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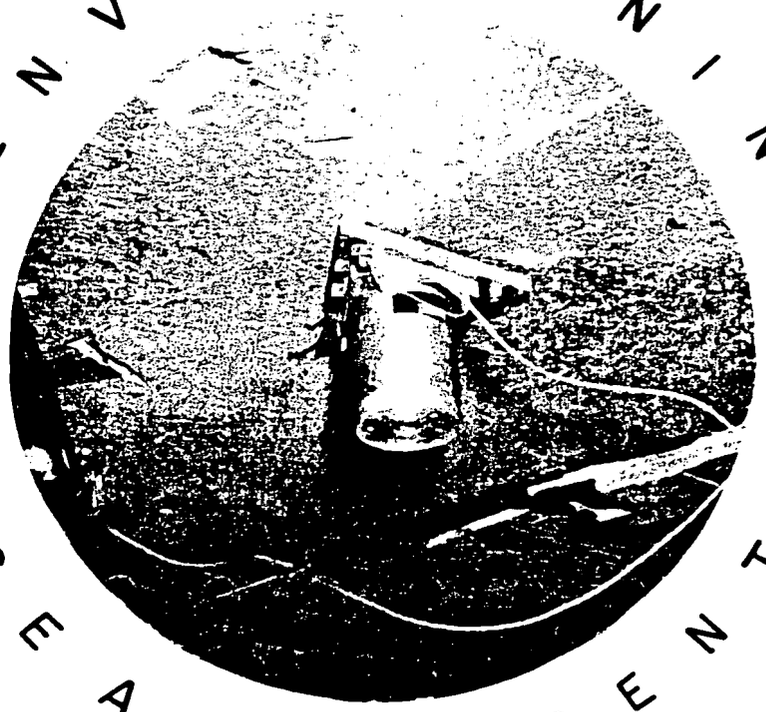

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RESEARCH DIRECTOR

February 2, 1970

DYNAMIC AND STATIC RESPONSE OF THE GOVERNMENT OIL SHALE MINE AT RIFLE, COLORADO, TO THE RULISON EVENT

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CONTENTS

	Page
Historical Description	1
Summary	2
Introduction	3
Location and General Program	4
Pillar Displacement Measurements	5
Roof Strain Extensometers	6
Roof Sag Measurements	6
Microseismic Measurements	7
Source Location Microseismic Measurements	8
Roof, Pillar and Floor Vibrations	8
Data	9
Conclusions	10

TABLES

1. Horizontal wire line extensometer data.
2. Tensile strain extensometer data.
3. Roof sag data.

ILLUSTRATIONS

Fig.

1. Map Showing Location of Oil Shale Mine and Rulison Ground Zero.
2. Gaging Panel for Pillar Displacement Measurements.
3. Idealized Plan Map of the Oil Shale Mine Showing Location of Pillar and Roof Strain Instruments.
4. Roof Strain Extensometer.
5. Idealized Section of Typical Sag Pin Installation.
6. Plan Map Showing Location of Sag Pins.
7. Plan Map Showing Location of Geophones and Microseismic Recording Apparatus.
8. Plan Map Showing the Location of the Accelerometers.
9. Plan View of Low Frequency Geophone Locations.
10. Typical Geophone Mount on Mine Roof.
11. Geophone Frequency Response Curve.
12. Sample Record - Pre-Shot Microseismic Recording.
13. Microseismic Recording - Rulison Event.
14. Sample Record - Post-Shot Microseismic Recording.
15. Reproduced Record of Noises Recorded by the Source Location Microseismic Equipment.
16. Oscillograph Display of the Rulison Event.
17. Amplitude Versus Time and Frequency, LF1.
18. Amplitude Versus Time and Frequency, LF2.
19. Amplitude Versus Time and Frequency, LF3.
20. Amplitude Versus Time and Frequency, LF4.
21. Amplitude Versus Time and Frequency, LF5.
22. Amplitude Versus Time and Frequency, LF6.

Dynamic and Static Response of the Government
Oil Shale Mine at Rifle, Colorado, to the RULISON Event

by

Robert H. Merrill, D. W. Wisecarver, Robert D. Munson
and Wilson Blake

HISTORICAL DESCRIPTION

PROJECT RULISON

Project Rulison is a joint experiment sponsored by Austral Oil Company, Incorporated, Houston, Texas, the U. S. Atomic Energy Commission, and the Department of the Interior, with the Program Management provided by CER Geonuclear Corporation of Las Vegas, Nevada under contract to Austral. Its purpose is to study the economic and technical feasibility of using underground nuclear explosions to stimulate production of natural gas from the low productivity, gas-bearing Mesaverde formation in the Rulison Field.

The nuclear explosive for Project Rulison was detonated successfully at 3:00 p.m. plus 0.1 seconds Mountain Daylight Time, September 10, 1969 at a depth of 8,425.5 feet below ground level and was completely contained. Preliminary results indicate that the Rulison device behaved about as expected; i.e., with a yield of $40 \begin{smallmatrix}+20\\-4\end{smallmatrix}$ kilotons. The wellhead of the emplacement well, Hayward 25-95A, is at an elevation of 8,154 feet above mean sea level (MSL) and is located 1,976.31 feet east of west line and 1,813.19 feet north of south line of Section 25, Township 7 South, Range 95 west of 6th P.M., Garfield County, Colorado which corresponds to geodetic coordinates of longitude 107°, 56', 53" West and latitude 39°, 24'. 21"N.

SUMMARY

The purpose of this instrumented study was to determine changes in roof or pillar displacement, the microseismic noise rate and the roof and pillar vibrations resulting from the ground motion from the RULISON event. The Oil Shale Mine was operated by the U. S. Bureau of Mines between 1947 and 1956, and more than 90 percent of the mined area is over fifteen years old. The roof rock is known to deteriorate with time and, as a consequence, there has been a history of roof falls in roof areas where deterioration is greatest. There is no evidence of a major roof fall since March 1955, and the last known small fall was in January 1966.

Between 1964 and 1967, roof sag pins were measured to determine the stability of a portion of the Oil Shale Mine. These measurements showed that the roof deterioration had reduced considerably and that the roof sag was influenced more by temperature than by deterioration.

Because the mine roof is old and there is evidence of questionable stability, there was a reason to believe that the ground motion from the RULISON event would create an unstable condition, especially if the motion were to cause resonant vibrations in roofs or pillars.

The measurements were performed to detect both dynamic and static response to the motion. Static roof displacements were measured at seven locations and static changes in roof strain measured at three places. Static changes in pillar displacement were measured at four locations. The microseismic noise rate was monitored by 15 geophones located throughout the mine. Of these geophones, 7 were used in an effort to locate sources of microseismic disturbances. Roof and pillar vibrations were measured

by 6 geophones individually arranged to measure vertical or horizontal response.

The analyses of the data leads to the conclusion that the mine responded to the ground motion generated by RULISON. The microseismic and vibration data show that the mine vibrated and generated microseisms; however, the response was back to normal within 8 to 10 seconds. The maximum acceleration, displacement and particle velocity was 422×10^{-1} in/sec^2, 241×10^{-4} in, and 754×10^{-3} in/sec; these values were measured from a geophone located on a roof with a 60-foot span and in a crosscut. This roof geometry represents the condition for least roof support in the mine.

The results of this study conclusively show that, if there were any damage created by the ground motion, the damage was too small to be seen or measured with these instruments.

INTRODUCTION

At the request of the Effects Evaluation Division, U. S. Atomic Energy Commission, the Denver Mining Research Center, U. S. Bureau of Mines, measured pre- and post-RULISON displacements, strains, microseismic noise rates and roof, floor, and pillar vibrations in rock around the underground openings of the Oil Shale Mine. The mine is located in the mahogany ledge of the Green River formation near the landmark called Anvil Points, about 8 miles west of Rifle, Colorado. The mine was operated in the period between 1947 and 1956 by the U. S. Bureau of Mines to demonstrate costs and mining techniques for the recovery of higher grade oil shales. Only a small amount of mining has been performed since 1956 to supply shales for research in processing.

The purpose of the measurements was to evaluate the effects of ground motion from the RULISON event upon the stability of the mine. The instruments and procedures used in the study are a part of the Bureau's continuing research effort to perfect instruments, techniques, and methods to design and control mine openings. The measurements included change in roof sag, roof strain, pillar displacement, microseismic noise rate, microseismic source location and roof, pillar, and floor vibrations; these measurements are briefly described and summarized in this report.

LOCATION AND GENERAL PROGRAM

The RULISON experiment involved the detonation of a nominal 40 kiloton device at 3:00 p.m., Wednesday, September 10, 1969. The shot point is located in the valley of Battlement Creek about 7 air miles from the town of Grand Valley, and about 8 air miles from the Oil Shale Mine (see Fig. 1). The shot hole is in the Tertiary and Upper Cretaceous (Mesaverde) beds of the Piceance Creek Basin; the Mesaverde formation (at a depth of about 6,200 feet) contains interspersed lenticular sandstones which are the gas-bearing rocks of the Rulison field. The shot point was at a depth of 8,425.5 feet which is approximately sea level elevation.

At the time of detonation, there were 23 persons at the safety control point 2 (see Fig. 1) and no personnel were located at points nearer the mine. From this point, the observers could distinctly feel the ground motion and observe falling rocks and clouds of dust on or near the cliff face about the mine area.

Before the detonation, all of the station instruments were read, and the tape recorders or direct-writing oscillographs placed in operation. The personnel were evacuated from the mine to safety control point 2 and

were not allowed to enter the mine yard or mine until about 1 hour following detonation.

Instruments to measure changes in roof sag, roof strain, pillar displacement, microseismic noises, microseismic noise location, roof, floor and pillar vibration were installed between August 18 and 29. Measurements began on the existing roof sag pins April 22; all other measurements began between August 25 and September 3. Continuous recordings were taken on some instruments during the period of the detonation. All measurements were discontinued September 11. Descriptions of the instrumentation, data, and results, are summarized as follows:

Pillar Displacement Measurements

Pillar displacements were measured with wire line extensometers. Any change in distance in excess of 0.005 inch netween adjacent pillars, or along a wall in the mine could be detected and measured with the extensometer.

The instrument consists of an anchor on one pillar connected by invar wire to a gaging panel on an adjacent pillar. The gaging panel is illustrated in figure 2. The invar wire was horizontally tensioned by attaching a weight to the free end after the wire was properly positioned in the groove of the aligning pulley. Once the wire was tensioned, a sliding post (attached to the wire) was in such a position that its distance from a reference post on the panel could be measured. A dial micrometer having a 0.001 inch sensitivity and 1.0 inch range was used to gage the distance between the sliding and reference posts (see Fig. 2).

Three extensometers were installed between pillars. Their locations and measured distances are shown in figure 3. Pillar B-4 was selected as a reference pillar. Extensometer wires connected pillars B-2, B-6, and D-5 to the reference pillar.

A fourth extensometer was installed along the left rib of Able haulageway. The extensometer wire was between points 114 feet apart. Therefore, because the extensometer could detect changes greater than 0.005 inch, the strain sensitivity over 114 feet is:

$$\frac{0.005 \text{ in}}{114 \text{ ft} \times 12 \text{ in}} = \frac{0.005 \text{ in}}{1{,}368 \text{ in}} = 3.65\ \mu \text{ in/in or} \approx 4\ \mu \text{ in/in.}$$

The average modulus of elasticity of the oil shale rock is $\approx 3 \times 10^6$ psi. Therefore, a static change in horizontal stress greater than 12 psi would be expected to create a measurable displacement and strain.

Roof Strain Extensometers

Roof strain extensometers were installed in the roof along Able drift near stations 1A, 2A, and 3A (see Fig. 3). The extensometer consists of a rod anchored at one point on the roof, and a fixed reference point anchored 36 inches from the other anchor. An adjustable reference point and a linear, variable differential transformer (LVDT) are located near the fixed reference point (see Fig. 4). The reproducibility of the extensometer measurement is about 20 μ inches. Therefore, the strain sensitivity is $\frac{20 \times 10^{-6} \text{ in}}{36 \text{ in}}$ or $\approx 5\ \mu$ in/in strain.

The extensometers were oriented so that measurements would be normal to the west rib of Able drift. Therefore, any permanent displacement greater than 20 μ inches in the roof (along a line parallel to the span), or roof strain greater than 5 μ inches, could be detected with this instrument.

Roof Sag Measurements

Changes in roof sag were made by measuring the distance between rods anchored at points 5, 10, and 15 feet in the roof, and a reference rod anchored about 6 inches in the roof. A typical sag pin installation is

illustrated in figure 5. Briefly, each instrument consists of two rods anchored in a borehole drilled normal to the back. The reference rod is about 1 to 1-1/2 inches from the adjacent rod anchored in the bottom of the other borehole. A group of one or more sag pins is called a sag station. The distance between the two rods was measured directly with a standard machinist's depth gage. Sag pins were anchored at roof depths of 5, 10, and 15 feet at stations 1, 2, 3, and 4 (see Fig. 6). Sag pins were anchored at depths of 15 feet at stations 1A, 2A, and 4A, and at a depth of 10 feet at station 3A. The distance between the end of the anchored rod and the end of the reference pin was measured three times and an average computed. The reproducibility of this measurement is largely dependent upon the operator; in this investigation the reproducibility was 0.010 inch, or less.

Microseismic Measurements

Microseismic apparatus was located at various points in the mine to detect self-generated, subaudible, rock noise. Rock under stress normally emits these subaudible noises, and a change in the number of noises per unit time and the amplitude of these noises semi-quantitatively indicate a change in stress and/or the stability of the mine rock.

Nine geophones were placed in boreholes at locations illustrated in figure 7 and their output cabled to amplifying and recording instruments housed in a trailer at the portal of adit 2. Recordings of microseismic noises were made before, during, and after the shot.

Source Location Microseismic Measurements

In addition to the conventional microseismic monitoring (low recording speed) of the underground workings, broad-band microseismic monitoring (high recording speed) were made in an effort to locate any unusual microseismic noise sources. This equipment and procedure is capable of locating the origin of any rock noise detected, hence, allowing areas of instability to be accurately defined and mapped.

A seven-channel, broad-band microseismic system was used with seven accelerometer locations as shown on figure 8. Accelerometers MF 2, MF 3, and MF 4 were attached to the roof and the remaining geophones were attached to rock in the lower part of pillars.

To determine the microseismic background rate, measurements were made on the 3rd, 4th, and 10th of September, prior to the RULISON shot, and on September 10 and 11 after the shot. Measurements consisted of recording microseismic data on magnetic tape during a 48-minute interval. During the pre-shot periods calibration shots (150 grams in a water-stemmed hole) were detonated to determine P- and S-wave velocities in the mine structure. Other than the noises from the calibration shots, no rock noises were detected during the pre-shot monitoring. Continuous recording began 13 minutes prior to the RULISON shot and continued for 35 minutes following the shot.

Roof, Pillar and Floor Vibrations

Low frequency microseismic equipment was installed at locations shown in figure 9. Geophones LF 1, LF 2, and LF 4 were mounted on the roof. LF 3 was on the floor and LF 5 and LF 6 were mounted on a pillar halfway between the floor and roof. Figure 10 shows a typical geophone mount on the roof.

The geophones were standard velocity type, with a 2-cycle natural frequency. Each geophone output was shunted with 1500 ohms to flatten the response curve. A typical response curve is shown in figure 11. All data were recorded on magnetic tape, using a 14-channel FM magnetic tape recorder. A tape speed of 7-1/2 IPS was used to provide maximum running time while retaining good signal-to-noise ratio (48 db), and frequency response (dc to 5 k Hz). The data were dual-recorded with a separation of 14 db, with the high gain being unity.

Several 150-gram calibration shots were detonated on September 10, in two drill holes (see Fig. 9) in the mine. These data were used to check geophone polarity, evaluate the geophone mountings and location, and to determine P and S velocities.

The recording system was started 15 minutes before shot time, 3:00 p.m. MDT (1500 hours), and allowed to run for 1-3/4 hours after the shot to record resultant after-shocks or low frequency microseismic noises.

DATA

Data from the wire line extensometers is given in table 1. The three measurements taken within a measurement cycle and the average are given. Installation and initial readings were completed September 3, 1969. The long spans of wire were extremely vulnerable to personnel traffic through the mine. However, after September 3, the wires were not damaged either by personnel or mine equipment.

Data from the roof strain instruments are given in table 2.

Sag data are given in table 3. Although readings at each station were obtained by making five measurements and taking the average, for simplicity, only the average is given in the table.

Representative samples of microseismic recordings showing pre-shot, shock arrival, and post-shot periods are given in figures 12, 13, and 14, respectively. Recording times as shown in the figures are short compared with the longer periods of pre- and post-shot recording; however, these records are representative of the data obtained over the longer periods.

A copy of the record taken by the source location microseismic equipment, for a period of about 18 seconds before and about 80 seconds after the detonation, is shown in figure 15. The response was high on all channels with the exception of MF 3, which was inoperative. There was an abundance of noise for about 8 to 10 seconds, and most of the noise following 10 seconds has been identified as dust particles striking the accelerometers. There was no identifiable source of sustained noise; rather, the noises were general and randomly located throughout the area of investigation.

The data from measurements of vibrations in the roof, pillars and floor were reproduced on direct-writing oscillographs, and these data were digitized and computer processed for amplitude spectra, displacements, and accelerations. A typical oscillograph display of the data is shown in figure 16.

The lower portion shows a compressed time scale to allow decoding of the WWVB signal and the expanded upper portion for measuring the travel time. The travel time for P is 3.597 seconds for a distance of 7.89 miles giving a velocity of 11,582 feet/second.

The analog data were digitized and computer processed to provide amplitude spectra, displacements, and accelerations. Figures 17 through 22 show these results as well as the original velocity data. One interesting

observation is, as the unsupported roof area around the geophone increases so does the particle velocity amplitude.

CONCLUSIONS

The ground motion from the Rulison event created a disturbance in the rock around the Oil Shale Mine, but the disturbance was very short and did not create any visible or measurable damage.

To illustrate, the measured vibrations in the roof, pillars and floor occurred upon the arrival of the ground motion, and were no longer detectable 20 seconds later. There was no evidence of resonant vibrations in the roof or any other major difference between vibrations measured at the various points. There is a minor difference between the amplitude of vibrations measured in the roof near sag stations 1A and 3A and at the intersection of Charlie Haulageway and Cross-Cut 5 (see Figs. 17 and 20). The vibrations were smallest at station 1A and largest at the intersection. This result is to be expected because the roof spans at 1A and 3A are 50 and 60 feet, respectively, and the roof is "bound" on each side by a pillar. The roof span at the intersection is 60 feet, and the roof is not bound on two sides by pillars. The maximum measured acceleration was 422×10^{-1} in/sec^2, the maximum displacement was 241×10^{-4} in, and the maximum particle velocity was 754×10^{-3} in/sec.

The maximum response from the source location instrumentation was also from the roof at the Charlie Haulageway and Cross-Cut 5 intersection. The vibrations from the ground motion created noises at all points of measurement; the noises began at the start of ground motion and only noise from dust particles were detected 10 seconds after the arrival. The noises were abundant during that period but there was no evidence that the noises

were being generated at a few common sources. Rather, the noises appeared to be from randomly located points in the rock.

Because the instruments used to measure roof, pillar and floor vibrations are also capable of detecting low frequency microseismic noises, the records were examined for any noises occurring from the ground motion. No vibrations other than the group within 20 seconds following the ground motion could be found.

The wide-range microseismic equipment did not detect any appreciable rock noise 20 seconds after the shot (see Fig. 13). As in all of the other measurements of seismic response, the greatest amplitudes and largest number of noises appeared with the first arrival, and gradually lessened to almost zero response within 10 seconds.

Although the vibrations are considered small, and the microseismic noises were both small and of short duration, there is always the possibility that the motion will create a permanent displacement in the roof or pillars. This was not the case at the Oil Shale Mine. Examination of tables 1, 2, and 3 discloses that the roof did not sag, nor did it suffer a significant change in strain, and there was no measurable displacement between or along pillars.

To illustrate, all of the measured pillar displacements were less than the reproducibility of the instrument (0.005 inch), the maximum roof strain was 14 μ inches at station 2A, which is well below the reproducibility, and the maximum roof sag was 0.008 inch, again, less than the reproducibility of the instrumentation.

Visual inspection of the mine and mine road is the responsibility of other personnel and is not a part of this report. However, the personnel in the group that made the measurements herein are all in agreement that, if the ground motion created any damage to the Oil Shale Mine rock, the damage is so small that it could neither be seen nor measured.

TABLE 1. -Horizontal wire line extensometer data

Extensometer - No.	Length (feet)	Date	Reading 1	Reading 2	Reading 3	Average	Change (inches)	Remarks
HE-1	84.5	9/ 3/69	0.526	0.527	0.526	0.526	-	Wire broken. Replaced 9/5/69.
		9/10/69	0.392	0.392	0.394	0.393	-	Pre-Shot Reading.
		9/10/69	0.389	0.386	0.391	0.389	- 0.004	Post-Shot Reading.
		9/11/69	0.388	0.392	0.392	0.391	- 0.002	
HE-2	75.5	9/ 3/69	0.456	0.457	0.453	0.455	-	Wire broken. Replaced 9/5/69.
		9/10/69	0.301	0.305	0.302	0.303	-	Pre-Shot Reading.
		9/10/69	0.300	0.296	0.297	0.298	0.005	Post-Shot Reading.
		9/11/69	0.302	0.300	0.298	0.300	0.003	
HE-3	114.8	9/ 3/69	0.682	0.680	0.678	0.680	-	
		9/10/69	0.682	0.682	0.684	0.683	+ 0.003	Pre-Shot Reading.
		9/10/69	0.680	0.680	0.682	0.681	+ 0.001	Post-Shot Reading.
		9/11/69	0.680	0.679	0.682	0.680	0.000	
HE-4	80.0	9/ 3/69	0.334	0.335	0.335	0.335	-	Wire broken. Replaced 9/5/69
		9/10/69	0.416	0.419	0.415	0.417	-	Pre-Shot Reading.
		9/10/69	0.416	0.419	0.412	0.416	- 0.001	Post-Shot Reading.
		9/11/69	0.416	0.416	0.417	0.416	- 0.001	

TABLE 2. Tensile strain extensometer data

Date	Station 1A	Change	Station 2A	Change	Station 3A	Change	Remarks
9/3/69	-260 μ in.	-	-490 μ in.	-	-670 μ in.	-	At station 1A - LVDT reset between 9/3 and 9/4 readings.
9/4/69	-504 μ in.	-	-490 μ in.	-	-650 μ in.	+20 μ in.	
9/5/69	-560 μ in.	-56 μ in.	-495 μ in.	- 5 μ in.	-670 μ in.	-	
9/10/69	-540 μ in.	-36 μ in.	-500 μ in.	-10 μ in.	-700 μ in.	-30 μ in.	
9/10/69	-560 μ in.	-56 μ in.	-520 μ in.	-25 μ in.	-690 μ in.	-20 μ in.	Pre-shot reading.
9/11/69	-520 μ in.	-16 μ in.	-500 μ in.	-10 μ in.	-670 μ in.	-	Post-shot reading.

TABLE 3. Roof sag data

Date	Depth (feet)	Station 1*	Change*	1A*	Change*	2*	Change*	2A*	Change*	3*	Change*	3A*	Change*	4*	Change*	4A*	Change*
Apr. 22	5	1.110				0.607				0.169				0.963			
	10	1.746				1.390				1.091		0.803		0.793			
	15	0.996		0.947		1.062		0.591		0.968				0.645		0.391	
Aug. 11	5	1.111	+0.001			0.608	+0.001			0.165	-0.004			0.997	+0.034		
	10	1.740	-0.006			1.375	-0.015			1.095	+0.004	0.789	-0.014	0.797	+0.004		
	15	0.994	-0.002	0.925	-0.012	1.039	-0.023	0.583	-0.008	0.933	-0.035			0.617	-0.028	0.390	-0.001
Aug. 20	5	1.118	+0.008			0.625	+0.018			Not Measured				0.986	+0.023	Not Measured	
	10	1.745	-0.001			1.375	-0.015					0.792	-0.011	0.800	+0.007		
	15	0.983	-0.013	0.927	-0.010	1.039	-0.023	0.579	-0.012					0.625	-0.020		
Sept. 4	5	1.110	0.000			0.623	+0.016			0.162	-0.007			0.997	+0.034		
	10	1.753	+0.007			1.377	-0.013			1.096	+0.005	0.796	-0.007	0.799	+0.006		
	15	0.977	-0.019	0.934	-0.003	1.035	-0.027	0.574	-0.017	0.928	-0.040			0.615	-0.030	0.383	-0.008
Sept. 11	5	1.111	+0.001			0.629	+0.022			0.164	-0.005			0.992	+0.029		
	10	1.745	-0.001			1.375	-0.015			1.097	+0.006	0.797	-0.006	0.800	+0.007		
	15	0.981	-0.015	0.929	-0.008	1.029	-0.033	0.576	-0.015	0.926	-0.042			0.620	-0.025	0.380	-0.011
Change Sept. 4-11			+0.001				+0.006				+0.002				-0.005		
			-0.008				-0.002				+0.001	+0.001			+0.001		
			+0.004		-0.005		-0.006		+0.002		-0.002				+0.005		-0.003

*Measured in inches.

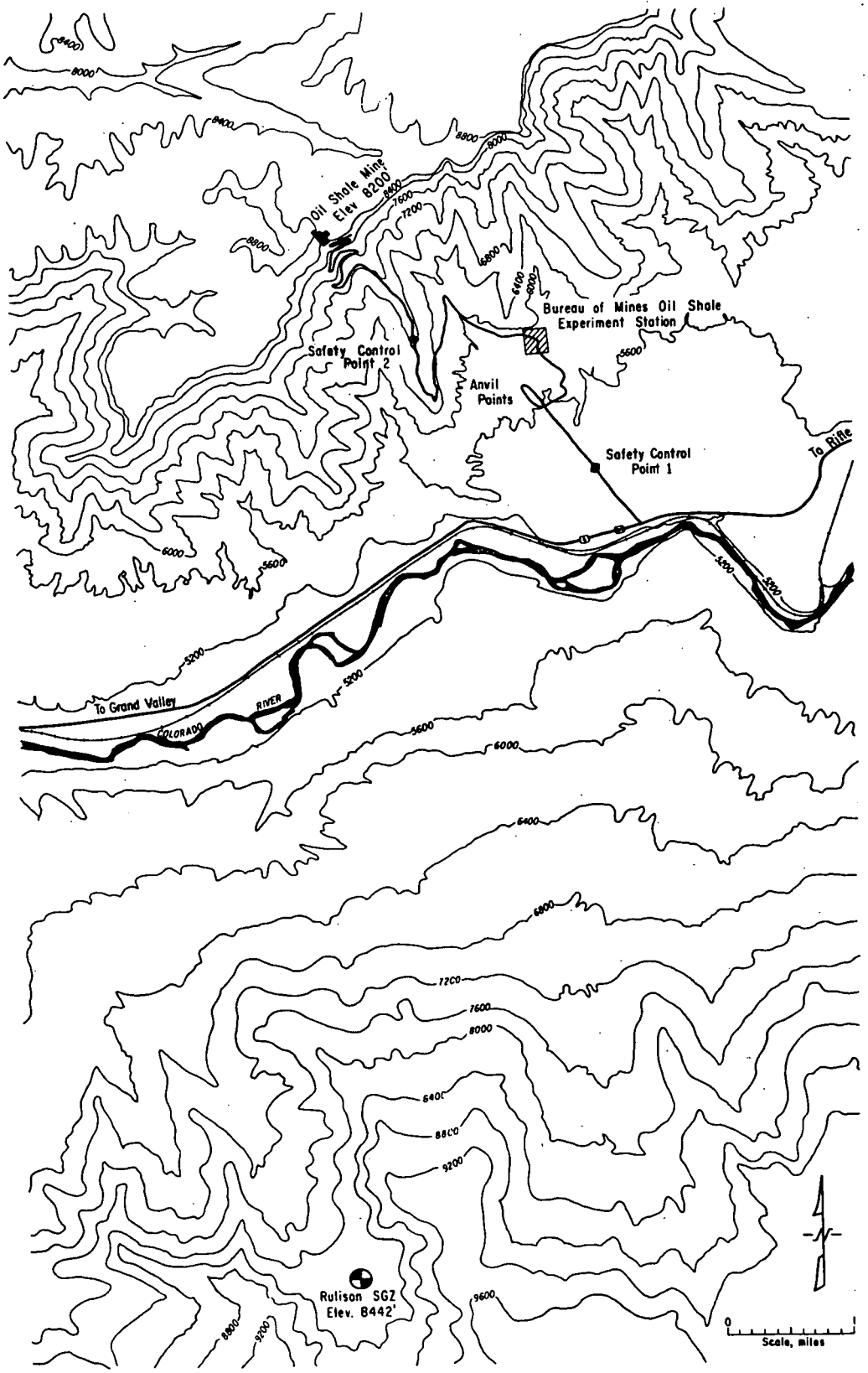


FIGURE 1.- Map Showing Location of Oil Shale Mine and Rulison Ground Zero

FIGURE 2.– Gaging Panel for Pillar Displacement Measurements.

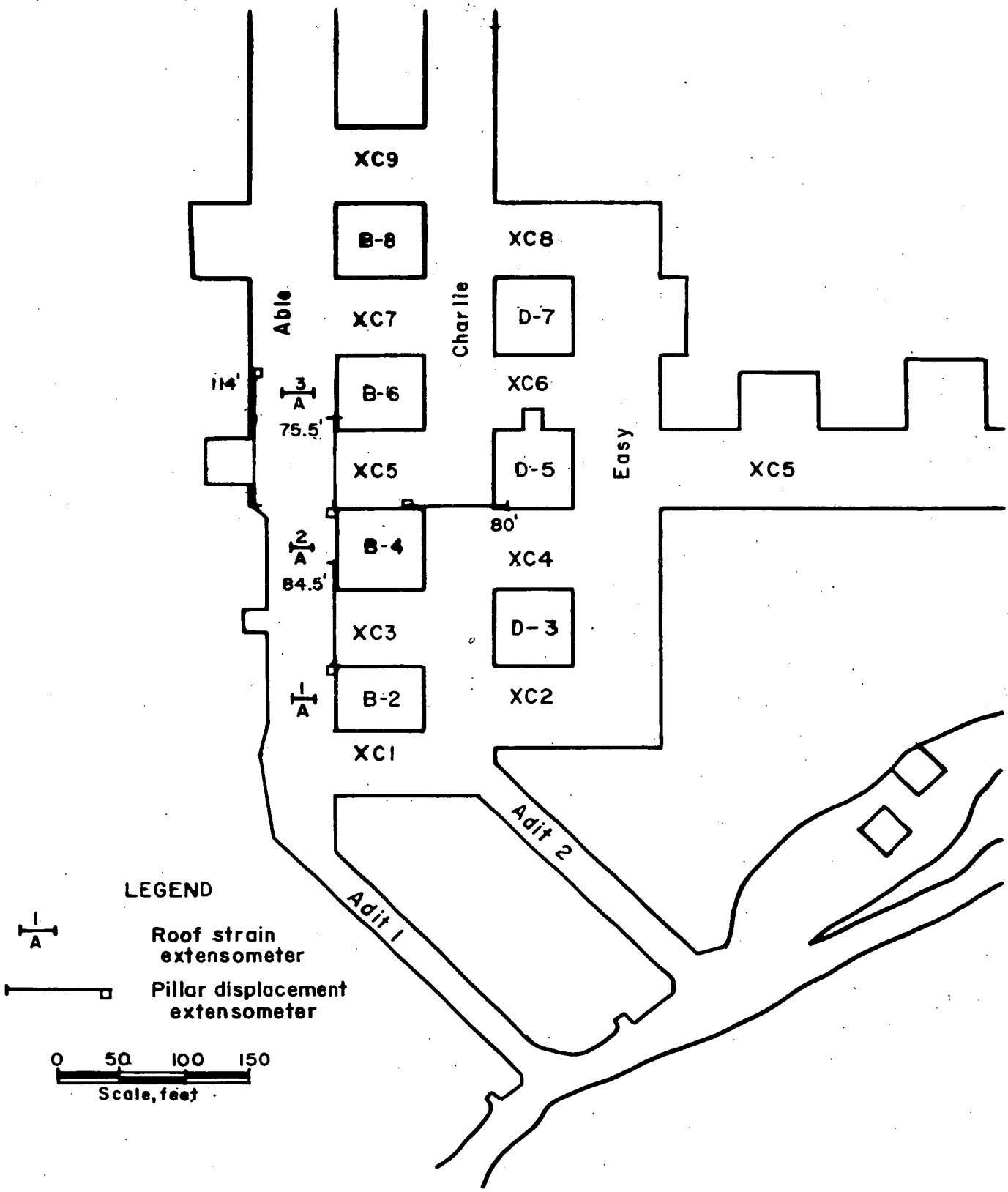


FIGURE 3.- Idealized Plan Map of the Oil Shale Mine Showing Location of Pillar and Roof Strain Instruments.

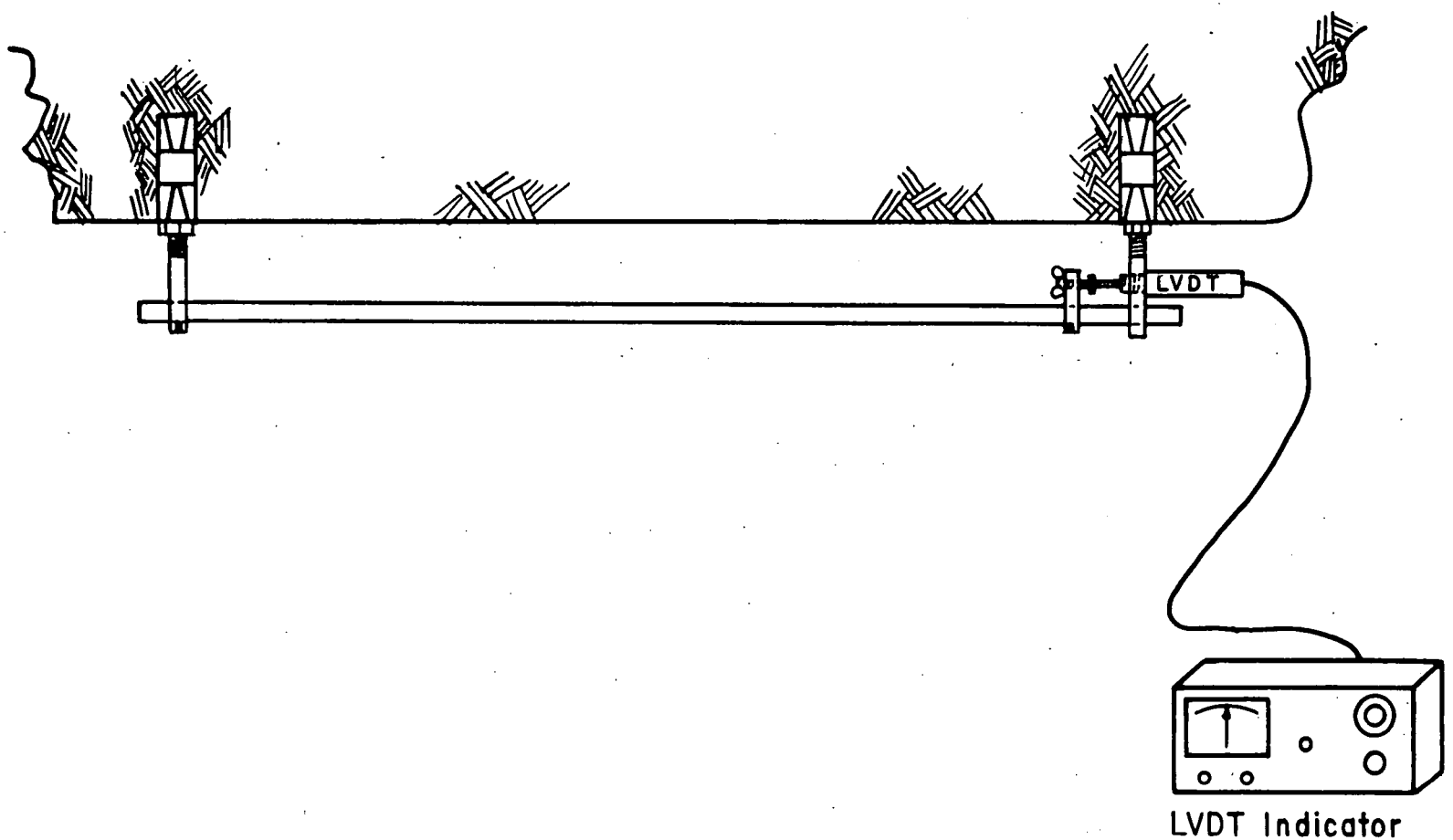


FIGURE 4.- Roof Strain Extensometer.

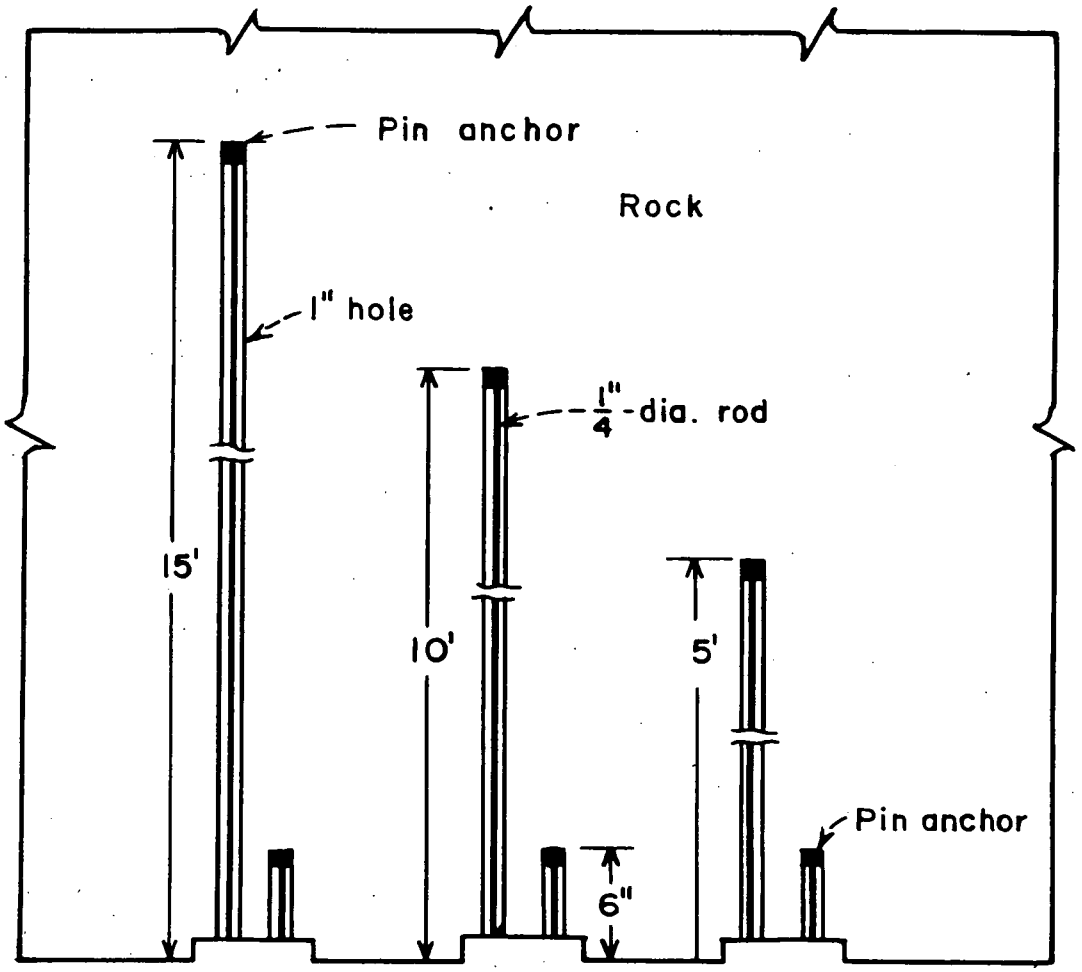


FIGURE 5.– Idealized Section of Typical Sag Pin Installation.

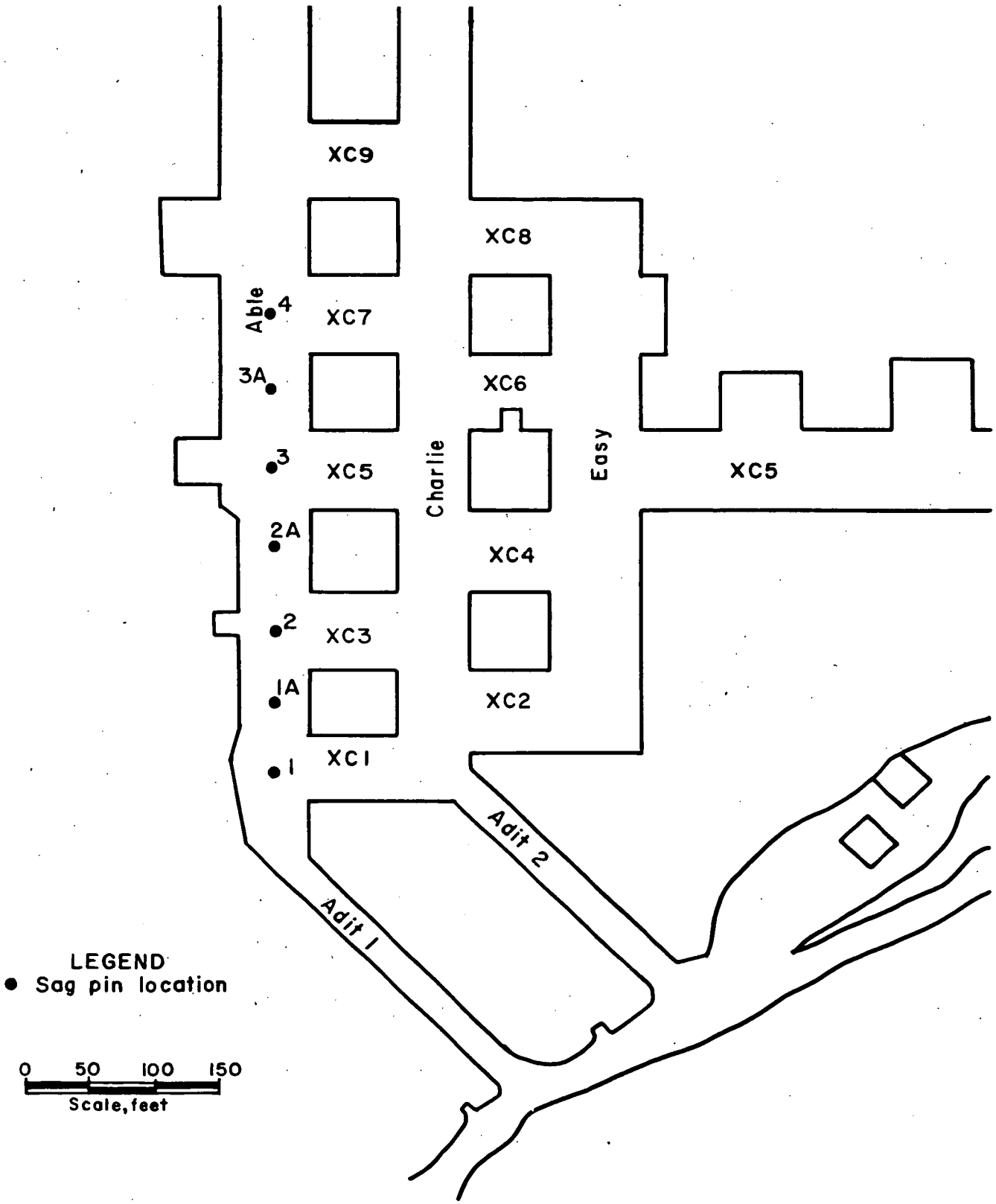


FIGURE 6.- Plan Map Showing Location of Sag Pins.

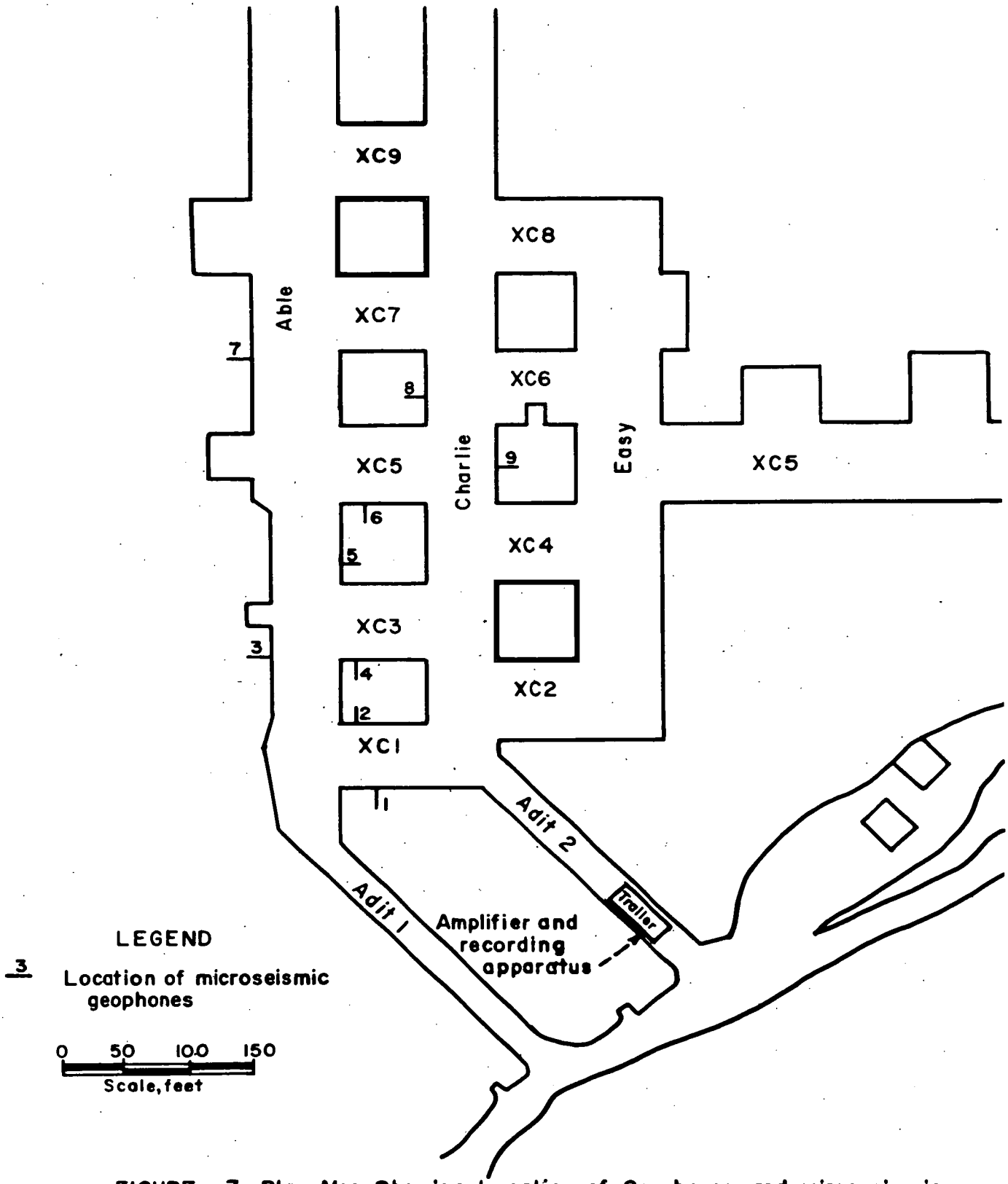


FIGURE 7.- Plan Map Showing Location of Geophones and microseismic Recording Apparatus.

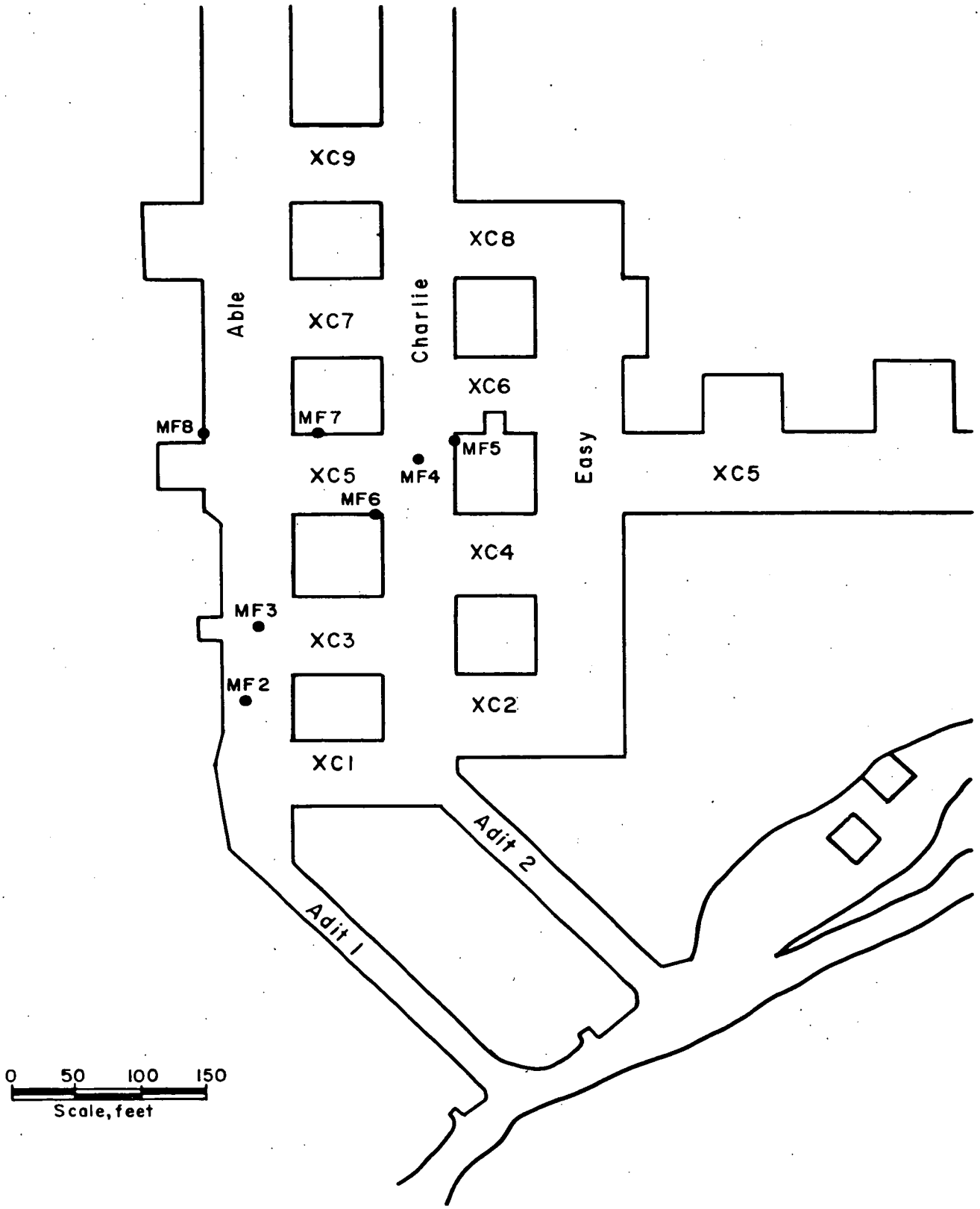


FIGURE 8.-Plan Map Showing the Location of the Accelerometers.

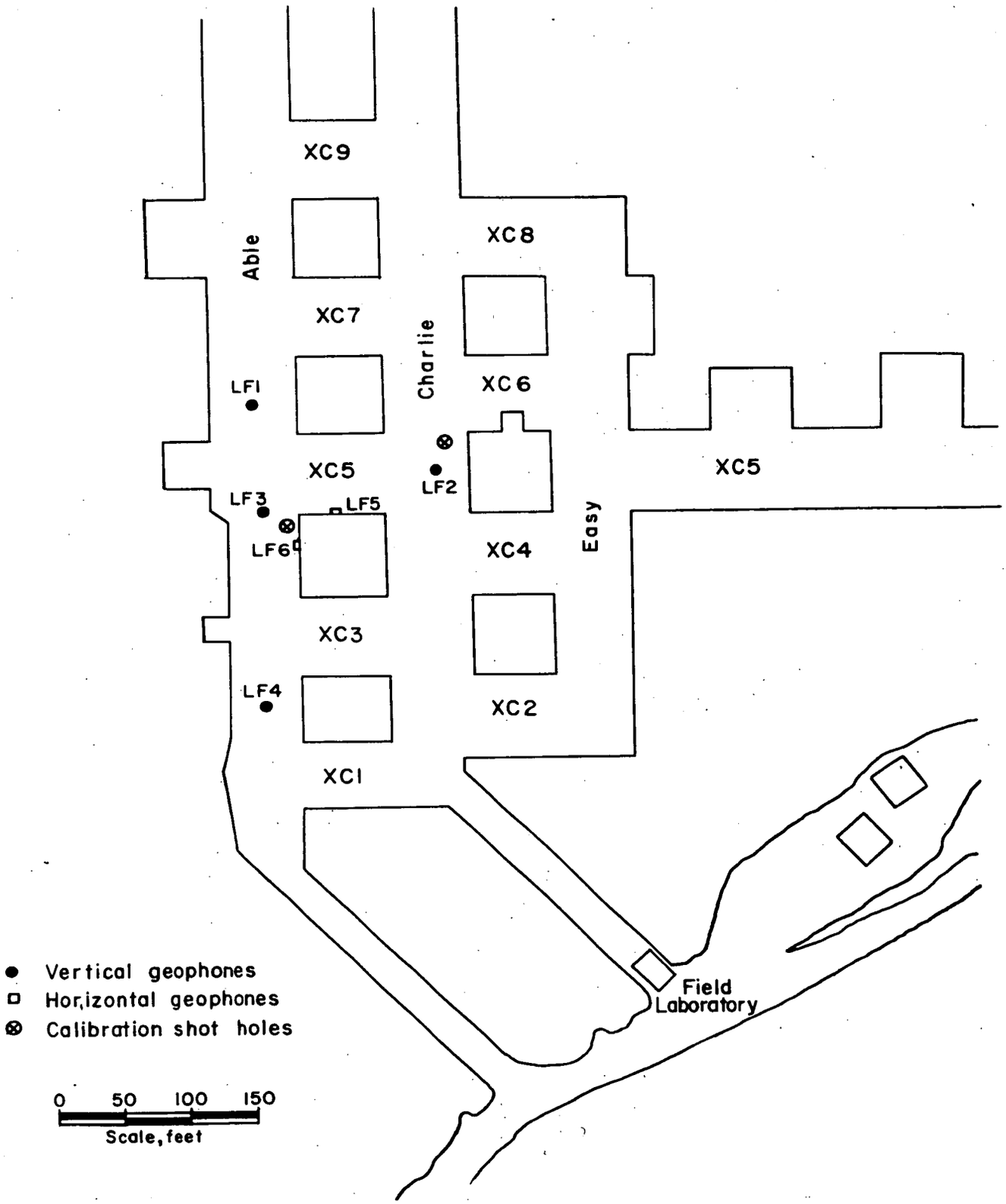


FIGURE 9.- Plan View of Low Frequency Geophone Locations.

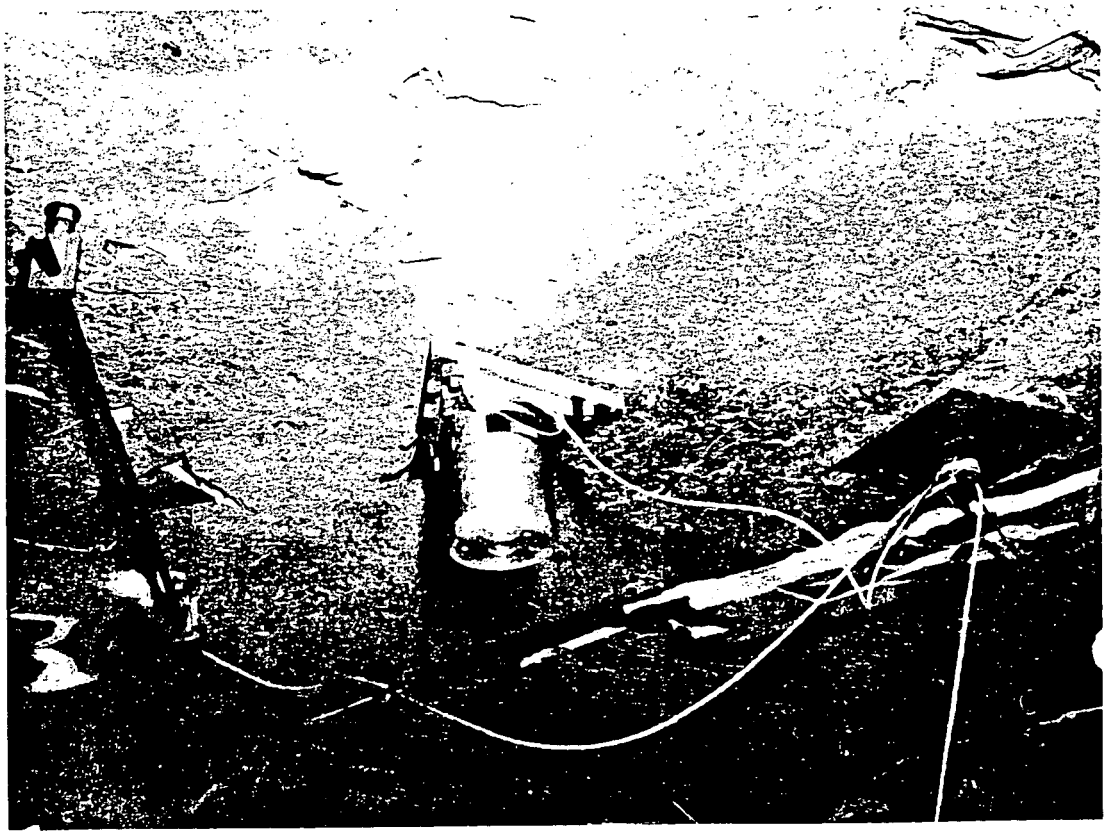


FIGURE 10.- Typical Geophone Mount on Mine Roof.

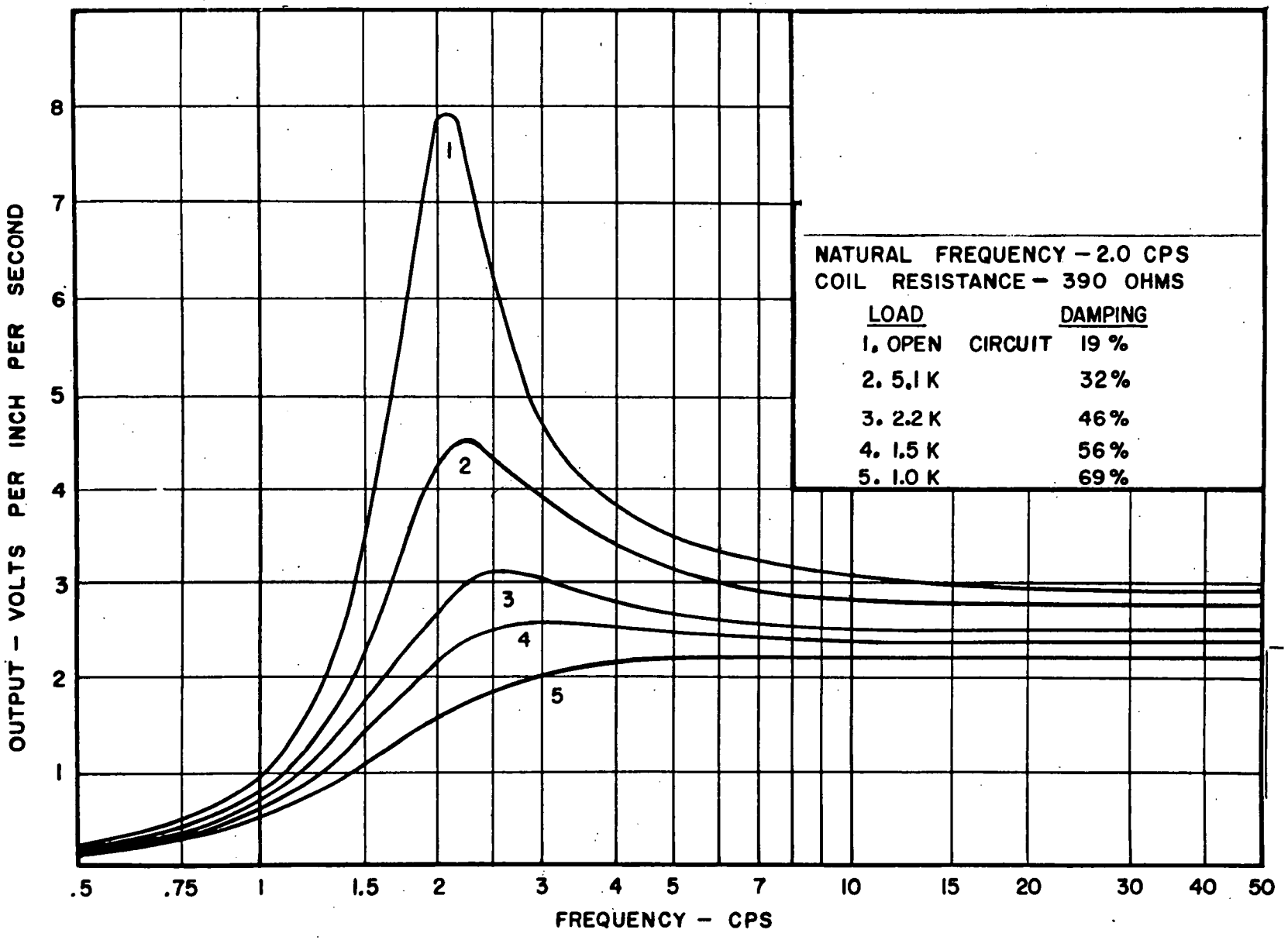


FIGURE 11.-Geophone Frequency Response Curve.

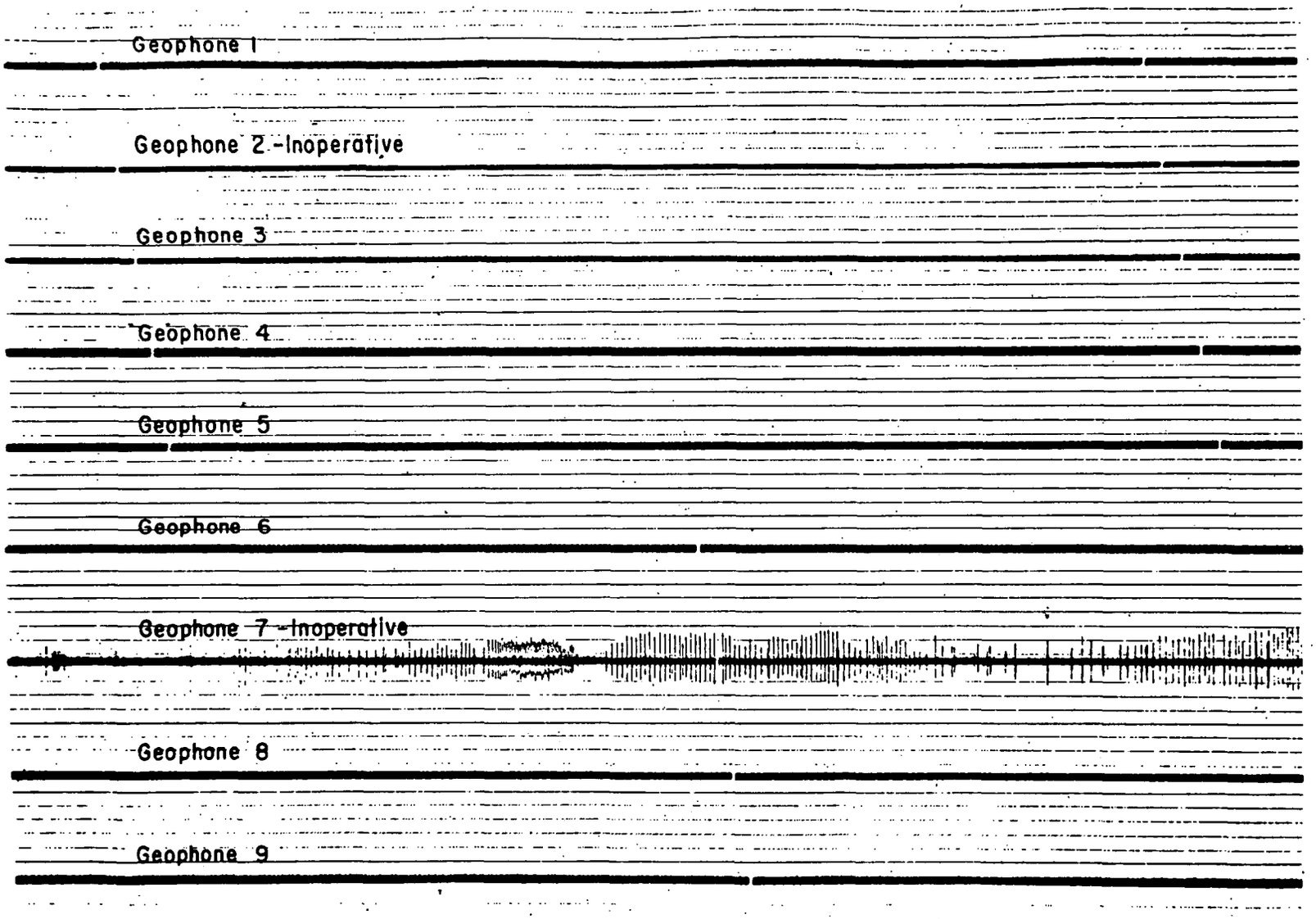


FIGURE 12.-Sample Record-Pre-Shot Microseismic Recording

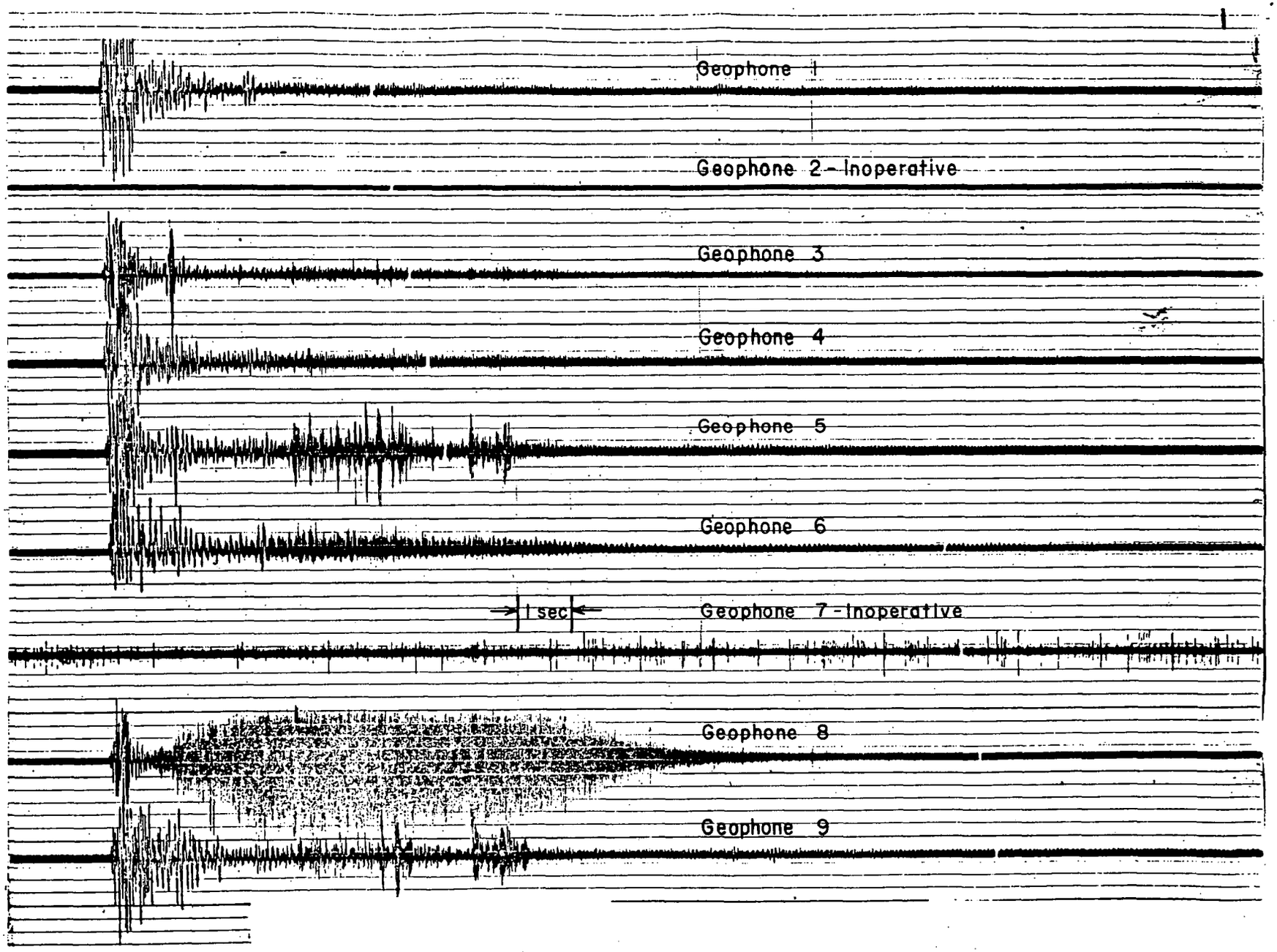


FIGURE 13.- Microseismic Recording - Rulison Event.

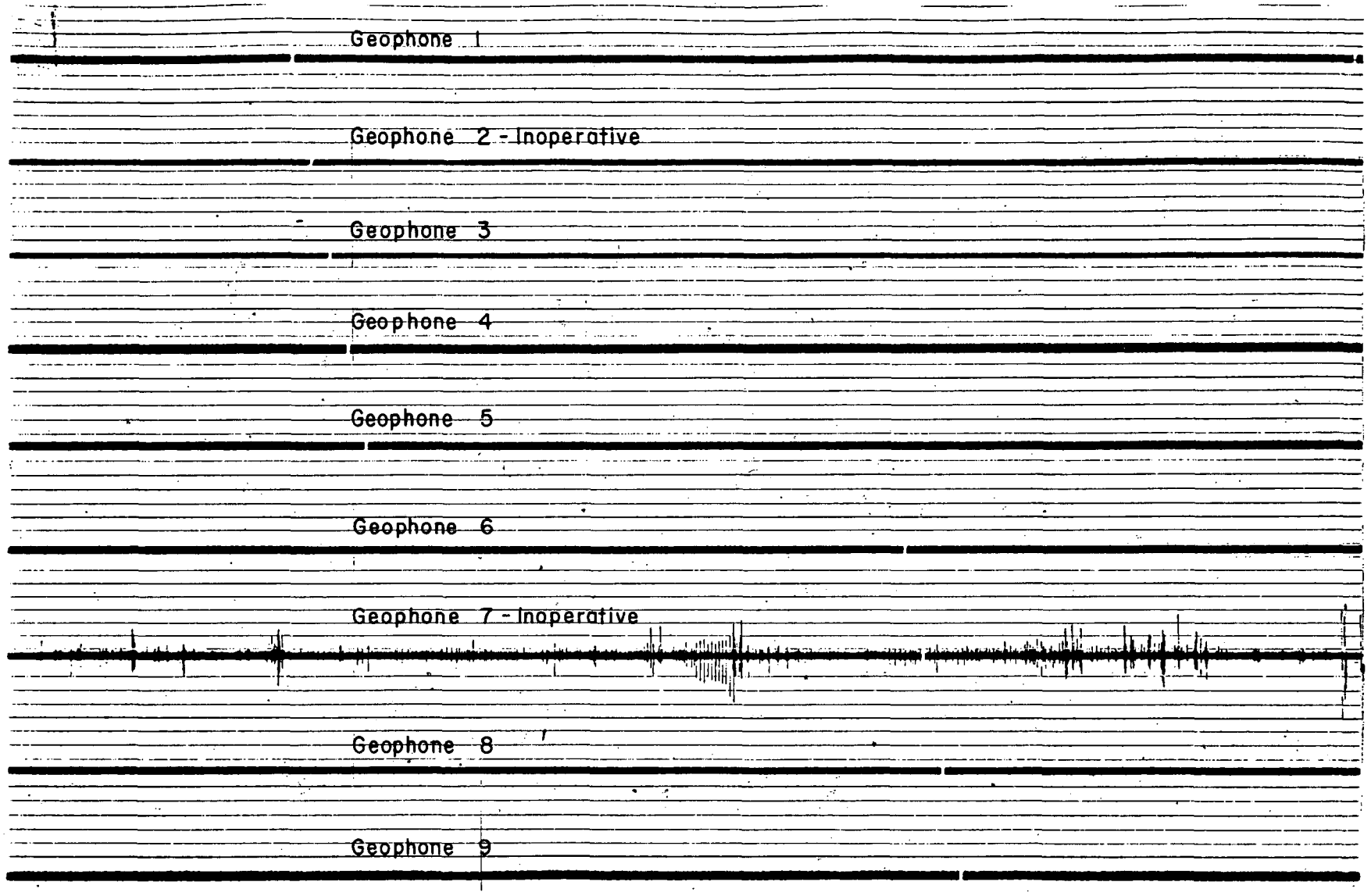


FIGURE 14.- Sample Record - Post Shot Microseismic Recording

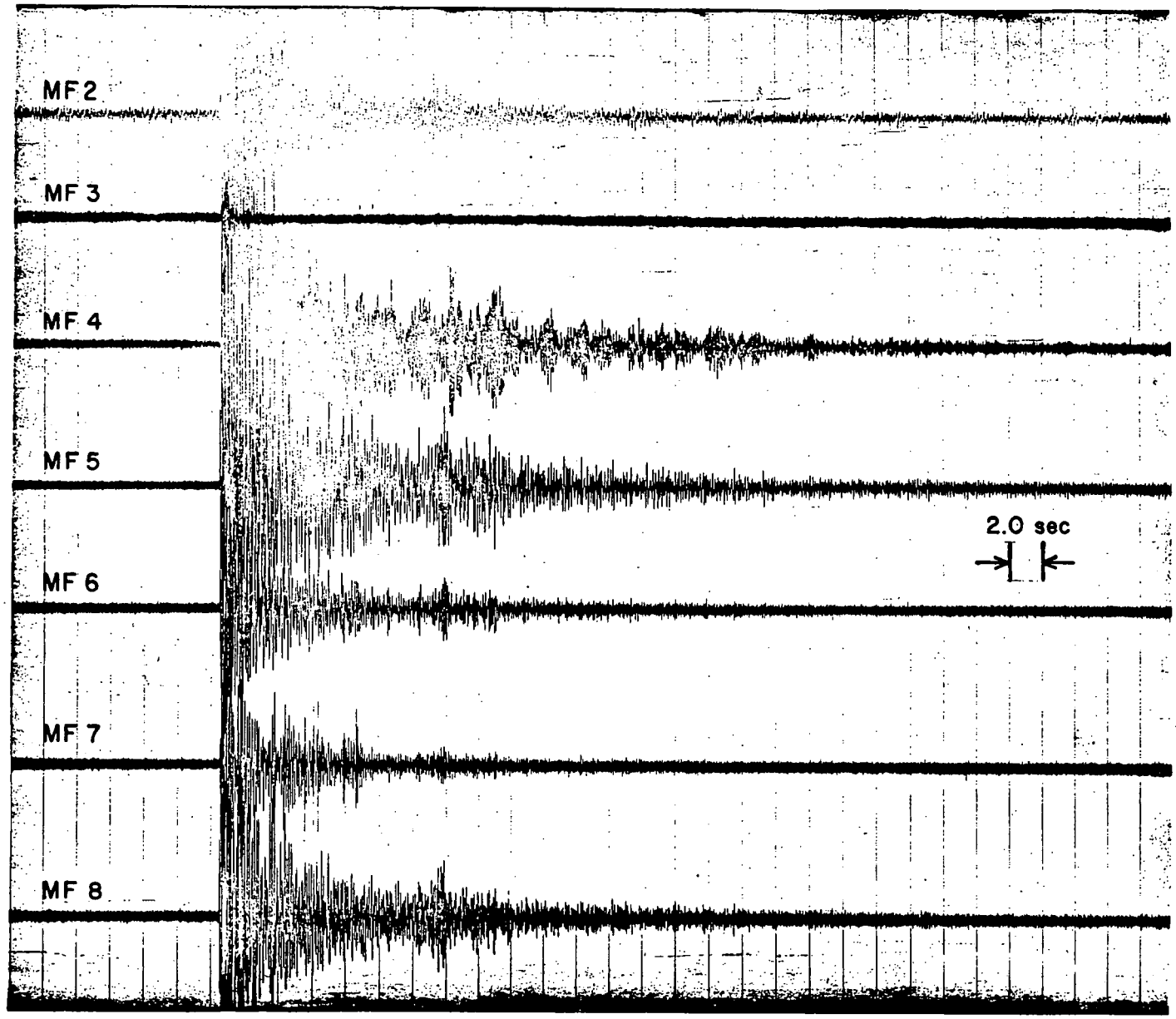


FIGURE 15.–Reproduced Record of Noises Recorded by the Source Location Microseismic Equipment.

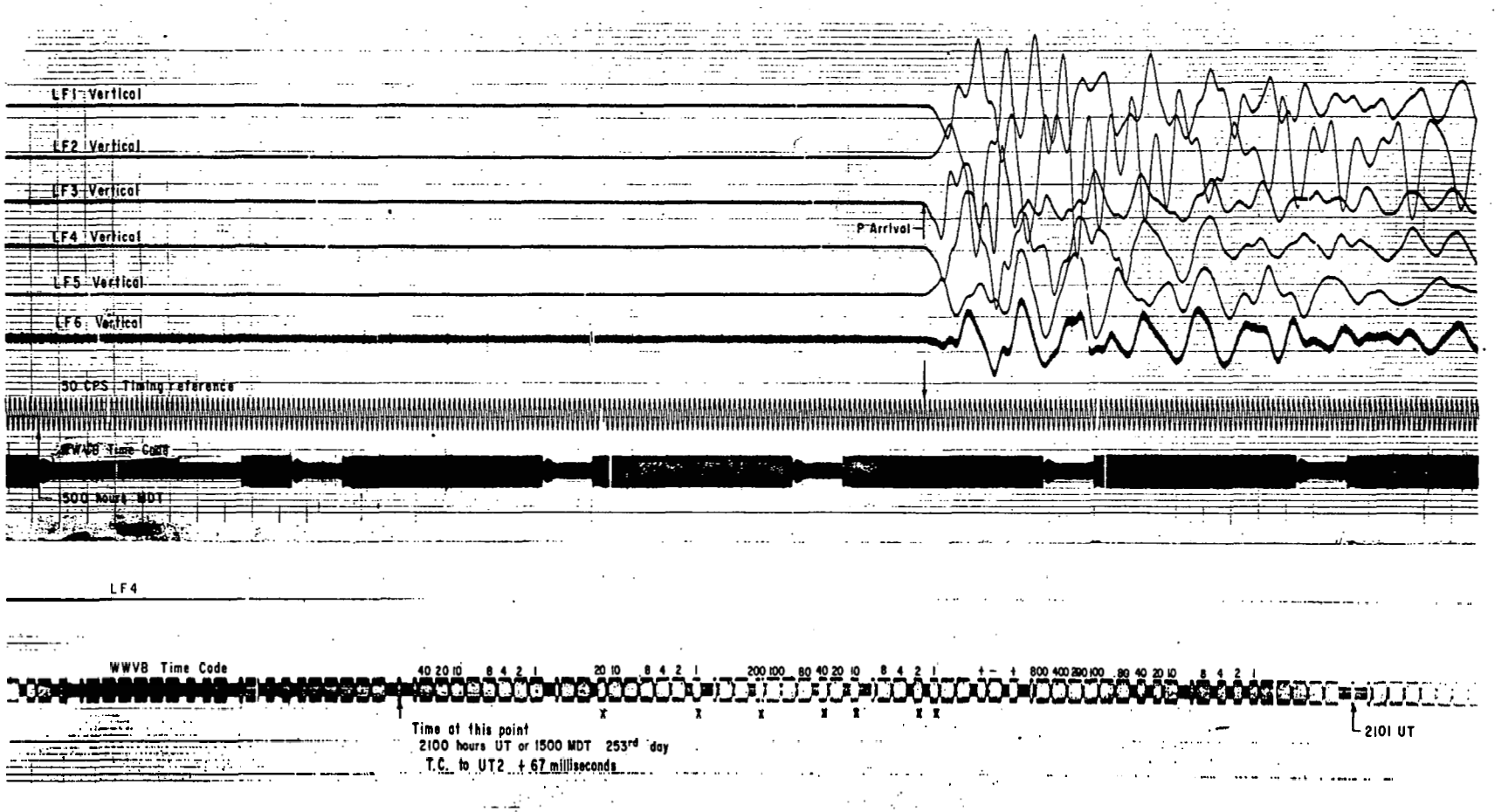
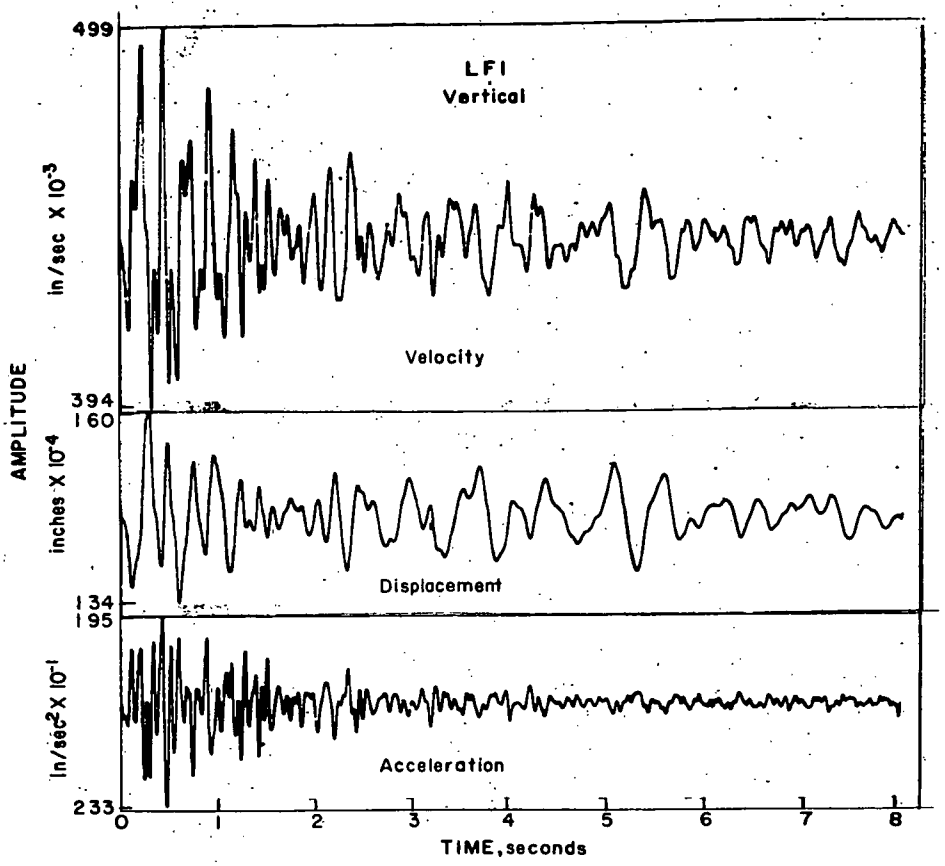


FIGURE 16.-Oscillograph Display of the Rulison Event.



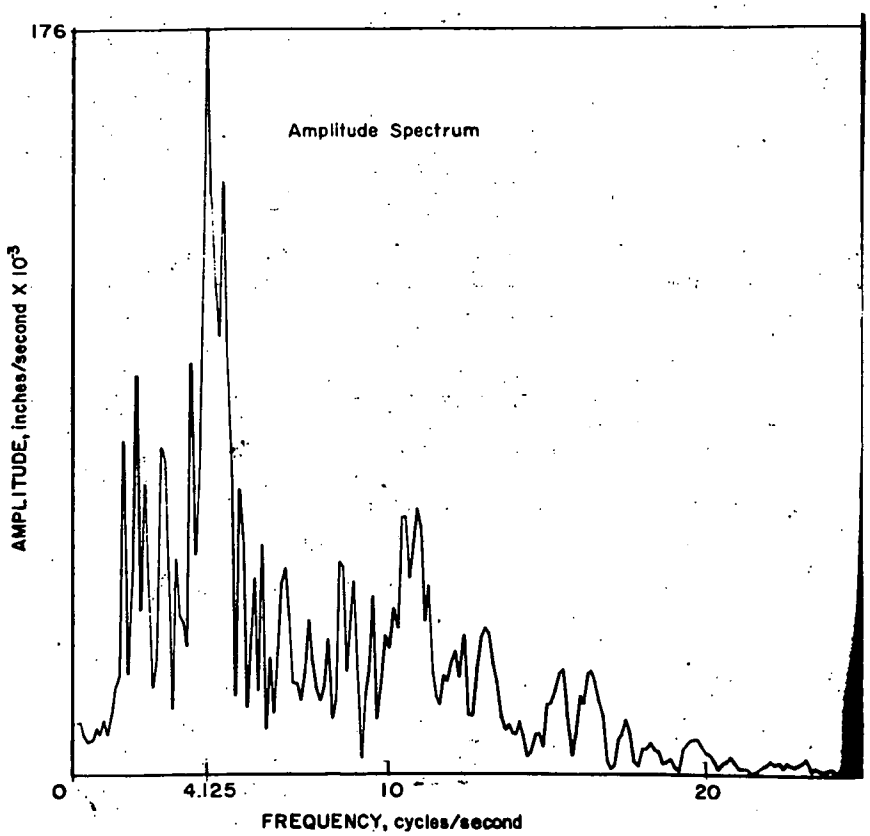
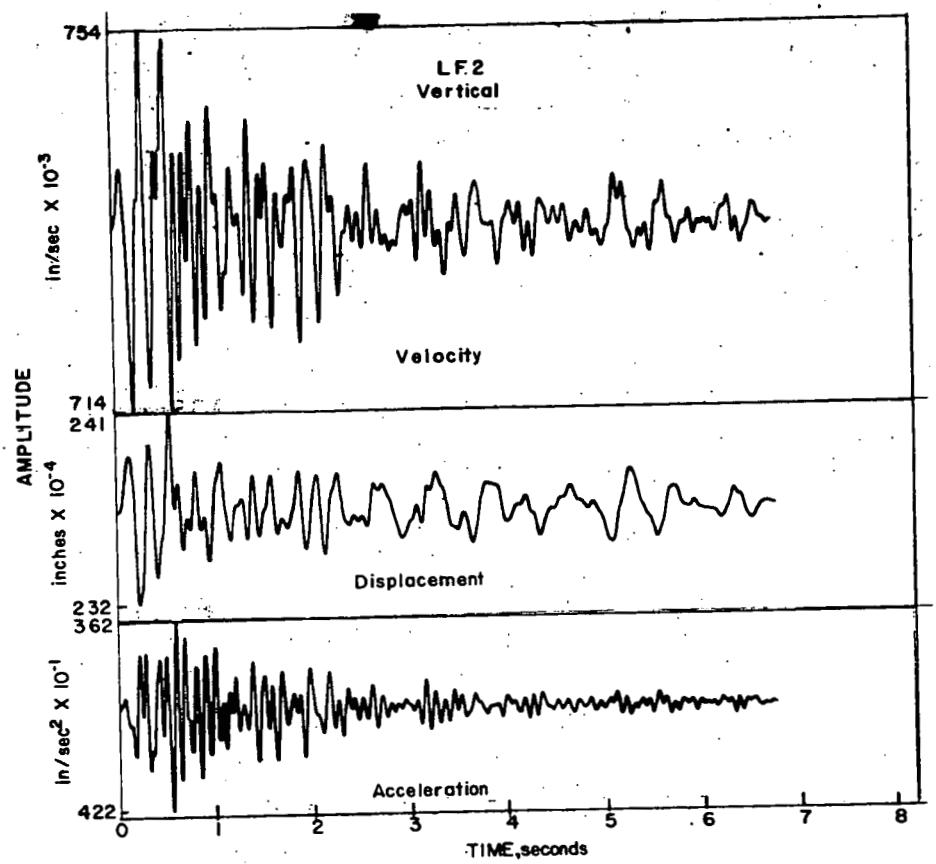


FIGURE 17.- Amplitude Versus Time and Frequency, LFI.



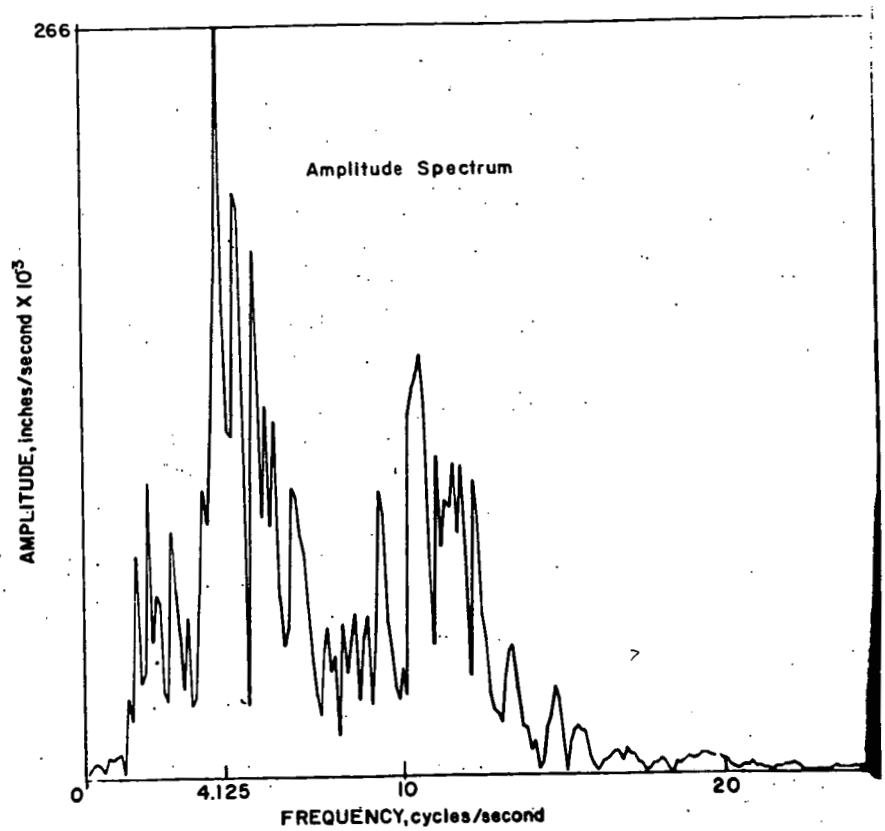
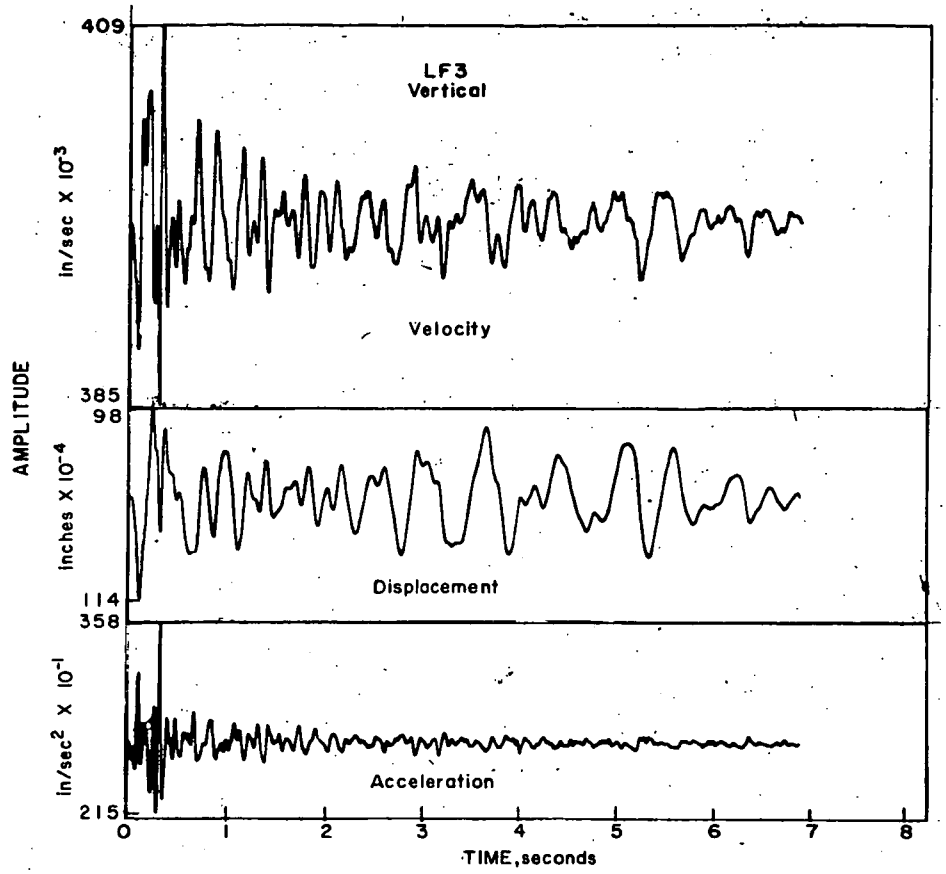


FIGURE 18.- Amplitude Versus Time and Frequency, LF2.



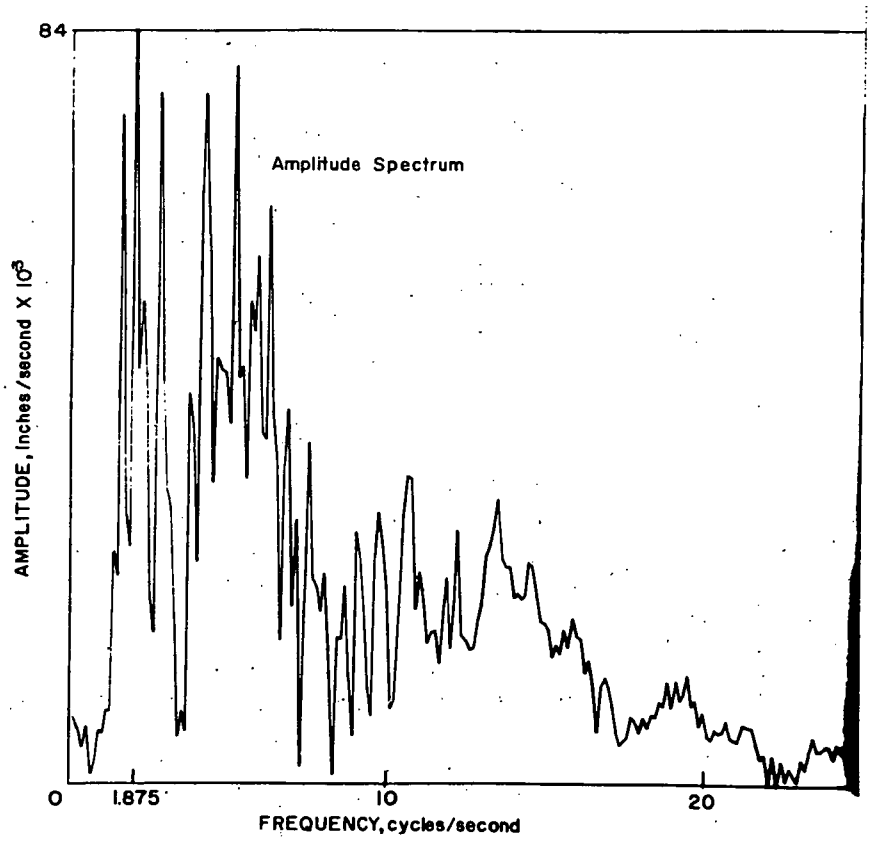


FIGURE 19.-Amplitude Versus Time and Frequency, LF3.

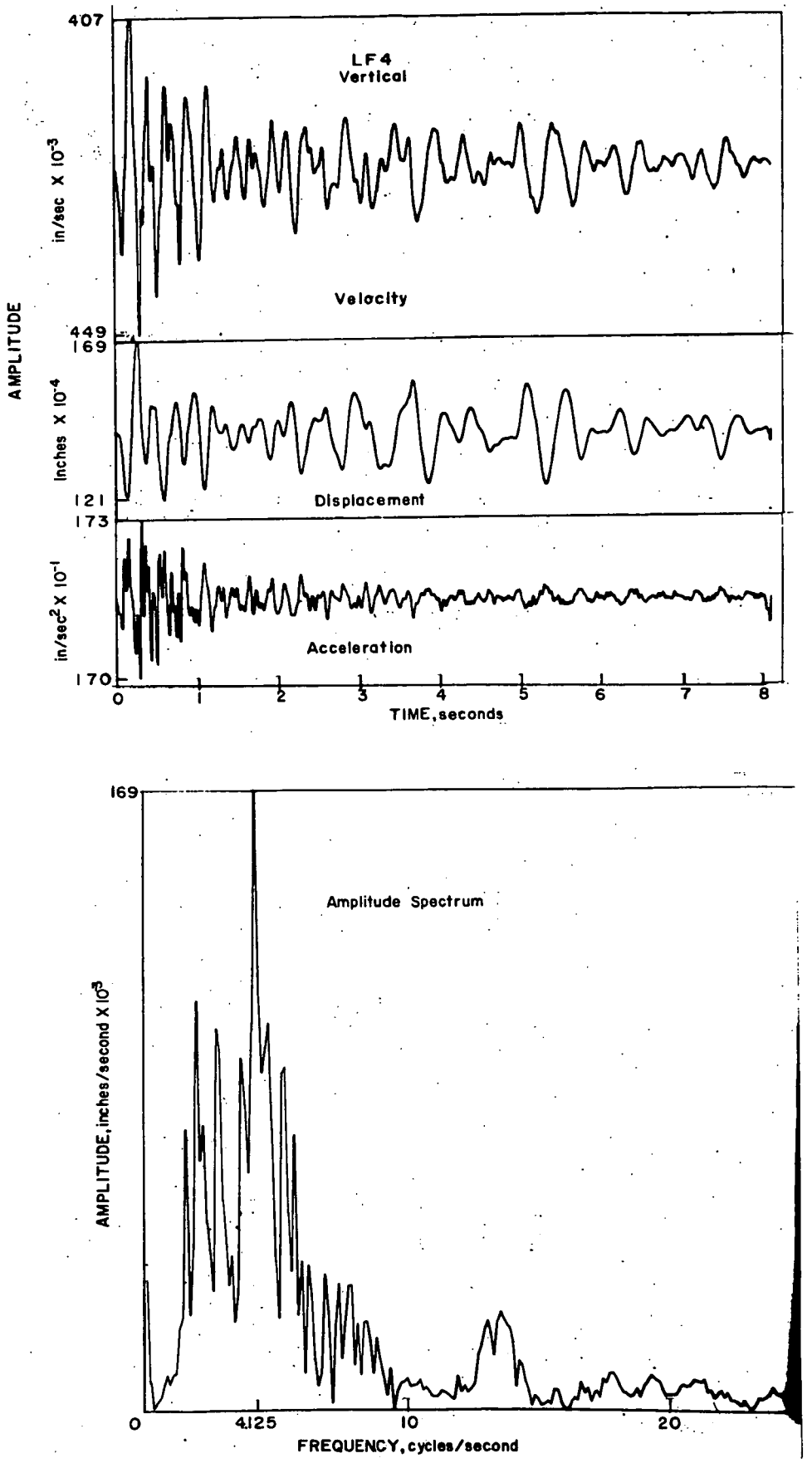
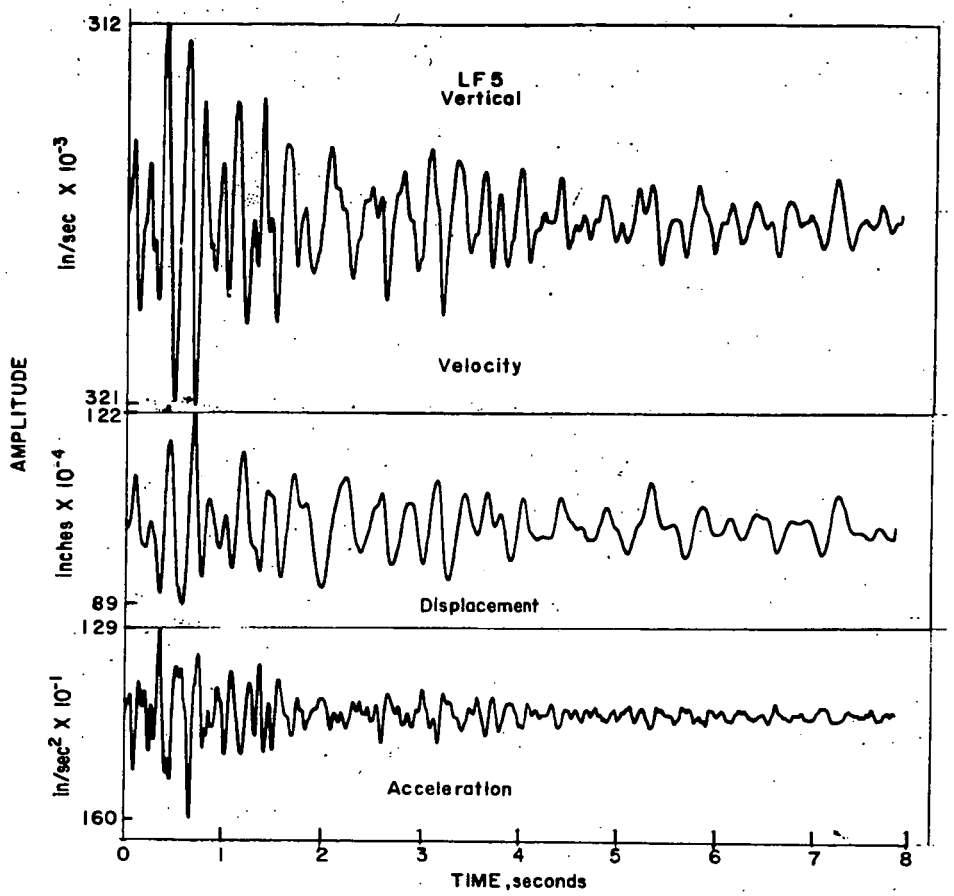


FIGURE 20.- Amplitude Versus Time and Frequency, LF4.



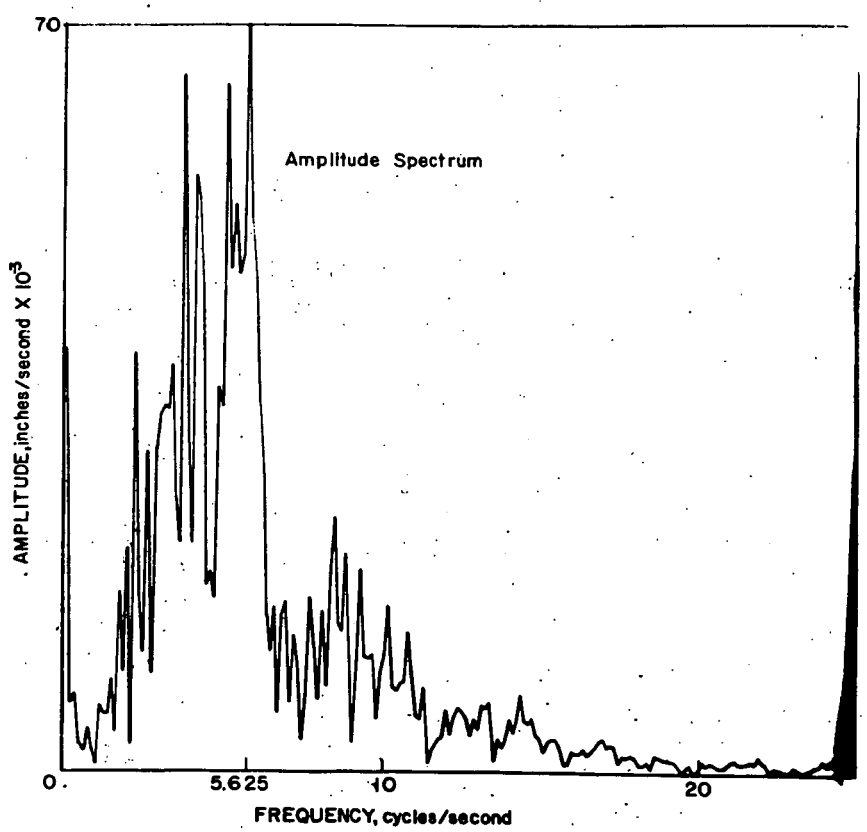
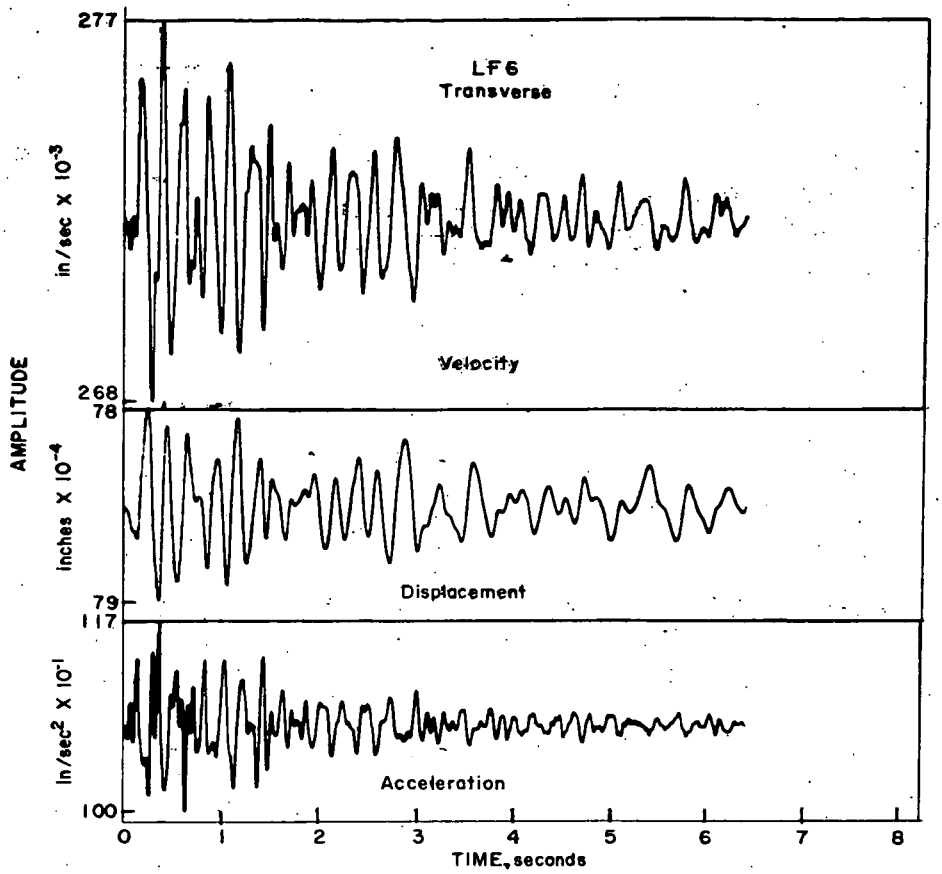


FIGURE 21.- Amplitude Versus Time and Frequency, LF5.



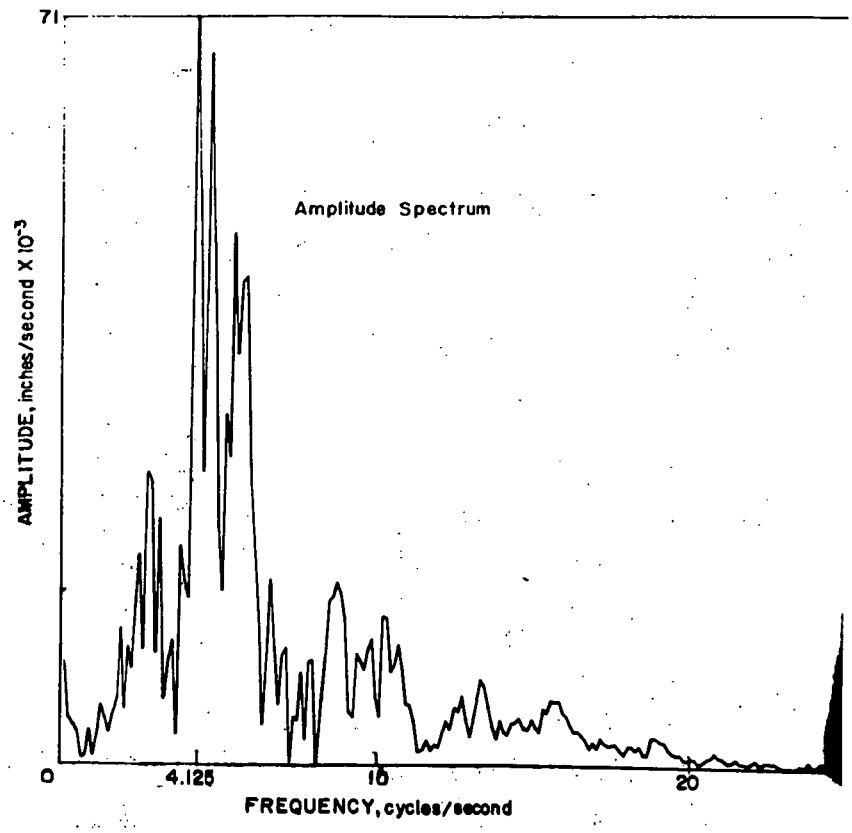


FIGURE 22.-Amplitude Versus Time and Frequency, LF6.