

MICROGEOPHYSICS  
CORPORATION

TUSCARORA  
SEISMICITY



## TUSCARORA SEISMICITY

TABLE OF CONTENTS	PAGE
1.0.0 INTRODUCTION	1
1.1.0 Microearthquake Mapping	1
1.2.0 Rock Properties, P-Wave Delay	3
2.0.0 HISTORICAL SEISMICITY AND GEOLOGY	6
2.1.0 Historical Seismicity	6
2.2.0 Geologic Setting	6
3.0.0 OPERATION	8
4.0.0 MICROEARTHQUAKES	13
4.1.0 Introduction	13
4.2.0 Observations	13
4.2.1 Detection Threshold	13
4.2.2 Velocity Model	14
4.2.3 Hypocenters	14
4.2.4 Occurrence Statistics	14
4.2.5 Strain Release	25
4.2.6 First-Motion Studies and Cross Sections	25
4.2.7 Poisson's Ratio	26
4.3.0 Interpretation	31
5.0.0 P-WAVE DELAY	34
5.1.0 Procedure	34
5.2.0 Observations	35
5.2.1 Event 1	43
5.2.2 Event 2	43
5.2.3 Event 3	43
5.2.4 Event 4	43
5.2.5 Event 5	43
5.2.6 Event 6	43




TABLE OF CONTENTS

PAGE

5.2.7	Event 7	43
5.2.8	Residuals	44
5.2.9	Elevation Corrections	44
5.3.0	Results	44
5.4.0	Previous Work	46
5.5.0	Interpretation	46


## LIST OF FIGURES

	PAGE
INTRODUCTION	
1.1 Location and Index Map	2
HISTORICAL SEISMICITY AND GEOLOGY	
2.1 Historical Seismicity	6a
2.2 Geology & Historical Seismicity Map	7
OPERATION	
3.1 Station Location Map	9
3.2 Operational Schedule	12
MICROEARTHQUAKES	
4.1 Velocity Model	15
4.2 Number of Events Per Day	20
4.3 Number of Events on Day 260 by Hour	21
4.4 Event Day 260 (I&II)	22
4.5 Events Day 260 10 Hours-13 Hours (II)	23
4.6 Events Day 260 05 Hours-10 Hours (I)	24
4.7 Poisson's Ratio 1st Motion	27
4.8 Poisson's Ratio 1st Motion	28
4.9 1st Motion Map	29
4.10 Wadati Diagram	30
P-WAVE DELAY	
5.1 Pseudo Refractions - Teleseism	36
5.2 Pseudo Refractions - Southern Nevada	37
5.3 Pseudo Refractions - SSR Nuclear Explosion	38
5.4 Pseudo Refractions - Shot SNRP	39
5.5 Pseudo Refractions - Iran	40
5.6 Pseudo Refractions - Russia, Siberia	41
5.7 Pseudo Refractions	42
5.8 P-Wave Delay Example	45



LIST OF TABLES

	PAGE
1.0.0 INTRODUCTION	
2.0.0 HISTORICAL SEISMICITY AND GEOLOGY	
3.0.0 OPERATION	
3.1 Station Coordinates	10
4.0.0 MICROEARTHQUAKES	
4.1 Event Log	16
5.0.0 P-WAVE DELAY	
5.1 Teleseism Data	35



LIST OF PLATES

INTRODUCTION

HISTORICAL SEISMICITY AND GEOLOGY

OPERATION

MICROEARTHQUAKES

- |     |                 |          |
|-----|-----------------|----------|
| 4.1 | Hypocenters     | Appendix |
| 4.2 | Cross Section   | Appendix |
| 4.3 | Strain Release  | Appendix |
| 4.4 | Poisson's Ratio | Appendix |
| 4.5 | Poisson's Ratio | Appendix |

P-WAVE DELAY

- |     |                                    |          |
|-----|------------------------------------|----------|
| 5.1 | P-Wave Delay - Raw Data            | Appendix |
| 5.2 | P-Wave Delay - Altitude Correction | Appendix |
| 5.3 | P-Wave Delay - Depth to Interface  | Appendix |



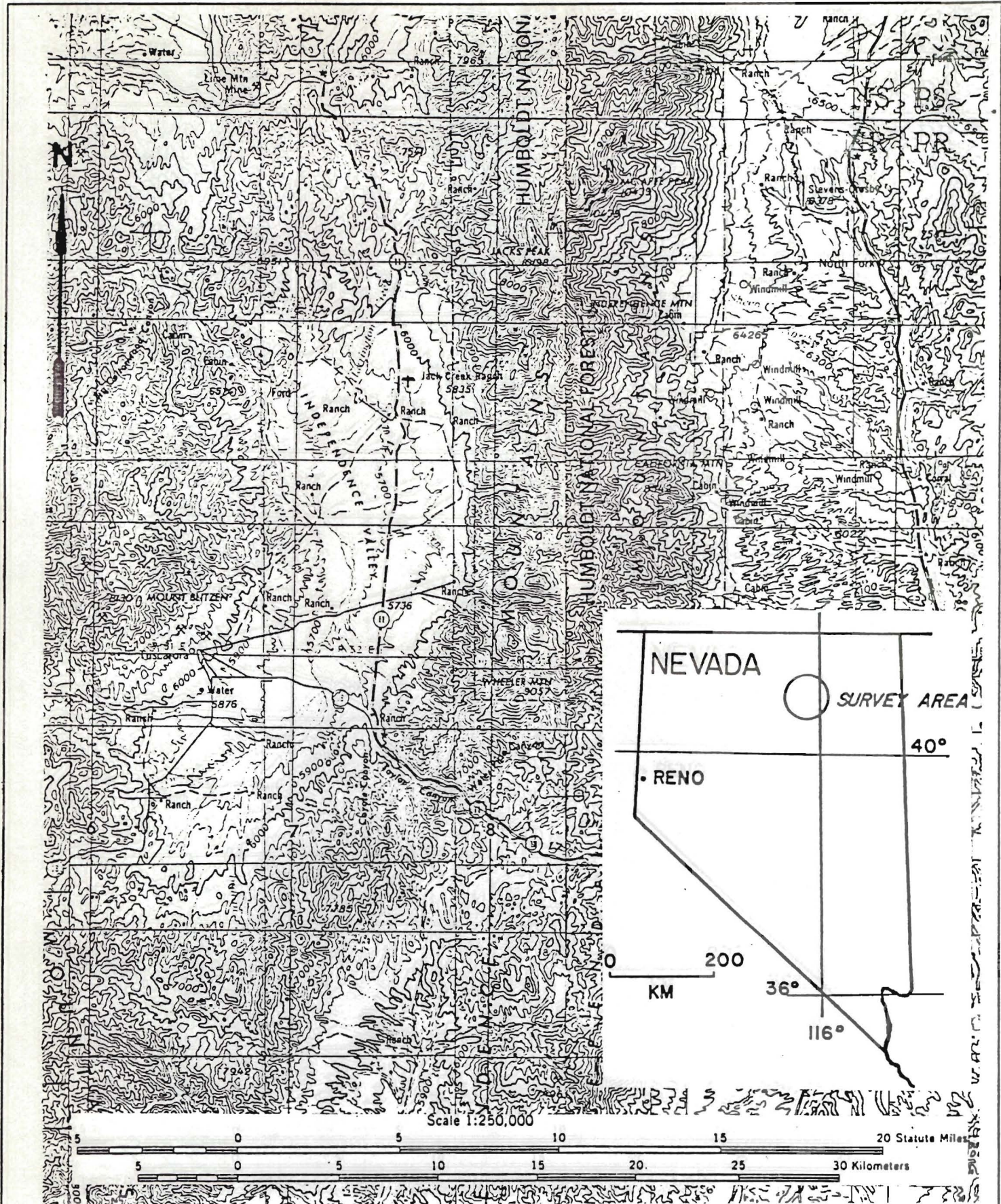
### 1.0.0 INTRODUCTION

From September 10 to September 22, 1978, MicroGeophysics Corporation conducted a passive seismic survey in the area of Tuscarora, Nevada (see location and index map). Passive seismic mapping techniques have been important and useful for geothermal exploration. These seismic techniques are derived from classical seismology and include microearthquake mapping, and measurement of acoustic rock properties. Both of these methods will be discussed below.

#### 1.1.0 Microearthquake Mapping

Microearthquakes are natural, discrete, seismic disturbances. These disturbances are the result of catastrophic rock failure under stress. Microearthquakes and microearthquake systems of varying activity levels have been observed at every proven geothermal area. Microearthquakes and the implied contemporary tectonism are a necessary ingredient for a commercial geothermal occurrence (Lange and Westphal, 1969; Ward and Bjornson, 1971; Ward and Jacob, 1971; Hamilton and Muffler, 1972; Ward, 1972; Combs and Hadley, 1977). Microearthquake activity indicates that active tectonism is currently occurring, therefore the associated porosity and permeability are being augmented. The zone of increasing porosity and permeability can be an excellent geothermal target. The zone may contain either the reservoir itself or the circulation path for geothermal fluids. Of course the microearthquake method does not directly indicate sufficient temperature or sufficient water recharge for a commercial system.

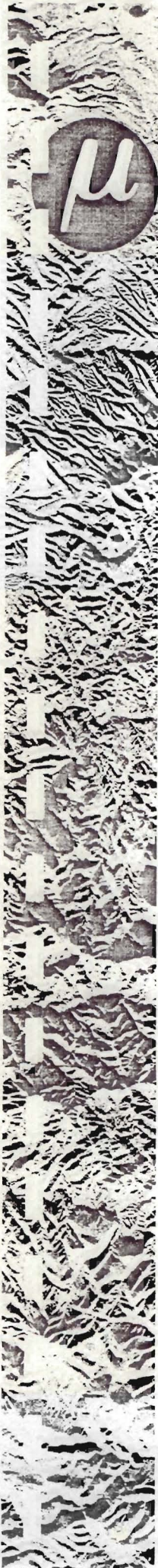
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# LOCATION AND INDEX MAP

FIGURE 1.1






Mapping of discrete events for a geothermal area produces data about fault locations. First-motion studies produce data on the type and style of faulting and the direction of motion on faults. The statistics of occurrence of microearthquakes are used to compile a recurrence curve and to characterize and compare active geothermal areas. Some rock properties such as Poisson's Ratio can also be mapped utilizing local events. The location and style of faulting, characteristics of activity, and mapping of rock properties aid in the geologic understanding and delineation of a geothermal system.

#### 1.2.0 Rock Properties, P-Wave Delay

A change in temperature will change the velocities of S- and P-waves in rock slightly. The acoustic attenuation of sound waves in rock is more dependent on temperature than is velocity. Fractures in rock change the S- and P-wave velocity in rock to some degree. The effect can be most easily observed as changes in the ratio of S-wave to P-wave velocities. Thus, if attenuation and the velocities can be measured with some degree of confidence, it may be possible to isolate two of the requirements for a commercial reservoir; i.e., high fracture porosity and rock at elevated temperatures.

Reliable sources of S- and P-wave energy include regional earthquakes (distances greater than 200 km) and industrial-blasting events. These events and the high frequencies in some teleseisms are useful if phases can be separated into either S- or P-wave type of energy. A frequency-dependent transfer function between




each station and a master station can then be calculated. The amplitude spectrum of this function will indicate the amount of attenuation taking place and the phase spectrum will indicate the time shift of the data. These values can be compared to a homogeneous model and anomalous areas isolated.

If S- and P-wave arrivals can be analyzed separately, both velocities and attenuation for the two modes of propagation can be calculated. If both S-wave and P-wave delay are calculated, a nonlinear combination of the two velocities, i.e., Poisson's Ratio can be calculated. The Poisson's Ratio can be used to delineate areas of anomalous fractures. The variation of Poisson's Ratio with fracturing, however, is not straight forward. For example, the Poisson's Ratio will decrease in general as fracturing increases. However, Poisson's Ratio may increase if the fractures are fluid filled.

The following report includes a section on geology and historical seismicity, and sections on operations, microearthquakes and rock properties. The final section is a summary of the conclusions from each of the previous sections. Appendices include information about the instruments used, the methods used, and a log of the microearthquakes detected.

## INTRODUCTION BIBLIOGRAPHY

- 
- Combs, J. and David Hadley, 1977, Microearthquake Investigation of the Mesa Geothermal Anomaly, Imperial Valley, California, *Geophysics*, Vol. 42, No. 1, pp. 17-33.
- Hamilton, R.M. and L.J.P. Muffler, 1972, Microearthquakes at the Geysers Geothermal Area, California, *JGR*, Vol. 77, No. 11, pp. 2081.
- Lange, E., T.V. McEvelly and W.H. Westphal, 1969, Microearthquakes at the Geysers, Sonoma County, California, *JGR*, Vol. 74, pp. 4377.
- Ward, P.L., 1972, Microearthquakes: Prospecting Tool and Possible Hazard in the Development of Geothermal Resources, *Geothermics*, Vol. 1, No. 1, pp. 3.
- Ward, P.L. and S. Bjornson, 1971, Microearthquakes, Swarms and Geothermal Areas of Iceland, *JGR*, Vol. 76, No. 17, pp. 3953.
- Ward, P.L. and R.H. Jacob, 1971, Microearthquakes: In the Ahnuachapan Geothermal Field, El Salvador, Central America, *Science*, Vol. 173, pp. 328.

## 2.0.0 HISTORICAL SEISMICITY AND GEOLOGY

### 2.1.0 Historical Seismicity

Figure 2.1 is a plot of the historical seismicity for Nevada including years 1940 to 1974 (NOAA). The area near Tuscarora has not experienced any nearby macroearthquake activity in the 30 years observation period.

### 2.2.0 Geologic Setting

The Tuscarora prospect is situated in Northern Nevada approximately 60 miles north to Elko, Nevada.

The stratigraphy of the area is comprised of a sequence of Paleozoic sediments in contact with large bodies of Cenozoic volcanics mainly comprised of rhyolitic volcanics. The fault style is complex with thrust fault and normal faulting.

The Jack Creek fault striking nearly north-south is a dominant feature within the area of interest. A second fault system strikes east by northeast and may constitute a major fault direction. Figure 2.2 is a generalized geology map for the area.



# GEOLOGY & HISTORICAL SEISMICITY MAP


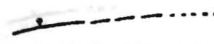

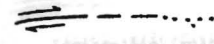
## FIGURE 2.2



Scale 1:500,000



DRAWN BY IJW DRAWING NO AX-1104 CHECKED BY JLB DATE 11-14-78

-  Contact
-  High-angle fault  
Dashed where inferred or uncertain;  
dotted where concealed. Bar and ball on downthrown side
-  Low-angle fault  
Dashed where inferred or uncertain;  
dotted where concealed. Sawteeth on upper plate
-  Strike-slip fault  
Dashed where inferred or uncertain;  
dotted where concealed. Arrows indicate relative movement

Q

QUATERNARY

T

TERTIARY

C

CRETACEOUS KM

NEVADA

SURVEY AREA

• RENO

0 200

36°

116°

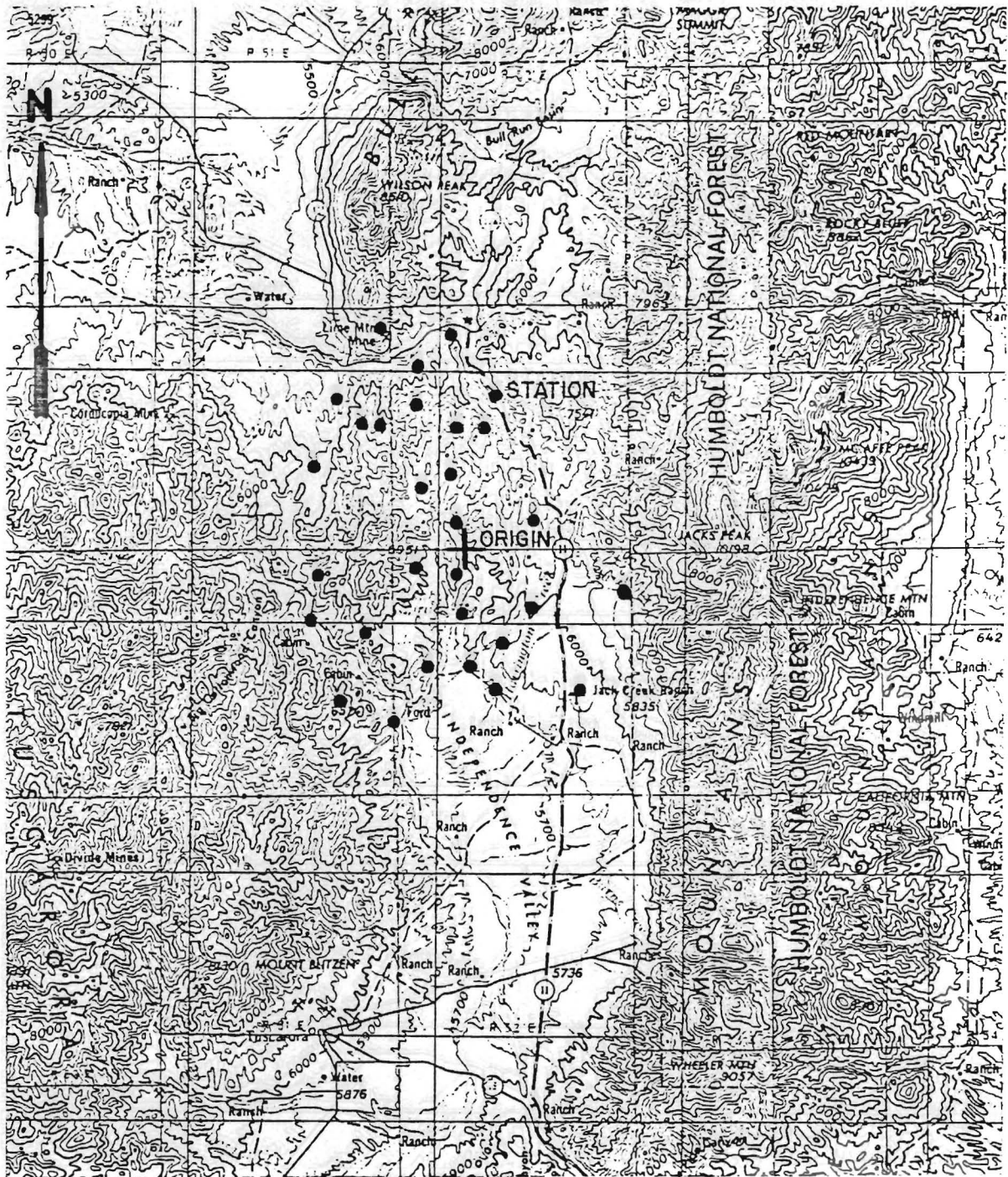
40°

### 3.0.0 OPERATION

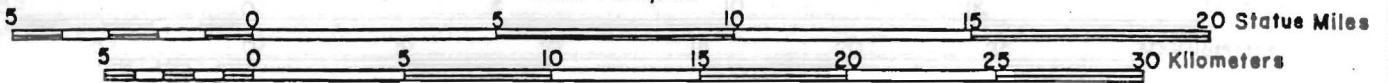
A passive seismic survey was conducted near Tuscarora, Nevada, from September 10 to September 22, 1978. Eleven days of recordings were obtained. Four to eight stations were operational on any one day (see operating schedule). The array was modified daily; a total of 30 stations were occupied. A station location map is shown in Figure 3.1. The station coordinates are listed in Table 3.1 and a detailed operations schedule is shown in Figure 3.2.

Each station of the passive seismic array consists of an MEQ-800-B smoked-paper recorder system with a companion digital magnetic tape recorder (see instrumentation appendix). Station locations were determined by considerations of access, specific array geometry and uniform coverage of the target area. Once a nominal station location was available, the location with the highest gain was selected. Where hard rock outcrops were available, the seismometer was cemented to the outcrop and then covered by soil to eliminate possible wind noise. When hard rock was not available the seismometer was buried from one to two feet within the soil. The data quality was generally good with less than five percent loss due to wind or cultural noise.

RAW YTI JRAI 3 NC :202 ECK BY I C '11-9



Scale 1:250,000



**STATION LOCATION MAP**  
FIGURE 3.1



TABLE 3.1  
STATION COORDINATES

<u>STATION</u>	<u>X (km)</u>	<u>Y (km)</u>	<u>Z (km)</u>
1	0.30	-6.25	0.25
1A	-4.65	-3.27	0.33
2	0.75	-3.90	0.29
3	-3.69	-7.30	0.21
4	-5.32	-6.25	0.32
5	-1.13	-1.55	0.30
6	5.65	-2.41	0.47
6A	1.75	-3.14	0.34
6B	-0.68	0.65	0.44
7	3.23	-6.19	0.29
8	-1.18	-3.19	0.26
8A	-3.00	-1.23	0.39
9	-2.34	-5.32	0.33
10	0.56	5.60	0.36
10A	1.91	1.00	0.48
10B	0.49	4.15	0.50
11	-1.07	8.00	0.24
11A	-2.86	6.68	0.27
11B	-2.86	5.22	0.53
11C	-1.22	4.16	0.54
11D	-1.12	2.78	0.45
12	-4.12	8.14	0.40
12A	-6.12	5.56	0.34

12B	-4.37	4.45	0.45
12C	-2.65	1.84	0.50
13	-7.20	3.13	0.28
14	-6.90	-3.50	0.21
14A	-6.50	-0.77	0.21
14B	-5.06	4.42	0.47

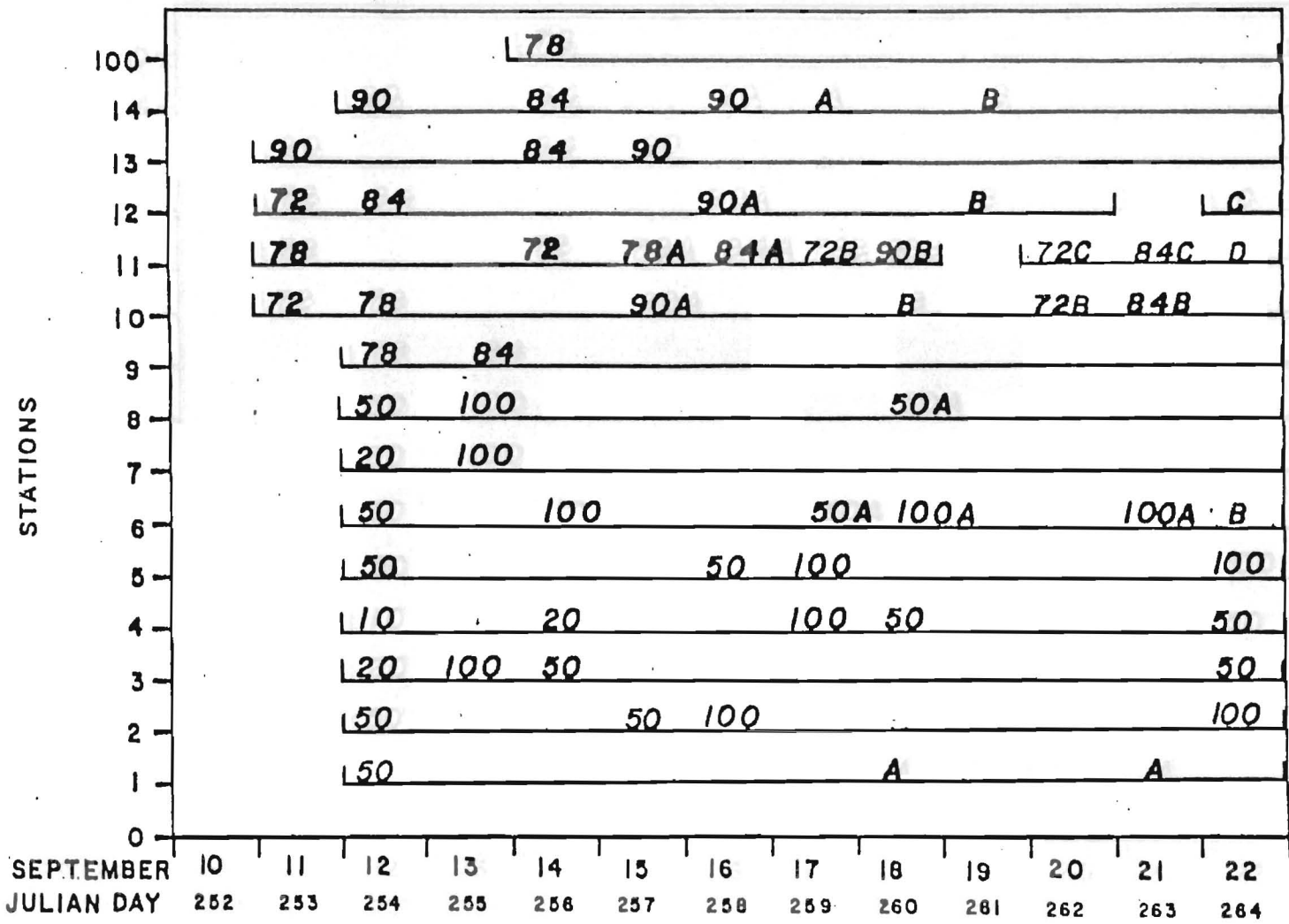
Station coordinates X, Y, and Z are kilometers

+X East

+Y North

Altitude datum is 1.5 km above sea level.

Origin is at longitude  $116^{\circ} 06.73'$  West, and latitude  $41^{\circ} 29.51'$  North.



# OPERATIONAL SCHEDULE

FIGURE 3.2

#### 4.0.0 MICROEARTHQUAKES

##### 4.1.0 Introduction

The following section of this report concerns the microearthquakes detected during the 11-day passive seismic survey near Tuscarora, Nevada. Microearthquakes occurred sporadically during the 11-day survey. Included within the microearthquake section of this report are discussions of the detection threshold, velocity model, hypocenters, event occurrence statistics, estimated strain release and a fracture-area map, first-motion studies, and Poisson's Ratio map.

The section concludes with an interpretation of the microearthquake data presented.

##### 4.2.0 Observations

###### 4.2.1 Detection Threshold

The detection-threshold distance is defined as the largest hypocentral distance at which a given magnitude earthquake will produce a trace displacement on the detecting instrument of at least 2 mm. Therefore, any event within the detection-threshold distance would be detected on at least one station if the event exceeds the magnitude for which the detection-threshold distance is calculated. The detection-threshold distance for Richter magnitudes -1.0 and 0.0 are 4 and 7 km from each station. A magnitude -0.5 event occurring within the Tuscarora survey area would have been detected during the 11-day survey.

#### 4.2.2 Velocity Model

The velocity model used to locate the microearthquakes has the form of a linear increase of velocity with depth. This model has two parameters; an initial velocity at the datum and a rate of change of velocity with depth. The value of these two parameters is adjusted to produce the best least-square fit to the measured time arrivals of the microearthquakes. In this case, the velocity model that produced the best fits was a linear-increase-with-depth velocity model with an initial velocity of 3.5 km/sec and an acceleration of 0.14 km/sec/km. Figure 4.1 shows the resulting velocity model. Also shown on Figure 4.1 is a layered velocity model as reported by Hill and Pakiser (1966). The layered model agrees favorably with the derived linear increase of velocity with depth model.

#### 4.2.3 Hypocenters

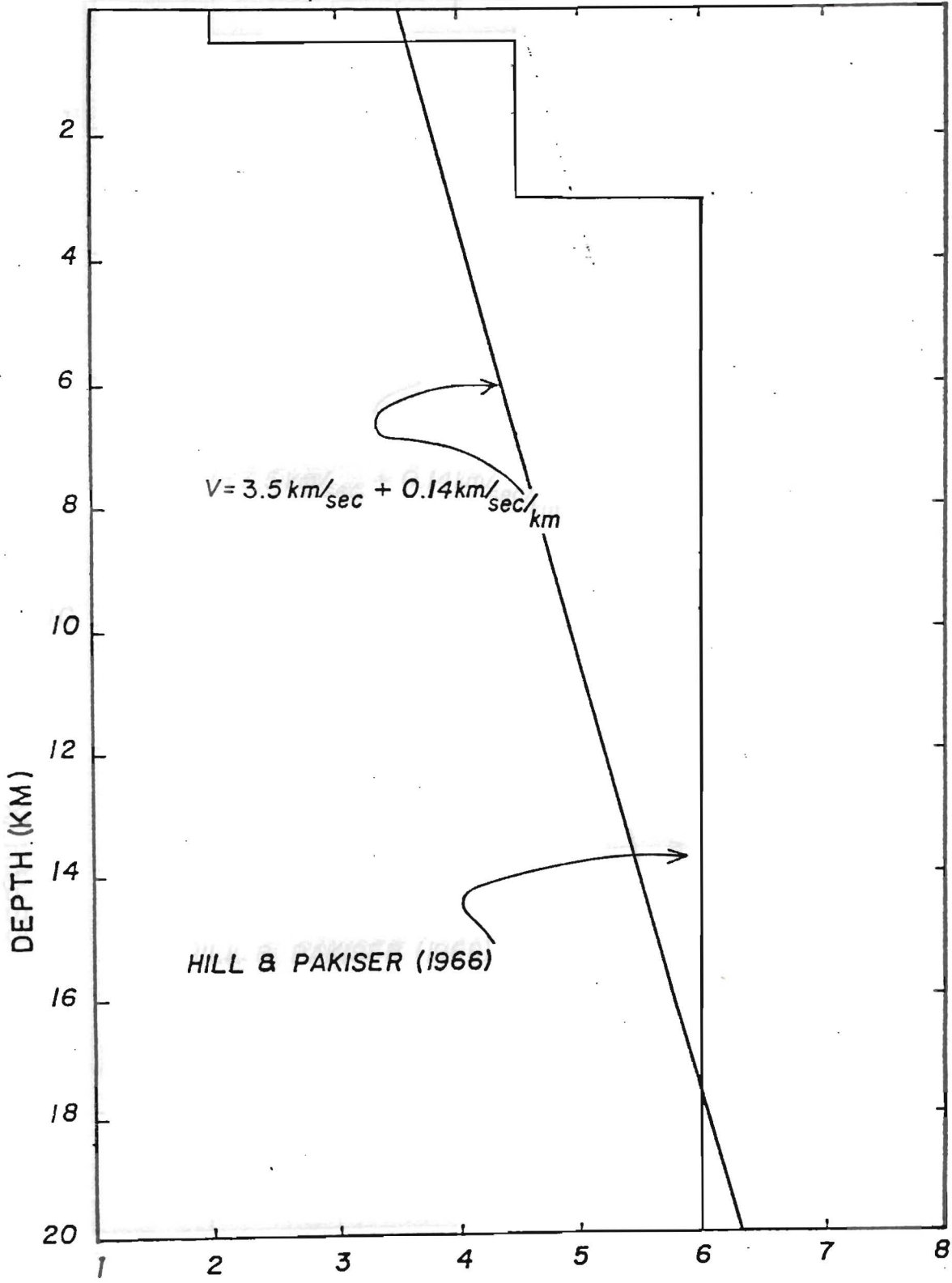
Plate 4.1 illustrates the hypocenters located. A list of all located events is contained in Table 4.1. Plate 4.2 shows cross sections.

#### 4.2.4 Occurrence Statistics

Figures 4.2 and 4.3 are plots of the number of events versus the time of occurrence. Figure 4.2 plots the number of events versus the day of the survey. Of the total 108 events, 103 occurred on day 260 (September 17, 1978). Figure 4.3 details the occurrence of events by the hour within day 260. The occurrence of events splits into two groups, one at 5 hours to 11 hours, with 58 events and the second at 14 hours to 16 hours with a total of 45 events.

VELOCITY (KM/SEC)

DRAWN BY J.L.H. CHECKED BY P.L.L. DATE 11-14-78



HILL & PAKISER (1966)

VELOCITY MODEL  
TUSCARORA

FIGURE 4.1

TABLE 4.1  
EVENT LOG  
Tuscarora, Nevada

<u>DAY</u>	<u>UCT ORIGIN TIME</u>	<u>X (km)</u>	<u>Y (km)</u>	<u>Z (km)</u>	<u>MAG</u>
254	16:03:43.72	7.5	-5.8	9.3	0.15
255	23:50:10.57	7.1	-5.2	5.7	1.31
256	18:37:33.56	0.4	4.8	4.7	1.47
260	05:03:33.96	2.4	-11.2	4.0	0.25
260	05:04:12.97	9.3	-4.4	0.0	0.45
260	05:12:26.44	1.5	-1.2	7.3	0.55
260	05:14:09.52	6.3	-6.1	10.9	1.34
260	05:15:41.21	6.5	-1.9	9.0	0.45
260	05:18:40.79	7.2	-5.0	10.0	0.03
260	05:19:01.14	5.7	-11.3	8.6	0.89
260	05:23:25.54	4.8	-2.6	10.2	-0.05
260	05:24:29.21	2.2	5.1	9.7	0.45
260	05:24:45.55	2.4	-0.8	5.7	0.50
260	05:25:42.59	6.2	-6.8	9.8	0.47
260	05:27:16.24	4.5	0.1	5.6	0.53
260	05:29:26.02	9.0	-3.5	10.7	0.07
260	05:45:33.14	3.5	-0.6	5.8	0.05
260	05:46:22.91	4.8	-1.7	8.8	-0.24
260	05:47:47.65	4.6	-3.0	9.6	0.33
260	05:52:12.69	2.7	-3.4	9.6	0.52
260	05:52:19.39	1.6	-1.0	10.0	0.23
260	05:57:37.60	2.5	-2.2	7.5	0.06
260	06:03:10.88	1.9	-1.0	5.1	-0.25
260	06:03:41.80	4.3	-1.5	8.8	-0.22
260	06:08:48.97	4.8	-3.8	9.9	1.38
260	06:09:44.63	11.8	-1.1	0.0	0.33


<u>DAY</u>	<u>UCT ORIGIN TIME</u>	<u>X (km)</u>	<u>Y (km)</u>	<u>Z (km)</u>	<u>MAG</u>
260	06:11:26.10	4.5	-3.0	10.0	0.07
260	06:11:48.05	5.5	-5.7	9.3	1.78
260	06:13:38.54	5.0	-2.7	9.4	0.25
260	06:16:58.00	8.7	1.1	7.7	0.51
260	06:17:53.06	7.9	-3.9	11.2	1.13
260	06:24:22.95	4.4	3.6	4.5	0.29
260	06:24:54.02	6.0	-7.1	8.7	0.94
260	06:29:32.82	9.9	-0.4	8.6	0.54
260	06:37:16.65	4.3	2.1	9.0	0.94
260	06:50:58.18	7.8	-3.5	10.6	1.54
260	06:52:31.37	4.2	-5.9	3.4	0.05
260	06:56:27.57	4.5	-2.5	9.5	-0.23
260	07:01:02.32	1.7	2.7	3.8	-0.43
260	07:01:55.97	1.3	2.5	8.3	0.38
260	07:12:27.00	4.5	-3.2	9.9	0.46
260	07:14:42.03	5.2	-3.2	7.2	-0.27
260	07:14:56.51	7.5	-8.3	13.9	-0.17
260	07:49:36.05	4.7	-2.5	10.9	0.53
260	07:54:38.85	1.3	1.7	7.7	-0.01
260	07:55:25.14	-4.2	-2.5	10.4	0.43
260	07:57:18.89	5.0	-2.8	10.3	-0.38
260	08:59:01.80	4.1	-2.0	9.5	0.74
260	09:38:40.92	6.4	-10.5	0.0	-0.53
260	09:51:40.02	13.7	-0.4	0.0	0.09
260	10:34:34.40	1.8	5.0	14.3	0.45
260	14:44:43.47	1.7	-1.5	7.8	0.27
260	14:46:03.71	9.7	-11.8	6.0	0.04
260	14:47:56.53	3.7	1.7	3.8	0.28
260	14:50:05.13	4.2	5.4	2.0	-0.03



<u>DAY</u>	<u>UCT ORIGIN TIME</u>	<u>X (km)</u>	<u>Y (km)</u>	<u>DEPTH Z (km)</u>	<u>MAG</u>
260	14:51:41.02	7.8	-3.9	5.3	-0.07
260	14:52:41.93	9.2	-10.2	6.5	-0.48
260	14:54:38.23	4.0	-2.3	11.5	0.98
260	14:55:20.31	6.2	1.3	8.7	0.90
260	14:55:37.61	1.9	0.2	11.5	0.86
260	14:58:34.68	6.5	-4.3	3.2	0.08
260	14:58:58.53	4.0	1.3	10.3	0.14
260	15:00:29.94	7.8	-3.9	2.8	0.07
260	15:00:52.27	7.7	-5.2	8.2	0.36
260	15:01:13.43	4.1	-7.0	4.5	0.92
260	15:01:39.73	3.4	-3.7	10.0	0.45
260	15:01:57.06	2.8	-5.7	11.2	1.18
260	15:02:51.08	0.8	1.7	9.2	0.95
260	15:03:24.62	9.9	-0.4	3.2	0.45
260	15:04:00.37	8.1	-7.5	12.4	0.76
260	15:04:38.78	6.3	5.0	3.2	0.36
260	15:06:44.25	7.5	-5.4	11.5	-0.15
260	15:06:59.84	10.2	3.6	0.0	1.14
260	15:08:43.27	-0.3	2.6	12.7	1.18
260	15:09:32.84	2.8	0.1	4.8	0.43
260	15:12:00.38	5.8	-10.4	6.7	0.14
260	15:16:25.17	7.5	-3.8	13.8	2.44
260	15:17:20.87	5.0	-0.2	8.9	1.18
260	15:18:33.69	1.7	3.2	8.5	0.41
260	15:41:15.02	4.2	-9.4	8.2	1.38
260	15:46:16.27	5.4	-4.7	4.2	0.90
260	15:50:01.87	3.5	-1.9	7.9	1.06
260	15:56:52.33	3.1	-1.3	7.9	0.31

Altitude datum is 1.5 km above sea level.

Origin is at longitude 116° 06.73' West, and  
latitude 41° 29.51' North.

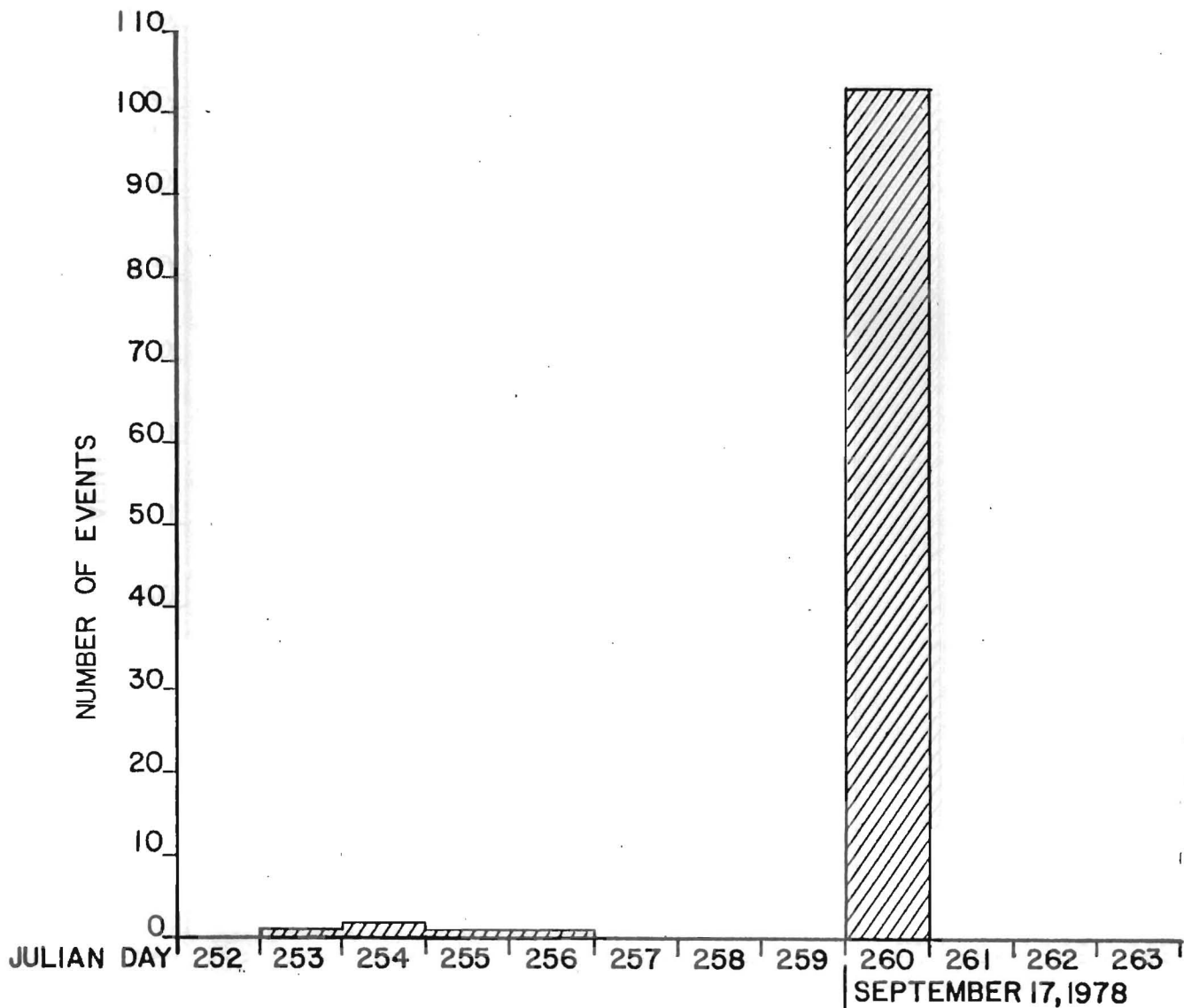


A characteristic of seismicity is the recurrence curve. The recurrence curve is a plot of the earthquake magnitudes versus the log of the cumulative number of earthquakes. This plot is typically a linear plot which indicates that for a given magnitude event a larger number of events will occur at a lesser magnitude. For a slope of  $-1.0$ , a ten-fold increase in the number of events will occur for a decrease in the magnitude of one.

The recurrence curve shown in Figure 4.4 is based on all the natural microearthquakes recorded at Tuscarora. An event is designated as a microearthquake when the event has a similar signature to other well recognized events. A b-slope of  $-1.0$  is shown for comparison. A b-slope of  $-0.9$  is considered an average value for worldwide seismicity.

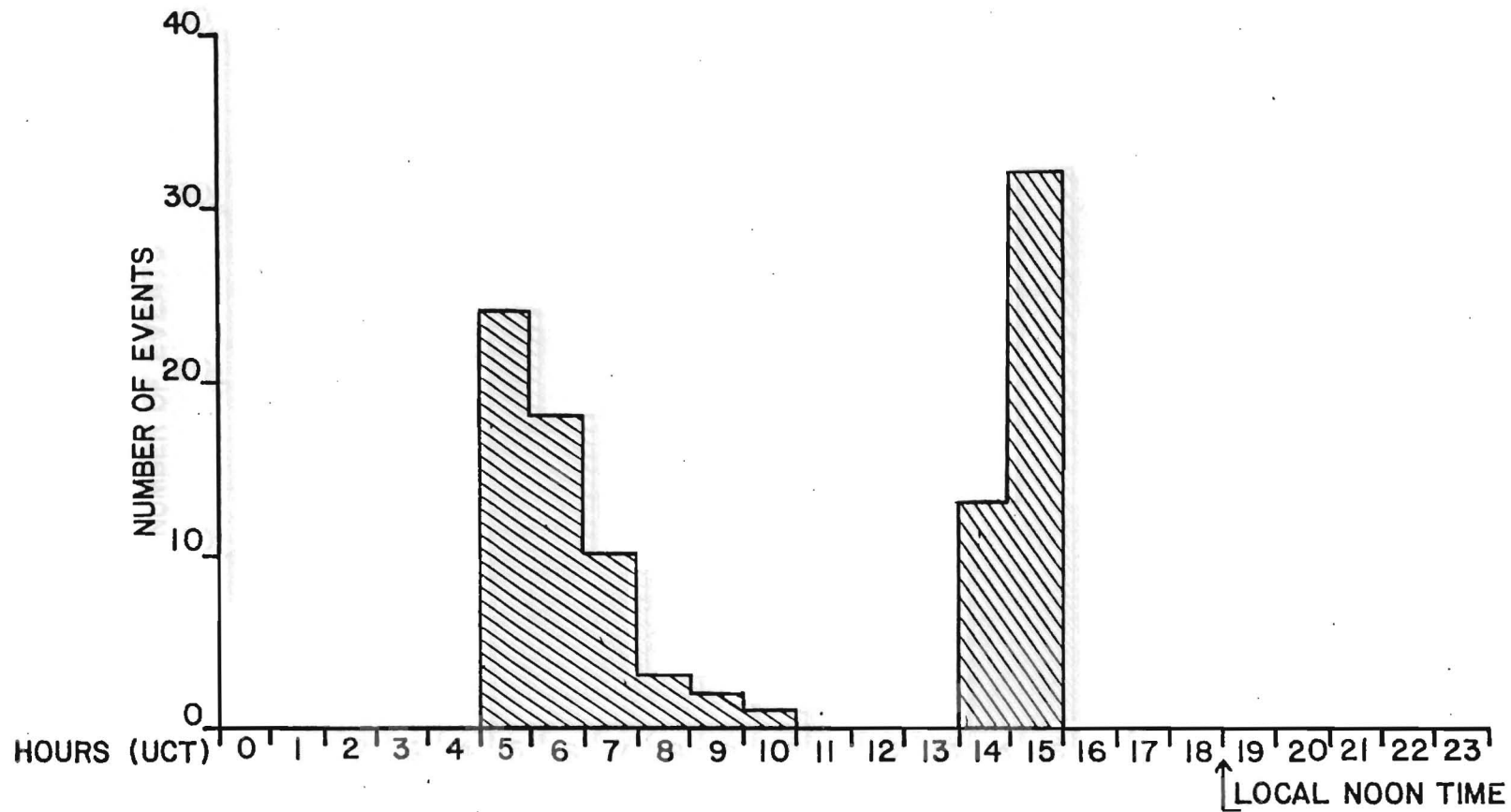
Figures 4.5 and 4.6 are recurrence curves for the two populations of events previously described. Again each is shown with a comparison slope of  $-1.0$ .

As the magnitude decreases, the number of earthquakes detected no longer fits the straight line. This phenomena is caused by the decreased capability of the array to detect these very small (less than  $-1.0$  magnitude) events. An empirical detection threshold is determined to be the approximate point that the recurrence curve departs significantly from linearity at small magnitudes. It can be seen from Figures 4.4, 4.5, and 4.6 that this point is about  $0.0$  magnitude. Therefore, it can be surmised that all events with magnitudes greater than  $0.0$  that occurred during this survey were detected.



NUMBER OF EVENTS PER DAY

FIGURE 4.2

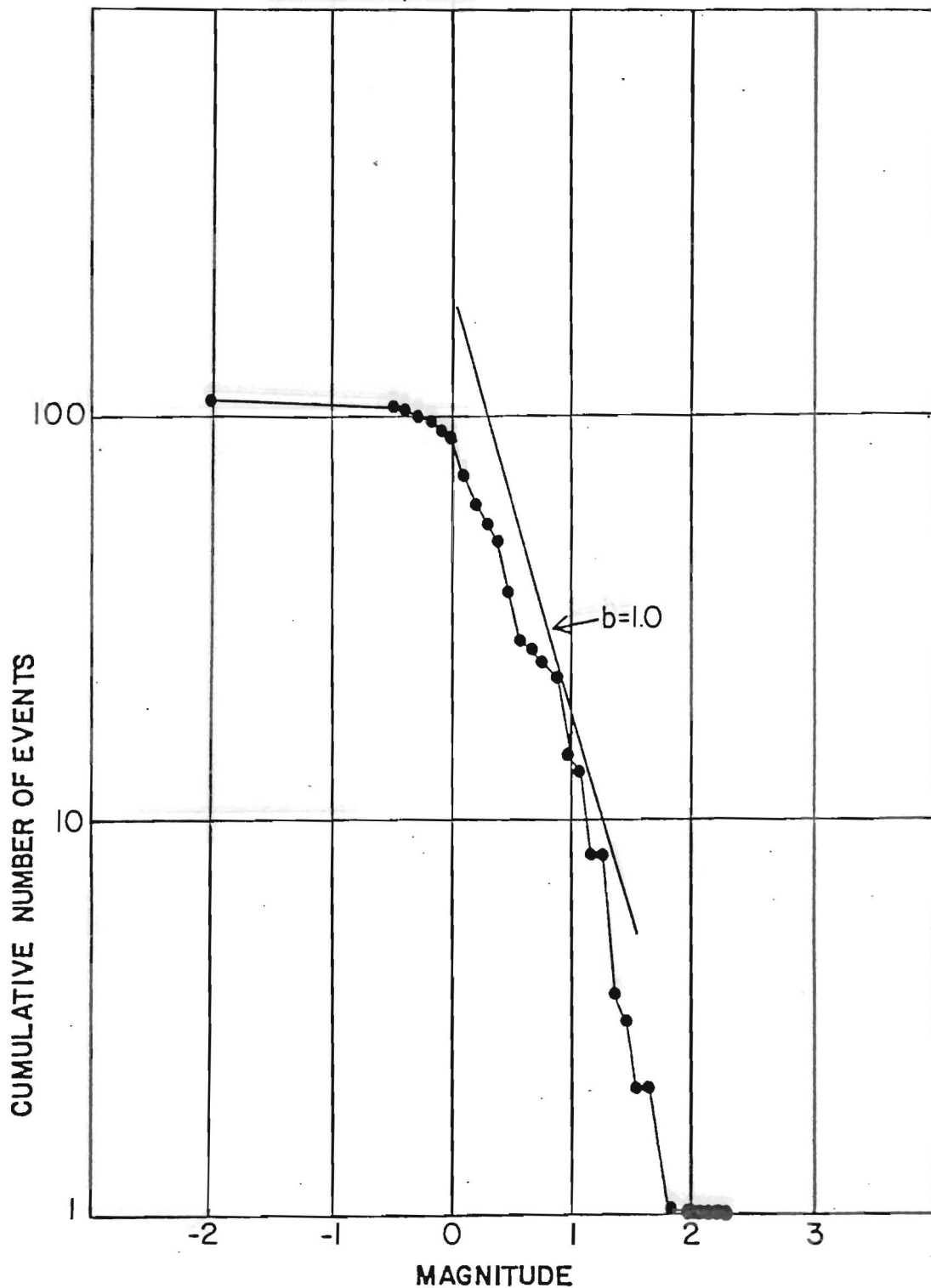


**NUMBER OF EVENTS ON DAY 260 BY HOUR**

FIGURE 4.3

# EVENTS DAY 260 (I&II)

DRAWN BY TVW DRAWING NO. AX-110Z CHECKED BY PJ DATE 11-14-78

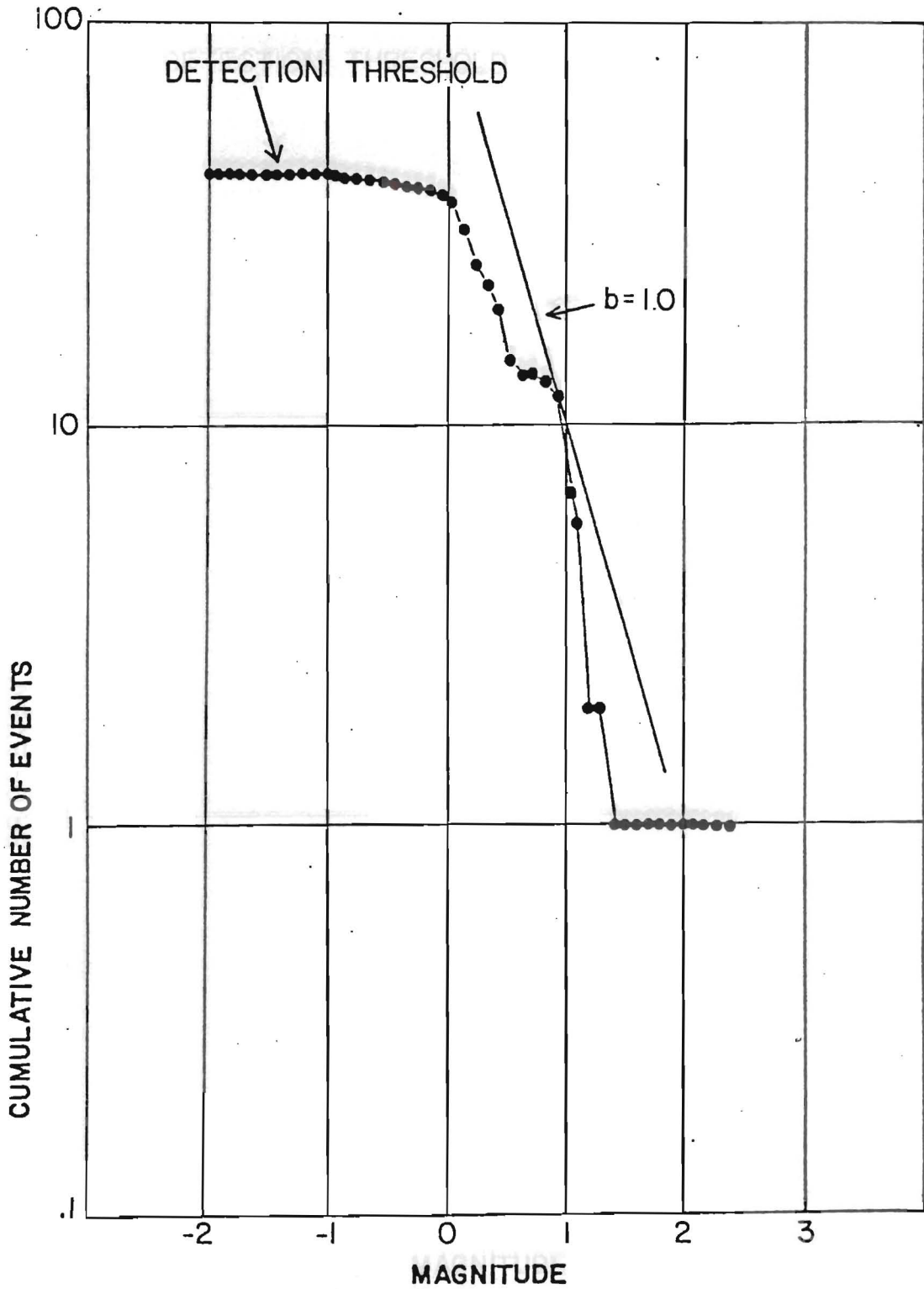


RECURRENCE CURVE

FIGURE 4.4

### EVENTS DAY 260 10Hrs-13Hrs (II)

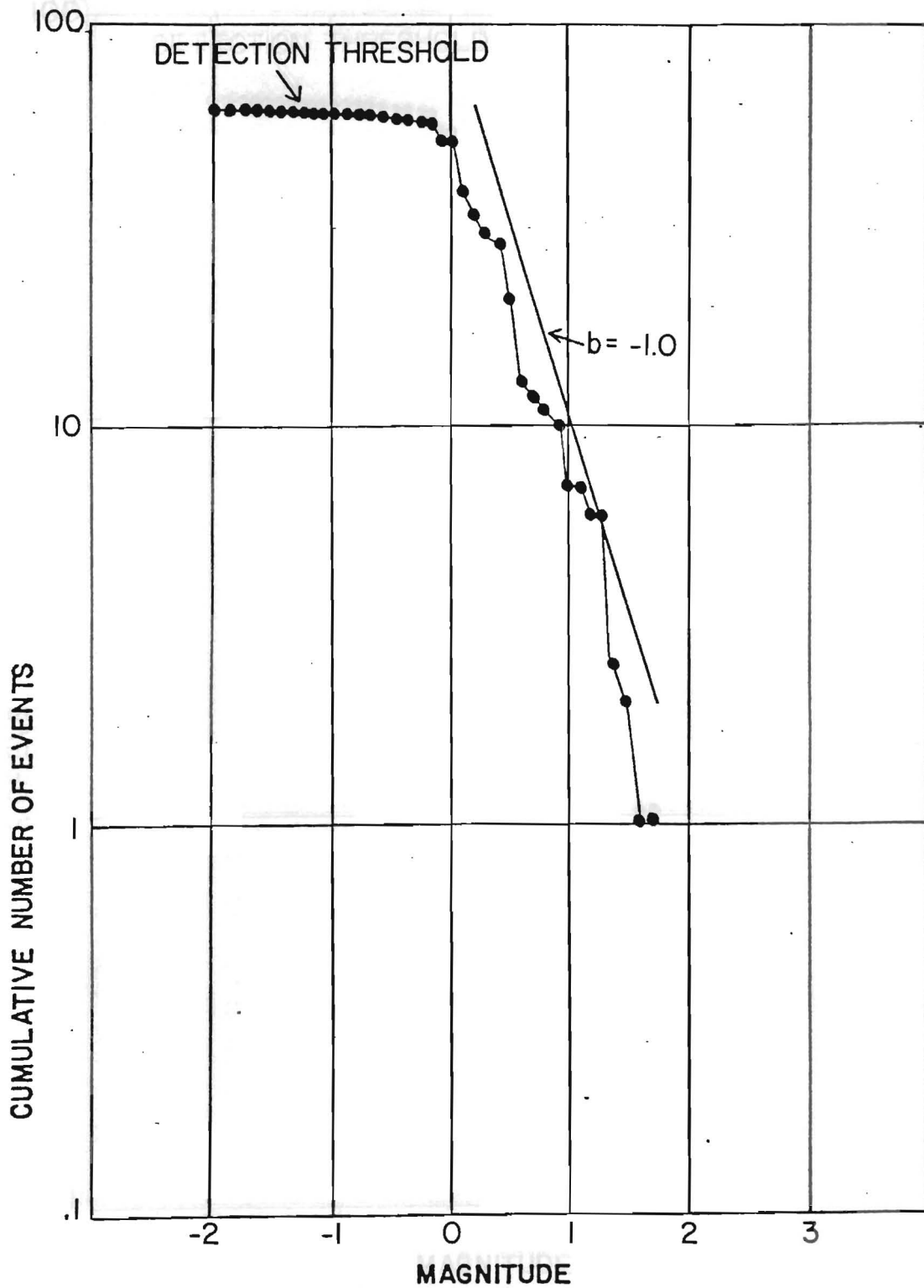
DRAWN BY TVW DRAWING NO. AX-106 CHECKED BY PB DATE 11-14-78



RECURRENCE CURVE

FIGURE 4.5

# EVENTS DAY 260 05 Hrs - 10 Hrs (I)



DRAWN BY IVW DRAWING NO. AX-1105 CHECKED BY PB DATE 11-14-78

### RECURRENCE CURVE

FIGURE 4.6

#### 4.2.5 Strain Release

The relationship between strain release and magnitude established by Richter is:

$$\text{LOG}_{10} E = 9.4 + 2.14 m - 0.054 m^2$$

$$S = (E)^{\frac{1}{2}}$$

Where E is the energy released in ergs

S is the amount of strain released in (ergs)<sup>1/2</sup>

And m is the magnitude (Richter).

The purpose for estimating strain release is to get an idea of the total energy and the total area of fracturing involved in the recorded seismic events.


The strain release was calculated from assigned magnitudes. The total strain release for the locatable earthquakes is estimated to be  $4.04 \times 10^7$  (ergs)<sup>1/2</sup> and corresponds to an equivalent amount of strain released from an earthquake of magnitude 2.92.

Plate 4.3 is a contour map of strain release in the survey area for the locatable earthquakes detected during this 11 day survey.

#### 4.2.6 First-Motion Studies and Cross Sections

If seismographs record the direction of the first motion of the seismic energy at several azimuths from the event, the double-couple model of rock fracture will yield fault planes. A set of two orthogonal fault-plane solutions are determined; the preferred solution is denoted the fault-plane solution and the other, the auxiliary solution. Trends of hypocenters or





mapped geologic structures are helpful in determining the preferred solution.

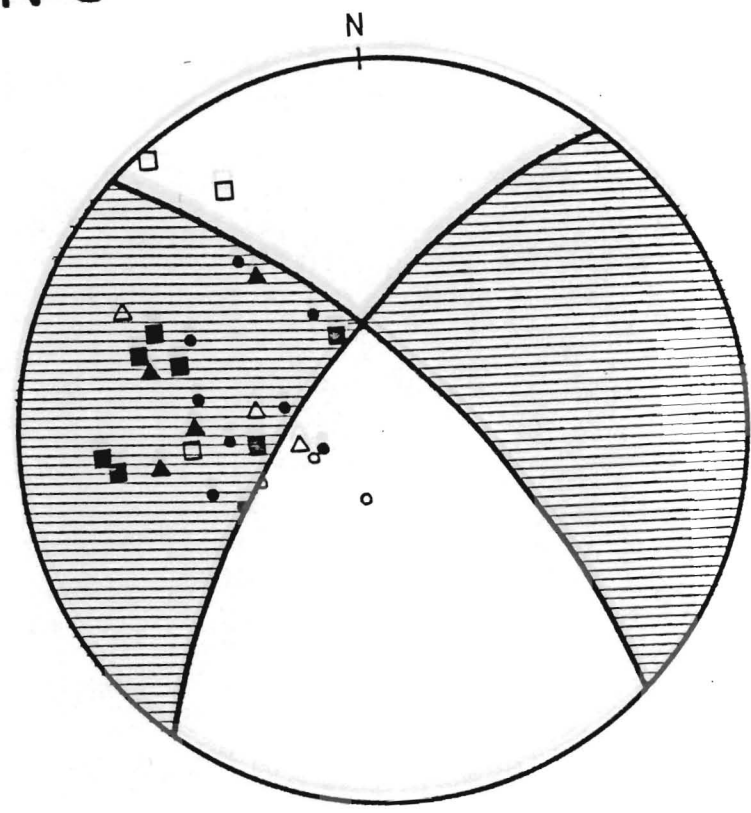
Fault-plane solutions are shown in Figures 4.7 and 4.8. Each first motion is also shown in its hypocentral position on Figure 4.9. The first-motion plots are upper hemisphere projections of the source emergence angle. The direction of the first-motion, dilatation or compression, is plotted. Since none of the events were interior to the network, control of first-motion plots was not optimal.

#### 4.2.7 Poisson's Ratio

If the S-P times for a specific event are plotted versus the P-phase arrival times at several stations, the resultant points will fall on a straight line if the subsurface is homogeneous. The point where this line crosses the S-P = 0 axis corresponds to the origin time of the earthquake. If inhomogeneities in the subsurface are suspected, and an origin is available from the computer fit to the data, a straight line can be drawn between the computed origin-time and the point corresponding to each station. This line defines the average crustal properties along the line from the earthquake location to the station. The crustal property defined is the P-wave to S-wave velocity ratio. The ratio is equal to the slope of the line plus 1.0. Such a plot is known as a Wadati plot (Figure 4.10). Individual-event Wadati plots were made for locatable events. It should be noted that the P-wave to S-wave

# POISSON'S RATIO 1<sup>ST</sup>. MOTION

DAY	TIME (hr. min.)	Symbol
260	14 54	●
255	23 50	■
260	05 18	▲



DAY	TIME (hr. min.)	Symbol
260	07 14	●
260	07 49	■
260	08 59	▲

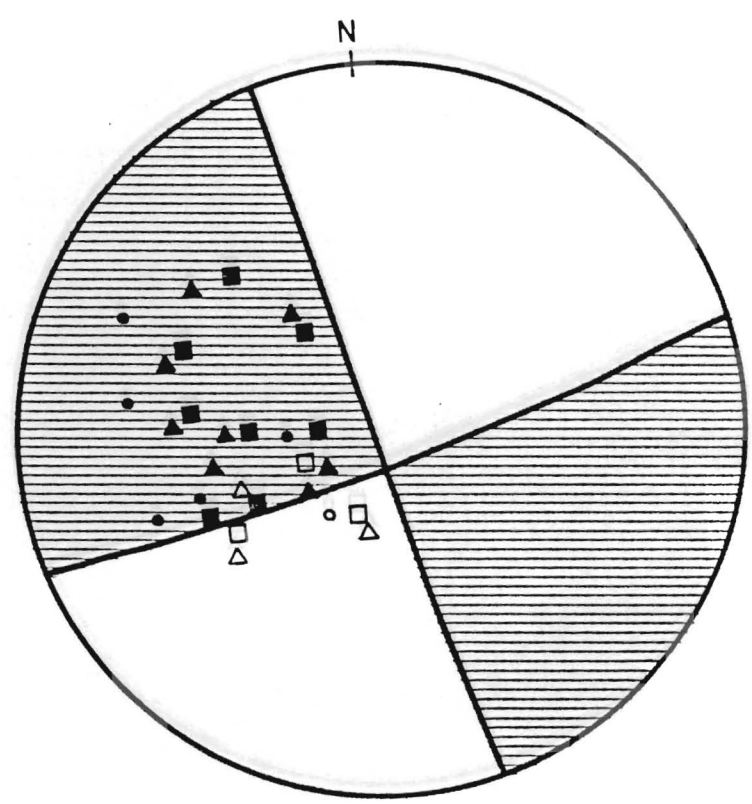


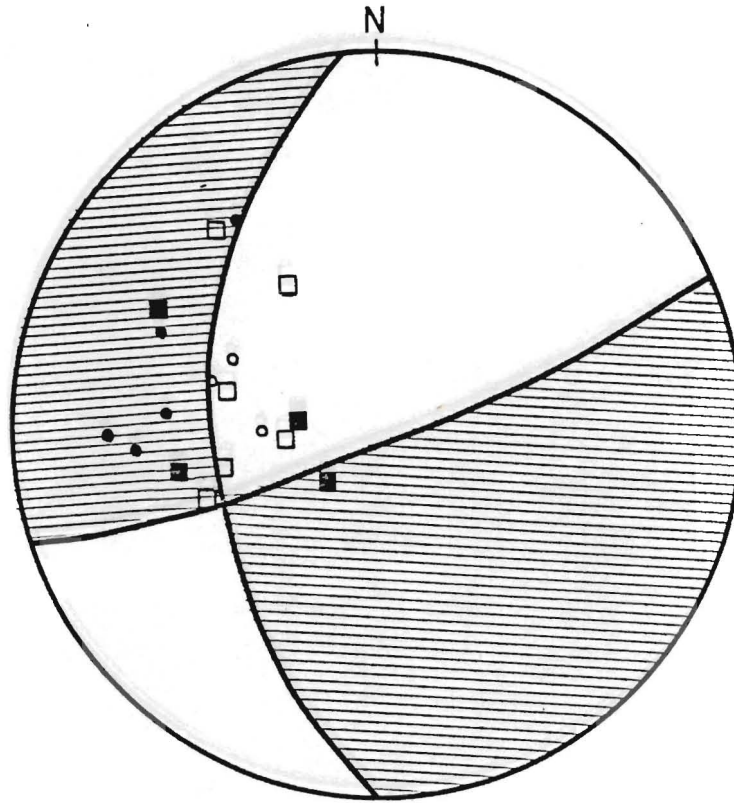
FIGURE 4.7

# POISSON'S RATIO I<sup>ST</sup>. MOTION

DAY TIME (hr. min.)

260 15 00 •

260 07 57 ■



DAY TIME (hr. min.)

254 16 03 •

260 15 16 ■

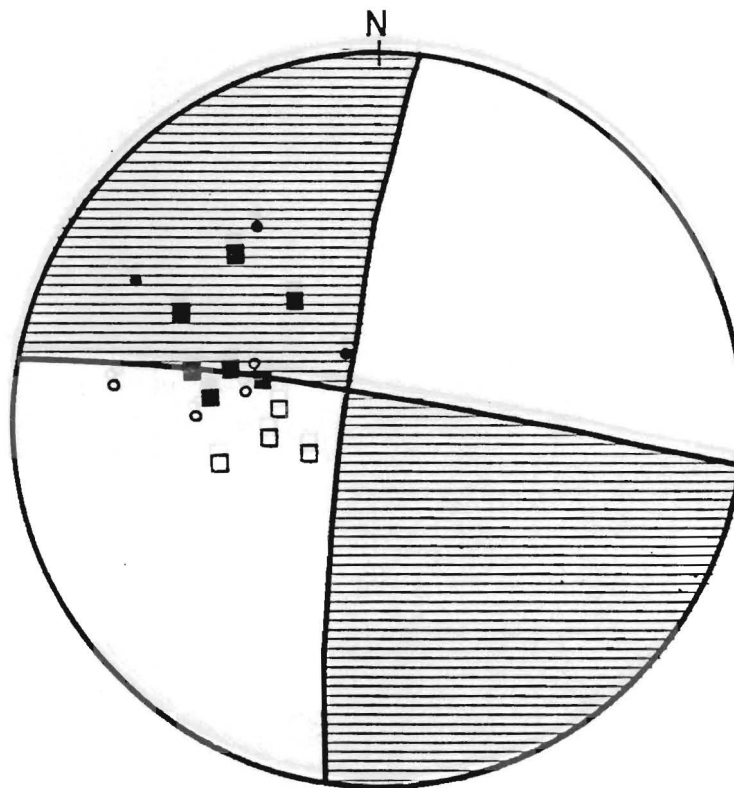


FIGURE 4.8

# FIRST MOTION MAP

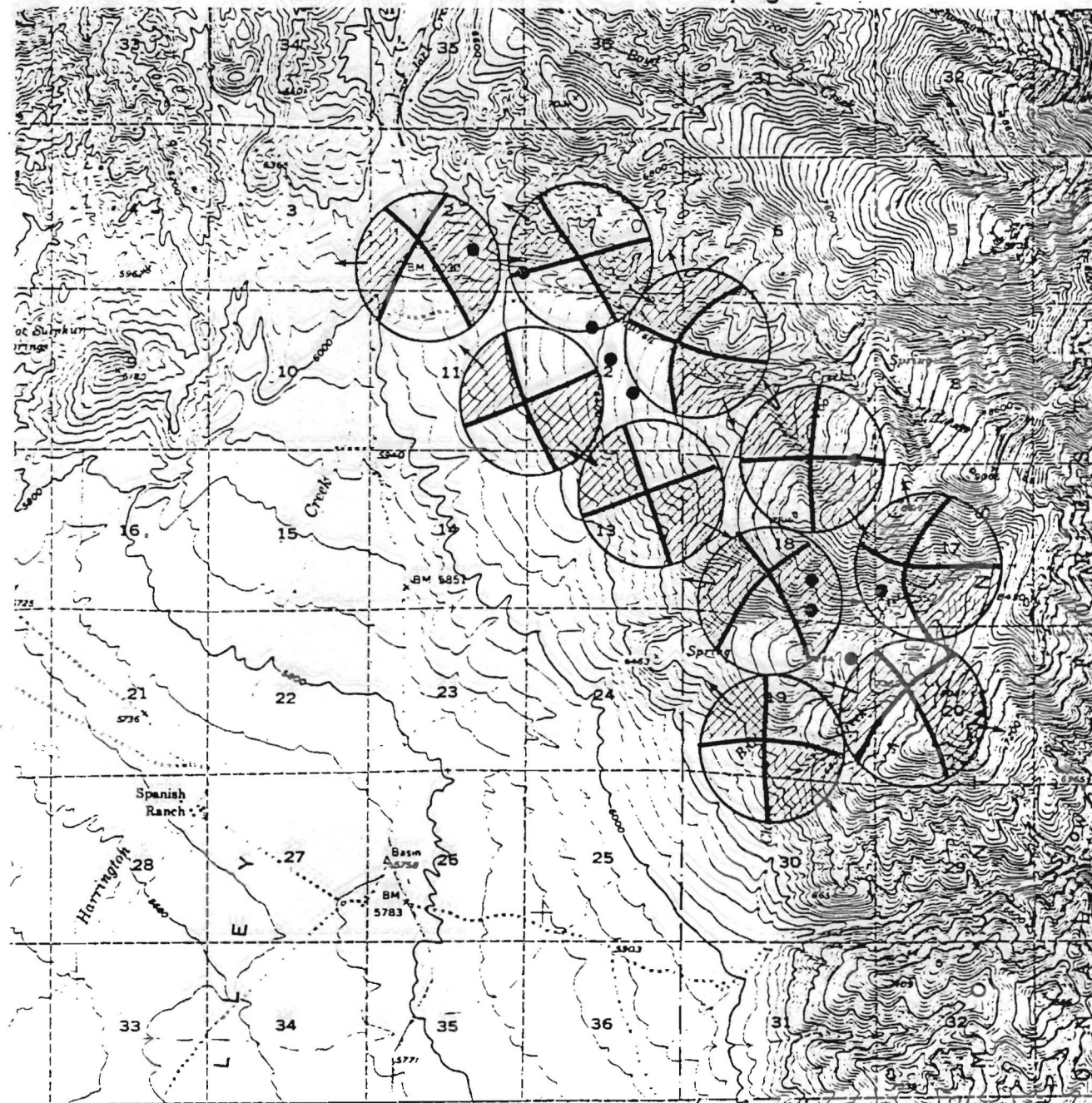


FIGURE 4.9

# WADATI DIAGRAM

DRAWN BY TVW DRAWING NO. AXI1111 CHECKED BY \_\_\_\_\_ DATE 12-01-78

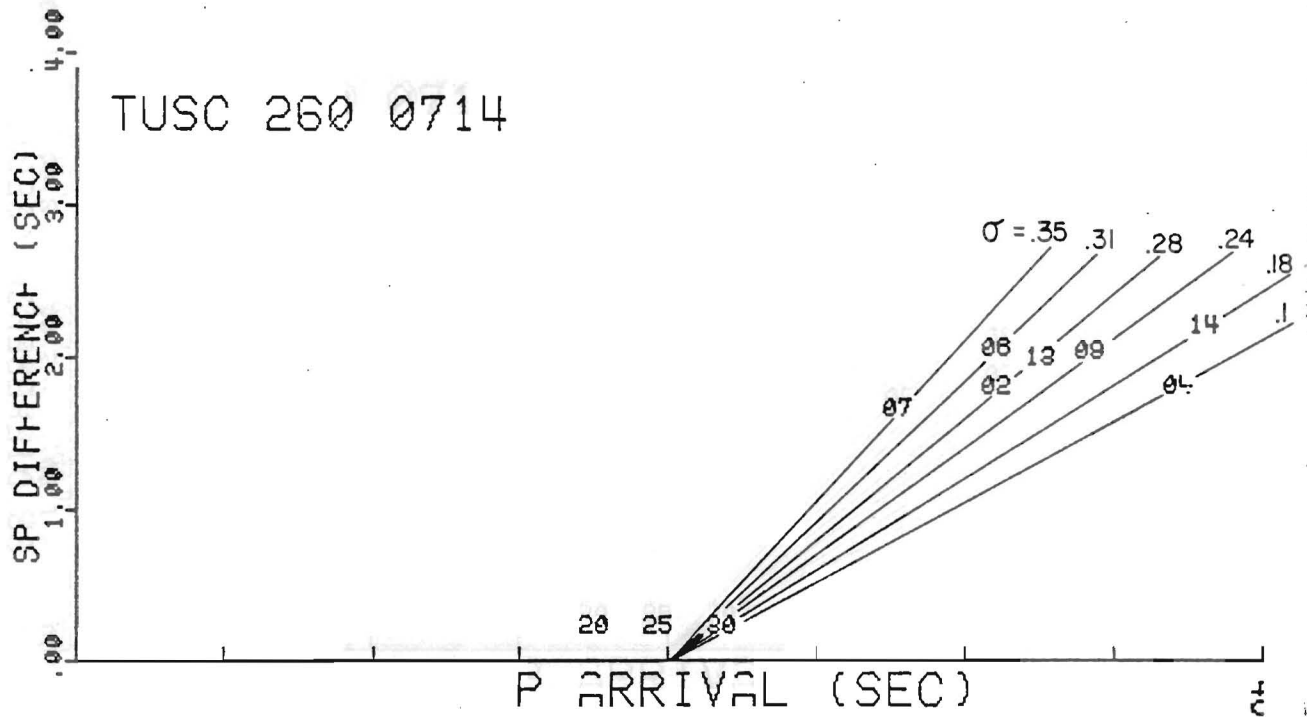



FIGURE 4.10



velocity ratio acquired for each event is correct only along the raypath between the specific event and a particular station. The purpose of the composite is to give average values for the ratio under each station.


Another way of displaying the data is to convert the velocity ratio to Poisson's Ratio. The equivalent Poisson's Ratio for different slopes is also shown in Figures 4.7 & 4.8.

Once the Poisson's Ratio is determined for a specific raypath joining a station to an event location, the projection of the raypath on the surface is plotted on a map. The Poisson's Ratio maps are shown in Plates 4.4 and 4.5. Most of the area is near a normal Poisson's Ratio:  $0.25 \pm 0.05$ .

#### 4.3.0 Interpretation

The area highlighted by this 11 day survey is the northeastern basin boundary fault and the Jack Creek Fault area.

The microearthquake activity in this area indicates almost vertical faulting with a slight dip to the south-southwest. Although the first-motion studies are not well controlled, a west-northwest fault trend should have a strong right-lateral strike-slip component. Most of the activity appears to occur at the intersection of the Jack Creek with the basin. The strain release is highly dominated by the magnitude 2.44 earthquake which occurred at the northeast corner of the basin.



The Poisson's Ratio is primarily controlled by the very high  $\sigma$  basin sediments which appear to be quite deep, in contrast to the very low  $\sigma$  hard rock mountain range. However, again the highest Poisson's Ratio is found at the north-northeasterly corner of the basin.

## MICROEARTHQUAKE BIBLIOGRAPHY

- Hill, D.P., and L.C. Pakiser (1966), Custral structure between the Nevada Test Site and Boise, Idaho, from seismic-refraction measurements: in Earth Beneath the Continents, J.S. Steinhart, T.J. Smith, Editors, Geophys. Monogr. 10, Am. Geophys. Union, Washington, D.C., pp. 391-419.



### 5.0.0 P-WAVE DELAY

The P-wave delay technique can be used to delineate areas within a prospect where anomalously high velocity or low velocity material exists. A change in velocity can also result from a change in the structure. A deep section of sediments relative to near surface basement would result in a relative delay in the transmission of a teleseism. This resultant delay would not be a product of a change in velocity.

The P-wave delay technique can be used to delineate the geologic structure and therefore aid in the characterization of the geothermal potential of a prospect.

#### 5.1.0 Procedure

Seven distant seismic events were recorded and used to generate residual travel times. Residual travel times are defined as the difference of the assumed model, which in this case is a plane wave transmission, and the observed wave front. The residuals are corrected for station elevation differences. The corrections in milliseconds are generated to datum by assuming a velocity and calculating, from the distance, the time correction. Since the origin time for the distance events is normally not well controlled, a relative travel time is used to generate the residuals. Relative residuals are then used to generate a distance for a given velocity model. These distances from each station to the velocity interface surface is drawn. The interface surface highlights areas where either the velocity or structure is anomalous.

### 5.2.0 Observations

Seven distant seismic events were recorded and used to construct the data base for the P-wave delay study. Table 5.1 lists these events. Each event is plotted as a pseudo refraction. The azimuth of the plane wave arrival, the phase velocity and the emergence angle if calculated from a data base provided by the NEIS (National Earthquake Information Service). The NEIS data base include the seismic event location, magnitude and origin time. All the pseudo refractions are shown in Figure 5.1 through 5.7.

TABLE 5.1  
TELESEISM DATA

EVENT NUMBER	TIME		DISTANCE	LOCATION	
	DAY	HR:MIN		LATITUDE	LONGITUDE
1	258	11:39	60.0°	48.31°N	154.24°E
2	256	15:15	7.9°	37.21°N	116.21°W
3	257	02:36	89.0°	49.85°N	78.69°E
4	257	11:00	2.2°	42°53'54.1"N	113°48'34.2"W
5	259	15:35	107.0°	33.21°N	57.35°E
6	264	14:59	72.0°	66.43°N	85.84°E
7	259	23:38	89.0°	25.63°S	178.14°W

The P-wave attenuation studies included data from 5 events. These events are listed on Plate 5.4. This plate shown attenuation in terms of relative signal strength for each of the 5 event arrival azimuths. The relative signal strengths in db were calculated by comparing ground motion at each station at one frequency to the average signal amplitude. The signal frequency for the 5 teleseisms was near 2 Hz. Therefore a spectrum comparison was not possible. The results of the attenuation studies are not at this time comparable to the P-wave delay results.

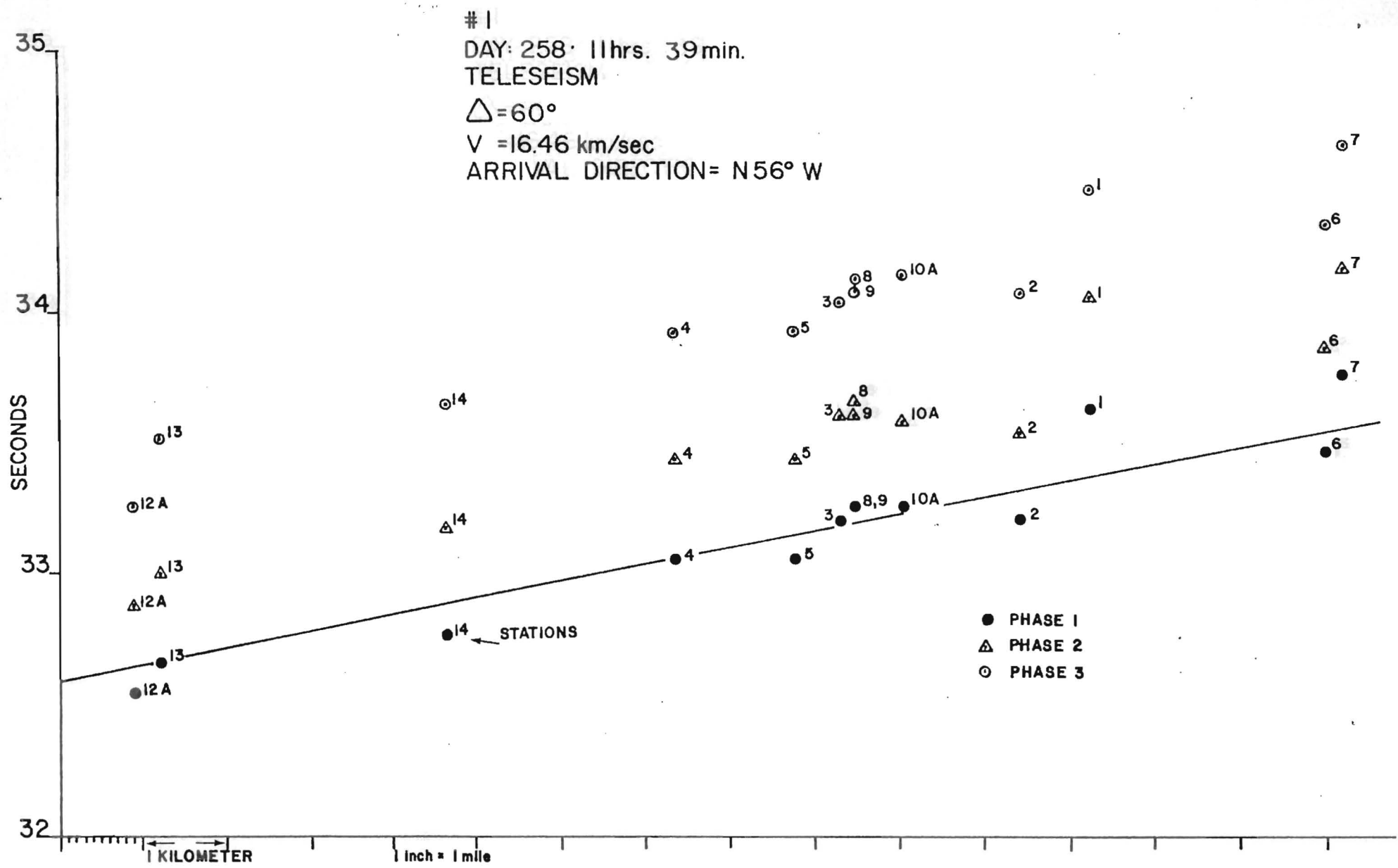


FIGURE 5.1

#2  
DAY: 256 15hrs. 15min.  
SOUTHERN NEVADA (surface shot)  
 $\Delta = 7.9^\circ$   
 $V = 7.96 \text{ km/sec}$   
ARRIVAL DIRECTION = SOUTH

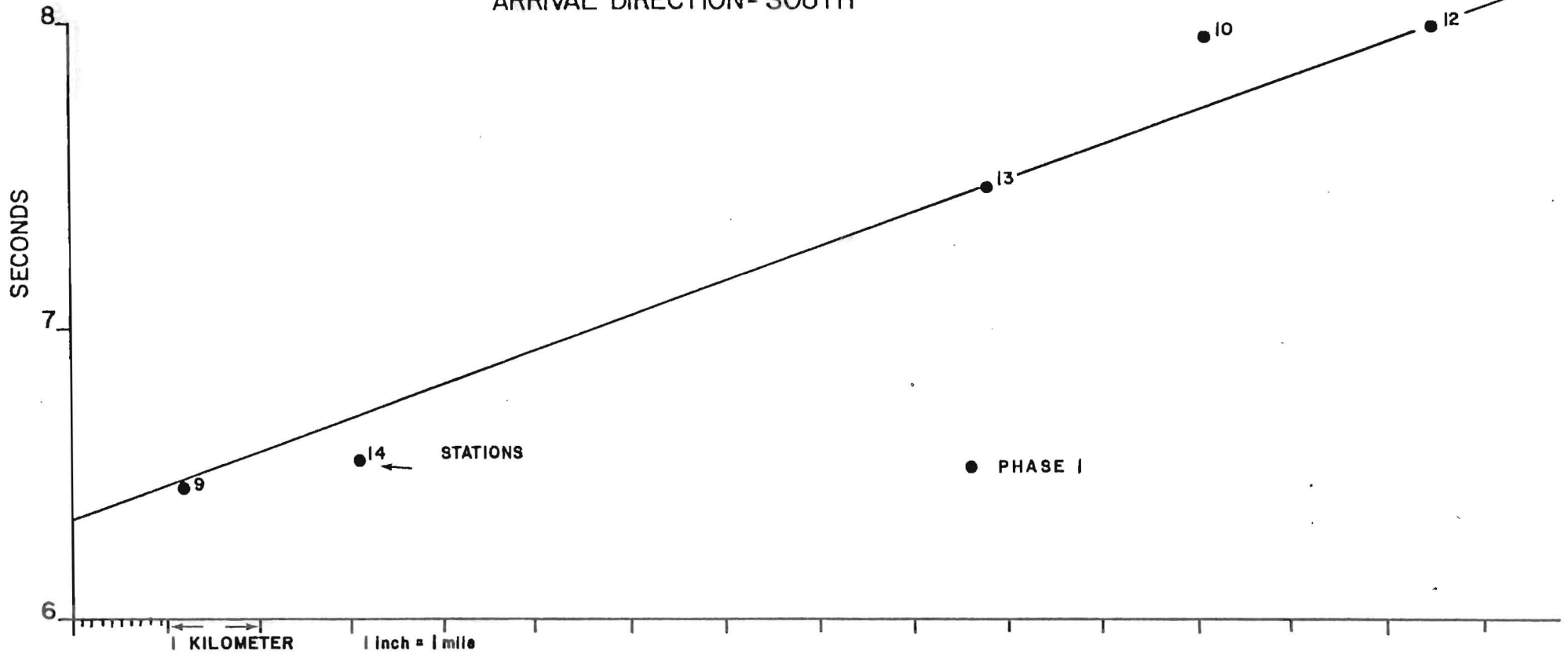


FIGURE 5.2

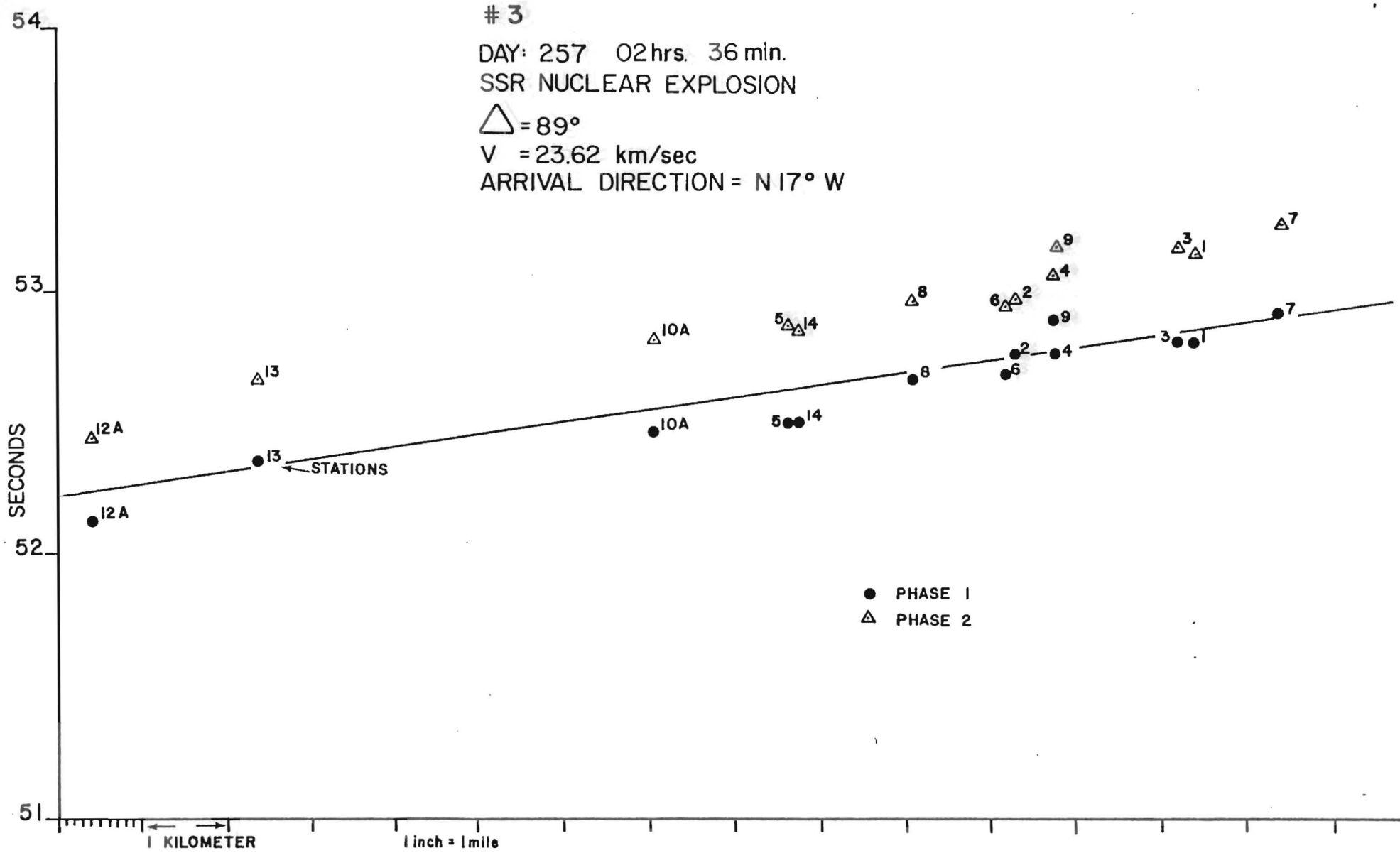


FIGURE 5.3

#4

DAY: 257 11hrs 00min.

SHOT SNRP

$\triangle = 2.2^\circ$

V = 8.0 km/sec

ARRIVAL DIRECTION = N 50° E

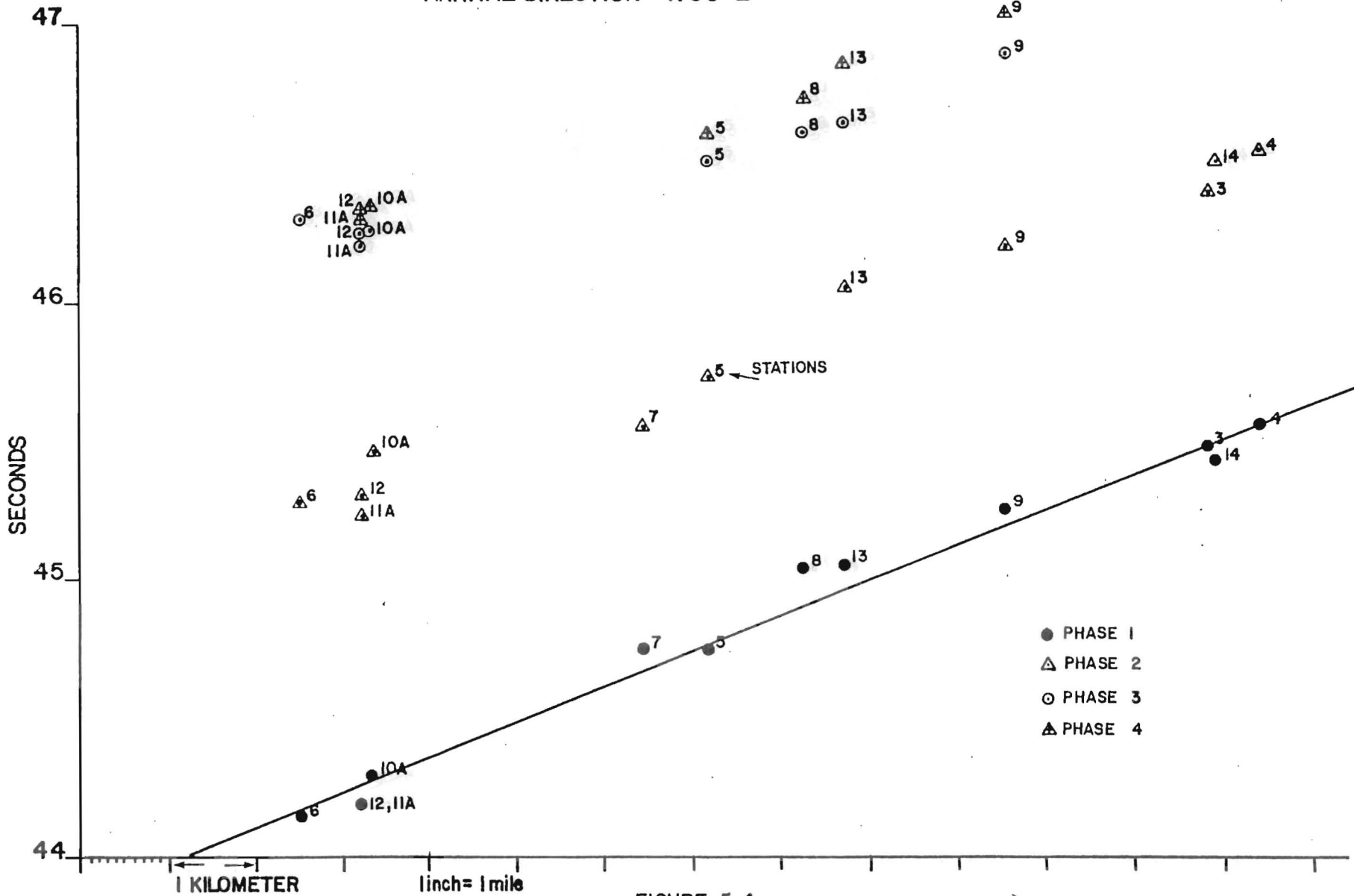


FIGURE 5.4

# 5  
DAY: 259 15hrs. 35 min.  
IRAN  
 $\Delta = 107^\circ$   
 $V = 25.3 \text{ km/sec}$   
ARRIVAL DIRECTION = N  $15^\circ$  E

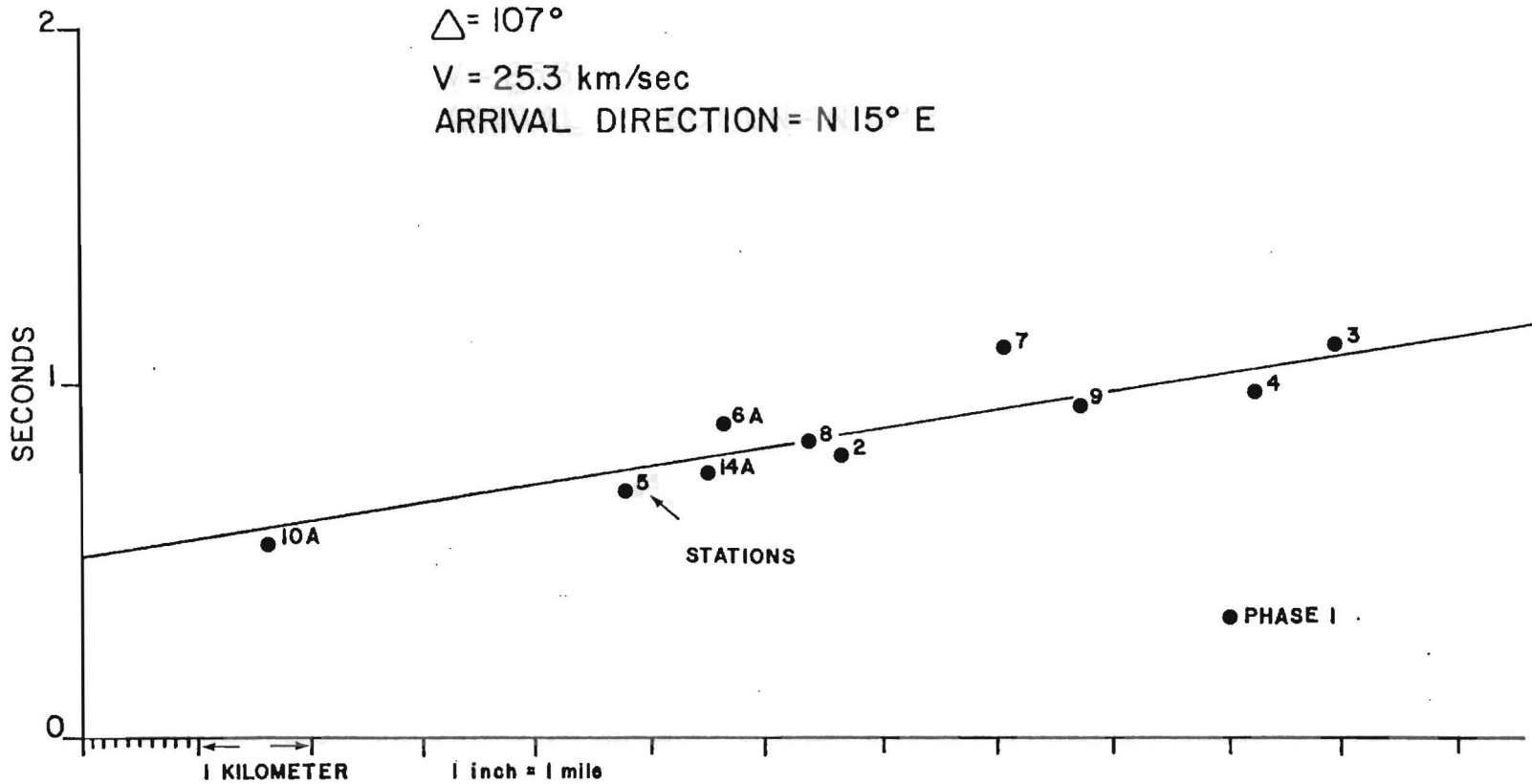


FIGURE 5.5

#6

DAY: 264 14hrs. 59min.

RUSSIA, SIBERIA

$\Delta = 72^\circ$

$V = 18.89 \text{ km/sec}$

ARRIVAL DIRECTION = N  $10^\circ$  W

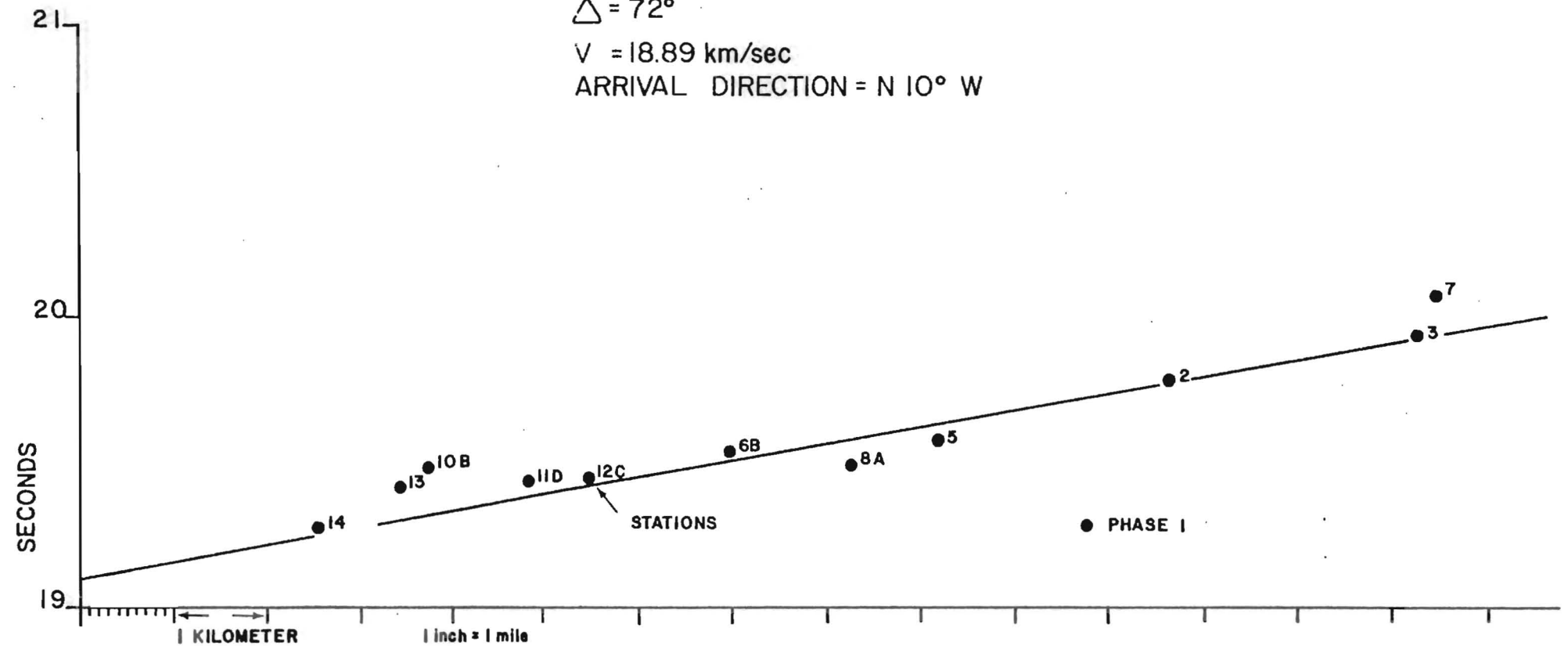


FIGURE 5.6



#7  
DAY: 259 23hrs. 38sec.  
 $\Delta = 89^\circ$   
 $V = 23.22 \text{ km/sec}$   
ARRIVAL DIRECTION = S  $45^\circ$  W

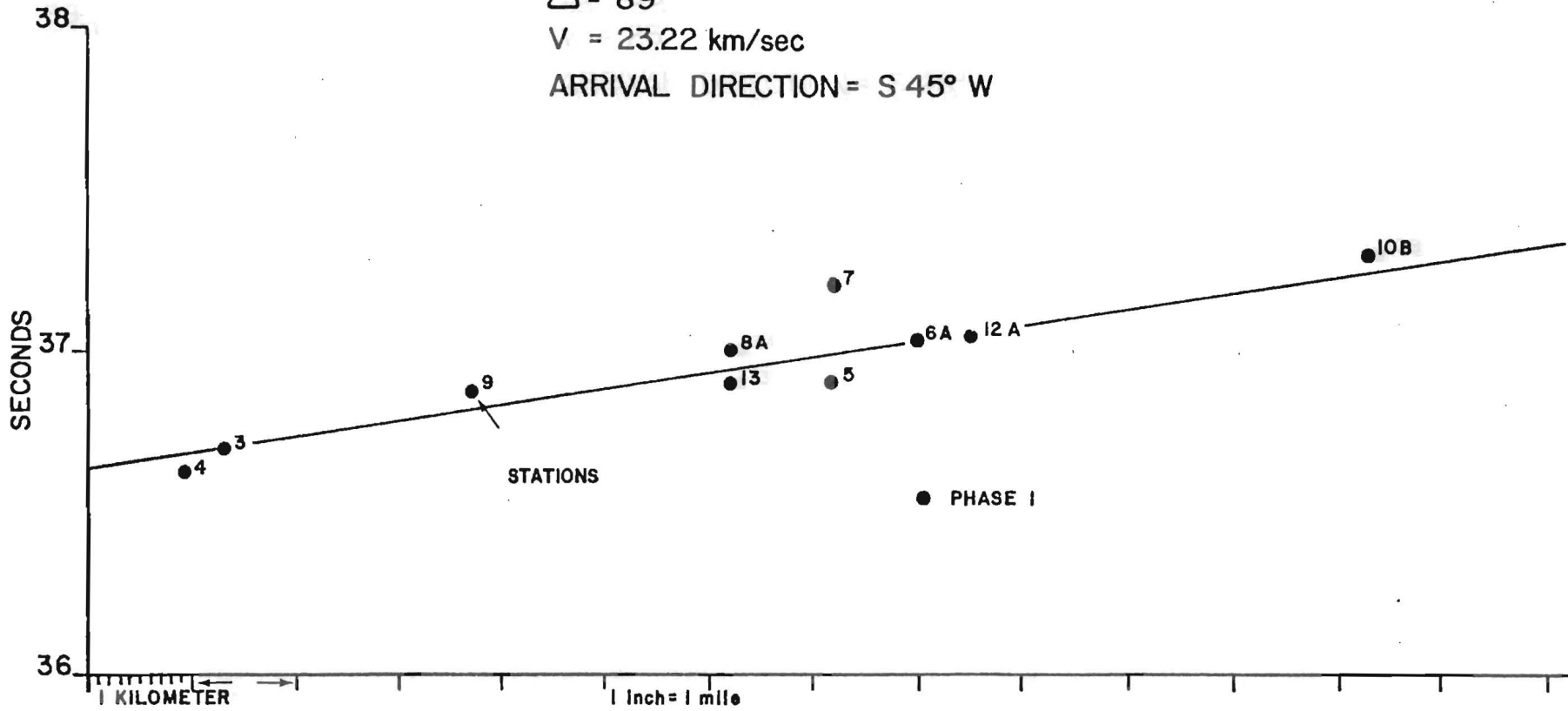



FIGURE 5.7



5.2.1 Event 1 is shown in Figure 5.1. This teleseism was recorded on 13 stations. The three phases shown represent sequential peaks and troughs in the wave form. These are picked to insure accuracy of the delay values. The largest delays are shown for stations 7 and 1 with advances at stations 14, 5, and 2. The position of the phase velocity line, however, is arbitrary and was assigned to stations 13, 4, 3, 8, and 10A. These stations were interpreted to represent consistent geologic conditions.

5.2.2 Event 2 is shown in Figure 5.2. This medium distant event is a test shot from the Nevada test site. There were 6 arrivals of good quality recorded. The largest delays are shown for stations 10 and 11. An advance is shown for station 14.

5.2.3 Event 3 is shown in Figure 5.3. This teleseism was recorded on 13 stations. This event is a test shot from Russia.

5.2.4 Event 4 is shown in Figure 5.4. This event is the Snake River shot. The origin time was 11:00:05.495. The location was  $42^{\circ}53'54.1''$ N latitude and  $113^{\circ}48'34.2''$ W longitude at an altitude of 4,218 feet. The total poundage was 8,000 pounds. Three phases were picked and represent a first arrival and two reflections.

5.2.5 Event 5 is shown in Figure 5.5. This event was recorded on 10 stations.

5.2.6 Event 6 is shown in Figure 5.6. This event is an arrival from Russia and was recorded on 11 stations. Stations 7, 13, and 10B show the largest delays.

5.2.7 Event 7 is shown on Figure 5.7. This teleseism arrived in the Figi Islands and was recorded on 10 stations. Station 7 shows the largest delays.

### 5.2.8 Residuals

Residuals are calculated from the psuedo refraction. The residuals are defined as the difference between an assumed plane wave and the recorded data. Plate 5.1 shows the data plotted. The station is shown as a lower hemisphere projection of the arriving ray. The values of delay or advance in milliseconds is shown adjacent to the array and example is illustrated in Figure 5.8.

### 5.2.9 Elevation Corrections

A surface velocity of 3.5 km/sec was assumed and a datum correction to sea level was calculated. The corrections ranged from 500 ms to 650 ms. Since the absolute level of the correction is arbitrary, then any convenient level can be used. A level to produce all delays. The resultant data map, with the elevation correction made, is shown in Plate 5.2.

### 5.3.0 Results

The corrected residuals are used to generate distance residuals with an assumed velocity of 3.5 km/sec. A 200 ms delay would produce "extra section" of +0.7 km along the ray path direction. The vertical section change for an emergence angle of  $25^\circ$  would be +0.63 km. An arbitrary depth to the velocity interface was chosen to be 2 km below sea level. This ray length then is also applied along the ray paths. Therefore, given a  $25^\circ$  emergence angle and a velocity delay of 200 ms, the calculated depth to the interface would be  $(1.81 \text{ km} + 0.63 \text{ km})$  2.44 km. Using this model, a reduction of the interface depth would occur for any delays less than 90 ms. Plate 5.3 is a contour map of calculated depth to the 2 km interface. This interface is approximately 3.5 km below the surface. This surface was drawn to represent the shape of the velocity structure at depth.

# P WAVE DELAY EXAMPLE

+247 (DELAY IN MILLISECONDS)

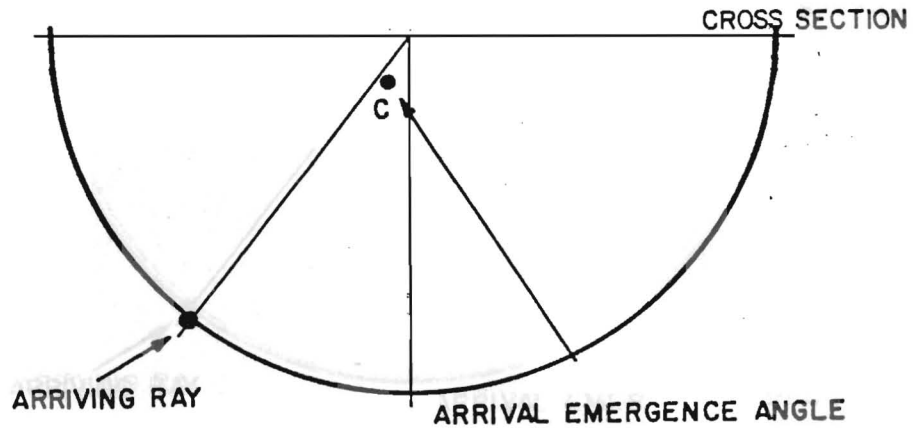
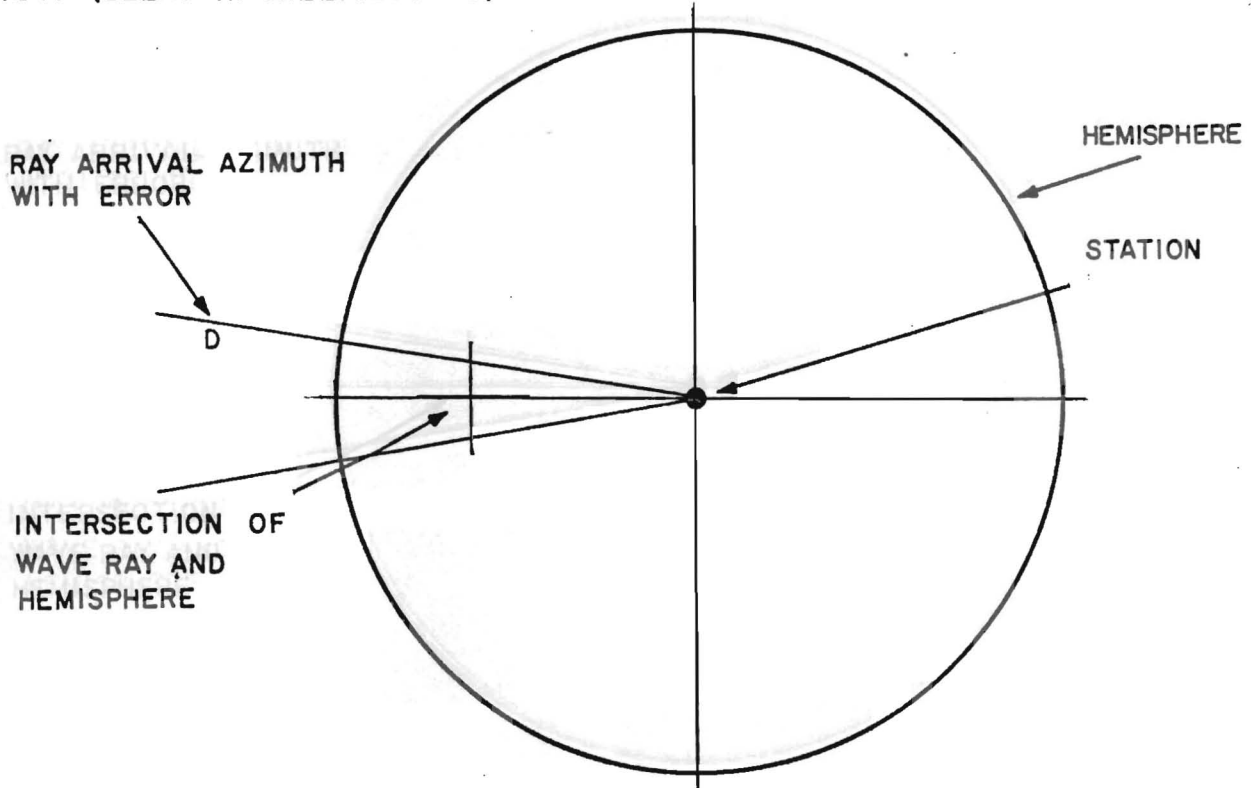


FIGURE 5.8

DATE 19  
CKE  
NO  
BY  
RAI

#### 5.4.0 Previous Work

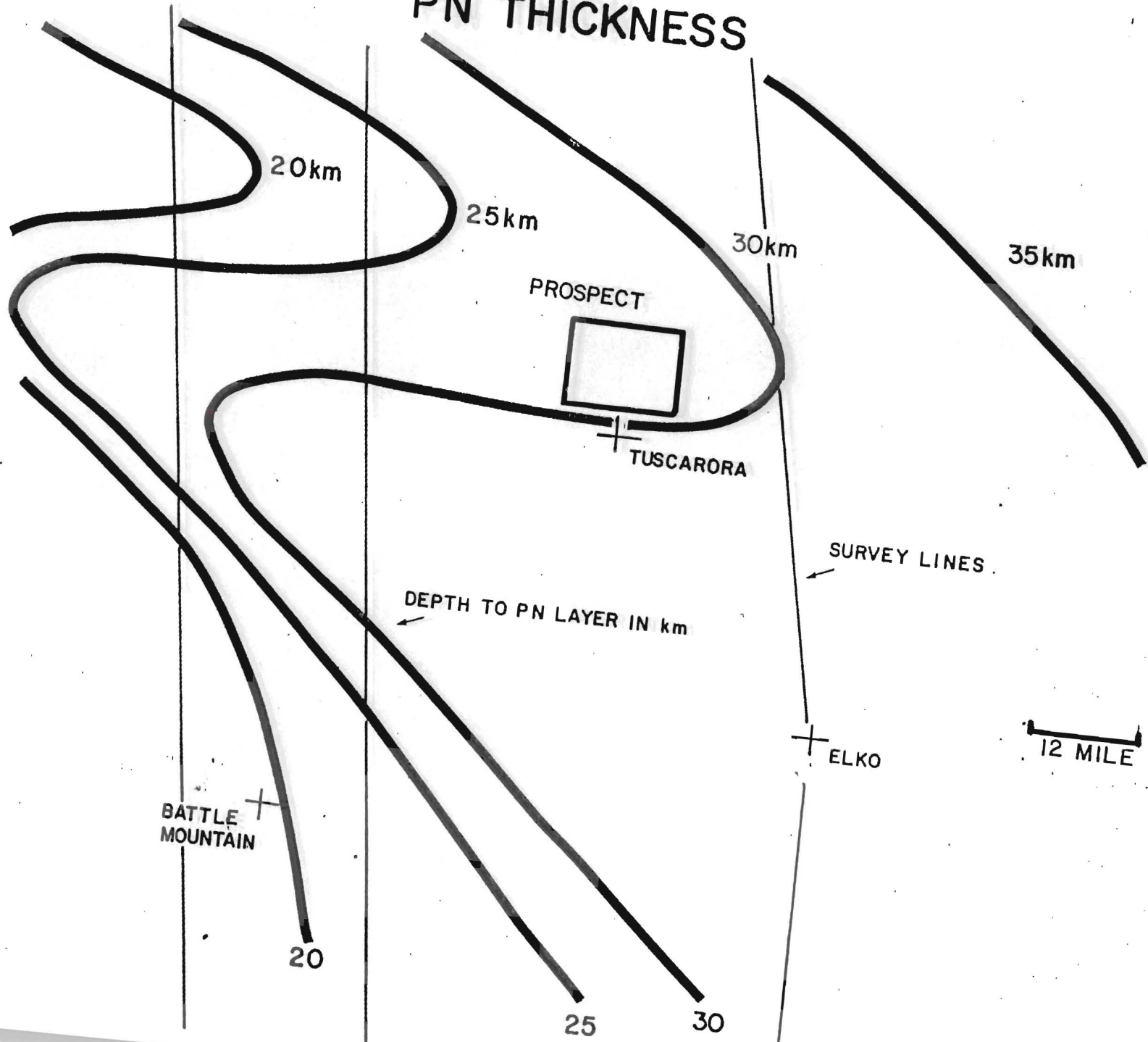
Figure 5.9 illustrates the results from "crustal thickness in northern Nevada from seismic refraction profiles" plotted are the depth to the  $P_n$  interface at nearly 30 km depth. The  $P_n$  interface has a 7.6 km/sec velocity.


#### 5.5.0 Interpretation

The P-wave delay data show a number of results. First, the Independence Valley Basin is reflected in the large depths to the velocity interface (see Plate 5.3). Large depths to the north-west of the basin suggest that a thick section of sediments or an extension of the basin exists to the north-west of the valley to the south-west of the springs. Lastly, a high structural ridge or high velocity structure exists from the springs to the north-east. A second ridge also extends south from the springs. The P-wave data suggest that the spring area is a focus for complex velocity structure. These complexities may either be a result of complex faulting or alteration. Both model alternatives are favorable to the occurrence of geothermal energy.

The P-wave delay data is also consistent with the results of the previous refraction shots in the area. The Tuscarora prospect lies at a transitional point in the depth to the Maho. This major transition suggests major crustal structure trending nearly east-west through the Tuscarora property. This structure no doubt has an influence on the occurrence of geothermal energy in the northern Nevada area.

# PN THICKNESS





APPENDIX  
PASSIVE SEISMIC METHOD

TABLE OF CONTENTS

Introduction

Microearthquakes

Microearthquakes Bibliography

Wave Delay and Attenuation

Wave Delay and Attenuation Bibliography




## PASSIVE SEISMIC METHODS

### Introduction

Conventional refraction and reflection seismic methods have been applied in some instances to the discovery of earth heat. However, the more widely used seismic methods are derived from classical seismology. This appendix will outline the use of the Passive Seismic Methods. The methods to be considered are the detection, location, and interpretation of the discrete seismic events called "microearthquakes", and the measurement of the velocity distribution or structural properties called "wave delay and attenuation".





## Microearthquakes


The correlation of microearthquakes and commercial geothermal reservoirs is empirical. However, a high rate of seismicity is a sufficient ingredient in several geothermal system models. One such model is based on the probable chemistry within a convecting system. As hot water or steam rises closer to the surface, it cools slightly and precipitates considerable material. Without the production of fresh conduits, the system will be plugged and the efficient convection mechanism will be terminated. Another model simply requires a fractured medium for deep convective circulation of meteoric waters to depths at which the normal gradient will produce commercially useful temperatures. In the second model, contemporary fracturing is not necessary. However, the best evidence for the existence of fractures may be present seismic activity.

Almost all sets of earthquakes for which magnitudes have been measured, follow an inverse straight-line relationship between the log of the number of earthquakes and magnitude. In general, a decrease in magnitude by 1.0 is accompanied by an increase in a factor of 10 or more in the number of events occurring. Thus, if the detection capability can be increased by one magnitude, 10 or more events will be recorded for every one previously recorded. To do this, a prospect area is blanketed with seismic stations at a nominal station spacing of 4-6 km. These stations, recording the ground motion at displacement gains of  $1-3 \times 10^6$  at 20 Hz, will record seismic arrivals of earthquakes down to Richter magnitude zero or below. Timing resolutions between stations is held to less than a few milliseconds and time differences of the arrivals for any pair of stations is determined.

In order to locate an event in space, a velocity distribution must either be assumed or determined. Most velocity models are one dimensional with the velocity varying between constant velocity layers. Other models allow the velocity to increase linearly with depth or with vertical travel time. Ignorance of the exact velocity model causes an accuracy problem in the computed locations. However, precision is affected little by the velocity model.

Microearthquake signals are dominated by frequencies between 5 to 25 Hz, making the picking of the onset somewhat subjective at the  $\pm 5$  ms level independent of the playback speed. This type of error causes the location to lose precision. This error can be controlled by a trained seismologist whose picks will be consistent.

The size of the expected location error is not easily addressed. The problem is complicated by geometry, velocity models, and geology. However, for an event recorded on eight or more stations with a nominal station spacing 5 km and minimum timing and velocity errors, the location should be precise to within  $\pm \frac{1}{2}$  km in plan and  $\pm 1$  in depth. Errors in the computed location will increase outside the network of stations.



Once the event locations are finalized, their relationships with possible geology or active faulting can be made. The statistics of occurrence can also be used to characterize an area. A list of products from a microearthquake survey follows:


- Hypocenter Map
- Fault Plane Solutions
- Occurrence Statistics
  - Event list
  - Recurrence curve
  - Clustering statistics (swarming)
- Rock Properties Distribution
  - Velocity distribution
  - Poisson's Ratio distribution


An interpretation of the above results in terms of active fault identification and modes of deformation, identification of volumes of rock with anomalous properties, seismic safety, and recommendations.



## MICROEARTHQUAKES BIBLIOGRAPHY

- Ak, Keiiti, A note on the use of microseisms in determining the shallow structures of the earth's crust (Random waves correlation earth): *Geophysics*, v. 30, no. 4, p. 665.
- Brune, J.N., and Allen, C.R., 1976, A microearthquake survey of the San Andreas fault system in Southern California: *Bull. Seismol. Soc. Am.*, v. 57, no. 2, p. 277-296.
- Caton, P.W., 1976, Plane wave apparent velocity vector techniques for evaluating and improving location accuracies with data obtained from small arrays (7 to 10 km in diameter): Unpublished paper, 71 p.
- Cheatum, C., and Combs, J., 1973, Microearthquake study of the San Jacinto Valley, Riverside County California: from the Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, p. 1-10.
- Combs, J., and Hadley, D., 1977, Microearthquake investigation of the Mesa geothermal anomaly, Imperial Valley, California: *Geophysics*, v. 42, p. 17-33.
- \_\_\_\_\_, and Robstein, Y., 1976, Microearthquake studies in the Coso geothermal area, China Lake, California: *Proc., 2nd U.N. Sympos. Develop. and Use of Geothermal Resources*, v. 2, p. 909-916.
- Crosson, R.S., 1972, Small earthquakes, structure and tectonics of the Puget Sound region: *Bull. Seismol. Soc. Am.*, v. 62, p. 1133-1171.
- Dahl, A.H., and Johnson, B.D., 1974, Preliminary results of a microseism study for the region around the Snake River Plain (1973-March 1974): Preprint presented at the Idaho Academy of Sciences, Ricks College, Rexburg, Idaho, April 19-20, 1974.
- Douglas, B.M., and Ryall, A., 1972, Spectral characteristics and stress drop for microearthquakes near Fairview Peak, Nevada: *Jour., Geophys. Res.*, v. 77, p. 351-359 .
- Fitch, T., 1969, Microearthquake activity following the Parkfield, California earthquake of June 1966: *Bull. Seismol. Soc. Am.*, v. 59, no. 2, p. 603.
- Hadley, D., and Combs, J., 1974, Microearthquake distribution and mechanisms of faulting in the Fontana San Bernadino area of Southern California: *Bull. Seismol. Soc. Am.*, v. 64, p. 1477-1499.

- 
- Hamilton, R.M., and Muffler, L.J.P., 1972, Microearthquakes at the Geysers geothermal area, California: Jour. Geophys. Research, v. 77, no. 11, p. 2081-2086.
- Johnson, L.A. and Butler, D., 1975, Prediction analysis applied to microearthquake hypocenter location: abstract in Abstract and Biographies of the 45th Annual International Meeting of the Society of Exploration Geophysicists, Tulsa, Oklahoma, paper GT-15.
- Kisslinger, C., and Engdahl, E.R., 1974, Semyenov Prediction, Test of the Semyenov Prediction Technique in the Central Aleutian Islands: Tectonophysics, v. 23, p. 237-246.
- Knapp, R.B., and Knight, J.E., 1977, Differential thermal expansion of pore fluids: Fracture propagation and microearthquake production in hot pluton environments: Jour. Geophys. Research, v. 82, p. 2515-2522.
- Lange, A.L., and Westphal, W.H., 1969, Microearthquakes near the Geysers, Sonoma County, California: Jour. Geophys. Research, v. 74, p. 4377-4378.
- Langenkamp, D., and Combs, J., 1974, Microearthquake study of the Elsinore Fault Zone, Southern California: Bull. Seismol. Soc. Am., v. 64, p. 187-203.
- Leslie, H.D., et al, 1976, Microearthquake location using a maximum likelihood processor: Geophysics, v. 41, no. 5, p. 960-969.
- Liaw, A.L., 1977, Microseisms in geothermal exploration; studies in Grass Valley, Nevada: PhD Thesis, University of California, Berkeley, California.
- Michaels, P.J., 1973, An application of the generalized linear inverse method in the location of microearthquakes and simultaneous velocity model determinations: MS Thesis, University of Utah, Salt Lake City, Utah.
- Oliver, J.E., 1966, Microearthquakes: ESSA Sympos. on earthquake prediction, Rockville, Maryland, Feb. 7-9, 1966, U.S. Dept. of Commerce, Environmental Sciences Services Admin.
- Pennington, W.D., Smith, R.B., and Trimble, A.B., 1974, A micro-earthquake survey of parts of the Snake River Plain and Central Idaho: Bull. Seismol. Soc. Am., v. 64, no. 2, p. 307-312.
- Peters, D.C., and Crosson, R.S., 1973, Application of prediction analysis to hypocenter determination using a local array: Bull. Seismol. Soc. Am., v. 62, no. 3, p. 775-788.



Sanford, A.R., et al, 1976, Microearthquake investigations of magma bodies in the vicinity of Socorro, New Mexico: Geological Society of America, 1976 Annual Meeting, Denver. Abstracts: p. 1085-1086.

\_\_\_\_\_, Alptekin, O., and Topozada, T.R., 1973, Use of reflection phases on microearthquake seismograms to map an unusual discontinuity beneath the Rio Grande Rift: Bull. Seismol. Soc. Am., v. 63, p. 2021-2034.

\_\_\_\_\_, Carapetian, A.G., and Long, L.T., 1968, High frequency microseisms from a known source: Bull. Seismol. Soc. Am., v. 58, no. 2, p. 639-644.

\_\_\_\_\_, and Singh, S., 1968, Microearthquake activity, minimum recording time for determining short-term seismicity forms: Bull. Seismol. Soc. Am., v. 58, no. 2, p. 639-944.

Spinel, R.C., et al, 1974, Microearthquake survey of median valley of the Mid-Atlantic Ridge at 360°30"N: Nature, v. 248, p. 577-579.

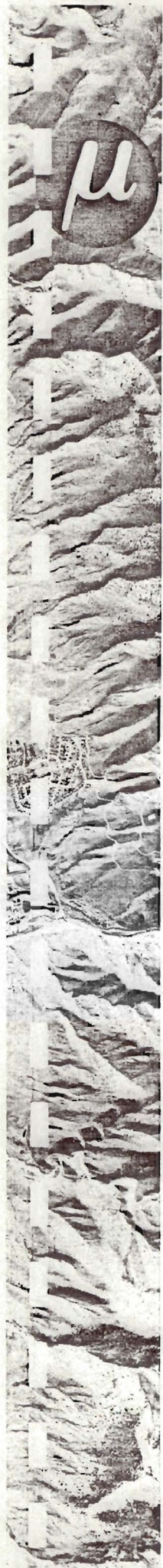
Steeple, D.W., and Pitt, A.M., 1976, Microearthquakes in and near Long Valley, California: Jour. Geophys. Research, v. 81, no. 5.

Ward, P.L., 1972, Microearthquakes: prospecting tool and possible hazard in the development of geothermal resources: Geothermics, v. 1, no. 1, p. 3-12.

\_\_\_\_\_, and Bjornsson, S., 1971, Microearthquakes, swarms, and the geothermal areas of Iceland: Jour. Geophys. Research, v. 76, no. 17, p. 3953-3982.

\_\_\_\_\_, and Jacob, R.H., 1971, Microearthquakes: In the Ahuachapan geothermal field, El Salvador, Central America: Science, v. 173, p. 328.

\_\_\_\_\_, Palmason, G., and Drake, C., 1969, A microearthquake survey and the Mid-Atlantic Ridge in Iceland: Jour. Geophys. Research, v. 74, p. 665-684.



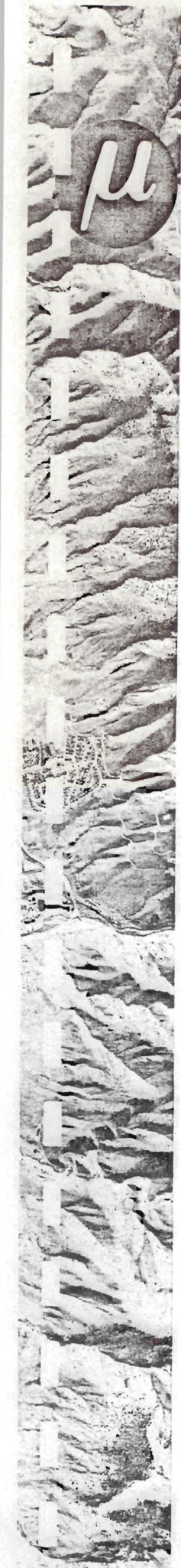
## Wave Delay and Attenuation

Changes in temperature affect the velocity of rock only slightly; however, the attenuation as it passes through the rock is very dependent on temperature. Fractures change the velocity to some degree, but strongly affect the ratio of P-wave and S-wave velocities. Thus, if these factors can be measured with some degree of confidence, it may be possible to isolate at least two of the requirements for a commercial reservoir, high porosity and rock at elevated temperatures.

Such experiments are best performed if an external source of seismic energy is available--either teleseismic or industrial blasting events at distances such that the received energy is approximately homogeneous. A frequency dependent transfer function between each station and master station can be calculated. The amplitude spectrum of this function will indicate the amount of attenuation taking place and the phase spectrum will indicate the time shift of the data. These values can be compared to a homogeneous model and anomalous area isolated.

The interpretation models available for P-wave and S-wave delay and attenuation studies involve either a rock property change or structural change. The attenuative models are ambiguous and no choice can be made without independent data. A list of products from a P-wave delay study follows:

- P-wave Delay Map
- S-wave Delay Map
- P-wave Attenuation Map
- S-wave Attenuation Map
- Event List
- Occurrence Statistics
- Interpretation of any anomalous velocity, structural, or attenuates with respect to potential geothermal occurrences.



WAVE DELAY AND ATTENUATION BIBLIOGRAPHY

- Eaton, G.P., Christiansen, Robert L., Iyer, H.M., Pitt, Andrew, Mabey, Don R., Blank, H. Richard, Jr., Zeitz, Isidore, and Gettings, Mark E., 1975, Magma beneath Yellowstone National Park: *Science (AAAS)*, v. 188, no. 4190, p.787-796.
- Iyer, H.M., 1975, Anomalous delays of teleseismic P-waves in Yellowstone National Park: *Nature*, v. 253, no. 5491, p.425-427.
- \_\_\_\_\_, 1974, Teleseismic studies indicate existence of deep magma chambers below Yellowstone National Park: *Earthquake Inf. Bull.*, v. 6, no. 2, p. 3-7.
- \_\_\_\_\_, Evans, John R., and Coakley, John, 1974, Teleseismic evidence for the existence of low-velocity material deep into the upper mantle under Yellowstone Caldera: *EOS (Am. Geophys. Union Trans.)*, v. 56, no. 12, p. 1190.
- Pitt, A.M., 1974, Evidence from local earthquakes for the existence of a region of seismic body wave attenuation in the upper crust under the Yellowstone Caldera: *EOS (Am. Geophys. Union Trans.)*, v. 56, no. 12, p. 1190.
- Steeple, Don W., and Iyer, H.M., 1975, Location and estimation of volumes of anomalously hot material beneath some geothermal areas from teleseismic P-delays: *U.N. Sympos. Develop. and Use of Geoth. Res. Abst.*, no. 2.



## INSTRUMENTATION

### Introduction

The passive seismic system used for geothermal exploration and deployed by MicroGeophysics Corporation (MGC) is a hybrid system. The system consists of both independent seismographs and RF telemetered stations. The network station capability is from six to ten stations. A schematic of the system is shown in Figure 1. The independent stations are basically MEQ-800 visual drum recorders, with an integral timing system synchronized to universal coordinated time. As an option, the seismic signal can also be recorded by a continuous magnetic tape recorder. This independent station schematic is shown in Figure 1. The RF-telemetry system consists of from two to eight satellite stations with a central recording system. The satellite stations are comprised of a geophone, amplified voltage controlled oscillator with a RF transmitter.

The central system receives data from each of the satellite stations, discriminates them, and records them. The recording can be on smoked paper, and/or magnetic tape, and/or event recording on a high speed photographic recording. A schematic is shown in Figure 1. A detailed explanation of each of the component parts for each system is given in the following sections.

#### L4-C Seismometer

The L4-C is a one-Hertz-natural-frequency vertical seismometer (manufactured by Mark Products). The damping is 0.6 of critical damping. The L4-C has an output of 6.9 volts per inch/second. A typical specification sheet is shown in Figure 2.

As sensor options, other geophones can be utilized. A common option is the L-10 geophone (manufactured by Mark Products). A typical specification sheet is also shown in Figure 2.

#### MEQ-800-B

The MEQ-800-B is a visual microearthquake recorder. The smoked drum recording has a nominal 120 mm/min rotation speed with 1 mm spacing between succeeding traces. The stylus and trace width is 0.05 mm. The amplifier has a maximum of 120 db of gain and selectable corners at 1, 5, and 10 Hz. The high cut filter has selectable corners of 10, 20, and 75 Hz. The amplifier gains can be changed by precise 6 db steps down from 120 db. The maximum pen deflection is  $\pm 25$  mm and can be limited under severe ground noise conditions to  $\pm 10$  mm or  $\pm 5$  mm.

The integral timing system consists of a clock, whose drift rate is less than  $\pm 1$  part in  $10^7$  (approximately  $\pm 10$  ms per day) and can be set to standard time and adjusted at 16 ms increments. Time is displayed on each trace by a slight deflection of the pen each second.



SYSTEM SCHEMATIC

INDEPENDENT STATIONS

4-5 Stations Available  
Remote Station Location

Components:

Geophone  
↓  
Amplifier  
↓  
Filters  
↓  
\*Recorder  
Smoked Paper  
Digital Tape (optional)

TELEMETRY STATIONS

4-5 Stations Available  
Remote Station Location

Components:

Geophone  
↓  
Amplifier  
↓  
Filter  
↓  
Voltage Controlled  
Oscillator (VCO)  
↓  
RF Transmitter

CENTRAL STATION

Components:

RF Receiver

Discriminator

\*Recorder

Smoked Paper  
Event Detection  
Digital Tape

\*Timing supplied by each station, synchronized daily.

FIGURE 1

# L4-C SPECIFICATIONS

Open Circuit Damping ( $b_o$ ) = 0.28 Critical

$$\text{Coil Current Damping } (b_c) = \frac{1.1 R_c}{R_c + R_s}$$

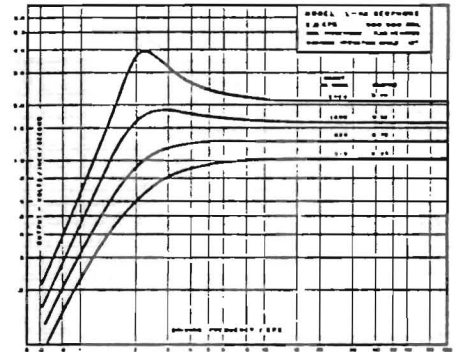
$$\text{Total Damping } (b_t) = b_o + b_c$$

## L-4C 1.0 Hz GEOPHONE

Coil Resistance (ohms)	84	134	206	320	500	870	1280	2000	3500	5500
Transduction (volts/inch/sec.)	0.87	1.13	1.34	1.7	2.1	2.8	3.5	4.2	5.55	6.9
Transduction (volts/meter/sec.)	34.2	43.5	53	67	83	110	136	165	220	273
Coil Inductance (henries)	0.092	0.147	0.230	0.35	0.55	0.95	1.40	2.20	3.85	6.05
Analog Capacity (microfarads)	875	550	356	230	147	85	58	37	21	13.4
Analog Inductance (henries)	29	46.4	71	110	173	300	440	690	1200	1900
Shunt For 0.70 Critical Damping	133	215	333	520	810	1400	2070	3250	5650	8900
Shunt For 0.60 Critical Damping	205	325	500	780	1220	2120	3100	4900	8500	13400

# L-4C 1.0 Hz GEOPHONE

TYPE	Moving dual coil, humbuck wound
FREQUENCY	1.0 ± 0.05 Hz measured on 200 pound weight at 0.09 inches/second
FREQUENCY CHANGE WITH TILT	Less than 0.05 Hz at 5° from vertical
FREQUENCY CHANGE WITH EXCITATION	Less than 0.05 Hz from 0 to 0.09 inches/second
SUSPENDED MASS	1000 grams
STANDARD COIL RESISTANCES	See Table
LEAKAGE TO CASE	100 megohm minimum at 500 volts
TRANSDUCTION POWER	8.8 · 10 <sup>-3</sup> watts inch second or 13.6 watts meter second
OPEN CIRCUIT DAMPING	( $b_o$ ) = 0.28 critical
CURRENT DAMPING	( $b_c$ ) = $\frac{1.1 R_c}{R_c + R_s}$ where: $R_c$ = coil resistance - ohms $R_s$ = shunt resistance - ohms
COIL INDUCTANCE	( $L_c$ ) = 0.0011 $R_c$ $L_c$ in henries.
ELECTRIC ANALOG OF CAPACITY	$C_c = \frac{73,500}{R_c}$ (microfarads)
ELECTRIC ANALOG OF INDUCTANCE	$L_m = 0.345 R_c$ (henries)
CASE HEIGHT	5½ inches — 13 cm.
CASE DIAMETER	3 inches — 7.6 cm.
TOTAL DENSITY	3.7 grams cm <sup>3</sup>
TOTAL WEIGHT	4½ pounds — 2.15 kilograms
OPERATING TEMPERATURE	Range: -20 to 140 F or -29 to 60 C
OPERATING PRESSURE	500 PSI



# L-10A SPECIFICATIONS

## L-10A GEOPHONE

Suspended Mass (m) ..... 12.5 grams

Open Circuit Damping ( $b_o$ ) .....  $b_o = \frac{4.2}{f} \pm 10\%$

Coil Circuit Damping ( $b_c$ ) .....  $b_c = \frac{15.7 \cdot R_c}{f(R_s + R_c)} \pm 10\%$

Analog Capacitance ( $C_c$ ) .....  $C_c = \frac{5010}{R_c}$   
 $R_c$  = Coil Resistance       $C_c$  = Microfarads

Analog Inductance ( $L_m$ ) .....  $L_m = \frac{5.16 \cdot R_c}{f^2}$   
 $f$  = geophone frequency       $L_m$  = henries

L-10B 4.5Hz										
Coil Resistance (ohms)	21	34	54	90	138	215	374	590	940	
Transduction (volts/inch/second)	0.193	0.245	0.30	0.387	0.49	0.60	0.80	0.98	1.25	
Coil Inductance (henries)	0.004	0.006	0.010	0.016	0.024	0.038	0.067	0.105	0.167	
Analog Capacitance (micro farads)	350	216	136	81.6	53.1	34.1	19.7	12.4	7.80	
Analog Inductance (henries)	3.58	5.82	9.24	15.4	23.6	36.8	64.0	102	161	
Shunt for 1.00 Critical Damping (ohms)	66.8	108.5	173	277	317	687	1200	1890	3000	
Shunt for 0.70 Critical Damping (ohms)	191	311	494	824	1260	1750	3420	5410	8570	
Shunt for 0.60 Critical Damping (ohms)	315	512	814	1355	2080	3240	5640	8910	10425	

$b_o = .445$        $b_c = \frac{2.33 R_c}{R_c + R_s}$

## L-10B GEOPHONE

Suspended Mass (m) ..... m = 19 grams

Open Circuit Damping ( $b_o$ ) .....  $b_o = \frac{2}{f} \pm 10\%$

Coil Circuit Damping ( $b_c$ ) .....  $b_c = \frac{10.5 \cdot R_c}{f(R_s + R_c)} \pm 10\%$

Analog Capacitance ( $C_c$ ) .....  $C_c = \frac{7330}{R_c}$   
 $R_c$  = Coil Resistance       $C_c$  = Microfarads

Analog Inductance ( $L_m$ ) .....  $L_m = \frac{3.41 \cdot R_c}{f^2}$   
 $f$  = geophone frequency       $L_m$  = henries

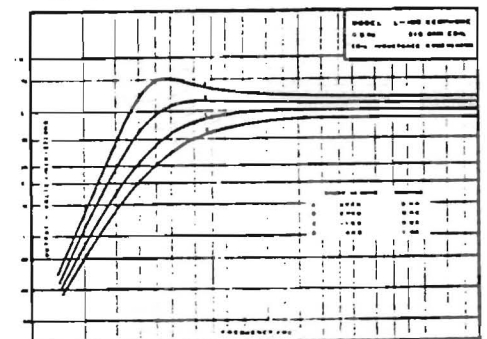


FIGURE 2

# INSTRUMENT RESPONSE

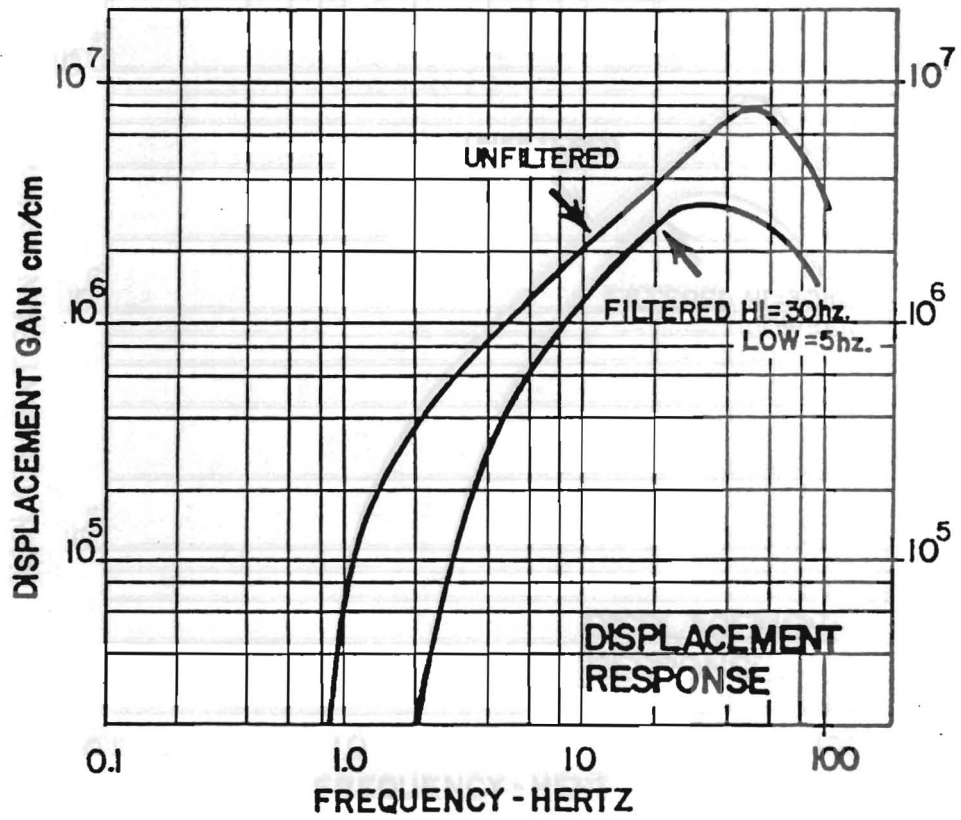
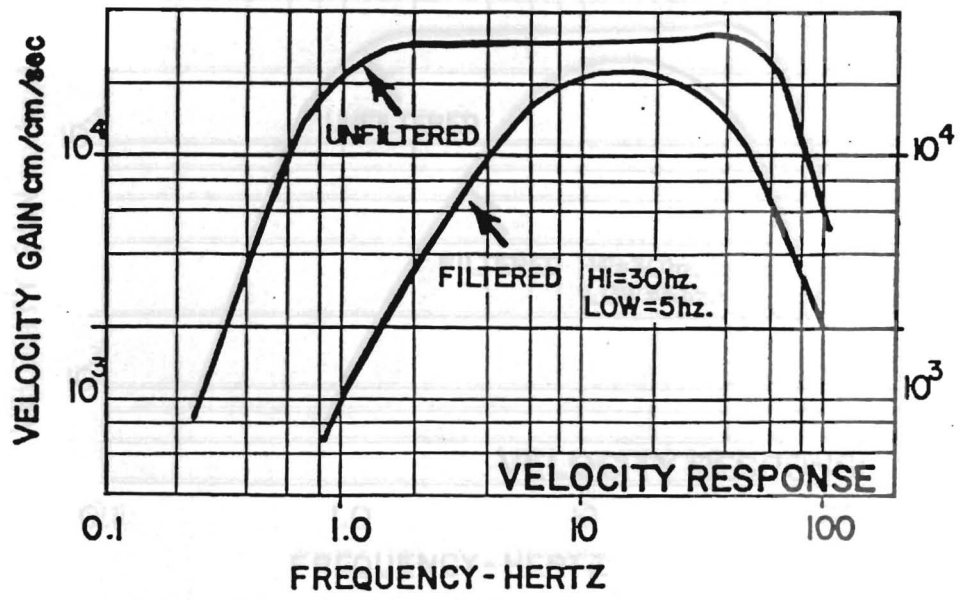


FIGURE 3

The frequency characteristics of the instrument with an L4-C are summarized in Figure 3. Both the velocity and displacement response for the MEQ-800-B microearthquake system are shown. The displacement response at a particular frequency ( $f$ ) can be calculated by multiplying the velocity gain at  $f$  time  $2\pi f$ . The filter response and gain level shown are typical settings for operations in the western continental United States.

#### DMTR

The digital magnetic tape recorder (DMTR) is a twelve-bit 100 sampler-per-second, reel-to-reel-tape recorder which records data continuously. Each data block begins on the minute at the command of the clock in the MEQ-800-B system. The hour and minute from the clock are written at the beginning of each block. WWVB is recorded continuously on one bit of the tape format. The dynamic range of 72 db on this tape recorder allows the recovery of data under exceptionally noisy conditions.

#### WWVB

WWVB is the radio call code for the National Bureau of Standards 60 kHz time-standard station in Fort Collins, Colorado. The WWVB time standard is used to set and synchronize the microearthquake system clocks. As shown in Figure 4 below, the signal consists of 60 markers each one minute, with one marker each second (time progresses from left to right). Each marker is generated by reducing the power of the carrier by 10 db at the beginning of the corresponding second and restoring it:

- (1) 0.2 seconds later for a binary zero
- (2) 0.5 seconds later for a binary one
- (3) 0.8 seconds later for a 10 second position marker and for a minute reference marker.

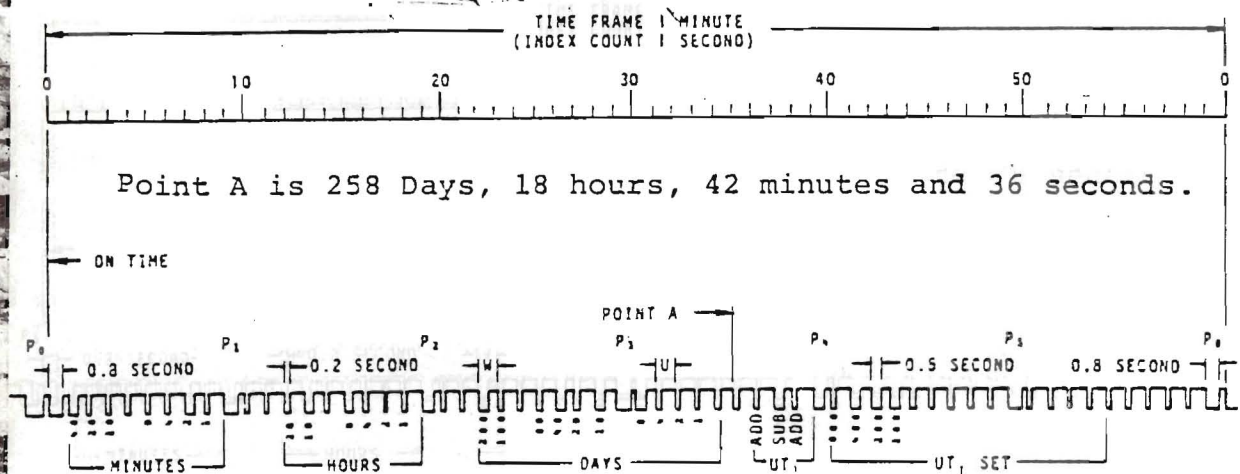



FIGURE 4



The WWVB code (as shown in Figure 3) is recorded daily on the visual drum as absolute time and date identification of the record, and is used to synchronize each MEQ system to standard time.

The MEQ systems' clocks are synchronized daily with WWVB by comparing (on an oscilloscope) the beginning of the WWVB second pulse with the MEQ-800-B internally generated one-second pulse. This comparison can be done to  $\pm 2$  milliseconds. Daily records are kept on the amount of correction for each clock. These time corrections are then applied to the records. Common corrections are on the order of 15 ms per day or less than one millisecond per hour.

#### WWV

WWV is the radio call code for the National Bureau of Standards 5, 10, 15, 25 mHz time standard station in Fort Collins, Colorado, as used by MicroGeophysics Corporation. The voice channel is used to generally coordinate time, while the second signals are used to precisely coordinate time. The use is similar to that of the WWVB channel.

#### Amplifier

The amplifier used is the AS-110 (manufactured by Sprengnether Instrument Company). This amplifier has identical characteristics to the Sprengnether MEQ-800 amplifier.

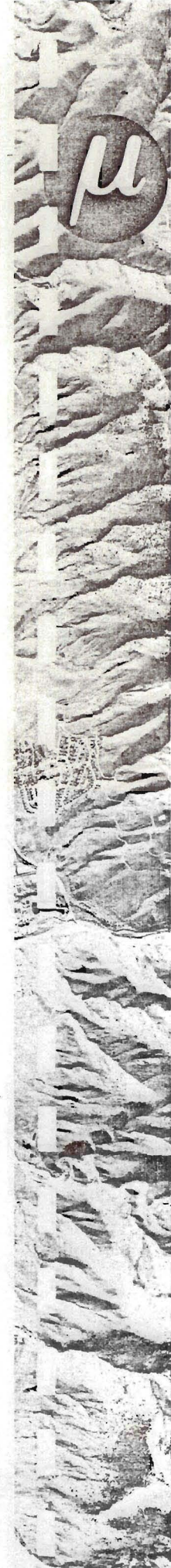
#### Telemetry

The following are excerpts for the Sprengnether Manual for the VCO and Discriminator equipment:

#### Telemetry VCO TC-10

The TC-10 Voltage Controlled Oscillator has been designed to fill a need for low cost, low power, high quality and versatile audio frequency telemetry components. Available in standard constant bandwidth channels from 340 to 3060 Hz with  $\pm 125$  Hz deviation the TC-10 VCO satisfies requirements for FM geophysical data telemetry in the frequency range DC to 50 Hz by telephone, land line, or by radio link. When used with the companion TC-20 Discriminator, 60 dB dynamic range (peak measurement is achieved in the 0-10 Hz bandwidth.

Versatility and simplicity of installation are assured by several special features incorporated into the VCO that are not normally available at such low cost. Eleven sensitivity ranges, from



50 mv to 100 v full scale deviation, are selectable on the front panel to facilitate system gain adjustments or multi-gain operations. Upper and lower band edge deviations can be effected from a front panel switch for ease in system setup and servicing. Center frequency, deviation, and output level can be monitored and adjusted from the front panel. Output is transformer coupled for flexible installation.

Power requirements are generous at  $\pm 10$  to 15 VDC at 15 ma for low power remote field installations. Small physical size is ideal for compact field case installation (the TC-10 matches the AS-110 amplifier in size and connector configuration) or for high density packing in rack mount multi-channel operations.

The TC-110 VCO represents state-of-the-art in circuit design, user convenience, and low price, satisfying virtually all requirements for high quality audio frequency FM telemetry.

#### Discriminator TC-20

The TC-20 Discriminator has been designed to fill a need for low cost, low power, high quality and versatile audio frequency telemetry components. Available in standard constant bandwidth channels from 340 to 3060 Hz with  $\pm 125$  Hz deviation the TC-20 satisfies requirements for FM telemetry of geophysical data in the frequency range DC to 50 Hz by telephone or land line or by radio link. When used with the companion TC-10 VCO, 60 dB dynamic range (peak measurement) is achieved in the 0-10 Hz bandwidth.

Several unique features are found on this low cost phase-locked loop discriminator that normally are incorporated only in more expensive units. A sense light on the front panel indicates low carrier level. Provision is made for a reference compensation tone and trim to effect compensation for frequency shifts in multiplexed tone bundles. The TC-20 also provides for an auxiliary-test input on the front panel to facilitate service checks and adjustments. The carrier after filtering can be monitored from the front panel and all major adjustments are made with front panel controls. The input is transformer coupled for flexibility in installation.

Power requirements are  $\pm 10$  to 15 VDC at 18 ma. Output filters (3 pole Butterworth) at 1, 5, 10, 20, 50 Hz (3dB) are available, factory adjusted. The panel width of 1-1/2" allows dense packing in rack installations.

The TC-20 represents state-of-the-art in phase-locked loop discriminators, offering the maximum in flexibility and convenience features at the lowest possible cost.

#### RF Telemetry Link

These RF telemetry links are Monitron low-power FR transmitters and receivers (manufacturer Monitron Corporation). The output power is less than 100 mw. Specifications are shown below.

System Gains: The typical gains of each system with typical settings are shown below:

System: MEQ-800 (Smoked Paper)

Filter Settings:

Hi = 30 Hz

Lo = 5 Hz

Geophone L4-C

#### Gain Settings

#### Displacement Gain at 20 Hz

60	0.04 x 10 <sup>6</sup>
66	0.08 x 10 <sup>6</sup>
72	0.16 x 10 <sup>6</sup>
78	0.33 x 10 <sup>6</sup>
84	0.165 x 10 <sup>6</sup>
90	0.3 x 10 <sup>6</sup>
96	2.6 x 10 <sup>6</sup>
102	5.2 x 10 <sup>6</sup>

System: VCO-TELEMETRY-VR-60

Filter Settings

Hi = 30 Hz

Lo = 5 Hz

Geophone L4-C

VCO = 5 Volts/f.s.

VR-60 + 100  $\mu$ /mm

#### Gains Settings

#### Displacement Gain at 20 Hz

60	0.2 x 10 <sup>6</sup>
66	0.4 x 10 <sup>6</sup>
72	0.8 x 10 <sup>6</sup>
78	1.65 x 10 <sup>6</sup>
84	3.25 x 10 <sup>6</sup>
90	6.5 x 10 <sup>6</sup>
96	13.0 x 10 <sup>6</sup>
102	26.0 x 10 <sup>6</sup>



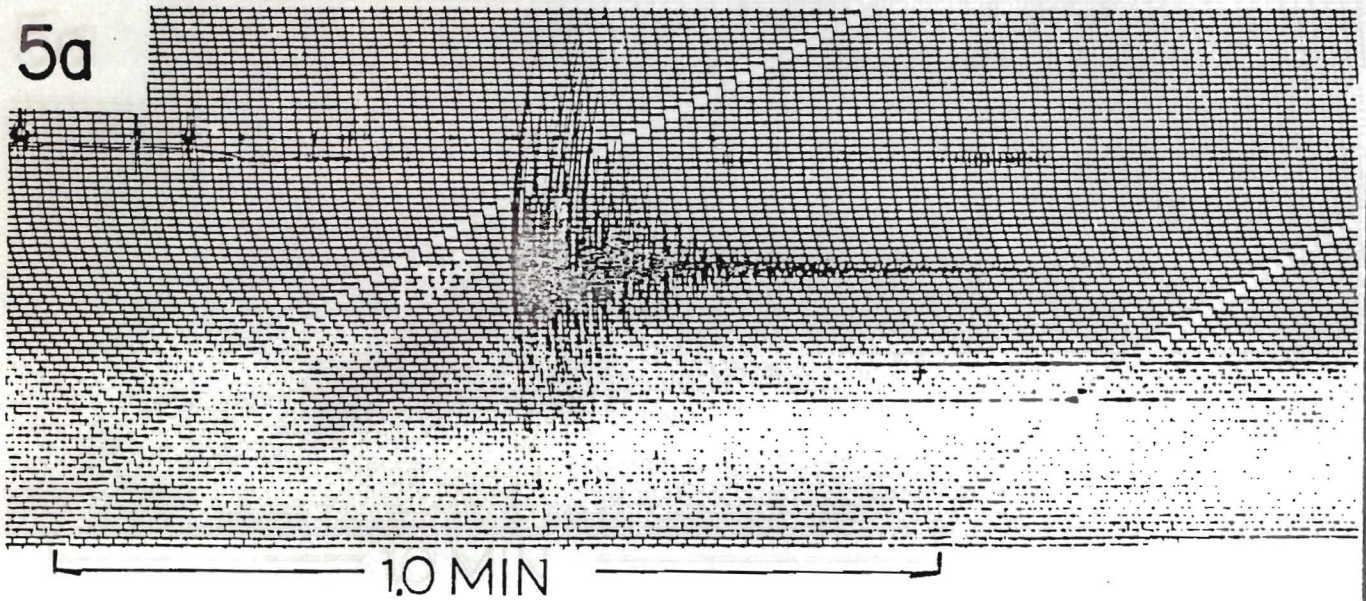
## DATA

An example of the output of a microearthquake system is shown in Figure 6. The smoked-paper output is shown in Figure 6(a) while Figure 6(b) and Figure 6(c) are the same earthquake recorded on magnetic tape and played back at two different speeds. The playback format is illustrated in the figure.

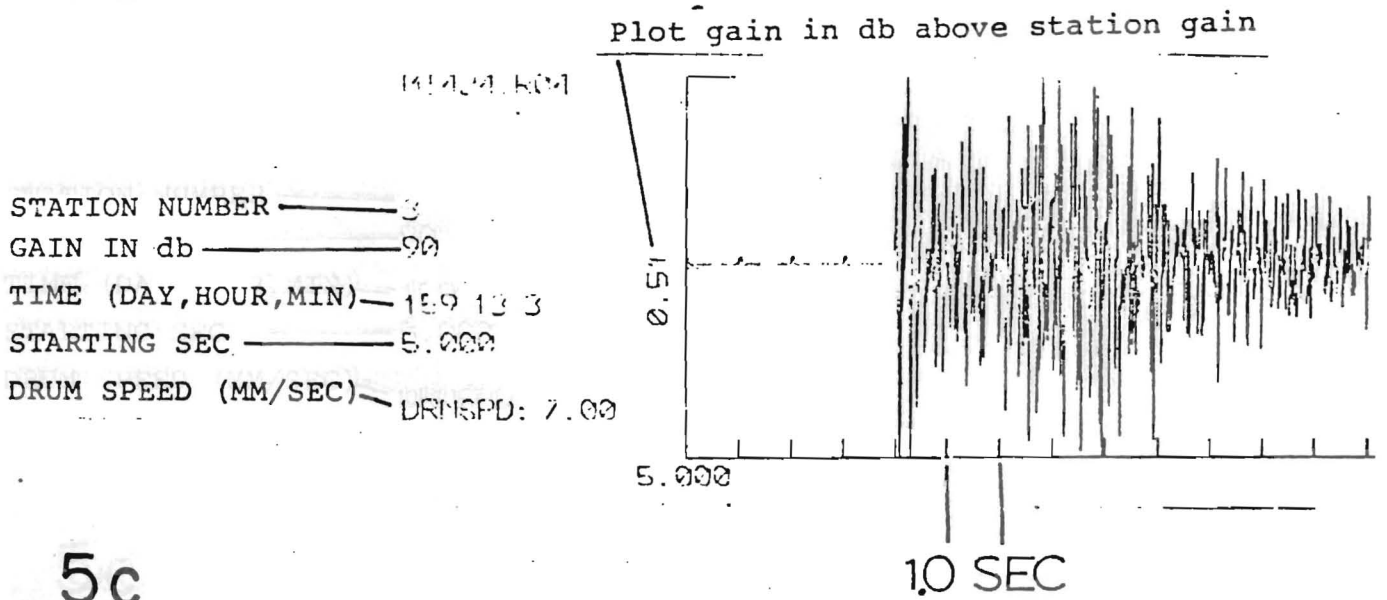
The smoked-paper record is used at the time of the recording (in the field) to estimate the seismicity and to locate any recorded microearthquake approximately. The paper records can be picked under magnification to a precision of less than  $\pm 30$  ms. The magnetic tape playbacks are then used to increase the timing precision of an event to  $\pm 10$  ms, a precision close to the subjective level of interpretation by an experienced seismologist. The magnetic tape playbacks are also useful in increasing the effective gain of recording and thereby recording very small amplitude events. In noisy areas, the tape playbacks can be used to recover data obscured on the paper monitor records by cultural noise on adjacent traces.



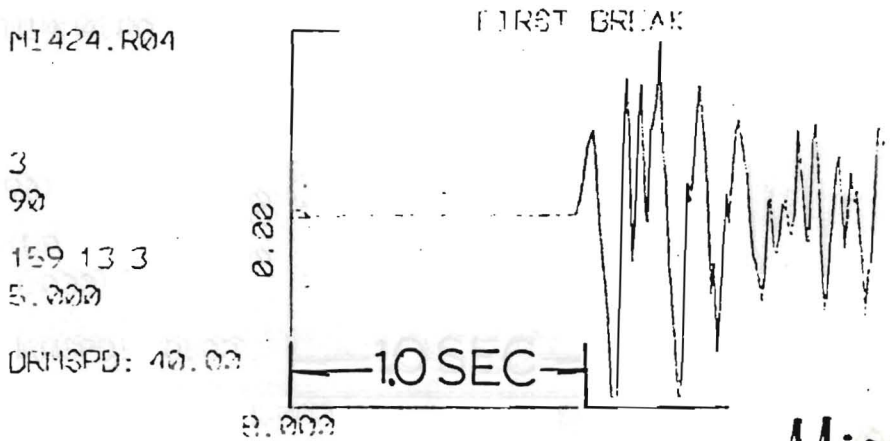
5a



5b



5c



Micro Geophysics

T43N  
T42N

T43N  
T42N

41°30'

41°30'

T42N  
T41N

T42N  
T41N

T41N  
T40N

T41N  
T40N

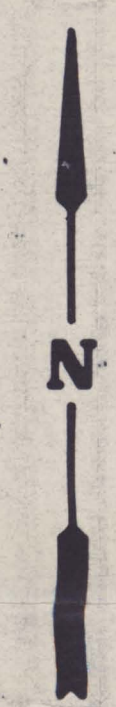
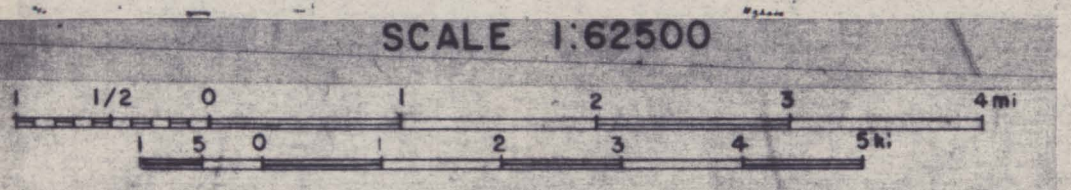
T40N  
T39N

R50E R51E

R51E R52E

R52E R53E

R53E R54E



**TUSCARORA, NEVADA**  
**HYPOCENTERS**

- <sup>10.0</sup> EPICENTER WITH DEPTH (KM)
- ▲<sup>12</sup> STATION LOCATIONS
- + ORIGIN 41°29.51' N LAT  
116°06.73' W LONG

PLATE #4.1

DRAWN BY MP  
NOVEMBER 28, 1978

**MICROGEOPHYSICS**

T43N  
T42N

T43N  
T42N

41°30'

41°30'

T42N  
T41N

T42N  
T41N

T41N  
T40N

T41N  
T40N

T40N  
T39N

41°15'

20°

P50E R51E

116°15'

R51E R52E

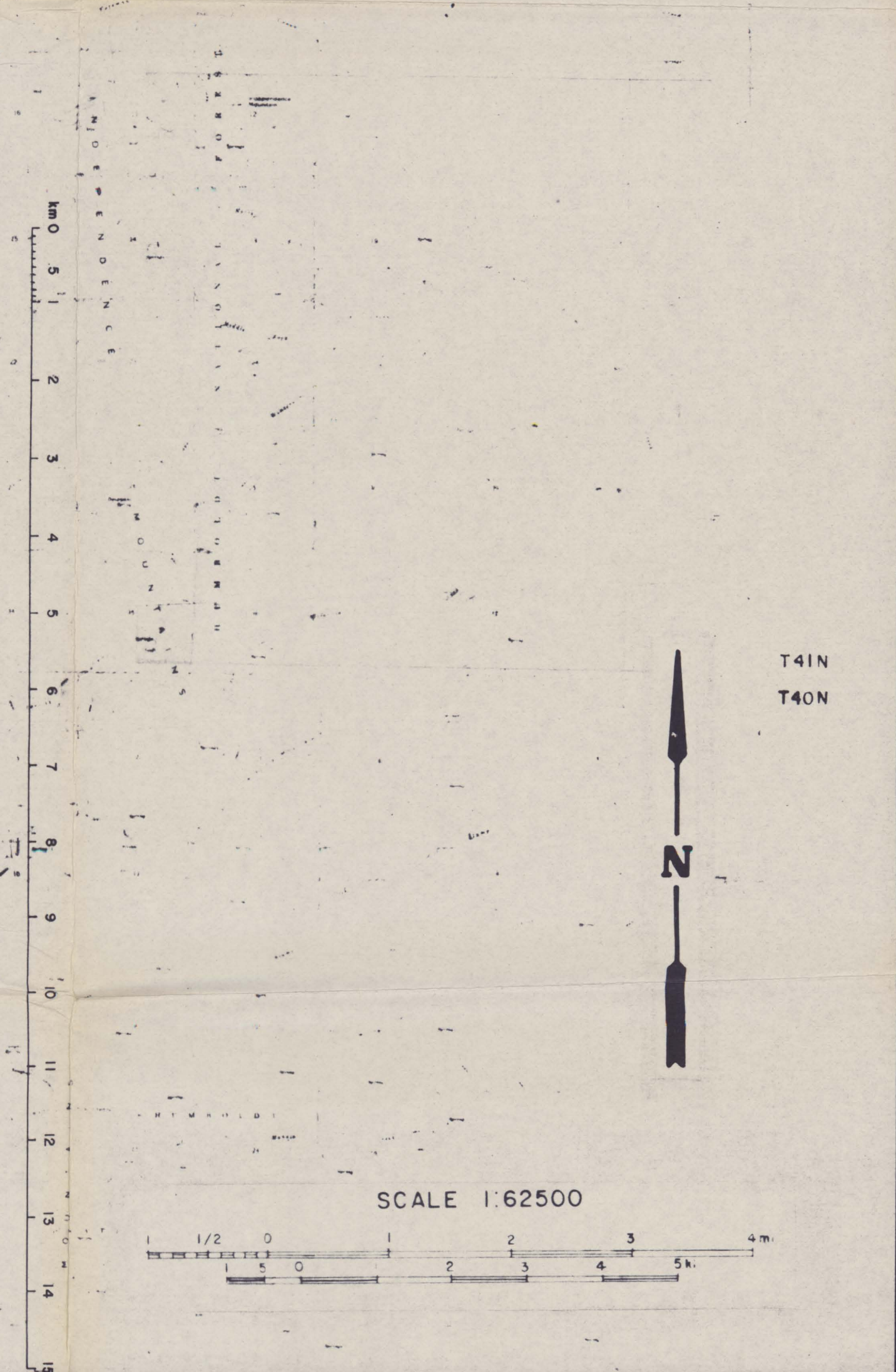
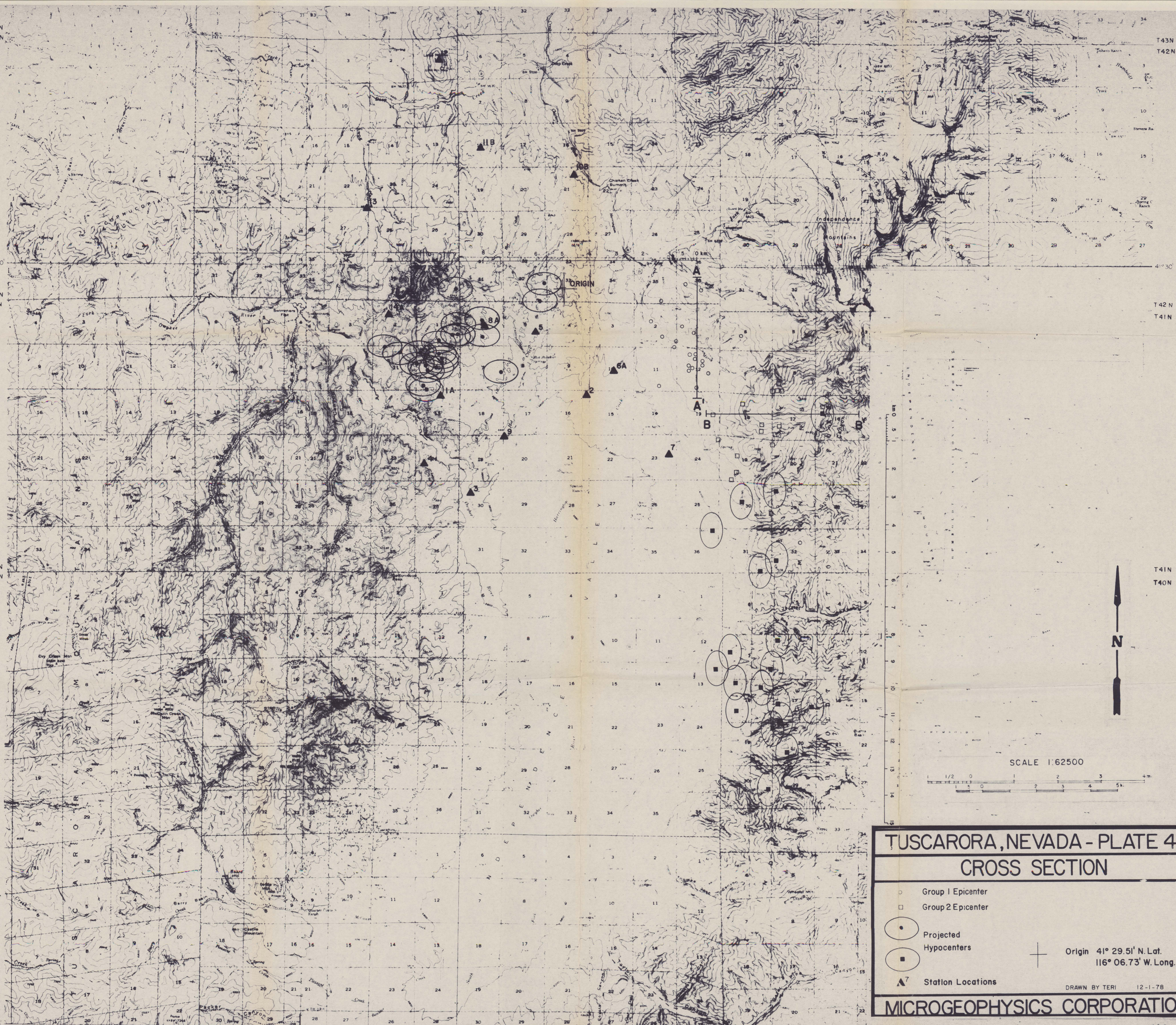
R52E R53E

116°00'

R53E R54E

41°15'

115°52'30"



**TUSCARORA, NEVADA - PLATE 4.2**

**CROSS SECTION**

- Group 1 Epicenter
- Group 2 Epicenter
- Projected Hypocenters
- ▲ Station Locations

Origin 41° 29.51' N. Lat.  
116° 06.73' W. Long.

DRAWN BY TERI 12-1-78

**MICROGEOPHYSICS CORPORATION**

T43N  
T42N

T43N  
T42N

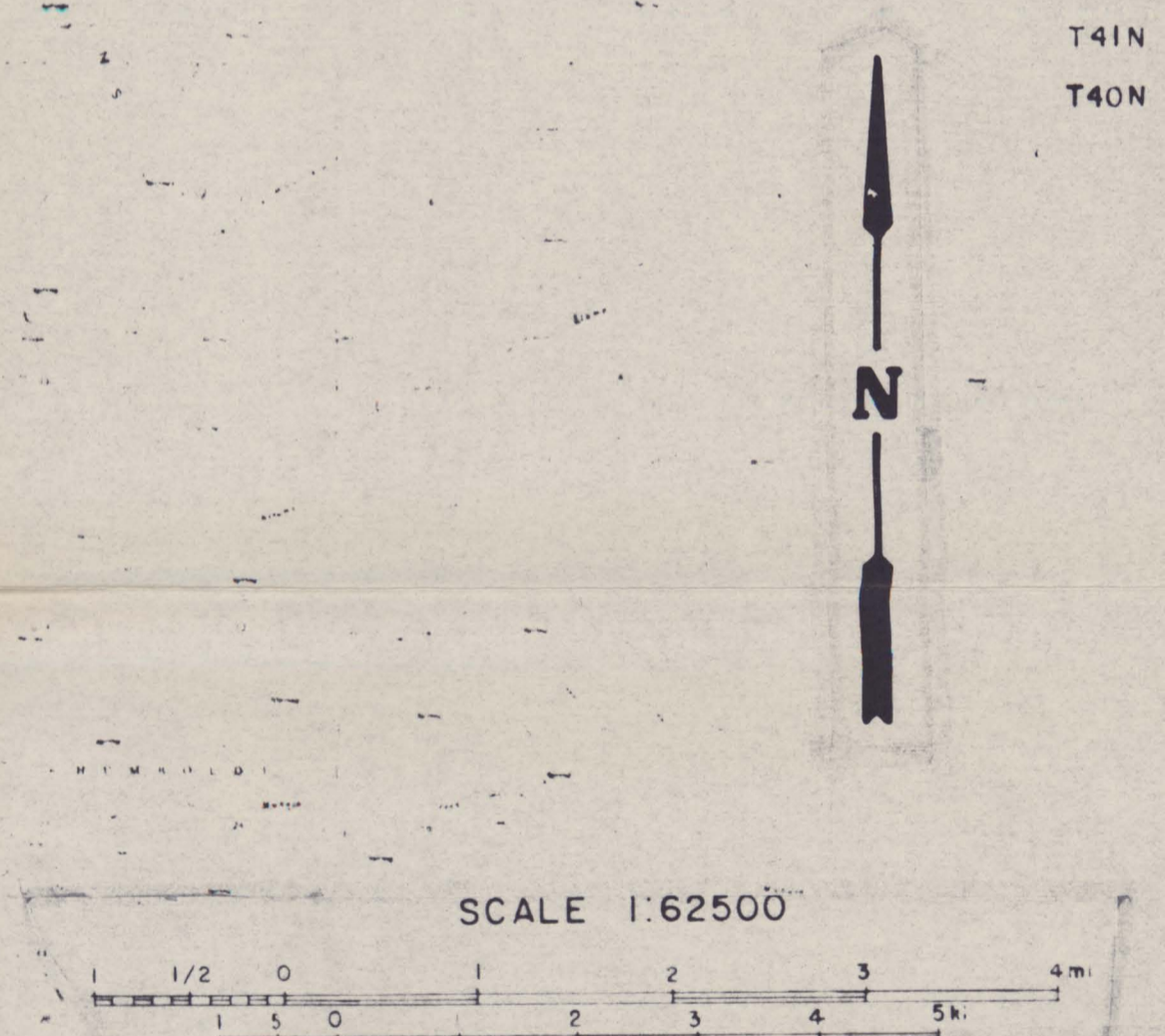
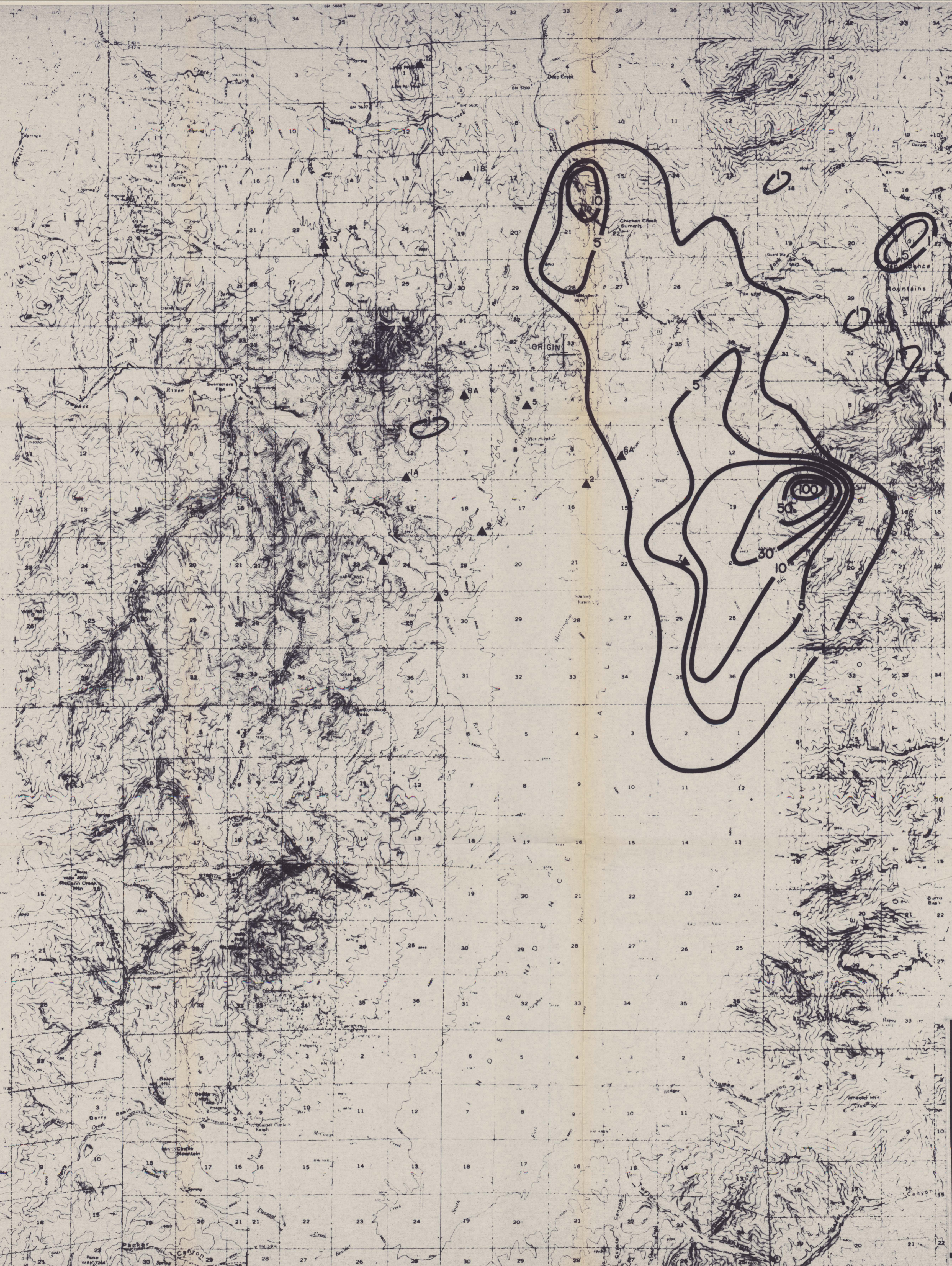
T42N  
T41N

T42N  
T41N


T41N  
T40N

T41N  
T40N

T40N  
T39N



TUSCARORA, NEVADA  
 STRAIN RELEASE PLATE 4.3

▲° STATION LOCATIONS  
 50   $\text{ergs}^{1/2} \times 10^{-5}$   
 + ORIGIN 41° 29.51' N LAT.  
 116° 06.73' W LONG.

DRAWN BY MP 11-30-78  
 MICROGEOPHYSICS CORPORATION

20° P50E R51E 116°15' R51E R52E R52E R53E 116°

T43N  
T42N

T43N  
T42N

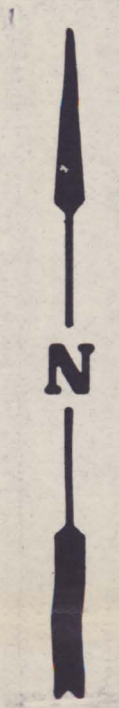
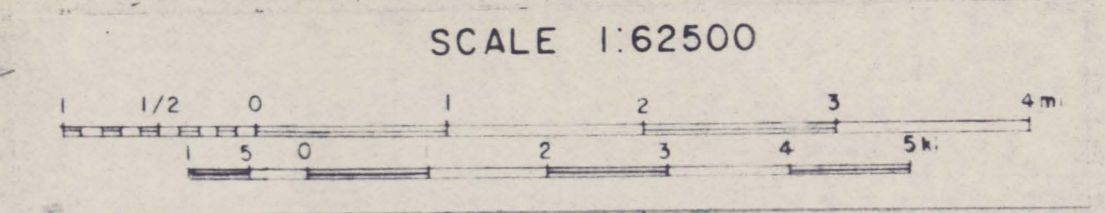
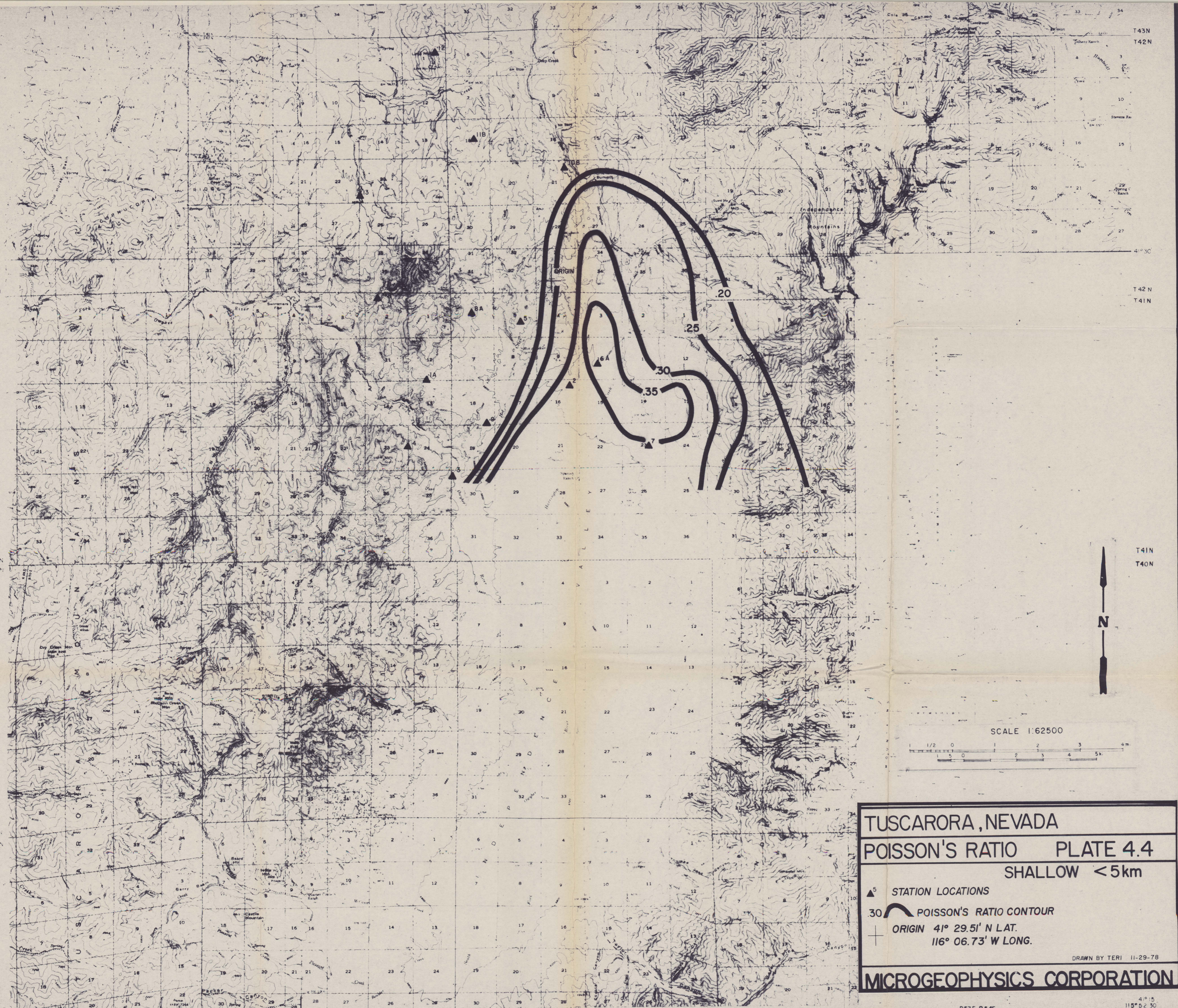
T41N  
T41N

T42N  
T41N

T41N  
T40N

T41N  
T40N

T41N  
T39N



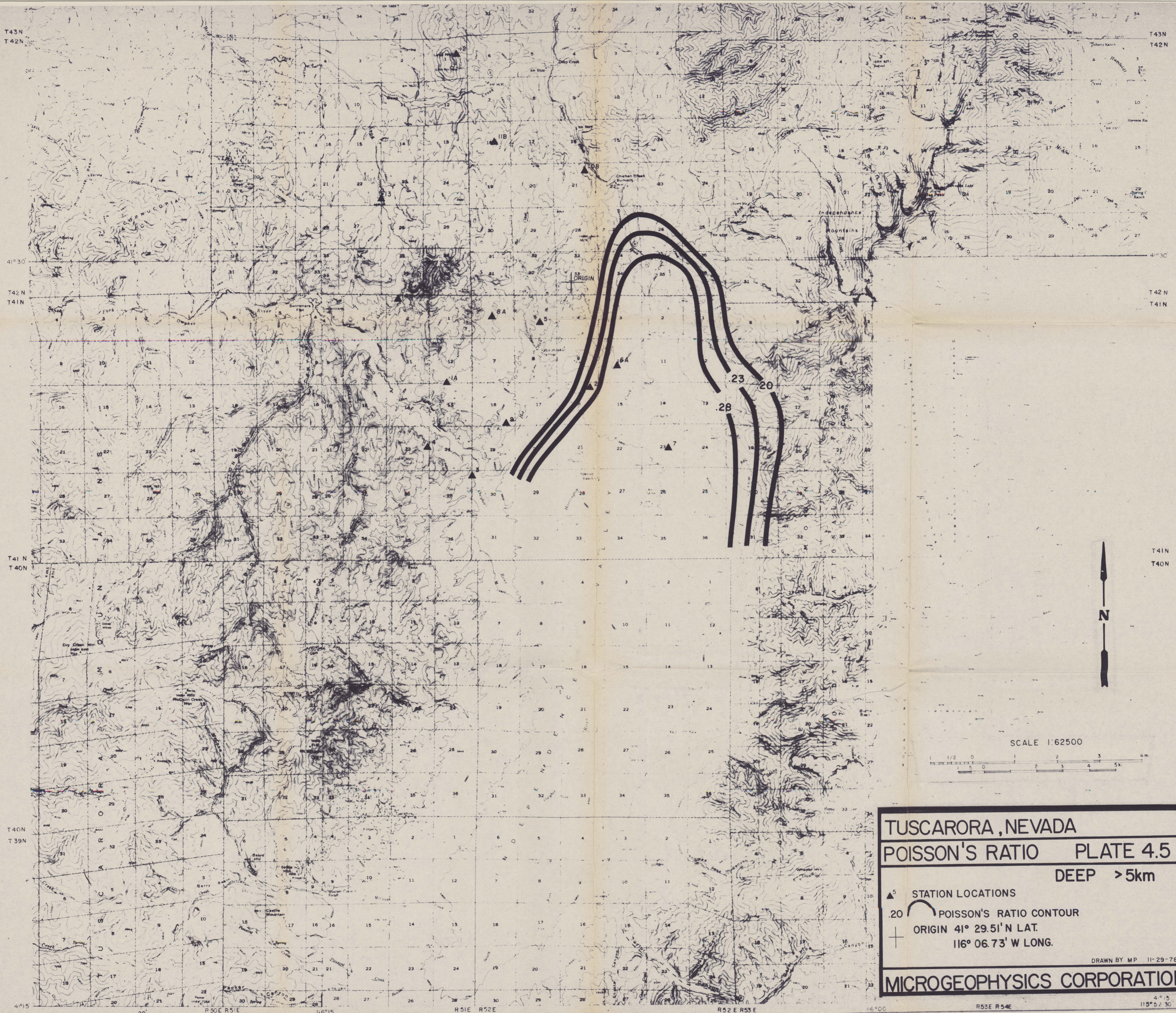
**TUSCARORA, NEVADA**  
**POISSON'S RATIO PLATE 4.4**  
**SHALLOW <5km**

▲<sup>5</sup> STATION LOCATIONS  
 30 POISSON'S RATIO CONTOUR  
 + ORIGIN 41° 29.51' N LAT.  
 116° 06.73' W LONG.

DRAWN BY TERI 11-29-78

**MICROGEOPHYSICS CORPORATION**

20° P50E R51E 116°15' R51E R52E R52E R53E 116°00' R53E R54E 4°15' 115°52'30"



T43N  
T42N

T43N  
T42N

41°30'  
T42N  
T41N

41°30'  
T42N  
T41N

T41N  
T40N

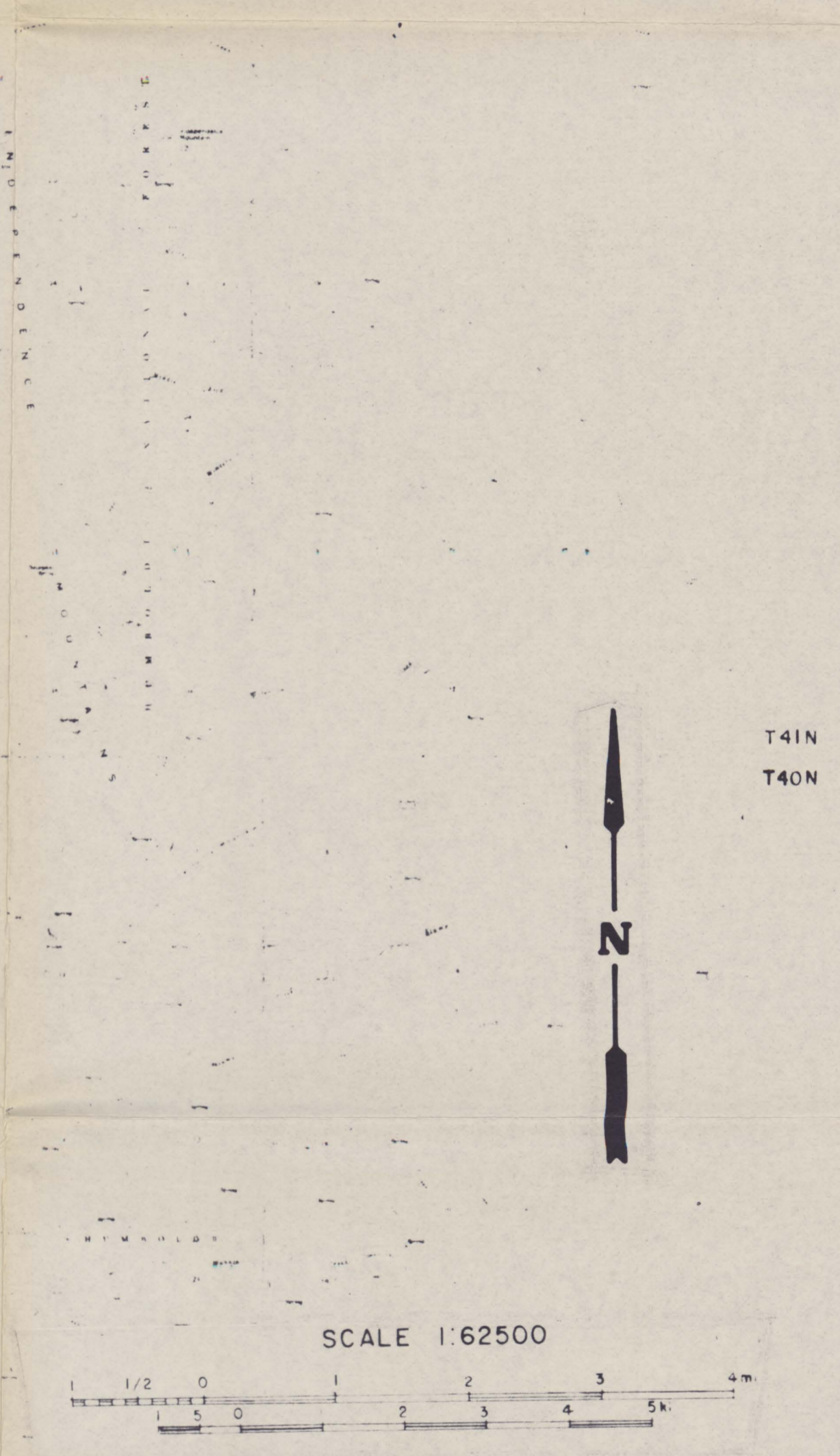
T41N  
T40N

T40N  
T39N

T40N  
T39N

41°15' 20' 25' 30' 35' 40' 45' 50' 55' 60' 65' 70' 75' 80' 85' 90' 95' 100'

R50E R51E 116°15' R52E R53E 116°00' R54E R55E 115°52' 30'



**TUSCARORA, NEVADA**

**POISSON'S RATIO PLATE 4.5**

**DEEP > 5km**

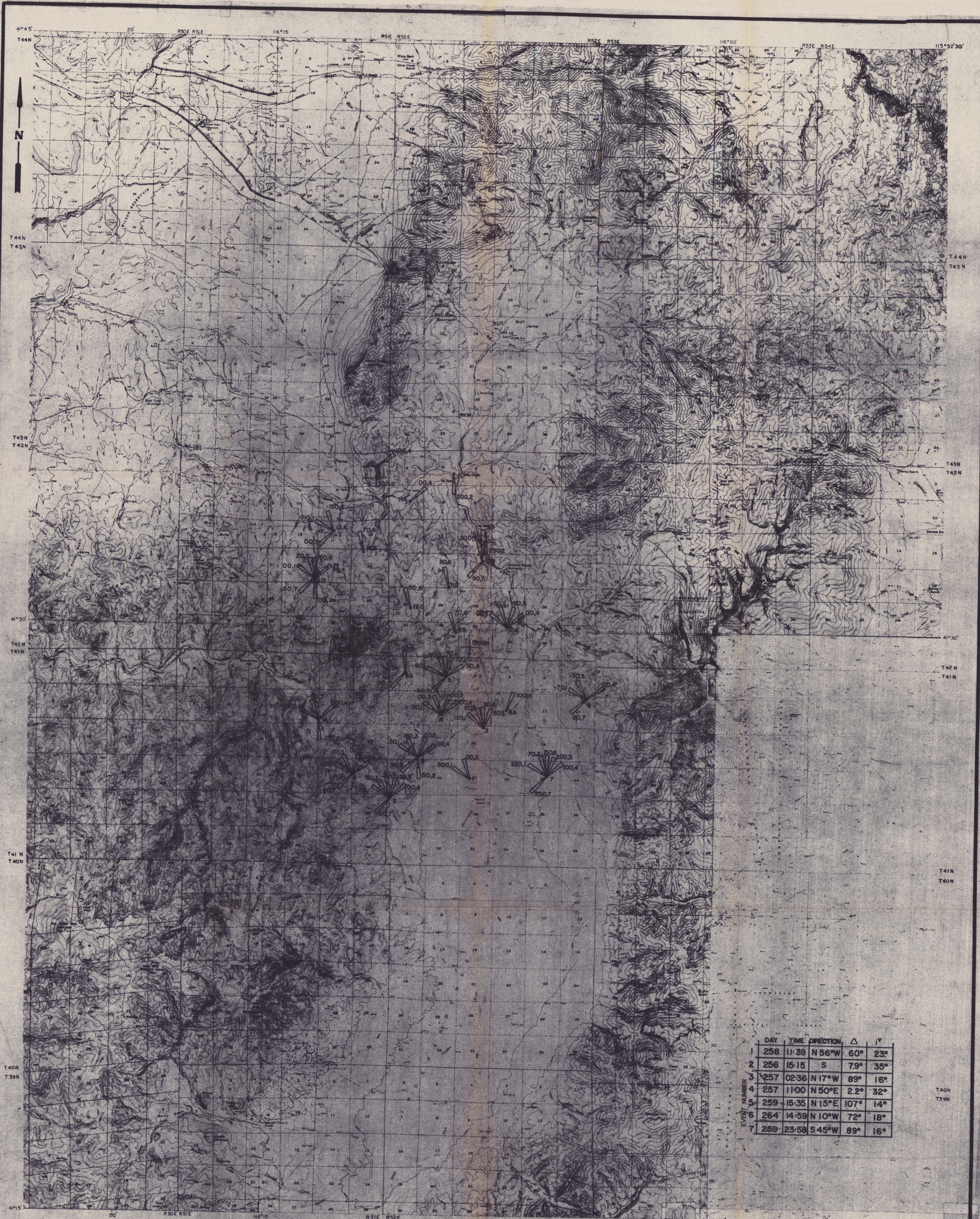
▲<sup>5</sup> STATION LOCATIONS

○ POISSON'S RATIO CONTOUR

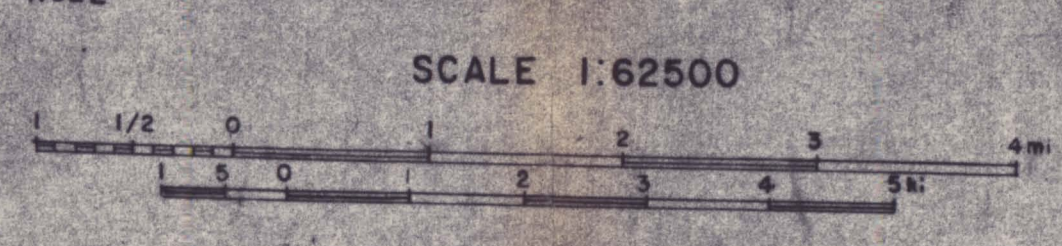
⊕ ORIGIN 41° 29.51' N LAT.  
116° 06.73' W LONG.

DRAWN BY MP 11-29-78

**MICROGEOPHYSICS CORPORATION**



EVENT NUMBER	DAY	TIME	DIRECTION	$\Delta$	$\delta$
1	258	11:39	N 56°W	60°	23°
2	256	15:15	S	7.9°	35°
3	257	02:36	N 17°W	89°	16°
4	257	11:00	N 50°E	2.2°	32°
5	259	15:35	N 15°E	107°	14°
6	264	14:59	N 10°W	72°	18°
7	259	23:58	S 45°W	89°	16°



**TUSCARORA, NEVADA PLATE 5.1**

**P-WAVE DELAY RAW DATA**

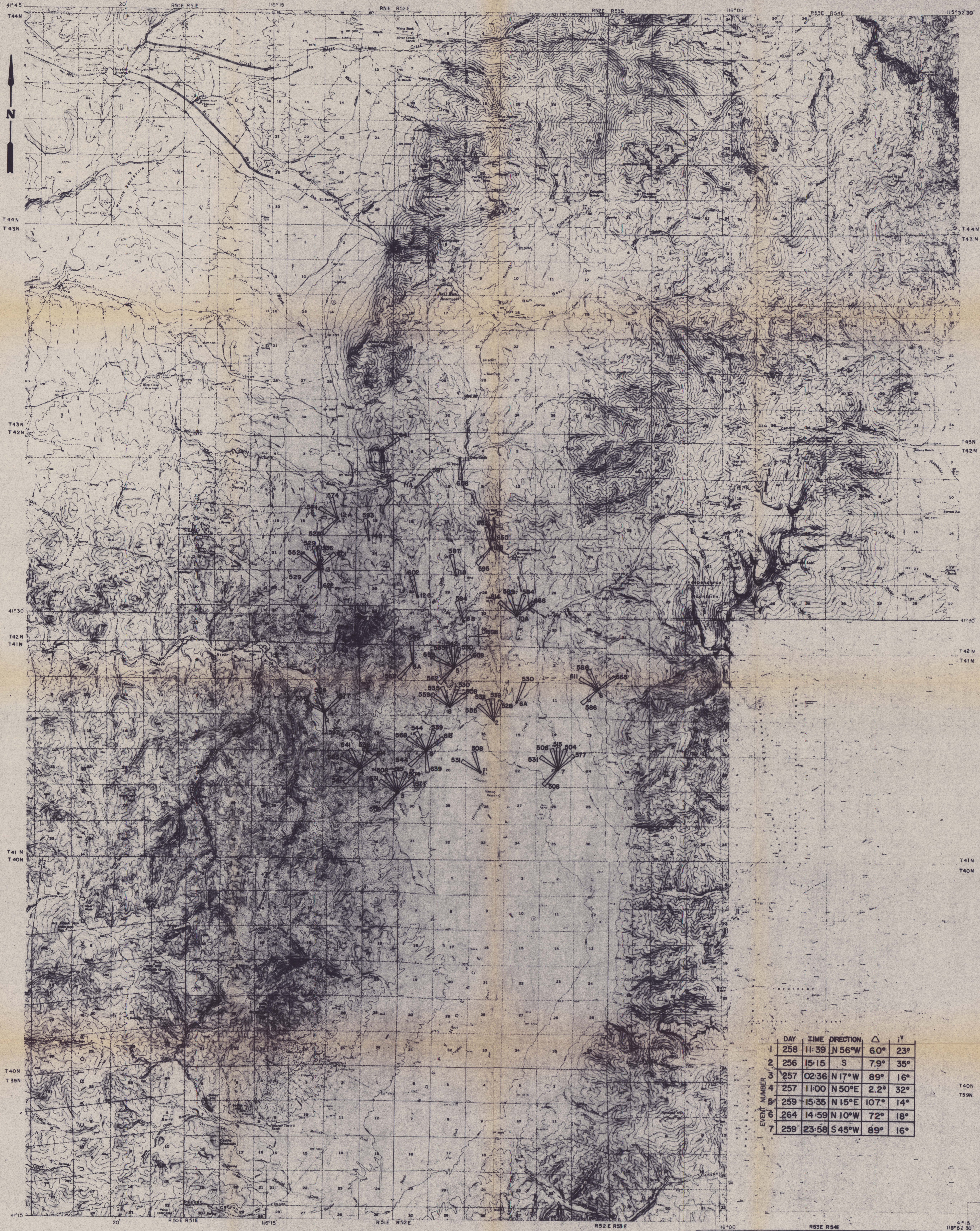
STATION  
 ARRIVAL AZIMUTH  
 DELAY OR ADVANCE, EVENT NUMBER

STATION  
 CALCULATED DEPTH(km), EVENT NUMBER

ORIGIN 41° 29.5' N LAT.  
116° 06.73' W LONG.

DRAWN BY TERI 2/2/79

**MICROGEOPHYSICS CORPORATION**



EVENT NUMBER	DAY	TIME	DIRECTION	$\Delta$	$\delta$
1	258	11:39	N 56°W	6.0°	23°
2	256	15:15	S	7.9°	35°
3	257	02:36	N 17°W	8.9°	16°
4	257	11:00	N 50°E	2.2°	32°
5	259	15:35	N 15°E	10.7°	14°
6	264	14:59	N 10°W	7.2°	18°
7	259	23:58	S 45°W	8.9°	16°

SCALE 1:62500

**TUSCARORA, NEVADA PLATE 5.2**  
**P-WAVE DELAY ALTITUDE CORRECTION**

STATION ARRIVAL AZIMUTH  
 253,7 DELAY OR ADVANCE, EVENT NUMBER

STATION CALCULATED DEPTH(km), EVENT NUMBER  
 3.2,4

ORIGIN 41° 29.5' N LAT.  
 116° 06.73' W LONG.

DRAWN BY TERI 2/2/79

**MICROGEOPHYSICS CORPORATION**

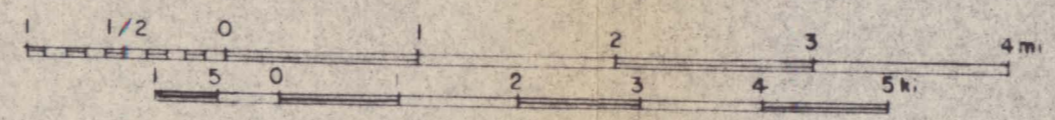




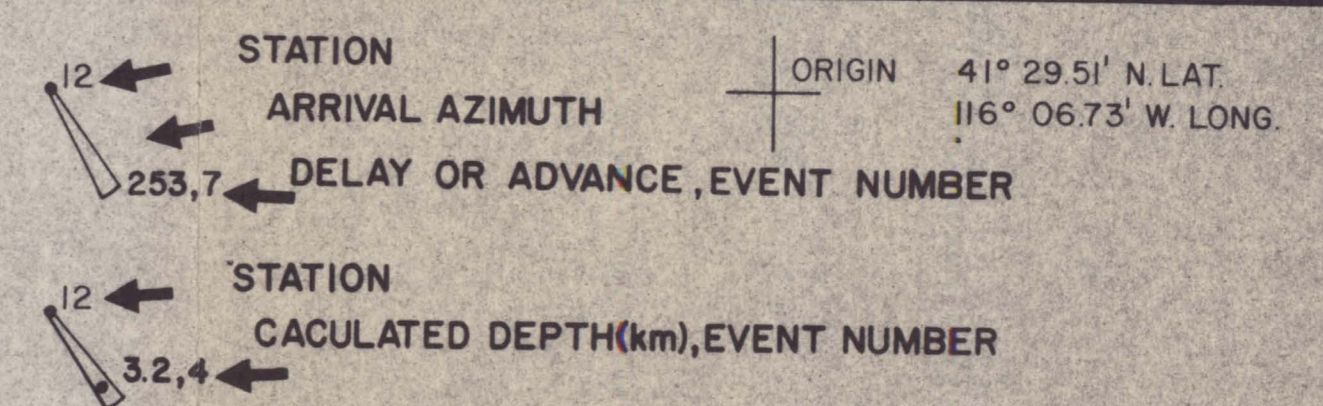
CONTOUR INTERVAL - 2 tenths of a kilometer

EVENT NUMBER	DAY	TIME	DIRECTION	$\Delta$	$i^v$
1	258	11:39	N 56°W	60°	23°
2	256	15:15	S	7.9°	35°
3	257	02:36	N 17°W	89°	16°
4	257	11:00	N 50°E	2.2°	32°
5	259	15:35	N 15°E	107°	14°
6	264	14:59	N 10°W	72°	18°
7	259	23:58	S 45°W	89°	16°

SCALE 1:62500



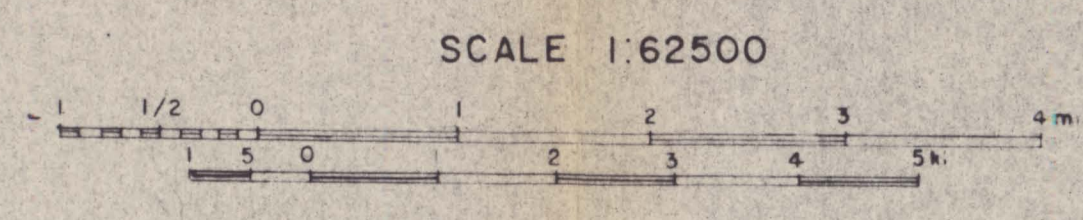
**TUSCARORA, NEVADA PLATE 5.3**  
**P-WAVE DELAY DEPTH TO INTERFACE**



DRAWN BY TERI 2/2/79  
**MICROGEOPHYSICS CORPORATION**



DAY	TIME	DIRECTION	$\Delta$	$i^v$
1	258	11:39 N 56° W	60°	23°
2	256	15:15 S	7.9°	35°
3	257	02:36 N 17° W	89°	16°
4	257	11:00 N 50° E	2.2°	32°
7	259	23:58 S 45° W	89°	16°



**TUSCARORA, NEVADA PLATE 5.4**  
 Relative Signal Strength In db, Relative To Average Signal Strength

12 STATION  
 203.1 RELATIVE SIGNAL STRENGTH, EVENT NUMBER

ORIGIN 41° 29.5' N LAT  
 116° 06.73' W LONG  
 DRAWN BY TERI 2/19/79

**MICROGEOPHYSICS CORPORATION**