# A SEISMIC SURVEY ACROSS LLEWELLYN GLACIER
Camp 26 Sector
Juneau Icefield, Alaska-Canada

by

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A NSF-URP Project

OPEN FILE REPORT - JIRP 1985

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1985

## Abstract

A four day seismic survey was conducted across the Llewellyn Glacier, British Columbia, Canada. The study was significant because the seasonal neve line was much further down the Llewellyn Glacier than it had been in recent years. In the past, studies in the area were difficult due to the presence of large criss-crossing crevasses throughout the area.

The seismograms were analyzed and the approximate glacial ice thickness was calculated. The shallowest depth that was determined was 890 feet at station #7. The thickest portion of the glacier was furthest from Camp-26. This was Seismic Station #6 and the thickness calculated was 1480. The rock-ice interface had relatively shallow dips ranging from 0° to 20°. In some instances a second reflection was found that showed another rock layer at about 1600 feet in depth. The glacial ice thickness was much thicker than had been thought before the project was conducted.

## Introduction

The theory of seismology is used to help investigate and determine the composition and state of planetary interiors. Explosion seismology involves the artificial production and recording of seismic waves, to reveal the geologic structure immediately below the surface. This technique to measure glacial ice thickness has been used since the 1930's. In 1930, Sorge and Loewe measured thicknesses of the Greenland ice-cap. Since that time extensive ice thickness measurements have been made in both the Arctic and Antarctic. (Bullen 1965). The present seismic survey was conducted to determine the glacial thickness across the Llewellyn Glacier, British Columbia. This year's study (summer 1985) was significant because the seasonal névé line was much further down the Llewwllyn Glacier than it had been in recent years. In the past studies in the area were difficult if not impossible due to the presence of large criss-crossing crevasses throughout the area.

## Location of the Seismic Survey

The seismic survey was conducted in a cross-sectional pattern across the Llewellyn Glacier in British Columbia, Canada (south of Atlin). Tests were conducted at eight stations across the glacier. (Figure 1). The location of the survey was chosen because the seasonal névé line was much further down the glacier than it had been in previous years. Past geophysical studies were very difficult and dangerous to conduct due to the numerous and extensive crevasses in the area.

## Theory of Explosion Seismology

Ice and snow have elastic properties therefore artificial explosives can be used to propagate waves. These waves can be recorded and analyzed by the use of a seismograph. There are two basic methods used in explosion seismology. These are the refraction and reflection methods. Refraction shooting is designed to determine seismic speeds and structure of layers in regions where speed does not decrease with depth. (Bullen 1965). The waves are refracted as they come in contact with layers which have different velocities. (Figure 2).

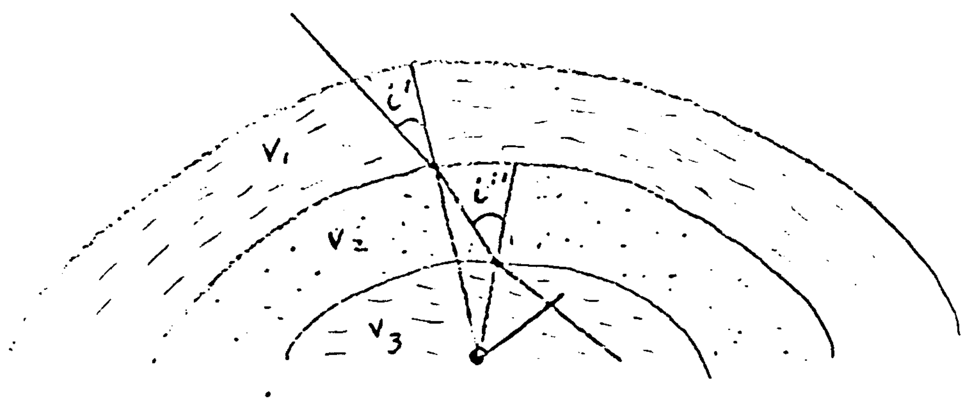



Figure 2. Theory behind refraction seismology. The shot is refracted as it comes in contact with layers with different velocities.

Reflection shooting attempts to record near vertical reflections from the boundaries of the layer investigated. (Bullen 1965). Reflection shooting is principally used when making determinations for ice thickness in a given place. Reflection seismology was the method used in the present study. In seeking reflections for the ice-rock interface special attention must be given to backround effects such as surface waves and scattered waves.

Complications due to surface waves are reduced be firing shots in deep bore holes. According to Bullen (1965), it can be possible to determine ice thicknesses to within 2% accuracy. In the present study the bore holes could only be augered as deep as the available equipment would allow. The holes were generally five-ten feet deep. It is possible that there is some error in our findings due to the fact that the bore holes used were not very deep.

Two methods of setting up the geophones were employed to overcome the above mentioned backround effects. The geophones were set up in an "L" shaped pattern. This pattern helps to show more accurately the difference in the "real" reflection and scattered reflections. When possible the array was set up over an open crevasse. This was done to reduce complications by breaking up the surface wave. Crevasses help to restrict surface wave readings.

## Seismological Equipment

Geophones are the recorders of the various waves as they are propagated over the area. There are two types of geophones. One type measures horizontal ground movement and the other measures vertical ground movement. The geophones that measure horizontal displacement were used in this study. A geophone is similar in theory and construction to a pendulum. The geophone (recorder) is placed in the ground or ice and when the earth moves a pendulum type device swings back and forth. The amount of swinging motion inside the geophone is recorded on magnetic tape and an amplified image of the movement is shown on a seismograph. Adjustments (gain for example) can be made to enhance the image and any reflections that may be present. The paper reproduction of the image is called a seismogram. The results of the seismogram are analyzed and the data is used in geophysical formulas to determine (in this case) glacial ice thickness.

## Calculation of Depth and Dip of the Ice-Rock Interface

When a reflection is detected in the seismogram, the times of the reflected waves for each particular geophone are noted. (Figure 3). Only the geophones which are in line with the shot location are taken into consideration.

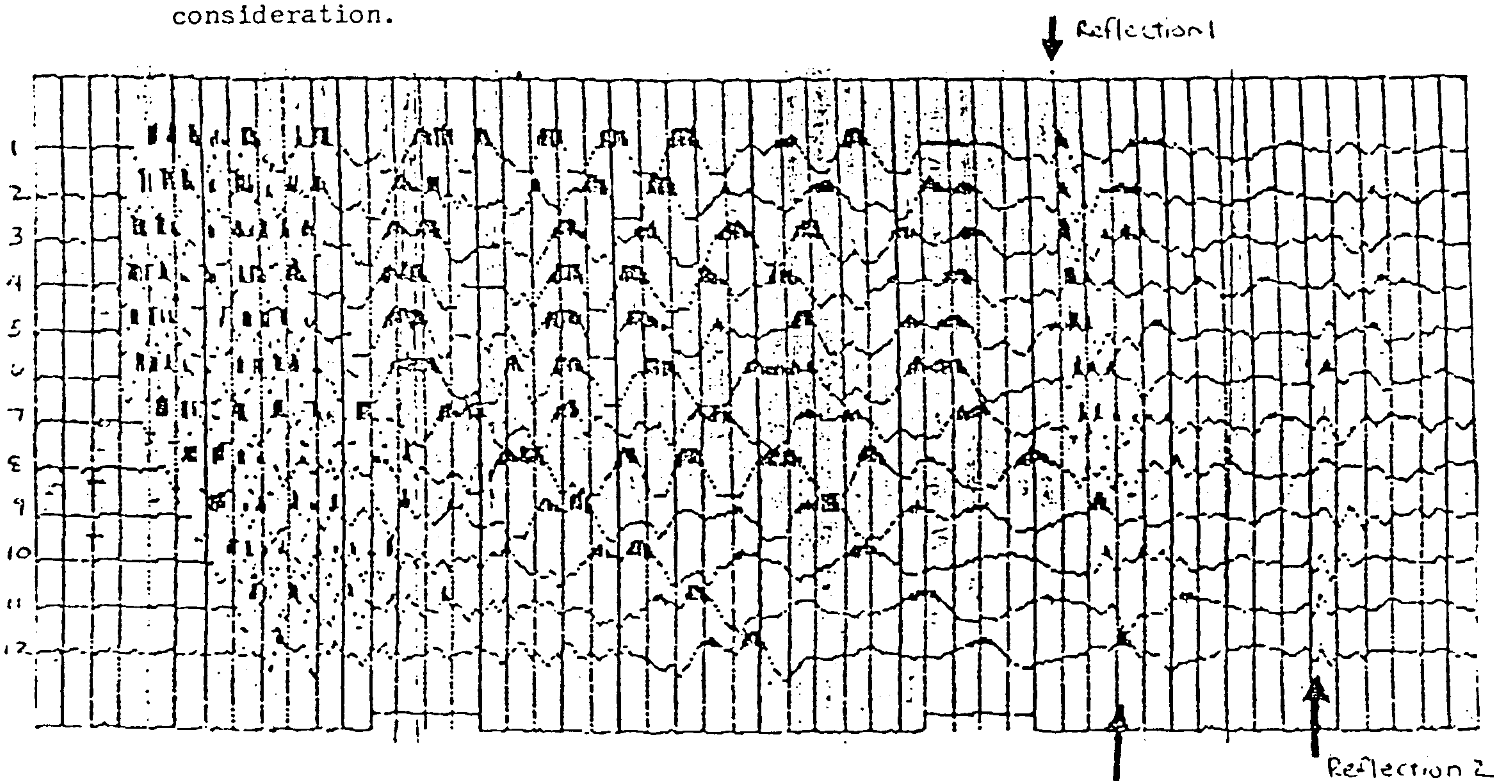



Figure 3. An example of a seismogram showing two reflections

For the example in Figure 3 only geophones 6-12 are of interest. This was the limb of the array in line with the shot. The geophone numbers are listed along the left hand side of the seismogram. The seismogram is recorded in increments of 5 ms. To find the reflection arrival time count the ms over to the peak of the reflection. The arrival of the reflected wave to geophone 7 occurred .208 s after the shot was set off. The time to geophone 12 was .216 s. The difference between the arrival times $\Delta t$ = .008 s. The variables needed to perform the depth calculations are $\Delta t$, $\Delta x$, $R_1$ and $R_2$. The distance $\Delta x$ between the two geophones is 250 ft. R is equal to the velocity of the ice multiplied by the respective values of t. Figure 4 is a step by step chart showing the procedure in calculating the glacial ice thickness.

<u>Procedure For Calculating Depth</u>

1. Measure arrival times $t_1$ and $t_2$. (See Figure 3).
2. The velocity at which sound waves travel through the ice is 12,500 ft/s. It is assumed that the ice is homogeneous.
3. The distance $\Delta x$ between the two geophones under inspection is recorded.
4. $\cos \theta = \frac{v \Delta t}{\Delta x}$
5. $\theta = \cos^{-1}$
6. $R_1 = vt_1$ ; $R_2 = vt_2$
7. Draw a horizontal line placing the shot and geophones in question at appropriate distances from one another. (See Figure 5)
8. Construct the $\angle \theta$ off of the last geophone.
9. From this $\angle$ draw $R_2$. Draw $R_1$ coming from the first geophone so that it intersects $R_2$.
10. Construct the line SI.
11. Construct the perpendicular bisector $\perp$ of SI.
12. The depth beneath the shot is measured from S to the $\perp$ bisector.

Figure 4. Procedure for calculating depth.

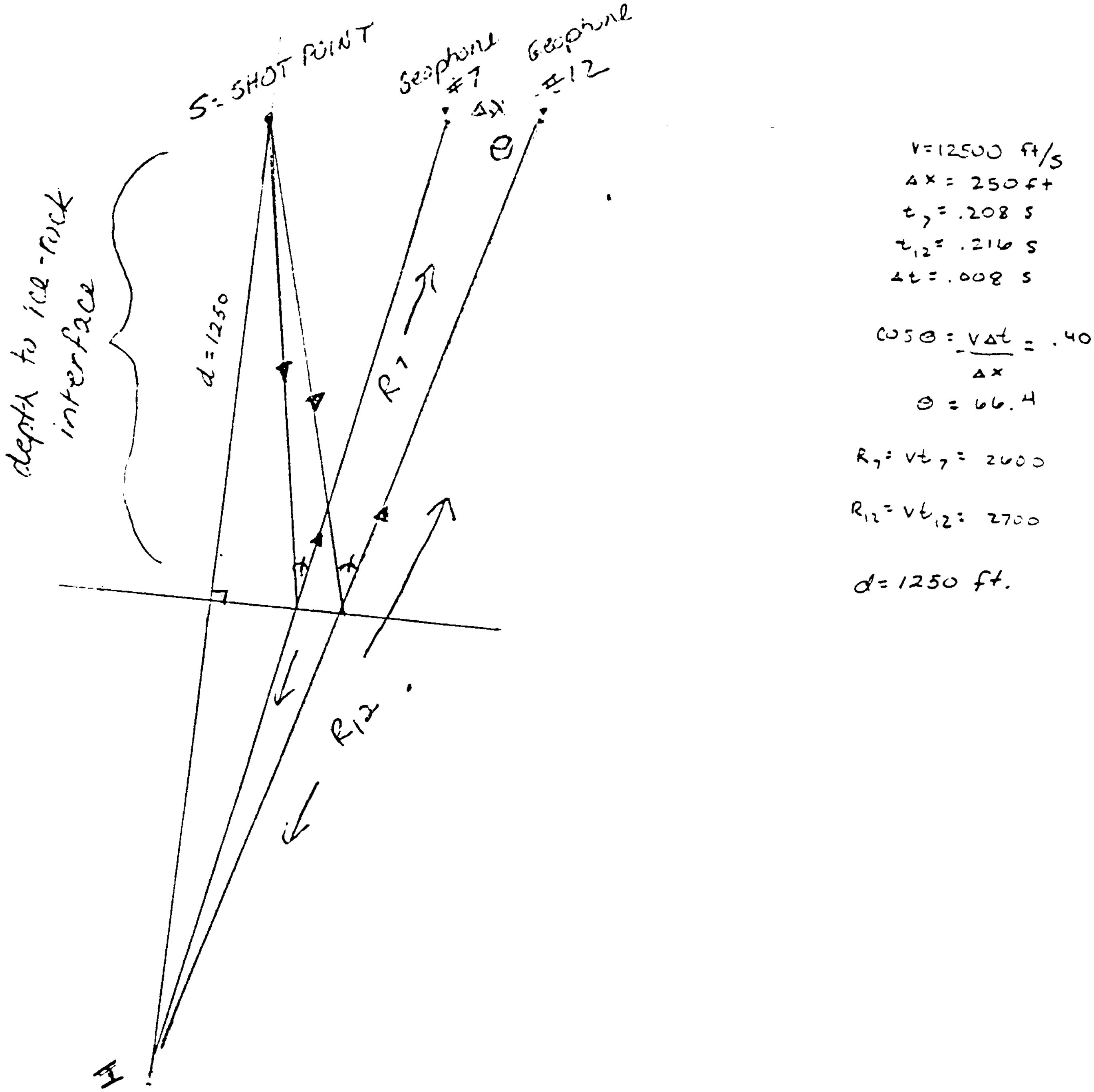



Figure 5. Geometry involved in calculating the depth.

## Daily Account of the Experiment

Day 1-Friday August 2, 1985

Today was a practice day to become familiar with the equipment. An "L" shaped array was set up. (Figure 1). By setting the geophones in different configurations possible noise can be ruled out and data can be confirmed if two reflections are obtained. The geophones are set up by first setting out a seismic cable in the pattern desired. The geophones are attached to the cables and buried every fifty feet in the snow. It is best to pack the snow down hard after the geophones are buried.

After the first array was set an air shot was set off. The blasting wires were attached to two stakes and the blasting cap was put in a booster. The equipment seemed to work fine.

Next, an explosive by the brand name Tovex was tested. It did not work. This particular explosive was manufactured in Canada. It was found later in the week that this type of Tovex would not explode at all. Perhaps it was too old or it had been frozen too often and the explosive power had been affected. The Tovex that had been manufactured in the USA was tested and it worked satisfactorily. A reflection was observed on this shot. One third a stick of the explosive seemed to give the right amount of energy to obtain detectable reflections.

This first day a few tips for using the equipment were learned:

1. Always make sure that the memory on the machine is clear before making a reading. If the memory is not clear the seismogram will contain all recordings from present and previous shots.

2. After the blast always make sure that the end wires that connect the circuit to the firing device are shunted. This shorts the circuit and prevents possible accidents while wiring the explosive.

3. Be as still as possible while the seismograph is recording, whether in the vehicle or in the immediate area.

Day 2- Saturday August 3, 1985

Went back to Seismic Station #1. Two shots were set at either end of the line. Several reflections ere obtained. There were three shots in which reflections could be obtained. These are shown in the section on the Data and Analysis.

After a sufficient amount of data was collected a new seismic station was set up further up the glacier, towards Camp F-10. This new location was designated Seismic Station #2. The array was set up with one limb perpendicular to a crevasse. Two shots were fired. Both were 400 feet off of either limb of the array. The first shot did not work very well. There did not seem to be enough energy in the explosion. This could have been caused by several reasons. It is possible that the shot was not set deep enough and the snow damped the waves. It is also possible that the charge was not packed tightly enough into the hole with enough snow packed down over top of it. Another shot was set which did reveal a reflection. The shot location on this array was closer to an ice layer and the recording seemed stronger. As it turned out both shots revealed depths that were fairly close together. (See section on Data and Analysis)

Day 3- Sunday August 4. 1985

A new array was set up which lay between seismic stations #1 and #2. This new array was designated Seismic Station #3. Several shots were attempted but no definite reflections could be found.

Two shots at four foot and six foot depths were tested. A three foot airshot and a shot 60' down in a crevasse were tested also. Possible reflections were found in the two ground shots. When the depths at these two shots were analyzed they resulted in fairly close values.

Two new arrays were set up later in the day. These new arrays were seismic stations #4 and #5. Prominent reflections were obtained from each station after only one shot. The shot at station #4 revealed three reflections.

Day- August 6, 1985

Seismic Stations #6, #7 and #8 were set up. Reflections were obtained from each station. This was the last day that the geophysics project was conducted.

## Data and Analysis

The seismographs for each of the eight seismic stations of the eight seismic stations were analyzed. The arrival times of the reflections were determined and the depths below the shot were calculated as in Figure 4. The seismograms and the geometrical analyses of the data are shown in Figures (6-38). The following is a summary of the depths found for each seismic station.

### Ice Thickness Below the Seismic Stations

Station #1-
- Shot 1-Airblast, depth = 1265, dip = 5°
- Shot 1-Groundshot, depth = 1235, dip = 3°
- Shot 2-Groundshot, reflection 1 depth = 1250, dip = 6°
  reflection 2 depth = 1600, dip = 10°

Station #2-
- Shot 1- depth = 1060, dip = 10°
- Shot 2- depth = 1015, dip = 16°

Station #3-
- Shot 1- depth = 1110, dip = 5°
- Shot 2- depth = 1175, dip = 13°

Station #4-
- Shot 1- reflection 1, depth = 1180, dip = 2°
  reflection 2, depth = 1170, dip = 13°
  reflection 3, depth = 1450, dip = 0°

Station #5-
- Shot 1- depth = 1070, dip = 7°

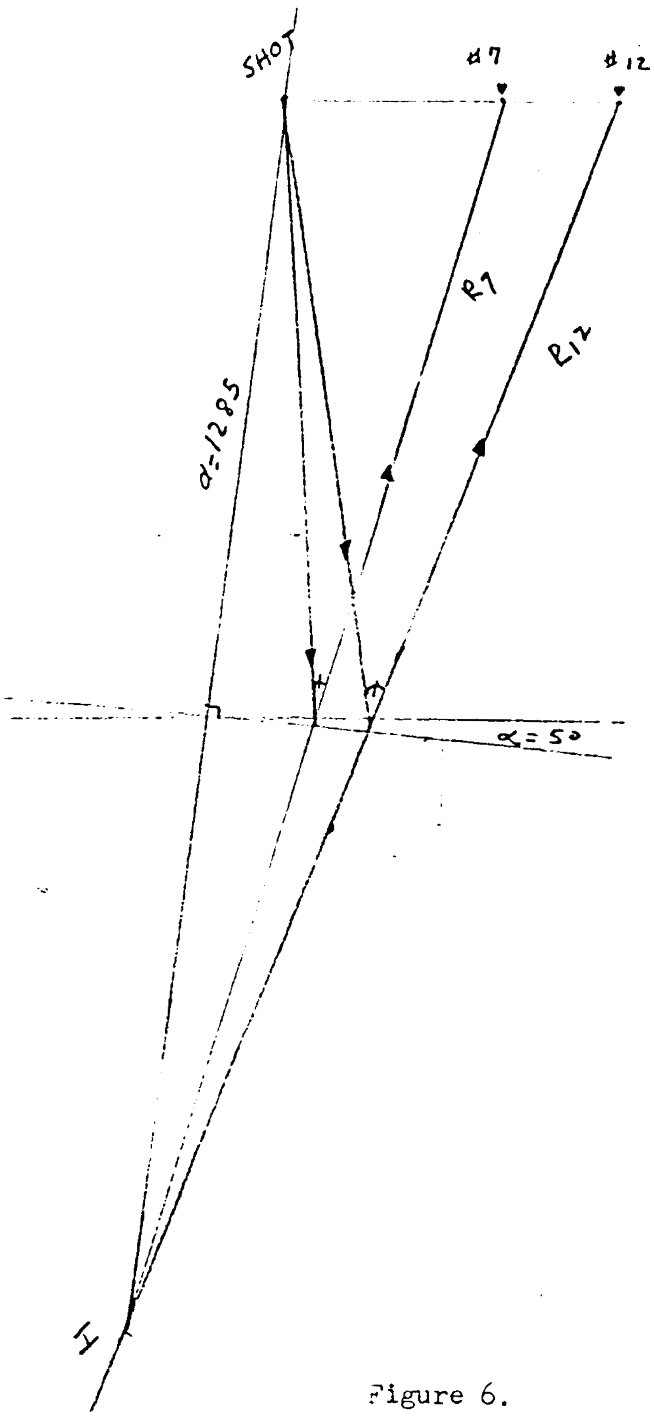
Station #6-
- Shot 1- depth = 600, dip = 9°
- Shot 2- depth = 1480, dip = 11°
- Shot 3- depth = 1300, dip = 7°

Station #7-
- Shot 1- depth = 860, dip = 7°
- Shot 2- depth = 390, dip = 25°

Station #8-
- Shot 1- depth = 1575, dip = 4°

Figure 39. Summary of the glacial ice thicknesses beneath the seismic stations.

Seismic Station #1
Shot #1
Airblast




$V = 12500$ ft/s

$\Delta x = 250$ ft

$t_7 = .213$

$t_{12} = .220$

$\Delta t = .007$

$$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.35$$

$\theta = 69.5$

$R_7 = vt_7 = 2662.5$

$R_{12} = vt_{12} = 2750$

$d = 1285$ ft

$\alpha = 5°$

Figure 6.

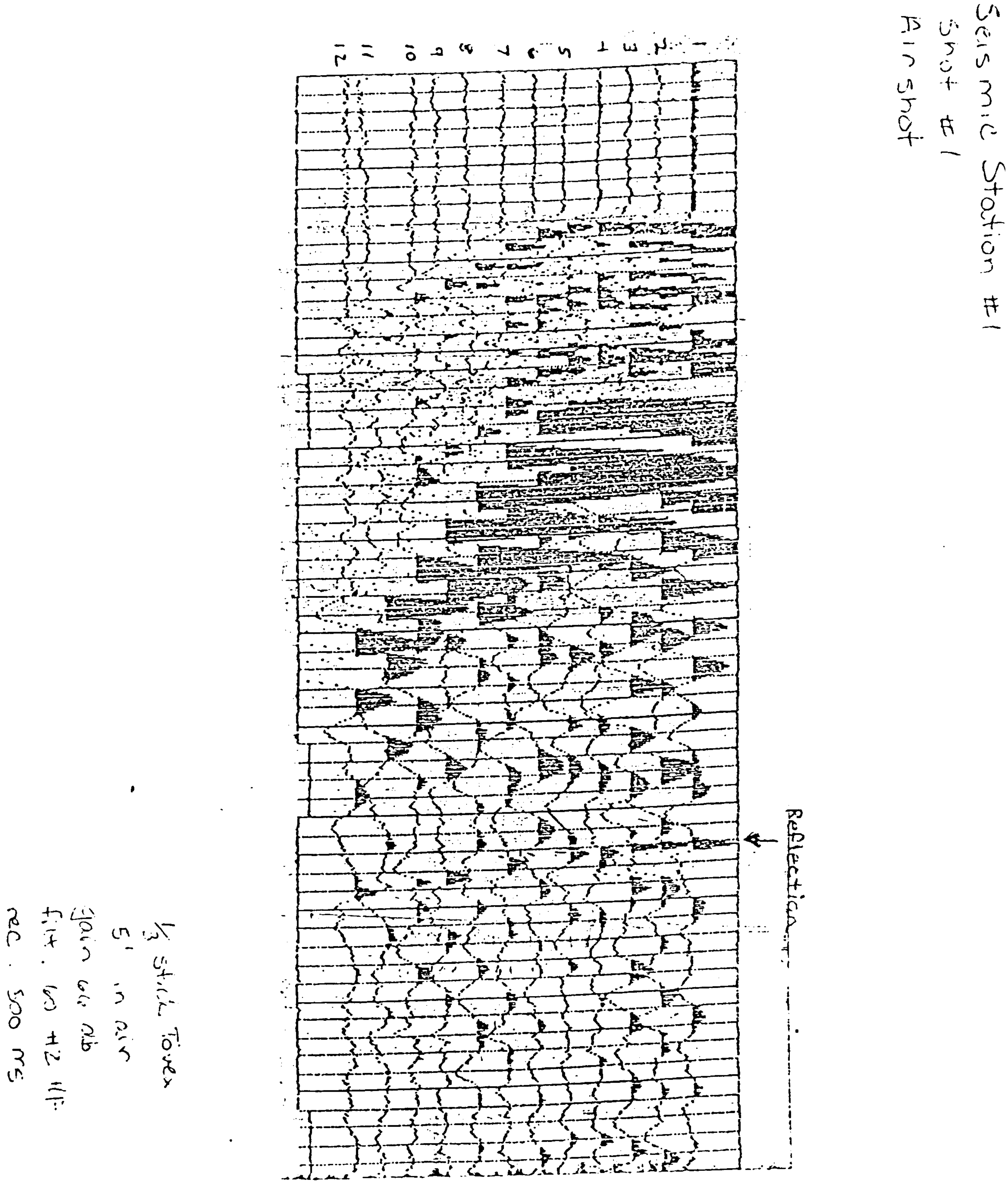
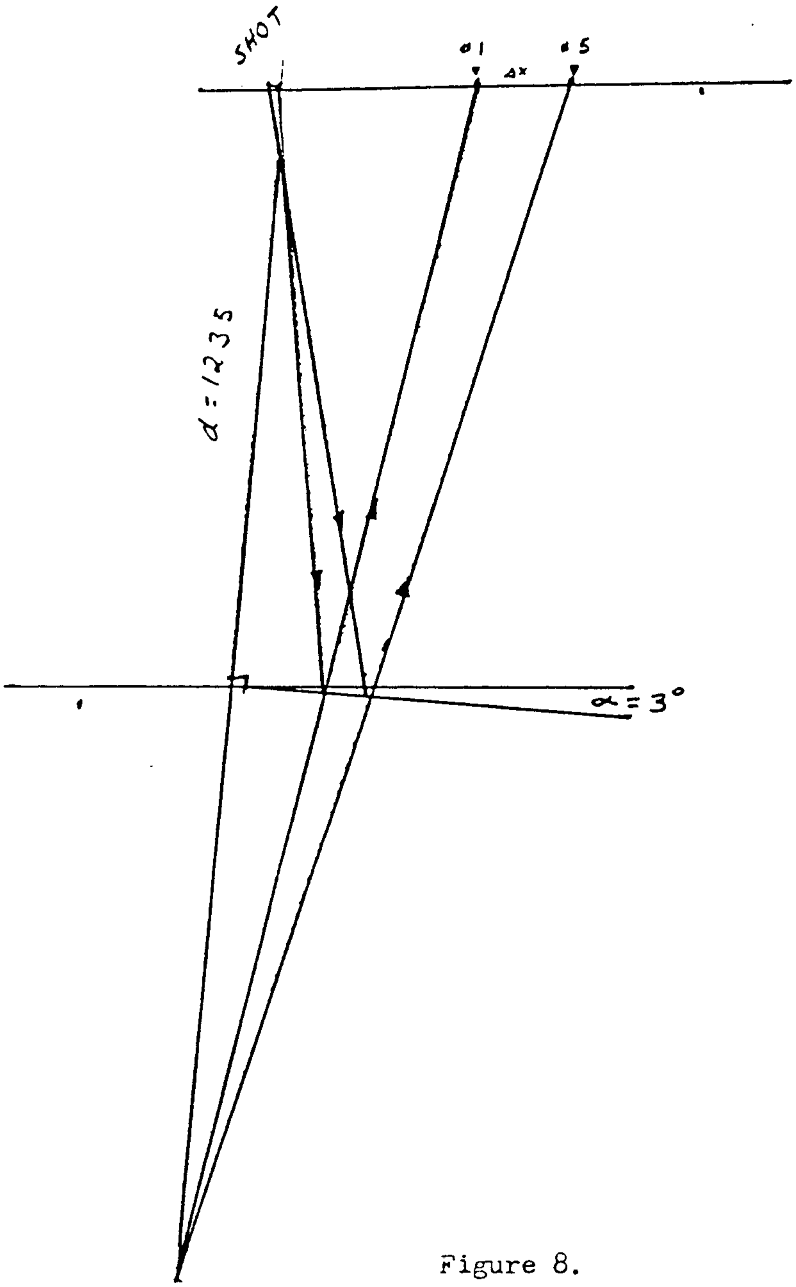

Seismic Station #1
Shot #1
Air shot
Reflection
1/3 stick Tovex
5' in air
rec. 500 ms

Figure 7.

Seismic Station #1
Shot 1
Groundshot




$V = 12500$ ft/sec
$\Delta x = 200$ ft
$t_1 = .203$ s
$t_5 = .208$ s
$\Delta t = .005$ s

$\cos\theta = \frac{V\Delta t}{\Delta x} = 0.3125$

$\theta = 72°$

$R_1 = Vt_1 = 2537.5$ ft

$R_2 = Vt_5 = 2600$ ft

$\Delta R = 62.5$

$d = 1235$ ft

$\alpha = \text{dip} = 3°$

Figure 8.

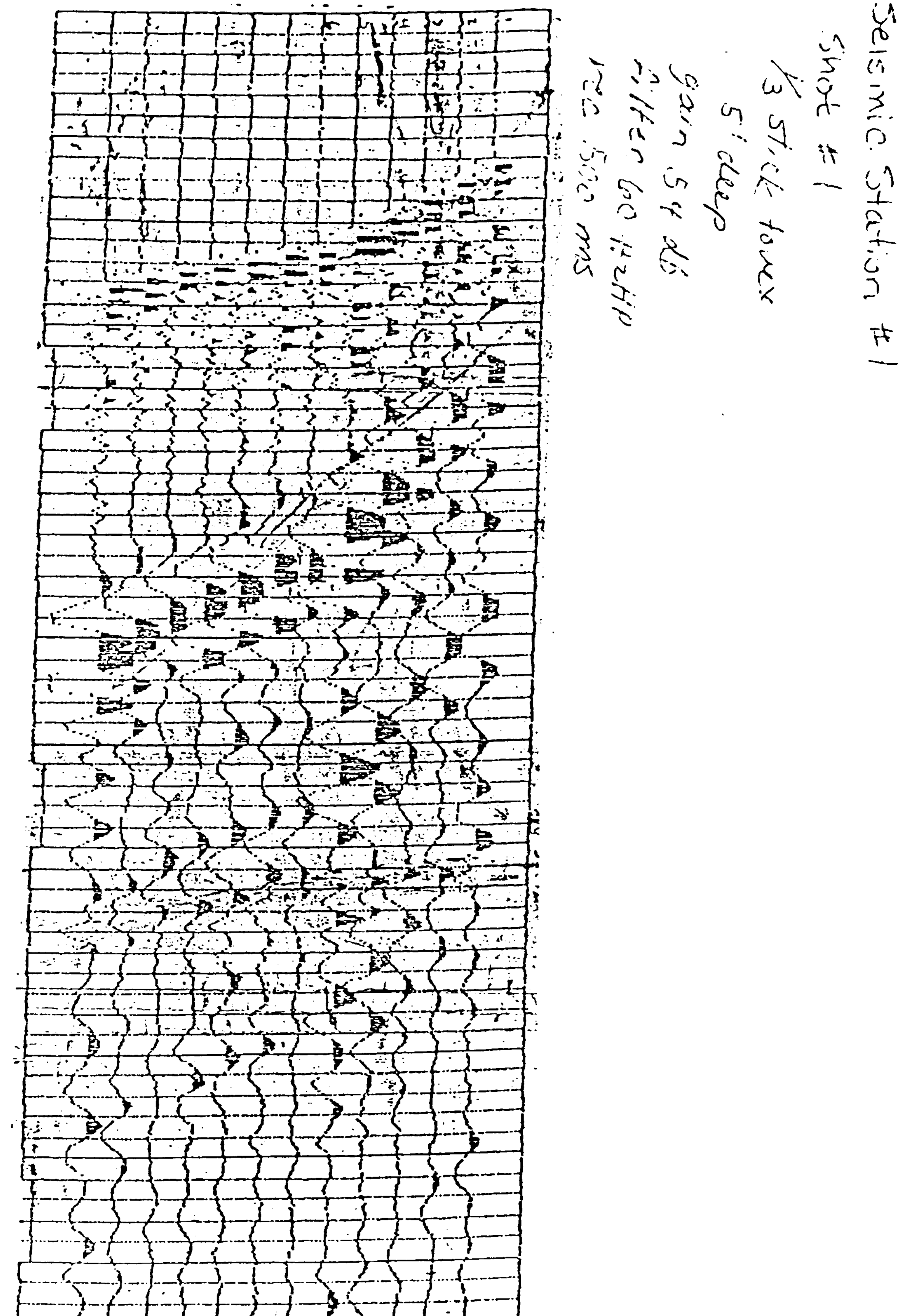
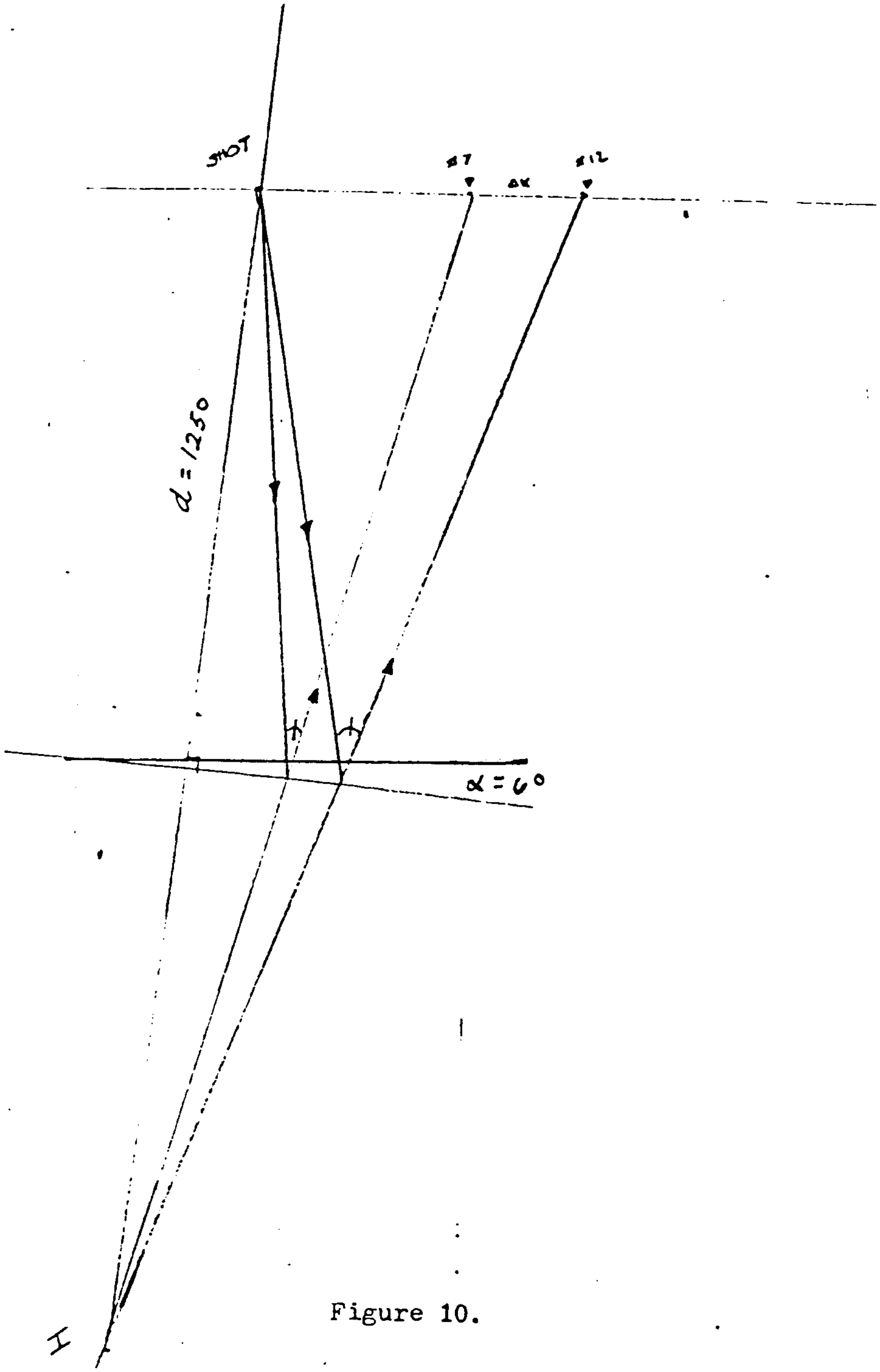

Seismic Station #1
Shot #1
1/3 stick tovex
5' deep
gain 54 db
filter 60 Hz HP
rec 500 ms

Figure 9.

Seismic Station #1
Shot 2
Reflection 1




$v = 12500$ ft/s
$\Delta x = 250$ ft
$t_7 = .208$ s
$t_{12} = .216$ s
$\Delta t = .008$ s

$$\cos\theta = \frac{v\Delta t}{\Delta x} = .40$$

$\theta = 66.4$

$R_7 = vt_7 = 2600$

$R_{12} = vt_{12} = 2700$

$d = 1250$ ft.

$\alpha = 6°$ dip

Figure 10.

Seismic Station #1
Shot 2
Reflection 2

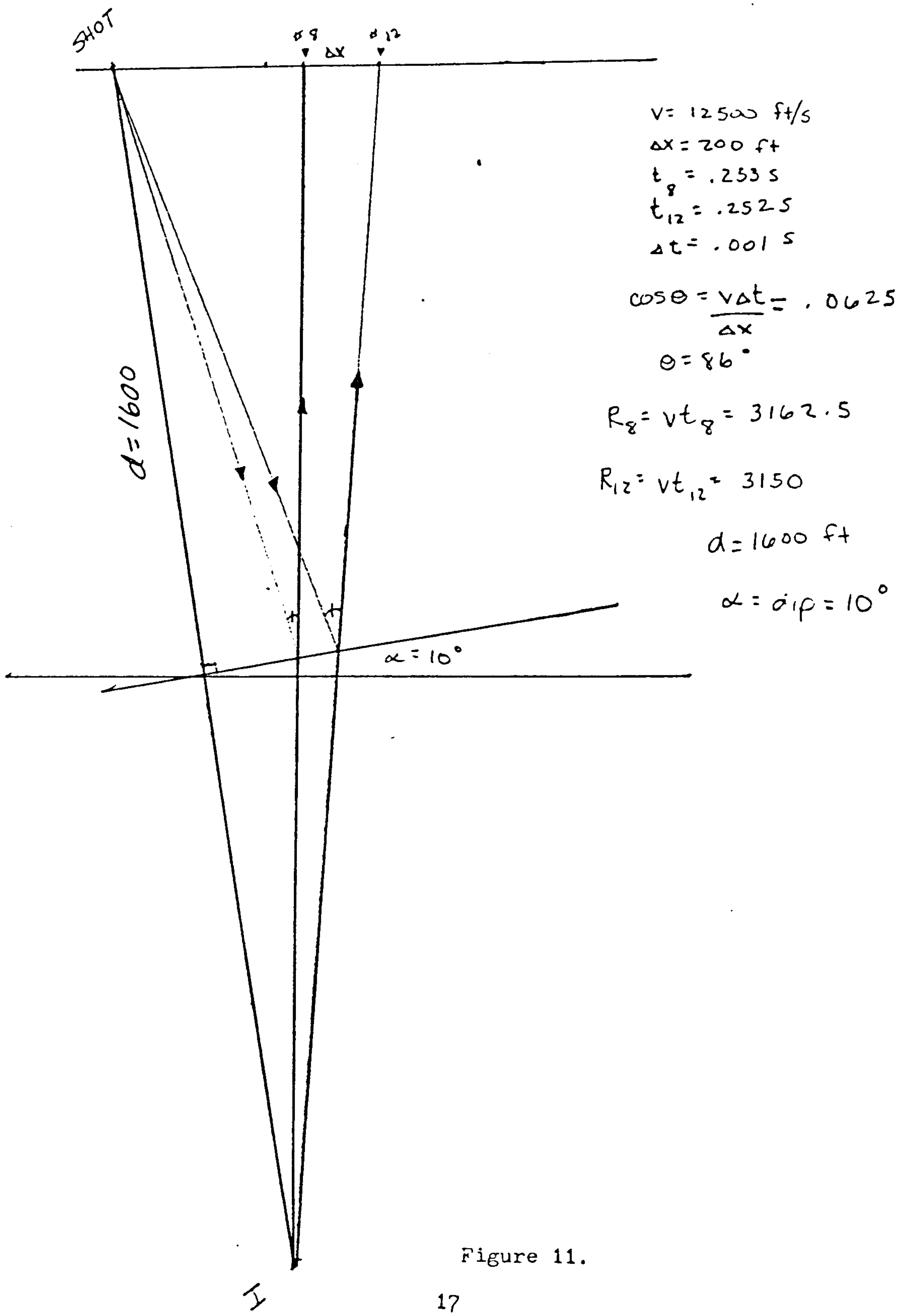
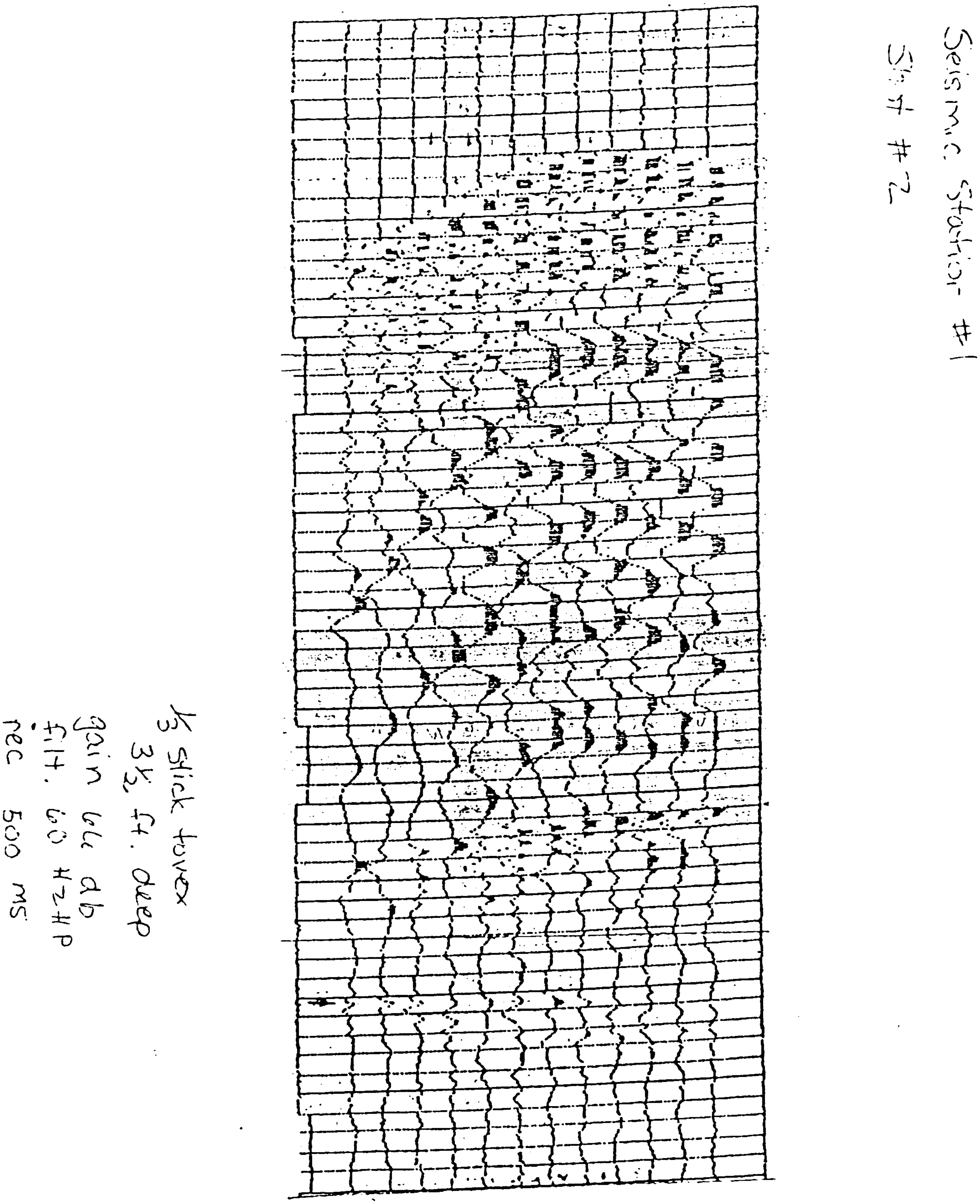


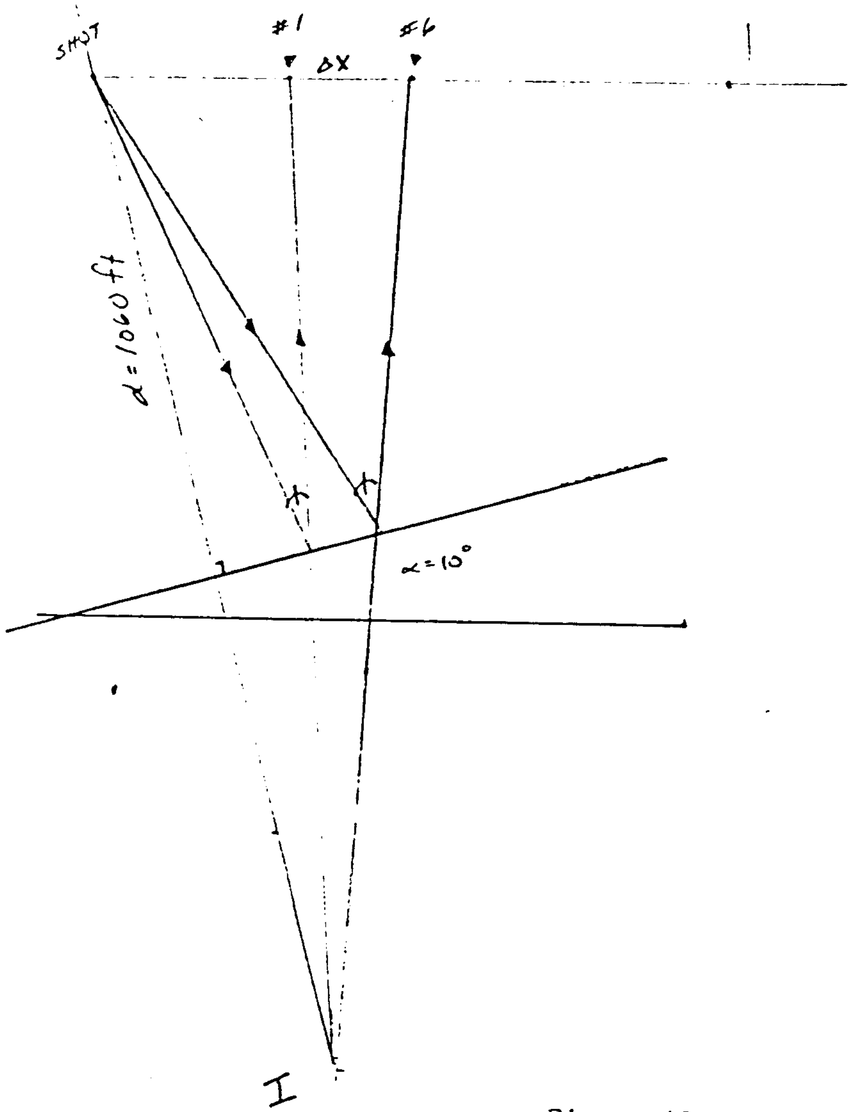

Figure 11.



Seismic Station #1
Shot #2
1/3 stick tovex
3 1/2 ft. deep
gain 66 db
filt. 60 Hz HP
rec 500 ms


Figure 12

Seismic Station #2
Shot 1




$v = 12500$ ft/s

$\Delta x = 250$ ft

$t_1 = .1625$ s

$t_6 = .1635$ s

$\Delta t = 0.001$ s

$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.05$

$\theta = 87.13^\circ$

$R_1 = vt_1 = 2031.25$

$R_6 = vt_6 = 2043.75$

$d = 1060$ ft

$\alpha = 10^\circ$ dip

Figure 13.

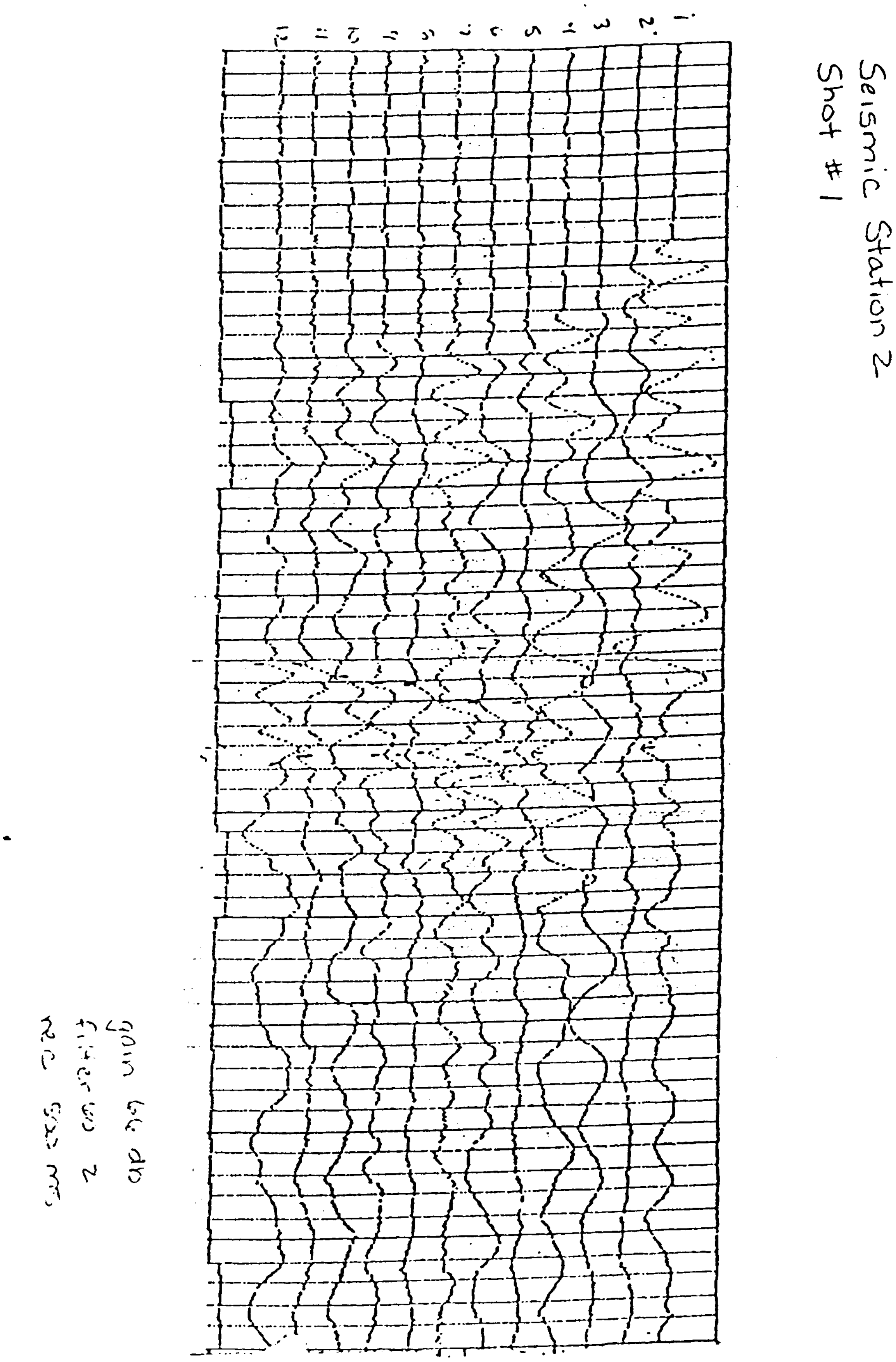
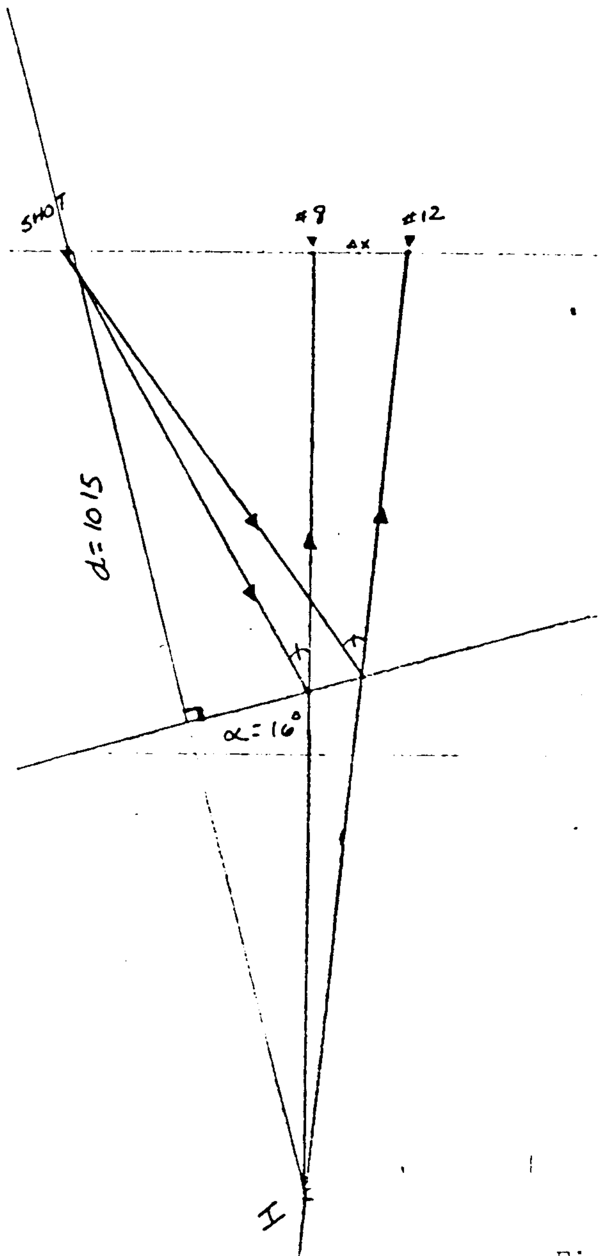



Figure 14.

Seismic Station #2
Shot 2




$V = 12500$ ft/s

$\Delta x = 200$ ft

$t_8 = .1565$ s

$t_{12} = .158$ s

$\Delta t = 0.0015$ s

$$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.09375$$

$\theta = 85°$

$R_8 = vt_8 = 1956.25$ ft

$R_{12} = vt_{12} = 1975$ ft.

$\alpha = \text{dip} = 16°$

$d = 1015$

Figure 15.

Seismic Station #2
Shot #2

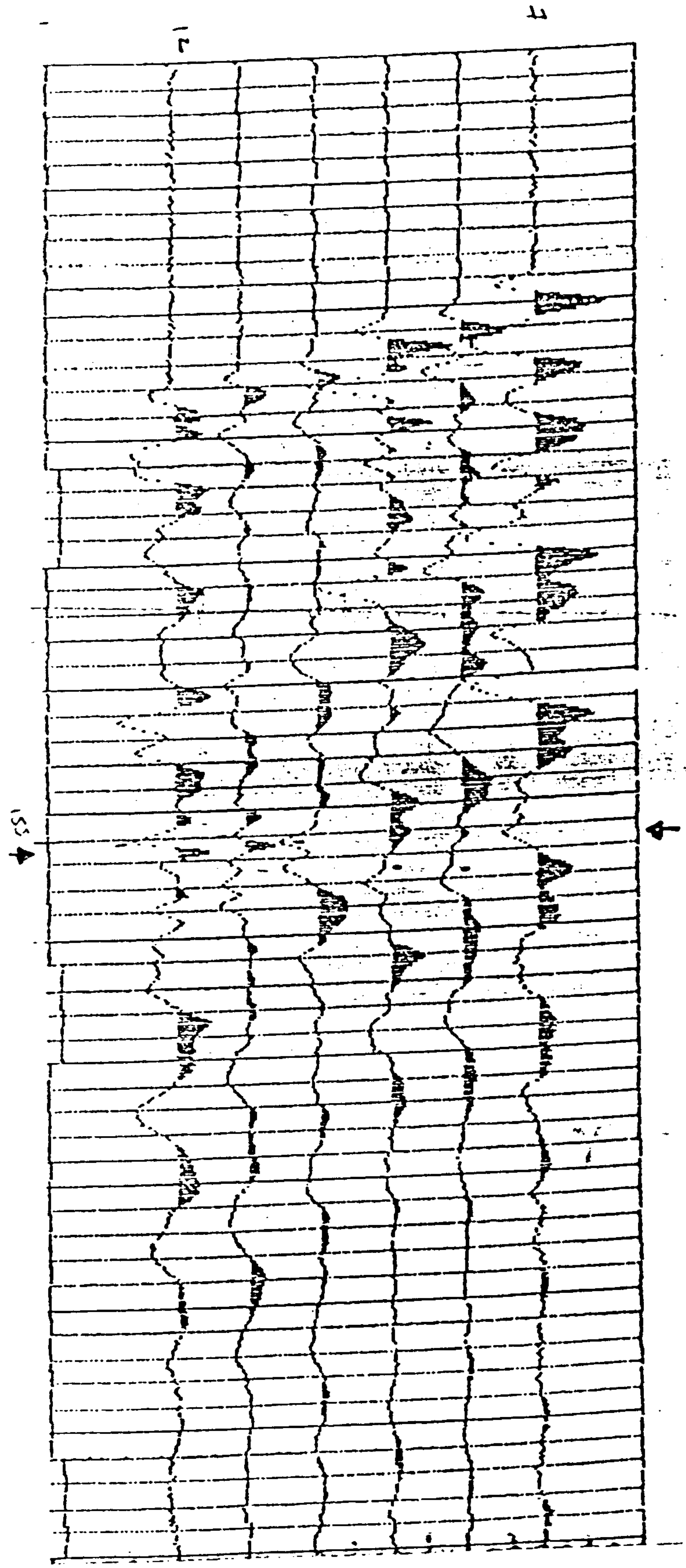
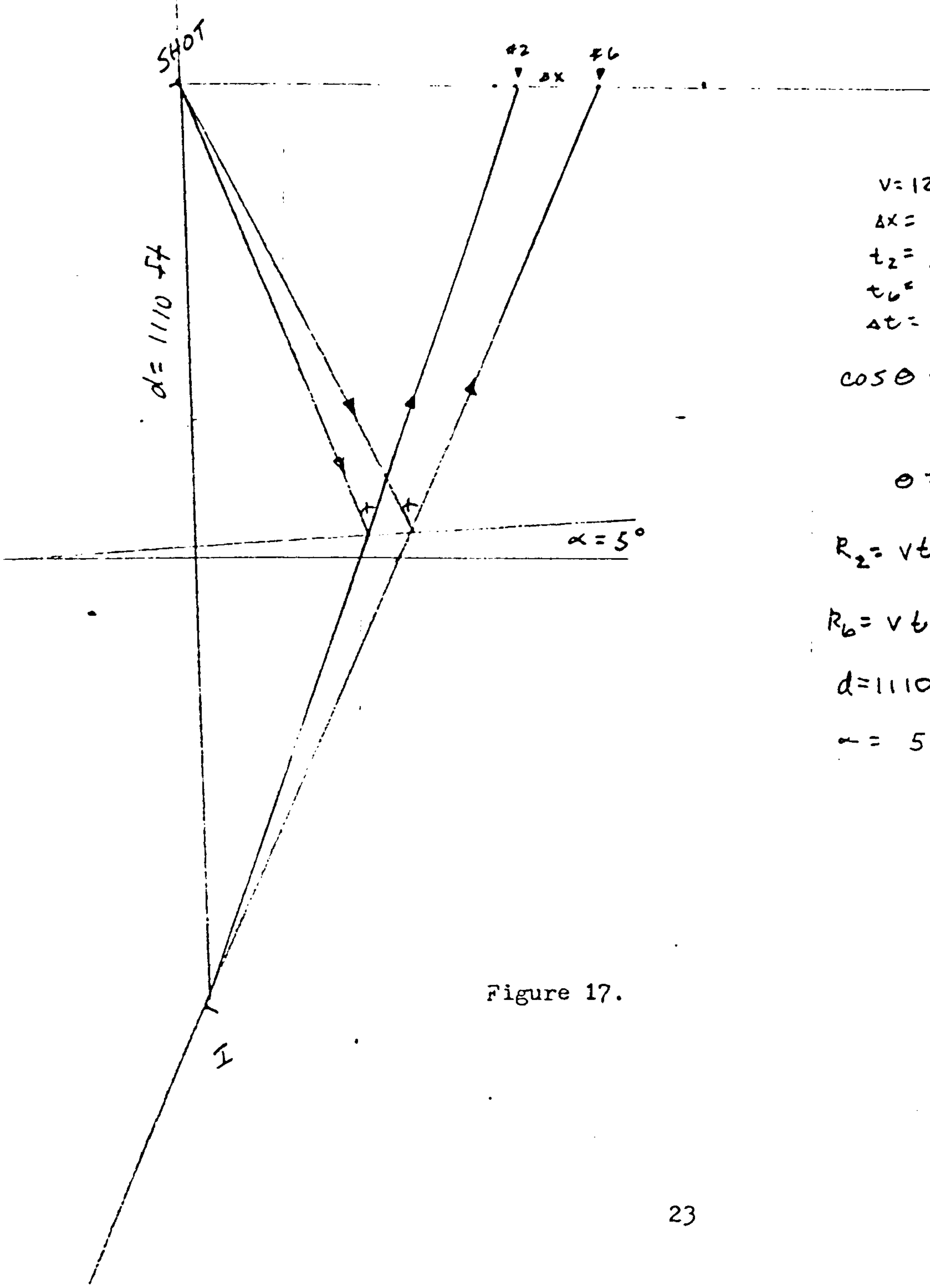


Figure 16.

Seismic Station #3
Shot 1




$v = 12500$ ft/s
$\Delta x = 200$ ft
$t_2 = .186$ s
$t_6 = .192$ s
$\Delta t = .006$ s

$$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.375$$

$$\theta = 68^\circ$$

$$R_2 = vt_2 = 2325$$

$$R_6 = vt_6 = 2400$$

$d = 1110$ ft

$\alpha = 5^\circ$

Figure 17.

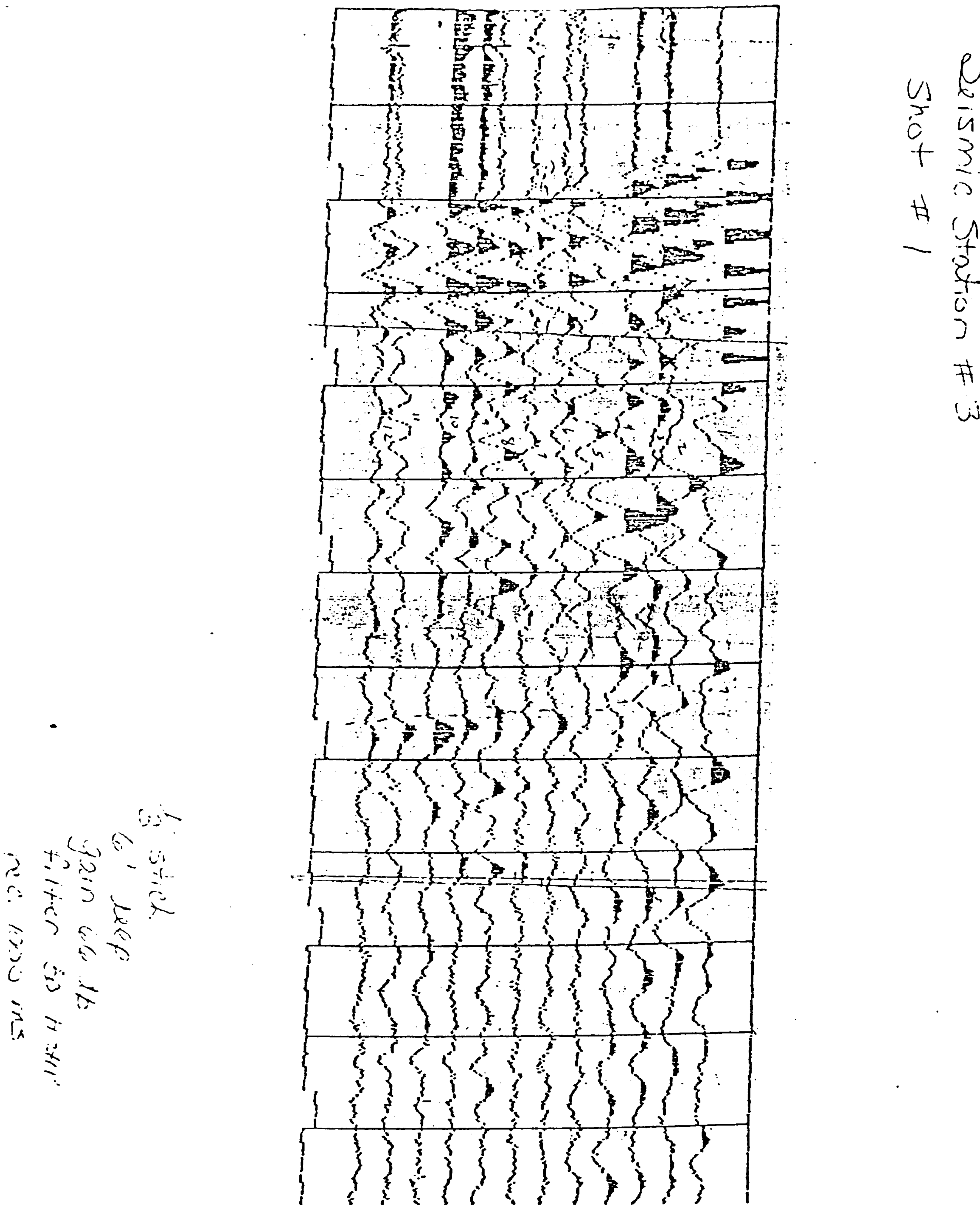
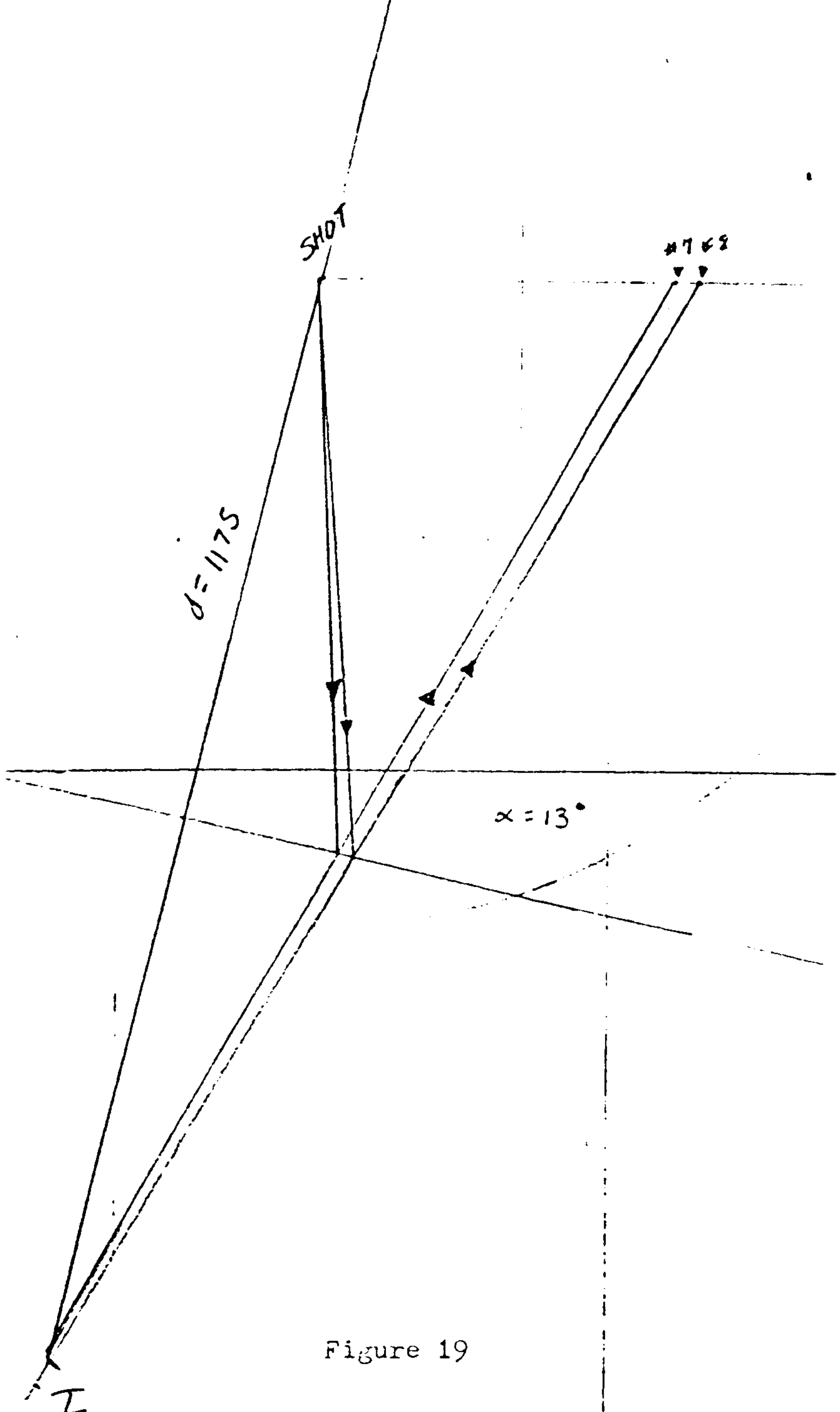



Figure 18.

Seismic Station #3
Shot 2




$v = 12500$ ft/s

$\Delta x = 50$ ft

$t_7 = .211$

$t_8 = .213$

$\Delta t = .002$

$$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.5$$

$$\theta = 60^\circ$$

$$R_7 = vt_7 = 2637.5$$

$$R_8 = vt_8 = 2662.5$$

$$d = 1175$$

$$\alpha = 13^\circ$$

Figure 19

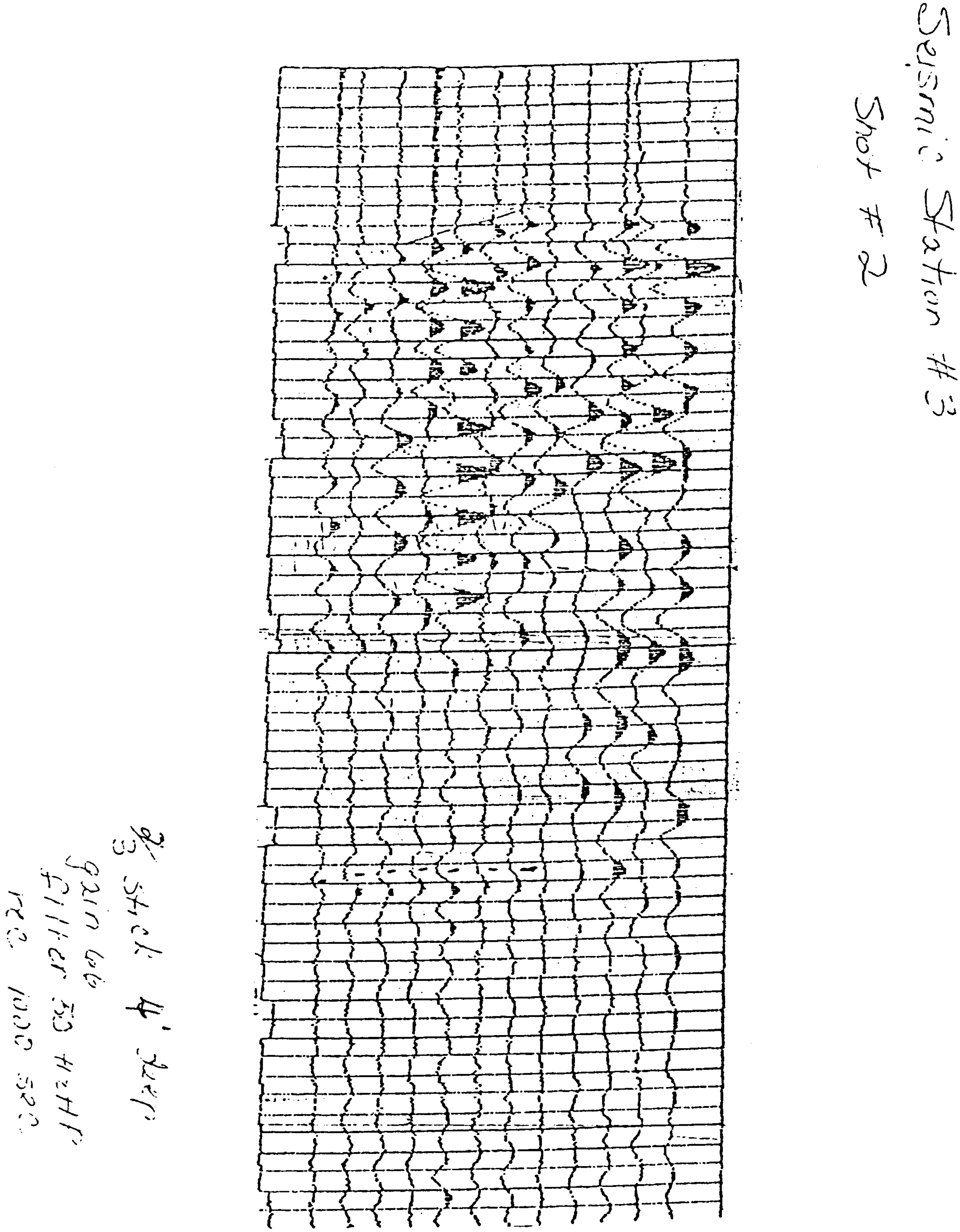
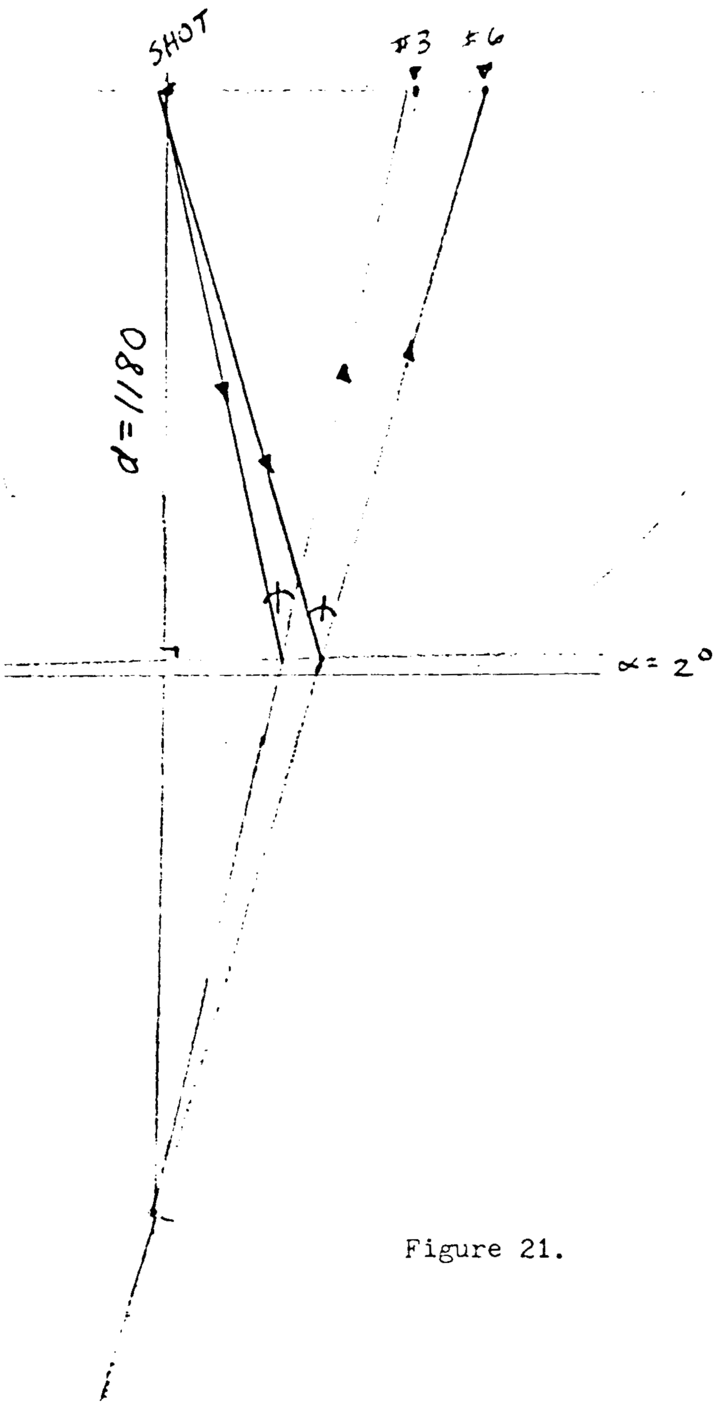



Figure 20

Seismic Station #4
Shot 1
Reflection 1




$V = 12500$ ft/s

$\Delta x = 150$ ft

$t_3 = .192$ s

$t_6 = .195$ s

$\Delta t = .003$ s

$$\cos\theta = \frac{v\Delta t}{\Delta x} = .25$$

$\theta = 75°$

$R_3 = vt_3 = 2400$

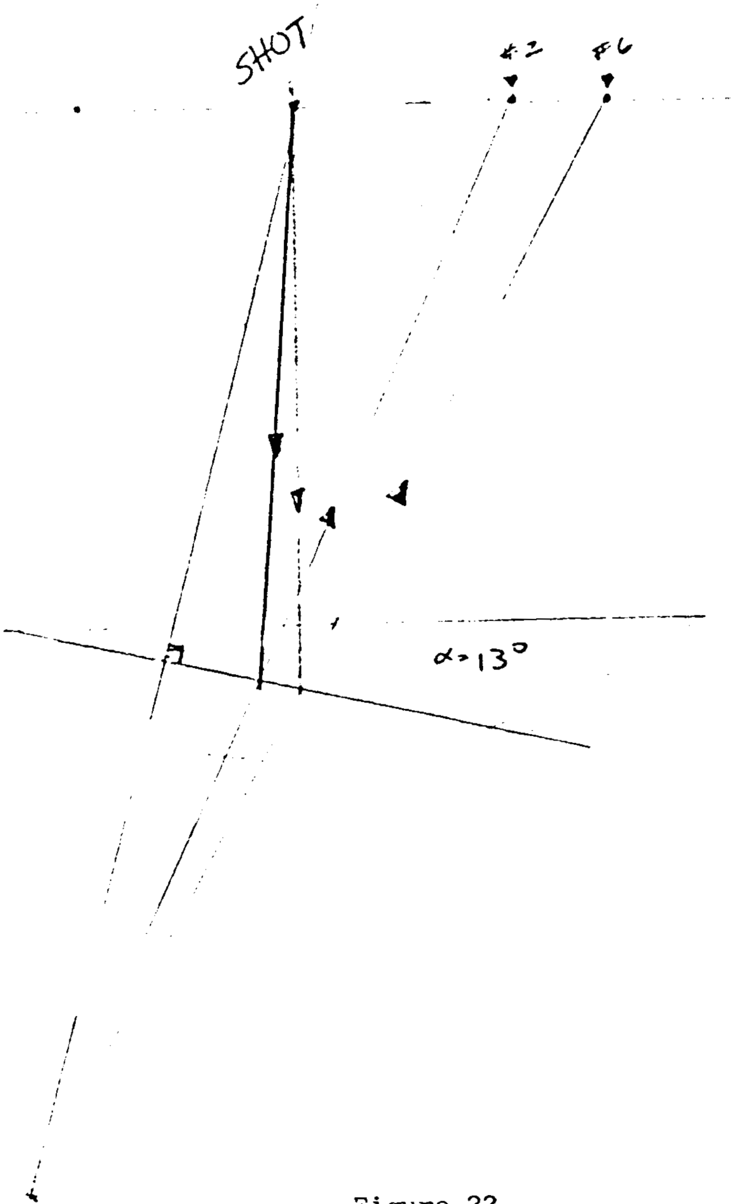
$R_6 = vt_6 = 2437.5$

$d = 1180$ ft

$\alpha = 2°$ dip

Figure 21.

Seismic Station #4
Shot 1
Reflection 2




$V = 12500$ ft/s

$\Delta x = 200$ ft

$t_2 = .199$ s

$t_6 = .2065$ s

$\Delta t = .0075$ s

$\cos\theta = \dfrac{v\Delta t}{\Delta x} = 0.46875$

$\theta = 62°$

$R_2 = vt_2 = 2487.5$

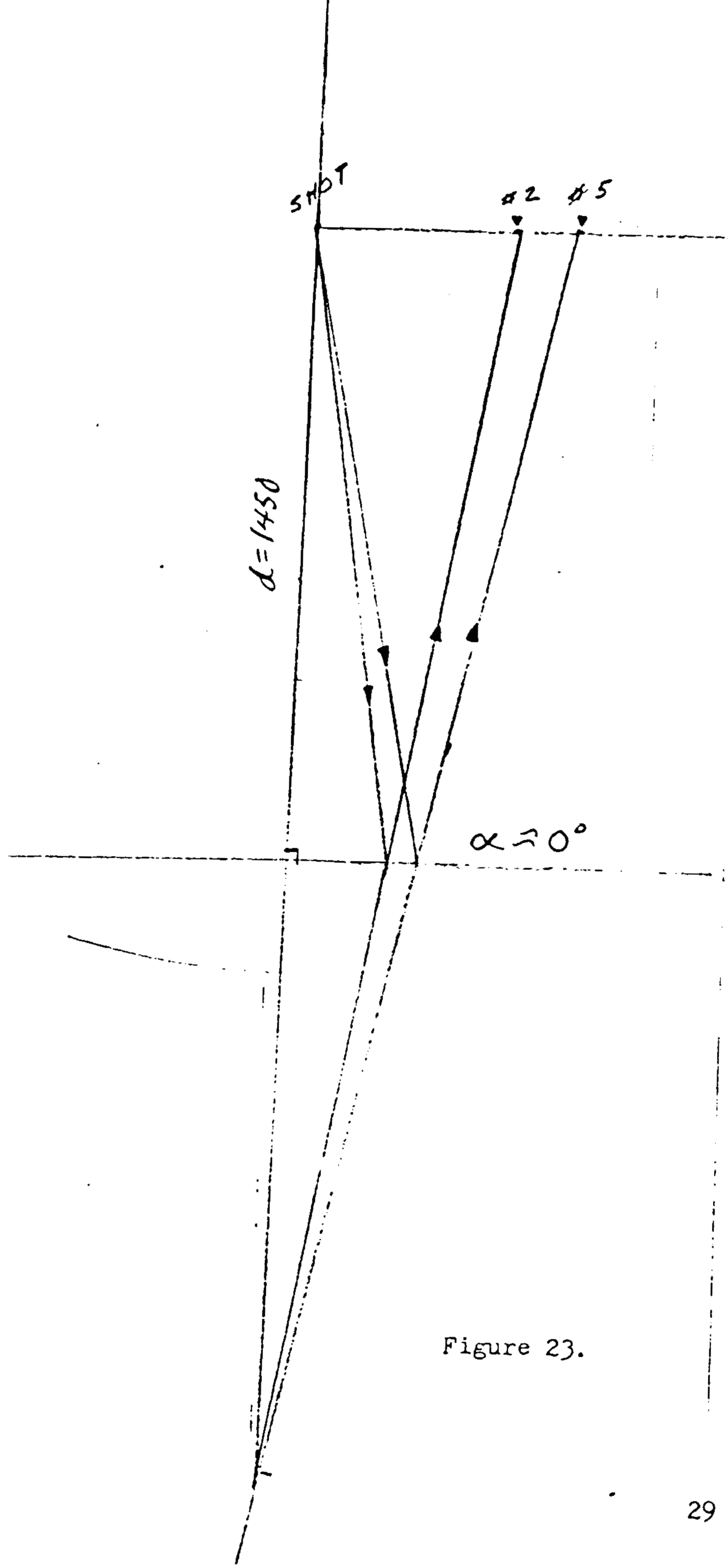
$R_6 = vt_6 = 2581.25$

$d = 1170$ ft

$\alpha = 13°$ dip

Figure 22.

Seismic Station #4
Shot 1
Reflection 3




$v = 12500$ ft/s
$\Delta x = 150$ ft
$t_2 = .2375$
$t_5 = .235$
$\Delta t = 0.0025$

$$\cos\theta = \frac{v\Delta t}{\Delta x} = 0.2083$$

$\theta = 78°$

$R_2 = vt_2 = 2968.75$

$R_5 = vt_5 = 2937.5$

$d = 1450$

$\alpha = \text{dip} \approx 0°$

Figure 23.

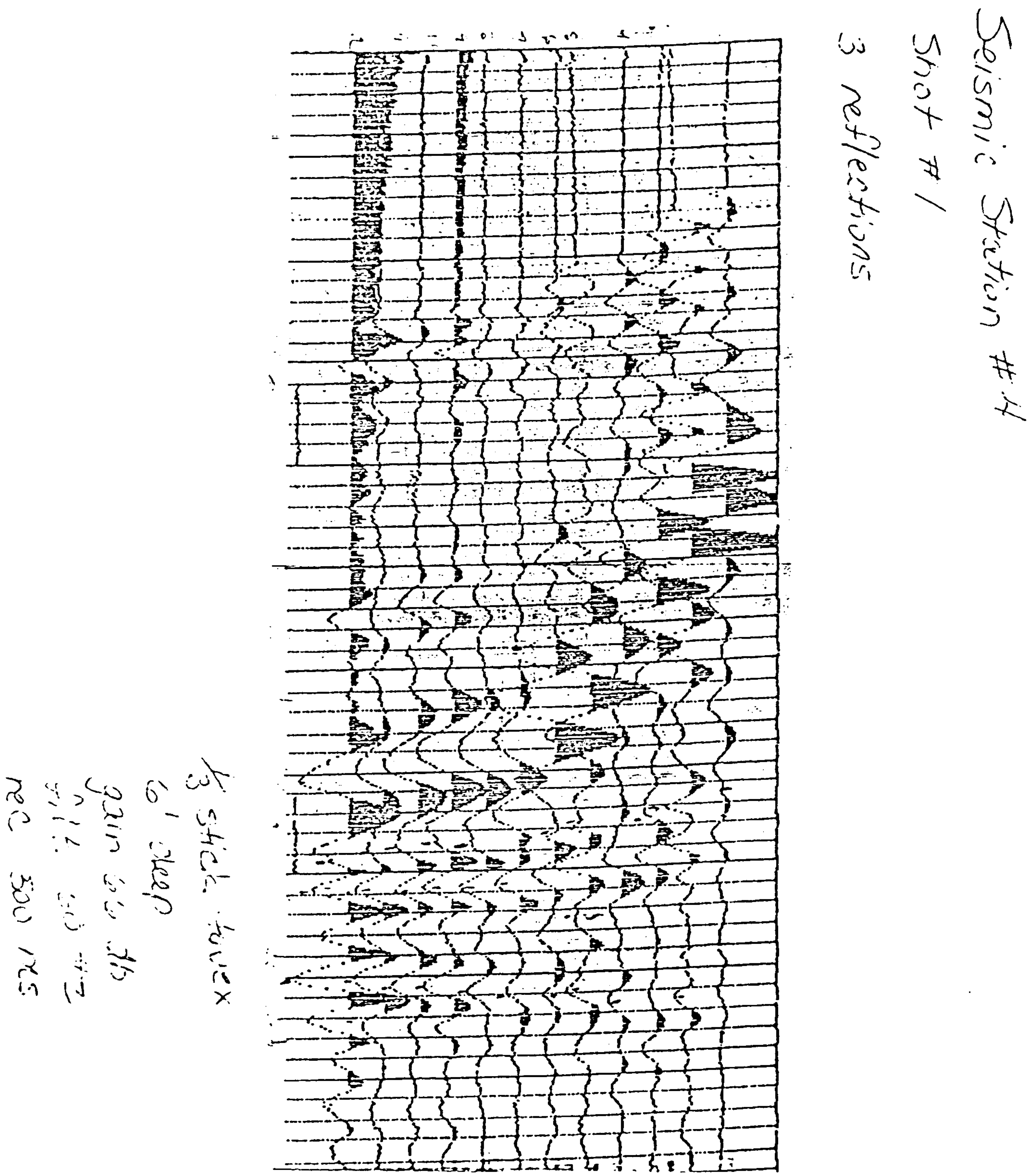
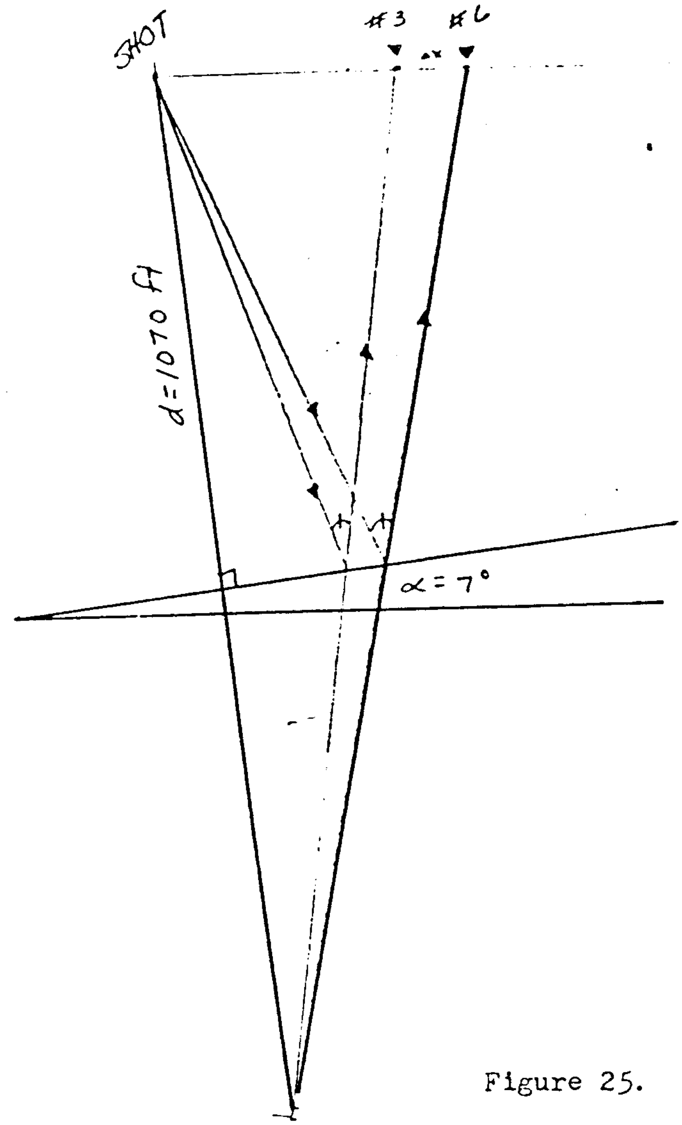



Figure 24.

Seismic Station #5
Shot 1




$V = 12500$ ft/s

$\Delta x = 150$ ft

$t_3 = .173$ s

$t_6 = .175$ s

$\Delta t = .002$ s

$$\cos\theta = \frac{V\Delta t}{\Delta x} = 0.1666$$

$\theta = 80°$

$R_3 = vt_3 = 2162.5$

$R_6 = vt_6 = 2187.5$

$d = 1070$ ft

$\alpha = 7°$ dip

Figure 25.

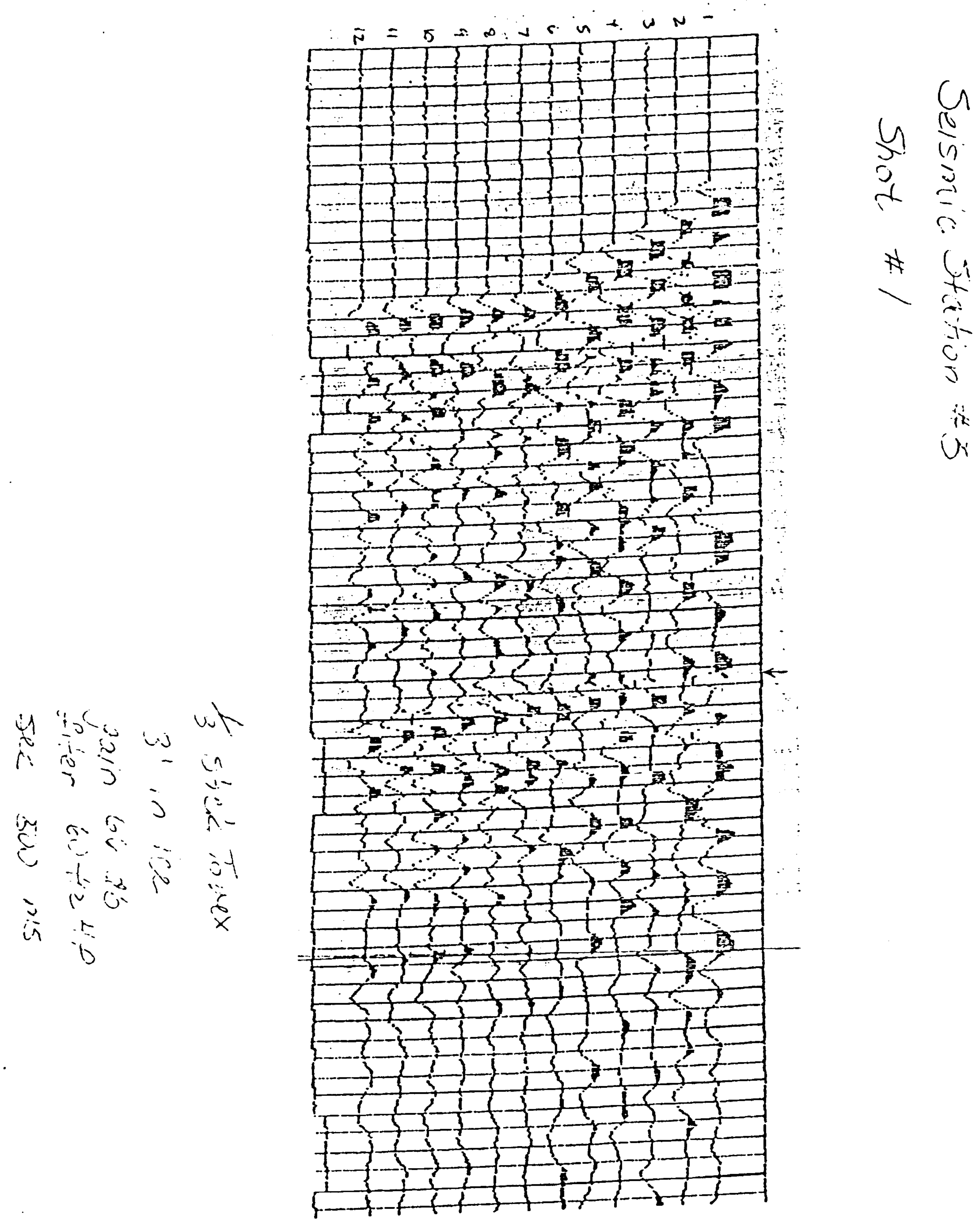
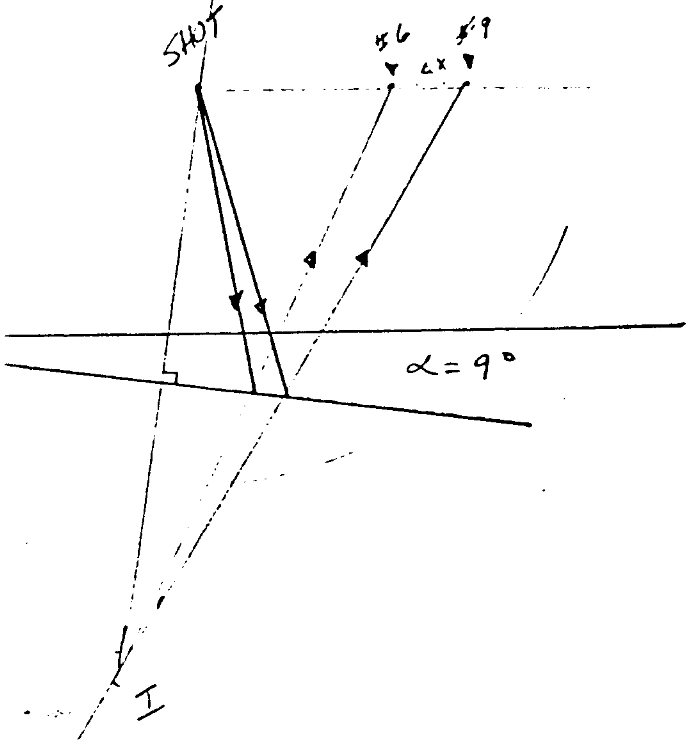



Figure 26.

Seismic Station #6
Shot 1




$V = 12500$ ft/s

$\Delta x = 150$ ft

$t_6 = .106$ s

$t_9 = .112$ s

$\Delta t = .006$ s

$\cos\theta = \frac{v\Delta t}{\Delta x} = .5$

$\theta = 60^\circ$

$R_6 = vt_6 = 1325$ ft

$R_9 = vt_9 = 1400$ ft

$d = 600$ ft

$\alpha = 9^\circ$

Figure 27.

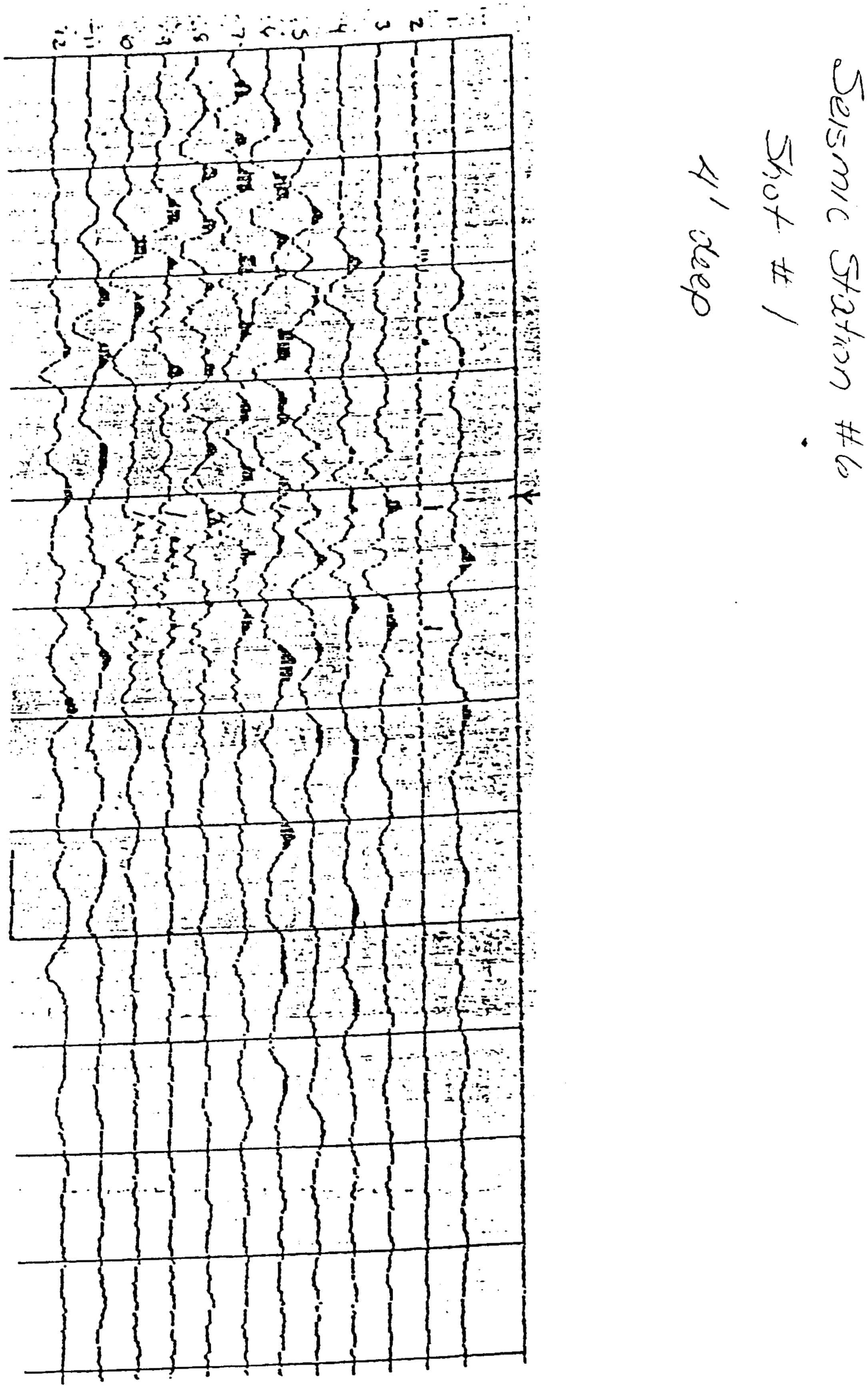
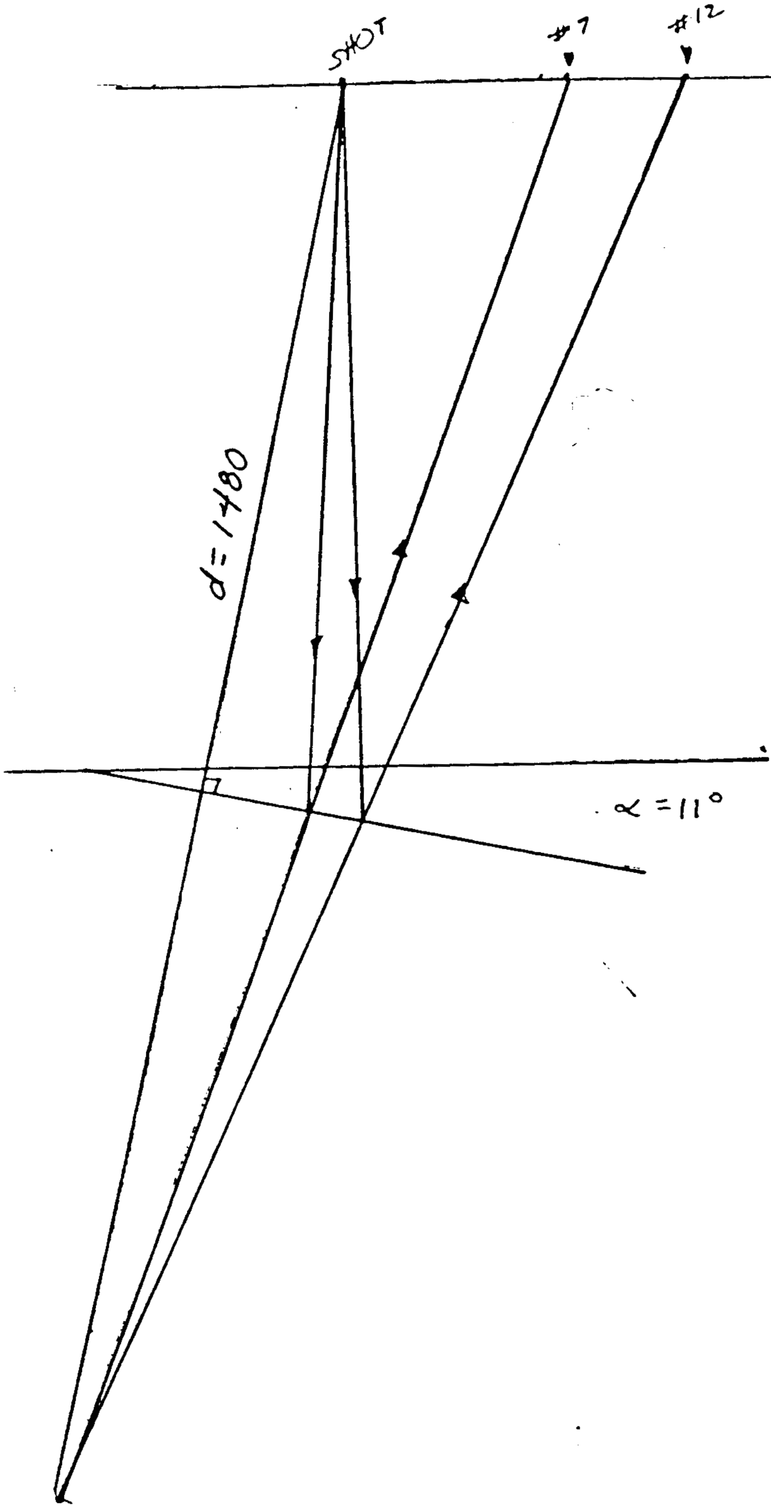



Figure 28.

Seismic Station #6
Shot 2




$V = 12500\ ft/s$

$\Delta x = 250\ ft$

$t_7 = .247\ s$

$t_{12} = .255\ s$

$\Delta t = .008\ s$

$$\cos\theta = \frac{V\Delta t}{\Delta x} = .40$$

$\theta = 66°$

$\ell_7 = Vt_7 = 3087.5$

$R_{12} = Vt_{12} = 3187.5$

$d = 1480\ ft$

$\alpha = 11°$ dip

Figure 29.

Seismic Station #6
Shot #2
Air shot

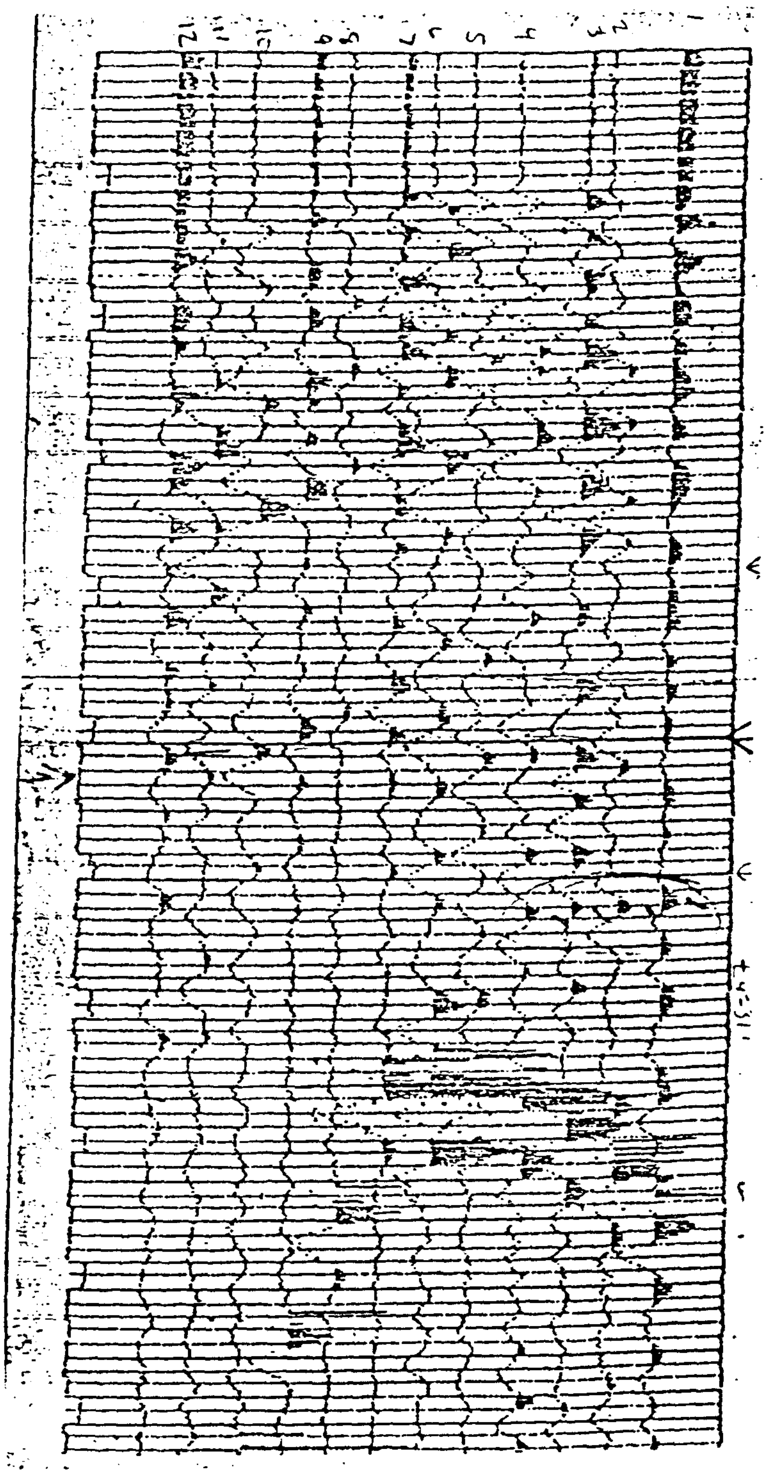
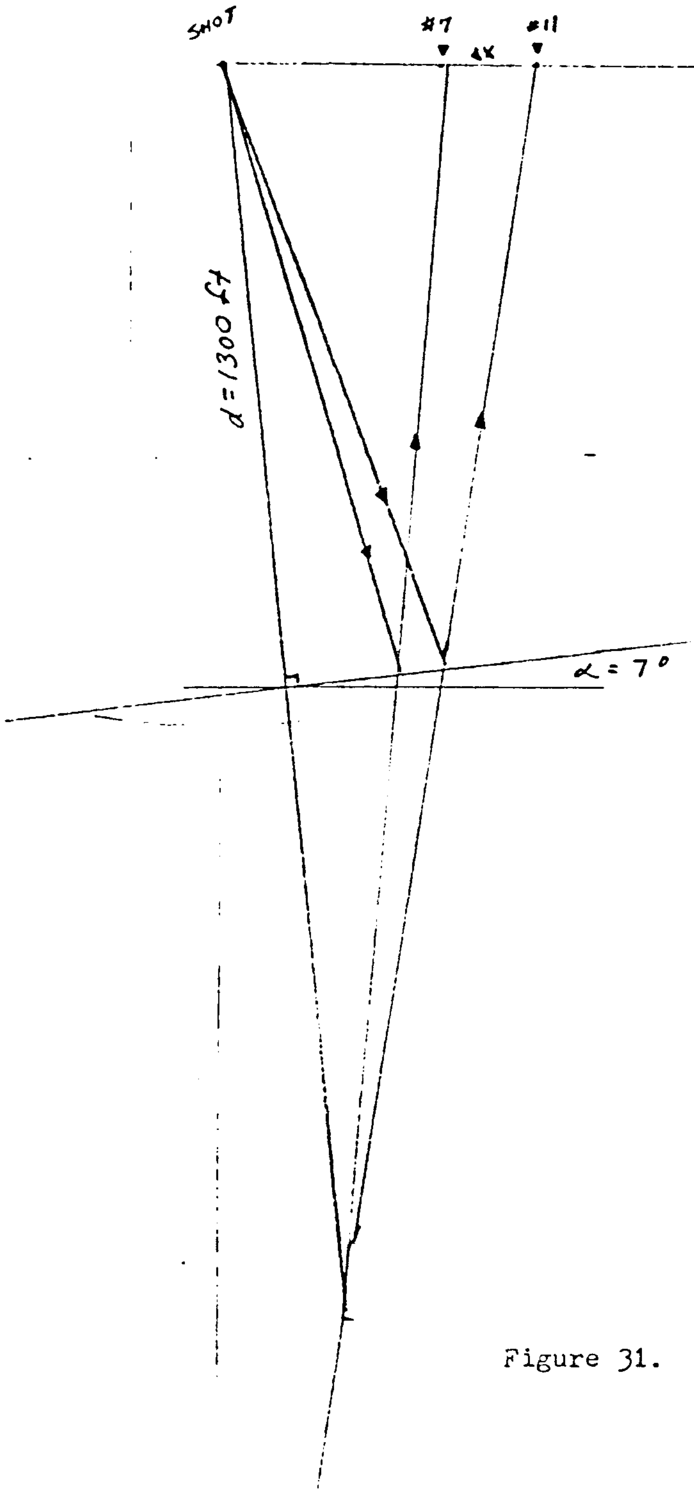


Figure 30.

Seismic Station #6
Shot 3




$V = 12500$ ft/s
$\Delta x = 200$ ft
$t_7 = .209$
$t_{11} = .211$
$\Delta t = .002$

$$\cos\theta = \frac{V\Delta t}{\Delta x} = 0.125$$

$\theta = 93°$

$R_7 = Vt_7 = 2612.5$

$R_{11} = Vt_{11} = 2637.5$

$d = 1300$ ft

$\alpha = 7°$

Figure 31.

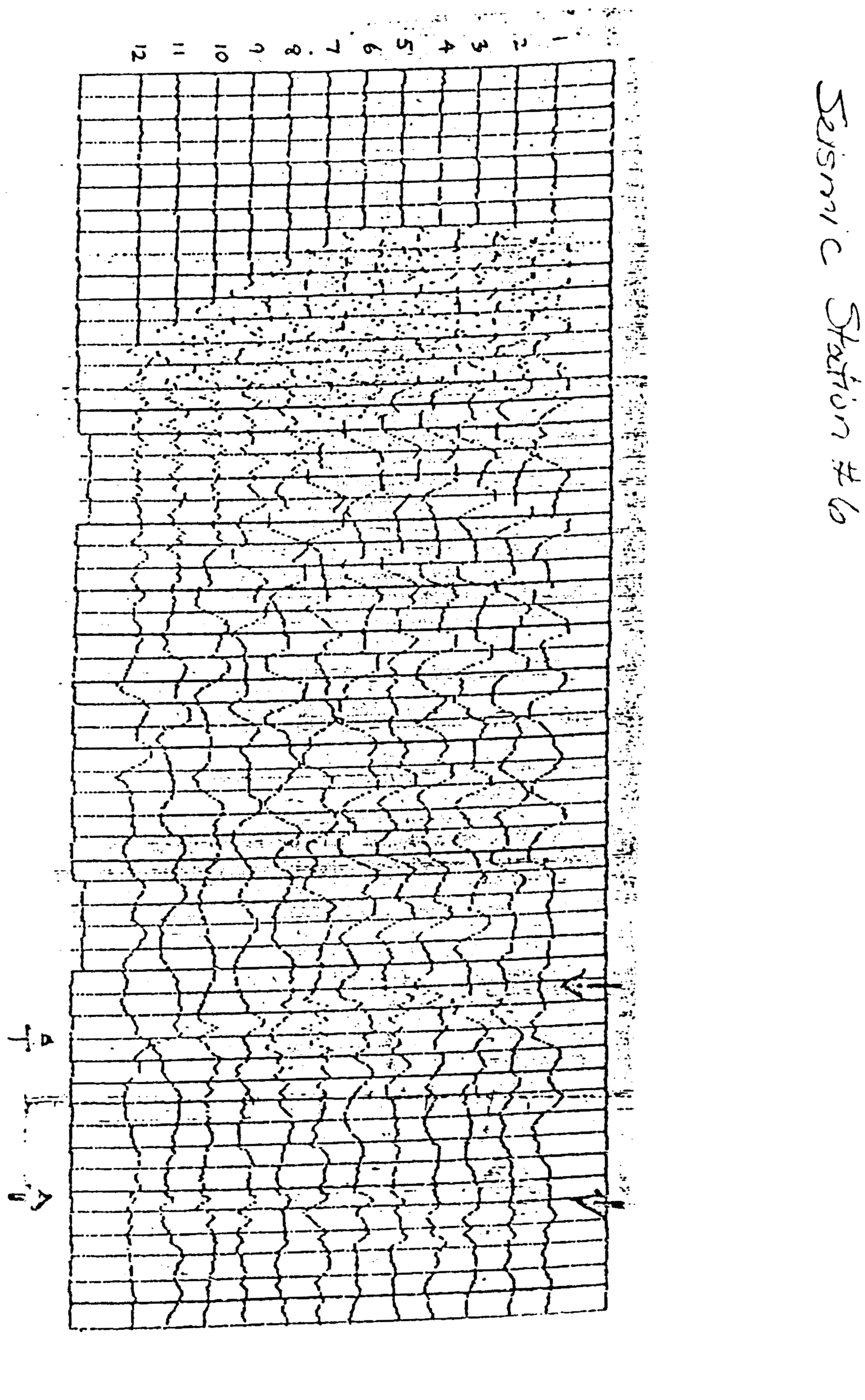
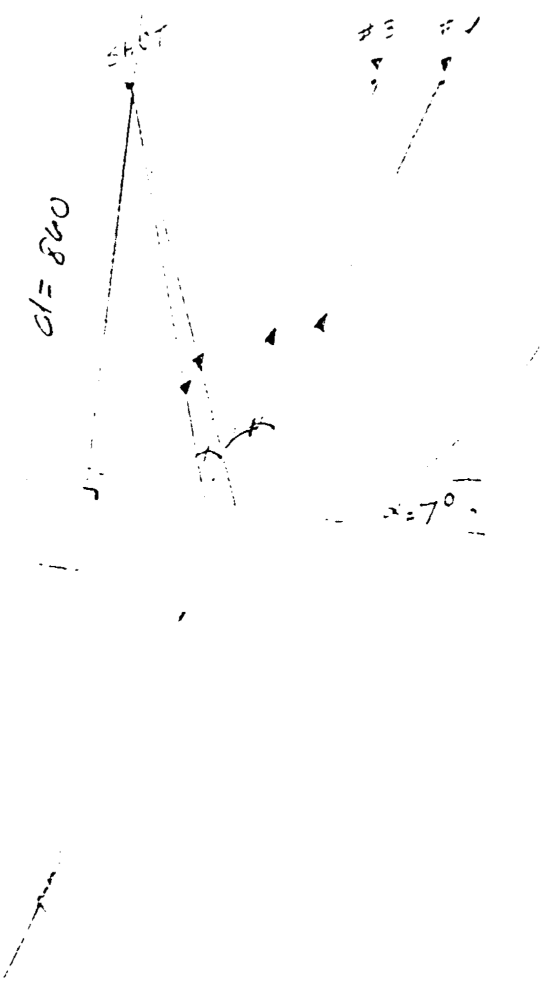



Figure 32.

Seismic Station #7
Shot 1




$V = 12500$ ft/s

$\Delta x = 150$ ft

$t_3 = .145$

$t_6 = .150$

$\Delta t = .005$

$\cos\theta = \frac{V\Delta t}{\Delta x} = .4166$

$\theta = 65$

$R_3 = 1812.5$

$R_6 = 1875$

$d = 860$ ft

$\alpha = 7°$ dip

Figure 33.

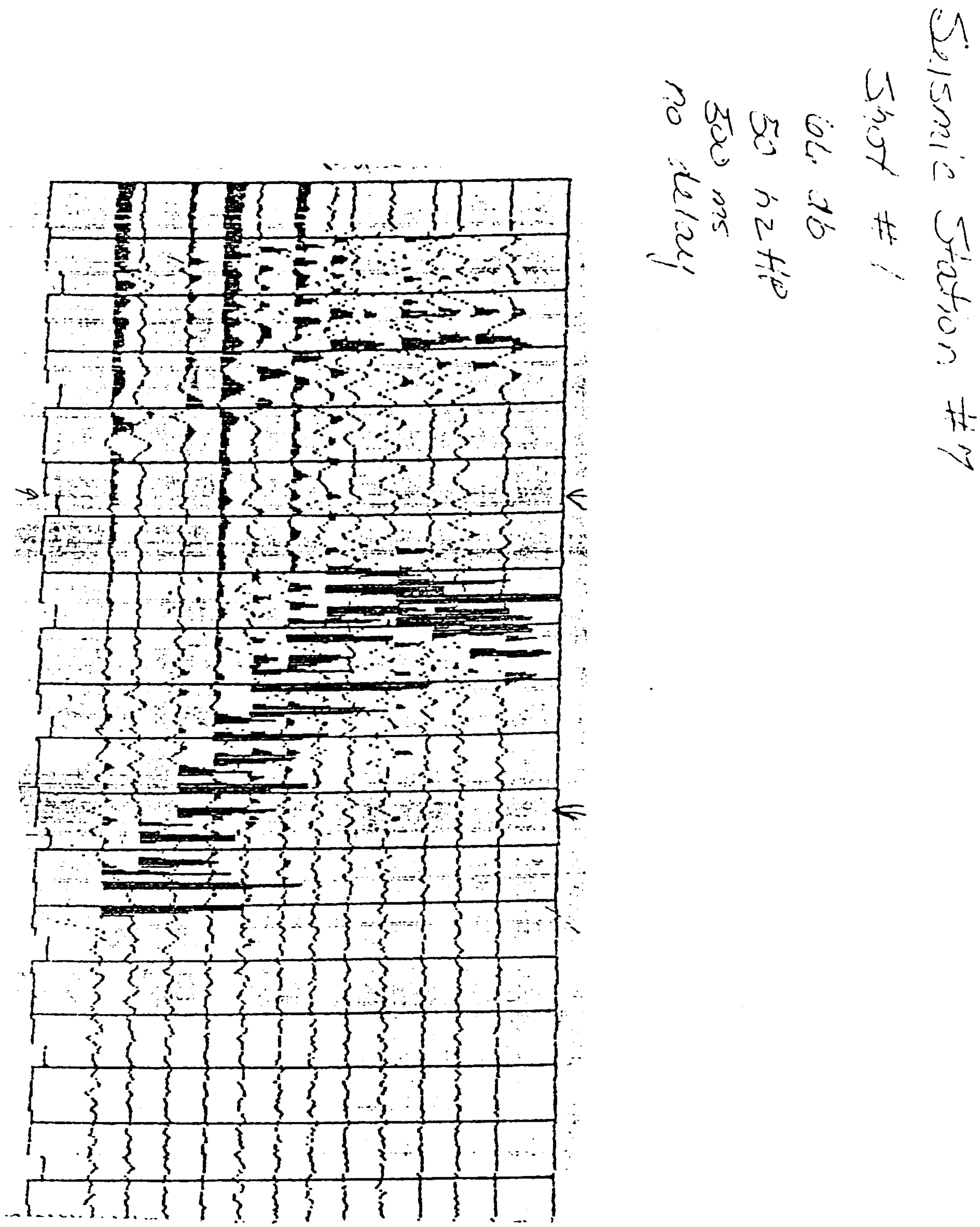
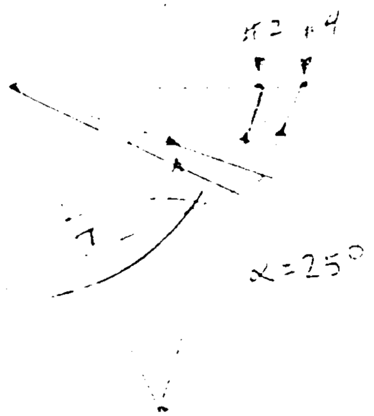



Figure 34.

Seismic Station #7
Shot #2




$V = 12500$ ft/s

$\Delta x = 100$ ft

$t_2 = .055$

$t_4 = .052$

$\Delta t = .003$

$\cos\theta = \frac{V\Delta t}{\Delta x} = .375$

$\theta = 67°$

$R_2 = 687.5$

$R_4 = 725$

$d = 390$ ft

$\alpha = 25°$

Figure 35.

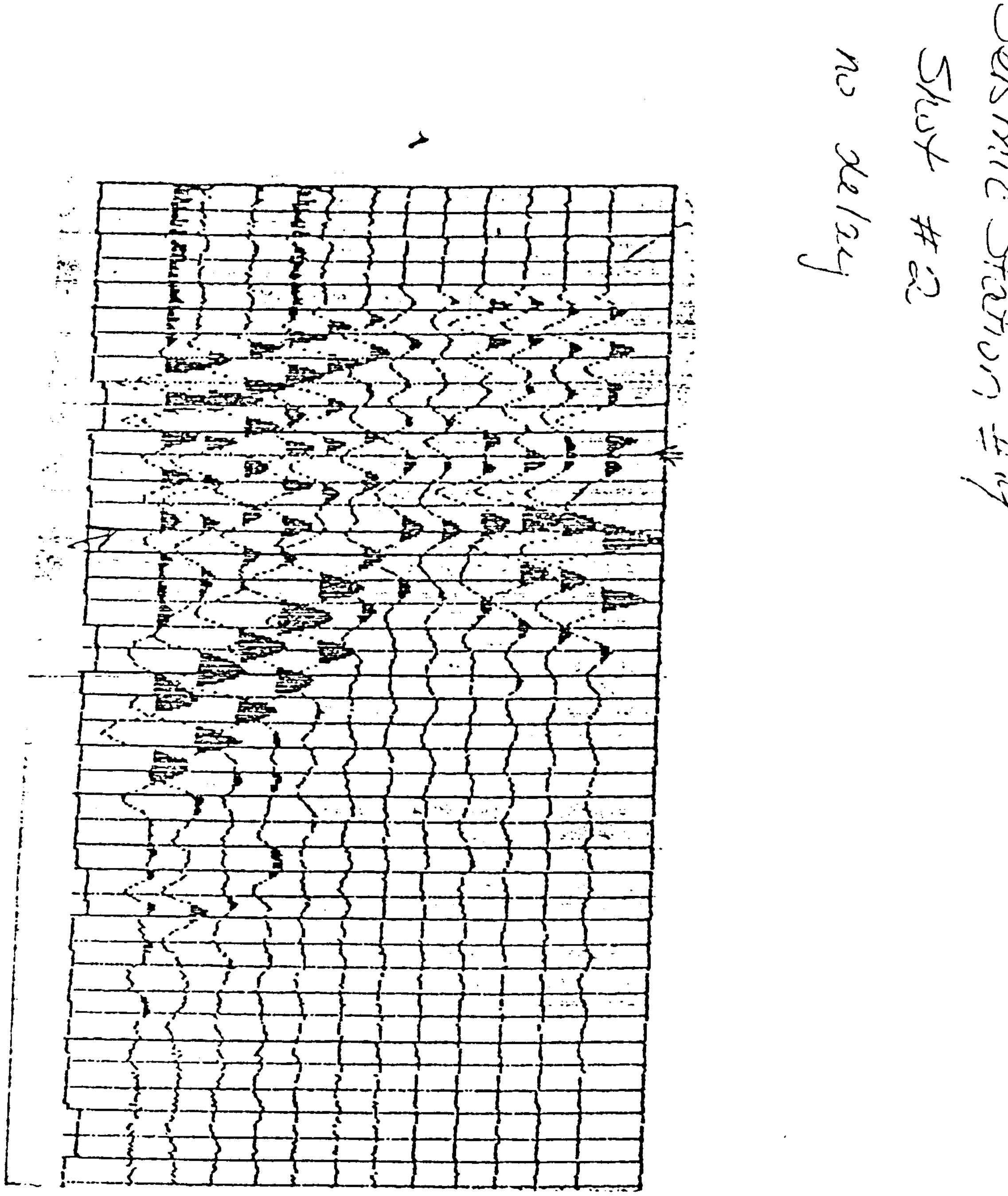
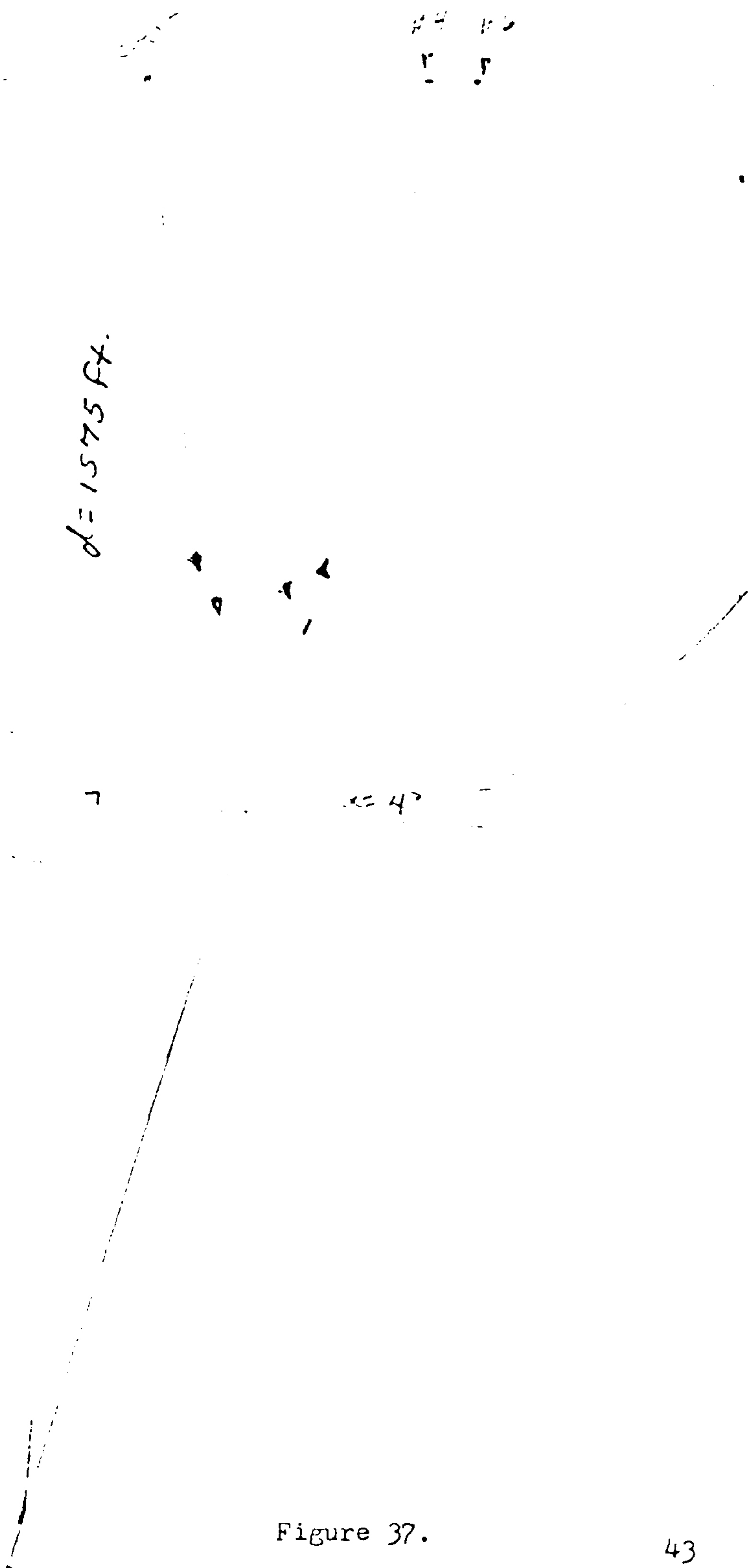



Figure 36.

Seismic Station #8
Shot 1




$V = 12500$ ft/s

$\Delta x = 100$ ft

$t_4 = .268$

$t_6 = .270$

$\Delta t = .002$

$$\cos\theta = \frac{v\Delta t}{\Delta x} = .25$$

$\theta = 75°$

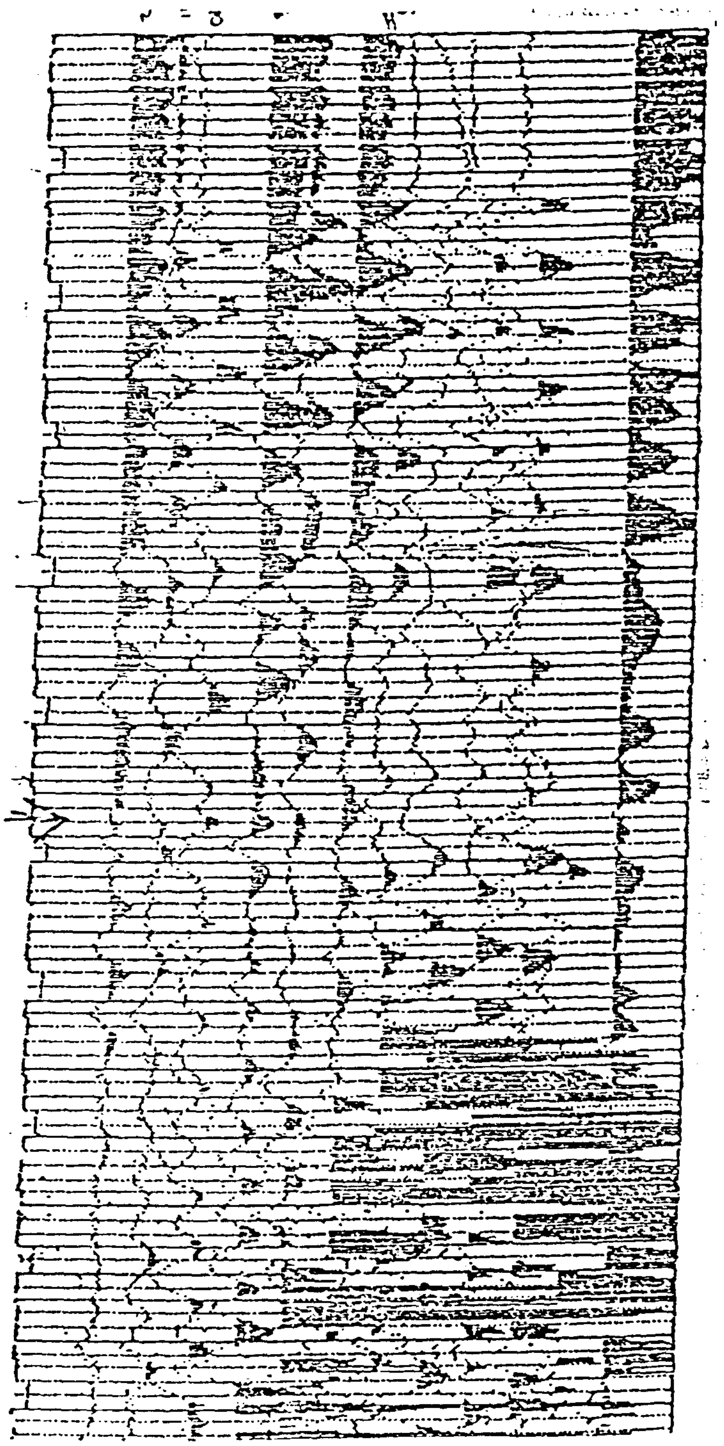
$R_4 = vt_4 = 3250$ ft

$R_6 = vt_6 = 3375$ ft

$d = 1575$ ft

$\alpha = 4°$ dip

Figure 37.



Seismic Station #8
Shot #1
Airshot

Figure 38.

## Analysis of the Data

The following is a discussion of the findings in the seismic survey. The stations will be discussed starting with Station #5 which is closest to C-26 and moving across the glacier to Station #6, the final station.

At Seismic Station #5, the depth below the shot was determined to be 1070 feet deep. The dip of the ice-rock interface was 7°. (Figure 40). Only one shot was fired but it seemed to produce a strong reflection.

Three shots taken at Station #1 were analyzed. All of the calculated depths seem to occur around the mid 1200's. One shot revealed two reflections. The depth of the first reflection was 1250 feet while the depth of the second reflection was 1600 feet.

The next station (Seismic Station #8) revealed a depth of 1575 feet. The seismogram was very difficult to read. There are no definite reflections. It is quite possible that the depth found was really a second reflection. This would match perfectly with the results found for the stations located on either side.

For Seismic Station #4 three reflections were found. The first depth calculated was 1180 feet. The second reflection revealed a depth of 1170 feet. This is less deep than the first reflection. Reflections 1 and 3 had dips of nearly 0° while the second reflection had a dip of 13.° The depth of the 3rd reflection was 1450. This is about the same depth as those found at stations 1 and 8. Since reflection 2 had a different dip and was at nearly the same depth as reflection 1, reflection 2 was disregarded.

Two seismograms were analyzed for Seismic Station number 3. The depths revealed were 1110 and 1175. These depths were similar to others found for the depth of the ice-rock interface.

Station number 7 revealed two depths. These depths were 860 and 390. The seismogram from which the depth of 390 was calculated was extremely hard to analyze. A distinct reflection could not be found therefore the depth of 390 was disregarded.

Seismic Station number 2 showed depths of 1060 and 1015. The final station #6 showed one depth of 600 feet and two over 1300 feet deep. The depth of 600 feet was disregarded.

## Conclusion

After conducting a four day seismic survey across the Llewellyn Glacier, the approximate glacial ice thickness was determined. An analyzation revealed that the shallowest depth was 890 feet at Seismic Station #7. The deepest portion was 14[illegible]0 feet at station 6. The rock-ice interface had relatively shallow dips ranging from 0° to 20°. In some instances a second reflection was found that showed another rock layer at about 1600 feet in depth. The glacial ice thickness was much thicker than had been thought before the project was conducted.

## References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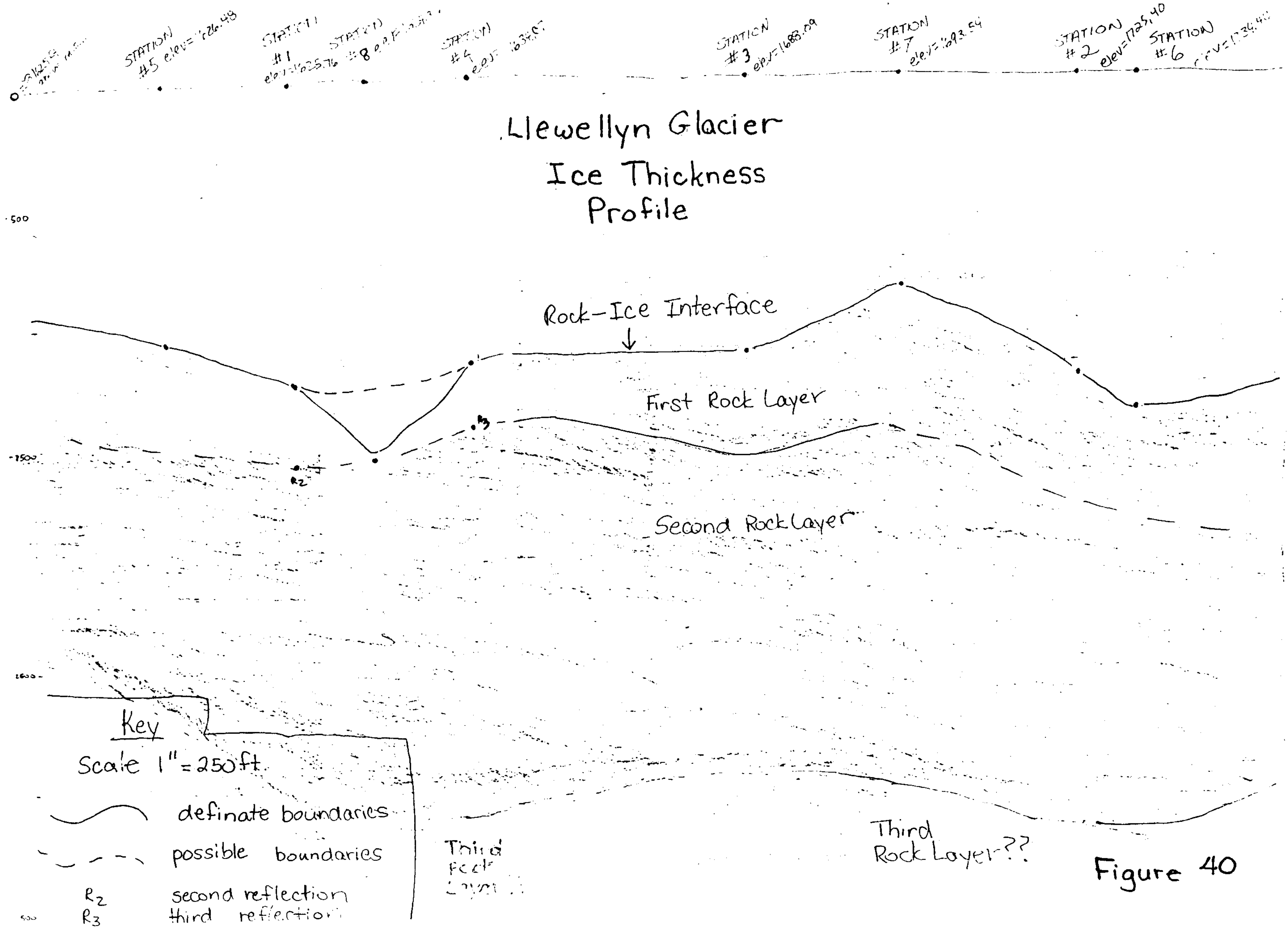
Hurley, P.M. (1967) Advances in Earth Science, 2nd edition, The M.I.T. Press, Cambridge Massachusetts, 500 pp.



STATION #5
STATION #1
STATION #8
STATION #4
STATION #3 elev=1688.09
STATION #7 elev=1693.54
STATION #2 elev=1725.40
STATION #6
Llewellyn Glacier
Ice Thickness
Profile
500
1500
Rock-Ice Interface
First Rock Layer
Second Rock Layer
R2
R3
Third Rock Layer??
Key
Scale 1" = 250 ft
definate boundaries
possible boundaries
R2 second reflection
R3 third reflection


Figure 40

Seismic Survey - Llewellyn Glacier
Summer 1985

Position of seismic stations #1 thru #8. Their approximate positions with respect to C-26 nunatak, Marble Mountain and Red Mountain.

Also shown is the geophone array patterns and positions of various shots.

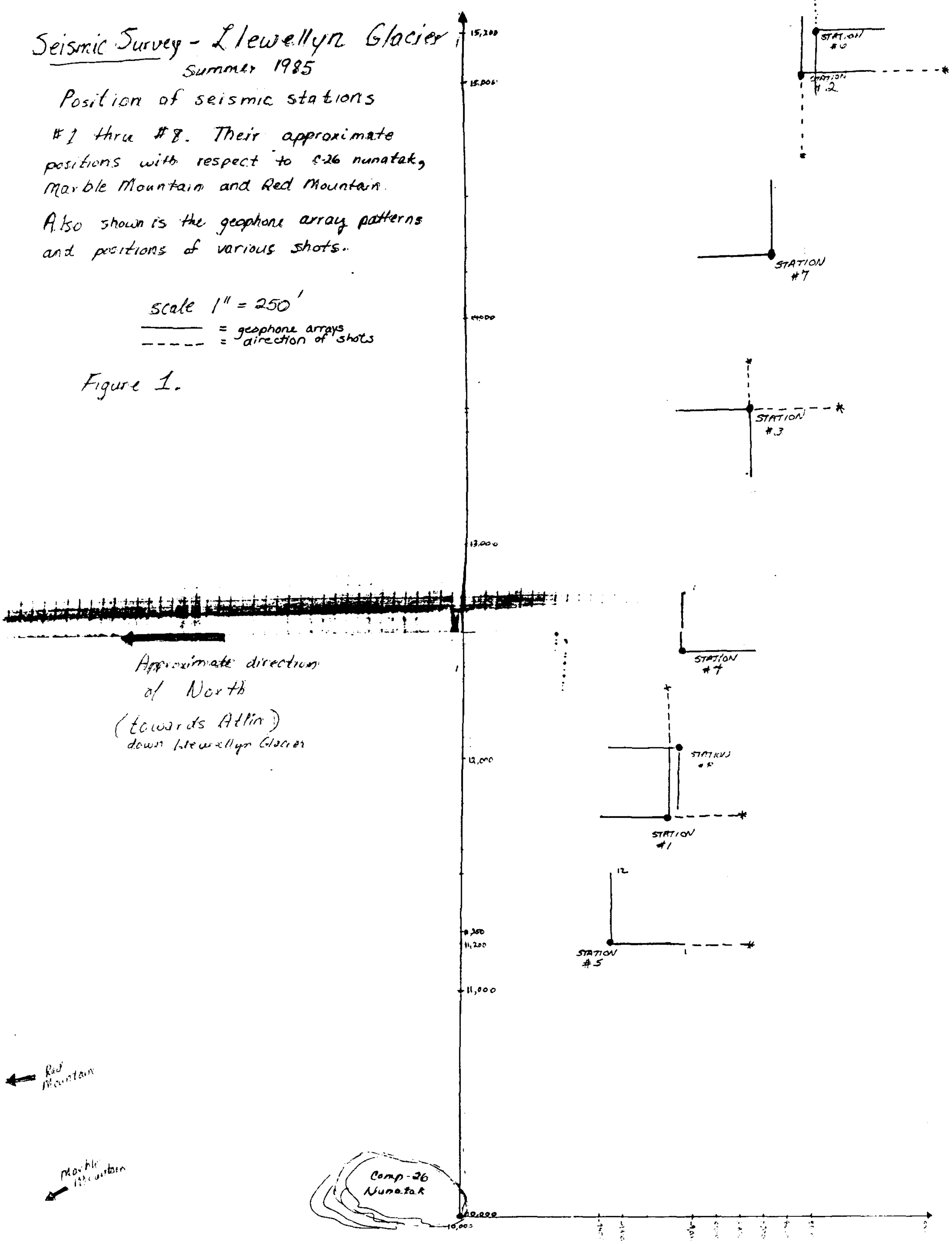



Figure 1.