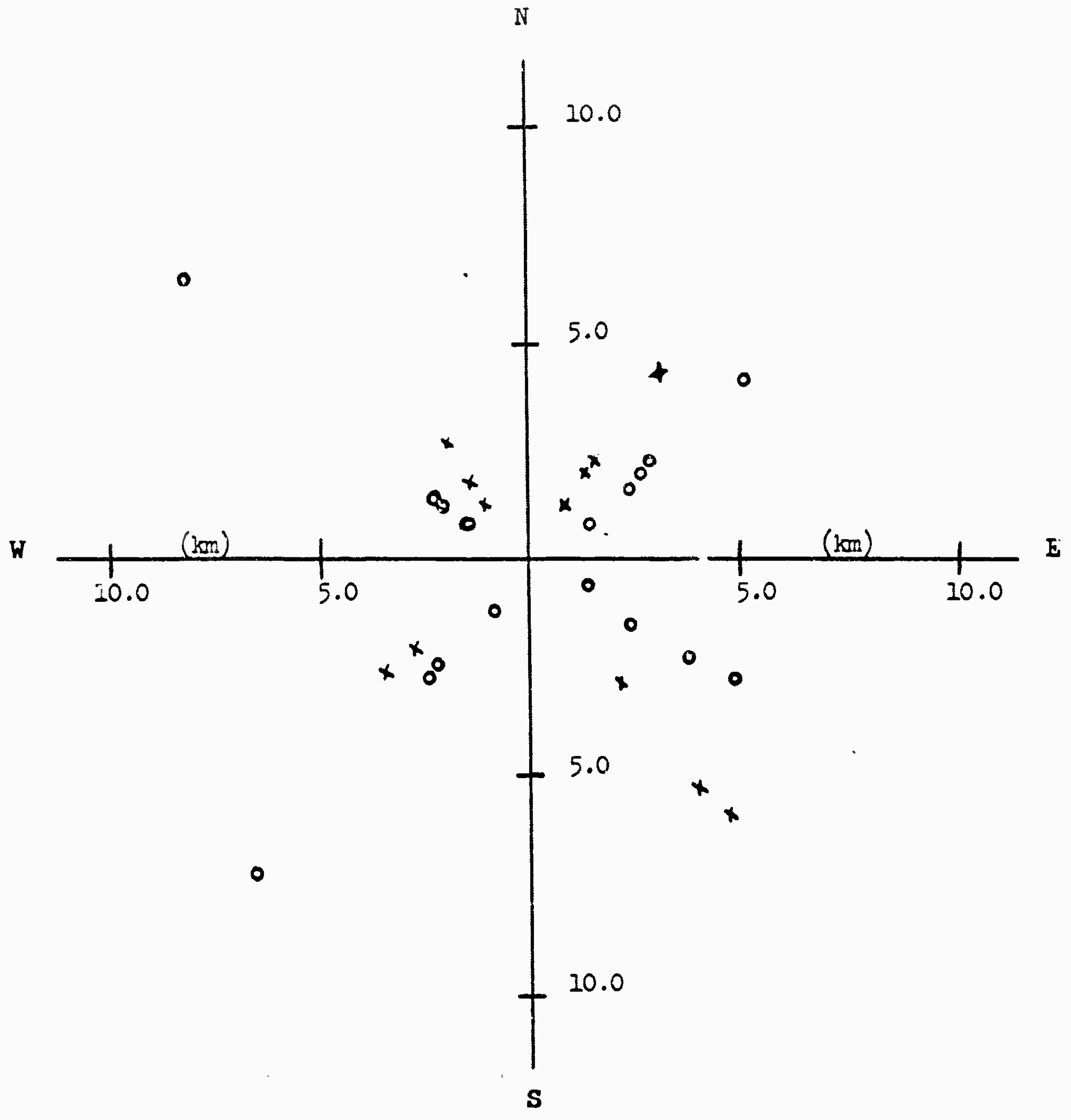

FIGURE 1 AZIMUTH - DISTANCE DISTRIBUTION OF COMPRESSIONS AND DILATATIONS

the probability level which is assumed. For example, using 28 points and a probability or significant level of .01, the upper and lower limits are 11 and 3 respectively. Assuming that no relationship exists between the parameters, the probability that a quadrant will have as many as 11 or as few as 3 points, the upper and lower limits, is less than .01. A portion of Quenoilles tables are reproduced here in Table 2.

TABLE 2 SIGNIFICANT LEVELS FOR NUMBER OF POINTS FALLING IN ANY QUADRANT

Number of Points	Lower Limit		Upper Limit	
	5%	1%	5%	1%
10 - 11	0	0	5	5
12 - 13	0	0	6	6
14 - 15	1	0	6	7
16 - 17	1	0	7	8
18 - 19	1	1	8	8
20 - 21	2	1	8	9
22 - 23	2	2	9	9
24 - 25	3	2	9	10
26 - 27	3	2	10	11
28 - 29	3	3	11	11
30 - 31	4	3	11	12
32 - 33	4	3	12	13
34 - 35	5	4	12	13
36 - 37	5	4	13	14
38 - 39	6	5	13	14
40 - 41	6	5	14	15
42 - 43	6	5	15	16
44 - 45	7	6	15	16
46 - 47	7	6	16	17
48 - 49	8	7	16	17
50 - 51	8	7	17	18
60 - 61	10	9	20	21
70 - 71	12	11	23	24
80 - 81	15	13	25	27
90 - 91	17	15	28	30
100 - 101	19	18	31	32
110 - 111	21	20	34	35

When the medial test was applied to the twenty-eight points the distribution, reading from Quadrant I through Quadrant IV was 5,4,5,6. This indicates no significant relationship between amplitudes and distance. The medial test is shown in Figure 2.

Ratios of amplitude over period were computed for these 28 points and are given here in Table 3.

TABLE 3 AMPLITUDE OVER PERIOD vs DISTANCE, VESUVIUS

Event No.	Amplitude/Period	Distance (km)
1	0.63	2.20
9	2.50	1.96
10	2.66	2 45
13	0.71	10.54
14	3.00	3.92
15	0.80	7.60
16	9.00	6.86
17	1.00	9.80
20	0.50	1.37
23	2.25	2.20
24	1.75	2.45
26	0.33	3.19
27	1.16	1.96
29	2.25	6.86
31	2.00	1.37
32	0.83	5.64
33	0.83	2.94
34	1.25	3.43
35	2.00	2.94
36	1.25	5.13
37	2.25	1.71
38	1.33	2.45
39	0.80	1.96
40	0.57	3.19
44	4.00	3.19
45	1.25	1.37
49	3.00	4.41
52	1.60	3.19

The above values were plotted against distance. The medial test was applied to determine if a significant relationship might now exist between "amplitude/period" and distance. The results shown in Figure 3 give a

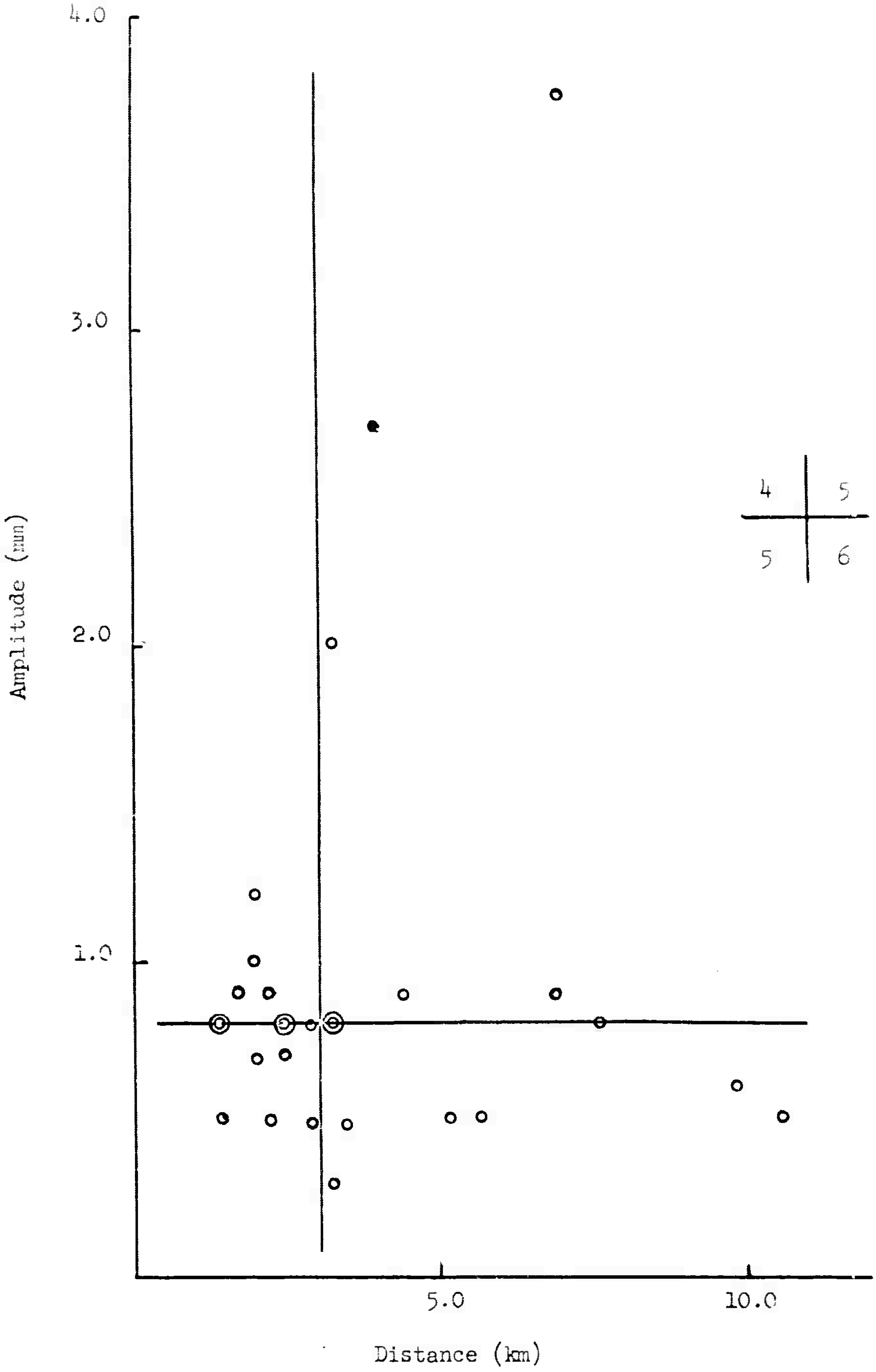

FIGURE 2 MEDIAL TEST, AMPLITUDE VS DISTANCE, VESUVIUS

distribution over the Quadrants I through IV of 6,8,6,8. While this is a slight improvement it cannot be considered a significant relationship.

The above test, though failing to show significance, does show a tendency toward significance by the slightly improved quadrantal distribution over that of the amplitude-distance distribution. In the hope of improving the significance and as a further check on the amplitude-distance relationship, the trace amplitudes were reduced to ground motion for the 28 events. This was done by dividing the trace amplitude by the magnification factor at the period of the observed wave. The ground motions are given in Table 4.

TABLE 4 GROUND AMPLITUDE vs DISTANCE, VESUVIUS

Event No.	Ground Amplitude 10^{-3} mm
1	3.06
9	6.27
10	5.02
13	3.09
14	16.36
15	4.80
16	33.53
17	4.22
20	4.38
23	5.64
24	4.39
26	2.07
27	4.34
29	6.34
31	5.02
32	3.11
33	3.11
34	4.03
35	5.67
36	3.14
37	5.64
38	6.24
39	7.65
40	5.20
44	14.14
45	3.14
49	6.42
52	5.66

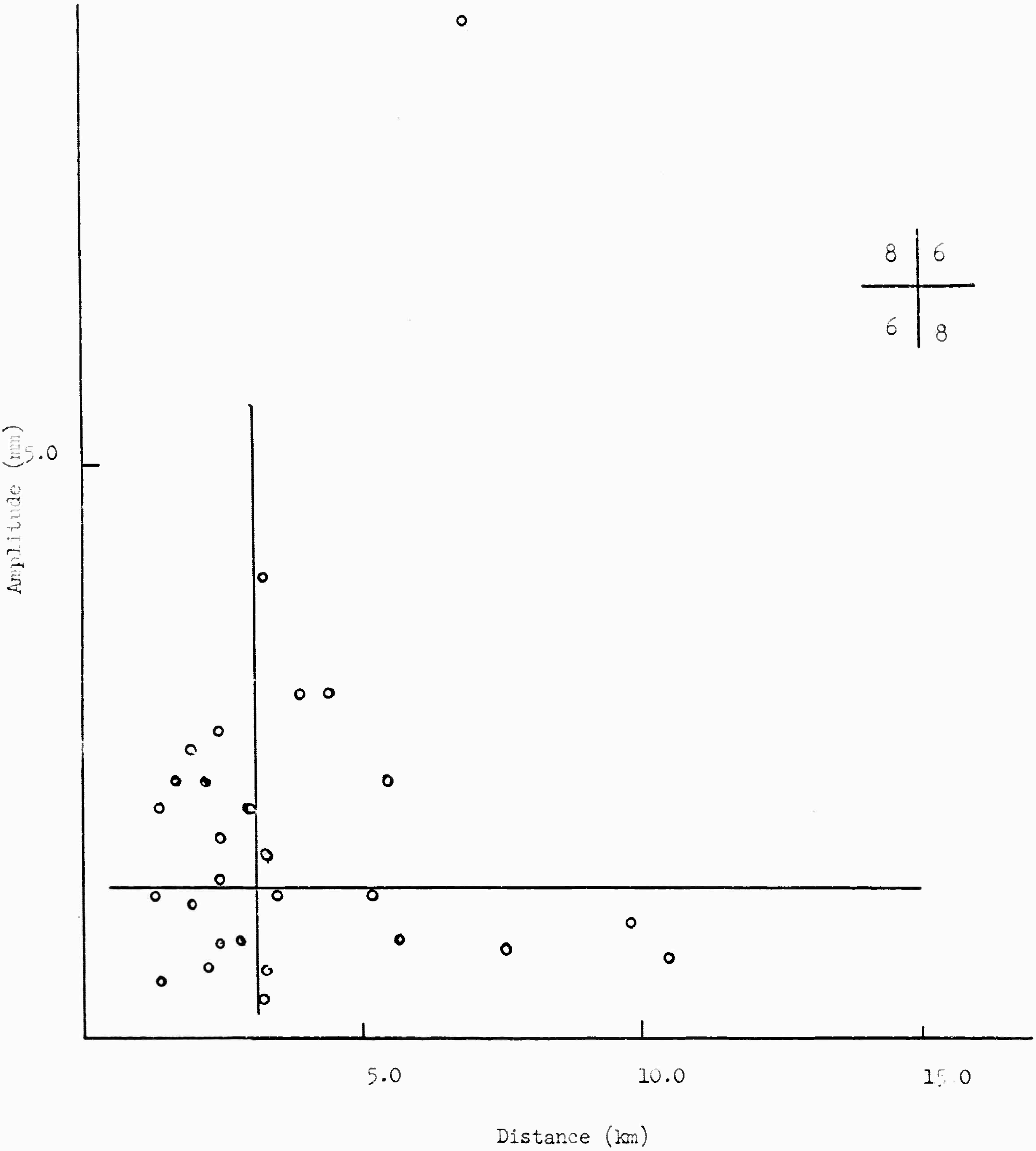

FIGURE 3 MEDIAL TEST, AMPLITUDE/PERIOD VS DISTANCE

The ground amplitudes of Table 4 were plotted against distance and the medial test again was applied as shown in Figure 4. The results give a 7,7,7,7, quadrantal distribution for the 28 points showing the complete lack of any significant relationship between amplitude and distance.

3.5 MAGNITUDE INVESTIGATION

A somewhat different approach was attempted. Variations in trace amplitude are observed and the above tests indicate that these are independent of distance. A number of factors could be involved to explain qualitatively at least why these variations occur. Factors such as azimuthal variations, differences in wave path, differences in instrumental response, variations with change in source location, and finally variations in energy at the source. Since the source area is limited and the distances are all small, the main factor would seem to be variation in energy at the source. Assuming all other factors to be constant, variations in energy at the source will become manifest as variations in amplitude of the recorded seismic waves. The seismologist deals with this problem by computing a magnitude for the earthquake in question.

Richter, in dealing with local California quakes, developed an empirical relationship of the type:

$$M = \log A - \log A_o \qquad (1)$$

Where A_o = Amplitude in millimeters with which a standard torsion seismometer with characteristics (T_o =0.8, V =2800, h = 0.8) should register an earthquake of magnitude zero.

The zero magnitude earthquake is further defined as a shock that would produce a trace amplitude of one-thousandth of a millimeter on a standard torsion seismometer at a distance of 100 kilometers.

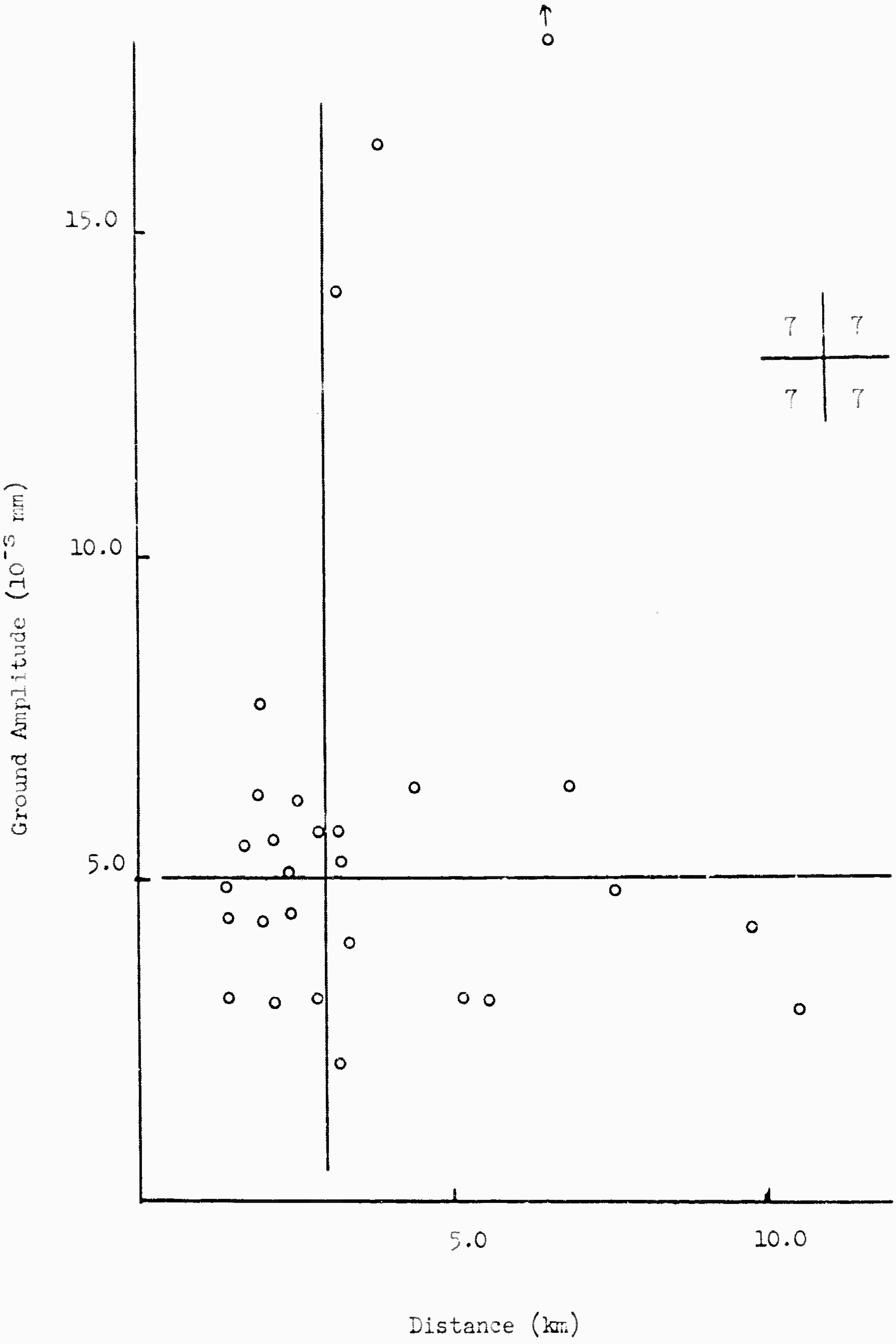

FIGURE 4 MEDIAL TEST, GROUND AMPLITUDE VS DISTANCE, VESUVIUS

Empirical values for log A_o have been developed by Richter for Southern California. These values are regional and are not meant to be applied in other areas. However, in an attempt to determine approximately the magnitude involved in the Vesuvian quakes, the values from Richter's table were used.

Figure 5 is a graph of log amplitude vs log distance with curves for earthquake magnitudes 1, 2, and 3 computed from Richter's values for log A_o at the various distances. Since the magnification of the Wiechert seismographs at Vesuvius is of the order of several hundred, the trace amplitude values were multiplied by a factor of ten to bring the magnification up to the same order of magnitude as that of the standard torsion seismometer. The response curves for the three components were not identical and this introduces a further approximation. The results, however, are considered to be of the right order of magnitude and indicate that the magnitudes are of the order 2. This represents a relatively high energy level for this type of quake and indicates that seismic activity at Mount Vesuvius is probably of a much higher level than that indicated by the limited number of quakes recorded from 1948 to 1961 by the low magnification Wiechert Seismographs. High sensitivity seismographs will undoubtedly reveal many hundreds of lower intensity quakes. A magnitude of 2 is about the lower limit of perceptibility and probably few of these quakes are felt. None of the quakes were recorded anywhere but at the Vesuvian Observatory.

Several examples of Vesuvian records are reproduced in Figure 6. The extremely short duration and high frequency character of such shocks is apparent in these records.

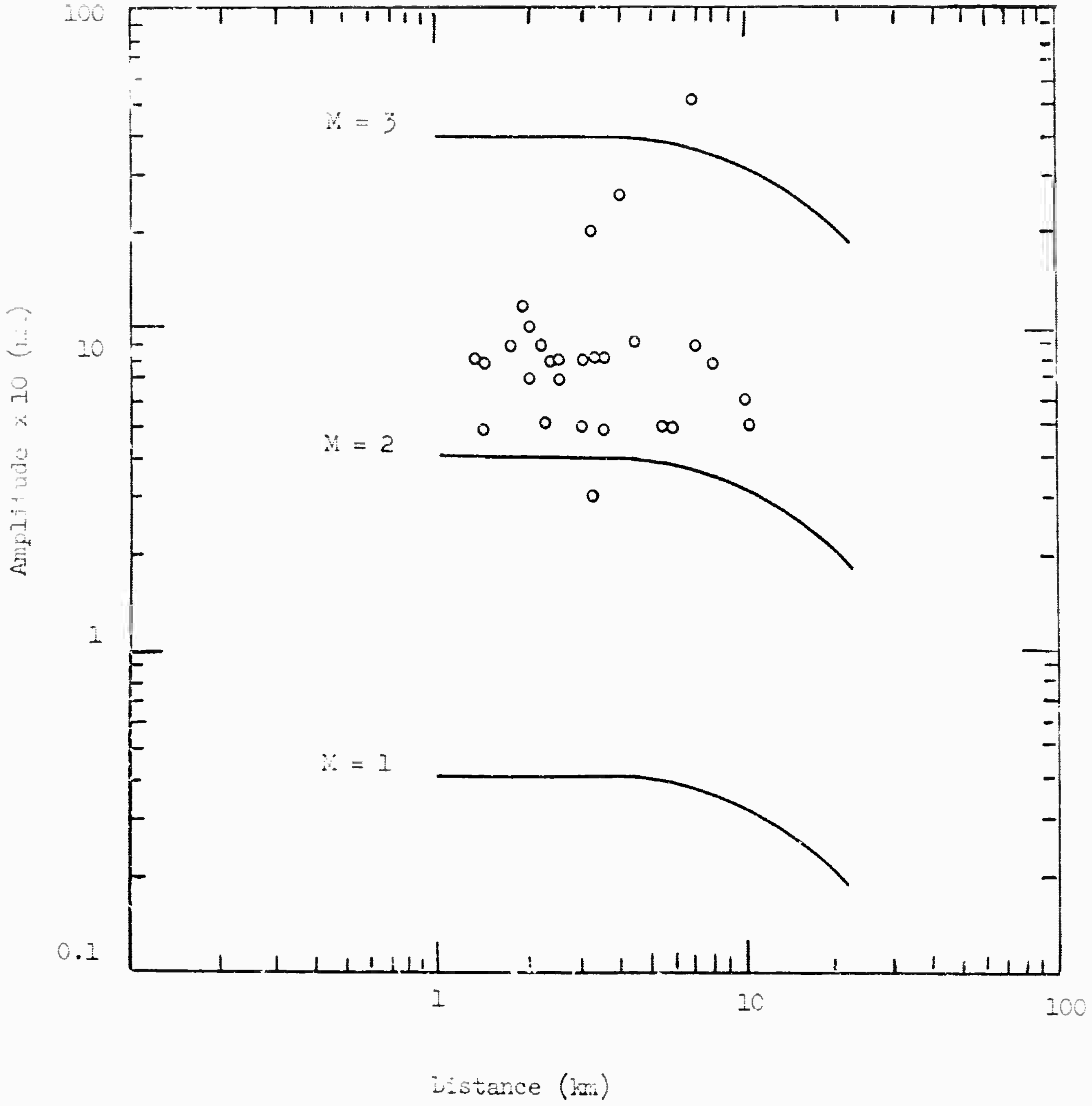

FIGURE 5 MAGNITUDE, LOG A VS LOG Δ, VESUVIUS

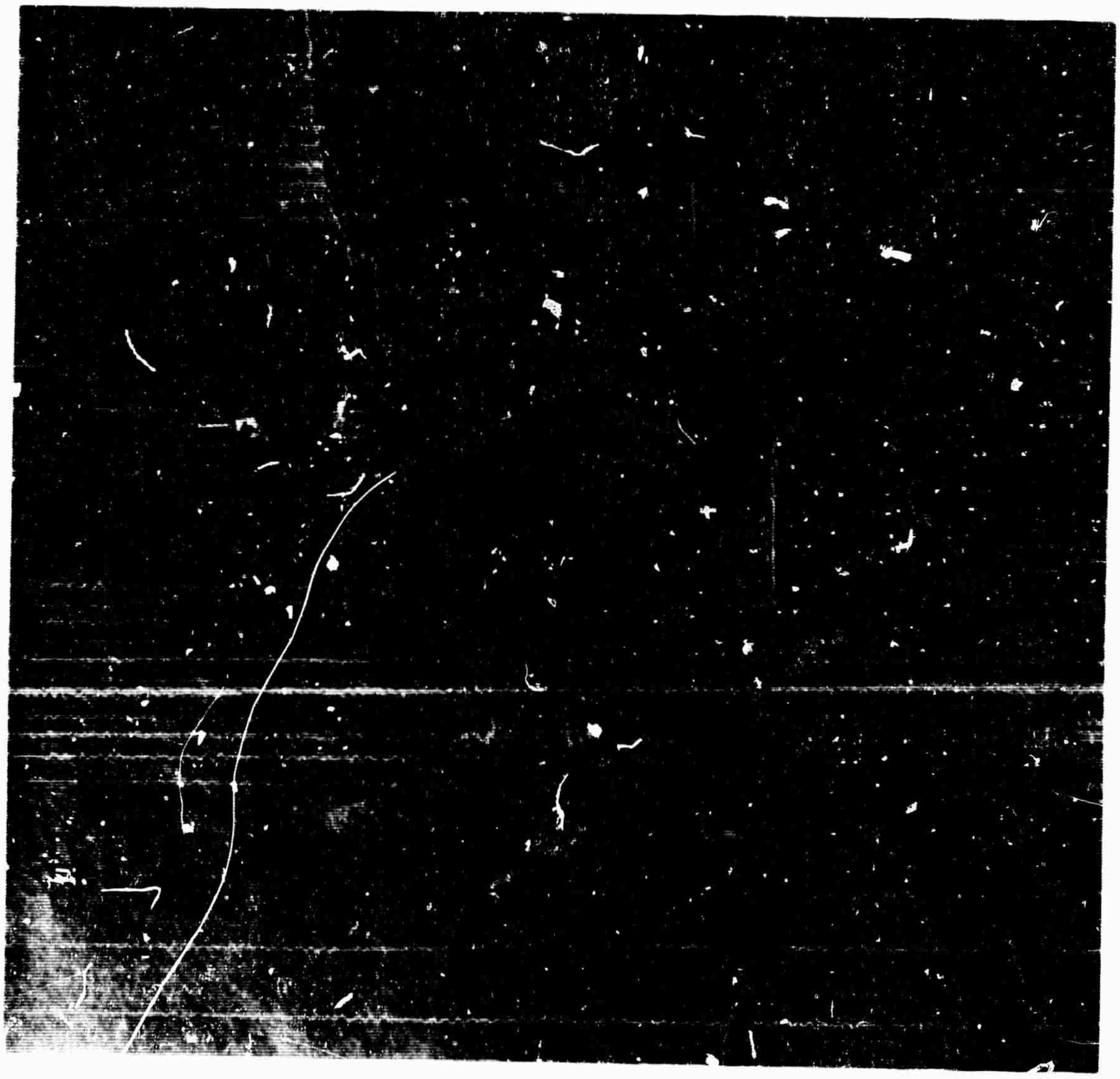

FIGURE 6 VESUVIAN SEISMOGRAM

4
MESSINA

4.1 THE MESSINA OBSERVATORY

The Seismological Observatory located at Messina, Sicily is part of the Institute of Geophysics and Geodetics of the University of Messina. Professor Antonino Girlanda is Director of the Observatory assisted by Dr. Biagio Federico and a staff of technicians.

The Messina Observatory is approximately 90 kilometers north and slightly east of Mount Etna. It is also approximately 300 kilometers south and slightly east of Mount Vesuvius. It is unlikely that Vesuvian quakes would be detected at this distance even by seismographs of intermediate magnification in the thousands. Examination of Messina records failed to show any activity that could be correlated with the quakes read at Vesuvius.

The greater proximity of Mount Etna however, gave promise that seismic events associated with it might be recorded at Messina. Mount Etna is in a state of almost continuous low intensity activity centered around small parasitic craters near the summit. No significant eruptions had occurred in the years prior to the examination of the records.

4.2 MOUNT ETNA - ABORTIVE ERUPTION

In December of 1949, however, Mt. Etna appeared to be preparing for a major eruption. A number of quakes were recorded at Messina which appeared to be centered near the volcano and an eruption appeared imminent. No eruption occurred, however, and this has been referred to as the Abortive Eruption of December, 1949. The recordings were made by low magnification Wiechert instruments and indicate fairly high source energy to be recorded at the distances involved. Readings from the seismogram are given in Table 5, using the same quantities as defined for Table 1.

TABLE 5 MESSINA - MOUNT ETNA QUAKES

No.	Date	Phase	Time	Direction	Amplitude	Period	Δ (Sg-Pg)
1	12-2-49	ePg	04-31-58.5	c	0.1	0.4	66.1 km
		ePg	58.5	E	0.1	---	
		eP	32-00.1	N	0.1	---	
		iSg	06.3	E	0.3	0.4	
		iSg	06.3	S	---	---	
		i	18.1	E	0.7	2.0	
2	12-2-49	iPg	04-47-30.5	c	0.1	1.2	78.8 km
		ePg	30.5	S	0.1	1.4	
		iP*	31.7	E	0.2	0.6	
		eSg	39.8	E	0.3	0.6	
		i	48.8	W	0.5	2.0	
3	12-2-49	ePg	05-39-45.4	c	---	---	88.9 km
		ePg	46.2	c	0.1	0.4	
		iPg	46.2	E	0.1	0.4	
		ePg	46.9	N	0.1	0.4	
		iSg	55.9	W	0.2	0.6	
		i	40-08.7	W	0.8	2.2	
4	12-2-49	iPg	06-02-36.6	c	0.2	0.6	91.5 km
		ePg	37.4	E	0.2	0.6	
		iPg	37.7	N	0.2	---	
		i	42.2	W	0.5	---	
		eSg	47.4	d	0.2	2.0	
		iSg	48.9	N	0.5	1.4	
		i	54.7	W	2.0	3.3	
5	12-2-49	ePg	06-22-14.8	c	0.1	---	50.8 km
		iPn	17.4	d	0.7	1.6	
		ePn	17.8	E	0.3	0.6	
		iPn	18.0	S	1.0	1.2	
		iSg	20.8	E	1.1	3.0	
		i	36.9	d	4.7	3.2	
6	12-2-49	ePg	06-43-41.3	c	0.1	1.2	59.3 km
		iSg	48.3	S	0.4	1.5	
		i	44-03.7	W	0.6	2.8	
7	12-2-49	e	06-48-13.2	W	0.1	1.4	
		e	23.9	W	0.4	2.6	
8	12-2-49	ePg	06-58-37.8	E	0.1	1.0	26.3 km
		eSg	40.9	S	0.1	1.0	
		i	44.5	W	0.3	1.6	
9	12-2-49	e	07-22-01.0	c	0.1	1.0	
		e	01.4	S	0.1	1.2	
		i	21.4	E	1.0	2.4	

No.	Date	Phase	Time	Direction	Amplitude	Period	Δ (Sg-Pg)
10	12-2-49	ePg	08-00-37.7	c	0.2	0.6	59.3 km
		eP*	37.8	N	0.2	1.2	
		eP*	38.2	E	0.1	---	
		iP*	38.3	c	0.5	1.0	
		iSg	44.1	E	0.8	2.0	
		iSg	47.4	E	1.4	2.4	
		i	56.8	W	5.0	3.0	
11	12-2-49	ePg	08-15-26.6	N	0.1	1.0	
		iPg	26.7	d	0.1	---	
		ePg	26.9	E	0.2	---	
		i	44.4	S	0.7	3.0	
		i	16-14.2	E	4.0	3.0	

The Jeffrey's Bullen Tables for near earthquakes are used at Messina and the distances listed above were computed from these tables.

Of these eleven quakes seven began with initial compressional phases, one with a dilatation, and three with indeterminate first motion. In the case of the dilatational first motion, the horizontal component motions indicate a source to the Northeast of Messina away from Mount Etna. For the seven compressional first motions, three have horizontal motions indicating a source to the Southwest in the direction of Mount Etna. The distances are 88.9, 91.5, and 50.8 kilometers respectively. The two larger distances would place the source near the center of Mount Etna while the shorter distance for the third of these three quakes would place the source to the Northeast of Mount Etna. Of the remaining four quakes one is a compression from the South at a distance 66.1 kilometers away, again falling to the north of Mount Etna. The second quake was from the north of Messina and the two remaining quakes were compressions with undetermined direction.

These data are very sparse and any conclusions to be inferred therefrom should be viewed in light of the paucity of the data. First motion from the region of Mount Etna is compressional in the few cases observed. Other quakes which should probably be classified as regional tectonic quakes originate in this general area off the flank of Mount Etna. These, too, displayed compressional first motion. The data is too scarce however, for these observations to be considered as more than observations.

A comparison of Messina Observatory records for quakes originating near the center of Mount Etna, with those originating to the north of Mount Etna between it and Messina, show a remarkable similarity in character. Seismograms of such quakes are shown in Figure 7.

5

MOUNT ETNA

5.1 EXPERIMENTAL SEISMIC INSTALLATION

An experimental seismographic installation using a Willmore three component system had been in operation on Mount Etna just prior to this investigators arrival there. Professor Alfredo Rittmann directs the Volcanological Institute of Mount Etna at the University of Catania, Sicily. The Willmore instruments were on loan to the Institute through the cooperation of Professor J. P. Rothe of the Institute de Physique du Globe in Strasbourg, France. Through the courtesy of Professor Rittmann, Professor Rothe and Dr. Haroun Tazieff of the Centre National de Volcanologie, Belgium, the Willmore records were made available for examination. The available records, however, showed very limited earthquake activity. Further, since the installation was experimental, instrumental constants, direction of motion and time corrections were usually not available.

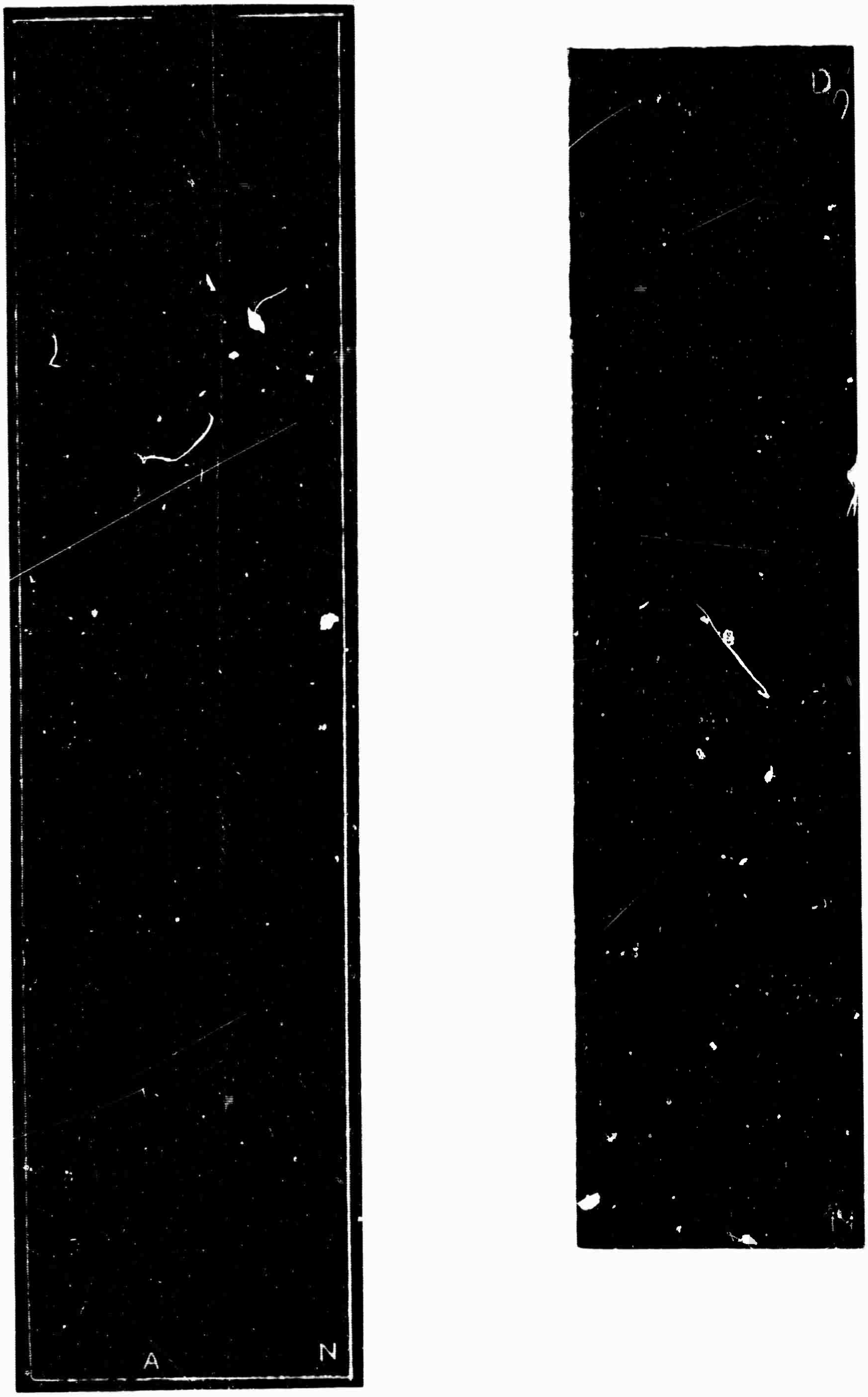

FIGURE 7 MESSINA SEISMOGRAMS

5.2 ANALYSIS OF EXPERIMENTAL SEISMOGRAMS

Six quakes were read with S-P values ranging from 1.2 to 4.5 seconds for five of the quakes while the sixth quake had an S-P of 24.5 seconds. This latter quake can be dismissed as a regional tectonic quake since the distance is of the order of 210 kilometers. The other five quakes ranged in distance from 10.1 to 38.1 kilometers and represent hypocenters located outward along the volcano's flank. No conclusions regarding first motion could be made since instrumental response was not constant due to the experimental nature of the installation.

The most prominent characteristic of the Mount Etna records however, was the persistent tremor. Tremor is usually associated with an eruptive period and Mount Etna is in a state of almost continuous low intensity activity. The tremor had a remarkably sinusoidal character showing a prominent beat phenomena. Readings were taken of the direction of motion for this beat phenomena at the start of the beat at five stations on two different days. Direction of motion was constant at each station during the period when readings were taken. For a total of 250 readings there were 124 up and 126 down with the individual station readings showing similar distributions. This is a random pattern of motion and indicates that the seismic signal is probably a complex mixture of motions from many sources within the volcano, and not a simple motion resulting from a pair of frequencies. A Willmore Seismogram from Mount Etna is shown in Figure 8.

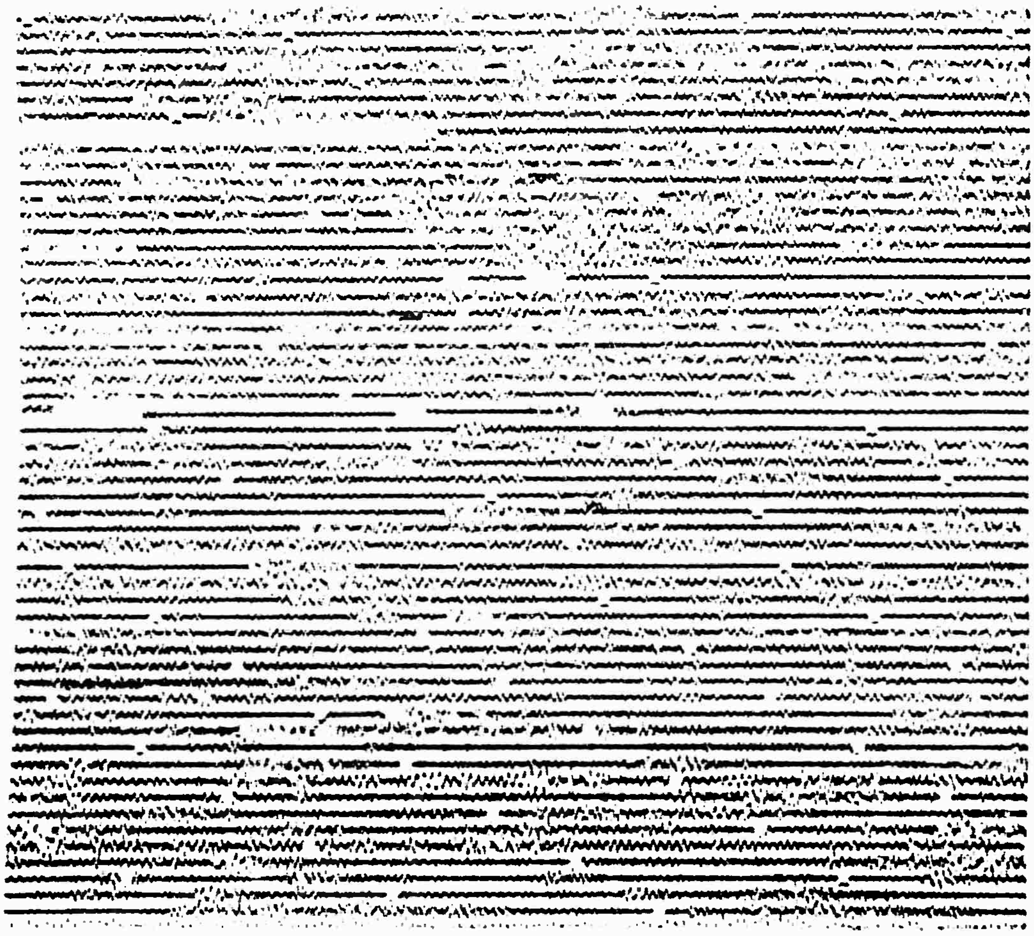

FIGURE 8 MOUNT ETNA, HARMONIC TREMOR

REGGIO CALABRIA

Records examined at Reggio Calabria through the courtesy of Professor Vittorio Barone-Adesi, Director of the Observatory, were all registered by Wiechert Seismographs. The seismograms represented regional and local seismic activity and no correlation could be established with volcanic activity at Mount Vesuvius or at Mount Etna.

7

HAWAIIAN VOLCANOES

7.1 THE HAWAIIAN VOLCANO OBSERVATORY

The Hawaiian Volcano Observatory is situated on the Island of Hawaii, the largest of the eight major islands comprising the Hawaiian group. It is on the northwest rim of Kilauea Caldera approximately 500 feet above the caldera floor. Almost due south of the Observatory in the southwest portion of the Caldera is Halemaumau, the fire pit or central vent of the Kilauea volcano. Almost due east of the Observatory is a smaller crater, Kilauea Iki, in which an eruption occurred in November, 1959.

At that time, Dr. Donald H. Richter was Scientist in Charge. Through his cooperation and assistance and with permission from Dr. Thomas B. Nolan, Director of The United States Geological Survey, under whose auspices the Hawaiian Volcano Observatory is operated, seismic data from the Kilauea Iki eruption were collected.

7.2 THE SEISMOGRAPH NETWORK

A network of nine stations is operated on the Island of Hawaii by the Volcano Observatory. Directly in the Kilauea Caldera is the North Pit Station. Just outside the Caldera within a distance of several kilometers are the stations Uwekahuna, Outlet, Desert, and Mauna Loa. With the exceptions of Uwekahuna, these stations record by telemetering to the Observatory. At distances measured in tens of kilometers are the stations Hilo, Naalehu, Pahoa and Kamuela. These stations are shown on the map in Figure 9. Station locations and instruments are given in Table 6.

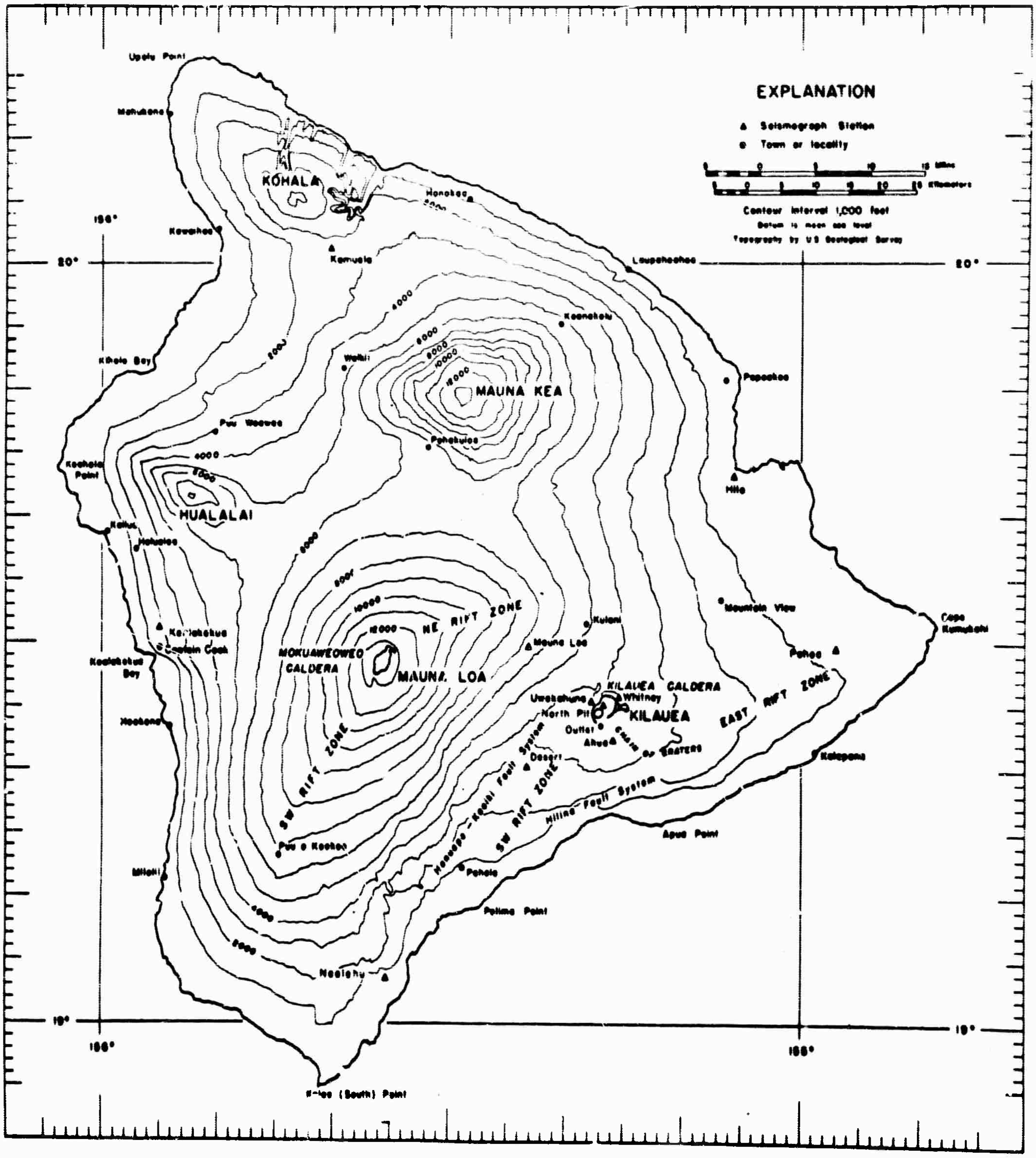

FIGURE 9 SEISMIC NETWORK, HAWAIIAN VOLCANO OBSERVATORY

TABLE 6 H. V. O. SEISMIC NETWORK

Station	Coordinates	Seismograph
North Pit	19° 24.9' N 155° 17.0' W h = 1115 m	HVO - 2, Z Component Remote recording
Uwekahuna	19° 25.4' N 155° 17,6' W h = 1240 m	HVO - 1, Z Component Springnether Short Period, E, Z Components Press-Ewing Long Period, N,E,Z Components
Outlet	19° 23.4' N 155° 16.9' W h = 1080 m	HVO - 2, Z Component Remote recording
Mauna Loa	19° 29.8' N 155° 23.3' W h = 2010 m	HVO - 2, Z Component Remote recording
Desert	19° 20.2' N 155° 23.3' W h = 815 m	HVO - 2, Z Component Remote recording
Hilo	19° 43.2' N 155° 05.3' W h = 20 m	HVO - 1, Z Component Wood-Anderson, N, E Components
Pahoa	19° 29,7' N 154° 56.8' W h = 205 m	Loucks-Omori, N, E Components
Naalehu	19° 03.8' N 155° 35.2 W h = 205 m	Loucks-Omori, N, E Components
Kamuela	20° 01.3' N 155° 40.3' W h = 815 m	Loucks-Omori, N, E Components

Seismographs

HVO-1, electromagnetic, T_o = 0.5 sec., maximum magnification about 20,000

HVO-2, electromagnetic, T_o = 0.8 sec., maximum magnification about 20,000

Springnether, electromagnetic, T_o = 1.3 sec., maximum magnification about 2,000

Wood-Anderson, torsion seismometer, T_o = 0.8 sec., maximum magnification about 2,800

Loucks-Omori, mechanical seismograph, T_o = 3.0 sec., maximum magnification about 200

7.3 Seismograph Readings

Kilauea Iki began eruption on November 14, 1959 at about 8:00 P.M. local time or 20 h GMCT. Prior to the eruption, earthquake activity began and increased until about 20 h GMCT when the eruption occurred. At this time earthquake activity as such ceased and was replaced by volcanic tremor, a continuous high frequency oscillation. In the hours preceding the eruption many hundreds of quakes occurred, so many that frequently they became masked and unreadable by overriding of one quake onto the trace of another. Beginning about 21 hr. GMCT on November 13, 1959, readings were made at as many stations as possible up to the time of the eruption. These readings are given in Table 7

TABLE 7 SEISMOGRAPH READINGS - KILAUEA IKI ERUPTION

Station Observations:
U = Uwekahuna
NP = North Pit
O = Outlet
D = Desert
ML = Mauna Loa
H = Hilo

S Phase readings are tabulated at Uwekahuna since this is the only station with high sensitivity horizontal seismometers. Readings at all other stations are exclusively P readings unless otherwise indicated.

Initial motion is indicated: c = compression, d = dilatation

Quake		U.		N.P.	O.	D.	M.L.	H.
No.	h m	P	S	P	P	P	P	P
1	21-39	19.4 c	20.4	18.3 c	19.6 c		21.9 d	
2	21-41					05.2 c		
3	21-45	10.6 d			10.9 c		13.2 c	
4	21-50				53.4 d			
5	22-00				56.7 c			
6	22-05					21.7 d		
7	22-09			20.3 c	20.9 d	21.7 d	22.1 d	
8	22-09					25.9 d		
9	22-09					42.2 d		
10	22-18					27.9 c		
11	22-18	46.5 c	47.1		46.7 d	50.1 c		
12	22-42					19.1 d	23.6 c	
13	23-23				29.1 c			
14	23-35				19.6 c			
15	23-39				03.0 -			
16	23-50	55.7 d	56.5		55.9 d		57.7 c	
17	00-04	26.1 c						
18	00-09	56.6 c	57.9			49.0 d	50.6 c	
19	00-10	57.5 c	58.3					
20	00-15				16.3 c			
21	00-18				38.7 d			
22	00-19	26.2 c	26.8			28.2 d	28.6 c	
23	00-22						12.9 d	
24	00-27	31.7 d	32.4					
25	00-28	06.4 d	07.4			08.3 c	08.8 c	
26	00-29	52.3 d	53.2					
27	00-30				16.4 d			
28	00-32	32.5 d	33.5		32.1 c		35.3 d	
29	00-35	45.0 d	45.9		44.9 c		48.4 d	
30	00-36	08.8 d	10.2		09.4 c		11.4 c	
31	00-37	51.2 d	51.6				56.5 c	
32	00-39	45.2 c	46.3				48.9 d	
33	00-39	58.5 d	59.3					
34	00-42	06.7 d	07.8		06.6 c		09.7 d	
35	00-43	25.4 c	26.0					
36	00-44						23.6 c	
37	00-45				41.6 d			
38	00-46	09.6 c	10.7			11.5 c		
39	00-47	15.5 d	16.2					
40	00-47	50.9 c	51.4					
41	00-48	50.9 d	51.4			53.4 d	53.6 c	
42	00-49	53.3 d	54.3					
43	00-51	33.1 c	33.6			35.2 d	35.6 d	
44	00-52	44.0 c	45.4				47.0 c	
45	00-54	02.0 d	02.9		02.1 c		05.9 c	
46	00-54				43.8 c			
47	00-54	55.4 c	56.3				54.8 c	02.4 c
48	00-55	56.0 c	57.1		56.3 d		58.5 c	

Quake		U.		N.P.	O	D	M.L.	H.
No.	h m	P	S	P	P	P	P	P
49	00-58	05.0 d	05.7					
50	00-59						09.5 d	
51	01-00	49.2 d	50.0					
52	01-01	49.2 d	50.0			51.5 c		
53	01-03	13.4 d	14.4		12.4 c			
54	01-03				50.0 c			
55	01-08				44.4 -			
56	01-11	23.5 d	24.6					
57	01-11				59.9 d			
58	01-12	25.2 d	26.1		26.9 d	28.5 d		
59	01-14	38.5 d	39.2			40.5 d	41.2 c	
60	01-21	58.4 d	59.3	58.9 c	58.3 c			
61	01-23				29.6 d		30.3 d	
62	01-28	12.6 d	13.4	11.9 c				
63	01-28	39.7 d	40.5	39.2 c				
64	01-31	08.0 c	08.8	07.4 c				
65	01-31	44.0 d	45.0	43.1 c				
66	01-33						15.4 d	
67	01-41	04.1 c	05.1			06.9 d	07.0 c	
68	01-41	30.0 c	31.3	29.4 c				
69	01-42	38.0 d	38.9	37.4 c	38.5 d			
70	01-43	32.8 c	33.8	32.3 c	32.8 c		35.7 c	
71	01-44			17.6 c	17.9 c		21.6 c	
72	01-45	24.3 d	25.0	23.5 d	23.7 c			
73	01-49			10.3 d			11.2 c	
74	01-49	56.9 c	57.6	55.9 c	56.5 c	58.7 c	59.7 c	
75	01-51				47.4 c			
76	01-[illegible]						56.4 c	
77	01-55	36.7 d	37.4	35.9 c	36.4 c			
78	01-56	38.3 d	39.1					
79	02-00				53.4 c			
80	02-01				26.2 c			
81	02-05	22.8 c	23.6	22.4 d	23.1 c	24.9 d	25.2 d	29.5 c
82	02-06				47.5 d			
83	02-09				16.1 c			
84	02-12	59.6 d	00.3	59.0 c	59.4 c	01.6 d	02.4 d	
85	02-16				42.7 d			
86	02-18	54.9 c	56.1					
87	02-22				41.4 c			
88	02-24				35.3 c			
89	02-26	43.4 c	44.3	43.1 d	43.7 d		46.4 c	
90	02-28	38.8 d	39.7	38.3 c				
91	02-33	47.1 c	48.6	46.4 d		49.2 c	49.2 c	53.8 d
92	02-34			31.4 c				
93	02-36			22.2 c				
94	02-36			49.2 c				
95	02-37	59.1 c	00.1	56.8 c	59.4 c	00.6 d	01.6 c	
96	02-39	19.3 c	20.4	18.0 c				

Quake		U		N.P.	O	D	M.L.	H.
No.	h m	P	S	P	P	P	P	P
97	02-41	25.2 d	26.1	24.9 c	25.3 c	27.4 d	28.1 c	
98	02-42			03.4 c				
99	02-44				07.6 c			
100	02-44			44.5 d				
101	02-48			17.0 c	17.4 d	19.3 d	19.5 c	
102	02-49				11.4 c			
103	02-57			16.7 c	16.7 c	18.9 d		
104	03-00	22.7 c	23.8	22.6 d	23.0 c	26.7 c	25.6 d	
105	03-01	12.7 d	13.5	12.3 c				
106	03-03			26.2 d				
107	03-10				19.9 d			
108	03-12				00.2 c			
109	03-12			52.0 d				
110	03-13	15.6 d	16.5	15.2 c	15.7 c			
111	03-15	36.2 d	37.5	35.7 d	36.1 c	38.0 c	38.2 d	
112	03-17	36.5 c	37.3	35.9 d		38.9 c	39.0 d	43.0 d
113	03-21			39.2 c				
114	03-22			09.6 d				
115	03-22			24.6 d				
116	03 23	24.6 d	25.1	23.9 c	24.6 c	26.4 d	28.1 c	
117	03-24	14.7 c	16.0			16.9 c	17.1 d	21.6 d
118	03-25			51.5 c	51.8 c			
119	03-27				45.9 c			
120	03-28	30.8 c	31.4	30.2 c		33.2 c	33.3 d	37.3 c
121	03-31	06.6 d	08.0	06.4 d		08.5 c		12.6 c
122	03-31			37.9 c				
123	03-35			27.0 c				
124	03 38	50.8 d	53.3	50.4 c		53.2 d	53.6 c	59.0 d
125	03-40	53.1 c	54.1	52.5 c		54.4 c	55.2 d	58.8 d
126	03-43	50.4 c	51.2	50.1 d				
127	03-48					29.9 d	30.3 c	35.7 c
128	03-51				55.8 d	57.1 c		
129	03-54				23.9 c			
130	03-54				53.6 d			
131	03-55				52.5 d			
132	03-56				34.2 c			
133	03-57				13.1 c			
134	04-01				31.9 d			
135	04-02	49.0 c	50.0	48.5 c		50.2 d	51.6 d	
136	04-04			36.0 c				
137	04-05			05.0 d				
138	04-05			24.6 c				
139	04-07						08.3 c	
140	04-08				22.1 c			
141	04-10					00.6 c	02.0 c	
142	04-10				22.6 c			

Quake		U		N.P.	O.	D	M.L.	H.
No.	h m	P	S	P	P	P	P	P
143	04-11				42.5 d			
144	04-15	25.1 d	26.0		25.6 d	27.2 d	27.7 c	
145	04-17			30.2 c				
146	04-18	46.0 c	47.3	45.7 d	47.0 d		48.8 c	
147	04-23	20.8 c	22.1	20.7 d		23.4 d	23.5 d	
148	04-24	52.5 d	53.6	52.2 d	52.2 c		54.8 d	
149	04-25				32.9 c			
150	04-26	45.6 c	46.6	45.2 d	45.4 c	47.1 c	48.1 d	51.5 c
151	04-28			16.7 c				
152	04-32				18.4 d			
153	04-34			18.4 i				
154	04-34			39.7 c				
155	04-34	54.3 c	55.8	54.3 d	54.4 d			
156	04-35				59.9 c			
157	04-38				14.9 c			
158	04-39	16.5 c	17.7		16.9 c	18.9 d	19.1 d	23.2 d
159	04-43	02.1 c	03.6		02.4 c	04.3 d	04.7 d	
160	04-44			01.4 d	01.5 c			
161	04-44	26.0 d	26.8	25.7 c	25.9 c	28.9 d	28.1 d	
162	04-45				18.4 d			
163	04-48				38.9 c			
164	04-48				55.4 d			
165	04-49				23.4 d	25.3 c		
166	04-51				17.2 d	21.3 c		
167	04-52			25.9 d	28.5 c			
168	04-52	32.6 c	33.8	32.5 d		35.1 c	35.1 d	38.9 c
169	04-56			07.6 c	08.1 d			
170	04-59				56.5 c			
171	05-00				33.7 d			
172	05-01				08.9 c			
173	05-04	39.2 d	40.8		39.4 d			
174	05-05	03.4 c	04.6		04.2 d	05.1 c	05.5 d	09.2 c
175	05-06				38.5 c			
176	05-07				22.4 c			
177	05-07	58.9 d	59.7		58.6 c			
178	05-10	06.5 c	07.6					
179	05-14	16.3 d	17.6				19.3 c	
180	05-15	40.3 c	41.2					
181	05-18	36.1 c	36.9			37.9 c	38.2 d	
182	05-22	37.3 d		38.6 d		39.7 c	39.9 d	
183	05-24			08.4 c				
184	05-24			33.9 d				
185	05-26			05.8 d		13.4 c	09.3 d	17.2 d
186	05-28			25.0 c				
187	05-30			15.8 c			19.7 d	
188	05-30			27.1 c				
189	05-31			38.4 c				

Quake		U		N.P.	O.	D.	M.L.	H.
No.	h m	P	S	P	P	P	P	P
190	05-33	17.6 c	18.7				20.5 d	
191	05-33			43.6 c				
192	05-34					09.9 c		
193	05-38			36.9 c				
194	05-42			06.6 d				
195	05-43	41.7 c	45.6					
196	05-47	05.7 d	06.7			07.2 d	07.8 c	11.2 c
197	05-48			23.1 c				
198	05-49			17.2 d				
199	05-50			08.2 c				
200	05-56			46.0 c				
201	05-58			12.9 c				
202	06-01			11.7 d				
203	06-03			05.3 c				
204	06-03	56.2 d	57.1				59.1 d	
205	06-06			39.7 c				
206	06-09	51.8 c				54.2 d	54.0 d	58.3 d
207	06-12	28.4 c	29.2				30.9 d	35.2 c
208	06-14			08.0 d				
209	06-19			55.7 d				
210	06-39						29.4 d	
211	07-35	17.4 c	18.9				20.2 c	
212	08-20	51.8 c	53.4				54.9 c	
213	08-33	13.7 c	15.2				16.6 d	
214	08-41	03.3 d	04.3				07.2 c	
215	10-16	53.2 c	54.5				56.0 c	
216	17-59	47.7 d	48.4					

The activity at the North Pit Station far exceeded that of any other station. From 22h GMCT until 01h 20m GMCT nothing could be read because of the number and size of the quakes. After 01h 20 m GMCT the magnification of the instrument was reduced by a factor of ten from 20,000 to 2,000 after which the records became readable.

A simple numerical count of first motion dilatations and compressions at each station is given in Table 8. The distributions for Uwekahuna, Mauna Loa, and Hilo are random. At North Pit and Outlet there is a significant preponderance of compressional motion. At Desert a weak preference for dila-

TABLE 8 FIRST MOTION COMPRESSION VS DILATATION

Station	U	NP	O	D	ML	H
Compression	51	55	61	26	39	9
Dilatation	50	33	34	29	38	8

tational motion is apparent. This possibly indicates a critical zone in which motion may originate with a preferential direction.

A group of quakes, sixty-four in number, was selected on the basis of being recorded at three or more stations. First motion compressions and dilatations were tabulated for this group giving the results shown in Table 9.

TABLE 9 SELECTED QUAKES - FIRST MOTION DISTRIBUTION

Station	No. of Quakes	No. of Compressions	No. of Dilatations
Uwekahuna	58	30	28
North Pit	36	19	17
Outlet	39	27	12
Desert	41	16	25
Mauna Loa	54	26	28
Hilo	18	10	8

This distribution shows a preferential pattern at Outlet and Desert and a random pattern at Uwekahuna, North Pit, Mauna Loa, and Hilo. The preferential pattern at Outlet shows a dominance of compressional first motion, while at Desert there is a dominance of dilatational first motion.

Regrouping these data into two sets, one with first motion exclusively compressional at Uwekahuna and the other with first motion exclusively dilatational at Uwekahuna, the first motion distributions at the remaining stations were reexamined. These groupings are shown in Tables 10 and 11.

TABLE 10 SELECTED QUAKES - UWEKAHUNA FIRST MOTION COMPRESSIONAL

Station	No. of Quakes	No. of Compressions	No. of Dilatations
Uwekahuna	30	30	0
North Pit	16	5	11
Outlet	16	10	6
Desert	21	9	12
Mauna Loa	29	12	17
Hilo	11	6	5

TABLE 11 SELECTED QUAKES - UWEKAHUNA FIRST MOTION DILATATIONAL

Station	No. of Quakes	No. of Compressions	No. of Dilatations
Uwekahuna	28	0	28
North Pit	15	10	5
Outlet	20	16	4
Desert	15	5	10
Mauna Loa	21	12	9
Hilo	4	2	2

Table 10 for compressional motion at Uwekahuna shows a significant dominance of dilatational motion at North Pit and of compressional motion at Outlet. Mauna Loa shows a weaker dominance of dilatational motion. Table 11 for dilatational motion at Uwekahuna now shows a reversal at North Pit with a dominance of compressional motion. At Outlet, however, the compressional motion dominance is very significantly strengthened. Desert which showed only a slight dominance of dilatational motion in Table 10 is also strengthened.

These observations lend strength to the concept of a critical zone in which seismic motion may originate with preferential first motion patterns.

The relative positions of these quakes can be somewhat indicated by the S-P values. These were computed for Uwekahuna for the 57 quakes in the selected group. The S-P values are given in Table 12.

TABLE 12 S-P VALUES AT UWEKAHUNA

S-P	No. of Quakes
0.1	1
0.2	1
0.5	3
0.6	4
0.7	5
0.8	5
0.9	11
1.0	9
1.1	4
1.2	3
1.3	5
1.4	2
1.5	3
2.5	1

More than half of the quakes fall in the S-P range 0.8 to 1.1 which would produce a distance variation of approximately one kilometer. Hence, the quakes should tend to cluster together. Variations in S-P, however, may indicate increase in depth rather than an increase in horizontal distance. In order to evaluate the real significance of first motion, distance and position of the station relative to the earthquake location must be known.

7.4 THE EPICENTER PROGRAM

In locating epicenters of local earthquakes one must know something about the crustal structure and seismic velocities of the area. Scientists at the Volcano Observatory have developed a crustal model with appropriate P and S wave velocities that fit the seismic observations of the Hawaiian area. This structural picture is shown in Figure 10. Using this structure and assuming

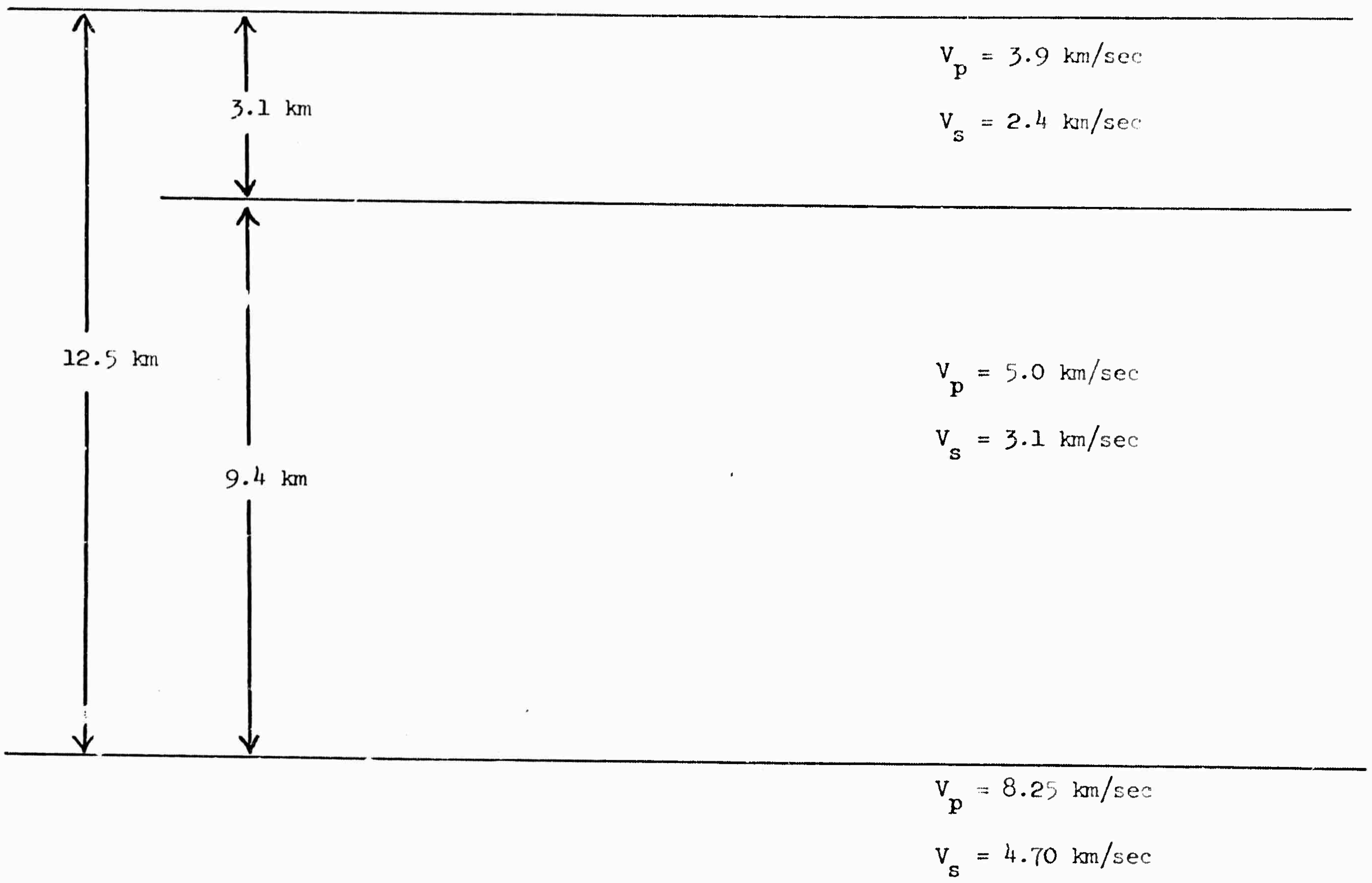

FIGURE 10 CRUSTAL STRUCTURE, HAWAII

zero focal depth, travel time equations have been computed as follows:

$$TP_1 = 0.26\,\Delta \qquad TS_1 = 0.41\,\Delta \tag{2}$$

$$TP_2 = 1.0 + 0.20\,\Delta \qquad TS_2 = 1.6 + 0.32\,\Delta \tag{3}$$

$$TP_3 = 4.4 + 0.12\,\Delta \qquad TS_3 = 6.8 + 0.21\,\Delta \tag{4}$$

Travel time curves based on these equations are shown in Figure 11. The P_2 phase does not appear before $\Delta = 7.7$ km and P_3 not before 17.65 km. Similarly, S_2 does not appear before $\Delta = 7.6$ km and S_4 not before 20.2 km. Travel time tables for zero focal depth are given in Table 13.

TABLE 13 TRAVEL TIMES FOR ZERO FOCAL DEPTH

Δ Km	P_1-H	P_2-H	P_3-H	S_1-H	S_2-H	S_3-H
0.0	.000			.000		
0.1	.026			.041		
0.2	.051			.082		
0.3	.077			.124		
0.4	.102			.166		
0.5	.128			.207		
0.6	.154			.248		
0.7	.179			.290		
0.8	.205			.331		
0.9	.230			.373		
1.0	.256			.414		
1.1	.282			.455		
1.2	.307			.497		
1.3	.333			.538		
1.4	.358			.580		
1.5	.384			.621		
1.6	.410			.662		
1.7	.435			.704		
1.8	.461			.745		
1.9	.486			.787		
2.0	.512			.828		
2.1	.538			.869		
2.2	.563			.911		
2.3	.589			.952		
2.4	.614			.994		
2.5	.640			1.04		

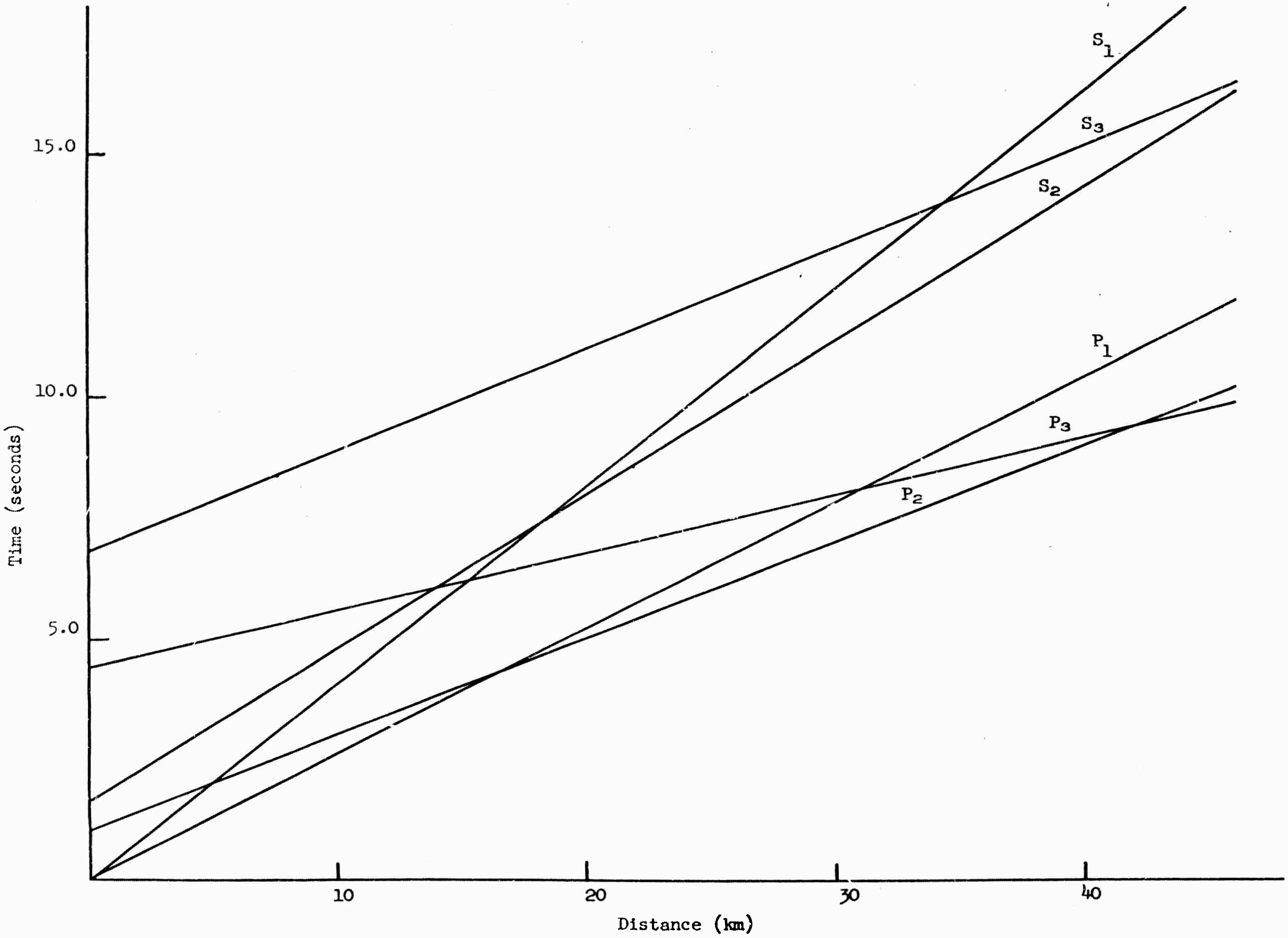

FIGURE 11 TRAVEL TIME CURVES, ZERO FOCAL DEPTH

Δ Km	P_1-H	P_2-H	P_3-H	S_1-H	S_2-H	S_3-H
2.6	.666			1.08		
2.7	.691			1.12		
2.8	.716			1.16		
2.9	.742			1.20		
3.0	.768			1.24		
3.1	.794			1.28		
3.2	.819			1.33		
3.3	.845			1.37		
3.4	.870			1.41		
3.5	.896			1.45		
3.6	.922			1.49		
3.7	.947			1.53		
3.8	.973			1.57		
3.9	.998			1.61		
4.0	1.02			1.66		
4.1	1.05			1.70		
4.2	1.08			1.74		
4.3	1.10			1.78		
4.4	1.13			1.82		
4.5	1.15			1.86		
4.6	1.18			1.90		
4.7	1.20			1.95		
4.8	1.23			1.99		
4.9	1.25			2.03		
5.0	1.28			2.07		
5.1	1.31			2.11		
5.2	1.33			2.15		
5.3	1.36			2.19		
5.4	1.38			2.24		
5.5	1.41			2.28		
5.6	1.43			2.32		
5.7	1.46			2.36		
5.8	1.48			2.40		
5.9	1.51			2.44		
6.0	1.54			2.48		
6.1	1.56			2.53		
6.2	1.59			2.57		
6.3	1.61			2.61		
6.4	1.64			2.65		
6.5	1.66			2.69		
6.6	1.69			2.73		
6.7	1.72			2.77		
6.8	1.74			2.82		
6.9	1.77			2.86		
7.0	1.79			2.90		
7.1	1.82			2.94		
7.2	1.84			2.98		
7.3	1.37			3.02		

Δ Km	P_1-H	P_2-H	P_3-H	S_1-H	S_2-H	S_3-H
7.4	1.89			3.06		
7.5	1.92			3.11		
7.6	1.95			3.15	4.09	
7.7	1.97			3.19	4.13	
7.8	2.0	2.56		3.23	4.16	
7.9	2.02	2.58		3.27	4.19	
8.0	2.05	2.60		3.31	4.22	
8.1	2.07	2.62		3.35	4.26	
8.2	2.10	2.64		3.39	4.29	
8.3	2.12	2.66		3.44	4.32	
8.4	2.15	2.68		3.48	4.35	
8.5	2.18	2.70		3.52	4.39	
8.6	2.20	2.72		3.56	4.42	
8.7	2.23	2.74		3.60	4.45	
8.8	2.25	2.76		3.64	4.48	
8.9	2.28	2.78		3.68	4.51	
9.0	2.30	2.80		3.73	4.55	
9.1	2.33	2.82		3.77	4.58	
9.2	2.36	2.84		3.81	4.61	
9.3	2.38	2.86		3.85	4.64	
9.4	2.41	2.88		3.89	4.68	
9.5	2.43	2.90		3.93	4.71	
9.6	2.46	2.92		3.97	4.74	
9.7	2.48	2.94		4.02	4.77	
9.8	2.51	2.96		4.06	4.81	
9.9	2.53	2.98		4.10	4.84	
10.0	2.56	3.00		4.14	4.87	
10.1	2.59	3.02		4.18	4.90	
10.2	2.61	3.04		4.22	4.93	
10.3	2.64	3.06		4.26	4.97	
10.4	2.66	3.08		4.31	5.00	
10.5	2.69	3.10		4.35	5.03	
10.6	2.71	3.12		4.39	5.06	
10.7	2.74	3.14		4.43	5.10	
10.8	2.76	3.16		4.47	5.13	
10.9	2.79	3.18		4.51	5.16	
11.0	2.82	3.20		4.55	5.19	
11.1	2.84	3.22		4.60	5.22	
11.2	2.87	3.24		4.64	5.26	
11.3	2.89	3.26		4.68	5.29	
11.4	2.92	3.28		4.72	5.32	
11.5	2.94	3.30		4.76	5.35	
11.6	2.97	3.32		4.80	5.39	
11.7	3.00	3.34		4.84	5.42	
11.8	3.02	3.36		4.89	5.45	
11.9	3.05	3.38		4.93	5.48	
12.0	3.07	3.40		4.97	5.52	

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km	P_1 -H	P_2 -H	P_3 -H	S_1 -H	S_2 -H	S_3 -H
12.1	3.10	3.42		5.01	5.55	
12.2	3.12	3.44		5.05	5.58	
12.3	3.15	3.46		5.09	5.61	
12.4	3.17	3.48		5.13	5.65	
12.5	3.20	3.50		5.18	5.68	
12.6	3.23	3.52		5.22	5.71	
12.7	3.25	3.54		5.26	5.74	
12.8	3.28	3.56		5.30	5.77	
12.9	3.30	3.58		5.34	5.81	
13.0	3.33	3.60		5.38	5.84	
13.1	3.35	3.62		5.42	5.87	
13.2	3.38	3.64		5.46	5.90	
13.3	3.40	3.66		5.51	5.94	
13.4	3.43	3.68		5.55	5.97	
13.5	3.46	3.70		5.59	6.00	
13.6	3.48	3.72		5.63	6.03	
13.7	3.51	3.74		5.67	6.07	
13.8	3.53	3.76		5.71	6.10	
13.9	3.56	3.78		5.75	6.13	
14.0	3.58	3.80		5.80	6.16	
14.1	3.61	3.82		5.84	6.19	
14.2	3.64	3.84		5.88	6.23	
14.3	3.66	3.86		5.92	6.26	
14.4	3.69	3.88		5.96	6.29	
14.5	3.71	3.90		6.00	6.32	
14.6	3.74	3.92		6.04	6.36	
14.7	3.76	3.94		6.08	6.39	
14.8	3.79	3.96		6.12	6.42	
14.9	3.81	3.98		6.16	6.45	
15.0	3.84	4.00		6.21	6.49	
15.1	3.87	4.02		6.25	6.52	
15.2	3.89	4.04		6.29	6.55	
15.3	3.92	4.06		6.33	6.58	
15.4	3.94	4.08		6.37	6.61	
15.5	3.97	4.10		6.41	6.65	
15.6	3.99	4.12		6.45	6.68	
15.7	4.02	4.14		6.49	6.71	
15.8	4.04	4.16		6.53	6.74	
15.9	4.07	4.18		6.58	6.78	
16.0	4.10	4.20		6.62	6.81	
16.1	4.12	4.22		6.66	6.84	
16.2	4.15	4.24		6.70	6.87	
16.3	4.17	4.26		6.74	6.90	
16.4	4.20	4.28		6.78	6.94	
16.5	4.22	4.30		6.82	6.97	
16.6	4.25	4.32		6.86	7.00	

Δ Km	P_1-H	P_2-H	P_3-H	S_1-H	S_2-H	S_3-H
16.7	4.28	4.34		6.90	7.03	
16.8	4.30	4.36		6.94	7.07	
16.9	4.33	4.38		6.99	7.10	
17.0	4.35	4.40		7.03	7.13	
17.1	4.38	4.42		7.07	7.16	
17.2	4.40	4.44		7.11	7.19	
17.3	4.43	4.46		7.15	7.22	
17.4	4.45	4.48		7.19	7.26	
17.5	4.48	4.50		7.23	7.29	
17.6	4.51	4.52		7.27	7.32	
17.7	4.53	4.54	6.54	7.31	7.36	
17.8	4.56	4.56	6.55	7.35	7.39	
17.9	4.58	4.58	6.57	7.40	7.42	
18.0	4.61	4.60	6.58	7.44	7.45	
18.1	4.63	4.62	6.59	7.48	7.49	
18.2	4.66	4.64	6.60	7.52	7.52	
18.3	4.68	4.66	6.61	7.56	7.55	
18.4	4.71	4.68	6.63	7.60	7.58	
18.5	4.74	4.70	6.64	7.64	7.62	
18.6	4.76	4.72	6.65	7.68	7.65	
18.7	4.79	4.74	6.66	7.72	7.68	
18.8	4.81	4.76	6.67	7.76	7.71	
18.9	4.84	4.78	6.69	7.81	7.74	
19.0	4.86	4.80	6.70	7.85	7.78	
19.1	4.89	4.82	6.71	7.89	7.81	
19.2	4.92	4.84	6.72	7.93	7.84	
19.3	4.94	4.86	6.74	7.97	7.87	
19.4	4.97	4.88	6.75	8.01	7.91	
19.5	4.99	4.90	6.76	8.05	7.94	
19.6	5.02	4.92	6.77	8.09	7.97	
19.7	5.04	4.94	6.78	8.13	8.00	
19.8	5.07	4.96	6.80	8.17	8.03	
19.9	5.09	4.98	6.81	8.22	8.07	
20.0	5.12	5.00	6.82	8.26	8.10	

Travel times were also computed for focal depths of 3, 4, 8, 12.5, and 32.5 kilometers and these values are given in Table 14. Travel time curves based on these computed values are shown in Figure 12, for the P-phase arrivals.

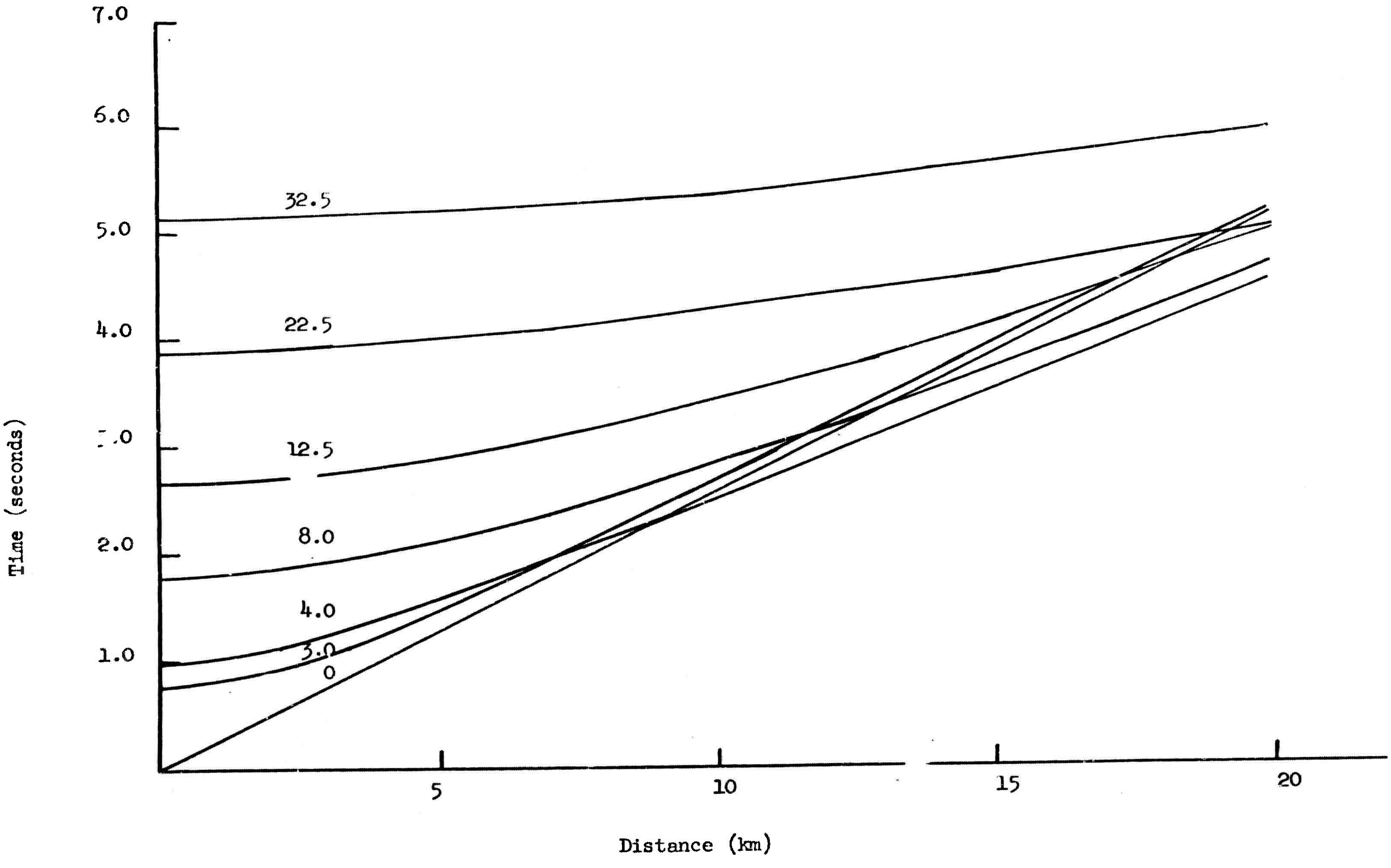

FIGURE 12 P WAVE TRAVEL TIME CURVES
FOR FOCAL DEPTHS 0, 3, 4, 8, 12.5, 22.5, 32.5 km

TABLE 14 TRAVEL TIMES FOR FOCAL DEPTH

h	0		3		4		8		12.5		22.5		32.5	
Δ in Km	P	S	P	S	P	S	P	S	P	S	P	S	P	S
0.0	0.00	0.00	0.77	1.25	0.98	1.58	1.78	2.87	2.68	4.32	3.89	6.42	5.10	8.58
0.1	0.03	0.04	0.77	1.26	0.98	1.59	1.78	2.88	2.68	4.33	3.89	6.42	5.10	8.58
0.2	0.05	0.08	0.77	1.26	0.99	1.59	1.78	2.88	2.68	4.33	3.90	6.43	5.10	8.58
0.3	0.08	0.12	0.77	1.27	0.99	1.60	1.78	2.89	2.68	4.34	3.90	6.43	5.11	8.58
0.4	0.10	0.17	0.78	1.28	0.99	1.61	1.79	2.90	2.68	4.35	3.90	6.43	5.11	8.58
0.5	0.13	0.21	0.78	1.28	1.00	1.62	1.79	2.90	2.68	4.36	3.90	6.44	5.11	8.58
0.6	0.15	0.25	0.78	1.29	1.00	1.62	1.79	2.91	2.69	4.36	3.91	6.44	5.11	8.59
0.7	0.18	0.29	0.79	1.30	1.00	1.63	1.79	2.92	2.69	4.37	3.91	6.44	5.11	8.59
0.8	0.21	0.33	0.80	1.31	1.00	1.64	1.79	2.93	2.69	4.38	3.91	6.44	5.12	8.59
0.9	0.23	0.38	0.80	1.31	1.01	1.64	1.79	2.93	2.69	4.38	3.92	6.45	5.12	8.59
1.0	0.26	0.42	0.81	1.32	1.01	1.65	1.79	2.94	2.69	4.39	3.92	6.45	5.12	8.59
1.1	0.28	0.46	0.82	1.34	1.02	1.66	1.79	2.95	2.69	4.40	3.92	6.45	5.12	8.59
1.2	0.31	0.50	0.83	1.36	1.03	1.67	1.80	2.95	2.69	4.41	3.92	6.45	5.12	8.59
1.3	0.33	0.54	0.84	1.37	1.03	1.67	1.80	2.96	2.70	4.41	3.92	6.46	5.13	8.60
1.4	0.36	0.58	0.85	1.39	1.04	1.68	1.80	2.97	2.70	4.42	3.92	6.46	5.13	8.60
1.5	0.38	0.62	0.86	1.41	1.05	1.70	1.80	2.97	2.70	4.43	3.92	6.46	5.13	[illegible]
1.6	0.41	0.67	0.87	1.43	1.06	1.71	1.81	2.98	2.70	4.44	3.93	6.46	5.13	8.60
1.7	0.44	0.71	0.88	1.45	1.07	1.73	1.81	2.99	2.70	4.45	3.93	6.46	5.13	8.60
1.8	0.46	0.75	0.90	1.46	1.07	1.75	1.82	3.00	2.71	4.45	3.93	6.47	5.14	8.61
1.9	0.49	0.79	0.91	1.48	1.08	1.77	1.83	3.00	2.71	4.46	3.93	6.47	5.14	8.61
2.0	0.51	0.83	0.92	1.50	1.09	1.78	1.83	3.01	2.71	4.47	3.93	6.47	5.14	8.61
2.1	0.54	0.88	0.94	1.53	1.10	1.80	1.84	3.02	2.71	4.48	3.93	6.48	5.14	8.61
2.2	0.56	0.92	0.95	1.55	1.12	1.82	1.85	3.02	2.72	4.48	3.94	6.48	5.15	8.61
2.3	0.59	0.96	0.97	1.58	1.13	1.84	1.86	3.03	2.72	4.49	3.94	6.48	5.15	8.61
2.4	0.62	1.00	0.98	1.61	1.14	1.85	1.86	3.03	2.72	4.50	3.94	6.49	5.15	8.61
2.5	0.64	1.04	1.00	1.64	1.15	1.87	1.87	3.04	2.72	4.51	3.94	6.49	5.16	8.62
2.6	0.67	1.08	1.02	1.66	1.17	1.89	1.88	3.05	2.73	4.51	3.95	6.50	5.16	8.62
2.7	0.69	1.12	1.04	1.69	1.18	1.90	1.88	3.05	2.73	4.52	3.95	6.50	5.16	8.62
2.8	0.72	1.17	1.05	1.72	1.19	1.92	1.89	3.06	2.73	4.53	3.95	6.51	5.16	8.62
2.9	0.74	1.21	1.07	1.74	1.21	1.94	1.90	3.06	2.74	4.53	3.96	6.52	5.17	8.62
3.0	0.77	1.25	1.09	1.77	1.22	1.97	1.90	3.07	2.74	4.54	3.96	6.52	5.17	8.62
3.1	0.79	1.29	1.11	1.80	1.24	1.99	1.91	3.08	2.74	4.55	3.96	6.52	5.17	8.62
3.2	0.82	1.33	1.12	1.83	1.25	2.02	1.92	3.10	2.75	4.56	3.96	6.53	5.17	8.62
3.3	0.85	1.38	1.14	1.86	1.26	2.05	1.93	3.12	2.76	4.56	3.97	6.53	5.18	8.62
3.4	0.87	1.42	1.16	1.89	1.28	2.07	1.94	3.14	2.76	4.57	3.97	6.54	5.18	8.63
3.5	0.90	1.46	1.18	1.92	1.30	2.10	1.95	3.16	2.76	4.58	3.97	6.54	5.18	8.63
3.6	0.92	1.50	1.20	1.96	1.31	2.12	1.96	3.17	2.77	4.59	3.97	6.54	5.18	8.63
3.7	0.95	1.54	1.22	1.99	1.32	2.15	1.97	3.19	2.78	4.60	3.97	6.55	5.18	8.64
3.8	0.97	1.58	1.24	2.02	1.34	2.18	1.98	3.21	2.78	4.60	3.98	6.55	5.19	8.64
3.9	1.00	1.62	1.26	2.05	1.36	2.20	1.99	3.23	2.78	4.61	3.98	6.56	5.19	8.65
4.0	1.03	1.67	1.28	2.08	1.37	2.23	1.99	3.25	2.79	4.62	3.98	6.56	5.19	8.65
4.1	1.05	1.71	1.30	2.12	1.39	2.26	2.00	3.27	2.80	4.66	3.98	6.57	5.19	8.65
4.2	1.08	1.75	1.32	2.15	1.40	2.29	2.01	3.29	2.81	4.68	3.98	6.57	5.19	8.66
4.3	1.10	1.79	1.35	2.18	1.42	2.31	2.02	3.30	2.81	4.70	3.99	6.58	5.20	8.67
4.4	1.13	1.83	1.37	2.22	1.44	2.34	2.03	3.32	2.82	4.73	3.99	6.58	5.20	8.67
4.5	1.15	1.87	1.39	2.26	1.46	2.37	2.04	3.34	2.83	4.75	3.99	6.59	5.20	8.67

h	0		3		4		8		12.5		22.5		32.5	
Δ in Km	P	S	P	S	P	S	P	S	P	S	P	S	P	S
4.6	1.18	1.92	1.41	2.29	1.47	2.40	2.05	3.36	2.84	4.77	3.99	6.60	5.20	8.68
4.7	1.21	1.96	1.43	2.32	1.49	2.43	2.06	3.38	2.85	4.79	3.99	6.60	5.20	8.69
4.8	1.23	2.00	1.45	2.36	1.51	2.46	2.07	3.39	2.85	4.82	4.00	6.61	5.21	8.69
4.9	1.26	2.04	1.47	2.40	1.52	2.48	2.08	3.41	2.86	4.84	4.00	6.62	5.21	8.69
5.0	1.28	2.08	1.49	2.43	1.54	2.51	2.09	3.43	2.87	4.86	4.00	6.62	5.21	8.70
5.1	1.31	2.12	1.51	2.47	1.56	2.54	2.10	3.45	2.88	4.88	4.00	6.62	5.21	8.70
5.2	1.33	2.17	1.53	2.50	1.58	2.57	2.12	3.47	2.89	4.90	4.00	6.63	5.21	8.71
5.3	1.36	2.21	1.56	2.54	1.60	2.60	2.13	3.48	2.90	4.93	4.01	6.63	5.22	8.72
5.4	1.38	2.25	1.58	2.58	1.62	2.63	2.14	3.50	2.91	4.95	4.01	6.64	5.22	8.72
5.5	1.41	2.29	1.60	2.62	1.64	2.67	2.15	3.52	2.92	4.97	4.01	6.64	5.22	8.72
5.6	1.44	2.33	1.63	2.65	1.65	2.70	2.16	3.54	2.92	4.99	4.01	6.64	5.22	8.73
5.7	1.46	2.37	1.65	2.69	1.66	2.73	2.18	3.56	2.93	5.01	4.01	6.65	5.22	8.74
5.8	1.47	2.42	1.67	2.73	1.69	2.76	2.19	3.57	2.94	5.04	4.02	6.65	5.23	8.74
5.9	1.51	2.46	1.70	2.76	1.71	2.79	2.20	3.59	2.95	5.06	4.02	6.66	5.23	8.74
6.0	1.54	2.50	1.72	2.80	1.73	2.81	2.21	3.61	2.96	5.08	4.02	6.67	5.23	8.75
6.1	1.56	2.54	1.74	2.84	1.75	2.84	2.22	3.63	2.97	5.10	4.03	6.68	5.23	8.75
6.2	1.59	2.58	1.76	2.87	1.77	2.86	2.24	3.65	2.98	5.12	4.03	6.69	5.23	8.76
6.3	1.62	2.62	1.79	2.91	1.79	2.89	2.25	3.66	2.99	5.15	4.04	6.70	5.24	8.76
6.4	1.64	2.67	1.81	2.95	1.81	2.92	2.26	3.68	3.00	5.17	4.04	6.71	5.24	8.77
6.5	1.67	2.71	1.83	2.98	1.82	2.95	2.28	3.70	3.01	5.19	4.05	6.71	5.24	8.77
6.6	1.69	2.75	1.85	3.02	1.84	2.99	2.29	3.71	3.02	5.21	4.06	6.72	5.24	8.77
6.7	1.72	2.79	1.88	3.06	1.86	3.02	2.30	3.73	3.03	5.23	4.06	6.73	5.24	8.78
6.8	1.74	2.83	1.90	3.10	1.88	3.05	2.32	3.75	3.04	5.26	4.07	6.74	5.25	8.78
6.9	1.77	2.88	1.93	3.13	1.90	3.08	2.33	3.78	3.05	5.28	4.07	6.75	5.25	8.79
7.0	1.79	2.92	1.95	3.17	1.92	3.11	2.34	3.80	3.06	5.30	4.08	6.76	5.25	8.79
7.1	1.82	2.96	1.97	3.22	1.94	3.15	2.36	3.82	3.07	5.32	4.09	6.77	5.25	8.79
7.2	1.85	3.00	2.00	3.27	1.96	3.18	2.38	3.85	3.08	5.34	4.09	6.78	5.25	8.80
7.3	1.87	3.04	2.02	3.32	1.98	3.21	2.39	3.88	3.09	5.37	4.10	6.78	5.26	8.81
7.4	1.90	3.08	2.05	3.37	2.00	3.24	2.40	3.90	3.10	5.39	4.10	6.79	5.26	8.81
7.5	1.92	3.12	2.07	3.42	2.02	3.27	2.42	3.92	3.12	5.41	4.11	6.80	5.26	8.81
7.6	1.95	3.17	2.09	3.48	2.04	3.30	2.44	3.95	3.13	5.43	4.12	6.81	5.26	8.82
7.7	1.97	3.21	2.12	3.53	2.06	3.34	2.45	3.98	3.14	5.45	4.12	6.82	5.26	8.83
7.8	2.00	3.25	2.14	3.58	2.08	3.37	2.46	4.00	3.15	5.48	4.13	6.82	5.27	8.83
7.9	2.03	3.29	2.17	3.63	2.10	3.40	2.48	4.02	3.16	5.50	4.13	6.83	5.27	8.83
8.0	2.05	3.33	2.19	3.68	2.12	3.43	2.50	4.05	3.17	5.52	4.14	6.84	5.27	8.84
8.1	2.08	3.37	2.21	3.71	2.14	3.46	2.51	4.08	3.18	5.54	4.15	6.85	5.27	8.84
8.2	2.10	3.42	2.24	2.73	2.16	3.50	2.52	4.10	3.19	5.57	4.15	6.86	5.28	8.85
8.3	2.13	3.46	2.26	2.76	2.18	3.53	2.54	4.12	3.20	5.59	4.16	6.87	5.28	8.86
8.4	2.15	3.50	2.29	3.79	2.20	3.56	2.56	4.15	3.21	5.61	4.16	6.88	5.28	8.86
8.5	2.18	3.54	2.31	3.82	2.22	3.59	2.57	4.18	3.22	5.64	4.17	6.88	5.29	8.86
8.6	2.21	3.58	2.33	3.84	2.23	3.62	2.59	4.20	3.24	5.65	4.18	6.89	5.29	8.87
8.7	2.23	3.62	2.36	3.87	2.25	3.65	2.61	4.22	3.25	5.68	4.18	6.90	5.29	8.88
8.8	2.26	3.67	2.38	3.90	2.27	3.69	2.62	4.25	3.26	5.70	4.19	6.91	5.29	8.88
8.9	2.28	3.71	2.41	3.92	2.30	3.72	2.64	4.28	3.27	5.73	4.19	6.92	5.30	8.88
9.0	2.31	3.75	2.43	3.95	2.31	3.75	2.65	4.30	3.28	5.75	4.20	6.93	5.30	8.89
9.1	2.33	3.79	2.45	3.99	2.33	3.78	2.67	4.32	3.29	5.77	4.21	6.94	5.30	8.90
9.2	2.36	3.83	2.48	4.03	2.35	3.81	2.69	4.35	3.30	5.79	4.21	6.95	5.31	8.91
9.3	2.38	3.88	2.50	4.07	2.37	3.85	2.70	4.38	3.32	5.82	4.22	6.96	5.31	8.91

h	0		3		4		8		12.5		22.5		3.25	
4 in km	P	S	P	S	P	S	P	S	P	S	P	S	P	S
9.4	2.41	3.92	2.53	4.11	2.39	3.88	2.72	4.40	3.33	5.84	4.22	6.97	5.31	8.92
9.5	2.44	3.96	2.55	4.15	2.42	3.91	2.73	4.42	3.34	5.87	4.23	6.98	5.32	8.93
9.6	2.46	4.00	2.58	4.19	2.44	3.94	2.75	4.45	3.35	5.90	4.24	6.99	5.32	8.94
9.7	2.49	4.04	2.60	4.23	2.46	3.97	2.76	4.48	3.36	5.93	4.24	7.00	5.32	8.95
9.8	2.51	4.08	2.63	4.27	2.48	4.00	2.78	4.50	3.38	5.96	4.25	7.01	5.32	8.95
9.9	2.54	4.12	2.65	3.31	2.50	4.04	2.79	4.52	3.39	5.98	4.25	7.02	5.33	8.96
10.0	2.56	4.17	2.68	4.35	2.52	4.07	2.81	4.55	3.40	6.01	4.26	7.03	5.33	8.97
10.1	2.59	4.21	2.70	4.39	2.54	4.10	2.82	4.58	3.41	6.04	4.27	7.04	5.34	8.98
10.2	2.62	4.25	2.73	4.43	2.56	4.13	2.84	4.60	3.43	6.06	4.27	7.05	5.34	8.99
10.3	2.64	4.29	2.75	4.47	2.58	4.16	2.85	4.63	3.44	6.09	4.28	7.06	5.35	8.99
10.4	2.67	4.33	2.78	4.51	2.60	4.20	2.87	4.65	3.46	6.12	4.28	7.07	5.35	9.00
10.5	2.69	4.38	2.80	4.55	2.62	4.23	2.89	4.68	3.47	6.14	4.29	7.09	5.36	9.01
10.6	2.72	4.42	2.82	4.59	2.63	4.26	2.90	4.70	3.48	6.17	4.30	7.10	5.37	9.02
10.7	2.74	4.46	2.85	4.63	2.65	4.29	2.92	4.73	3.50	6.20	4.30	7.11	5.37	9.03
10.8	2.77	4.50	2.87	4.67	2.67	4.32	2.94	4.75	3.51	6.23	4.31	7.12	5.38	9.03
10.9	2.79	4.54	2.90	4.71	2.70	4.36	2.96	4.78	3.53	6.26	4.31	7.13	5.38	9.04
11.0	2.82	4.58	2.92	4.75	2.71	4.39	2.98	4.81	3.54	6.28	4.32	7.14	5.39	9.05
11.1	2.85	4.62	2.94	4.79	2.73	4.42	2.99	4.84	3.55	6.31	4.33	7.15	5.40	9.06
11.2	2.87	4.67	2.97	4.83	2.75	4.45	3.01	4.87	3.57	6.34	4.33	7.16	5.40	9.07
11.3	2.90	4.71	3.00	4.87	2.77	4.48	3.03	4.90	3.58	6.36	4.34	7.17	5.41	9.08
11.4	2.92	4.75	3.02	4.91	2.79	4.52	3.05	4.93	3.60	6.39	4.34	7.18	5.41	9.09
11.5	2.95	4.79	3.04	4.95	2.81	4.55	3.06	4.96	3.61	6.42	4.35	7.20	5.42	9.09
11.6	2.97	4.83	3.07	4.99	2.83	4.58	3.08	4.98	3.62	6.45	4.36	7.21	5.43	9.10
11.7	3.00	4.88	3.10	5.03	2.85	4.61	3.10	5.01	3.64	6.48	4.36	7.22	5.43	9.11
11.8	3.03	4.92	3.12	5.07	2.87	4.64	3.12	5.04	3.65	6.50	4.37	7.23	5.44	9.12
11.9	3.05	4.96	3.14	5.11	2.89	4.68	3.14	5.07	3.67	6.53	4.37	7.24	5.44	9.13
12.0	3.08	5.00	3.17	5.15	2.91	4.71	3.16	5.10	3.68	6.56	4.38	7.24	5.45	9.14
12.1	3.10	5.04	3.20	5.19	2.93	4.74	3.17	5.13	3.70	6.59	4.39	7.25	5.46	9.15
12.2	3.13	5.08	3.22	5.23	2.95	4.77	3.19	5.16	3.71	6.61	4.39	7.25	5.46	9.16
12.3	3.15	5.12	3.24	5.27	2.97	4.80	3.21	5.19	3.72	6.64	4.40	7.26	5.46	9.16
12.4	3.18	5.17	3.27	5.31	2.99	4.84	3.23	5.22	3.74	6.67	4.40	7.27	5.47	9.17
12.5	3.21	5.21	3.30	5.36	3.01	4.87	3.24	5.25	3.76	6.69	4.41	7.28	5.48	9.18
12.6	3.23	5.25	3.32	5.40	3.03	4.90	3.26	5.27	3.77	6.72	4.42	7.28	5.48	9.19
12.7	3.26	5.29	3.34	5.44	3.05	4.93	3.28	5.30	3.78	6.75	4.42	7.29	5.43	9.19
12.8	3.28	5.33	3.37	2.48	3.07	4.96	3.30	5.33	3.80	6.78	4.43	7.30	5.49	9.20
12.9	3.31	5.38	3.40	2.52	3.09	5.00	3.32	5.36	3.82	6.81	4.43	7.30	5.50	9.20
13.0	3.33	5.42	3.42	5.56	3.11	5.03	3.33	5.39	3.83	6.83	4.44	7.31	5.50	9.22
13.1	3.36	5.46	3.44	5.60	3.13	5.06	3.35	5.42	3.85	6.86	4.45	7.33	5.51	9.23
13.2	3.38	5.50	3.47	5.64	3.15	5.09	3.37	5.45	3.86	6.88	4.45	7.34	5.51	9.24
13.3	3.41	5.54	3.50	5.68	3.17	5.12	3.39	5.48	3.88	6.91	4.46	7.36	5.52	9.25
13.4	3.44	5.58	3.52	5.72	3.19	5.16	3.40	5.51	3.89	6.94	4.47	7.37	5.52	9.26
13.5	3.46	5.62	3.54	5.76	3.20	5.19	3.42	5.54	3.91	6.96	4.48	7.39	5.53	9.26
13.6	3.49	5.67	3.57	5.79	3.22	5.22	3.44	5.56	3.93	6.99	4.48	7.41	5.54	9.27
13.7	3.51	5.71	3.60	5.83	3.24	5.25	3.46	5.59	3.94	7.02	4.49	7.42	5.54	9.28
13.8	3.54	5.75	3.62	5.89	3.26	5.29	3.48	5.62	3.96	7.05	4.50	7.44	5.55	9.29
13.9	3.56	5.79	3.64	5.91	3.28	5.32	3.50	5.65	3.98	7.08	4.50	7.45	5.55	9.30
14.0	3.59	5.83	3.67	5.95	3.30	5.35	3.52	5.68	3.99	7.10	4.51	7.47	5.56	9.30
14.1	3.62	5.88	3.70	5.99	3.32	5.38	3.54	5.71	4.00	7.13	4.52	7.49	5.57	9.32
14.2	3.64	5.92	3.72	6.03	3.34	5.41	3.55	5.74	4.02	7.16	4.52	7.50	5.57	9.32

h	0		3		4		8		12.5		22.5		32.5	
Δ in km	P	S	P	S	P	S	P	S	P	S	P	S	P	S
14.3	3.67	5.96	3.74	6.08	3.36	5.45	3.57	5.77	4.04	7.18	4.53	7.52	5.58	9.32
14.4	3.69	6.00	3.77	6.12	3.38	5.48	3.59	5.80	4.05	7.21	4.54	7.53	5.58	9.32
14.5	3.72	6.04	3.80	6.16	3.40	5.51	3.61	5.83	4.06	7.24	4.55	7.55	5.59	9.32
14.6	3.74	6.08	3.82	6.20	3.43	5.54	3.63	5.87	4.08	7.27	4.55	7.57	5.60	9.32
14.7	3.77	6.12	3.84	6.24	3.45	5.57	3.65	5.90	4.10	7.30	4.56	7.58	5.60	9.33
14.8	3.79	6.17	3.87	6.29	3.47	5.61	3.67	5.93	4.11	7.32	4.57	7.60	5.61	9.33
14.9	3.82	6.21	3.90	6.32	3.49	5.64	3.69	5.95	4.12	7.35	4.57	7.61	5.61	9.33
15.0	3.85	6.25	3.92	6.37	3.51	5.67	3.70	5.99	4.14	7.38	4.58	7.63	5.62	9.33
15.1	3.87	6.29	3.94	6.41	3.53	5.70	3.72	6.02	4.16	7.41	4.59	7.65	5.63	9.33
15.2	3.90	6.33	3.97	6.45	3.55	5.73	3.74	6.05	4.17	7.43	4.60	7.66	5.63	9.33
15.3	3.92	6.38	4.00	6.49	3.57	5.77	3.76	6.08	4.19	7.46	4.60	7.68	5.64	9.34
15.4	3.95	6.42	4.02	6.53	3.59	5 80	3.78	6.11	4.20	7.49	4.61	7.69	5.64	9.34
15.5	3.97	6.46	4.04	6.58	3.60	5.83	3.79	6.14	4.22	7.51	4.62	7.71	5.65	9.34
15.6	4.00	6.50	4.07	6.62	3.62	5.86	3.81	6.18	4.24	7.54	4.63	7.73	5.66	9.34
15.7	4.03	6.54	4.10	6.66	3.64	5.89	3.83	6.21	4.25	7.57	4.64	7.74	5.66	9.34
15.8	4.05	6.58	4.12	6.70	3.66	5.93	3.85	6.24	4.26	7.60	4.64	7.76	5.67	9.35
15.9	4.08	6.62	4.14	6.74	3.68	5.96	3.87	6.27	4.28	7.63	4.65	7.77	5.67	9.35
16.0	4.10	6.67	4.17	6.78	3.70	5.99	3.88	6.30	4.30	7.65	4.66	7.79	5.68	9.35
16.1	4.13	6.71	4.20	6.82	3.72	6.02	3.90	6.33	4.32	7.68	4.67	7.79	5.69	9.35
16.2	4.15	6.75	4.22	6.86	3.74	6.05	3.92	6.36	4.34	7.71	4.68	7.80	5.69	9.35
16.3	4.18	6.79	4.25	6.90	3.76	6.09	3.94	6.39	4.35	7.74	4.68	7.81	5.70	9.35
16.4	4.20	6.83	4.27	6.94	3.78	6.12	3.96	6.42	4.37	7.77	4.69	7.81	5.70	9.35
16.5	4.23	6.88	4.30	6.98	3.80	6.15	3.98	6.46	4.39	7.80	4.70	7.81	5.71	9.36
16.6	4.26	6.92	4.33	7.03	3.82	6.18	4.00	6.49	4.41	7.84	4.71	7.82	5.72	9.36
16.7	4.28	6.96	4.35	7.07	3.84	6.21	4.01	6.52	4.43	7.87	4.72	7.86	5.72	9.36
16.8	4.31	7.00	4.38	7.11	3.86	6.24	4.03	6.55	4.44	7.90	4.72	7.89	5.73	9.36
16.9	4.33	7.04	4.40	7.15	3.88	6.27	4.05	6.58	4.46	7.93	4.73	7.92	5.73	9.36
17.0	4.36	7.08	4.43	7.19	3.90	6.30	4.07	6.61	4.48	7.96	4.74	7.96	5.74	9.36
17.1	4.38	7.12	4.46	7.23	3.92	6.34	4.09	6.64	4.50	7.99	4.75	7.98	5.75	9.36
17.2	4.41	7.17	4.48	7.27	3.94	6.37	4.11	6.67	4.51	8.02	4.76	7.99	5.75	9.36
17.3	4.44	7.21	4.50	7.31	3.96	6.40	4.13	6.70	4.53	8.06	4.76	8.01	5.75	9.37
17.4	4.46	7.25	4.53	7.35	3.98	6.43	4.15	6.73	4.54	8.09	4.77	8.03	5.76	9.37
17.5	4.49	7.29	4.56	7.40	4.00	6.46	4.16	6.77	4.56	8.12	4.78	8.04	5.77	9.37
17.6	4.51	7.33	4.58	7.44	4.02	6.49	4.18	6.80	4.58	8.15	4.79	8.06	5.77	9.37
17.7	4.54	7.38	4.60	7.48	4.04	6.53	4.20	6.83	4.59	8.18	4.80	8.08	5.77	9.37
17.8	4.56	7.42	4.63	7.52	4.06	6.56	4.22	6.86	4.61	8.22	4.80	8.10	5.78	9.38
17.9	4.59	7.46	4.66	7.56	4.08	6.56	4.24	6.89	4.62	8.25	4.81	8.11	5.79	9.38
18.0	4.62	7.50	4.68	7.60	4.10	6.56	4.26	6.92	4.64	8.28	4.82	8.13	5.79	9.38
18.1	4.64	7.54	4.70	7.64	4.12	6.57	4.28	6.95	4.66	8.31	4.83	8.15	5.80	9.38
18.2	4.67	7.58	4.73	7.68	4.14	6.57	4.30	6.98	4.67	8.34	4.84	8.16	5.80	9.38
18.3	4.69	7.62	4.76	7.72	4.16	6.57	4.32	7.01	4.69	8.37	4.84	8.18	5.81	9.38
18.4	4.72	7.67	4.78	7.76	4.18	6.57	4.34	7.04	4.71	8.40	4.85	8.20	5.81	9.38
18.5	4.74	7.71	4.80	7.80	4.20	6.57	4.36	7.08	4.72	8.43	4.86	8.21	5.82	9.38
18.6	4.77	7.75	4.83	7.85	4.22	6.58	4.38	7.11	4.74	8.47	4.87	8.23	5.83	9.39
18.7	4.79	7.79	4.86	7.89	4.24	6.58	4.40	7.14	4.76	8.50	4.88	8.25	5.83	9.39
18.8	4.82	7.83	4.88	7.93	4.26	6.58	4.42	7.17	4.78	8.53	4.88	8.27	5.84	9.39
18.9	4.85	7.88	4.90	7.97	4.28	6.58	4.44	7.20	4.79	8.56	4.89	8.28	5.84	9.39
19.0	4.87	7.92	4.93	8.01	4.30	6.59	4.46	7.23	4.81	8.59	4.90	8.30	5.85	9.39

h	0		3		4		8		12.5		22.5		32.5	
in km	P	S	P	S	P	S	P	S	P	S	P	S	P	S
19.1	4.90	7.96	4.96	8.05	4.32	6.59	4.47	7.25	4.83	8.62	4.91	8.32	5.86	9.39
19.2	.92	8.00	4.98	8.09	4.34	6.59	4.49	7.27	4.85	8.65	4.92	8.33	5.86	9.39
19.3	4.95	8.04	5.00	8.13	4.36	6.60	4.51	7.29	4.86	8.68	4.93	8.35	5.87	9.40
19.4	4.97	8.08	5.03	8.17	4.38	6.60	4.53	7.31	4.88	8.71	4.94	8.37	5.87	9.40
19.5	5.00	8.12	5.06	8.22	4.40	6.60	4.55	7.33	4.90	8.74	4.96	8.38	5.88	9.40
19.6	5.03	8.17	5.08	8.26	4.42	6.61	4.57	7.35	4.92	8.78	4.97	8.40	5.89	9.40
19.7	5.05	8.21	5.10	8.30	4.44	6.61	4.59	7.37	4.94	8.81	4.98	8.42	5.89	9.40
19.8	5.08	8.25	5.13	8.34	4.46	6.61	4.61	7.39	4.95	8.84	4.99	8.44	5.90	9.41
19.9	5.10	8.29	5.16	8.38	4.48	6.61	4.63	7.41	4.97	8.87	5.00	8.45	5.90	9.41
20.0	5.15	8.33	5.18	8.43	4.50	6.61	4.65	7.43	4.99	8.90	5.01	8.47	5.91	9.41

With these calculations completed the task of locating epicenters was begun. The data as presented in Table 7 represents an initial correlation of arrivals at the various stations based on time. A number of these eyeball correlations failed to be consistent when the data were used to locate an epicenter.

Two graphical methods were used in locating epicenters at this point. The first method was based on Δ (P-H) arc distance values for each station. A trial H (Hypocentral time) value was computed with the equation:

$$P\text{-}H = 1.37\ (S\text{-}P) \qquad (5)$$

Using this H value, P-H values were calculated for each station and the corresponding distances, Δ (P-H) were taken from the travel time tables. These distance values were then plotted on a map of the area. Intersection of the distance arcs at a point determined the epicenter. If the distance arcs failed to intersect at a point the H value was adjusted until such an intersection was achieved. Should adjustment of H fail to effect an intersection, focal depth was adjusted.

The second method used was the hyperbolic locus method. The time difference between arrivals at any pair of stations will determine a hyperbolic locus by arbitrarily choosing hypocentral times. For a given H, distance arcs from each station of a chosen pair intersect at a point which is a point on the hyperbolic locus. Additional points on the locus are determined by successively chosen values of H. A second pair of stations gives a second hyperbolic locus and similarly for a third pair. The hyperbolic loci should intersect at a point which is the epicenter. Both the hyperbolic method and the arc-distance methods require a minimum of three stations to determine an epicenter. Table 7 lists 216 separate quakes but only sixty-five of these are recorded at three or more stations. Of these sixty-five quakes, epicenters were located for forty-two. These quakes and their epicenters are listed in Table 15 and shown in Figure 13.

TABLE 15 EPICENTERS KILAUEA

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
1	19° 24.2' N	U	3.8	1.10
	155° 19.4' W	O	4.6	.52
	H = 21-39-18.4	M.L.	12.4	.05
	h = 0 km			
3	19° 24.4' N	U	3.3	.15
	155° 19.2' W	O	4.5	.22
	H = 21-45-09.7	M.L.	12.3	.03
	h = 0 km			
7	19° 24.8' N	O	6.8	.10
	155° 20.5' W	D	10.0	.03
	H = 22-09-19.1	M.L.	10.4	.20
	h = 0 km			
16	19° 24.2' N	U	5.1	.30
	155° 20.2' W	O	5.8	.40
	H = 23-50-54.4	M.L.	11.7	.07
	h = 0 km			

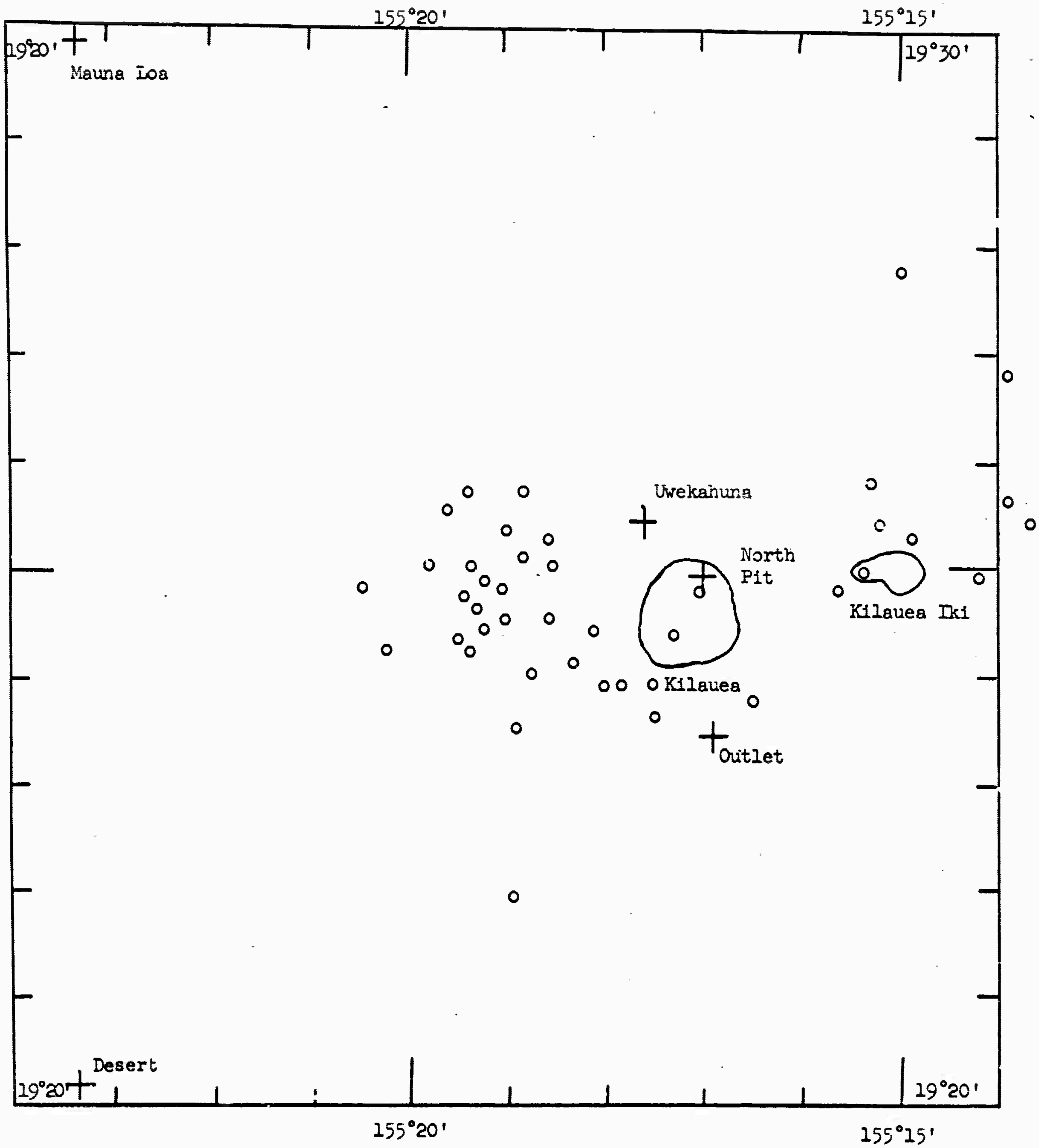

FIGURE 13 EPICENTERS, KILAUEA

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
22	19° 25.0' N	U	3.3	.20
	155° 19.4' W	D	11.1	.07
	H = 00-19-25.4	M.L.	11.4	.11
	h = 0 km			
25	19° 24.7' N	U	3.4	4.40
	155° 19.4' W	D	10.8	.19
	H = 00-28.05.5	M.L.	11.6	.15
	h = 0 km			
28	19° 22.9' N	U	5.2	1.40
	155° 18.9' W	O	3.5	.45
	H = 00-32-31.2	M.L.	15.0	.17
	h = 0 km			
29	19° 24.9' N	U	6.0	.50
	155° 14.2' W	O	5.4	.45
	H = 00-35-43.3	M.L.	18.4	.05
	h = 3.0 km			
30	19° 27.7' N	U	6.2	1.80
	155°15.0' W	O	8.5	.35
	H = 00-36-07.2	M.L.	15.1	.26
	h = 0 km			
34	19° 23.9' N	U	2.8	1.60
	155° 18.0' W	O	2.2	.45
	H = 00-42-05.6	M.L.	14.3	.12
	h = 3.0 km			
41	19° 25.1' N	U	2.2	9.00
	155° 18.8' W	D	12.0	.22
	H = 00-48-50.3	M. L.	11.6	.50
	h = 0 km			
43	19° 24.9' N	U	3.0	6.00
	155° 19.2' W	D	11.2	.10
	H = 00-51-32.3	M.L.	11.7	.15
	h = 0 km			
48	19° 24.6' N	U	3.3	6.20
	155° 19.3' W	O	4.6	.20
	H = 00-55-55.1	M.L.	12.0	.10
	h = 0 km			

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
59	19° 24.5' N	U	3.1	7.50
	155° 19.0' W	D	10.8	.35
	H = 01-14-37.7	M.L.	12.4	.40
	h = 0 km			
67	19° 25.3' N	U	1.6	3.00
	155° 18.6' W	D	12.2	.10
	H = 01-41-03.8	M.L.	11.5	.32
	h = 0 km			
70	19° 24.0' N	U	3.3	.70
	155° 18.7' W	O	3.3	.20
	H = 01-43-32.0	M.L.	13.4	.05
	h = 0 km			
74	19° 23.9' N	U	3.0	2.00
	155° 17.8' W	D	11.7	.05
	H = 01 49-55.6	M.L.	14.6	---
	h = 4.0 km			
81	19° 25.0' N	U	1.9	5.70
	155° 18.5' W	O	4.0	1.00
	H = 02-05-21.7	D	12.0	.36
	h = 4.0 km	M.L.	12.0	.82
84	19° 23.7' N	U	3.2	1.10
	155° 16.5' W	O	1.2	1.20
	H = 02-12-58.4	D	13.7	.94
	h = 4.0 km	M.L.	16.2	.14
89	19° 24.5' N	U	2.3	1.80
	155° 18.5' W	O	3.4	.15
	H= 02-26-42.8	M.L.	12.9	.20
	h = 0 km			
91	19° 25.8' N	U	3.1	16.00
	155° 15.9' W	D	16.6	.30
	H=02-33-45.2	M.L.	15.0	.10
	h = 8.0 km			
95	19° 24.3' N	U	4.0	3.00
	155° 19.5' W	O	5.0	.35
	H = 02-37-58.1	D	10.3	.06
	h = 0 km	M.L.	12.1	.16

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
97	19° 24.4' N	U	2.2	1.50
	155° 18.1' W	O	2.8	----
	H = 02-41-24.2	D	11.9	.02
	h = 3.0 km	M.L.	13.5	.04
101	19° 25.3' N	O	4.7	.70
	155° 18.8' W	N.P.	3.2	.20
	H = 02-48-16.2	D	12.1	.06
	h = 0 km	M. L.	11.6	.06
103	19° 24.1' N	O	2.7	.40
	155° 18.3' W	N.P.	2.7	.80
	H = 02-57-16.0	D	11.3	.50
	h = 0 km			
104	19° 26.8' N	U	6.9	1.60
	155° 13.9' W	O	8.2	.80
	H = 03-00-20.8	M.L.	17.5	.05
	h = 3.0 km			
116	19° 25.0' N	U	4.0	6.30
	155° 15.4'W	O	4.4	.25
	H = 03-23-23.6	D	16.6	.15
	h = 0 km	M.L.	16.5	.15
117	19° 25.4' N	U	6.7	15.80
	155° 13.7' W	D	19.2	.35
	H = 03-24-12.4	M.L.	18.7	.30
	h = 8.0 km			
120	19° 25.3' N	U	2.6	12.00
	155° 19.0' W	D	11.9	.45
	H = 03-28-30.1	M.L.	11.1	.60
	h = 0 km			
125	19° 23.9' N	U	2.7	3.00
	155° 17.5' W	D	12.1	.80
	H = 03-40-51.2	M.L.	14.9	.10
	h = 8.0 km.			
135	19° 23.4' N	U	4.4	3.50
	155° 18.9' W	D	9.6	.76
	H = 04-02-47.6	M.L.	14.1	.16
	h = 3.0 km			

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
144	19° 24.8' N	U	2.9	3.50
	155° 19.1' W	D	11.1	.13
	H=04-15-24.3	M.L.	11.9	.16
	h = 0 km			
147	19° 25.6' N	U	6.4	6.10
	155° 13.9' W	N.P.	5.6	8.00
	H=04-23-19.0	D	19.0	.11
	h = 4.0 km	M.L.	18.1	.25
150	19° 23.6' N	U	3.3	2.30
	155° 17.5' W	D	11.8	.31
	H=04-26-44.2	M.L.	15.3	.20
	h = 5.0 km			
158	19° 25.2' N	U	1.7	36.00
	155° 18.5' W	O	4.2	---
	H=04-39-15.6	D	12.4	.80
	h = 3.0 km	M.L.	12.0	1.60
159	19° 24.8' N	U	2.1	14.00
	155° 18.6' W	O	3.8	.55
	H=04-43-01.2	D	11.9	.09
	h = 3.0 km	M.L.	12.3	.77
168	19° 25.8' N	U	4.0	6.50
	155° 15.3' W	N.P.	3.2	13.00
	H=04-52-31.1	D	17.4	.21
	h = 5.0 km	M.L.	16.0	.12
174	19° 24.9' N	U	3.6	2.70
	155° 19.6' W	D	10.9	.40
	H=05-05-02.2	M.L.	11.3	.18
	h = 3.0 km			
181	19° 25.0' N	U	3.9	.70
	155° 19.8' W	D	10.9	.05
	H=05-18-35.1	M.L.	10.9	.09
	h = 0 km			
182	19° 25.4' N	U	4.0	1.70
	155° 15.2' W	D	16.9	.07
	H=05-22-35.8	M.L.	16.3	.04
	h = 5.0 km			

Quake Number	Epicenter	Station	Distance	Max. Ampl. in mm.
196	19° 24.4' N	U	1.9	2.80
	155° 17.3' W	D	13.0	.91
	H=05-47-03.9	M.L.	14.6	.20
	h = 8.0 km			
206	19° 25.7' N	U	3.0	8.00
	155° 19.4' W	D	12.4	.90
	H=06-09-51.0	M.L.	10.4	.18
	h = 0 km			

A number of difficulties arose in the epicenter program. There were a number of instances where the data were incompatible and no epicenter could be located. In these instances arrival times at the various stations were not from the same quake but were arrivals from different earthquakes that occurred almost simultaneously. If arrivals from both events reached a particular station, one of the arrivals was overridden and lost. Arrivals frequently failed to reach a particular station because the energy was attenuated and absorbed due to its high frequency character and low energy at the source.

This latter condition was very noticeable at the North Pit Station where the number of quakes recorded was much larger than at any other station. In spite of this, there were very few instances where the North Pit data were compatible with that of the other stations. It also seems likely that there may be a local velocity anomaly at North Pit which effects the arrivals.

In a number of cases it was not possible to achieve a unique epicenter. By varying the focal depth an epicenter could be found at any one of several depths varying from the surface on down. As the focal depth changed the epicenter shifted. This naturally gave rise to the question, which epicenter to use? If there was nothing in the character of the seismogram to indicate focal depth, then the surface focus was accepted as the proper one on the basis that these seismic events are associated with the volcanic action which was within a matter of hours of erupting. Hence, the activity was certainly very near to the surface.

7.5 THE COMPUTER PROGRAM

While the graphical location of epicenters was going on, a computer program was being developed to process the data. The program is based on the assumption of rectilinear paths for the seismic waves since the distances are very small. The basic equation of the program is the distance formula:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = V^2 (P_i - H)^2, \quad i=1,2,3,4 \qquad (7)$$

Where x_i = latitude of the station
y_i = longitude of the station
z_i = elevation of the station
V = velocity of the longitudinal wave
P_i = observed arrival time of P wave
H = hypocentral time

For local quakes a suitable origin point is selected to encompass the network of observing stations and the possible epicentral region. For the earthquakes under investigation in Hawaii, the origin point selected was 19° 20' N and 155° 10' W. Latitude and longitude for each station location were then converted to distance in kilometers from the origin using the conversion factors for one minute of arc of meridian and one minute of arc of parallel at this latitude. Station elevation, given in meters above sea level, is converted to kilometers.

Equation 7 involves four unknowns for which we wish to solve x, y, z, and H. Four equations are required so that observations at four stations are necessary for a solution. In order to program the solution it was necessary to express the equations in linear form. A mathematical reduction of the four Equations 7 by eliminating the variable H results in a linear system of three equations of the form:

$$A_i x + B_i y + C_i z + D_i = 0 \qquad i = 1,2,3 \tag{8}$$

Where $A_1 = 2\,[(P_4 - P_2)(x_4 - x_3) - (P_4 - P_3)(x_4 - x_2)]$

$B_1 = 2\,[(P_4 - P_2)(y_4 - y_3) - (P_4 - P_3)(y_4 - y_2)]$

$C_1 = 2\,[(P_4 - P_2)(z_4 - z_3) - (P_4 - P_3)(z_4 - z_2)]$

$$\begin{aligned} D_1 = {} & (P_4 - P_2)(x_3^2 + y_3^2 + z_3^2) \\ & (P_4 - P_3)(x_2^2 + y_2^2 + z_2^2) \\ & + (P_3 - P_2)(x_4^2 + y_4^2 + z_4^2) \\ & + V^2 (P_4 - P_3)(P_4 - P_2)(P_3 - P_2) \end{aligned}$$

Similar values of the
coefficients occur for
A_2 B_2 C_2 D_2 and A_3 B_3 C_3 D_3

Unfortunately the system 7.52 is not an independent system. Any pair of Equations 8 is independent but the third equation is always dependent. Geometrically each Equation 8 represents a plane and if the system were independent the solution would be a point which represents the epicenter. Since the system is dependent the solution will be a line solution.

When solutions of Equations 8 were attempted the results were erratic. This was disturbing but since the equations represented three planes determined by the station coordinates and the observed arrival times, it was at first felt that the result might be legitimate. The coefficients are determined by the observational data which is limited in its accuracy and the resulting numerical values for the coefficients did not reveal the dependent nature of the equations. A reexamination of the theoretical solution of Equations 8 revealed the dependent nature of the system.

This meant that our solution set of equations consisted of two equations in three unknowns, so a method had to be devised to handle this. The three unknowns in Equations 8 are x, y, and z. The method consisted of the following steps:

1. Assume a value for z.
2. Substitute z in Equations 8 and compute the values of x and y.
3. Substitute the assumed value of z and the computed values of x and y in the four Equations 7 and compute a value of H for each equation.

If the four values of H agree then the set of values x, y, z, and H are the solution. The usual circumstance is that the H values will not agree. If they do not agree then a new value is assumed for z and the process repeated. In practice, values of z were chosen for every 0.5 kilometers. As the z values are varied, the H values for each station will converge to a common value which represents the solution. As this convergence occurs, the individual values of H for a given equation will rise through a maximum value and then fall off. This maximum value is the convergence value. The full import of this rise to a maximum is not clear at this time.

This method worked very well and yielded epicentral solutions which gave an independent check on the graphical solutions previously achieved.

It should be pointed out that in the computer solution, values for z the focal depth, can legitimately be positive since the elevation of the Kilauea Crater is about one kilometer.

In the graphical solutions when difficulty was experienced in obtaining an epicentral fix due to an incorrect P arrival at one of the stations, it was not always clear which station was in error. However, in the computer program if there is an incorrect value, this will stand out very clearly in the print out result, since the legitimate values will produce convergence to a common value for H but the incorrect value will not.

This result led to a further adaptation of the computer program to quakes which were recorded at only three stations. When an incorrect P arrival time value occurred which failed to produce a convergence for H, this incorrect arrival was adjusted until its H value did converge. Obviously, this adjusted arrival time is fictitious and does not exist. For the quakes for which only three stations had P arrivals, a fictitious P arrival was fabricated for the fourth station. This set of data with the one spurious value was put into the computer, and this spurious value was adjusted until the computer produced a convergent solution. This procedure is not as arbitrary as it might seem. Basically it amounts to asking the computer to find a fourth P arrival that will fit the other three observed arrivals, given the crustal structure, velocity and coordinates of the stations. Another way of looking at it is that normally the computer is supplied with sixteen pieces of information and asked to compute four others. In the new scheme the computer is supplied with only fifteen pieces of information and asked to compute five others.

As a result of this we have been able to check the graphical epicenters and the computer epicenters against each other and find that there is excellent agreement.

7.6 FIRST MOTION PATTERNS

By combining the first motion data with the epicenter data the first motion pattern for each quake was obtained. The data showed a fairly high consistency, with three patterns resulting. When the compression - dilatation data were plotted at each station, quadrantal lines were drawn through the epicenter to separate the areas of dilatation from the areas of compression. In some cases the position of these lines could be varied by as much as ten to fifteen degrees of rotation about the epicenter but this did not fundamentally change the pattern. In other cases the pattern was rigidly fixed.

One of the quadrantal lines shows a trend Northeast - Southwest, and the other at right angles to this shows a Northwest - Southeast trend. The Northeast - Southwest direction coincides with the direction of the Southwest Rift Zone and the coincidence of these directions probably represents a relationship between this tectonic feature and the seismic motion.

If we assume that this Northeast - Southwest direction represents the line along which the seismic motion occurs then in fifteen cases the Northwest side of the block shifted to the Southeast. In fourteen cases the Northwest side shifted to the Northeast. These represent two of the three main trends observed. They represent opposite direction of motion and seem almost equally likely to occur.

As the epicenters shift from the area Southwest of Kilauea Caldera to an area Northeast of it, the epicenters tend to get deeper and the trend of the quadrantal line shifts from a Northeast - Southwest direction to a direction more East - West. Here again, a general correlation can be made between this direction and that of the East Rift.

The coincidence of these quadrantal lines with the Southwest Rift and with the East Rift seems more than accidental and augurs for a mechanistic connection. However, if the seismic motion occurs along the other quadrantal line which trends Northwest - Southeast, motion along the Southwest part of the block would be Northwest or Southeast.

In seven cases horizontal motion could not explain the distribution of motion. For these a vertical motion was assumed with two blocks separated by a Northwest - Southeast trending line. The Northeast block was characterized by upward motion and the Southwest block by downward motion. The three patterns of motion are shown in Figure 14, 15, and 16.

7.7 AMPLITUDE - DISTANCE RELATIONSHIPS

Maximum amplitude values at each station for each earthquake were combined with the corresponding distances computed in the epicenter program. The medial test was used to determine whether or not a significant relationship existed between amplitude and distance. It will be recalled that in the case of Vesuvian quakes no significant relationship was found. The medial test is shown in Figure 17.

On the strength of the medial test indicating a relationship between amplitude and distance an investigation into magnitude for these Hawaiian

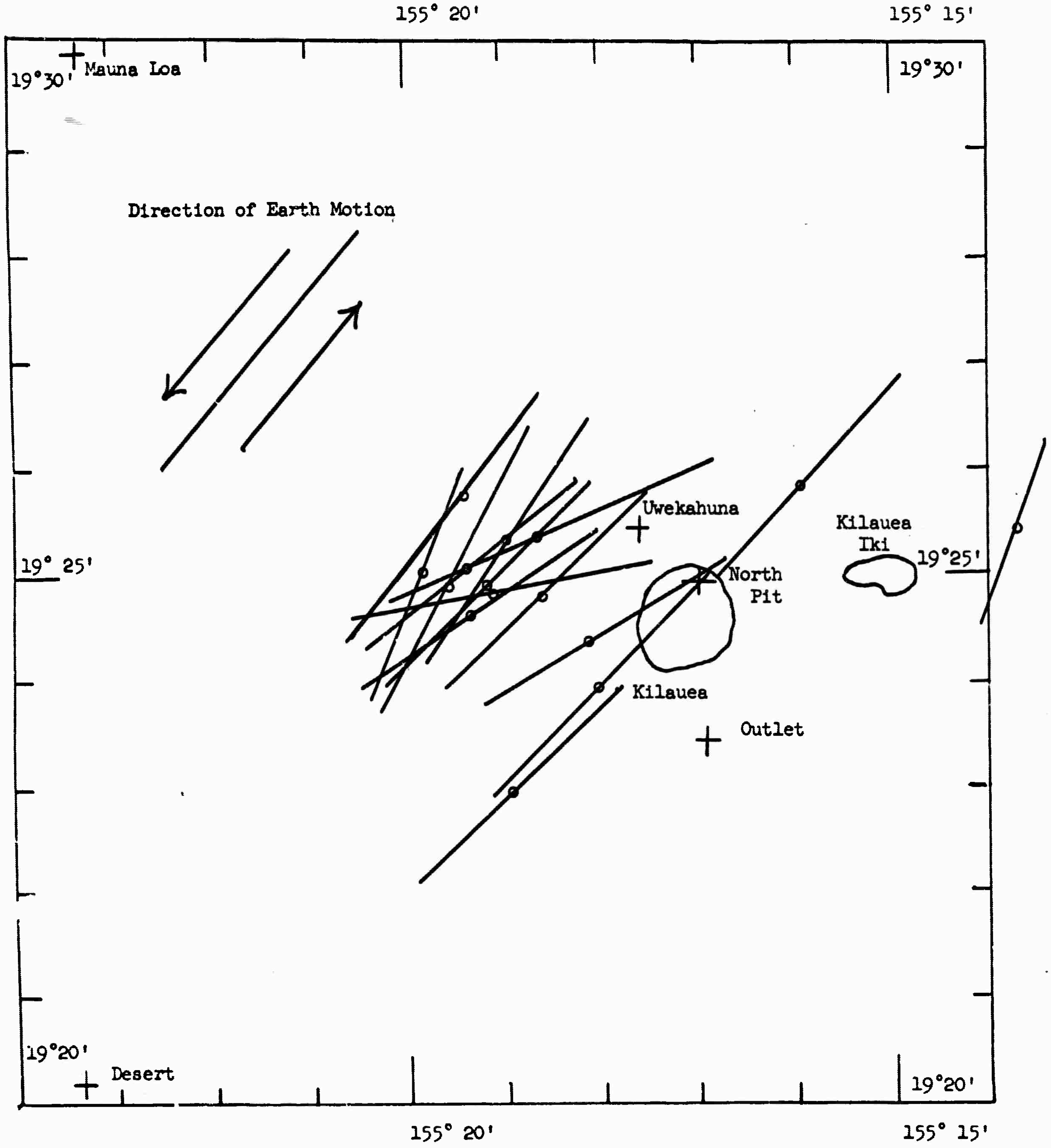

FIGURE 14 EARTH MOTION KILAUEA, PATTERN I

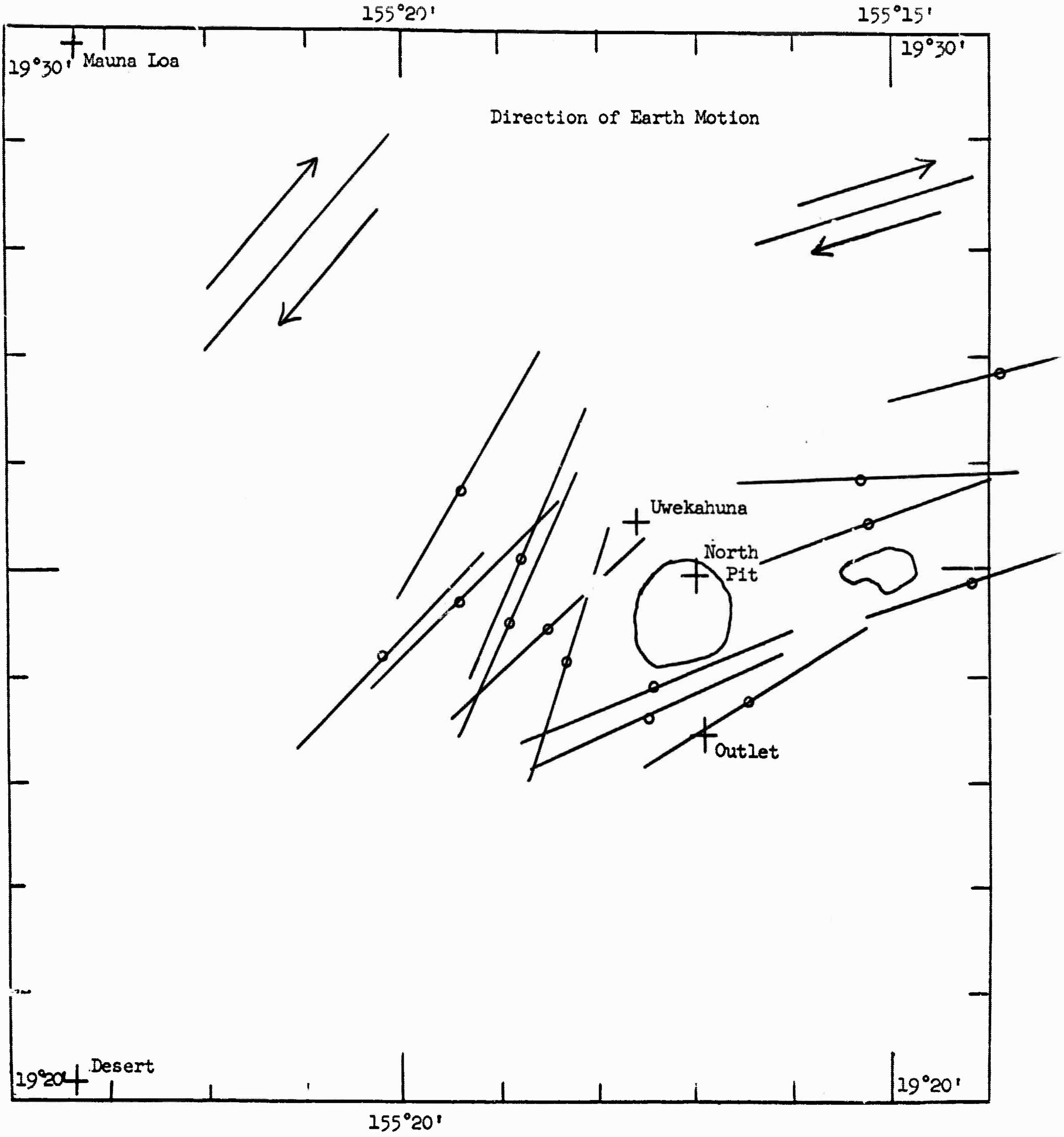

FIGURE 15 EARTH MOTION KILAUEA, PATTERN II

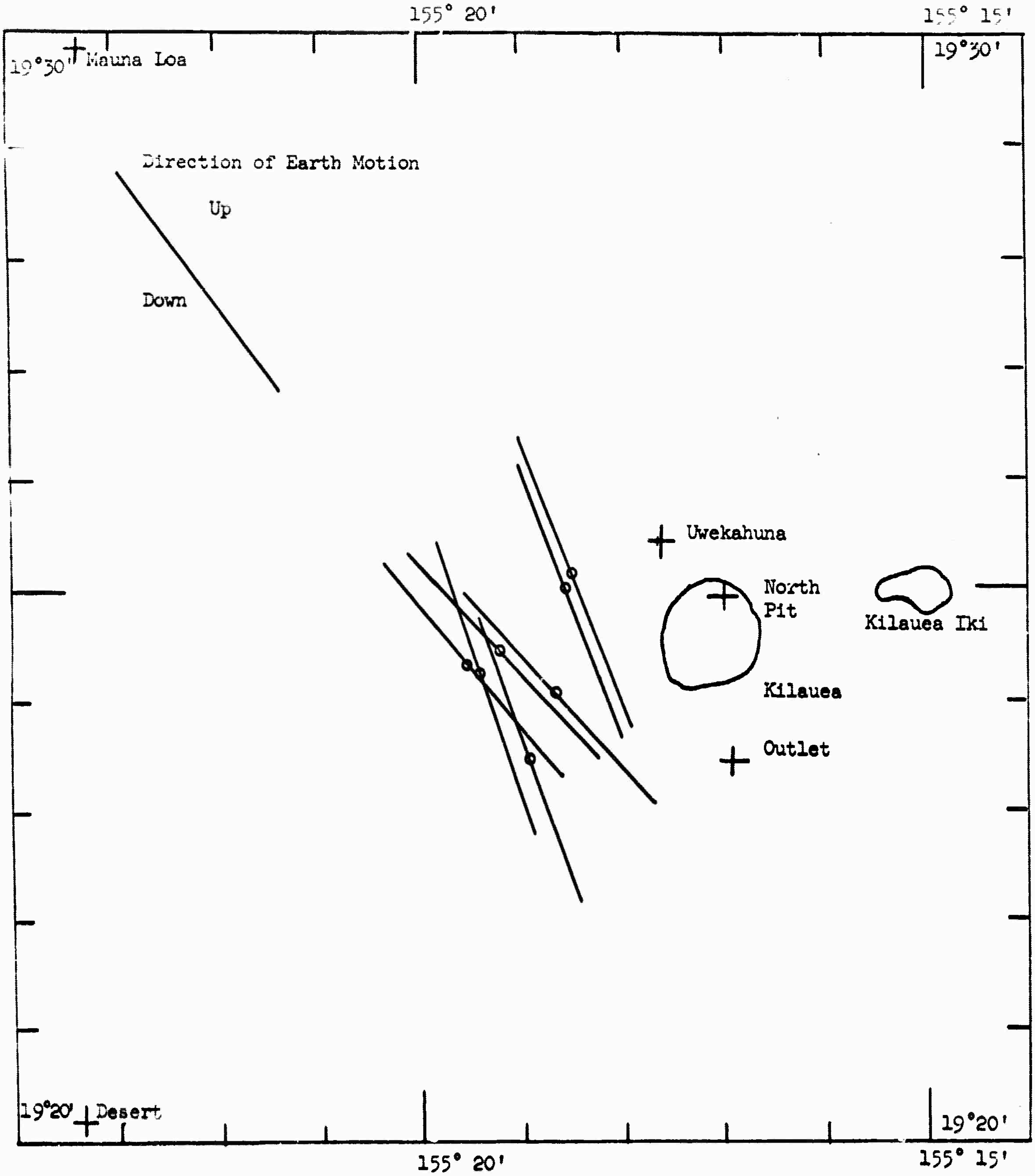

FIGURE 16 EARTH MOTION KILAUEA, PATTERN III

24 points
A > 2.5 mm
Δ < 10 km

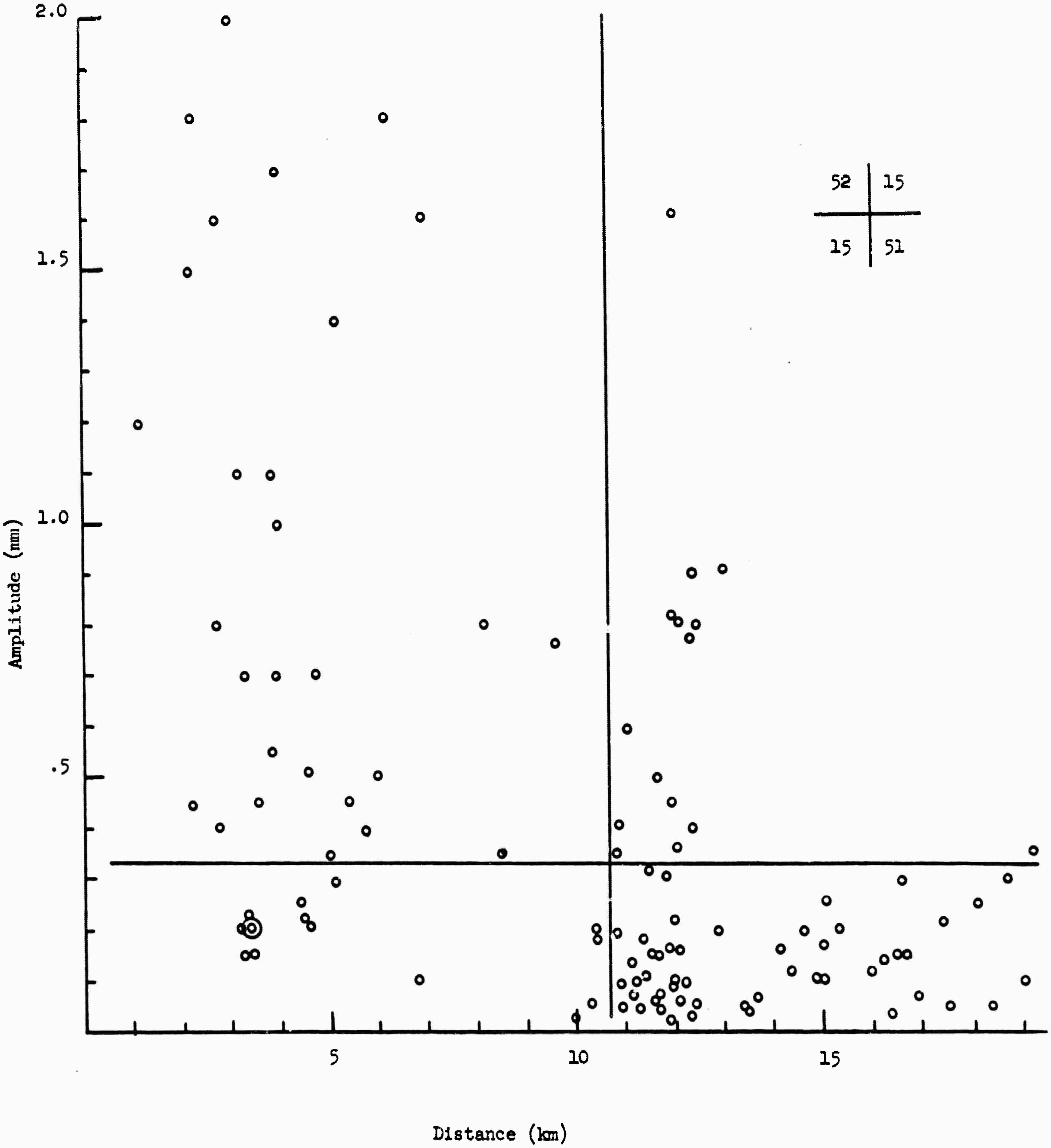

FIGURE 17 MEDIAL TEST, AMPLITUDE VS DISTANCE, KILAUEA

volcanic quakes was begun. Richter's relationship for shallow earthquakes in California between magnitude M, maximum trace amplitude A, and distance Δ is

$$M = \log A + 3 \log \Delta - 3.37 \tag{9}$$

When data for individual quakes were plotted as log A versus log Δ, the points tended to scatter, slope values were difficult to determine and showed a wide variation. At this time it appears that the use of data from a single quake is not reliable. Conclusions based on a single event should be avoided until individual station corrections have been computed.

The data for all the quakes of known epicenters were grouped together on a single graph of log A versus log Δ. The result was a fairly homogeneous picture. A center line was eyeballed through the data and the equation of this regression line was computed to be

$$\log A + 2.3 \log \Delta = 1.64 \tag{10}$$

Expressing magnitude M as a function of A and Δ gives the relationship

$$M = \log A + 2.3 \log \Delta - 1.64 \tag{11}$$

Applying Richter's definition of a zero magnitude earthquake, namely M = 0, $A = 10^{-3}$mm, Δ = 100 km to Equation 11 indicates that the quantities determined empirically from the observed data are in reasonable agreement with the magnitude concept.

For an earthquake of given magnitude, Richter's equation indicates that the amplitude varies inversely as the cube of the distance in Southern California. For Hawaiian quakes, Equation 11 indicates that for a shock of given magnitude, the amplitude varies inversely as the 2.3 power of the distance. Thus, amplitude seems to attenuate less with distance in Hawaii than in California. This may be correlated with the folded and faulted nature of the rocks in the California region. It is, however, somewhat surprising since high attenuation does seem to occur in the Kilauea Summit Region, particularly in the area of the North Pit Station which lies in the caldera. This fact probably accounts for a large part of the attenuation since the rocks in the caldera region are probably weak. The high frequency character of the volcanic - seismic events probably also accounts in part for the attenuation. These factors seem, therefore, to have a pronounced local effect which drops off with the distance.

Using Equation 11, curves for magnitude $M = +1$, $M = 0$, and $M = -1$ were computed and plotted on the graph of the $\log A$ versus $\log \Delta$. Practically all the quakes fell between these magnitude values which indicates the very low energy level of such shocks. The graph of these data is shown in Figure 18.

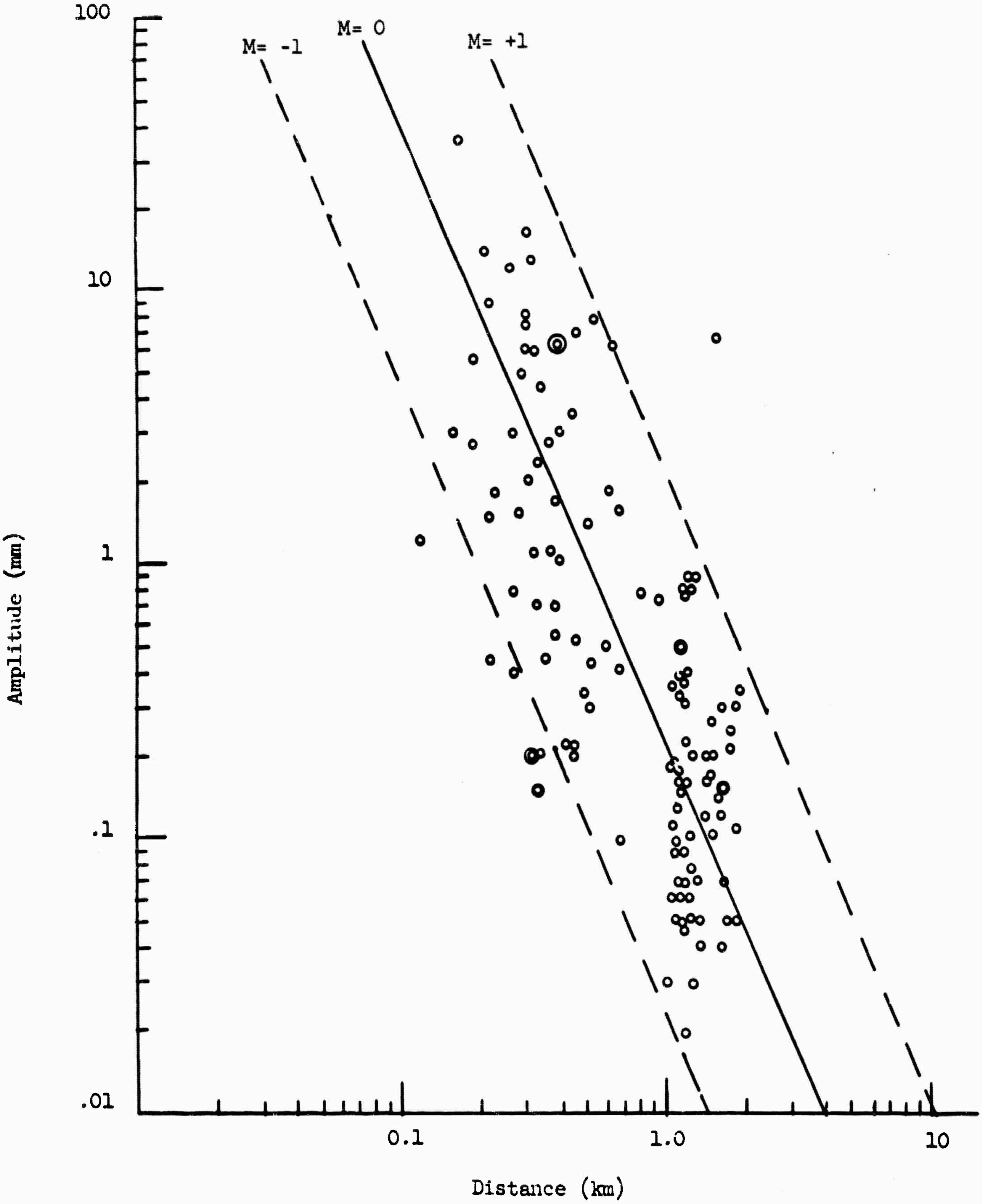

FIGURE 18 LOG A VS LOG Δ, KILAUEA

8

JAPANESE VOLCANOES

The Japanese Islands possess many volcanoes and these have become the object of intensive research. Many of the volcanoes are explosive in character and excellent observatories covering practically all aspects of geophysical science applicable to volcanoes have been set up to investigate the volcanic phenomena.

One such observatory is located at Mount Asama. Through the courtesy and kindness of Professor Ryutaro-Takahasi, Director of The Earthquake Research Institute, The University of Tokyo, preliminary arrangements were made to visit the Institute and examine the seismic data from Mount Asama. Final arrangements were completed through the kindness of the new Director, Professor Hirosi Kawasumi. Professor Takeshi Minakami, Director of The Mount Asama Observatory and Professor of Physical Volcanology and his Assistant, Dr. Kiyoo Mogi, rendered invaluable assistance in making the seismic records available for analysis.

8.1 MOUNT ASAMA VOLCANO OBSERVATORY

Mount Asama is located approximately one hundred kilometers west and slightly north of Tokyo. The Asama Volcano Observatory is located on the eastern flank of the volcano approximately four kilometers from the summit crater. Asama is one of the most active of the Japanese volcanoes and eruptions are frequently explosive. Such an explosive eruption occurred on August 18, 1961. The seismic activity associated with this event is the material investigated here.

At the time of the 1961 eruption a seismic network of seven stations was operating. Seismic signals are telemetered from the instruments to the Asama Observatory where they are recorded on smoked paper which gives a very fine definition of the high frequency motion. The seismographs are electromagnetic and are oriented as vertical or horizontal radial components. The station designations and seismographs located at each are given in Table 16.

TABLE 16 MOUNT ASAMA SEISMOGRAPH STATIONS

Station	Seismograph	Coordinates		
		North	East	Z (km)
A	HR	36° 23.9'	138° 32.2'	2.2
B	HR,Z	36° 24.1'	138° 32.9'	1.8
C	HR,Z	36° 24.0'	138° 34.0'	1.4
D	HR	36° 22.6'	138° 32.2'	1.5
E	HR	36° 23.3'	138° 33.3'	1.6
F	HR	36° 25.6'	138° 32.7'	1.5
G	Z	36° 23.6'	138° 29.8'	2.0

HR = Horizontal Radial component
Z = vertical component

In the investigations at Mount Asama, the Japanese scientists are primarily interested in the question of prediction of volcanic eruptions. Professor Minakami has developed a statistical method for such prediction based on observation of the number of seismic events occurring. The question of hypocentral depth is important and is determined from the character of the seismogram. Since the seismic events are considered as originating in the volcano structure, location of epicenters is not carried out and seismic velocities and local structure apparently have not been investigated. Two types of quakes, A and B, are distinguished by Minakami.

A-type quakes are deep with the hypocenters from one to ten kilometers. B-type quakes are shallow with the hypocenters from zero to one kilometers. Earthquakes of A-type are similar to tectonic quakes and show distinct P and S phases. B-type quakes frequently begin with large motions and show characteristically large surface waves.

Minakami refers to explosion earthquakes as resulting from individual explosions originating in the volcano. The hypocenter of such an explosion is situated not much deeper than the active crater floor. Initial motion is a push in all directions.

8.2 SEISMOGRAPH READINGS

Prior to the August 18th eruption, seismic activity began to increase. Volcanic explosions occurred intermittently with increasing intensity and frequency, culminating in the paroxysm at 14^h 41^m 50^5 local time August 18, 1961. At about 1000 hours, seismic recording was switched off because of the interference coming from electrical phenomena associated with the eruption. Recording was resumed at approximately 1500 hours after the paroxysmic eruption.

The following seismic readings are given only in seconds, with hours and minutes omitted. Direction of motion is indicated as dilatation or compression for all components. For the vertical component this has the usual meaning. For the horizontal radial components, a push is designated as a compression and a pull as a dilatation.

TABLE 17 SEISMOGRAPH READINGS

Station	A	B		C		D	E	F	G
Quake	H	H	Z	H	Z	H	H	H	Z
				August 11					
1	42.8 c	43.3 c							
2	12.4 d								
				August 12					
3	39.5 c	40.5 c							
4	15.5 c	15.5 c	15.2 d			15.2 c		15.1 c	
5	20.2 c	20.6 c	20.2 d	21.1 c		21.5 c	21.4 c		
6	47.4 d	46.6 c							
7	57.0 c	56.8 d				56.9 c		58.3 c	
8	33.2 c	34.3 d	34.2 d				35.3 d	35.3 d	
9	39.5 c	40.8 c							
10	51.8 c								
				August 13					
11	20.2 d	20.2 c							
12	31.8 d	32.0 c							
13	03.0 c	02.5 c							
14	32.2 d								
15	49.7 c	49.8 d							
16	01.0 d	01.1 c					01.6 d		01.3 d
17	38.0 d								
18	58.5 d								
19	53.5 d	54.0 c							
20	19.0 d	18.7 c							
21	24.5 d	24.7 c		27.2 d		28.3 d	28.5 c	27.5 d	24.8 c
22	42.2 d	42.5 c		44.6 d	44.6 c	45.0 c	42.7 d	4.2 c	42.2 c
23	02.2 c	03.1 d							
24	15.7 d								
25	43.0 c	42.9 d	43.0 d			43.4 c		44.1 c	
26	01.7 d	02.3 c		02.7 d					
27	00.4 d	01.3 d						01.8 c	
28	54.1 d	55.2 d							
29	31.0 c	32.0 c	33.5 d			33.0 c	33.6 d	34.3 d	
30	05.8 d								
31	10.3 c								
32	19.2 d	20.2 d							
33	45.5 d	47.3 d				47.3 c		47.7 d	
34	02.7 d	02.6 d		03.2 c		02.1 c			
35	28.2 c	29.5 c							
36	07.8 c	07.9 d	08.8 d	08.9 c		09.3 d	09.4 d	10.1 c	07.5 c
37	29.2 d	30.2 d	29.2 d			31.3 c	30.2 c	29.5 c	29.7 c
38	17.3 c	17.3 d		18.4 c		17.5 d	17.6 d	19.1 d	17.5 c
39	35.9 d	37.7 d							

Station	A	B		C		D	E	F	G
Quake	H	H	Z	H	Z	H	H	H	Z
				August 14					
40	47.8 d	48.0 d							
41	10.5 d	11.6 c							
42	19.0 c	21.5 d							
43	18.4 d								
44	26.9 c								
45	37.8 d	39.5 d							
46	47.3 c	49.0 c							
47	04.8 c	05.0 c		07.0 c		05.7 c	05.7 c	06.1 d	05.5 c
48	51.3 d	51.0 d							
49	09.7 d					09.7 c		10.4 d	
				August 15					
50		52.6 c	52.3 d			53.2 c	53.7 c	52.0 d	
51		06.0 d	06.8 d			06.2 c	07.0 c	05.8 d	
52		14.9 d	15.0 c			15.1 c	15.6 d		
53		37.3 c	36.7 d						
54	40.0 c								
55	20.4 d								
56	00.5 d	00.5 d	00.2 c	01.0 c					00.3 d
				August 16					
57	44.8 c	45.2 c							
58	45.5 d	45.9 d		46.2 d		45.6 c	46.0 d	46.7 d	
59	31.2 c	32.0 c							
60	45.5 c	45.5 c	45.5 d					45.0 d	
61	35.3 d	35.5 c	35.1 d					35.2 d	
62	26.0 c	26.2 d	25.9 c					25.9 d	
63	55.2 d	55.5 d							
64	56.9 c	58.5 c		00.9 c		57.4 d	57.4 d	56.5 d	56.4 c
65	52.6 d	52.7 d	51.7 c				52.7 c		52.4 d
66	30.2 d	30.9 c				34.9 d	33.7 c	33.7 d	
67	57.0 c	58.5 c					58.4 c		
68	15.6 d	17.6 d							
69	21.5 d								
70	58.3 d								
71	22.7 d	23.1 c							22.0 d
72		52.8 d	52.8 d	54.0 d		52.8 c	52.6 d		52.2 c
73	28.4 d	29.1 d		30.0 d					
74	04.8 c	05.3 c							
75	18.1 d	18.7 c							
76	09.8 c								
77	52.7 d	54.7 d							
78	37.9 c	38.2 c							
79						28.5 c	28.8 d	29.1 d	
80		21.8 d		21.6 c		22.0 c	21.8 c	21.7 d	
81	12.4 c	13.5 d							
82	18.9 c	20.0 d							

Station	A	B		C		D	E	F	G
Quake	H	H	Z	H	Z	H	H	H	Z
				August 17					
83	06.2 c	06.6 c		08.0 c					
84	48.1 c	48.5 d							
85	44.7 d								
86	12.1 d					15.9 c		14.0 d	
87	09.6 d								
88	22.7 d	23.2 c							
89	21.1 c	21.2 d							
90	02.7 c								
91	07.5 c	07.7 c				07.8 c			
92	22.6 c	22.8 c							
93	02.4 d								
94	50.6 c								
95	27.3 c	27.6 d						29.0 c	
96	25.5 c					28.2 d	28.3 d	27.2 c	
97	18.3 d	17.8 d				19.7 d	20.0 c	20.7 c	
98	40.6 d	40.8 c				40.7 c			
99	46.7 c								
100	44.8 c	46.5 d				46.5 c	48.2 c	49.0 c	
101	05.0 d	05.3 d	05.0 c	06.9 d		05.6 d	05.5 d	06.1 d	04.6 d
102	47.2 d	48.0 d	47.4 c	49.3 c	48.7 d				
103	08.7 c	12.0 c	11.2 c			11.2 d	12.5 d	13.0 c	11.3 c
104	49.9 c	50.8 c		53.0 d		51.7 d	51.6 d		
105	21.7 c	22.8 d		23.9 d		23.5 c	23.6 c	23.5 d	
106	36.0 c	39.3 d				39.0 d	38.7 c	38.8 d	
107	36.8 c	38.9 d		39.6 c			39.1 c	38.8 c	
108	32.6 c								
109	58.7 c	59.5 c				00.0 c			59.1 c
110	38.8 c	37.6 c	37.9 d						
111		37.3 d	37.2 c	38.1 c	38.6 d				
112		43.1 d							
113	17.9 c	19.4 c							
114		12.8 d	12.8 d			13.3 c	13.5 c	12.6 c	
115		01.0 c		01.2 c					
116	22.6 d	24.0 c	22.8 c			24.5 c	24.1 c	25.0 c	
117		22.8 c							
118		05.5 c		05.9 c	05.9 c				
119		13.6 d	14.0 c						
120		38.5 d	37.7 c						
121		20.1 d		20.7 c	20.8 c				
122		24.6 c							
123	38.9 d								
124	40.1 d	42.4 c							
125	11.3 c	12.2 c							
126	47.1 d	47.4 c	47.2 d	47.6 c					
127	11.2 d	12.8 d							
128	21.6 d	22.5 d							
129	10.5 d	11.9 c	11.0 c			11.7 c		12.0 c	

Station	A	B		C		D	E	F	G
Quake	H	H	Z	H	Z	H	H	H	Z
130		25.7 c	26.0 d		26.2 d	25.7 c	25.9 c	26.5 d	
131	46.7 d	46.7 c	47.0 c	47.0 d	47.5 c	47.6 d	47.3 c	47.3 c	
132	17.8 d								
133	33.6 d								
134	55.0 c	56.5 c	55.8 c		56.6 c	57.3 c	56.5 c	56.6 c	
135	27.5 d								
136	47.6 c								
137	42.6 c	42.8 c	42.3 c						
138	29.2 c	30.2 d							
139	20.5 c								
140	37.7 c								
141	29.0 c								
142		55.7 c	55.2 d			54.7 c	55.3 c	56.0 c	
143		19.4 c							
144	51.7 c								
145	56.8 d	56.9 c		57.6 d					
146	13.6 c	13.8 c				14.8 c		15.6 c	
147	16.1 d							17.1 d	
148	18.4 c	18.2 d				19.2 c	19.6 c	19.1 d	
				August 18					
149	03.2 c								
150	07.2 c								
151	12.8 c								
152	58.4 c								
153	08.8 d	09.1 c							
154	16.5 d	16.1 d	16.2 d	16.6 d	16.4 d	16.0 c	16.2 c	16.4 c	15.5 d
155	45.2 c	45.8 c	45.1 c				47.5 d		
156	34.8 d		38.1 d						
157	51.5 c	51.5 c							
158	16.4 c	17.4 c	17.0 d	17.6 c	17.5 c				
159	23.9 c	24.5 d	24.3 c	25.7 d					
160	48.2 c	49.6 c							

The total number of push and pull motions, labeled c and d respectively in Table 17, for the horizontal radial component of motion were counted, giving the results shown in Table 18.

TABLE 18 HORIZONTAL RADIAL MOTION

	A	B	C	D	E	F	G
Push]	72	64	17	30	24	23	10
Pull]	68	54	13	12	15	20	11

These figures show that in all cases the push motion predominates at all stations and for stations D and E the predominance is very large. However, the significant point is that the pull type motion occurs very frequently. Just how many of these quakes are volcanic quakes and how many are explosion quakes is unknown, but on the basis of the quakes examined, it is evident that the seismic motion is not exclusively push or pull.

8.3 EPICENTERS

Although no crustal model or velocities were available for the Mount Asama Region, it was decided to assume values for these quantities and attempt to locate epicenters. A velocity to 2.0 kilometers per second was used for the computation and was assumed to apply to focal depths of several kilometers. Epicenters were located both graphically and by the computer method. There were sixty-six such cases in the observed data. Forty of these were chosen on which to attempt epicenter locations. Twenty-seven of these cases failed and only thirteen gave satisfactory epicenters. These epicenters are shown in Table 19.

TABLE 19 EPICENTERS - MOUNT ASAMA

Quake	Epicenter	Station
4	36° 23.9' N	A
	138° 30.0' E	B
	H = 13.5	D
	h = +1.0 km	F
7	36° 23.2' N	A
	138° 33.1' E	B
	H = 55.9	D
	h = +1.5 km	F

Quake	Epicenter	Station
25	36° 23.9' N	A
	138° 31.6' E	B
	H = 42.2	D
	h = +1.0 km	
34	36° 23.3' N	A
	138° 31.4' E	B
	H = 1.1	C
	h = 0 km	D
50	36° 23.6' N	B
	138° 30.7' E	E
	H = 51.2	F
	h = +1.0 km	G
51	36° 23.3' N	B
	138° 31.1' E	E
	H = 4.5	F
	h = +1.5 km	G
58	36° 23.6' N	B
	138° 31.5' E	D
	H = 44.4	E
	h = 0 km	F
65	36° 25.0' N	A
	138° 30.0' E	B
	H = 50.1	E
	h = 0 km	G
109	36° 25.0' N	A
	138° 30.8' E	B
	H = 57.4	D
	h = 0 km	G
114	36° 24.6' N	B
	138° 31.0' E	D
	H = 11.0	E
	h = -0.5 km	F
116	36° 24.3' N	B
	138° 30.0' E	D
	H = 21.8	E
	h = 0 km	F

Quake	Epicenter	Station
130	36° 24.4' N	B
	138° 30.0' E	D
	H = 23.3	E
	h = 0 km	F
142	36° 23.1' N	B
	138° 33.3' E	D
	H = 54.8	E
	h = +0.5 km	F

These locations were plotted individually with first motion data for the horizontal radial component. The results were not very satisfactory. In five cases a quadrantal pattern of motion could be observed but the patterns were not all similar. There were four other cases of push and pull motions for which no quadrantal pattern could be observed. Finally, there were four cases in which all motion was push or compressional, three of which were logical patterns. In the fourth case, the pattern of motion could not be reconciled with the location of the epicenter.

The seismic stations at Mount Asama are all located on the flanks of the volcano at elevations below the summit. Hypocenters, therefore, may be either above or below the elevation of the seismic station. Interpretation of the earth's motion must take into consideration the epicentral location, focal depth, and the horizontal and vertical components of seismograph motion. If the motion originates above the seismic station and is a push, it will appear as a push on the horizontal radial seismograph and as a dilatation on the vertical seismograph since the vertical component is downward. The same seismograph motions would result if the motion originated as a pull below the station level. In this latter case, without knowledge of the epicentral location and focal depth, the motion could easily be misinterpreted as a push originating in or near the summit crater. In circumstances such as this, interpretation of ground motion becomes rather complex. The assumptions made concerning the P wave velocity and a crustal model, present additional complications which may account for some of these interpretive difficulties. An example of the interpretation of seismic motion and earth motion is shown in Figure 19.

8.4 FREQUENCY OF OCCURRENCE OF QUAKES

One of the outstanding characteristics of volcanic earthquakes is the fact that they occur in swarms preceding an eruption. Numerous investigations of earthquake frequency have been made. In general, the smaller the magnitude of the shock, the greater the frequency of occurrence. Gutenberg and Richter in SEISMICITY OF THE EARTH show that the frequency of occurrence N and the magnitude M computed from surface wave amplitude are related by the equation

$$\log N = a + b\,(8 - M) \qquad (12)$$

Where a and b are constants

In Japan, M. Ishimoto and K. Iida have developed another empirical equation relating the frequency of occurrence N and the maximum trace amplitude A of the seismogram. This equation is

$$NA^{m} = c \qquad (13)$$

Where m and c are constants

The magnitude M of Equation 12 is determined from the maximum trace amplitude. It was shown by Suzuki that the b of Equation 12 and the m of

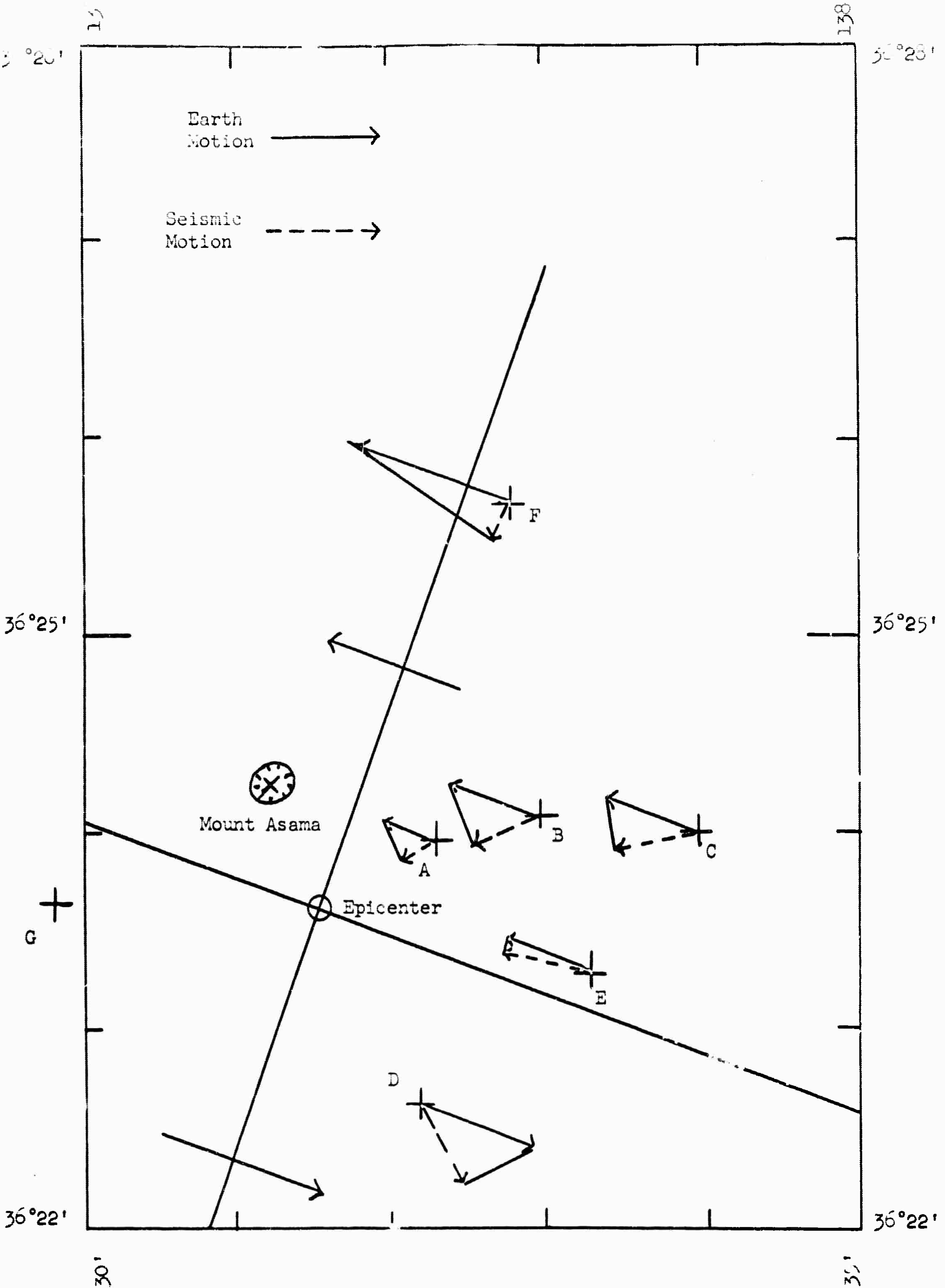

FIGURE 19 EARTH MOTION, MOUNT ASAMA

Equation 13 are so related that

$$b = m - 1 \tag{14}$$

In practice, amplitudes are read over a range A to A + dA and the number in this group is then tabulated. In addition to tabulating the frequency or number of occurrences within a range dA, the frequencies can be summed up so that a value is obtained for the total number of quakes producing all amplitudes from the largest down to a specified value of A. Minakami in Japan has used this approach to show that A-type and B-type volcanic earthquakes have different characteristics.

Indicating the sum of the frequencies of occurrence over an amplitude range from infinity to some value A by N_s, we can write:

$$N_s = \int_{\infty}^{A} N dA \tag{15}$$

$$N_s = \int_{\infty}^{A} cA^{-m} dA \tag{16}$$

$$N_s = \frac{c}{1-m} A^{1-m} \Big]_{\infty}^{A} \tag{17}$$

In practice N_s is obtained numerically so that we may express it in summation form:

$$\sum_{A=\infty}^{A} N = \frac{c}{1-m} A^{1-m} \Big]_{\infty}^{A} \tag{18}$$

The term b in Equation 12 and the term m in Equation 13 are constants. The physical significance of these constants is not very well understood and it is quite remarkable that such constants exist. In the investigation of volcanic quakes, Minakami has found that m has different values depending on the type of quake under consideration.

A-type volcanic quakes are similar to tectonic quakes with values for m in the range 1.8 to 2.2. B-type volcanic quakes and explosion quakes seem to be similar and have much larger values for m ranging from 2.7 to 4.0.

Amplitude data for the Kilauea Iki eruption were analyzed to see what sort of m value would result. When the data are plotted as $\log \Sigma N$ against $\log A$, the curve should be linear and have slope $1-m$ from which m can easily be found. Amplitude, frequency of occurrence, and summation values are given in Table 20. The data are shown graphically in Figure 20 with the value of m equal to 2.6.

TABLE 20 AMPLITUDE - FREQUENCY DATA, KILAUEA IKI

Trace Amplitude in mm	Frequency N	ΣN
1.0	250	342
2.0	42	92
3.0	20	50
4.0	6	30
5.0	4	24
6.0	4	20
7.0	5	16
8.0	2	11
>8.0	9	9

The data for the North Pit station was analyzed separately to see if this method might reveal something unusual. It will be recalled that the North Pit data, rarely agreed with that data from the other stations. The value of m was found to be 2.0 which can be considered to be in the same range as the value determined for all the other stations.

A similar analysis was made for the Vesuvian quakes. The number of data points was smaller and the curve showed a much different character -

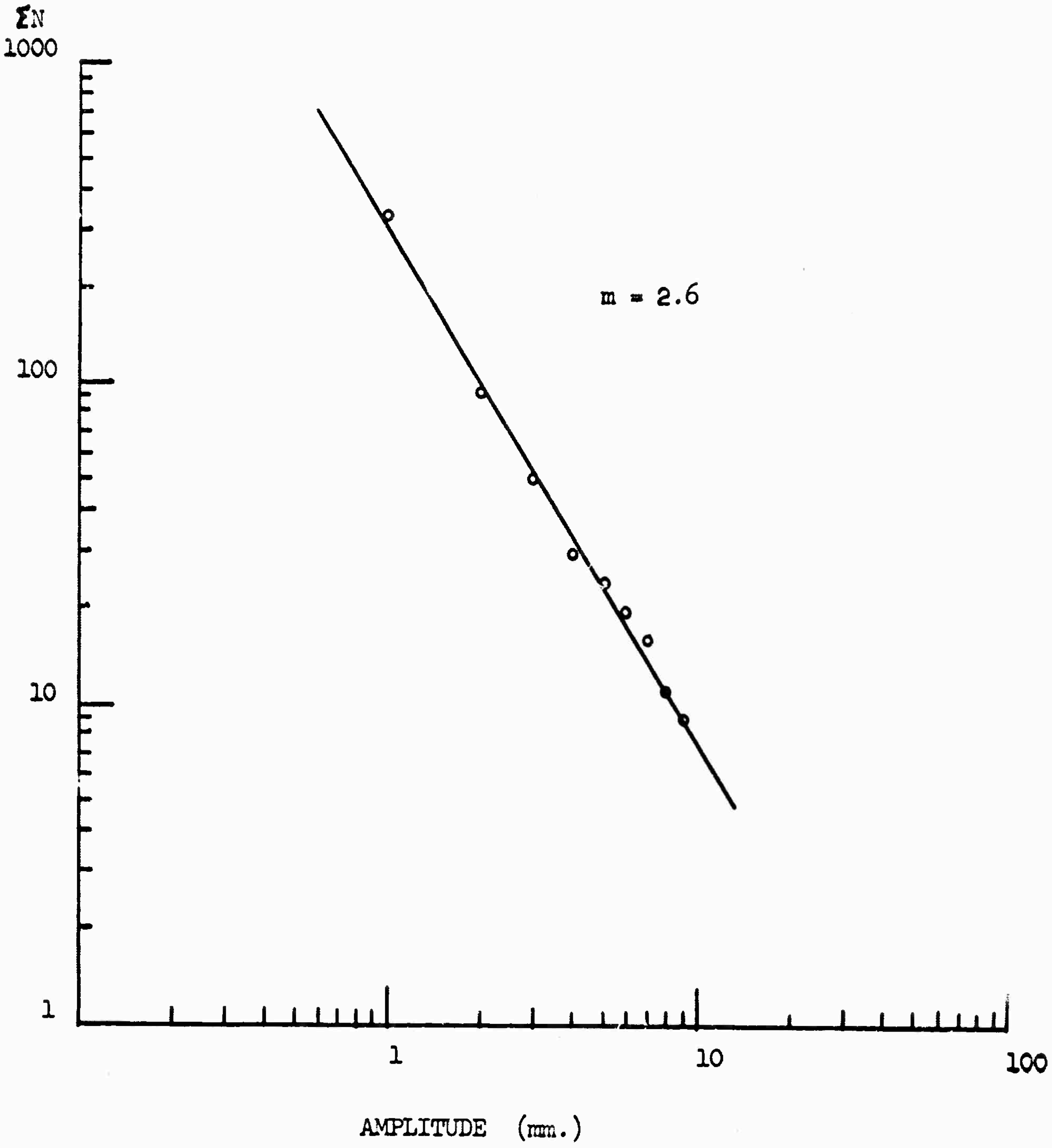

FIGURE 20 LOG ΣN VS LOG A, KILAUEA

two distinct slopes are apparent. The steeper slope gives a value for m = 4.84, which would place Vesuvius in the explosive type, thus verifying through seismic measurement the known historical character of Mount Vesuvius. The graph of this data is shown in Figure 21.

The type of curve resulting from the graph of Vesuvian amplitudes has been found in model experiments by Mogi, in which he correlated the results with the mechanical structure of the medium, which in turn is related to the homogeneity or heterogeneity of the medium.

As indicated previously, the significance of the coefficient m is not too well understood at this time. Perhaps the first thought that arises as a possible explanation for the variation in m, is the question of focal mechanism. An investigation of initial motion patterns for explosive versus non-explosive mechanisms might shed some light on this problem. Focal depth may be a significant factor since the m values for A-type and B-type quakes found by Minakami are different. Finally, it seems quite probable that the type of stress application may be significant. In the case of a tectonic quake, the stress application produces a mechanical rupture or fault; in the case of a volcanic eruption, the stress application may approximate a uniform internal hydrostatic system giving rise eventually to an explosive eruption. In the case of an externally applied intensive stress system, the situation is again different and may be revealed by a characteristic value for m just as the tectonic quakes and volcanic explosion quakes have characteristic values.

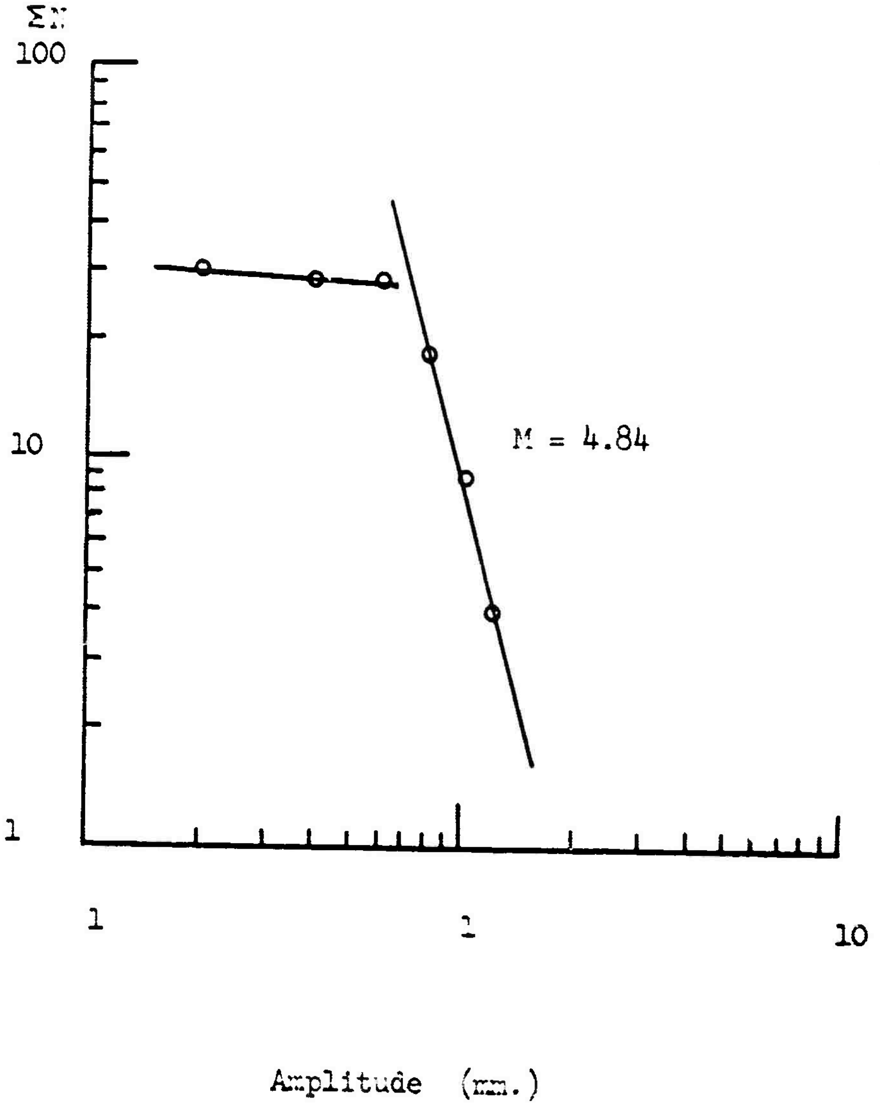

FIGURE 21 LOG ΣN VS LOG A, VESUVIUS

9

SUMMARY AND CONCLUSIONS

Seismic effects, that is earthquakes occuring in volcanic regions and resulting from volcanic processes, have been the subject of this investigation. Three areas selected for investigation were Italy, Hawaii and Japan. Seismographs from these areas were studied and statistical analysis was applied to the data. The following main conclusions have resulted from the investigation:

1. First motion patterns can usually be delineated in non-explosive volcanic regions which indicate that an exclusive first motion push occurs infrequently.

2. In areas where the volcanic mechanism is explosive, a first motion push does occur but not exclusively and many other seismic events also occur which show a quadrantal pattern.

3. Interpretation of a first motion push is subject to serious misinterpretation if location of the epicenter and focal depth are unknown.

4. Volcanic quakes occur in swarms and are generally of low energy having magnitudes on the Richter Scale that range from plus one down into negative values.

5. Volcanic quakes are characterized by high frequency motion which attenuates rapidly and consequently are not usually recorded at distances beyond a few tens of kilometers.

6. Data from a single seismic station tends to show randomness rather than reveal identifying characteristics. When used in conjunction with other stations, the data then responds to analysis.

7. The frequency of occurrence of volcanic quakes shows promise of being a reliable statistical variable with m in the equation $NA^m = c$ being the important coefficient.

8. Tectonic quakes and explosion quakes can be identified by the characteristic m value.

9. The m value gives promise of being an identifying characteristic for an explosive source above ground.

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