THE GENERATION OF LOW-FREQUENCY LONG-DURATION VIBRATIONS FROM SURFACE MINE BLASTING AT BLANFORD, IN

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*** SUMMARY

Bureau of Mines personnel conducted a study of vibrations generated by production and special test blasts at Peabody's Universal Mine at Blanford, IN during the period Sept. 9 to 13, 1985. These results were combined with data from Peabody and the Indiana Department of Natural Resources (DNR) to determine the following:

1. Blast design influences on vibration amplitudes and frequency.

2. Structural and geologic influences on vibration amplitudes and frequency.

3. Site-specific influences on vibrations as received at the homes.

4. Other site-specific influences on the town structures such as settlement-induced strains and distortions.

Three areas of concern were examined for the earlier May 15, 1985 study: (1) vibration amplitudes, (2) vibration (frequency) characteristics, and (3) causes of unusual vibrations (1). This follow-up study, which included additional data, found similar results for the first two of these plus additional insight into the third, causes and structural conditions present.

The vibration amplitudes from production blasts are high relative to measurements from other sites at comparable scaled distances. Most were greater than the mean from the surface coal mine summary propagation plot published in Bureau of Mines Report RI 8507 (2), figure 10. Many even exceeded the envelope of maximum observed values in RI 8507. By contrast, vibrations from the single holes, at the same charge weight per delay as the production blasts, fell close to the mean line. This strongly suggests multiple hole interactions and constructive wave interference for the short delays used and the low frequency vibrations which result at this site.

The frequency and duration characteristics are atypical of measurements made by the Bureau at a score of other surface coal mines. At distances exceeding about 5,000 ft and for blasts prior to Apr. 15, 1985, many blast records have prominent and clear very low frequencies of 3-5 Hz. These are almost certainly (Rayleigh and Love) surface waves. These low frequencies and long durations are greatly in excess of those from other studies in Indiana and neighboring states. They resemble blast records reportedly obtained in the water-saturated hydraulically-filled ground in Dade County, Florida. Low frequency blast vibrations of sufficient amplitude could produce excessive structural displacement and strain, as described in BuMines RI 8507. The Bureau of Mines vibration data collected Sept. 1985 did not have as prominent a low frequency wave tail as the earlier data, consistent with homeowners observations that "the blasts have not recently been bad."

The propagating medium appears responsible for determining the wave characteristics at distances exceeding about 500 ft. This medium, which is the local geological composition and structure, has a natural frequency of about 8-10 Hz and also produces surface waves of several types, all about 4 Hz. Blast designs appear to contribute to the problem when they contain 100-200 ms periodicities in their delay sequencing. The low frequencies which generally result produce problems with the scaling predictions. The 8 ms delay criteria appears insufficient to effectively separate individual charges. Blast designs which use fewer charges, (e.g., less decks) and possible greater charge weights may actually reduce impacts by minimizing the 4 to 8 Hz generation.

The propagating medium is also responsible for the low attenuation. Vibration amplitudes are somehow prevented from decaying as rapidly with distance as in previous studies of surface coal mines. The likely cause of this is geological structure or horizontal workings providing a strong acoustic reflection layer.

Considering structural damage in Blanford, it is not likely that the blasts studied in this report could have produced any but the most superficial of effects. The presence of very low frequencies increases the blasting vibration unwantedness; however, levels, even at those frequencies, are below those corresponding to cases of documented cracking (2).

Of 8 homes surveyed, all but one have elevation differences consistent with the presence of minor wall cracks. There is no way to tell if these differences represent subsidence and/or settlement effects, or if the houses were simply not built level. Repeated surveying, a simple procedure, would reveal any ongoing changes. Static strain or not, it is unlikely that blasting is responsible at the levels generated. Vibration amplitudes decay very rapidly with depth below the ground. Furthermore, severe enough vibrations to produce structural effects in the ground would have disasterous impacts on the much closer and already disturbed mine pit highwalls.

*** ACKNOWLEDGMENTS

This study was done by the authors, all members of the Blasting Technology Group at the Twin Cities Research Center of the Bureau of Mines. It is a follow-up of an earlier study reported to OSM as "Assessment of Blasting Vibrations from Surface Mine Blasting in Peabody's Universal Mine, Blanford, IN" May 15, 1985 (1). Both efforts were done at the request of James Gilley of the Eastern Technical Center of OSM, Pittsburgh, PA. Assisting in the data collection were Eric Gerst of the Indiana Department of Natural Resources, and Art Anderson of the OSM Washington Office. The Peabody Coal Company fired all the blasts including the 7 studied by the Bureau of Mines in the period Sept. 9 to 13, 1985. Peabody officials also provided many of the historical and current vibration records, blasting logs and drillhole data, as well as close cooperation with Bureau of Mines researchers. Useful suggestions were also received from the local citizens group, the Blanford Action Committee.

*** EXPERIMENTAL PROCEDURES

DATA AVAILABLE

Three sets of data were used for this study: (1) records available for the May 15, 1985 analysis and report, (2) additional records and data subsequently obtained from Peabody and the Indiana DNR, and (3) U.S. Bureau of Mines-obtained blast records from 7 shots during the week of Sept. 9 to 13, 1985. Table A-1 lists all the measurements made at homes.

May 15, Report Data

Available for the previous report were 432 vibration measurements obtained by Peabody and the DNR at 7 residences in and around Blanford from 235 production blasts in the period May 15, 1984 to April 25, 1985. Blast design logs for all shots and Shirley Zell's perception log were also available, as were the regional maps and some drilling logs from Peabody.

The DNR had seismographs installed in the following homes during a part of the study period:

(1) Massa
(2) Volk
(3) Hollingsworth
(4) Zell

The Peabody Company has seismographs in the following homes:

(1) Massa
(2) Polomski
(3) Jackson
(4) Verhonik

Supplementary Peabody and DNR Data

Following analyses for the May 15, 1985 report, additional data were requested in anticipation of a follow-up study. This consisted of 30 3-component seismic records from Peabody to provide more comparisons between measuring sites and shots measured at a given site. Previously, only single component peak value from Peabody's blasting logs were available. Also obtained were 82 shot-to-recording distances for the DNR measurements for the propagation plots for 3 of the 7 homes monitored.

Bureau of Mines Measurements

Using a seven station array of 3-component seismographs, Bureau researchers collected 123 vibration records from 5 production blasts and two specially-fired single-hole shots (table 1). Measurements were made as close to the blast as 54 ft to identify the vibration source chracteristics. For the same shots, measurements were made at larger distances, up to 5,700 ft, to show how the vibrations changed character as they propagated.

TABLE 1. - Bureau of Mines vibration tests at Blanford, Sept. 1985

Shots	Number of stations	Distance range, ft	Direction of array, approx.	Blast Design				
				Pattern	Hole depth, ft	Number of decks	Charge Weights	
							Per Hole	Per Deck
1	7	54-2,693	E-W	Echelon, 100x17ms	54	4	450	125
2	7	92-2,675	do	do	54	4	450	125
3	7	90-2,640	do	do	50	4	400	125
4	7	65-2,615	do	one hole	~50	1	125	125
5	7	54-2,620	do	one hole	~50	1	125	125
6	81	290-5,710	N-S	Echelon, 100x17 ms	83-85	4	950	250
7	7	200-5,400	N-S	do	82-85	4	950	250

[1]Seismograph lent by Indiana DNR.

Single-hole (single charge) blasts were made to identify the effect of blast design and specifically delays between individual charges on the wave characteristics, both close-in and at large distances.

In addition to the vibration monitoring, Bureau researchers performed level-loop surveys of 8 Blanford homes to determine possible subsidence- or settlement-induced strains and distortions.

Additional Information Available

Supplementing the vibration data, blasting logs and survey data, the following information was available for this analysis:

(1) A regional map showing the mine layout as of Apr. 85, and town location.

(2) Fifteen drilling logs from Peabody, used to determine overburden characteristics and the No. 6 coal depth.

(3) Four specially-drilled deep-hole logs from Peabody, made for structural assessment around the Polomski's. This home is being used as a continuously-monitored test structure by the Peabody Company.

(4) Subjective perception logs of house vibrations kept by Alice Massa, covering Sept. 1984 to April 1985, and John Albrecht, covering March 1983 to Sept. 1985.

(5) Map showing areas in and around Blanford underlain by previous underground mining. The small-scale map based on a USGS 7-1/2-minute quadrangle did not indicate sufficient detail to permit location of homes over openings or pillars.

SITES

Surface

The general mine layout and town of Blanford are shown in figure 1. Closer views of the town, the mine's north end, and the instrument arrays used for the Bureau of Mines' blasts are shown in figures 2-4. Volk and Polomski are neighbors, as are Zell and Massa. Hollingsworth is about 1,400 ft north of Volk. Jackson's is the closest house to the mine, being within about 1,000 ft when Peabody is blasting at the pit's farthest north end. Verhonik is far east of the other sites. The remaining homes, Marietta, Skorich, Albrecht, Otto Finger, Erma Finger, Jovanovich, and Ahlemeyers, were not instrumented for vibrations although they were examined by level-loop surveys. Note that the Vernardi home, located on figures 2-4, was not surveyed because it did not have a clearly-visible survey horizon. Mr. Vernardi, however, is an active member of the Blanford Action Committee.

Subsurface

The geology of western Indiana is composed of sedimentary rocks, generally interbedded shales, limestones, and sandstones overlain by alluvium, sand, and gravel. Fifteen drilling logs were provided by Peabody for holes between the current mining and the town. Generally, the top zone is characterized as "sand

and drift" and is 60-75 ft thick. Below this is coal, shale, or material classified as "coal and jack." Some topographic relief is provided by surface streams in the area. The logs do not include any information on voids or old underground workings. Presumably, the "coal" referred to is the No. 6, currently being worked, at a depth of 50 to 100 ft.

Near Blanford, underground mining has occurred in the number VI and in deeper seams V, IV, and III. Downhole logging at the Polomski house show that the number VI, V, IV, and III coals are at a depth of 85, 225, 325, and 395 feet, respectively. A total of four holes were drilled near the Polomski house to depths between 340 and 420 feet and according to the driller and the downhole logs no underground workings were encountered.

Further information was requested on the abandoned underground mines. However, it was not received in time for this report. Most important is knowledge on specifically where homes are over abandoned workings and where significant voids exist along the propagation path of the blast vibrations. Also needed are depths for the theoretical models, (Gupta and O'Brien). It is likely that old maps alone will not provide sufficient accuracy for surface feature correlation. If considered useful, such analysis will be done at a later date, or possible geophysical studies such as reflection seismology to determine the location, depth, and extent of the old abandoned underground mines (figure A-1).

BLAST DESIGNS

Production Blasting, July 84 to April 85

Peabody used 4 basic blast designs during the 10-month period covered by the vibration data at their Universal Mine (figure 5 and table 2). Three of them were echelon arrays with different between row and between hole delays, along with a few minor variations. Charges were full-column or multiply-decked with up to four independently-delayed explosive charges per hole. Both Nonel and Hercudet systems were used. The other major blasting method was casting, with short delays of 8, 10, or 12-1/2 ms between holes in a row parallel to the pit highwall. The time between rows was much greater at about 200 ms allowing high relief and good rock moveout (figures 6 through 10).

Research suggests that delay intervals are related to vibration frequency (3, 4). This is more likely for close-in hard-rock cases where the propagating medium does not have a dominating influence on the wave characteristics. Similarly, some influence of delays on maximum peak particle velocity values may occur, depending on the wave interference for blasts with as many as 200 independently-delayed charges. Because relief is thought to be a minor influence on vibrations, the number and depth of decks was not expected to be a major factor for vibrations. Similarly blast casting might also be thought to be a minor influence, with the increased between-row relief balancing, in part, the larger charges of up to 3,000 lbs/delay. Despite these expectations and speculations, no careful study has been published comparing the influences of decking and casting on vibration levels and wave character. Blanford residents called the period which includes the blast casting as "very bad" or "worst" but rather than casting as such, the large charge weights per delay could have been responsible.

TABLE 2. - Blast designs used at the Universal mine

Type	Delays, ms		Numbers of decks	Typical charge weights per delay, lbs
	Holes in a row	Between rows		
Echelon	17	42	1	1,500, maximum of 2,258
Echelon	17	100	2 - 4	325 except one at 625 on 4-22-85
Echelon	17	200	2 - 4	200-400 except 1-5-85: 1,475 1-12-85 (17:18): 1,911
Casting	8, 10, or 12-1/2	140 - 210	1	2,000, maximum of 3,842

Table 2 summarizes the major blast designs used at the Universal Mine between July 1984 and April 1985. Casting was limited to the period October 22, 1984 to March 1, 1985. After March 1, 1985, blasts utilized the 17 x 100 ms echelon pattern, also being the method in September 1985 when Bureau of Mines personnel made their measurements.

Production and Test Blasts for Bureau of Mines September 9 to 13, 1985

Seven shots were fired during the Bureau of Mines' study period. Three were production shots at the far north end of the pit (figure 2). The next two were single hole shots in the same area with one bottom deck load at the same charge weight per delay. The last two were again standard 17 x 100 ms echelon production blasts, except they were 2,800 ft south along the highwall (figures 3 and 4).

*** RESULTS OF FINDINGS

VIBRATION AMPLITUDES AND PROPAGATION PLOTS

Propagation plots of measured blast vibrations were prepared for site and shot comparisons and also comparisons with measurements made at other surface coal mines. Scale distances employed the charge weights per delay as specified in Peabody's blasting logs. There is a significant chance that individual charges, thought to be independent, are interacting constructively, because of the complexity of the multi-hole, multi-decked blasts, cap inaccuracy, and the site conditions. This problem is addressed later in the report.

The 25 propagation plots in this report represent various combinations of sites, blast arrays, and special test blasts. For easy comparisons, most of the plots include propagation summary lines derived from RI 8507 (2) data, a summary of surface coal mines. In a departure from the earlier OSM report (1), these lines represent the mean least square regression of the maximum peak particle velocity. That is, for each shot which produced 3 component values, radial (also called longitudinal), vertical, and transverse, only the single maximum of the 3 was plotted. All the Blanford data were similarly treated, unless the individual components are given. This simplified the appearance of the plots and conforms to regulatory practices of evaluating the highest of the three components.

Most of the propagation plots also have a dashed line showing the envelope which encloses the highest vibrations measured for surface coal mines summary in Bureau of Mines RI 8507 (2).

Production Blast Monitoring at Residences

Vibrations measured at each of seven Blanford homes by Peabody and the Indiana DNR are given in figures 11 through 17. The majority of values exceed the mean from RI 8507. Furthermore, many exceed the maximum-value envelope. Only Hollingsworth appears nearly "normal" or typical of measurements made elsewhere. Two explanations are possible:

(1) Abnormally efficient propagation--which should show up as an unusually shallow slope in the propagation line

(2) Scale distance values in error because of a failure in the 8-ms criteria for selecting charge-weight-per-delay values

(3) Cap scatter. (This study did not include determination of actual initiation times.)

Because the data in these figures were collected to assess damage risk and not propagation, they are clustered within a narrow scaled distance range and do permit reliable propagation equation determination. Bureau of Mines data, discussed later in this section, were expressly obtained for propagation analyses and better show generation and propagation effects.

Vibrations from homes which are near each other are plotted in figures 18 and 19, and an overall summary is given in figure 20. Despite additional vibration values, the results are unchanged from the May 15 report. Predictions of vibrations at this site using normally-defined scaled distances are not similar to other surface coal mines. Why this is so is the purpose of an experiment designed by the Bureau of Mines and discussed in the next section.

Bureau of Mines Vibration Tests

The Bureau measured blasting vibrations at Peabody's Universal Mine from five production and two single hole (single charge) blasts, using a wide propagation array (figures 2-4). Table 1 summarizes these tests.

Figure 21 compares the production and single-hole shots. The two mean regression lines are almost parallel indicating similar amplitude attenuation with distance. Since the intercepts are dissimilar, there are differences in the blast source itself. The intercept value is the vibration level which is projected at a scaled distance of unity. In other words, the coefficient K in the propagation equation:

$$\text{vibration amplitude} = K\,(\text{scaled distance})^{a}$$

where "a" is the slope of the regression line.

In figure 22, production shots 6 and 7 were separated from shots 1, 2, and 3, since they were in different locations in the pit and had different burdens, spacings, hole depths, and seismograph array geometries. The regression lines are again nearly parallel indicating similar attenuations. The intercepts are not the same indicating differences in the blasts.

The three regression lines of the Universal Mine data (single charge and production shots) have less attenuation with distance than the data for surface coal mines in RI 8507 (2) (figure 23).

A statistical analysis of data comparisons is given in table 3. The only data which can be statistically pooled with previous coal mine data are the single charge shots number 4 and 5. The groups that failed the F1 test are

TABLE 3. - F-tests[1] at 95 pct confidence. Universal mine data compared to RI 8507 surface coal data.

Data group	F1 test	F2 test
Universal #1, 2, 3, 6, 7	failed	borderline fail
Single charge #4, 5	passed	-----
Universal #6, 7	failed	passed
Universal #1, 2, 3	failed	failed

[1]The tests in table 3 are one-way analysis of variance. The F1 test determines if the data can be pooled. If this test is failed, then the F2 test is applied. If the F2 test is passed the slopes are not different and the intercepts are. When this test is failed then both the slope and intercept are different.

statistically different and cannot be represented by one regression line. This suggests that the production shots as sources, are outside the previous data considered representative of surface coal mines (2).

In the F2 test, only Universal number 6 and 7 passed, probably because most of its data points fell within one standard deviation of the previous data from RI 8507. When Universal 6 and 7 are pooled with Universal 1, 2, and 3, enough data points fall outside one standard deviation of the RI 8507 data that they borderline fail as a group. Nevertheless, all the production shots (1, 2, 3, 6, and 7) fall on the high side (in the case of 6 and 7, figure 25) or statistically outside (F1 test for 1, 2, and 3) the data range as reported in RI 8507.

Figures 24 to 26 compare the individual production and single hole shots to previous surface coal data in RI 8507. The single charge shots fall mostly within one standard deviation of the historical surface coal data. Production shots 6 and 7 are mostly within one standard deviation too, except at a scaled distance of 300 where they are higher than the surface coal data. The production shots 1, 2, and 3, were mostly outside one standard deviation. The north end of the pit produced the highest vibration level when multi-delay shots were used. Alternate causes are shot geometry effects (discussed later) or actual structural differences.

The vibration levels from 5 different blast designs were separated and plotted in figures 27 through 31. These figures also show a regression line and standard deviation representing previous surface coal data from RI 8507. All 5 designs yielded higher vibrations than previous surface coal data. The lowest of the five were the 42 x 17 ms echelon and casting designs. More data would be needed to be sure of the 42 x 17 ms echelon with only 11 data points. Worth noting that the 42 x 17 ms echelon and blast casting designs used full columns and the other echelon blasts used 2 to 4 decks per hole.

A difference of vibration amplitudes was noted for the two array directions. Higher vibration levels were recorded (to the west) from production shots 1, 2, and 3 than (to the north) from production shots 6 and 7. In figure 22, the vibration amplitudes are plotted versus scaled distance for comparison purposes. Although shots 6 and 7 consisted of more shot holes, which were 30 feet deeper and contained more pounds of explosives, the higher vibration levels resulting from shots 1, 2, and 3 are probably a result of the acute angle between the array and the firing orientation of the shots. The array to the west was at an angle of only 28° with respect to the firing orientation of shots 1, 2, and 3 while the array to the north was at an angle of 98° to shots 6 and 7. A similar increase in vibration amplitudes with decreasing angle between instrument and firing orientation has been observed by Kopp (8) and Wiss (7). They report that the lowest vibration amplitudes are observed in the opposite direction of initiation (180°) and the greatest amplitudes (two to six times larger) are observed in the direction of initiation (0°). Amplitudes from shots 1, 2, and 3 are more than 1-1/2 times larger than those from shots 6 and 7.

Propagation plots were prepared for the four types of vibrations observed in Blanford (figures 32-35). These types, A through D, are discussed in the section on vibration frequency characteristics following. The different types represent different amounts of low-frequency. Interestingly, these low frequency vibrations are not of particularly high amplitude, with few values above the envelope line. Further analysis of this kind of data is needed, including correlations with blast designs.

Causes of High Vibration Levels

The propagation plots reveal both blast design and propagation media influences on vibrations.

Blast Design as a Source Function for Vibration Generation

Comparisons between the single hole blasts and the production blasts at the same charge weight per delay strongly suggest that the method for computing charge weights per delay are failing at this site. In other words, the vibrations as measured are not excessive in an absolute sense, only high compared to their scale distances. Two results support this supposition:

(1) The single hole shots agree with the summary data from other surface coal mines and can be statistically pooled with them. The five production shots studied, however, are higher by factors of 2 for shots 6 and 7, and 3.3 for shots 1 to 3.

(2) The relatively simple full column shots produce less vibration for a given scaled distance (computed traditionally) than the multi-decked shots.

Note that scaled distances are based on charge weights per delay, for delay separations, exceeding 8 ms. This long-accepted criterion is based on research by Duvall published in 1963 (6). Some blasters feel that they can violate this rule if the charges are spatially separated. This also introduces geometric factors such as propagation time across the array.

More recent research by Wiss (7) specifically examined area surface coal mines with softer rock and larger holes and blasts than Duvalls's studies. He recommended 17 ms separation for defining charge weights per delay. Because the mechanism for preventing individual charge vibration interactions is destructive wave interaction, it is expected to be related to vibration frequency. Hence, what works at high frequency in hard rock (Duvall) may not at lower frequency (Wiss) nor at Blanford with its relatively low 8-10 Hz blast vibration. Table 4 lists the number of charges going off within three different time intervals, including 60 ms, which will place two 8-Hz waves 180° out of phase.

Recalling the differences between the single charges and production shots of 2.0 and 3.3 times, and the charge weight square root factor for scaling, this is consistent with 4 to 10 charges interacting or with charge weights per delay of 4 to 10 times higher than expected. With this adjustment the Universal Mine data is consistent in vibration amplitude with other mines studied by the Bureau. This is an area needing additional research.

Low Attenuation of Vibration

The low values of slope for the propagation equations represent low attenuations of blast vibrations at Blanford. This is the case for both the single hole and production shots, strongly suggesting that this factor is not related to blast

TABLE 4. - Analysis of charges for production blasts

Blast design	Maximum number of charges per time interval		
	8 ms	17 ms	60 ms
42 x 17 echelon	2	2	5
100 x 17 echelon	3	3	8
200 x 17 echelon	2	3	7
casting, short array	1	2	5
casting, long array	3	6	13

design and in particular not to interactions between charges. The reasons for this are conjectural at this time. Both the low attenuation and generation of strong dominant surface waves hint at geologic and structural influences.

VIBRATION FREQUENCY CHARACTERISTICS

General Types

Many of the blasting vibrations measured at Blanford are characterized as having very prominent low frequencies following the initial arrivals by about 1 second. These appear very much like surface waves with clear sinusoidal vibrations having frequencies of 3-4 Hz. Total vibration durations exceed 3 seconds in many cases. Both the prominent low frequencies and extended vibration durations are not typical of the many blasting vibrations measured elsewhere in Indiana and other states in previous studies by the Bureau of Mines (2, 5, 6).

Two basic surface waves exist:

(1) Rayleigh waves are vertically polarized with retrograde elliptical particle motions. They should have significant motion in the longitudinal and vertical directions, and little in the transverse. The generation of these waves requires only a single free surface (the ground or sharp acoustic contrasting layer at depth).

(2) Love waves are horizontally polarized shear waves. They should be strong only in transverse components. Generation of love waves requires a layer with top and bottom boundaries having good reflection properties. Extensive underground voids could provide such a reflecting surface, as could any low velocity layer.

To facilitate comparisons between shots and sites, vibration records were characterized according to the amounts of low frequency (3-5 Hz) present in the three components of motion:

A All components have significant, clear and/or dominant low frequency of about 4 Hz,

B Only transverse components have clear and prominent low frequency,

C Longitudinal and vertical components have prominent low frequency. Transverse has only high frequency (>10 Hz) or is complex in form,

D Only vertical components have clear and prominent low frequency.

Figures 36 through 39 show examples of the above types of vibrations for a single shot on Jan. 25, 1985, at four sites. These are typical of the 522 vibration records although some appeared intermediate in form and not as clear as these. Furthermore, the relationship between the four types is not clear. It is likely that a type D develops into C and then A as the wave propagates farther along in a medium favorable for its development. Type B could also be an "early A" or the local presence of a strong subsurface reflector.

For comparison purposes, a series of shots was selected during which many of the homes were simultaneously monitored. Table 5 summarizes the available comparisons, as an expanded version of table 2 from the earlier report (1). All the original vibration data used for the analyses in table 5 are from the Indiana DNR and the Peabody Company. Also, all listed shots in table 5 between Aug. 15, and Feb. 21 are blast casting.

Impacts of Low Frequency Vibrations

Comparisons of Blanford amplitudes and frequencies with BuMines' safe level criteria from RI 8507, Appendix B, show that many values are in the realm where displacement rather than velocity limiting is required. Although none of the vibration amplitudes exceed the Bureau's safe level criteria they are close to the turn-down point where frequency is critical and displacements must be limited to insure that excessive strains are not produced. These waves will produce significant structural response, and combined with their long duration, are likely to produce significant psychological reactions from those impacted. Note that the OSM regulations reflect, but differ, and are somewhat higher (less restrictive) than the Bureau's safe values. It is worth repeating that none of the Blanford vibration levels were high enough to produce a significant structural damage probability, according to known practice and experience.

It is also worth repeating that frequencies in the range of 4 to 12 Hz produce significant vibration response in low-rise structures and should be avoided where possible. Because of serious displacement and strain, frequencies below about 4 Hz are even more undesirable (2).

Comparisons Between Shots at a Given Monitoring Site

These are obtained by reading vertically in table 5. Seven sites had usable shot comparison data:

(1) Volk: Most records are type A but some of the more distant measurements are type C. No clear distance correlation exists. The transverse component varies greatly in both frequence and amplitude, being very small in most C events.

(2) Polomski: This home is next to Volk's. Again, most records are type A. However, the C-cases this time are the closer-in shots. The two C's are somewhat unclear, and could be irregular A's.

(3) Hollingsworth: All are type A except the closest shot which has only a clear low frequency vertical, or type D characteristics. This house is farther than the Volk and Polomski houses, but is in the same part of town (figure 2).

TABLE 5. - Shot and site comparison summary

Date	Vibration characteristics at various monitoring locations						
	Volk	Polomski	Hollingsworth	Massa	Zell	Jackson	Verhonik
5-15-84					B		
8-15					B		
11-23						C	B
12-1	A		A	~A			
12-4							
12-6	C		A	C or A			B
1-17-85	C		A	A			~B
1-21	A		A				B
1-25	C		A	A		D	B
1-28				A			B
2-2	A	A	A	A			B
2-6	A	A	A	A or C		D	B
2-9	A	A	D	A		D	B
2-19	A	A or C		C			~B
2-21		~C		C		C	~B

(4) Massa: Most are again type A. The two closest are type C but some of the A's are borderline type C. Several were too small in amplitude to reliably analyze.

(5) Zell: The Zell home is within 100 ft of Massa's and would be expected to have similar vibrations. Unfortunately, none of the blasts were monitored simultaneously at the two homes. The two shots measured at Zell's are both type B, although the May 15 blast has some emerging low frequency in the longitudinal.

(6) Jackson: These records were mixed, two C's and two D's. The two type D were farther; however, the whole distance range was not wide, being 4,859 to 6,371 ft.

(7) Verhonik: Virtually all type B. Some have a little low frequency in the longitudinal, such as at Zell's. The Verhonik house was not located precisely, but is at least a 1/4 mile east of Jackson's and far from the other homes.

Concluding this comparison, there does not appear to be much change at a given site from shot-to-shot for these mostly casting blasts. This is despite the varying shot locations on the highwall which produced different vibration travel paths. Each site is mainly self-consistent except for a possible distance effect which is not clear. A possible future effort would be characterization of vibrations from all 173 blasts to compare the effects of decking, echelon and casting designs on the various site measurements. The four basic blast designs are analyzed and compared to sample vibration records later in this section.

Comparisons Between Sites for a Given Shot

These are obtained by reading horizontally in table 5. The result is almost unchanged from the May 15 report (1). Distance appears to be a possible factor. Site differences appear real, because of their consistency; however, variations between (casting) shots do not. Neighbors had similar vibrations, where comparisons were possible. The Zell and Verhonik sites are the only ones with type B vibrations (Love waves). More measurements at Zell's would have provided additional comparisons, including similarities and differences with his neighbor, Massa.

Delay Sequence and Vibration Frequency

The four basic Universal Mine blast designs were discussed previously, three being echelons with different between-row delays and also blast casting (table 2). It has been long suspected, and recent research is showing that blast delays will influence the frequency of the generated vibrations (3, 4). Far from clear are the influences of the propagation media when it is structurally complex and dispersive (has frequency-dependent attenuation). Most surface coal mines represent complex situations with soil top layers, beds of soft rock of varying thicknesses and properties, and lenses or areas of non-rock, such as sand, alluvium, and lacustrine.

Production Blasting, July 84 to April 85

Time sequences for the four types of blasts shown previously in figures 6 through 10 are given in figures 40 through 44. All calculations are based on nominal initiation times. Included are initiation system travel times down the holes and between holes and rows based on Nonel at 6,000 ft/s and Hercudet at 8,000 ft/s. Burdens, spacings, designed delay sequences, and depths are from Peabody's blasting logs. Not included are the geometric effects of the observer's location related to the shot pattern orientation.

The shot layout is not a point source and the wave propagation velocity is not infinite. Therefore, true separation times between charges at different distances would require slight adjustments for propagation times amounting to a few milleseconds (e.g., 3 ms for two charges, with a 30-ft distance difference and a propagation velocity of 10,000 ft/s). Because of this effect, shots which have two or more individually-delayed charges which fire at nearly the same time may not appear to do so for observers in specific directions. Conversely, other time separations may be shortened because of this doppler-shift effect.

(1) Echelon blast, 42 x 17 ms: Figure 40 shows the time sequence by rows, which overlap in time. Additional delays between the rows would avoid the close pairing. However, no serious low-frequency periodicities exist and energy flow is very uniform. The time history corresponding to this particular blast is shown and is typical of the 10 available for this blast design. It is dominated by an irregular-shaded wave pattern of 125 ms periodicity (~8 Hz). None of the shots had significant amounts of very low frequency (V.L.F.), defined as large amplitude vibration of frequency below 5 Hz.

(2) Echelon blast, 100 x 17 ms: Figure 41. Blasts using this pattern had 2 to 4 decks and a time-bunching of charges similar to the previous pattern. Also like the 42 x 17 ms pattern is the uniform energy flow. However, the 105 ms row-periodicity (9.5 Hz) is close to, what appears to be, the ground natural frequency as shown by the single hole blasts discussed in the next section. All vibration records were either similar to the Jackson example shown (7 to 10 Hz) or of higher frequency. None had V.L.F. The duration of the vibration record is longer than the 42 x 17 ms echelon blast, consistent with the over 2-times longer blast initiation sequence of 1,070 ms compared to 428 ms.

(3) Echelon blast, 200 x 17 ms: Figure 42. The between-row delays are now long enough to separate the row events as isolated bursts of energy. In the case of this particular blast, these "bursts" continue for the incredibly long time of 4-1/2 seconds. A row-periodicity of 204 ms is created by this blast design, equivalent to about 5 Hz. The vibration time histories have a clear periodicity of about 110 ms (~9 Hz), particularly the first-arriving longitudinal component. However, a large amplitude periodicity of about 5 Hz is also visible and strongest on the transverse, consistent with the row periodicity. This is a case where the blast design appears to be influencing the vibration frequency at a large distance.

(4) Casting, short array: Figure 43. This is a simple array design with a full column charge. The time sequence is again a series of bursts at about 200 ms periodicity corresponding to the between-row delays. The vibration record

has abundant dominating V.L.F., this one being a type A. Many of these shots produced V.L.F., however, they included the complete variety of types A through D, at the 7 sites. Possibly, filling in the empty periods in the time sequence might prevent the on- and off-effect which produces the unwanted periodicity. Fortunately, the vibration amplitudes are not high for these shots. A peak particle velocity above 0.5 in/s at these frequencies would be at the limit of the Bureau's safe-level criteria for cosmetic cracking for any and all residences.

(5) Casting, long array: Figure 44. Many of the casting blasts were more complex than the previous one. They generally have more holes per row eliminating the quiet periods and depending on the exact timing, produce a complex blast sequencing such as shown. Because of the zig-zag front row pattern used on many of the blasts, more time is allowed between it and the next row, and in fact for over half the total initiation time, only the front row holes have fired. Note that figure 44 omits the front row holes between the first at 209 ms and the 18th at 464 ms. The row periodicity is not as uniform as the previous example, the short casting shot, being 300 ms between 1 and 2 and 115 ms between 2 and 3. Two vibration examples are shown. Massa's contains strong V.L.F., but the waveform is not nearly as clear or clean as the previous casting shot. Verhonik's record has some V.L.F., however, the record is dominated by a 110 ms periodicity (~9 Hz). Unlike the other example with clear 110 ms periodicity, the 100 x 17 ms echelon in figure 41, this one has emerging V.L.F. in longitudinal and transverse.

Bureau of Mines Measurements of Production and Single-Hole Blasts, September 1985

Vibration Characteristics: To investigate the influence of shot design and geology on generating and propagating ground vibrations, two instrument arrays were set up. One array extended approximately 2,640 ft in a westerly direction from shots 1 to 5 to the Polomski house. The second array extended approximately 5,600 ft in a northerly direction from shots 6 and 7 to the Zell house. Figures 2 to 4 show the locations of the two arrays and of the seven shots. Table 1 summarizes the 7 test blasts.

Production Shots: Figures 45 to 50 show the ground vibration recordings for production shots 3 and 6 for the three components of ground motion measured; longitudinal, vertical, and transverse. Ideally the closest station should best reflect the source, i.e., the shot design, and minimize the effects of geology on the propagating waveform. Figures 51 and 52 show the blasthole pattern for shots 3 and 6, respectively. Included are the detonation times for each of the four decks per shot hole. For shot 3 the nearest recording was at 90 ft and shows that the ground motion lasted approximately 350 ms longer than the time between the first and last hole to detonate. A similar observation can be made for shot 6 (see figures 53 and 54.) The fact that the ground vibrations away from the shot last longer than the shot itself is due to the arrival of multiple reflected and retracted phases and the response of the medium to these phases.

A comparison of the nearest recordings made for each shot reveals obvious differences on the character of the two waveforms which can be mostly attributed to the difference in the two shot designs. Shot 6 contained a sequence of delayed explosive charges lasting 1.72 seconds and shot 3, 1.30 seconds. The longer sequence of shot 6 is seen in the longer duration of recorded ground vibrations at the nearest station. The longitudinal component record for shot 6 shows that vibration amplitudes gradually increased to a maximum for several cycles and then decayed gradually. An analysis at the sequence of delays determined that at the beginning and end of the shot only single decks were detonated, but in between, multiple decks were detonating at nearly the same instant in time and thus generating the maximum amplitudes. The record of the longitudinal component for shot 3 shows lower vibration amplitudes in the first half and very end, with larger, impulsive phases in the third quarter. Although the sequence is uniform with interaction of multiple decks occurring throughout, the packet of large amplitudes correlates with the detonation times for the back two rows which are more confined than the three front rows. Shot 6 contained only one back row and obviously was not an important factor in generating ground vibrations.

As mentioned above, an analysis of shot 6 determined that up to three decks were detonating at nearly the same instant in time. This occurred at intervals of approximately 100 ms, the time delay between rows, and likely contributed to the predominant 10 Hz component observed in the recordings. Since most residential structures have a natural frequency between 5 and 20 Hz, a shot should be designed to minimize generation of frequencies within this range.

As the nearest recordings tend to be strongly influenced by the shot design and less so by the geology, the waveforms recorded across the array can be seen to become more complicated due to the subsurface geology. Phases which are separated in time near the shot and allow waveform characteristics to be easily discernible, interfere with one another both constructively and destructively at distance and lead to complications as observed in the waveforms recorded by the array. For instance, the longitudinal component recording of shot 6 at a distance of 547 feet has changed character considerably compared to the recording at 290 ft. Although the duration of the two are approximately the same, the shot design effects which were observed for the near station record have become more difficult to identify. The interference of phases has created a waveform of varied impulses and frequencies no longer resembling the harmonic motion recorded at the near station.

The duration of the ground vibrations at the far stations is two to three times that at the near stations and is due primarily to low frequency surface waves. These surface waves are first noticeable near 400 ft, but do not have large amplitudes relative to the earlier arriving, higher frequency body waves until about 1,000 ft for the westerly array (shot 3) and 2,000 ft for the northerly array (shot 6). The significance of this is not yet understood and may be either a result of shot design or geology. It does warrant further investigation since surface waves are predominant at the larger distances and have a frequency of 5 to 10 Hz--near that of residential structures, and corresponding to excessive displacements and strains.

Single-Hole Shots:. Two single-hole shots (4 and 5) were detonated to obtain a more simplified source than a production shot consisting of a sequence of delayed explosive charges. These were recorded by the instrument array to the west in order to study the effects of blast design on generating vibrations and to observe changes in the character of vibrations as they propagate.

The ground vibrations from shot 4 were recorded as they propagated across the instrument array and are shown in figures 55 to 57. The single-hole shot consisted of 125 lbs of ANFO in a 12-1/4-in-diameter hole at a depth of 50 ft. The 3-ft column of explosive took approximately 0.3 ms to detonate. The nearest recording station was only 65 ft from the shot hole and shows that the ground vibrations had already been strongly affected by the medium through which they propagated. The simple single-hole source has been transformed into a complicated signal lasting over 500 ms with predominant motion or vibration in the beginning of the signal occurring for 150 ms.

It is interesting to note the change in character of the signal from the near instrument station to the far. The character of the waveforms out to approximately 400 ft can be described by relatively high amplitude, high frequency vibrations in the early part of the signal which are associated with the arrival of reflected and refracted body waves, both P (compressional) and S (shear). The complexity which these waves are responsible is best illustrated by comparing the longitudinal component of waveforms recorded at 65 and 407 ft. Although it is not possible to identify individual phases at the further station, it is obvious that the predominant single pulse observed at 65 ft has become several pulses at 407 ft. If the propagation medium was infinitely homogeneous, then a wave recorded across the array would be very similar in character and change predictably only in amplitude and frequency. However, the subsurface generally comprises several different materials (e.g., soil, weathered rock, shale, sandstone, coal, etc.), each material providing a separate transmission path and each interface giving rise to new phases as a wave propagates across the boundary. These phases eventually arrive at a station and comprise the recorded waveform.

The higher velocity body waves are followed by lower velocity, lower frequency surface waves. As their name implies, these surface waves are a result of a boundary in the propagating medium, e.g., the air-ground interface, and are actually composed of P and S waves which constructively interfere during propagation. Since high frequencies attentuate more rapidly than low frequencies, the recordings made between 800 and 2,600 ft reveal the predominance of the later-arriving surface waves which are responsible for the relatively larger vibrations at distance. The importance of surface waves in the mining and blasting industry also lies in their frequency which is near the natural frequency of residential structures (2). Vibrations near the natural frequency of a structure can cause the structure to become "excited" and resonate at amplitudes higher than the ground vibration amplitudes. Although the blasting at the Universal Mine and the geology combine to generate surface waves, the amplitude of these vibrations are below levels which have been determined to cause damage to residential structures (2).

Blast Design and Geologic Influence: A comparison of ground vibrations recorded by the west instrument array for production shot 3 and single-hole shot 4 reveal some similarities. As previously mentioned, vibration amplitudes attentuated at the same rate. This suggests that the production shot with a sequence of over 100 delays lasting 1.3 seconds is not exciting the subsurface structure and causing resonance. Further proof is found in the duration of surface waves measured at the stations between 400 and 1,200 ft (figures 45 to 47 and 55 to 57).

The duration of ground motion associated with the surface waves for the production shot is the same for the single-hole shots at these stations. (Amplitudes are greater for shot 3 because multiple decks were detonated simultaneously.)

Two stations were chosen to examine the frequency content of the ground vibrations for both production and single hole shots, one near (90 and 65 ft, respectively) and one far (1,190 and 1,165 ft, respectively). The frequency spectra for the near stations longitudinal component are similar and shown in figure 58. Predominant frequencies for the production shot were between 5 to 10 Hz and for the single-hole shot between 5 to 15 Hz. The frequency spectra for the far station (figure 59) compare even more favorably with a predominant frequency near 6 Hz. Overall, there is a very good correlation between spectra for the production shot and the single-hole shot and supports the theory that the subsurface geology controls the frequency content of a signal. However, it does appear that the delay interval frequency of 100 ms may have affected the spectral content for the near recording.

Theoretical Models

Two mathematical models exist for describing surface wave generation. The Gupta model (9, 10) for shear waves, dominant on longitudinal and transverse, and the O'Brien model (11), dominant on longitudinal and vertical. Both models appear to use the same equation, which is simple when $V_2 >> V_1$, except that V refers to shear and compressional velocities for the two models, respectively.

The O'Brien model requires a low velocity surface layer with a strong velocity contrast. The relationship is:

$$T = \frac{4h}{V_1}$$

where T is the surface wave period, 1/frequency

h is the low-velocity layer thickness, and
V_1 is the low-frequency layer velocity, compressional
V_2 is the high-velocity layer velocity, compressional

Using the Volk 11-25-85 record, calculations of velocity and thickness (depth) are possible. The surface wave arrives 1.6 seconds later than the direct arrival (measured by Bureau researchers at the mine at about 10,000 ft/s). The surface wave period is 0.26 seconds or 4 Hz. Using the 1.6 second travel time difference, the low velocity layer has a velocity of about 2,700 ft/s. From the equation, this indicates a layer thickness of 175 ft. It is difficult to believe that there is a near surface layer this thick with an average propagation velocity of 2,700 ft/s. Although unlikely, it is possible if the zone is highly fractured. The Gupta model presumably requires the shear wave propagation velocity which was not measured. More work is needed, including measurements of propagation velocity and subsurface structure characteristics.

UNDERGROUND OPENINGS

This is an entirely different case than the above models. Instead of a low velocity layer over an underlying high velocity, this is a case of voids, probably flooded, which act as reflectors rather than refractors. Because of the various surface wave characteristics observed in Blanford, more than one generation model may be at work.

Summarizing the influences on vibration frequency, the propagating medium appears to have a dominating influence at large distances, greater than about 400 ft from the Bureau's single-hole and production blasting comparisons. Closer than this at this site, the vibration record resembles the blast sequencing. However, review of the five examples of blast designs, figures 40 through 44, suggests that design periodicities can show up in records obtained at large distances. The natural ground frequency of 8 to 10 Hz can be excited as can the 5 Hz surface wave. More work is needed on surface wave generation mechanisms and correlation with underground structures.

LEVEL LOOP SURVEYS

Surveys were made of 8 Blanford homes with an automatic level to determine if differential settlement or subsidence occurred. An identifiable survey horizon was chosen, the foundation or a brick or block mortar joint. Relative elevations were determined. Note that this does not directly tell if a structure is under stress. Measured deviations could be from differential settlement. Alternatively, the structures could have been built slightly out of level and be totally free of true strain, not having moved at all. Unless the builder can guarantee a certain level tolerance, the only way to identify ongoing vertical movement is by periodic resurvey.

Figures 60 through 67 show the 8 homes and survey results. Through an oversight, the Zell home was not photographed. Table 6 summarizes the results. Note that several of the structures had "deformations" (assuming the homes were originally level) of more than one part in 300.

Boscardin cites the following deflection ratio criteria (12):

structural damage:	1/150
cracking of panel and load bearing walls:	1/300
non-cracking case:	1/500

where these are angular distortions.

These relatively high values, if representing true distortion, provide an explanation for wall cracks and other types of minor damage. Resurveys are recommended, particularly where other evidence of subsidence exists, such as sink holes.

TABLE 6. - Summary of level loop survey of 8 Blanford residences

House	Angular distortion, maximum	Elevation ft change, maximum	Static strain, maximum, μin/in
Ahlemeyers	1/337	.060	1,009
Albrecht	1/253	.115	988
Finger, E.	1/298	.080	1,006
Finger, O.	1/200	.089	1,850
Jovanovich	1/217	.150	1,060
Marietta	1/562	.085	285
Skorich	1/245	.060	1,714
Zell	1/65	.370	4,461

Accuracy ± .005 ft

*** CONCLUSIONS

The propagating medium appears responsible for the adverse vibration impacts in Blanford through two mechanisms:

(1) favors generation of low-frequency waves of several types, between 4 and 10 Hz.

(2) produces interactions between delayed charges beyond what would be expected from the blasts as designed, because of constructive wave interference for these long period waves.

Redesign of the blasts may allow the minimizing of undesirable vibrations, possibly even employing the new precision initiators now being developed.

Other useful research could be done at this site, particularly correlation of the various blast designs with the vibration wave characteristics. Because of the site complexity and the questionable scaling propagation predictions, it is recommended that extensive monitoring at several locations in Blanford be continued. More information is needed on subsurface conditions to identify the causes of the strong surface wave generation and explanations of why significant differences exist at the various monitoring sites.

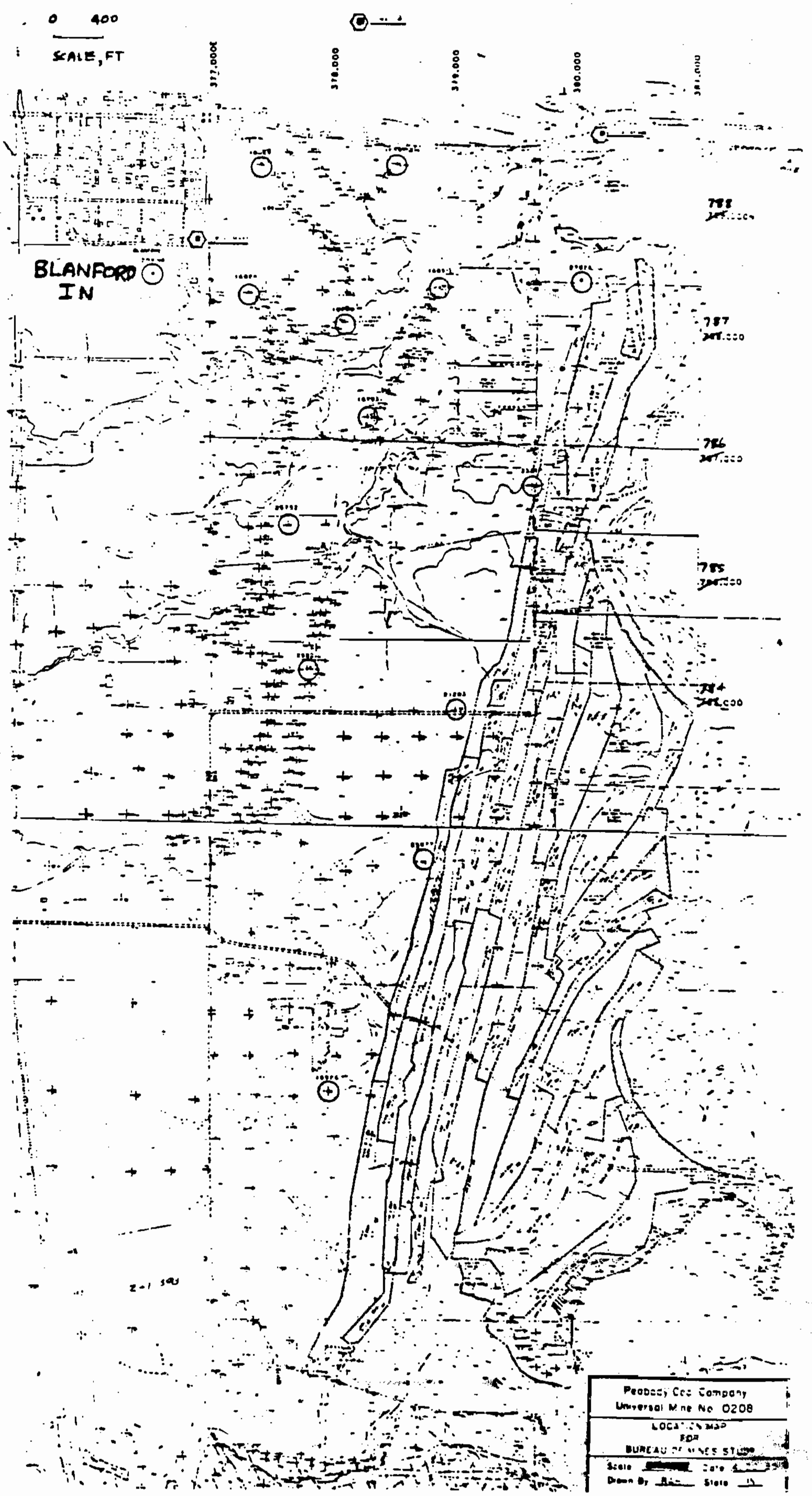


FIGURE 1. - Peabody's Universal mine and Blanford, IN

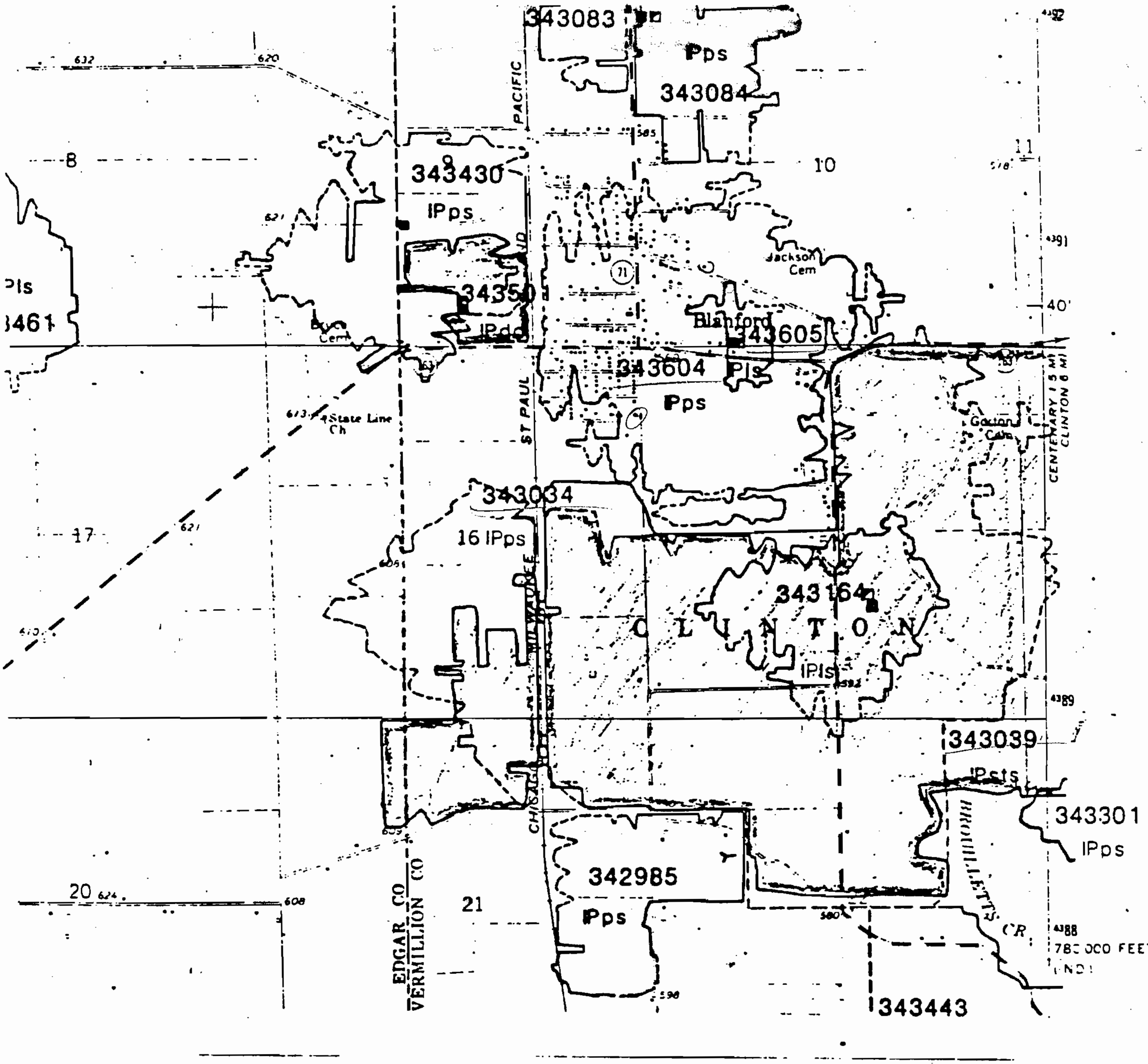


FIGURE A-1. - Areas around the town of Blanford undermined by abandoned coal mine workings.

343604 West Clinton No 1, Seams 4 and 5, 1913-1931

343605 West Clinton No 2, Seam 4, 1921?

343039 Binkley Mining Co. No. 6 Seam 3 1925
343034 Binkley Coal Co. No. 1 Seam 5 1912-1917
343164 W.S. Bogle & Co. No. 4 Seam 1913-1918

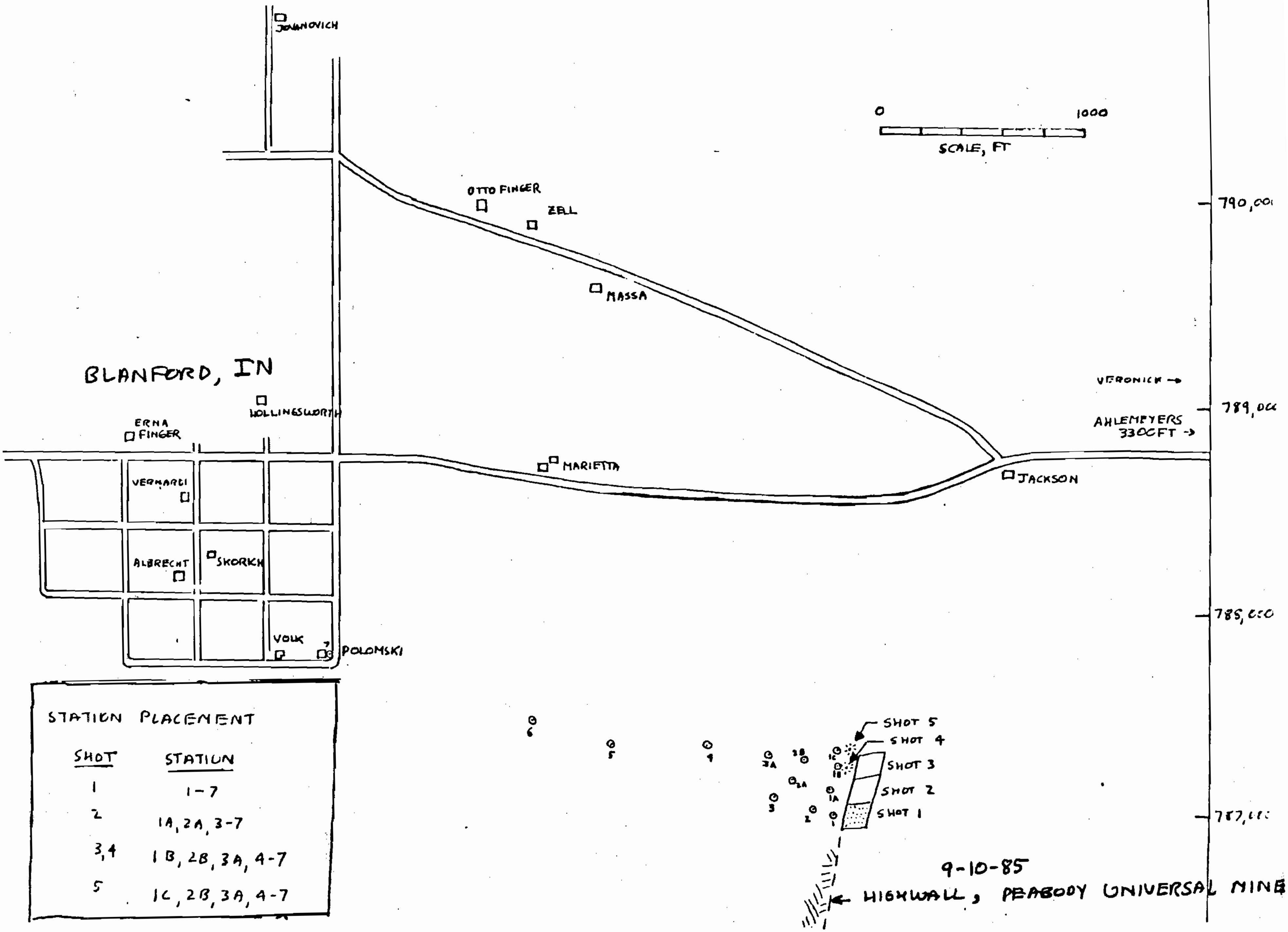


FIGURE 2. - Shot and seismograph array for BuMines shots 1-5, 9-10-85.

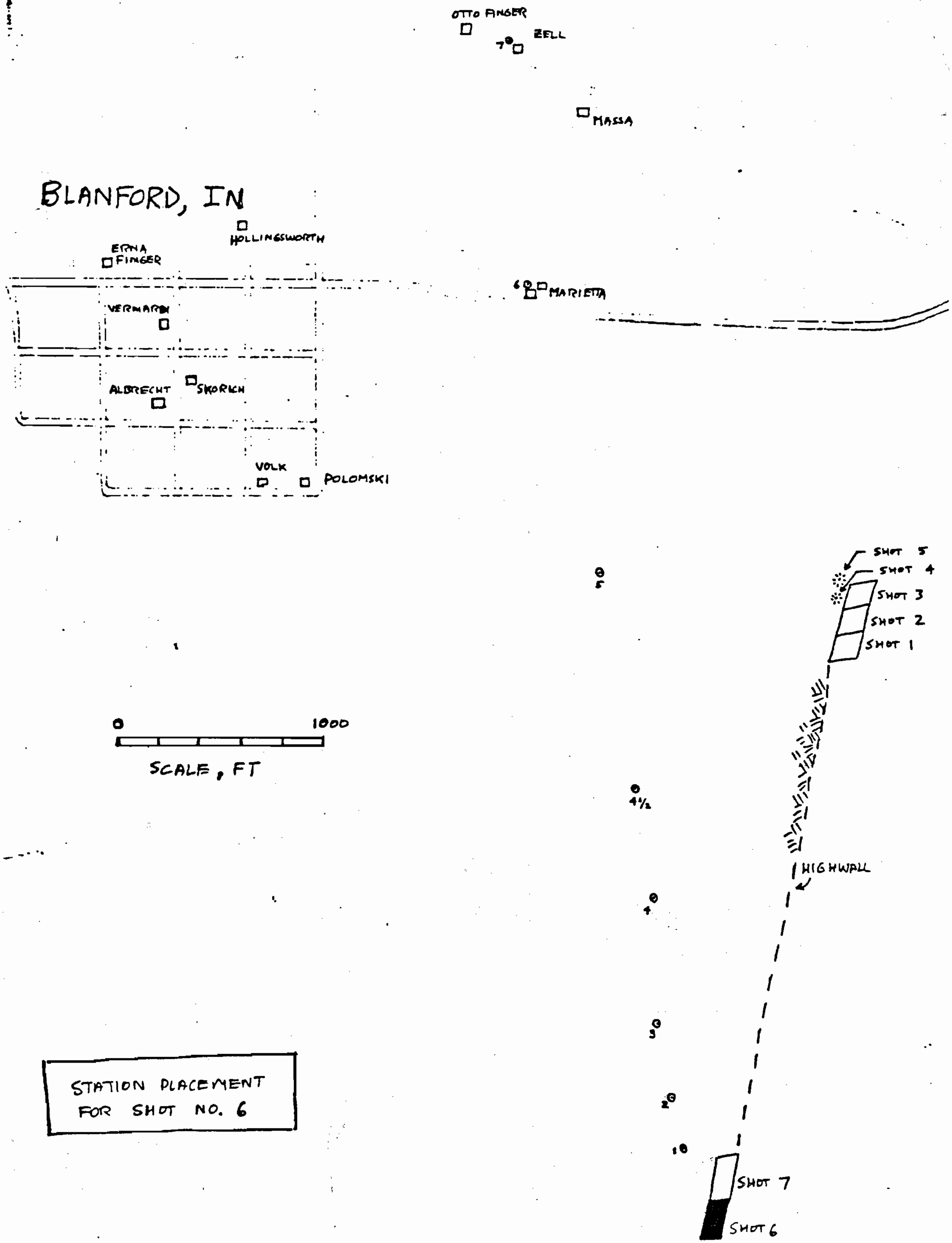


FIGURE 3. - Shot and seismograph location for BuMines shot 6, 9-12-85.

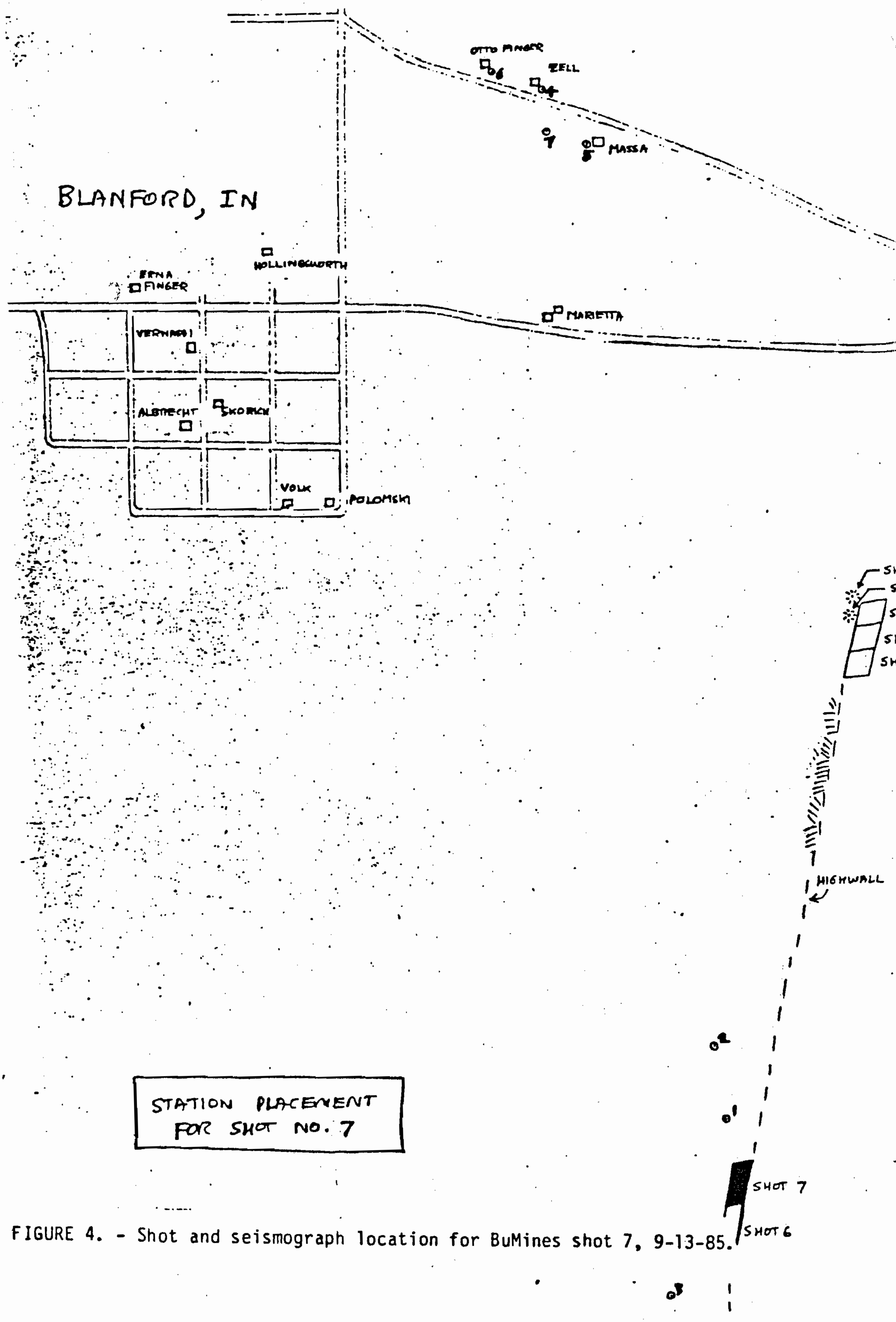


FIGURE 4. - Shot and seismograph location for BuMines shot 7, 9-13-85.

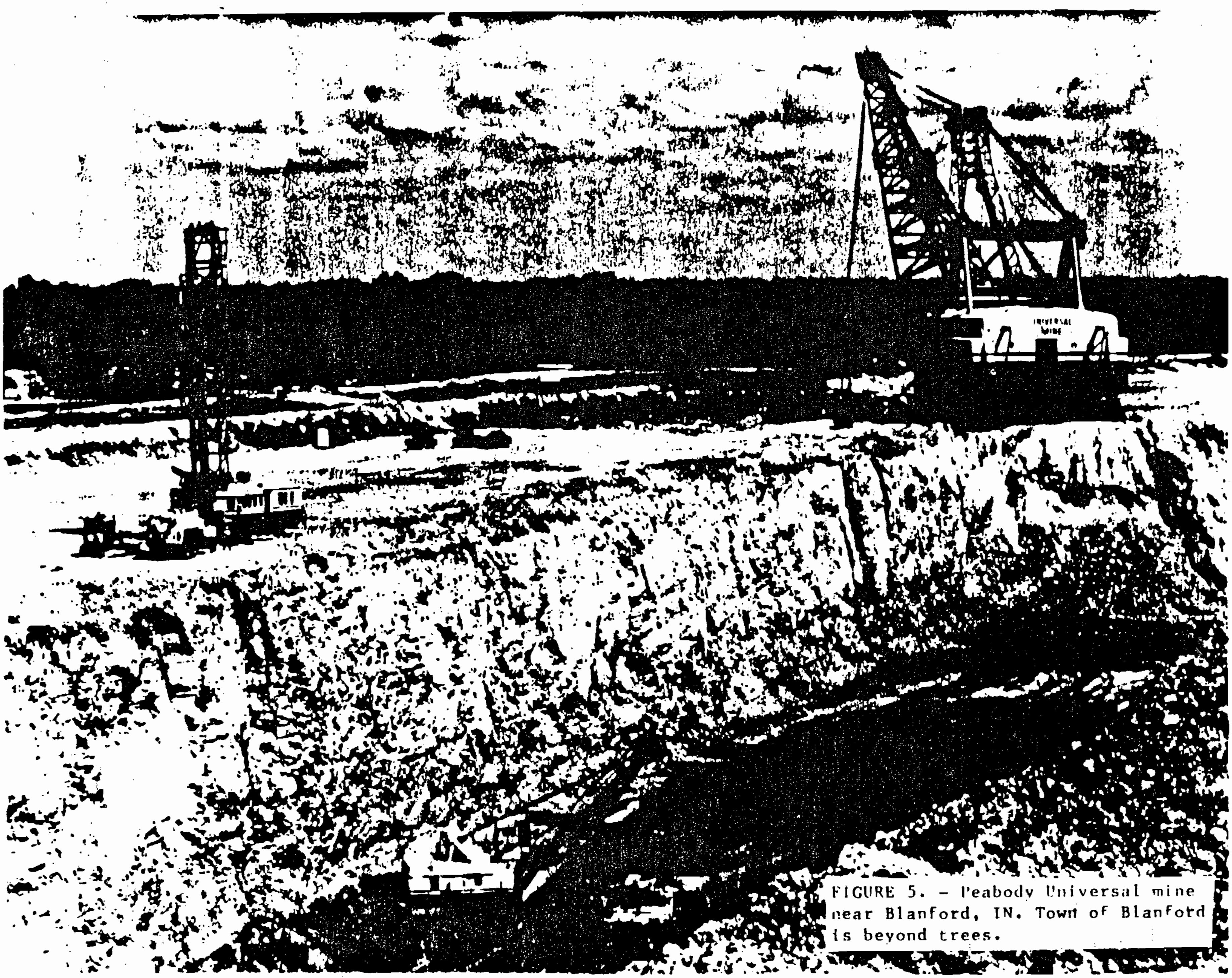
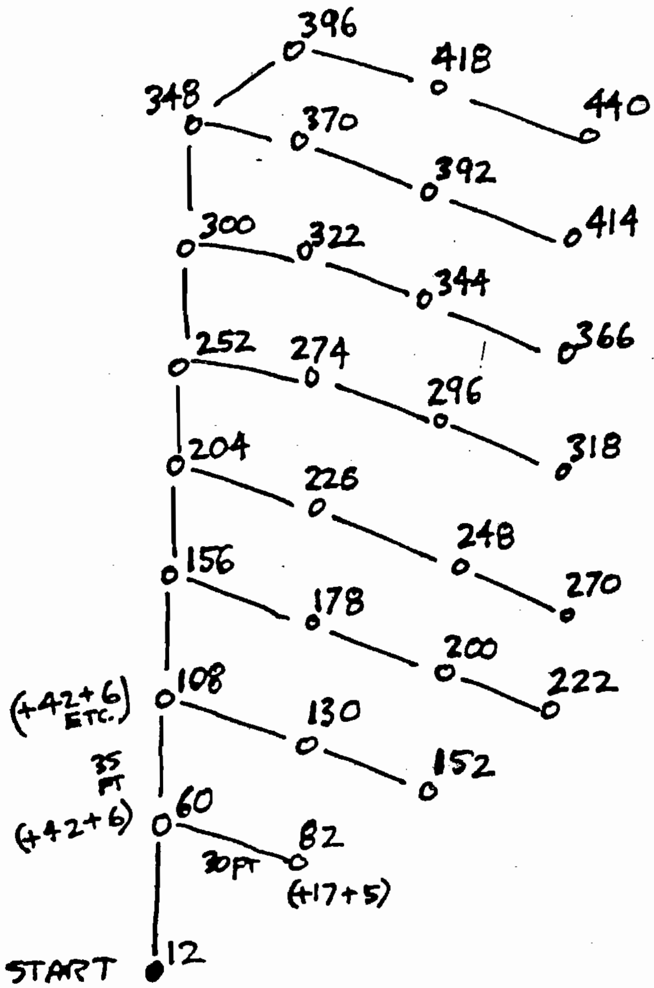
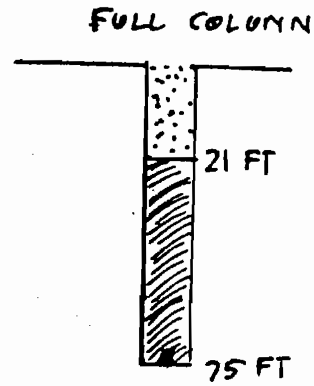


FIGURE 5. - Peabody Universal mine near Blanford, IN. Town of Blanford is beyond trees.

FIGURE 6. - Echelon blast design with 42 ms between rows and 17 ms between holes in a row, 1-9-85, 15:17.





Nonel down hole travel time is 12.5 ms

Burden travel time: 5 ms
Spacing travel time: 6 ms

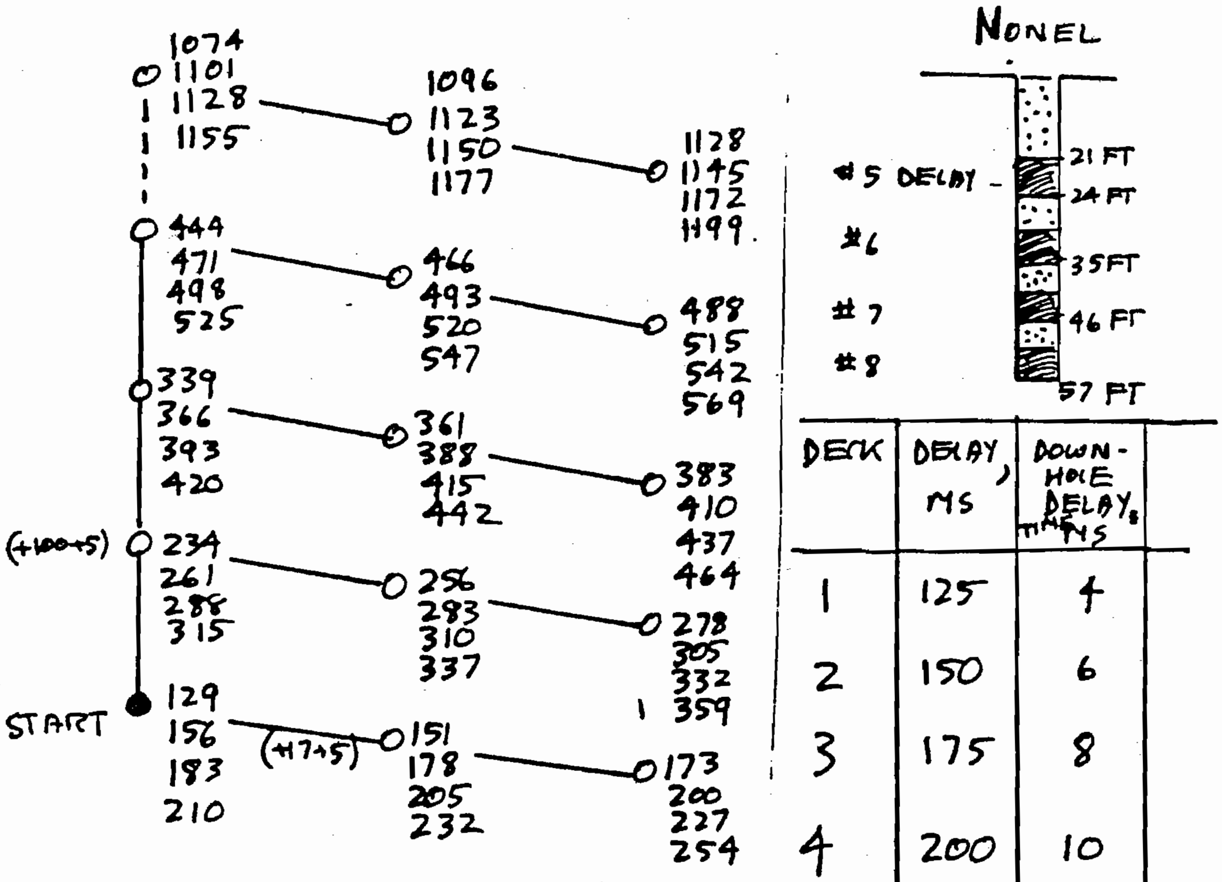
Note: Burden and spacing distances are those specified by Peabody and defined according to the highwall. "Burden" is perpendicular to the highwall, and "spacing" is parallel. Effective values, en enchelon, are not the same as these.

Shots were full column. No decking.

Charge weights were typically 1,500 lbs/delay, with a maximum of 2,258.

All delay times are nominal. Actual times will vary because of scatter.

FIGURE 7. - Echelon blast design with 100 ms between rows and 17 ms between holes in a row, 3-14-85, 10:37.



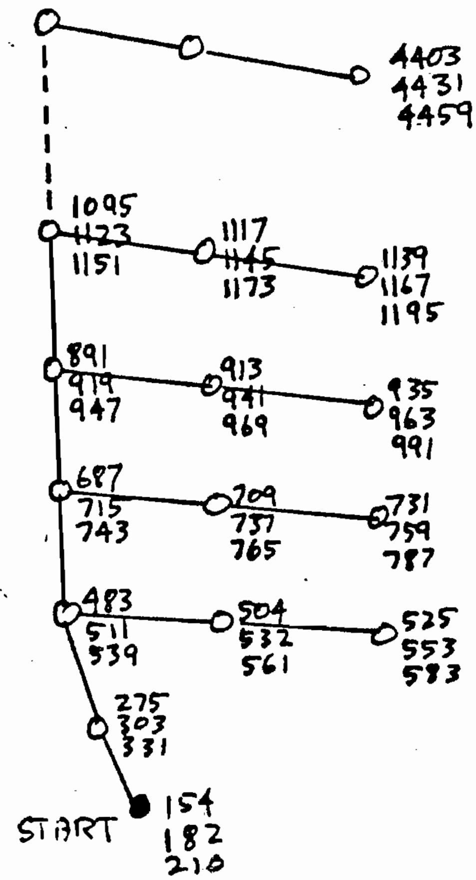
DECK	DELAY, MS	DOWN-HOLE DELAY TIMES, MS
1	125	4
2	150	6
3	175	8
4	200	10

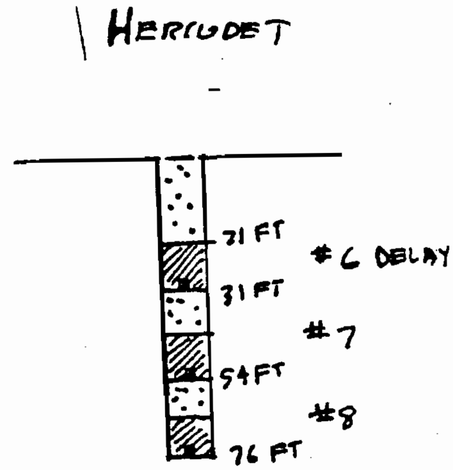
Number of decks ranged from 2 to 4.

Charge weights were about 325 lbs/delay.

All delay times are nominal.

FIGURE 8. - Echelon blast design with 200 ms between rows and 17 ms between holes in a row, 1-12-85, 17:18.





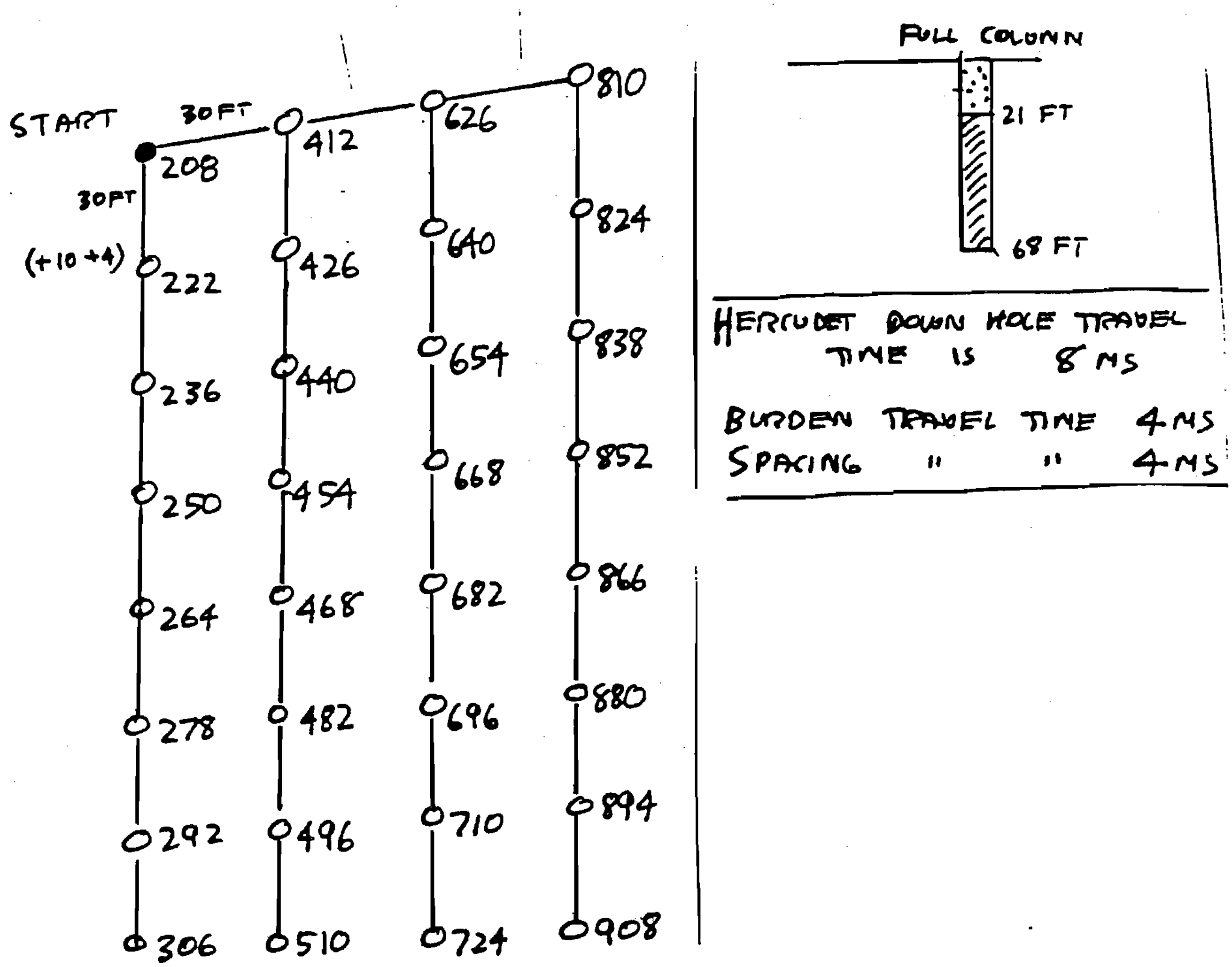
DECK	DELAY, MS	DOWN HOLE DELAY TIME, MS
1	150	4
2	175	7
3	200	10

Number of decks ranged from 2 to 4.

Charge weights were 200-400 lbs/delay except 1475 on 1-5-85 and 1911 on 1-12-85 (17:18).

All delay times are nominal. Actual times vary because of scatter.

FIGURE 9. - Casting blast design with about 200 ms between rows and 10 ms between holes in a row. This is a short array. 1-21-85.

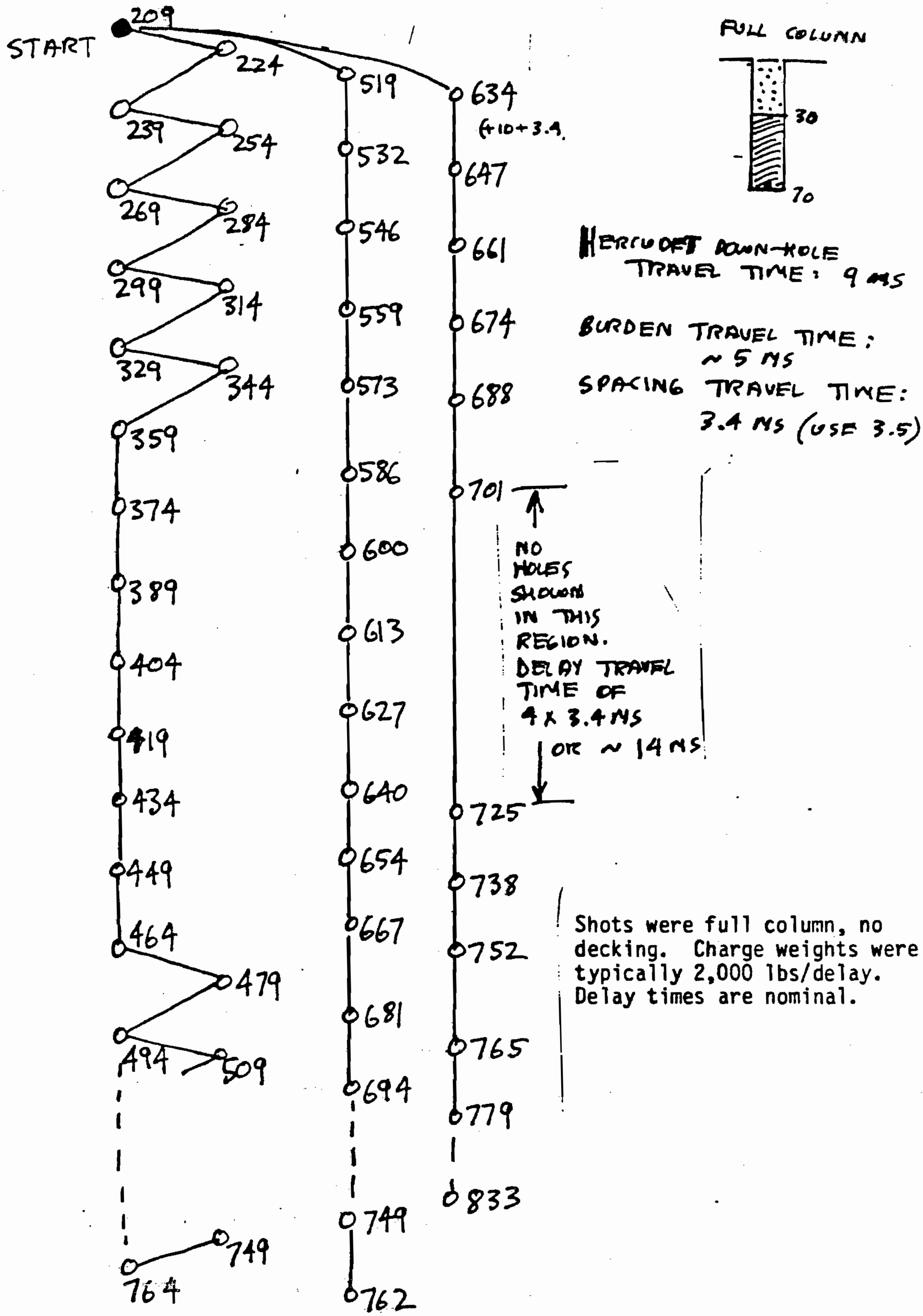


Shots were full column. No decking.

Charge weights were typically 2,000 lbs/delay.

All delay times are nominal.

FIGURE 10. - Casting blast design, long array, 2-16-85.



Shots were full column, no decking. Charge weights were typically 2,000 lbs/delay. Delay times are nominal.

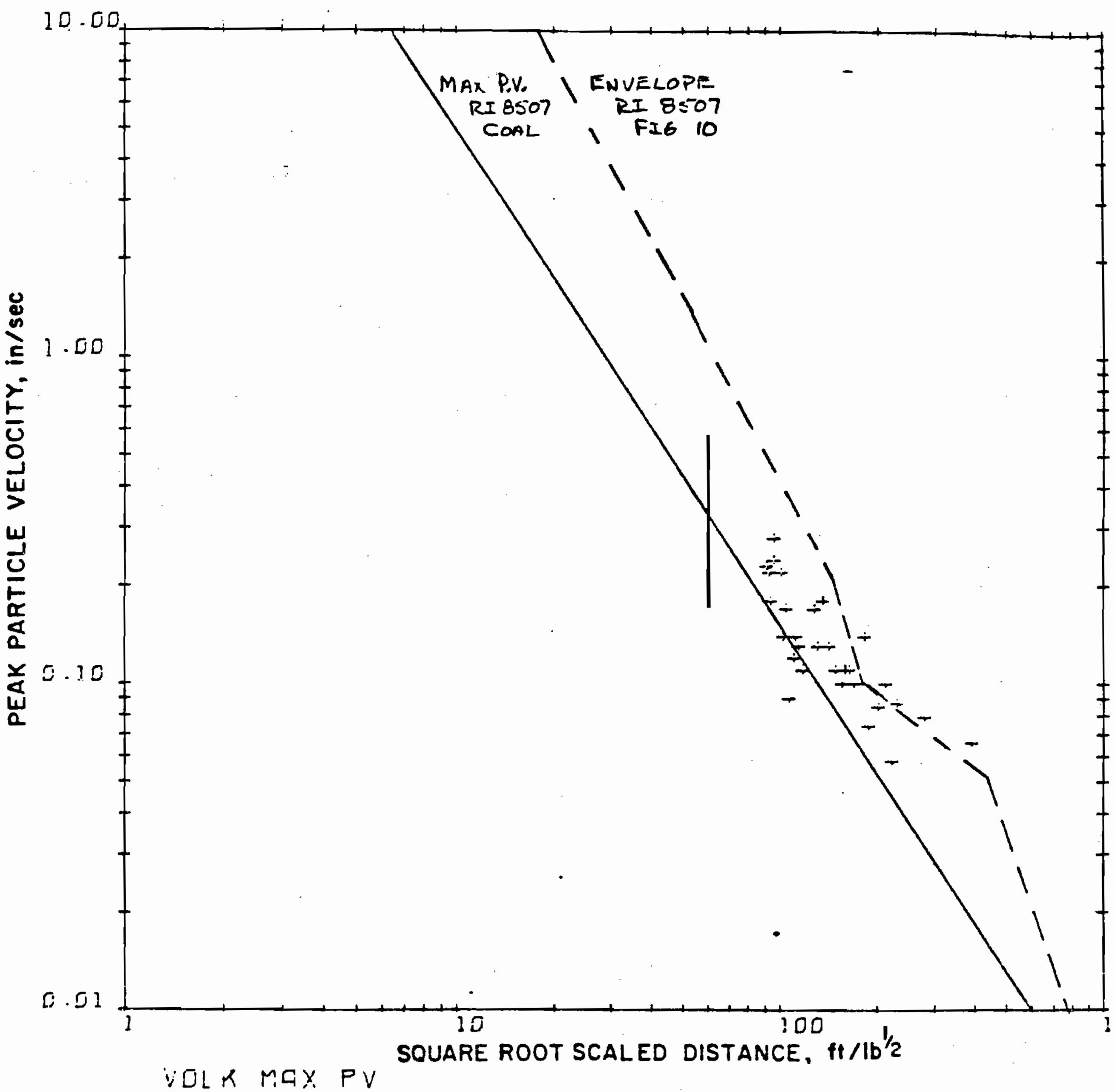


FIGURE 11. - Volk maximum particle velocity.

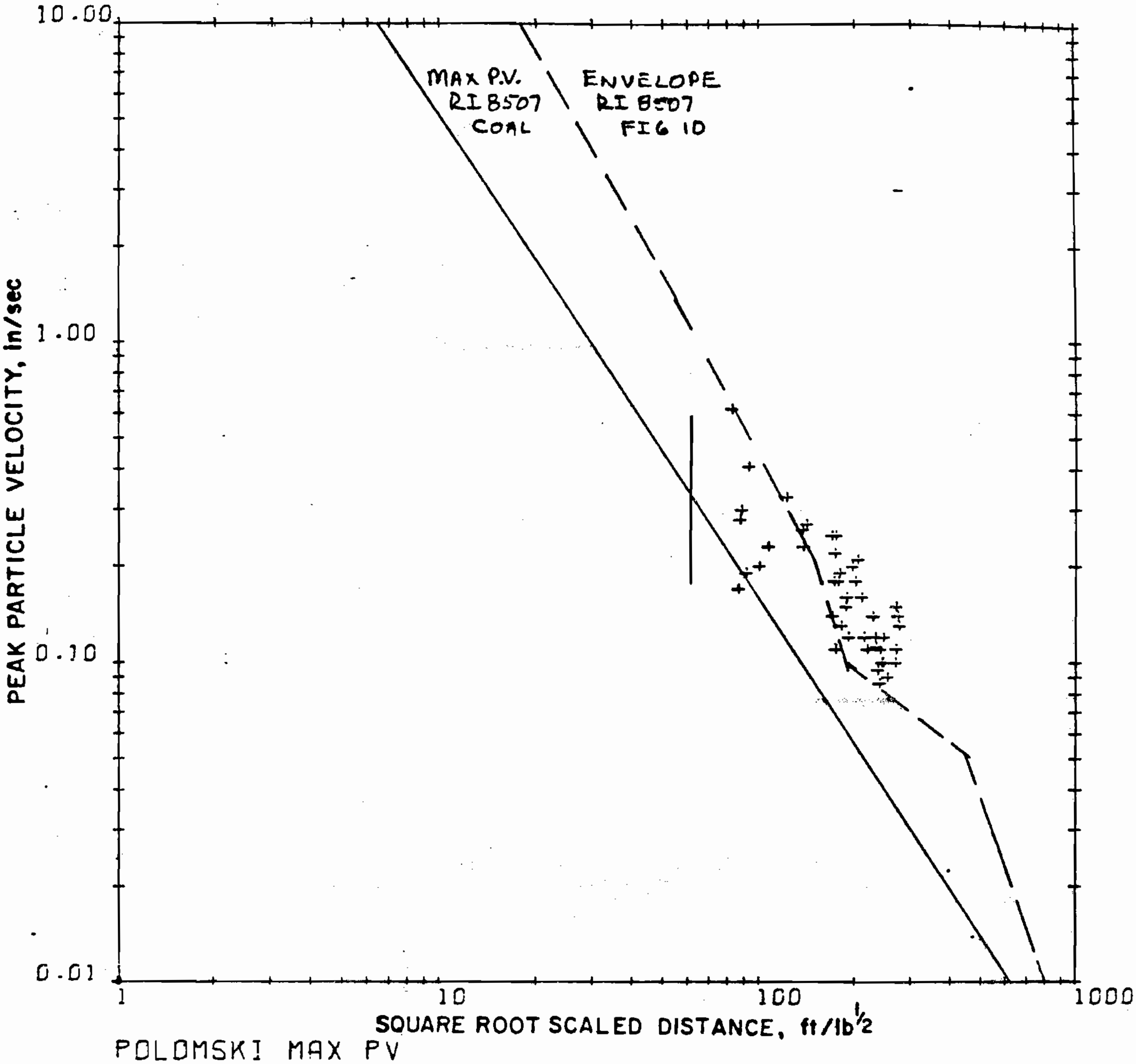


FIGURE 12. - Polomski maximum particle velocity.

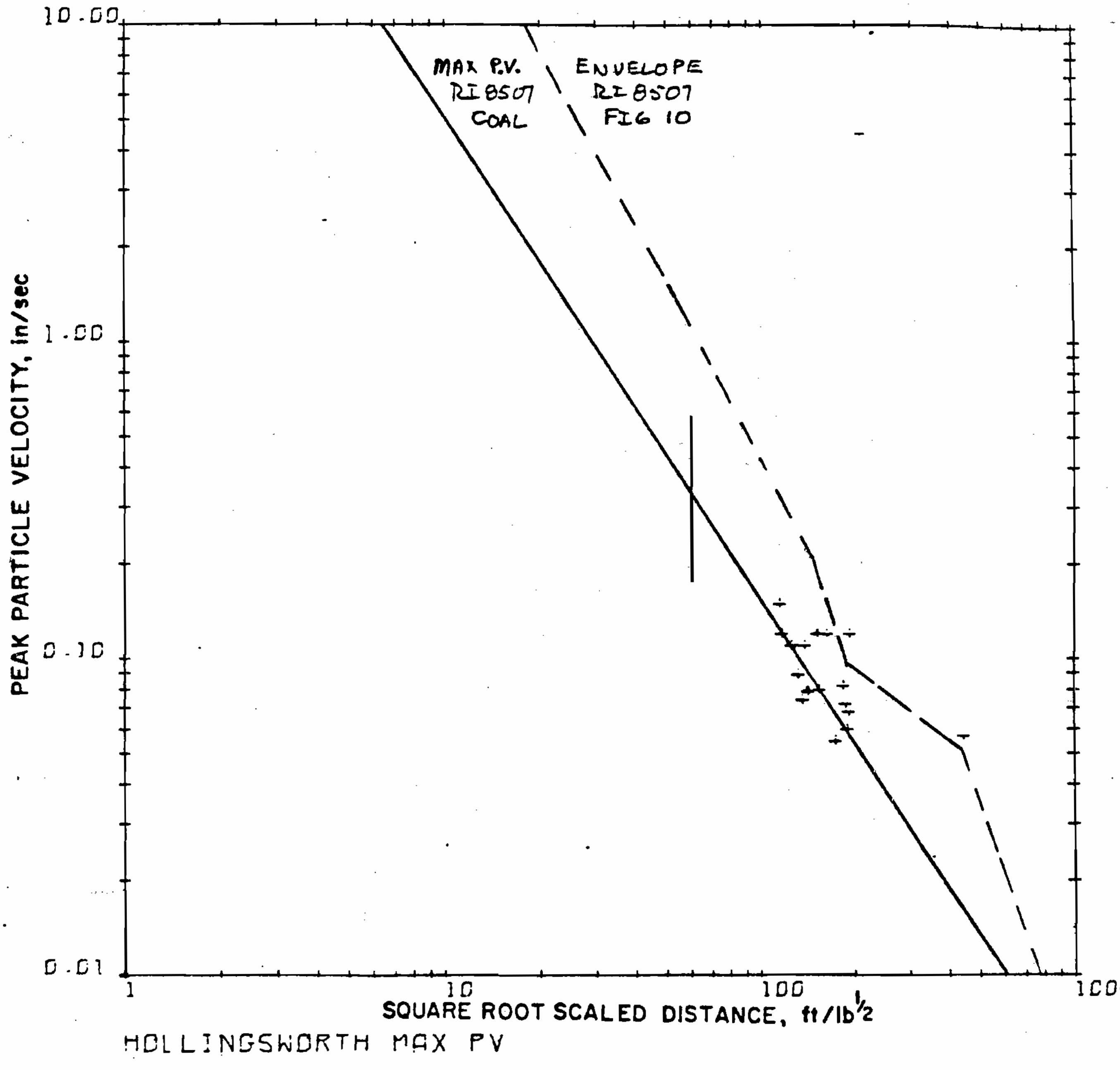


FIGURE 13. - Hollingsworth maximum particle velocity.

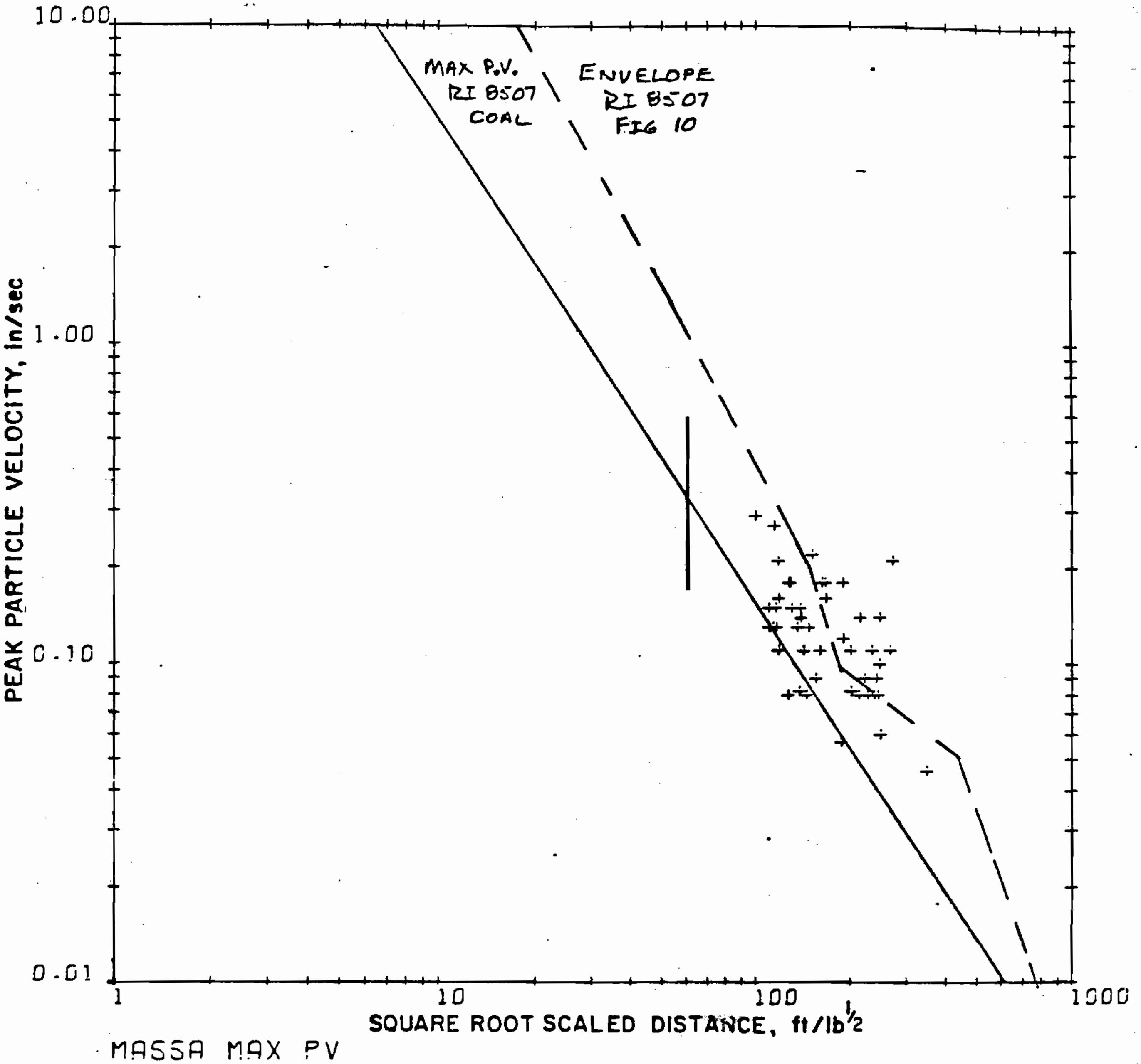


FIGURE 14. - Massa maximum particle velocity.

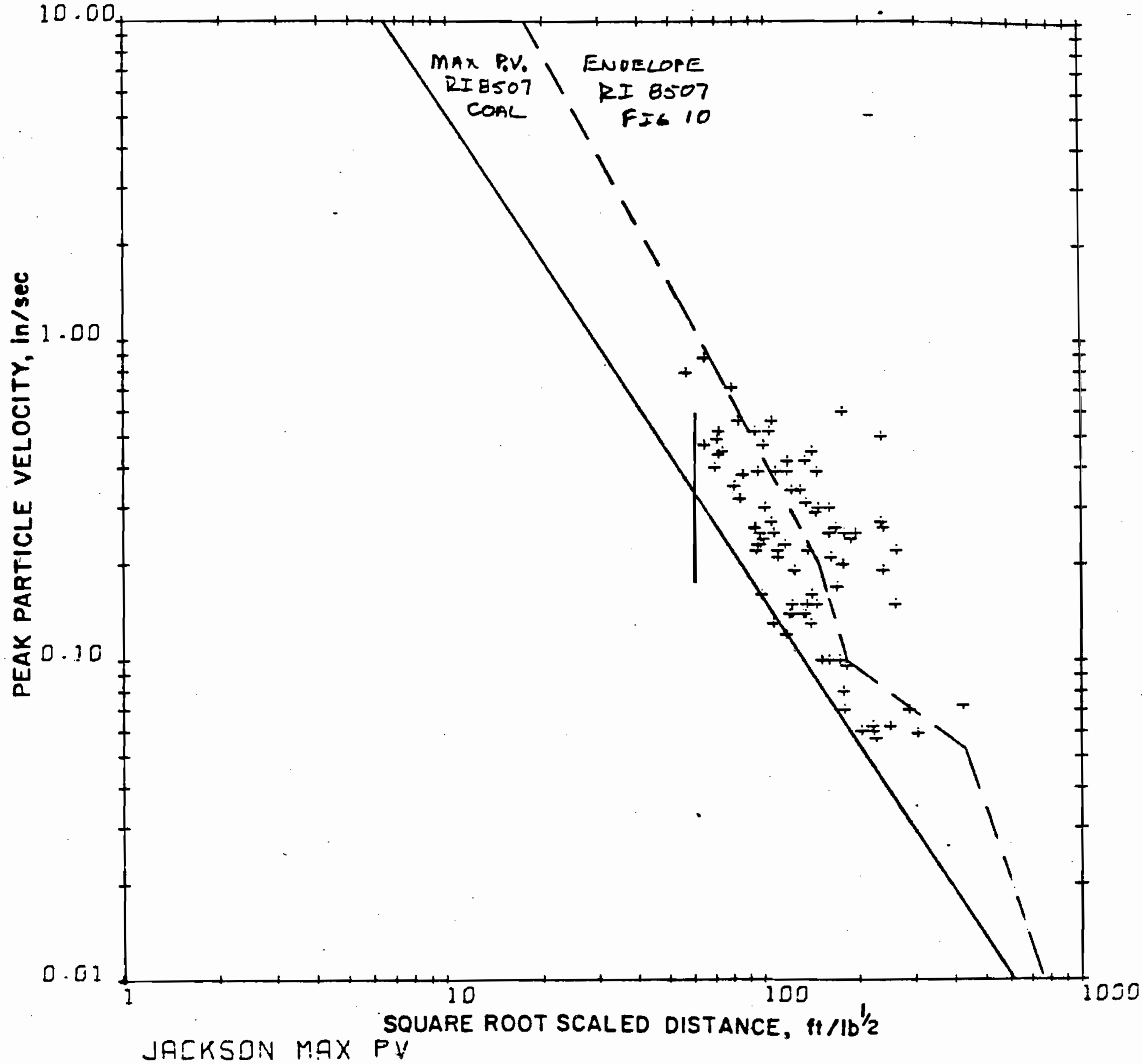


FIGURE 15. - Jackson maximum particle velocity.

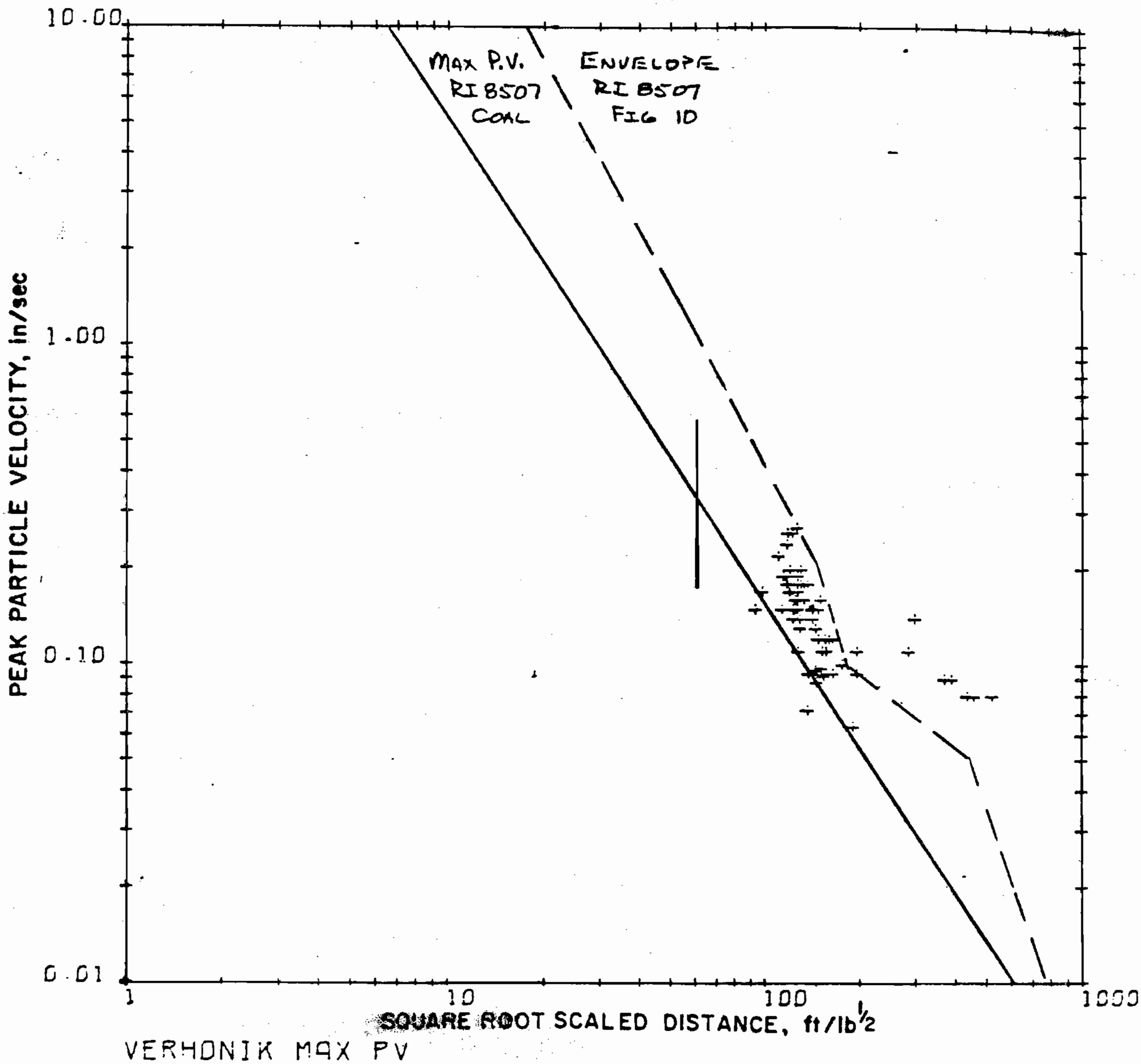


FIGURE 16. - Verhonik maximum particle velocity.

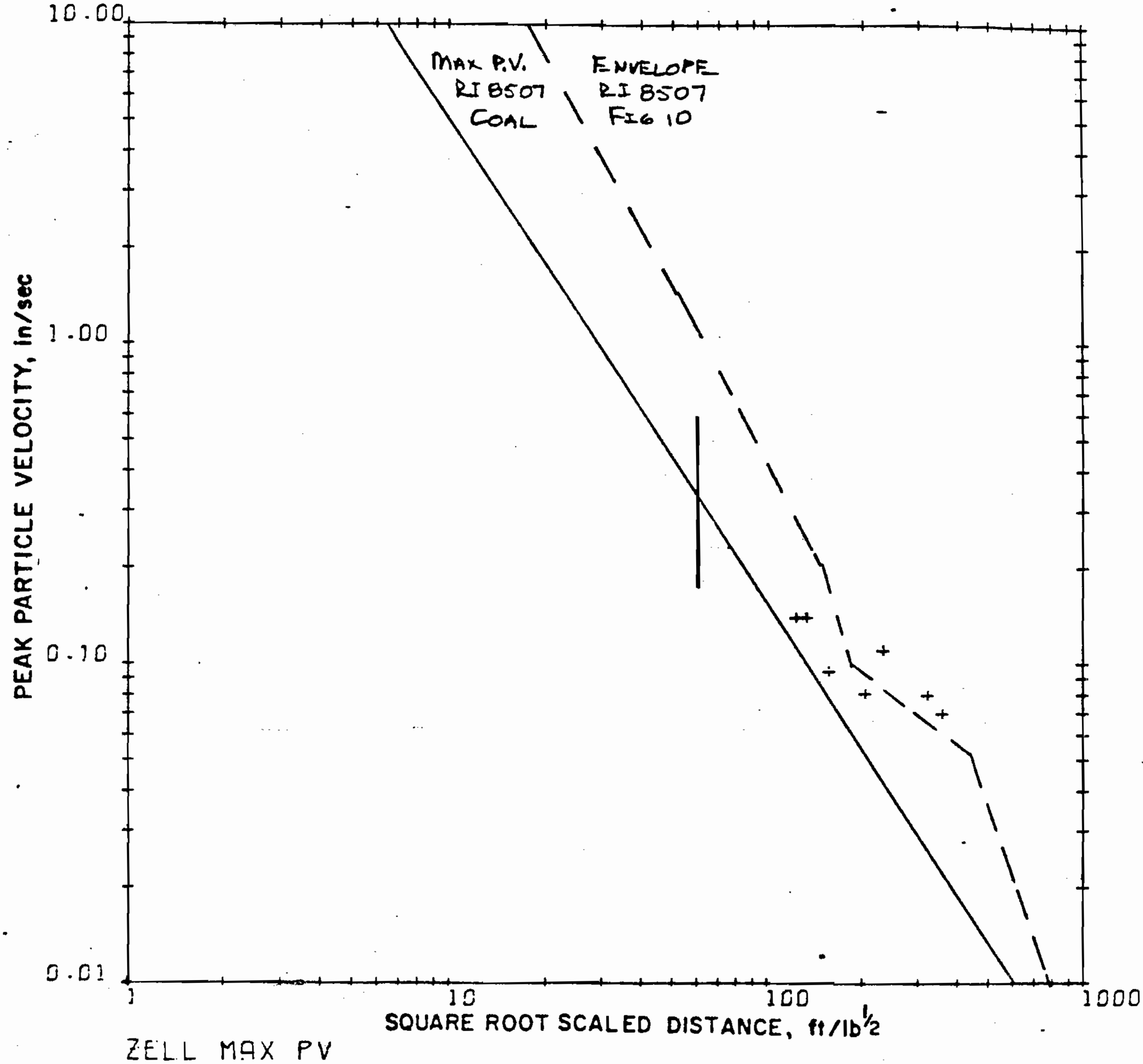


FIGURE 17. - Zell maximum particle velocity.

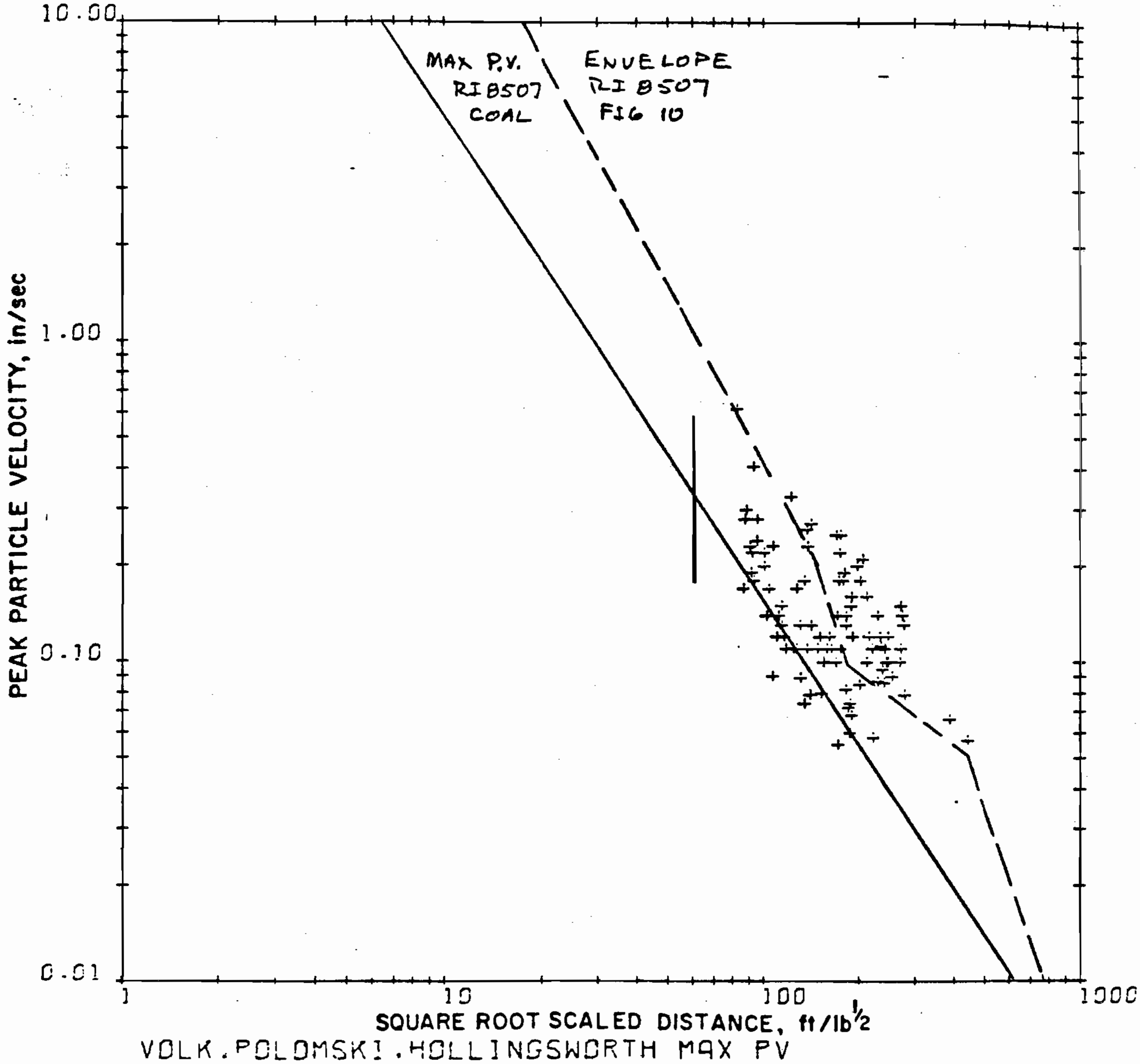


FIGURE 18. - Volk, Polomski, Hollingsworth maximum particle velocity.

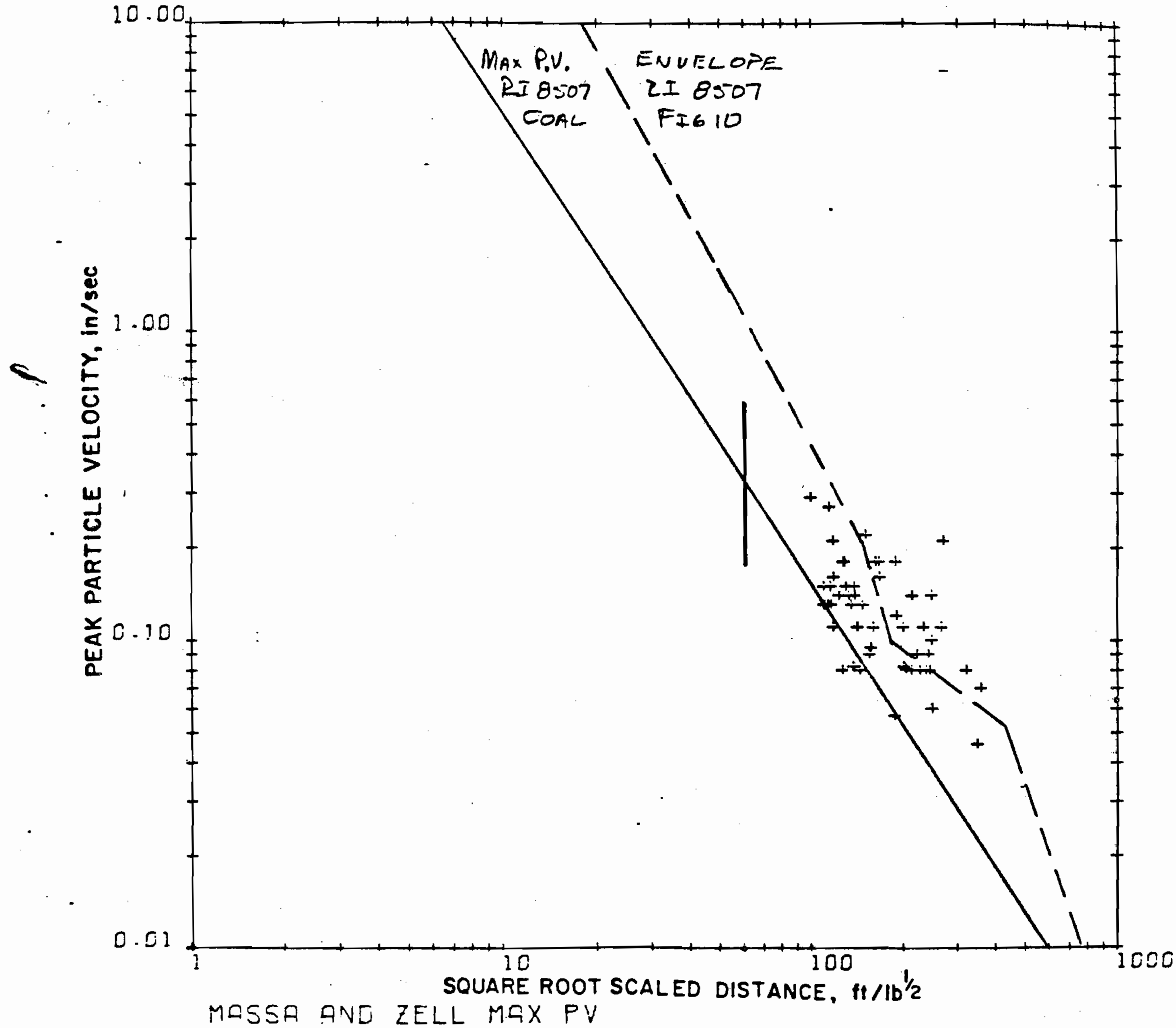


FIGURE 19. - Massa and Zell maximum particle velocity.

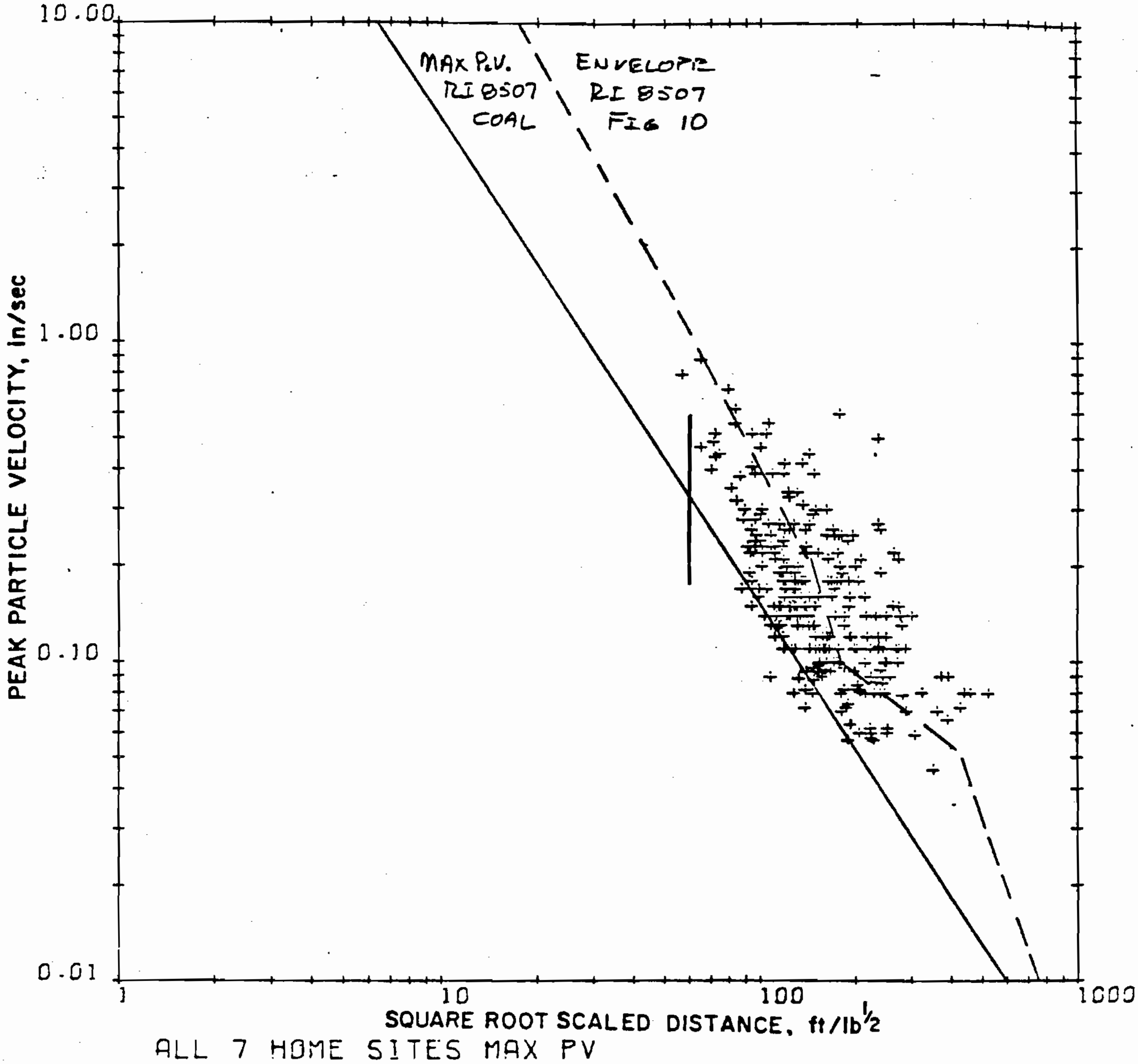


FIGURE 20. - All 7 home sites maximum particle velocity.

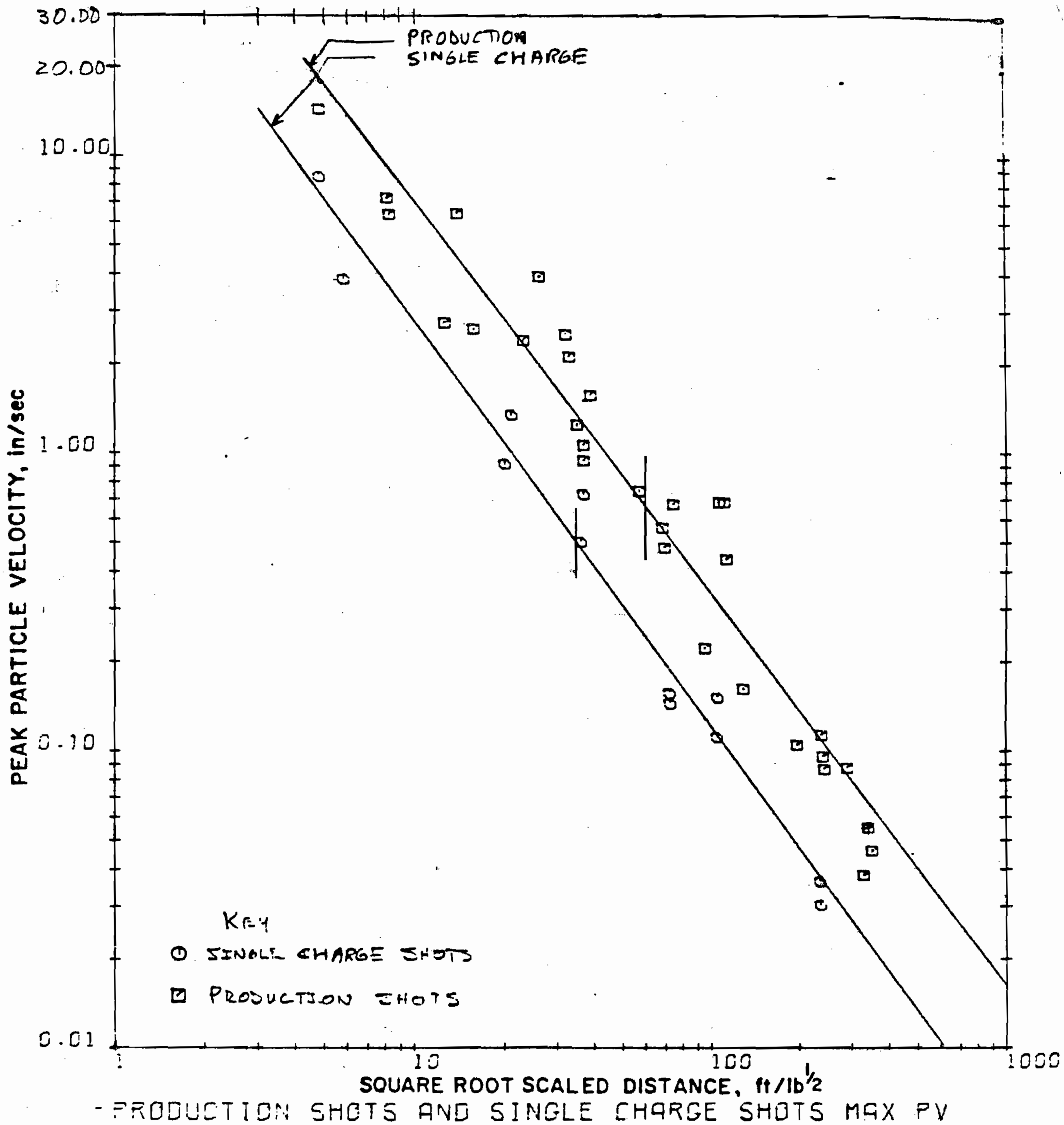


FIGURE 21. - Production shots and single charge shots maximum particle velocity.

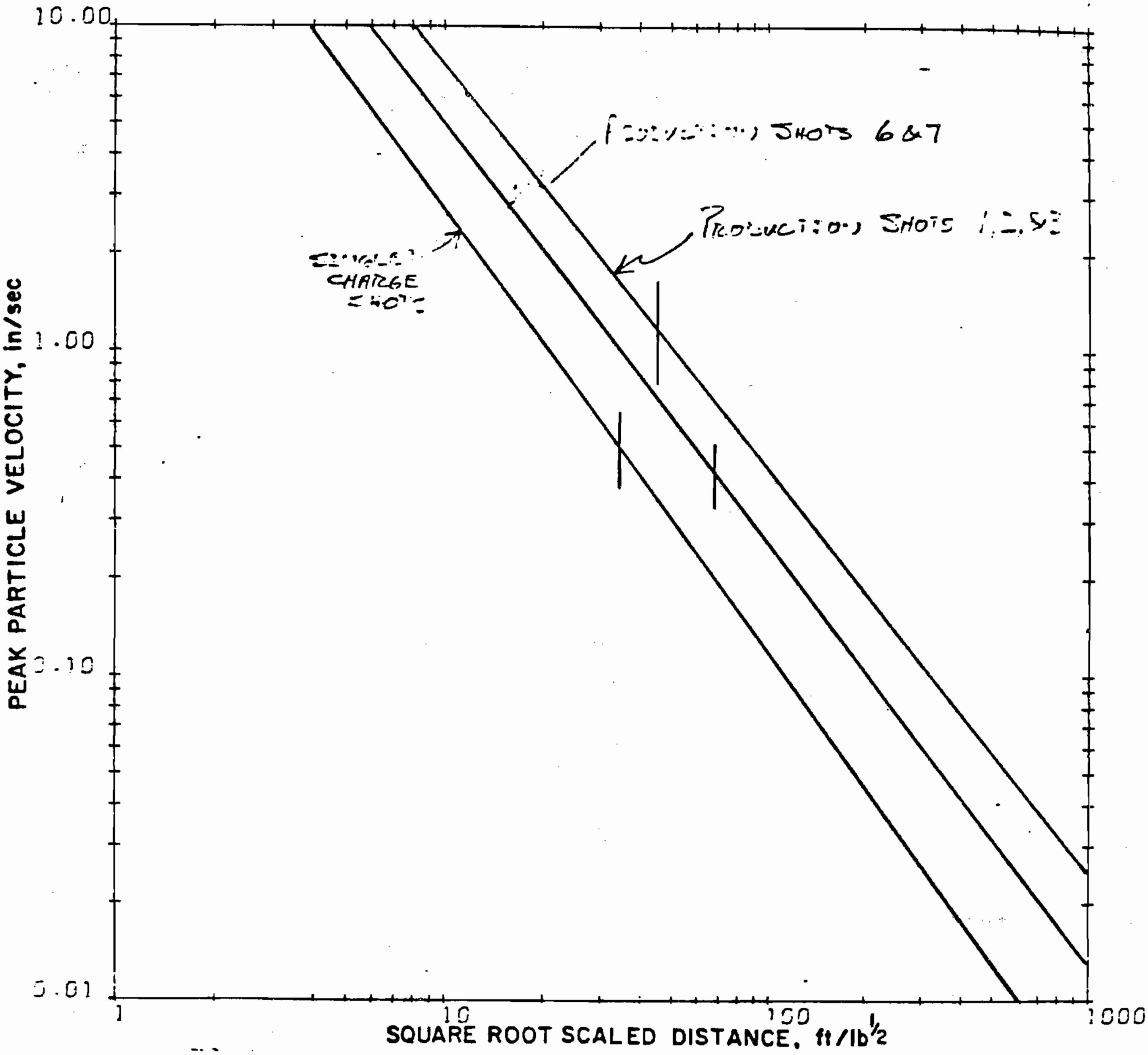


FIGURE 22. - BuMines data, shots 1, 2, and 3, single charge shots 4 and 5, and shots 6 and 7, maximum particle velocity.

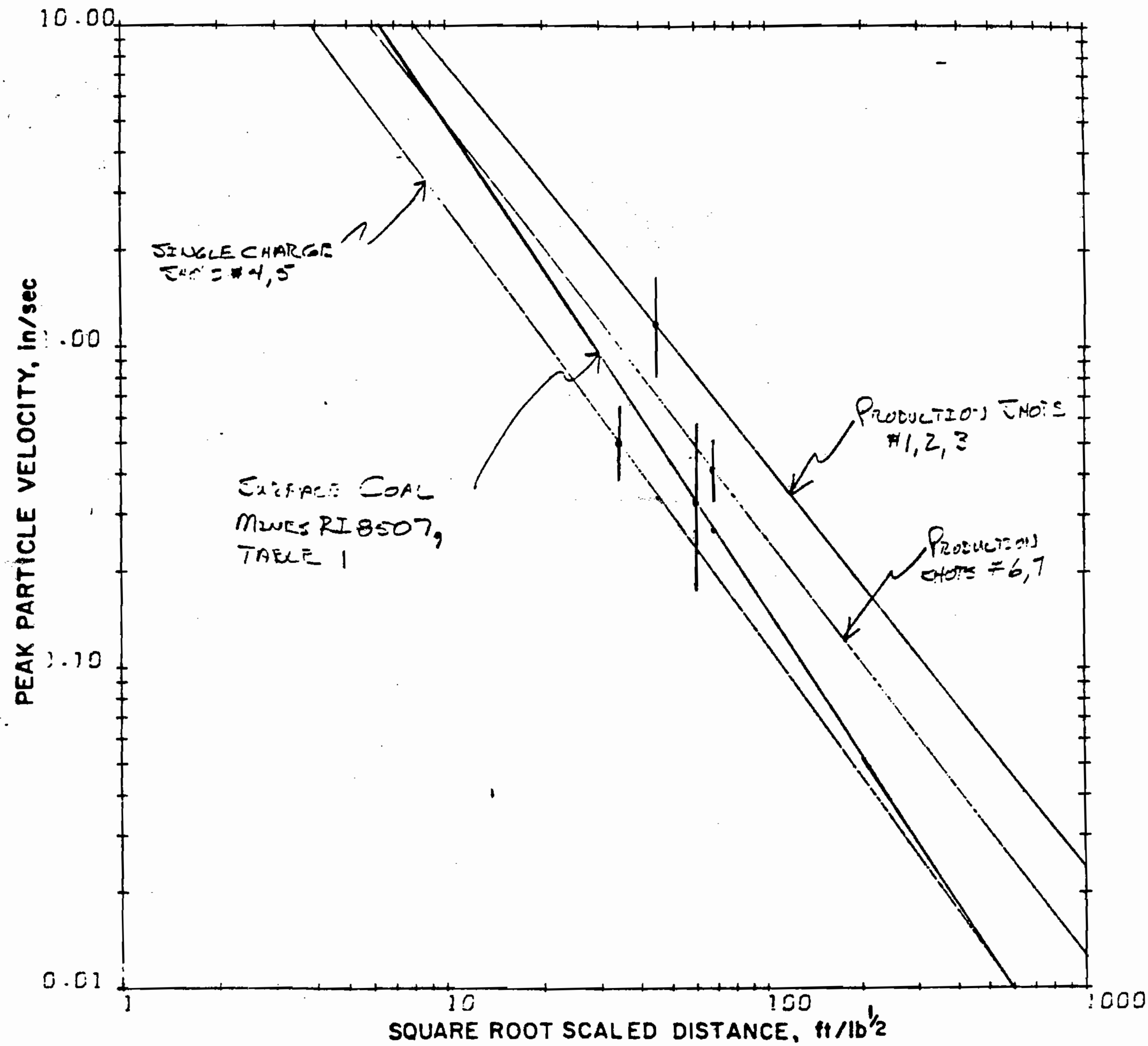


FIGURE 23. - Production and single charge shots at Universal Mine compared to BuMines data from surface coal mines (RI 8507) maximum particle velocity.

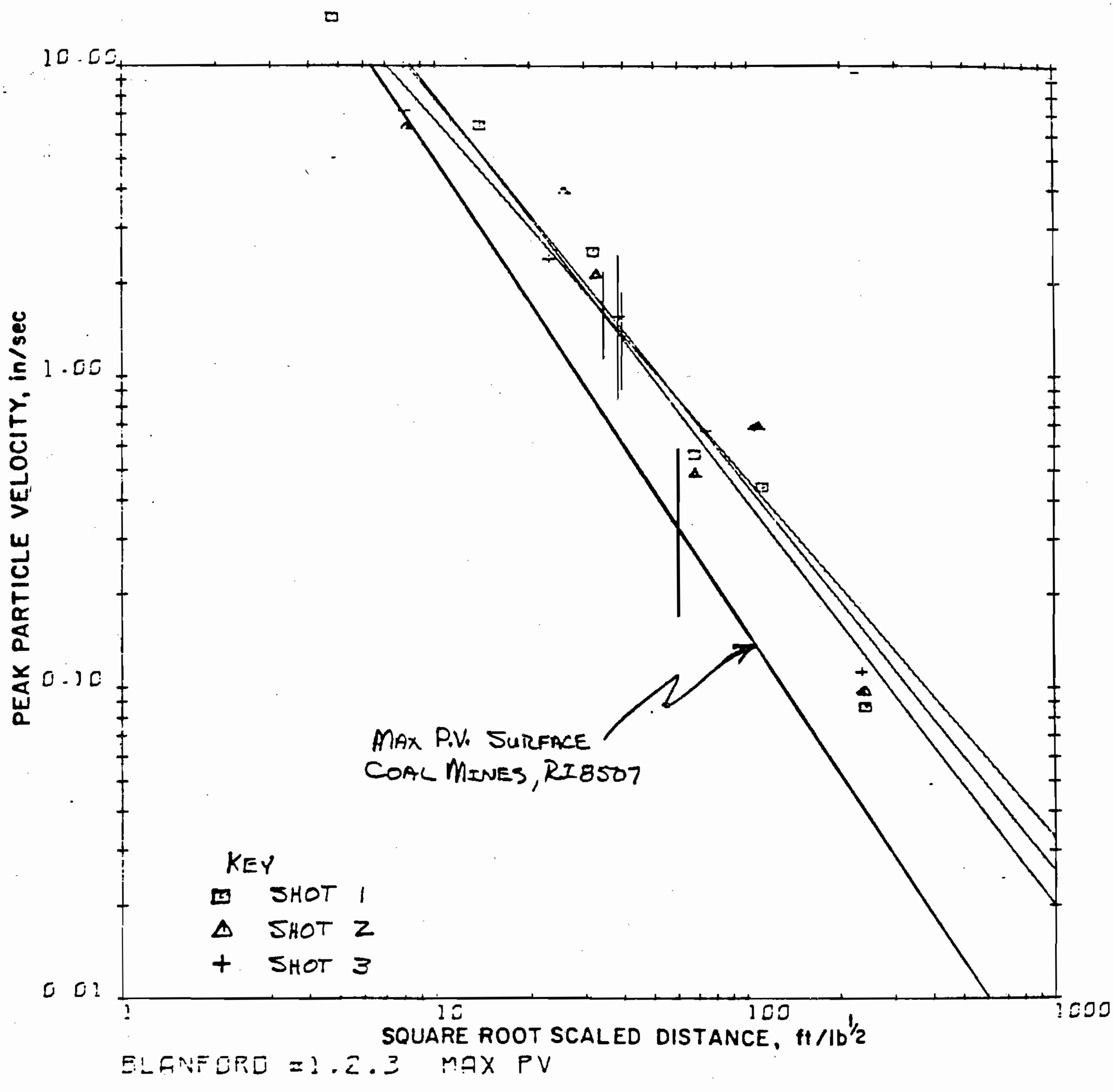


FIGURE 24. - Production shots, first location, Universal Mine.

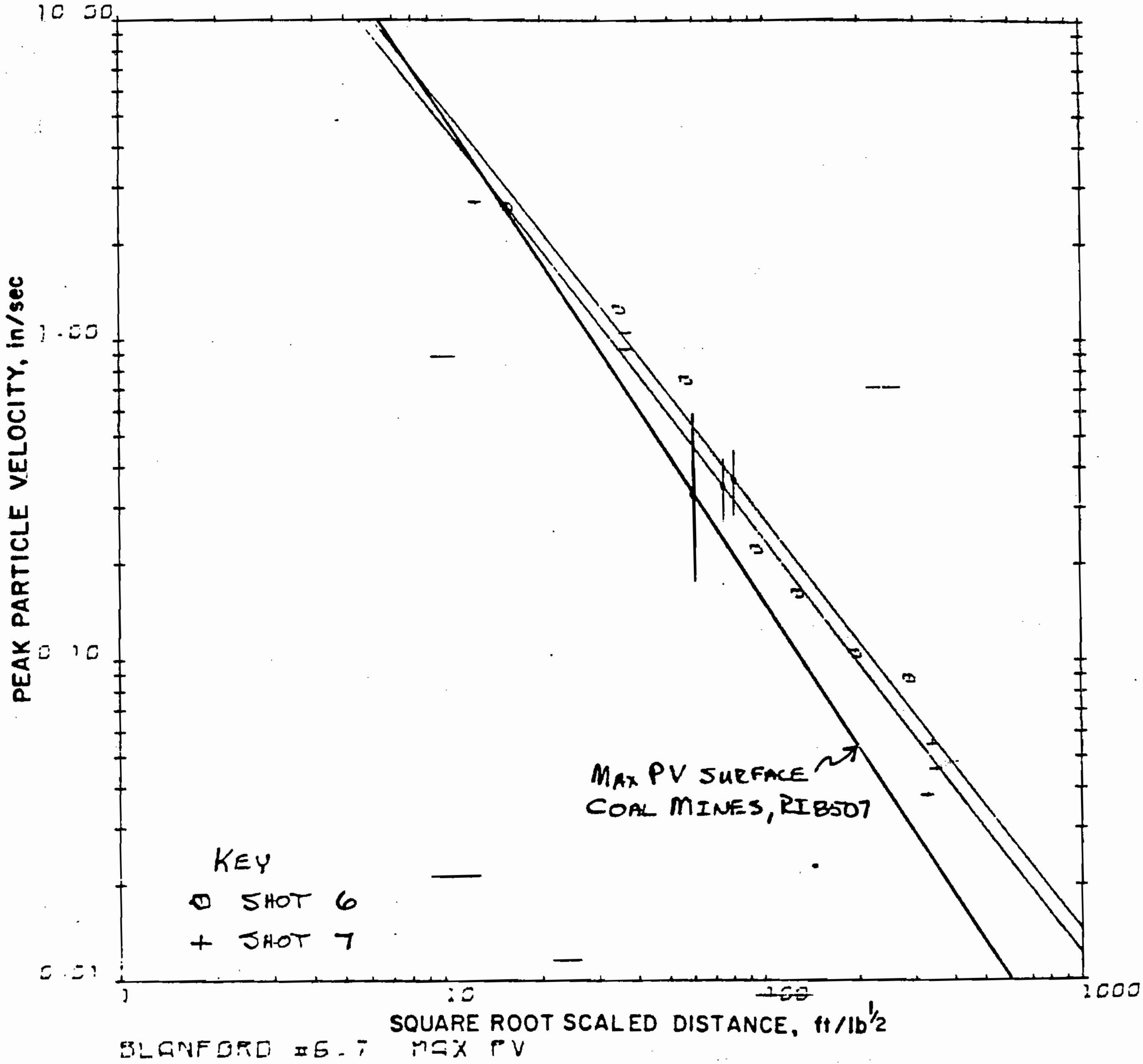


FIGURE 25. - Production shots, second location, Universal Mine.

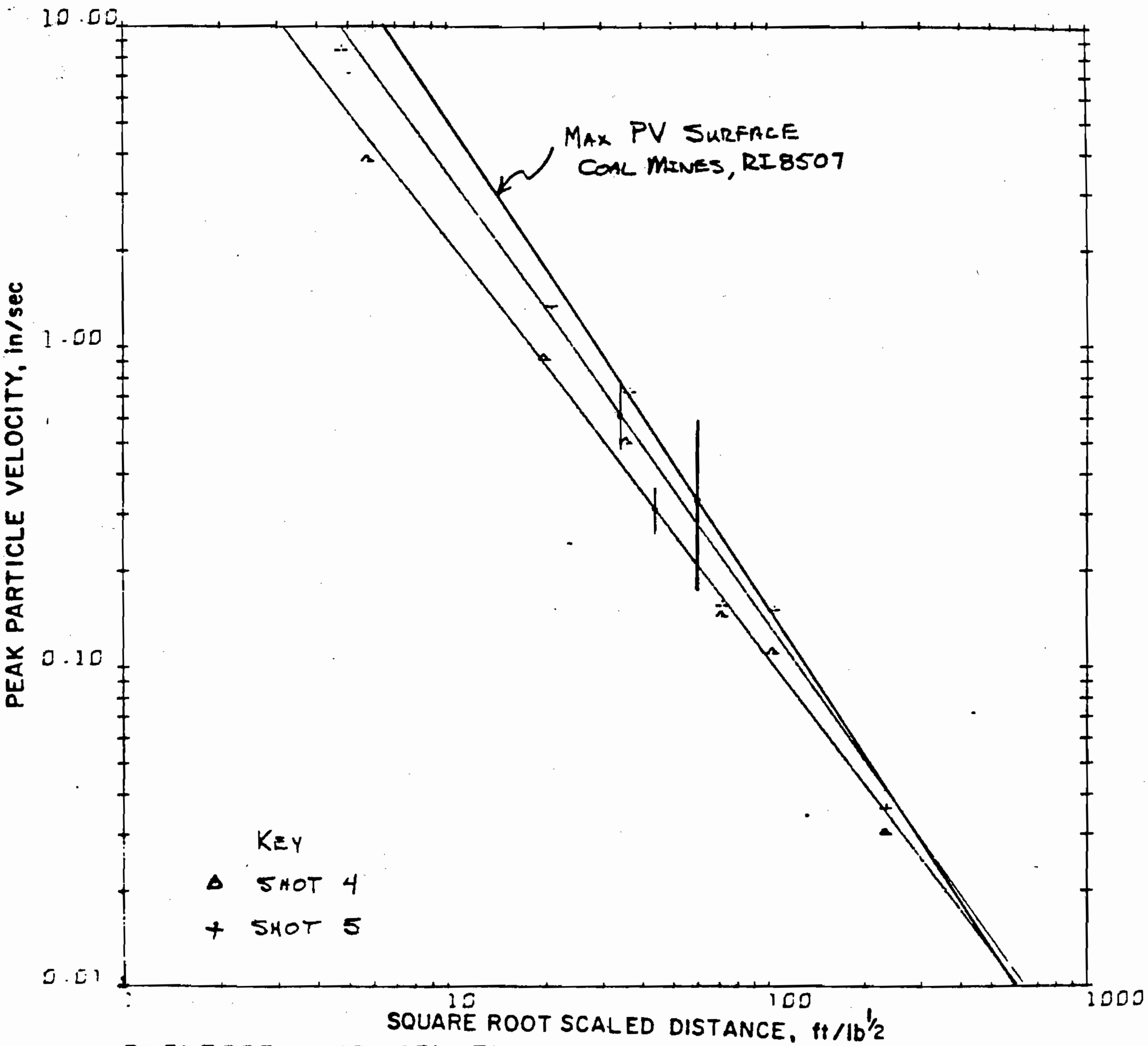


FIGURE 26. - Single charge shots, Universal Mine.

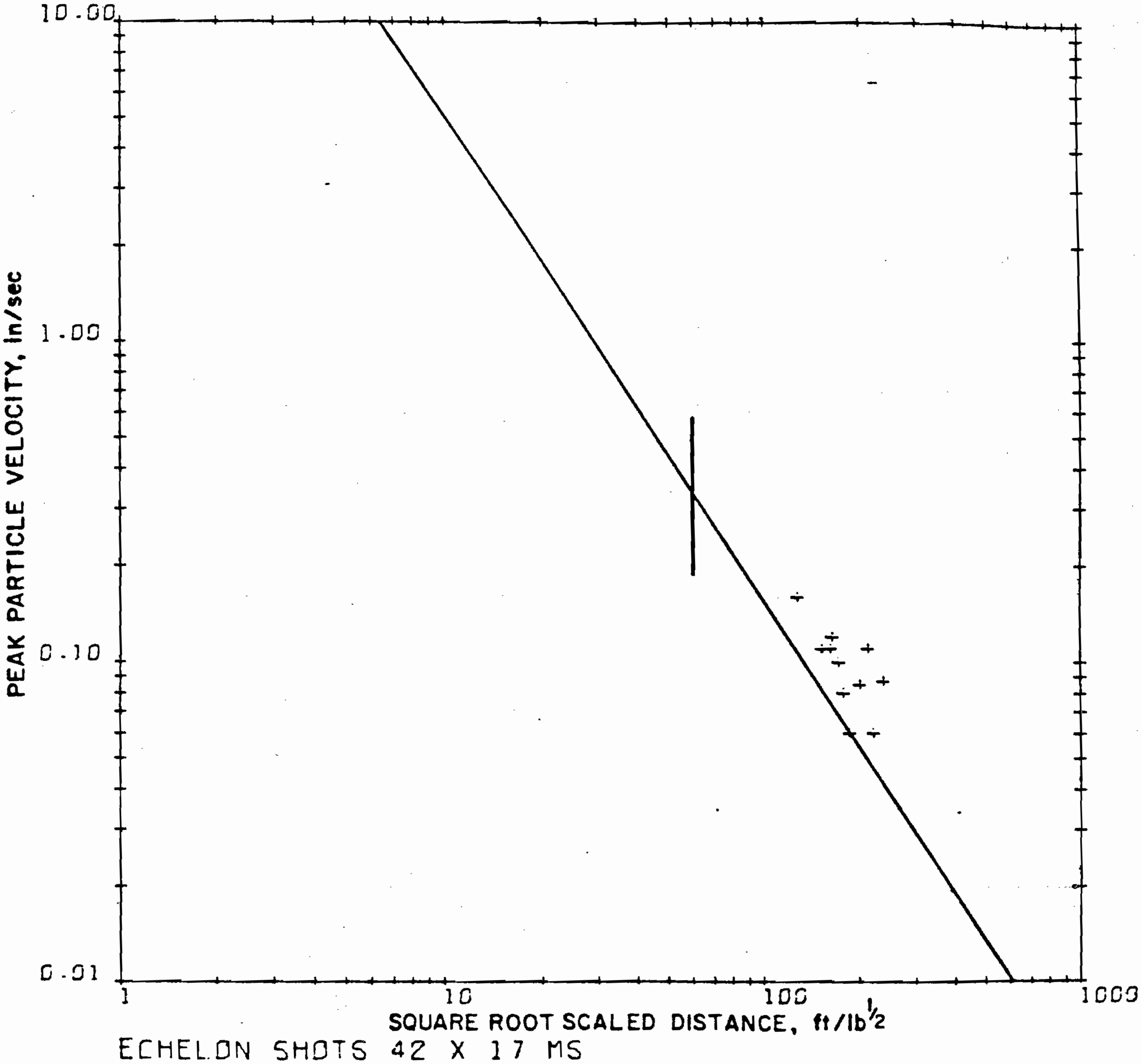


FIGURE 27. - Vibrations from echelon blasts, 42 x 17 ms.

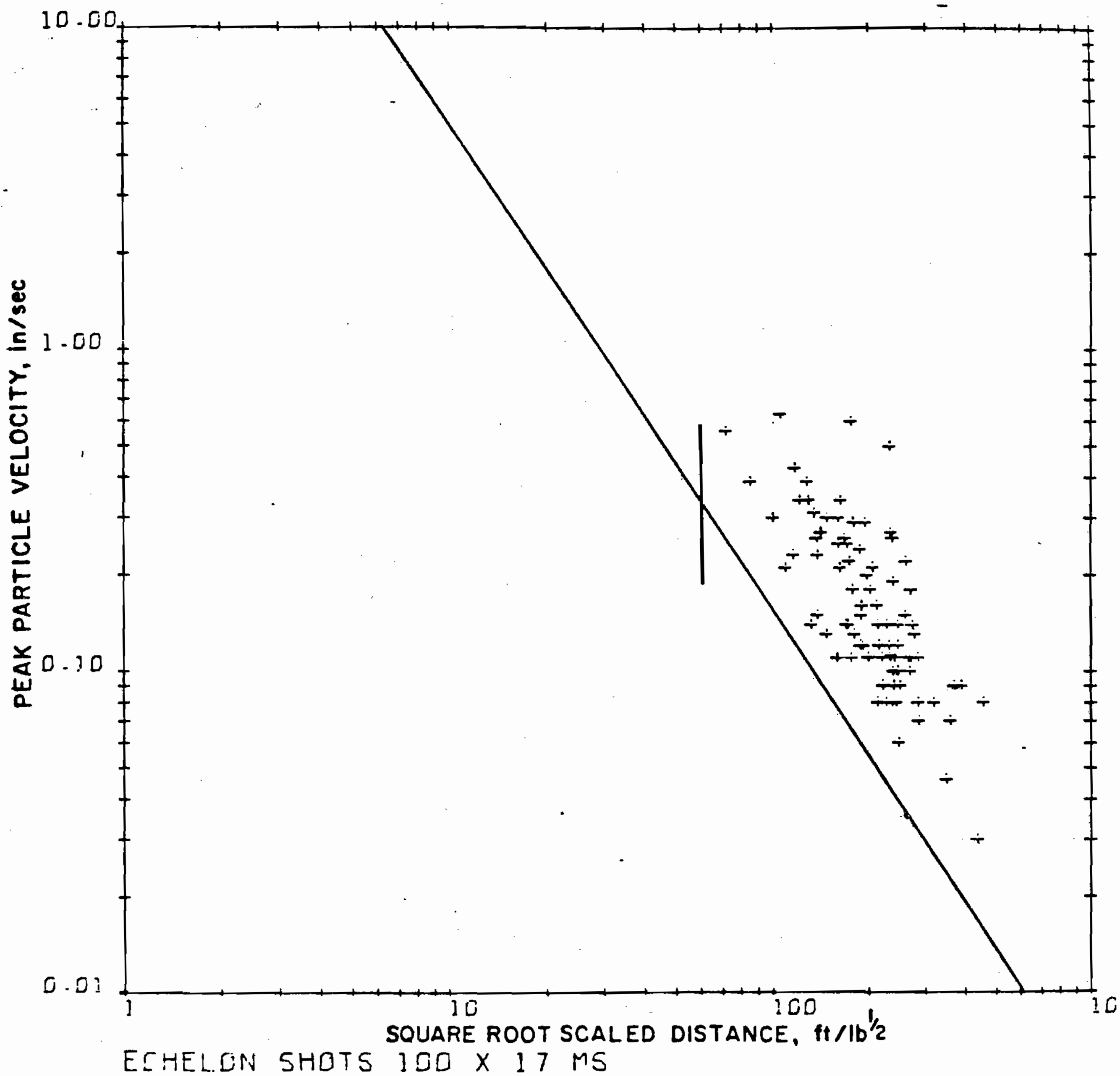


FIGURE 28. - Vibrations from echelon blasts, 100 x 17 ms.

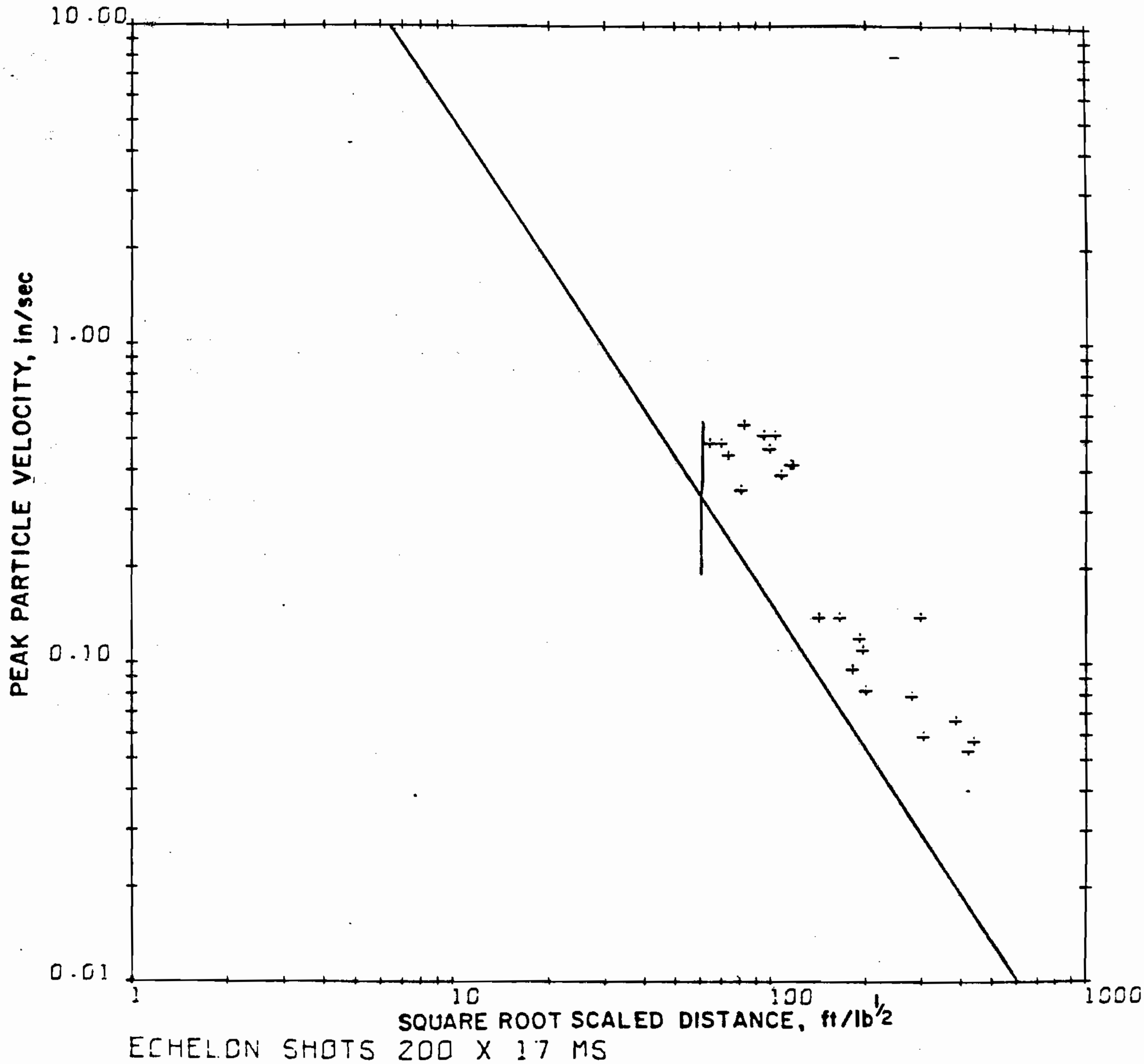


FIGURE 29. - Vibrations from echelon blasts, 200 x 17 ms.

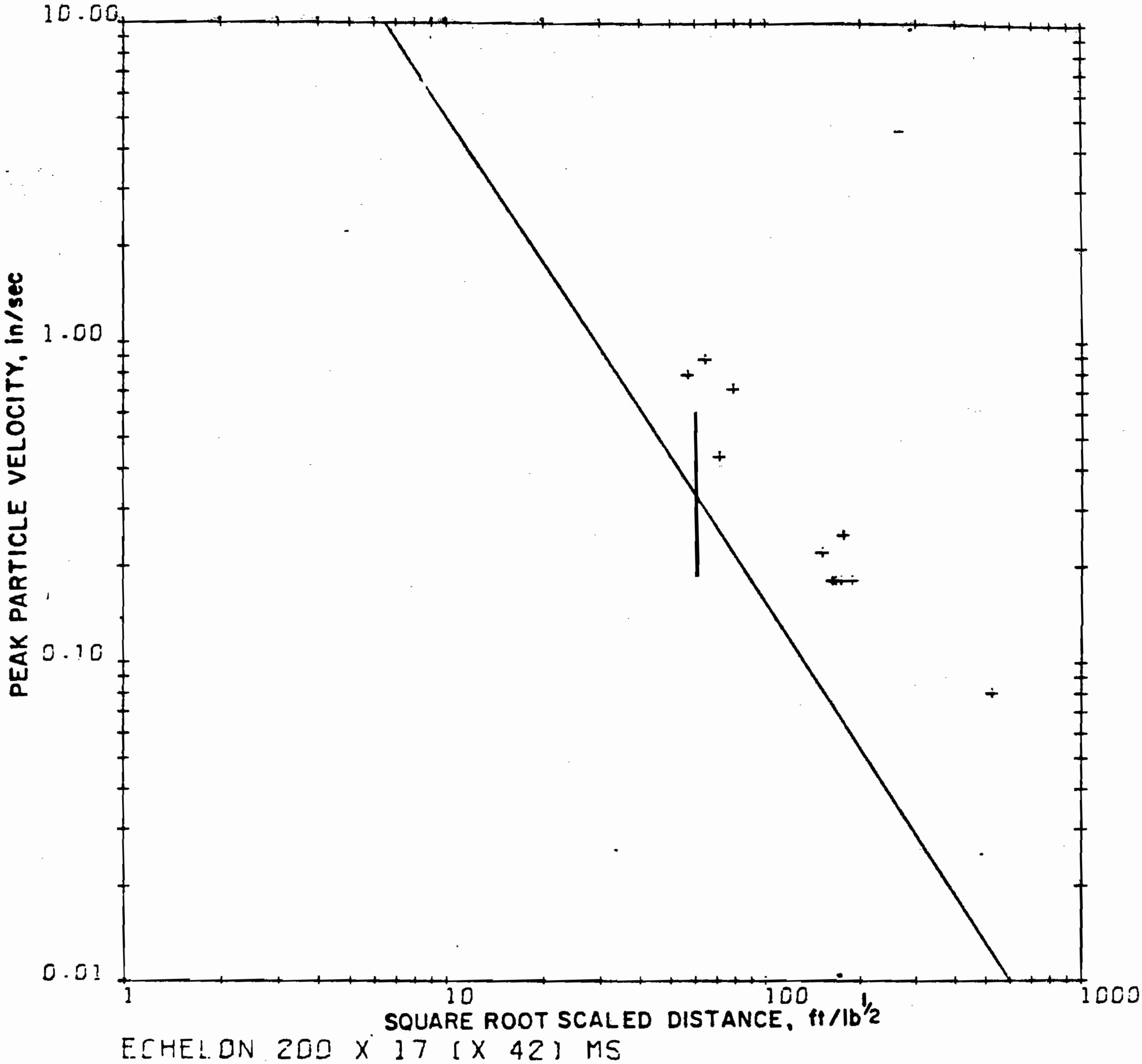


FIGURE 30. - Vibrations from echelon blasts, 200 x 17 (x 42) ms.

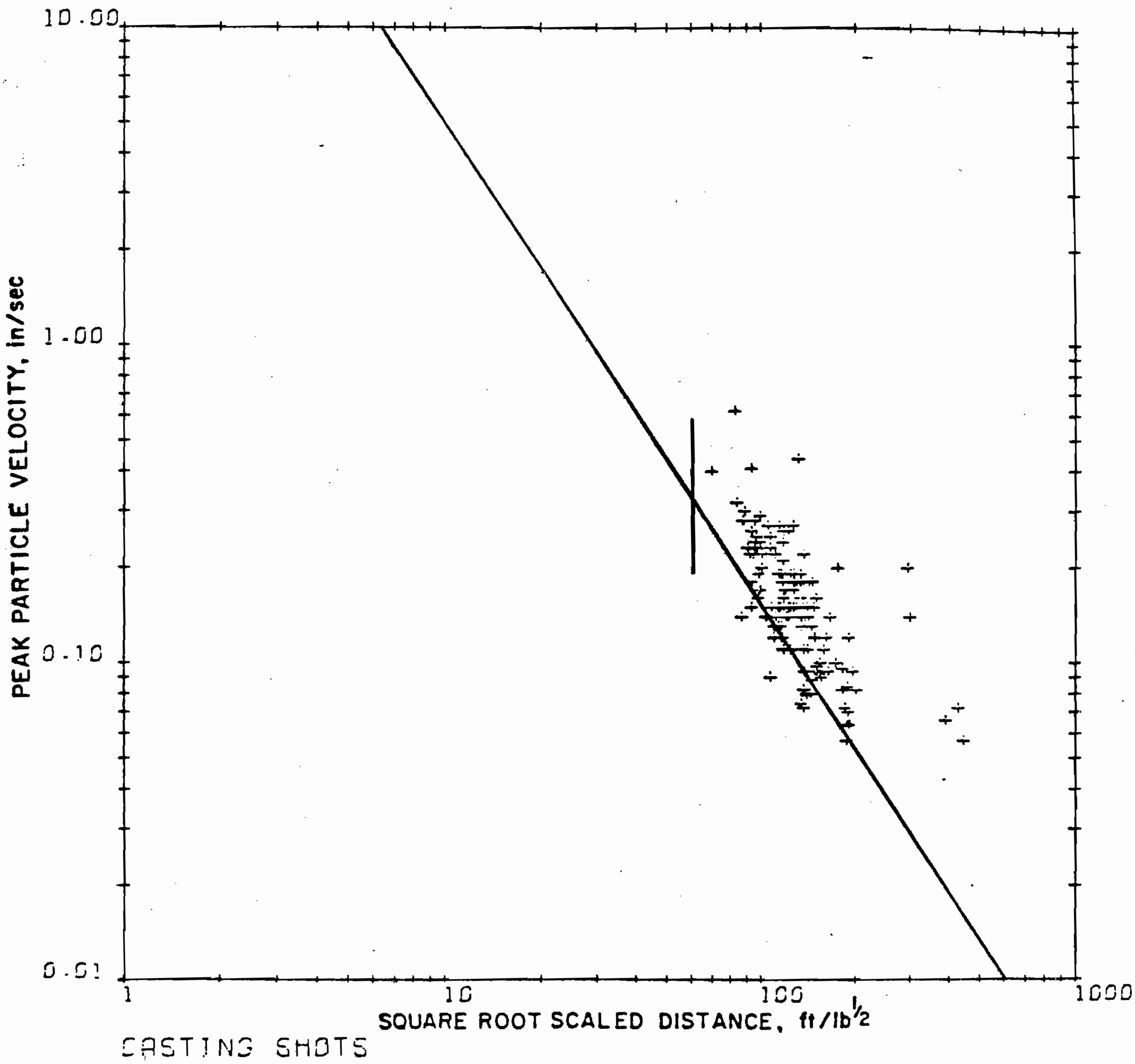


FIGURE 31. - Vibrations from casting blasts.

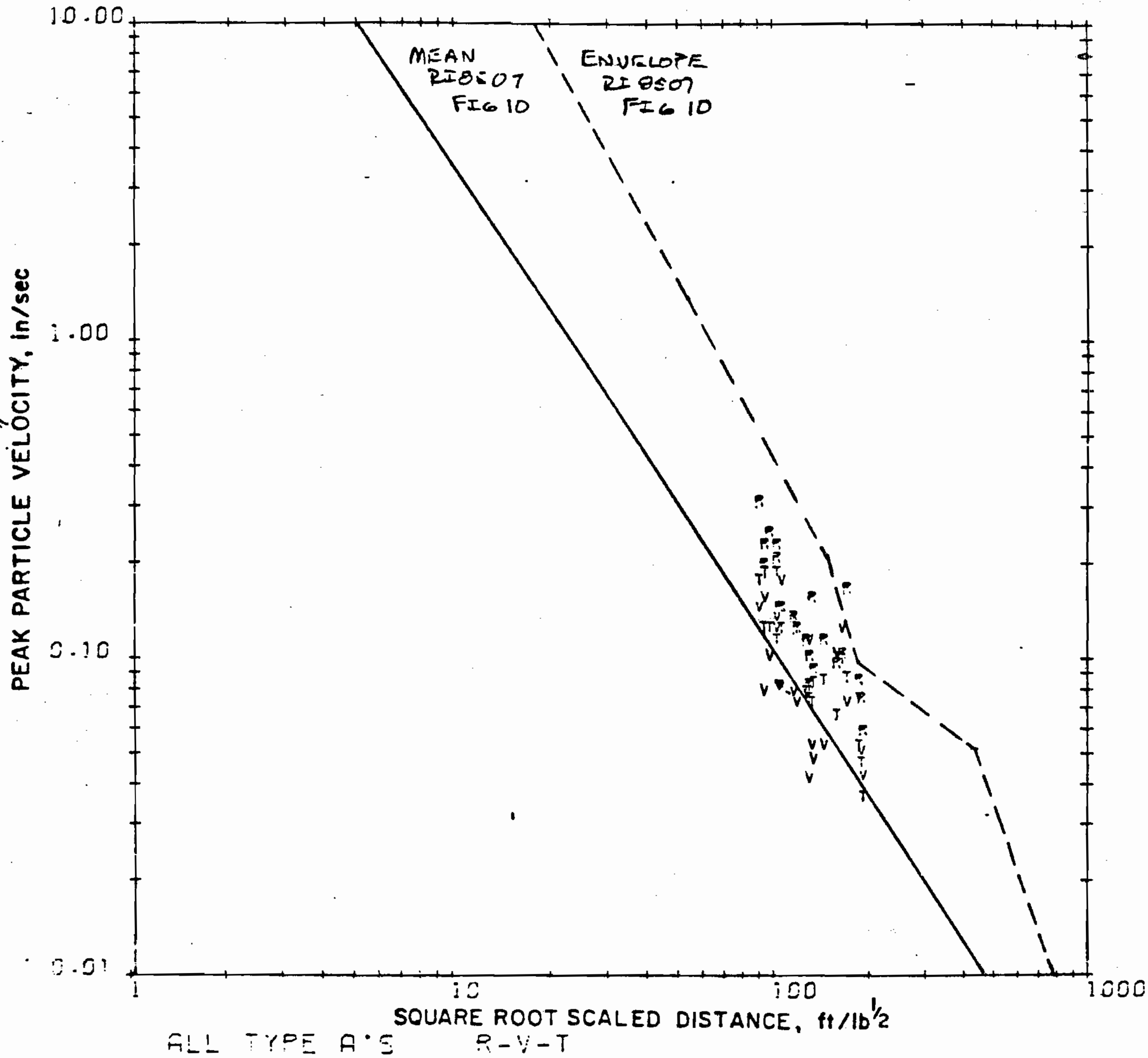


FIGURE 32. - Propagation of type A blasts.

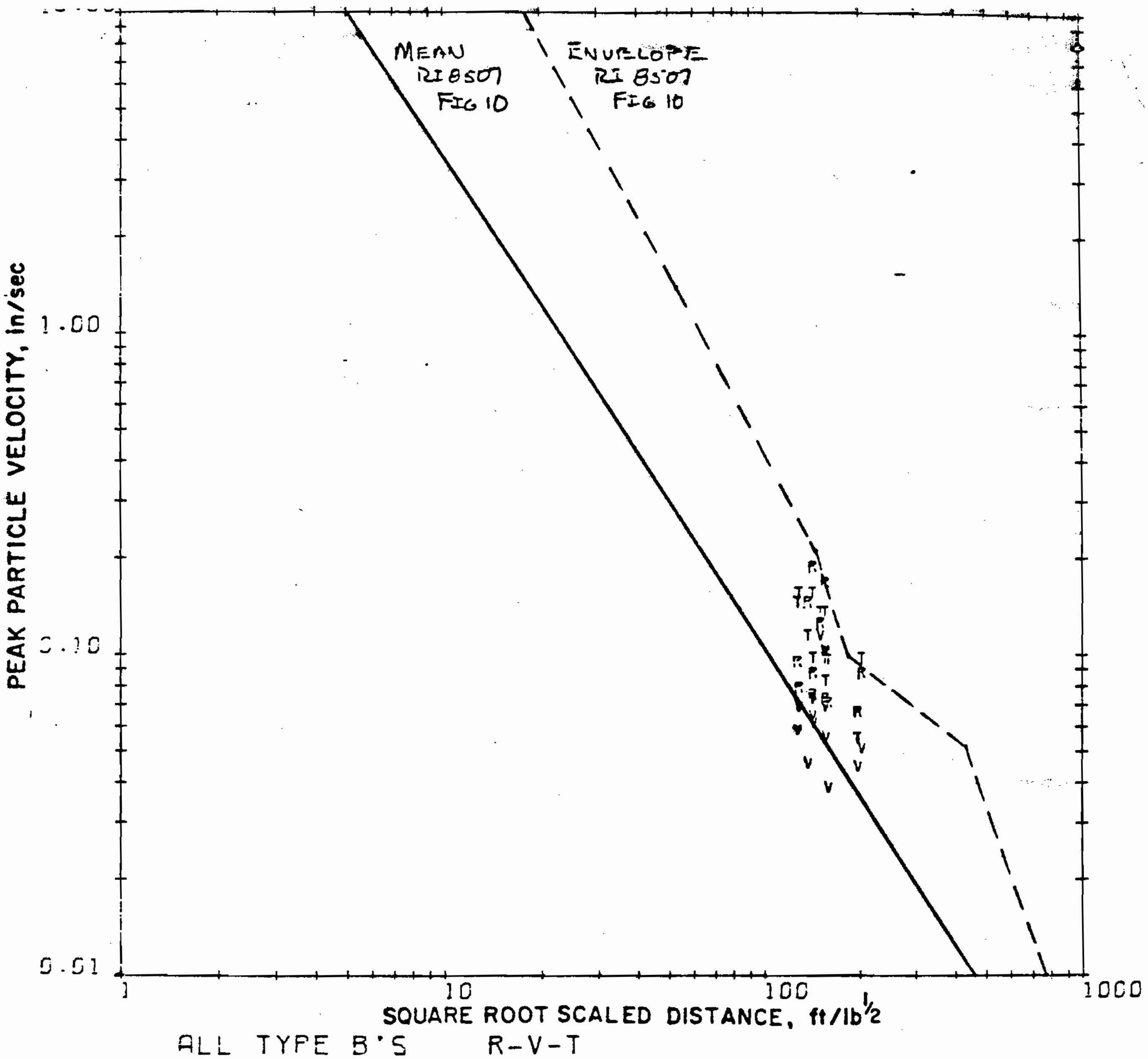


FIGURE 33. - Propagation of type B blasts.

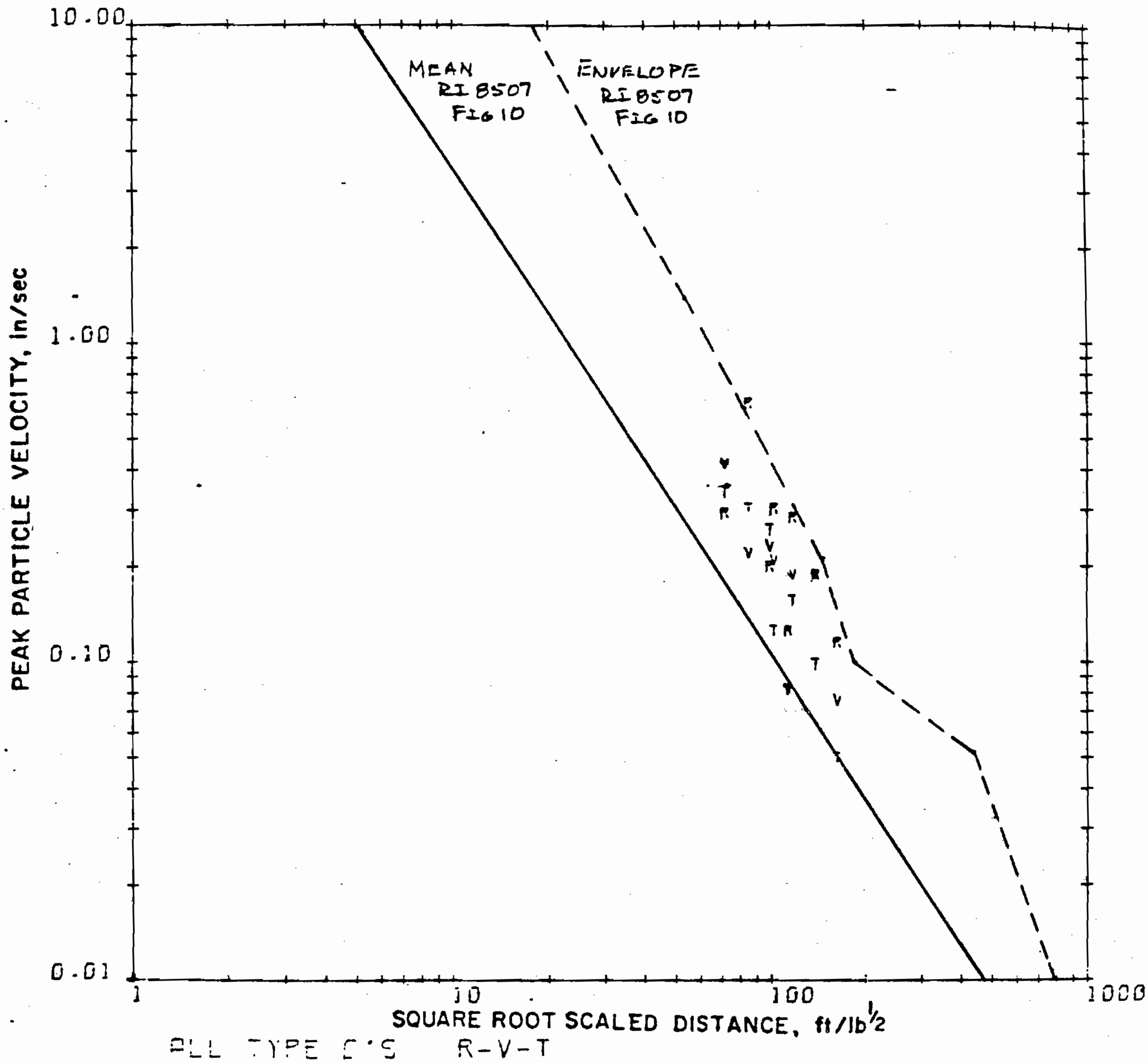


FIGURE 34. - Propagation of type C blasts.

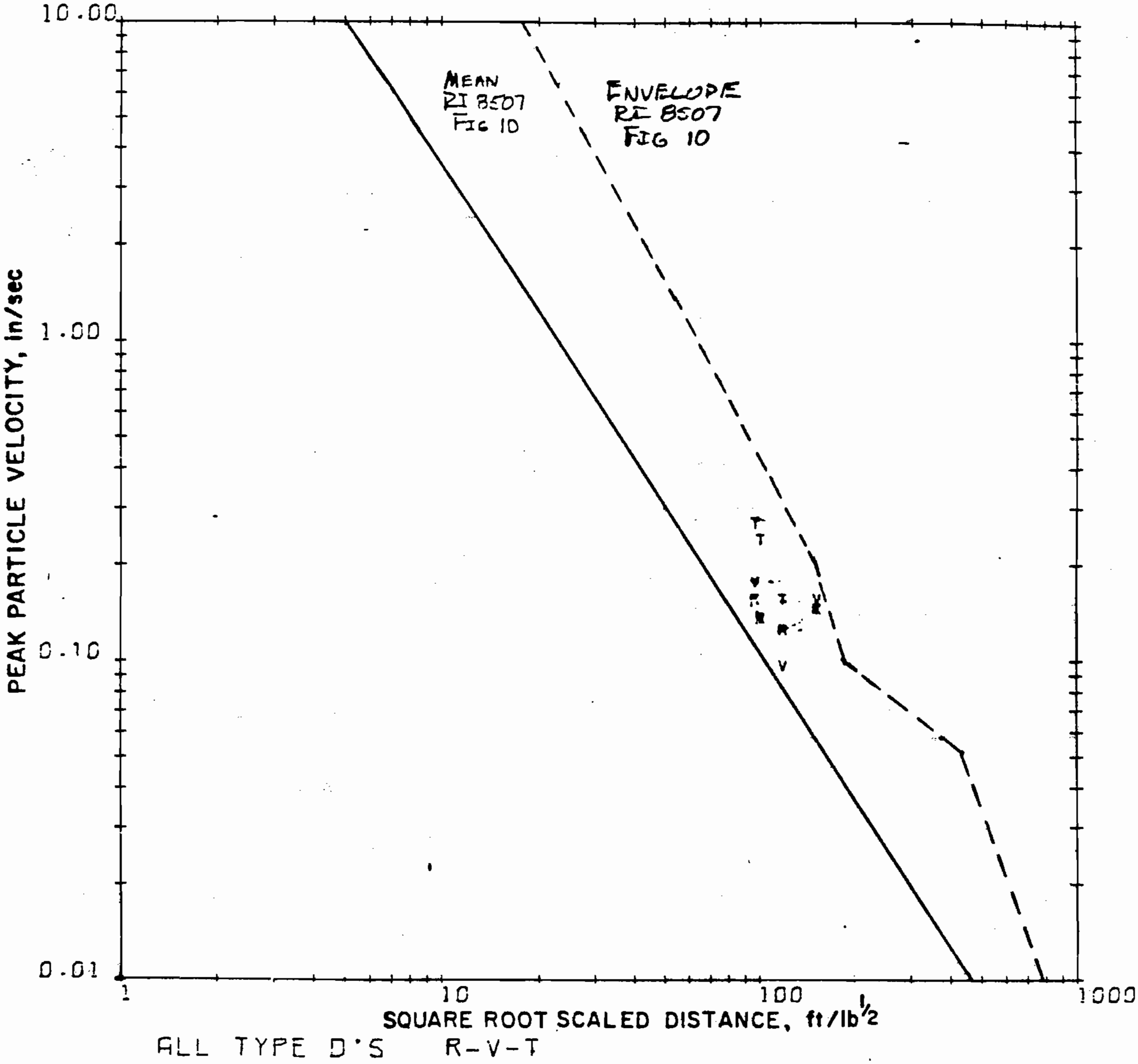


FIGURE 35. - Propagation of type D blasts.

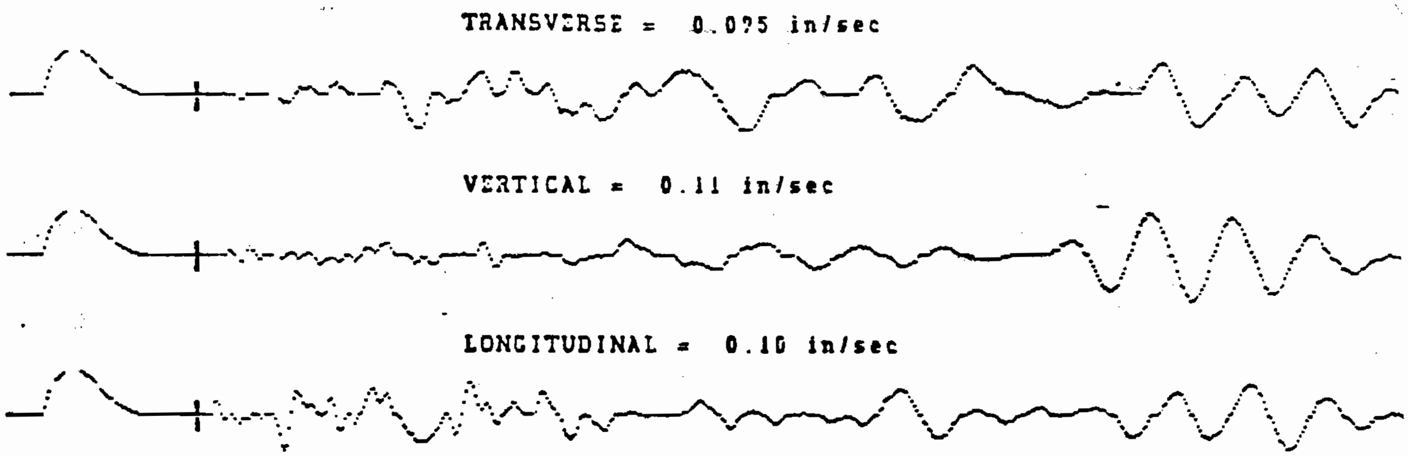


FIGURE 36. - Type A vibration. Significant low frequency on all 3 components. Hollingsworth site.

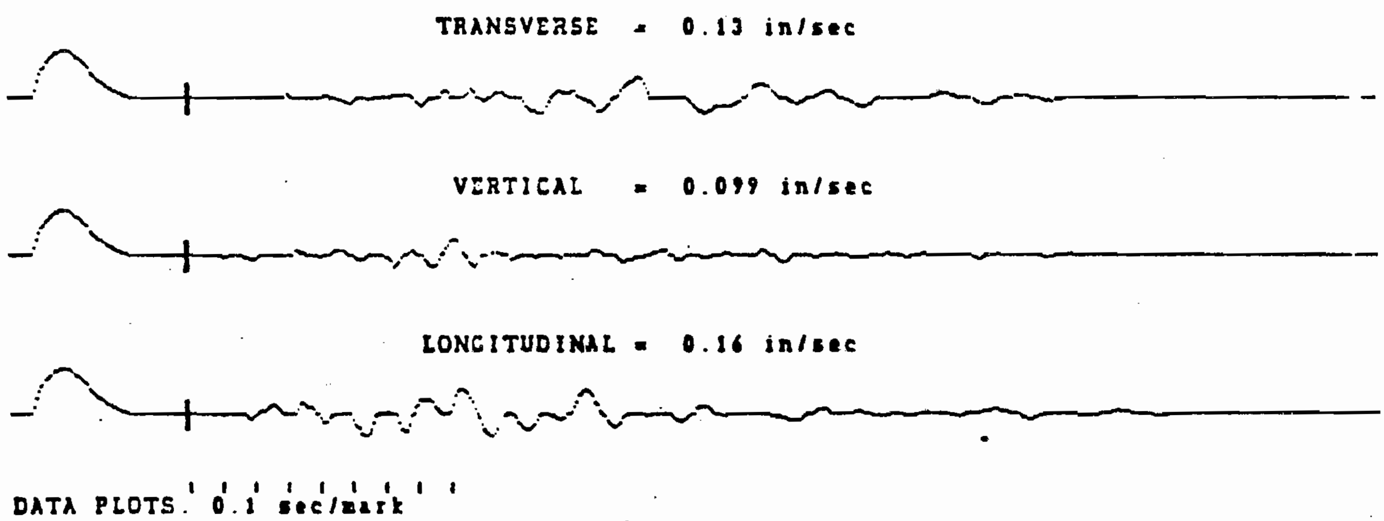


FIGURE 37. - Type B vibration. Significant although not very clean, low frequency on transverse. Verhonik site.

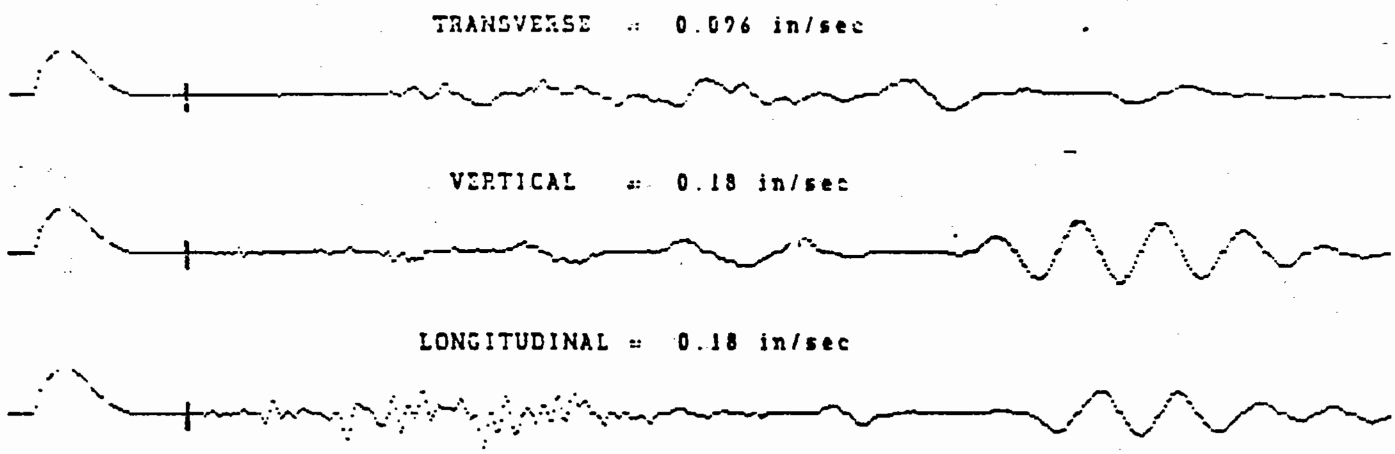


FIGURE 38. - Type C vibration. Significant low frequency on vertical and longitudinal components. Volk site.

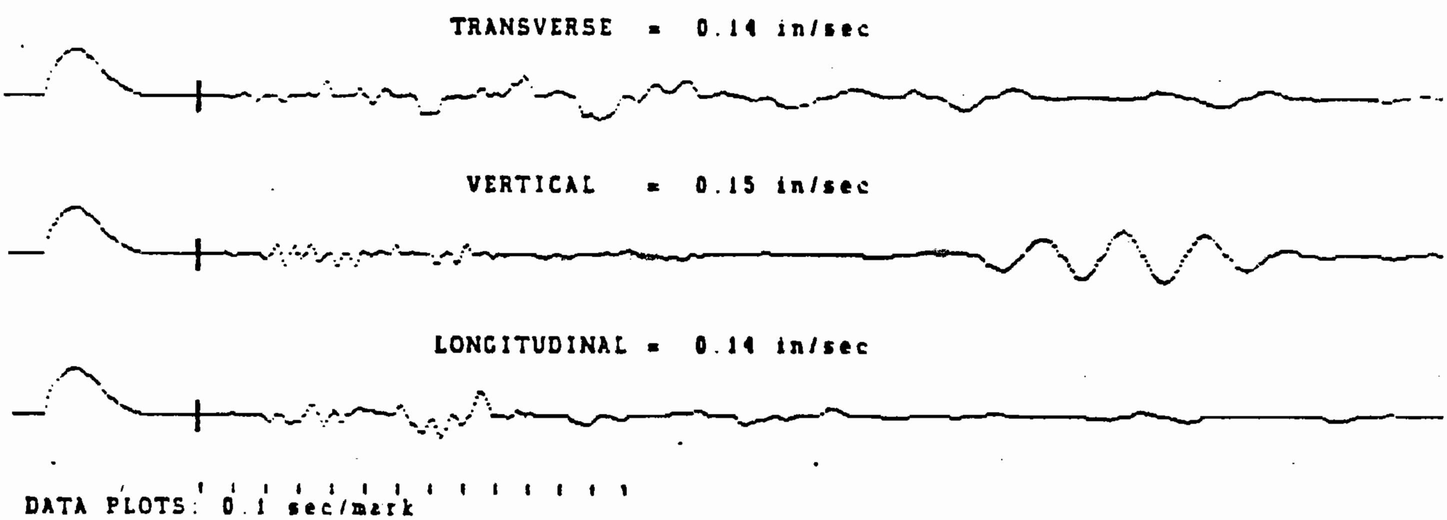
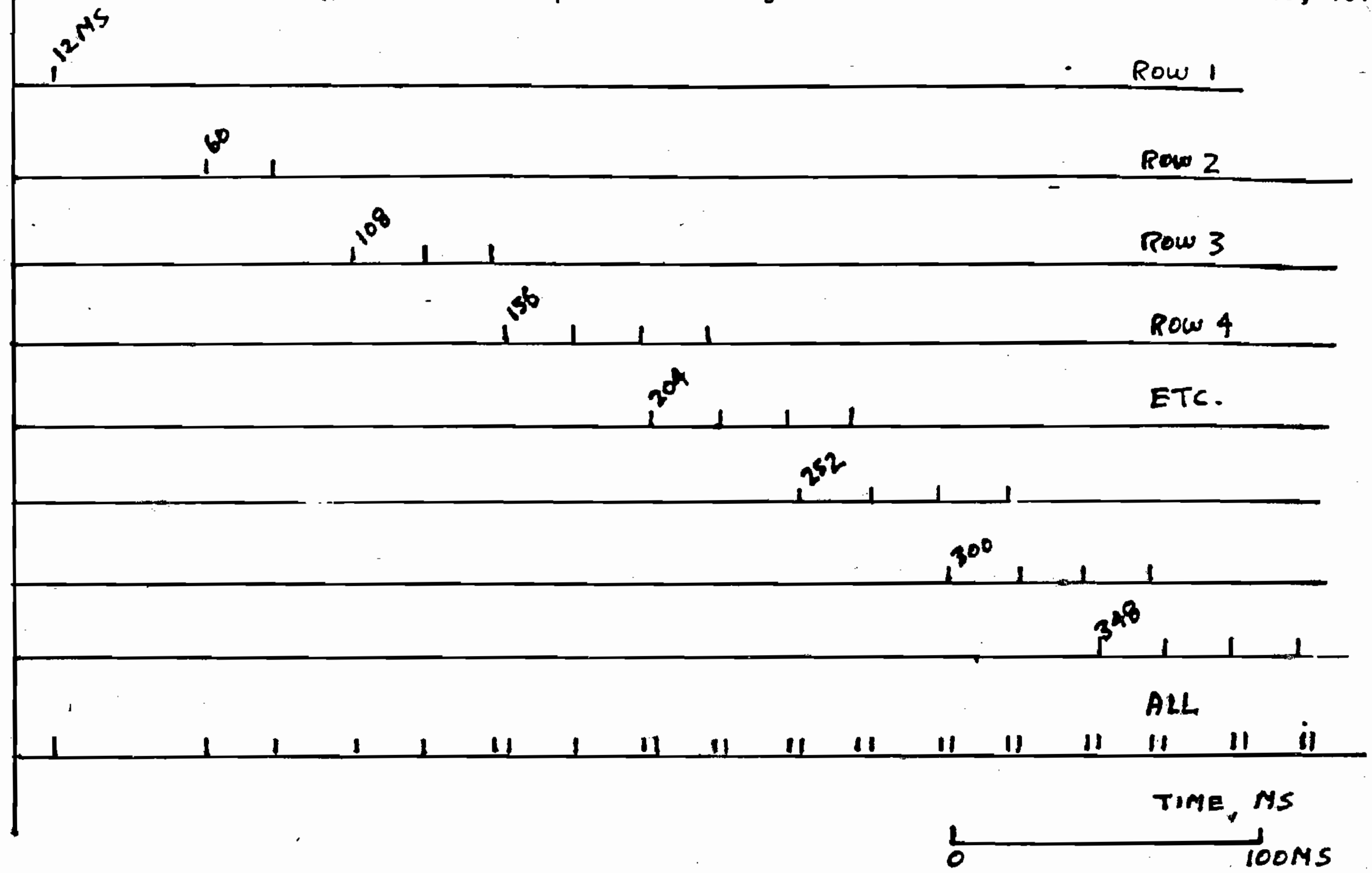


FIGURE 39. - Type D vibration. Significant low frequency only on vertical component.

FIGURE 40. - Echelon blast, 42 ms between rows and 17 ms between holes in a row. Sequence of charges and vibration record for 1-9-85, 15:



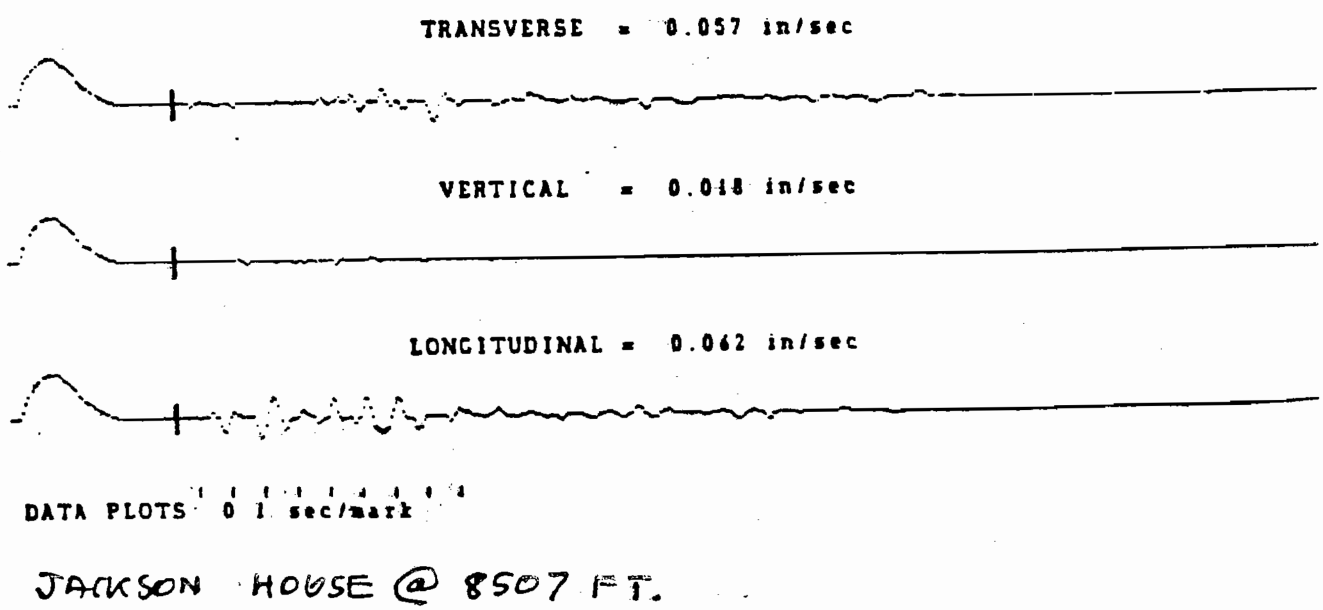
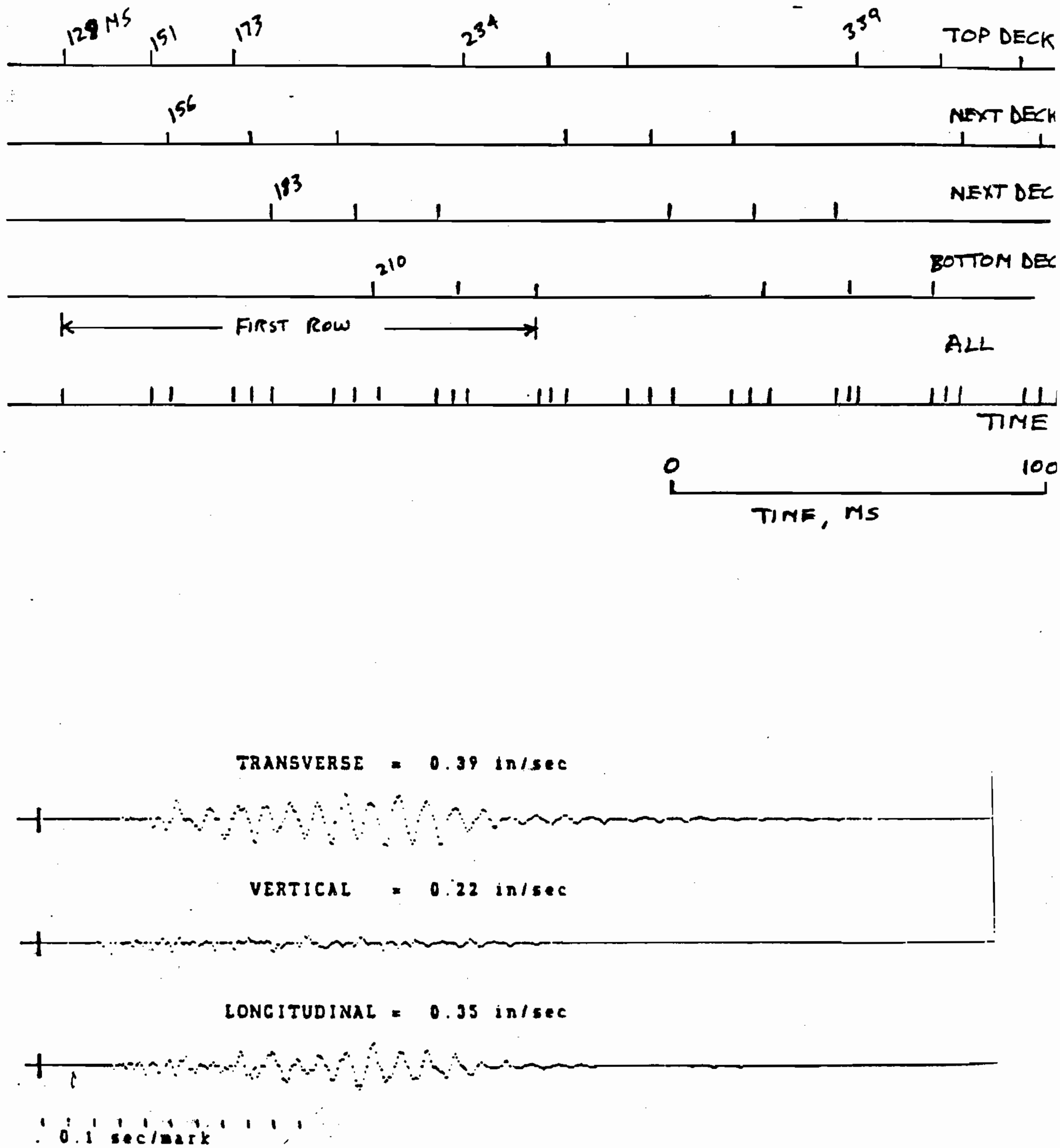
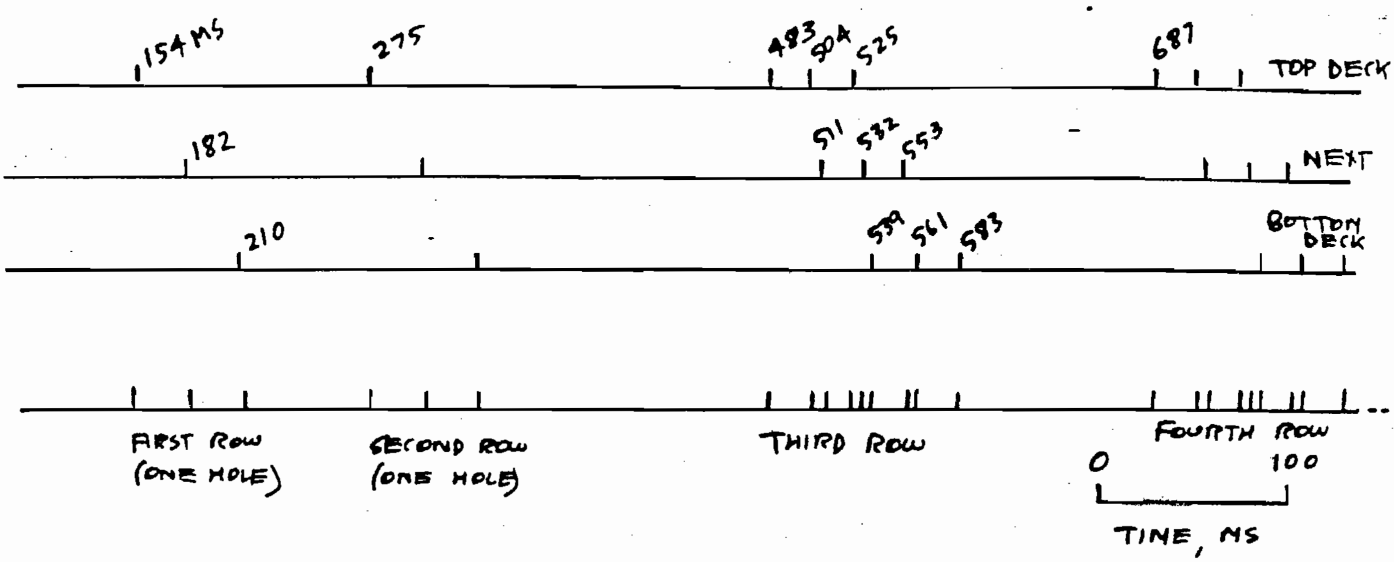


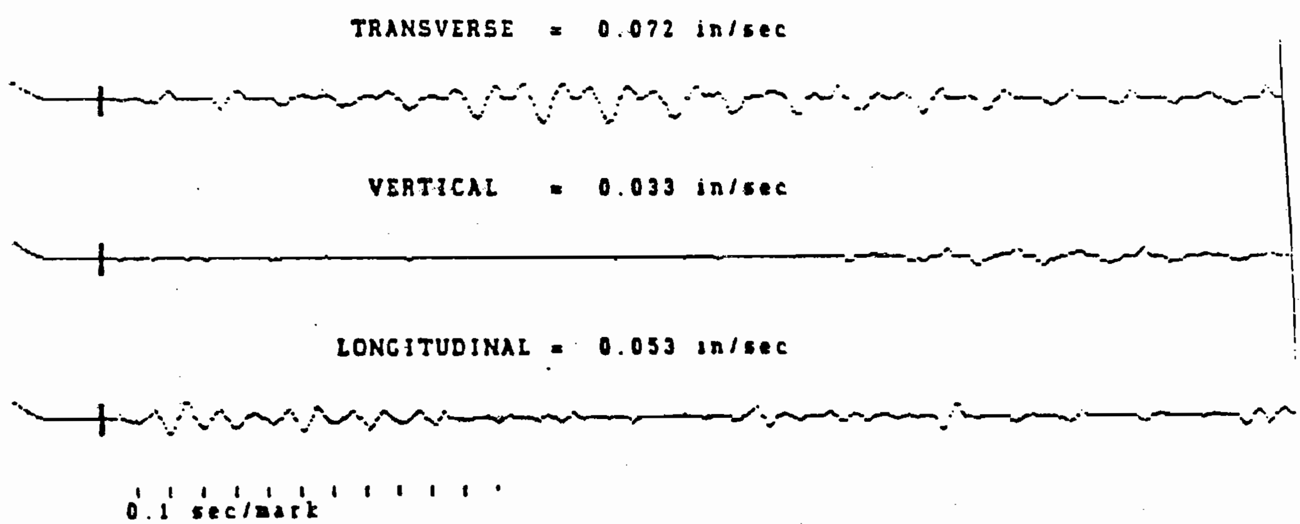
FIGURE 41. - Echelon blast, 100 ms between rows and 17 ms between holes in a row. Sequence of charges and vibration record for 3-14-85, 10:37.



JACKSON HOUSE @ 1320 FT.

FIGURE 42. - Echelon blast, 200 ms between rows and 17 ms between holes in a row. Sequence of charges and vibrations for 1-12-85, 17:18.





JACKSON HOUSE @ 7992 FT.

FIGURE 43. - Casting blast, short array with about 200 ms between rows and 10 ms between holes in a row. Sequence and vibrations for 1-21-85.

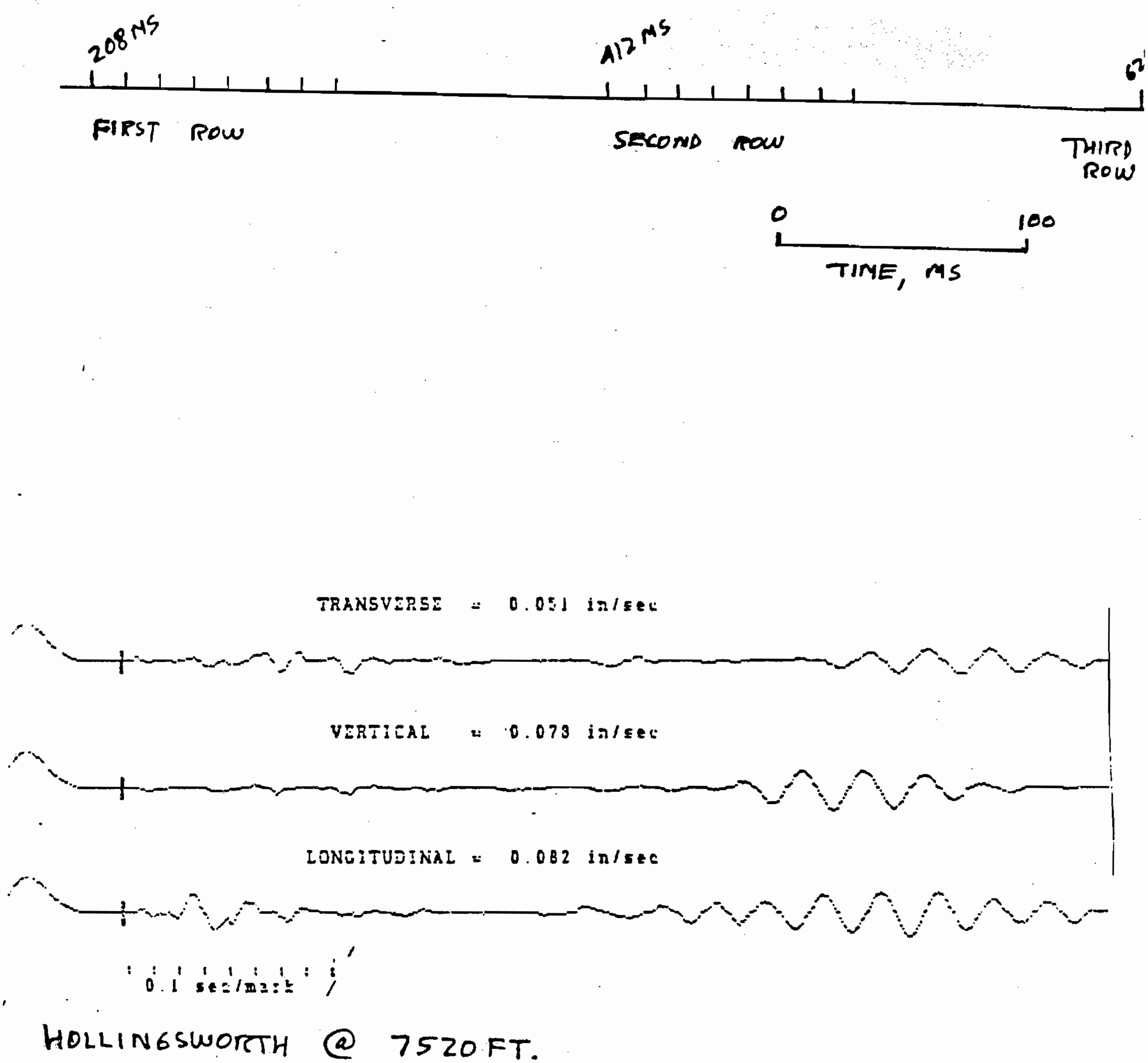
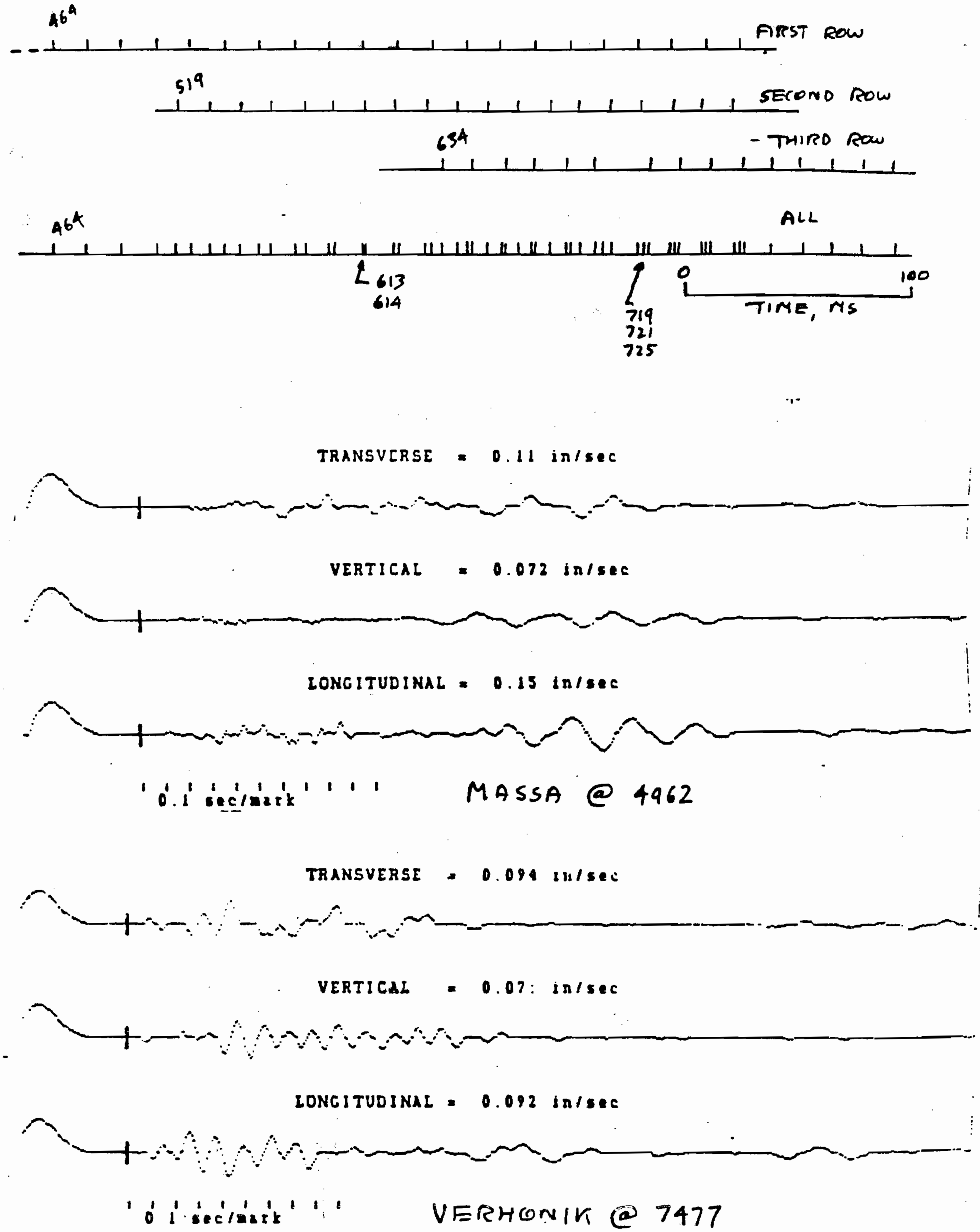


FIGURE 44. - Casting blast, long array with varying between row delays and 10 ms between holes in a row. Sequence and vibrations for 2-16-85 18:03.



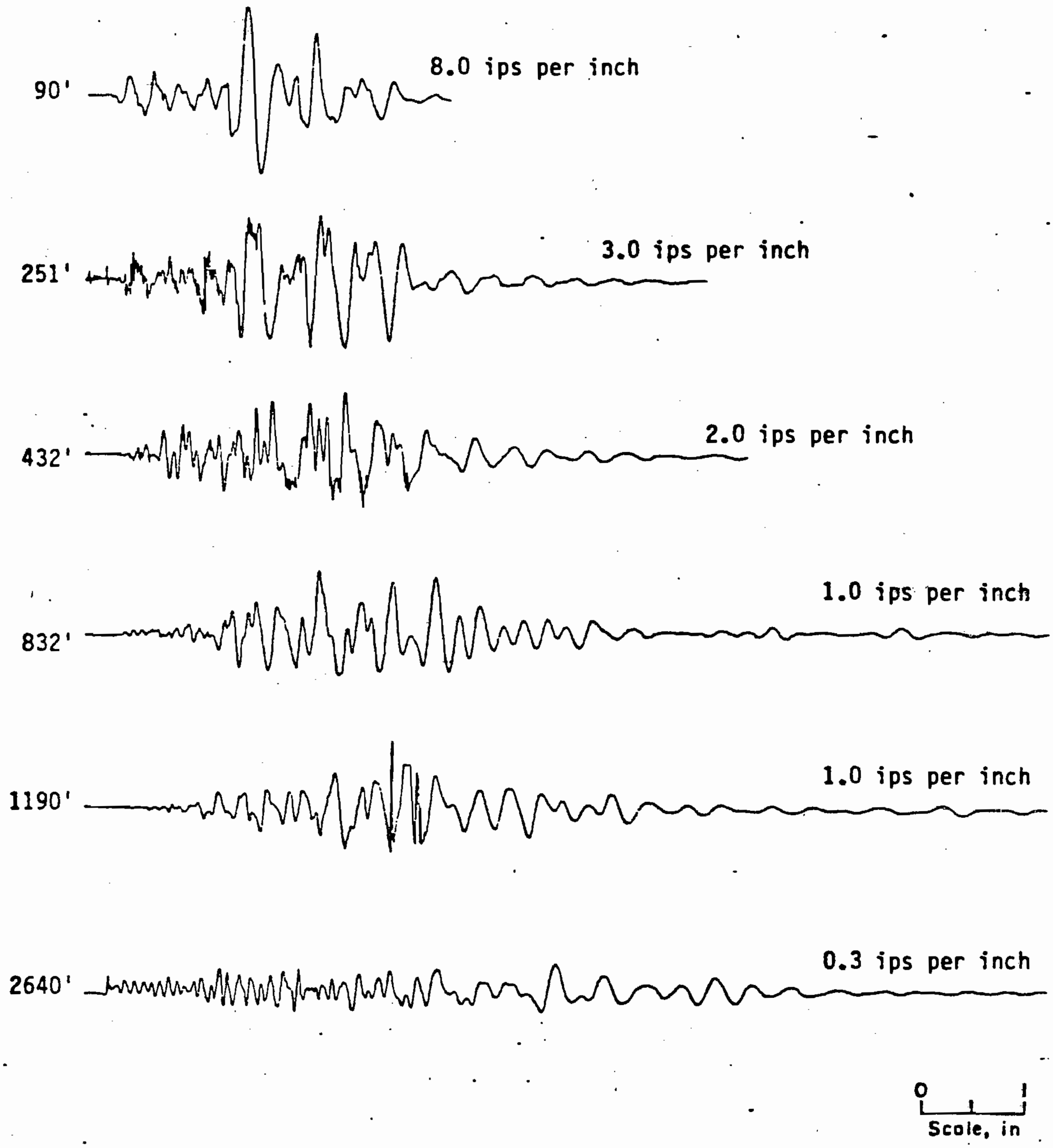


Figure 45.- Shot 3 - Longitudinal component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

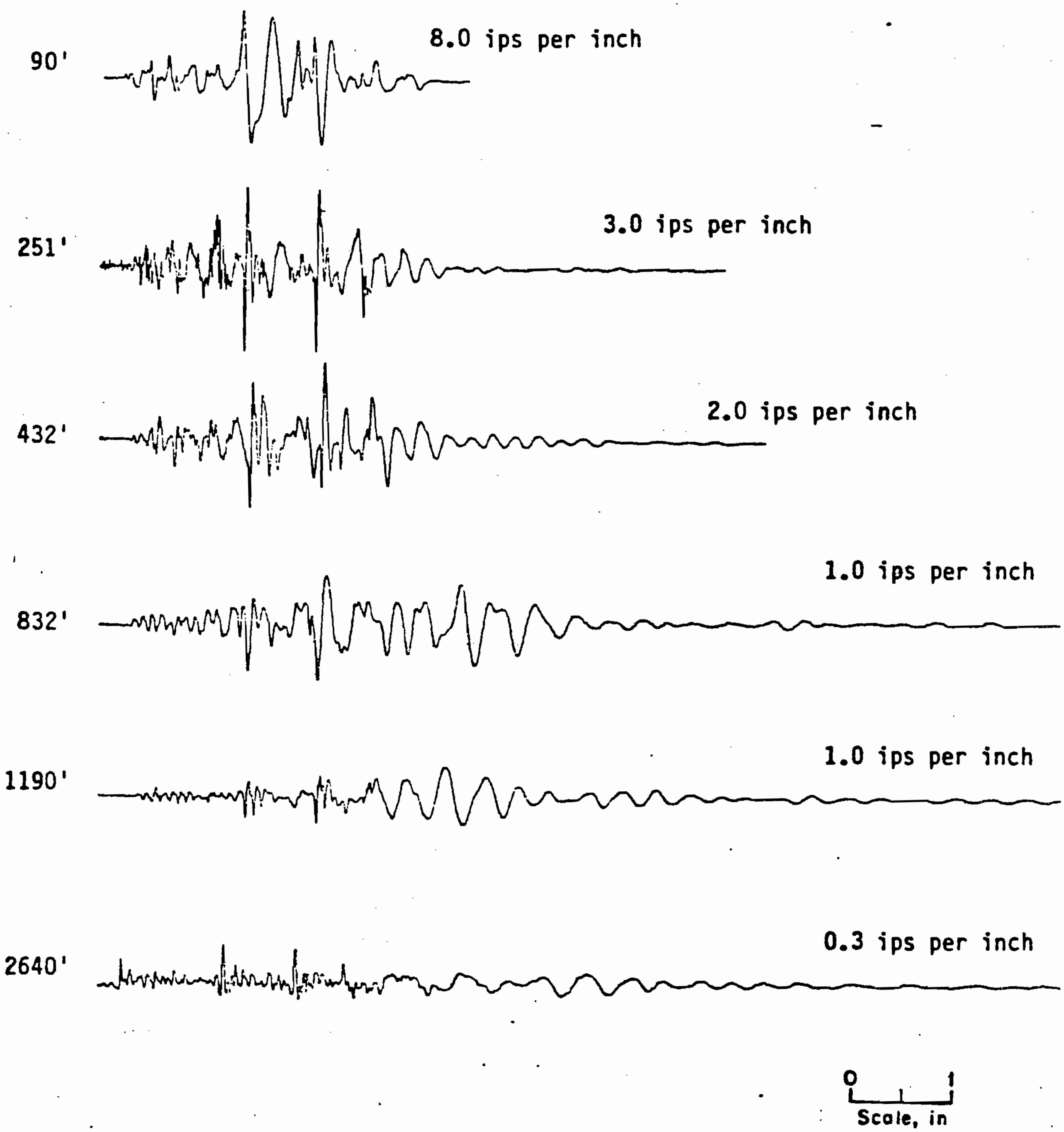


Figure 46.– Shot 3 - Vertical component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

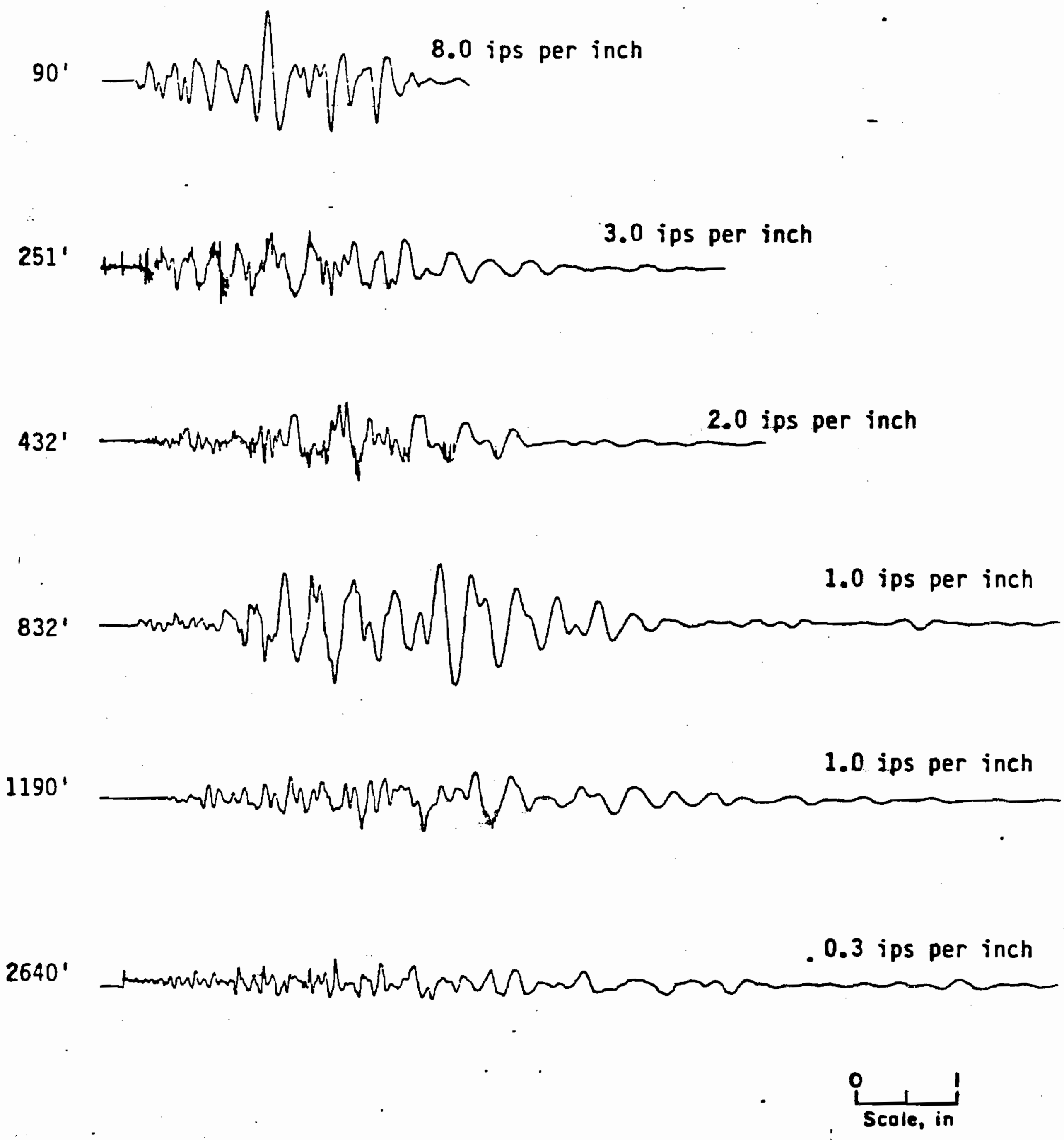


Figure 47.- Shot 3 - Transverse component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

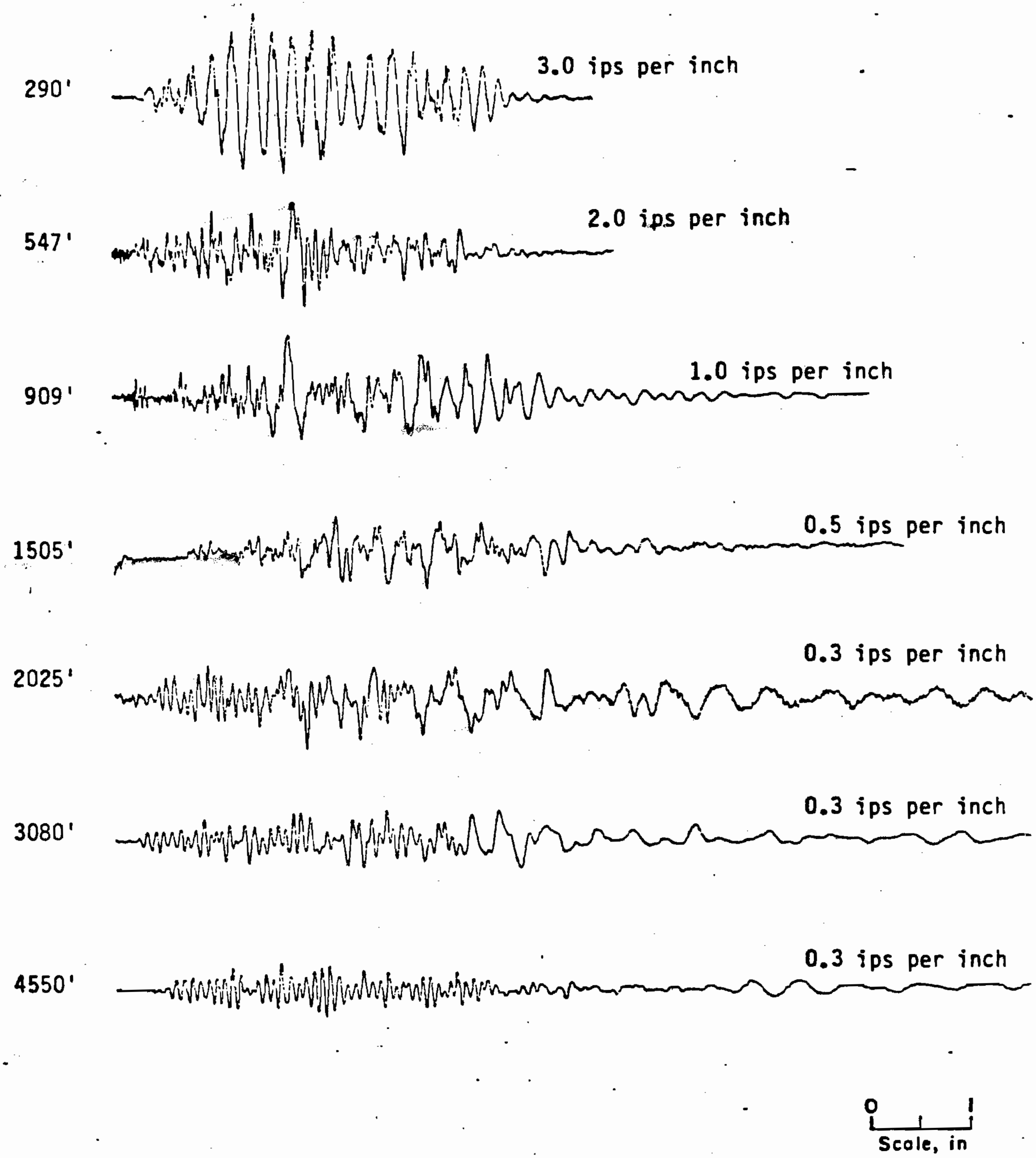


Figure 48.- Shot 6 - Longitudinal component. Ground vibrations recorded by north array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

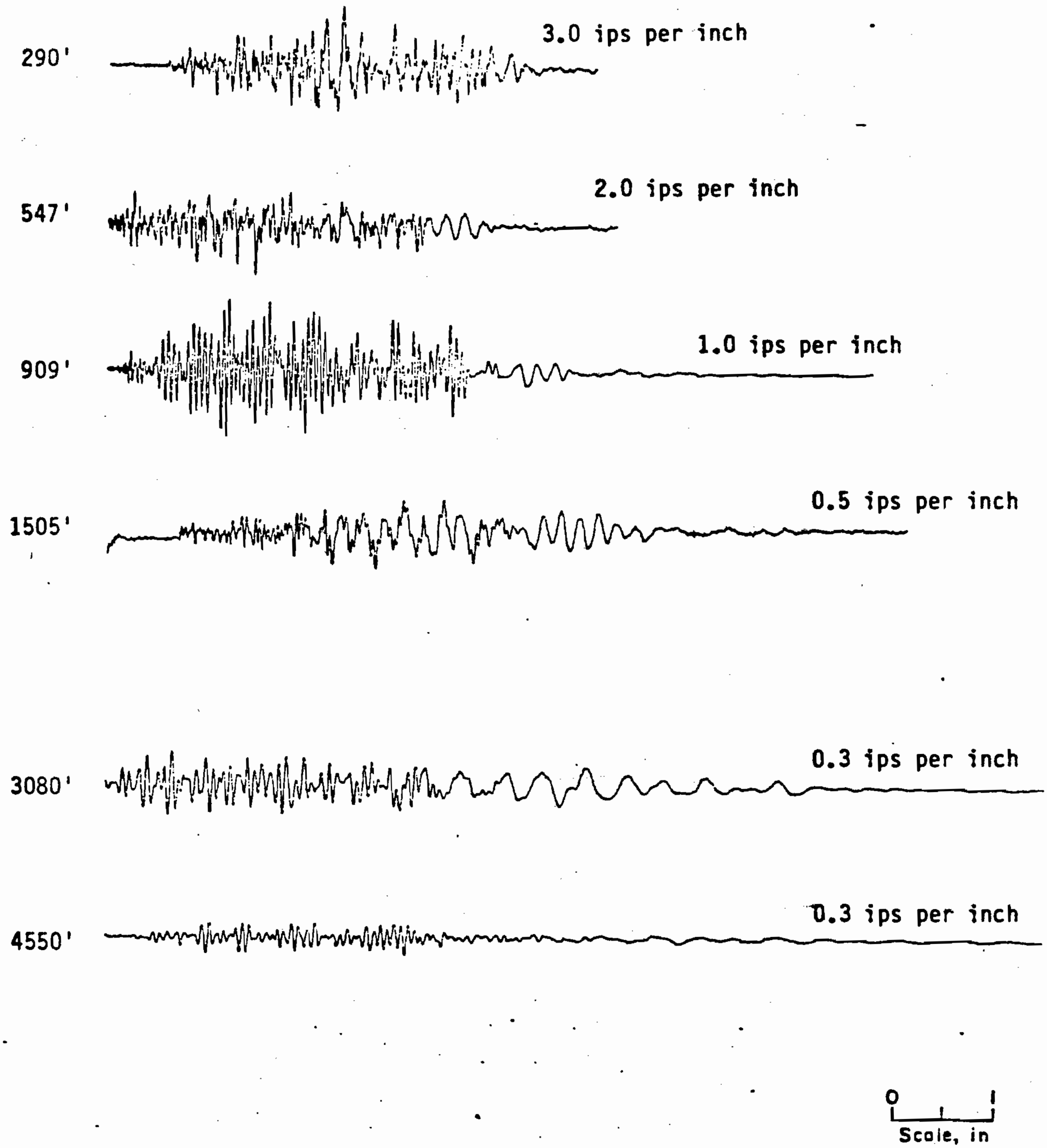


Figure 49.- Shot 6 - Vertical component. Ground vibrations recorded by north array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

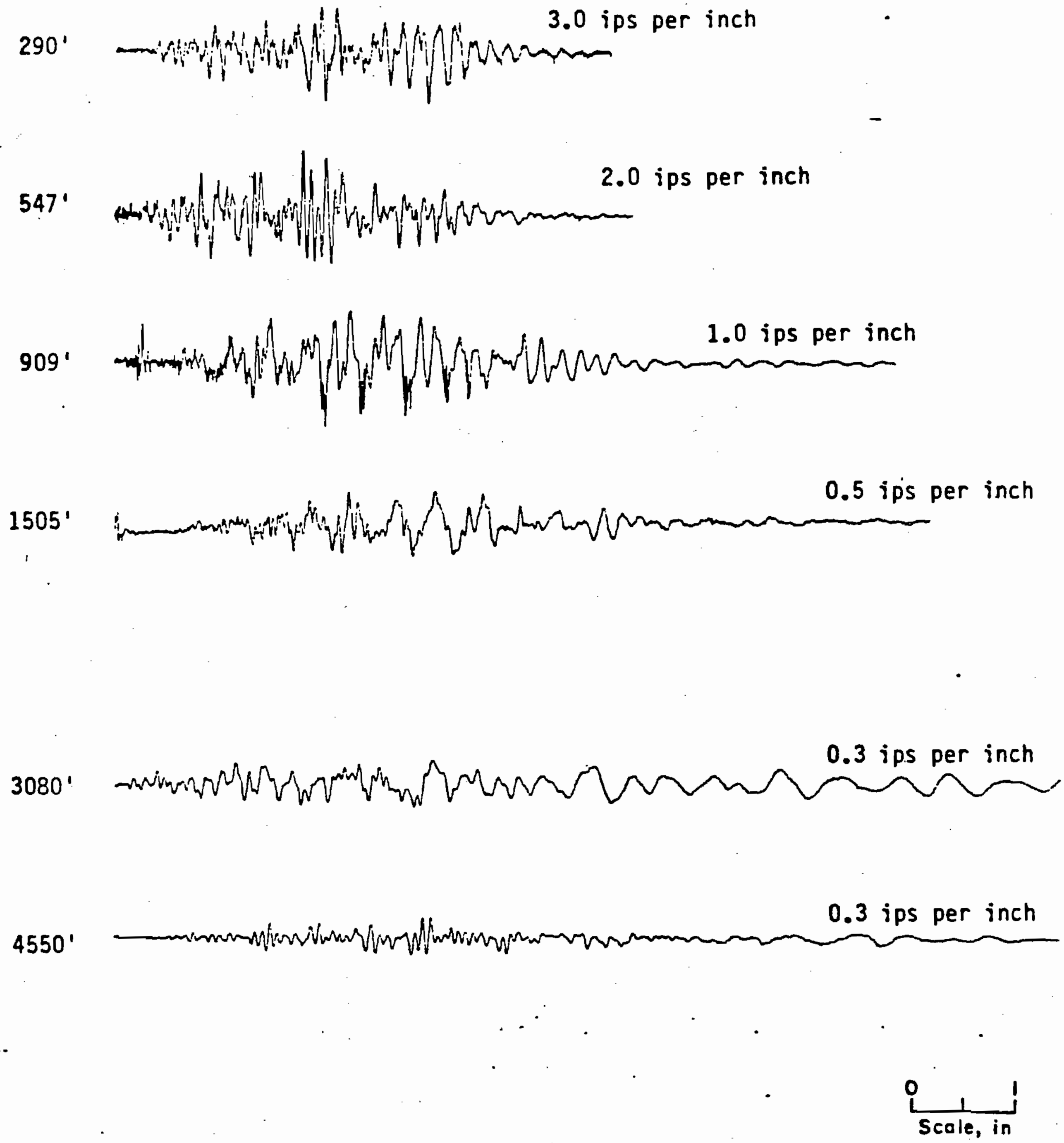


Figure 50.- Shot 6 - Transverse component. Ground vibrations recorded by north array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

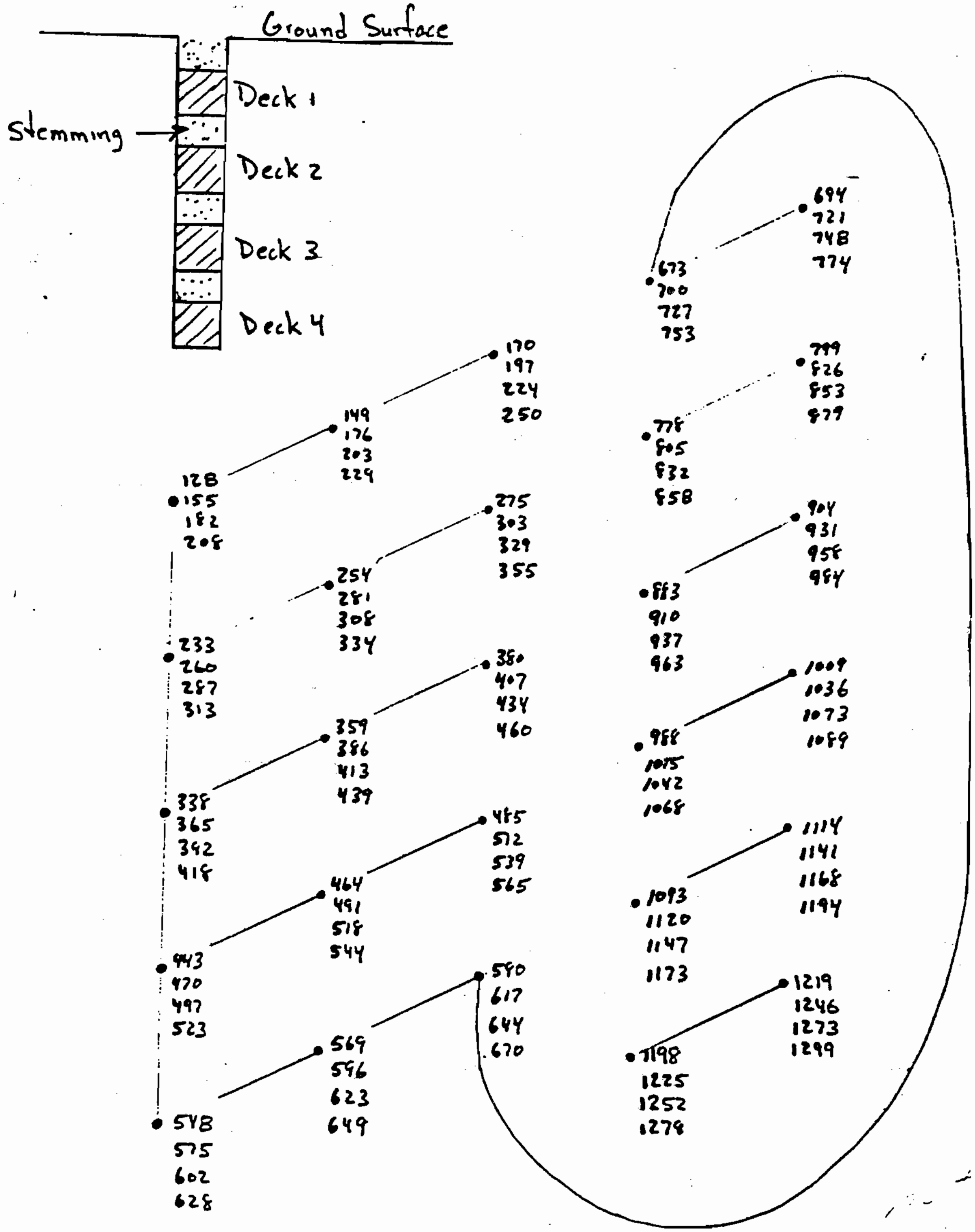


Figure 51.- Shot 3 pattern and initiation sequence.

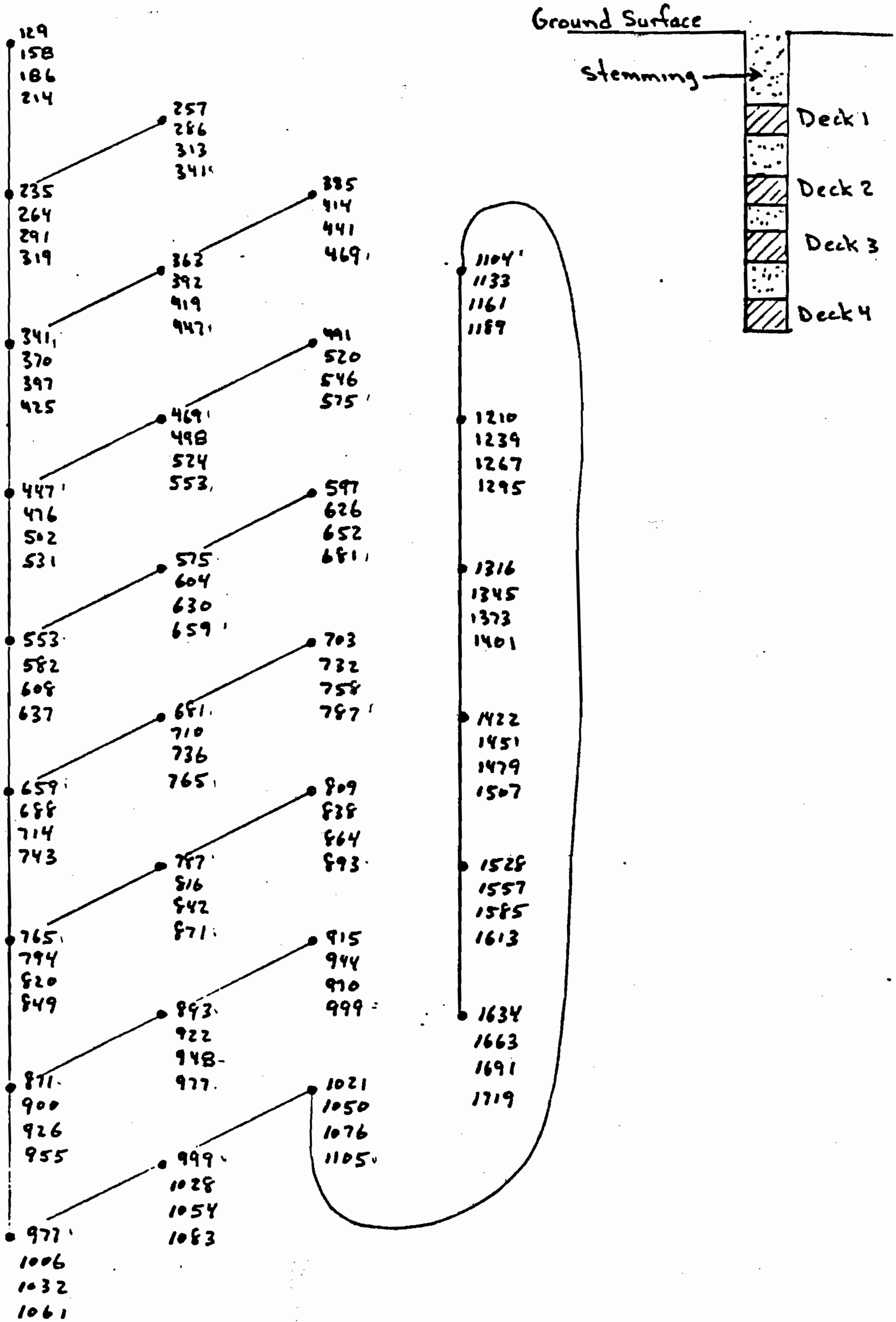


Figure 52.-Shot 6 pattern and initiation sequence.

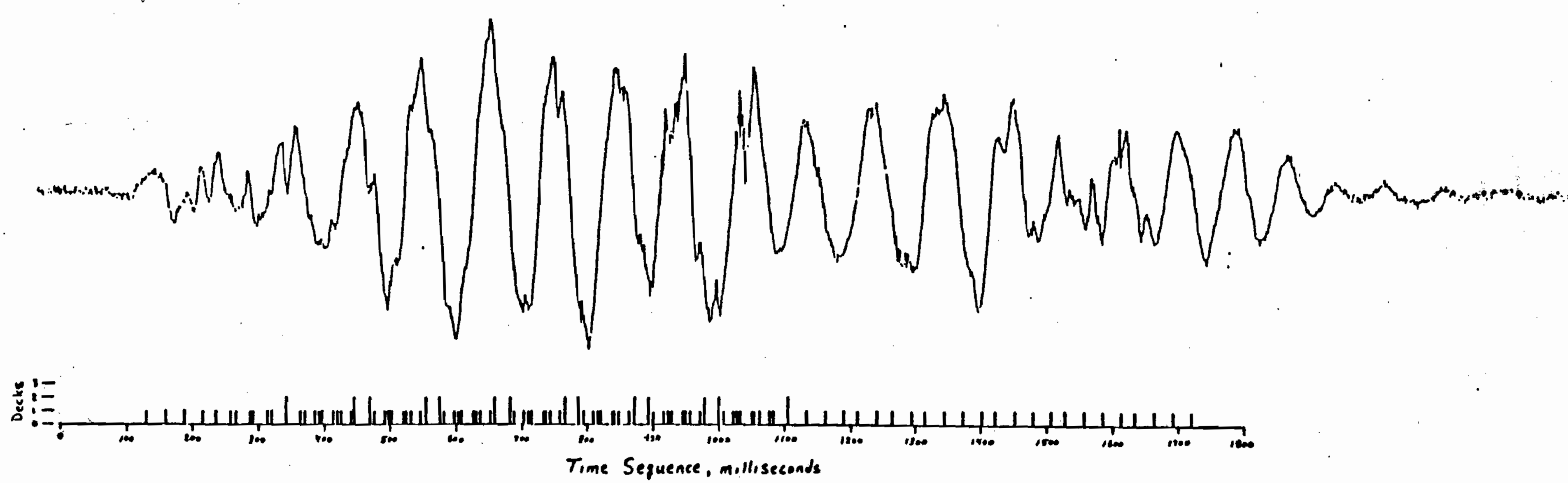


Figure 53.- Comparison of shot 6 initiation sequence and radial component of ground motion recorded at 290 feet.

Figure 54.- Comparison of shot 3 initiation sequence and radial component of ground motion recorded at 90 feet.

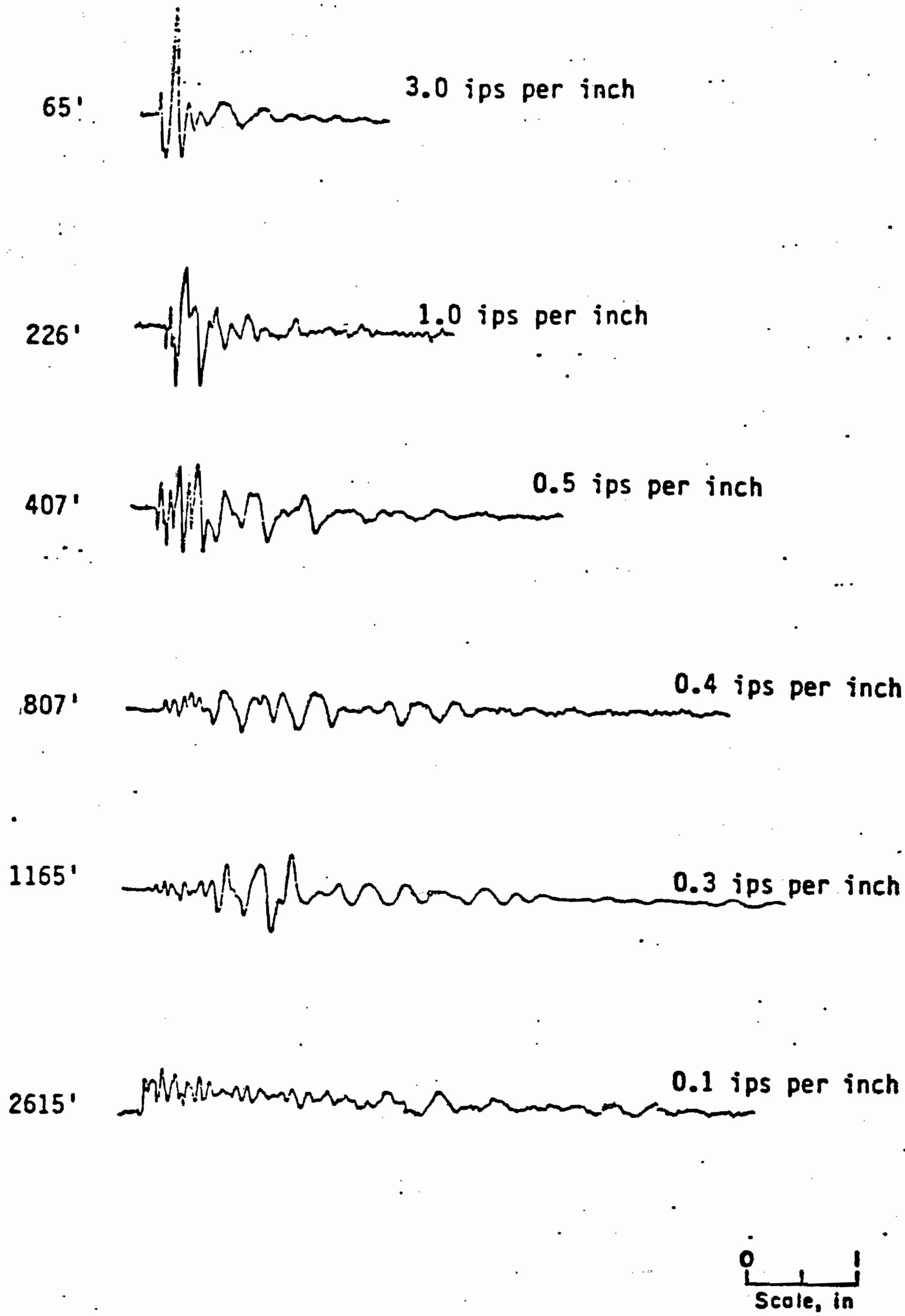


Figure 55.- Shot 4 - Longitudinal component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

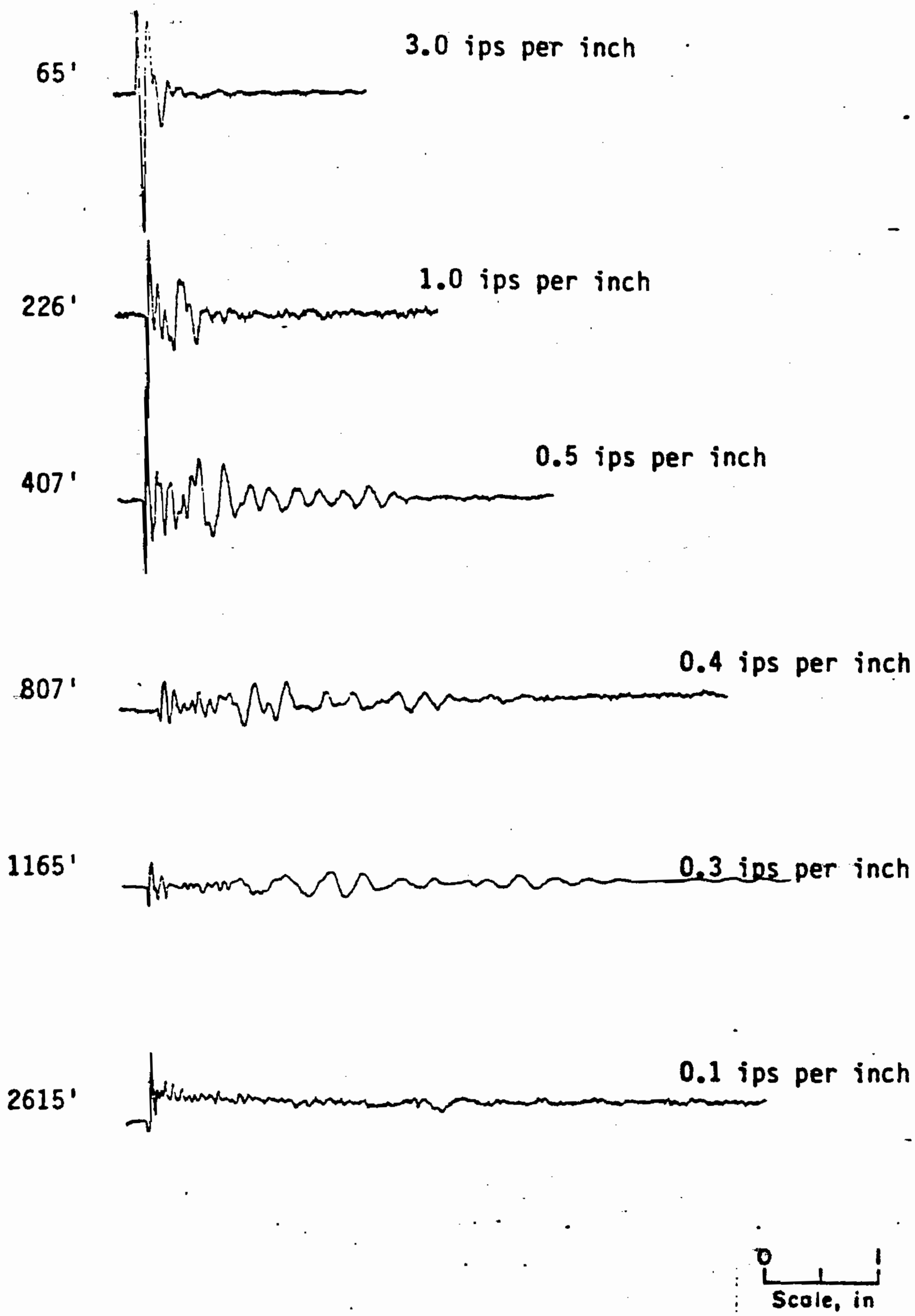


Figure 56.- Shot 4 - Vertical component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

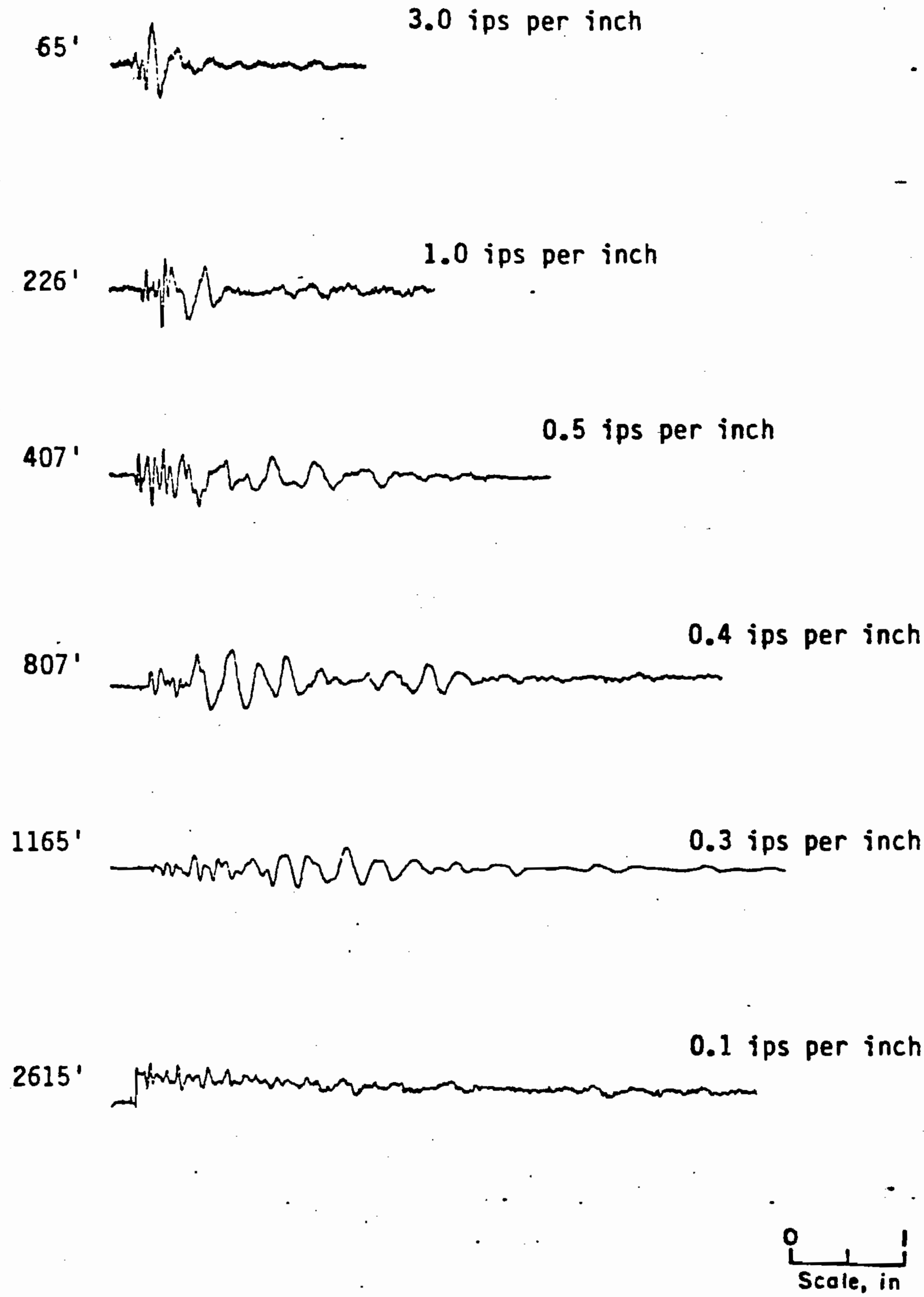


Figure 57. Shot 4 - Transverse component. Ground vibrations recorded by west array. Distances are in feet from the shot. Horizontal scale is 500 milliseconds per inch.

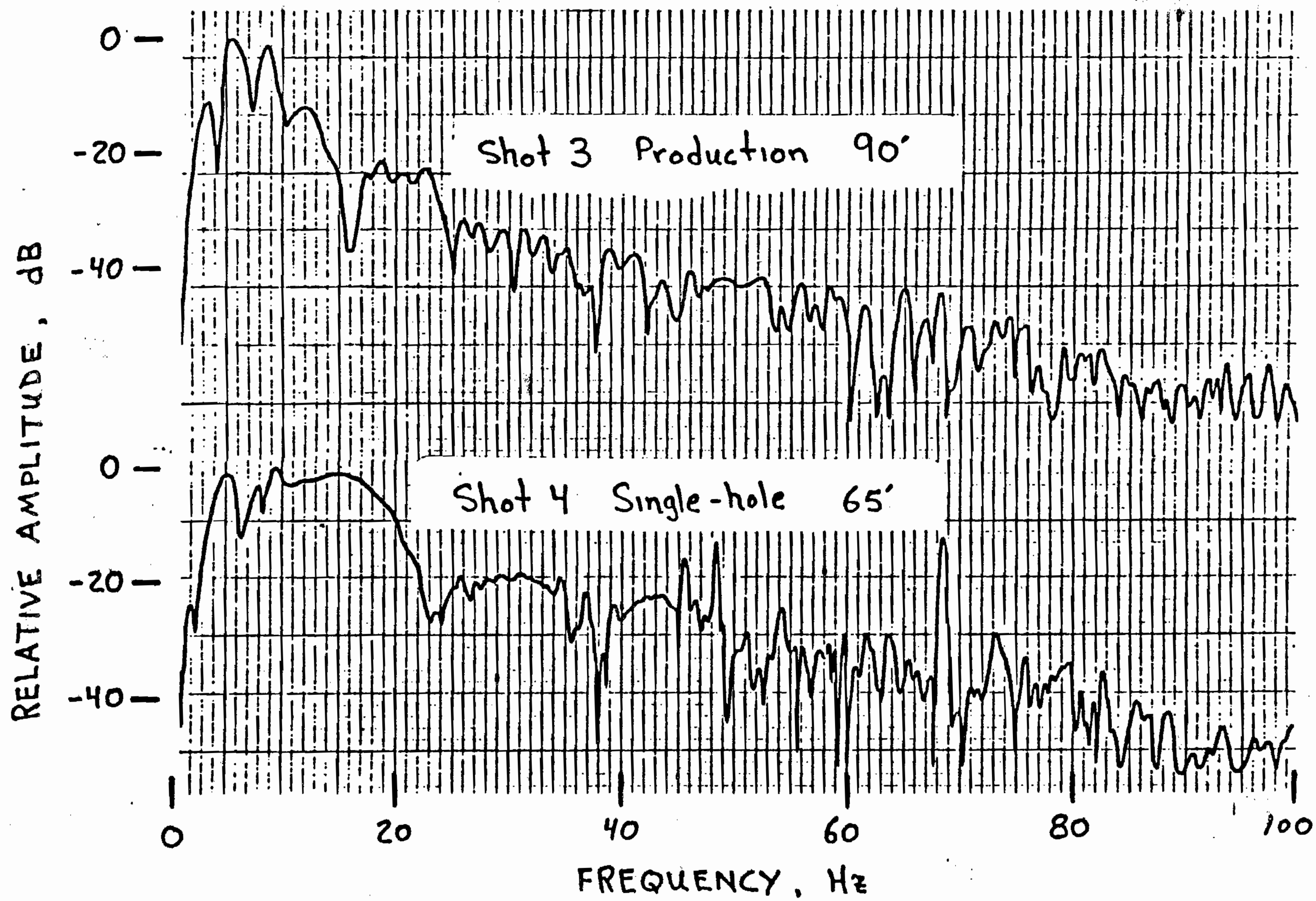


Figure 58. Frequency spectra comparing production shot and single-hole shot frequency content of recorded vibrations in the near-field.

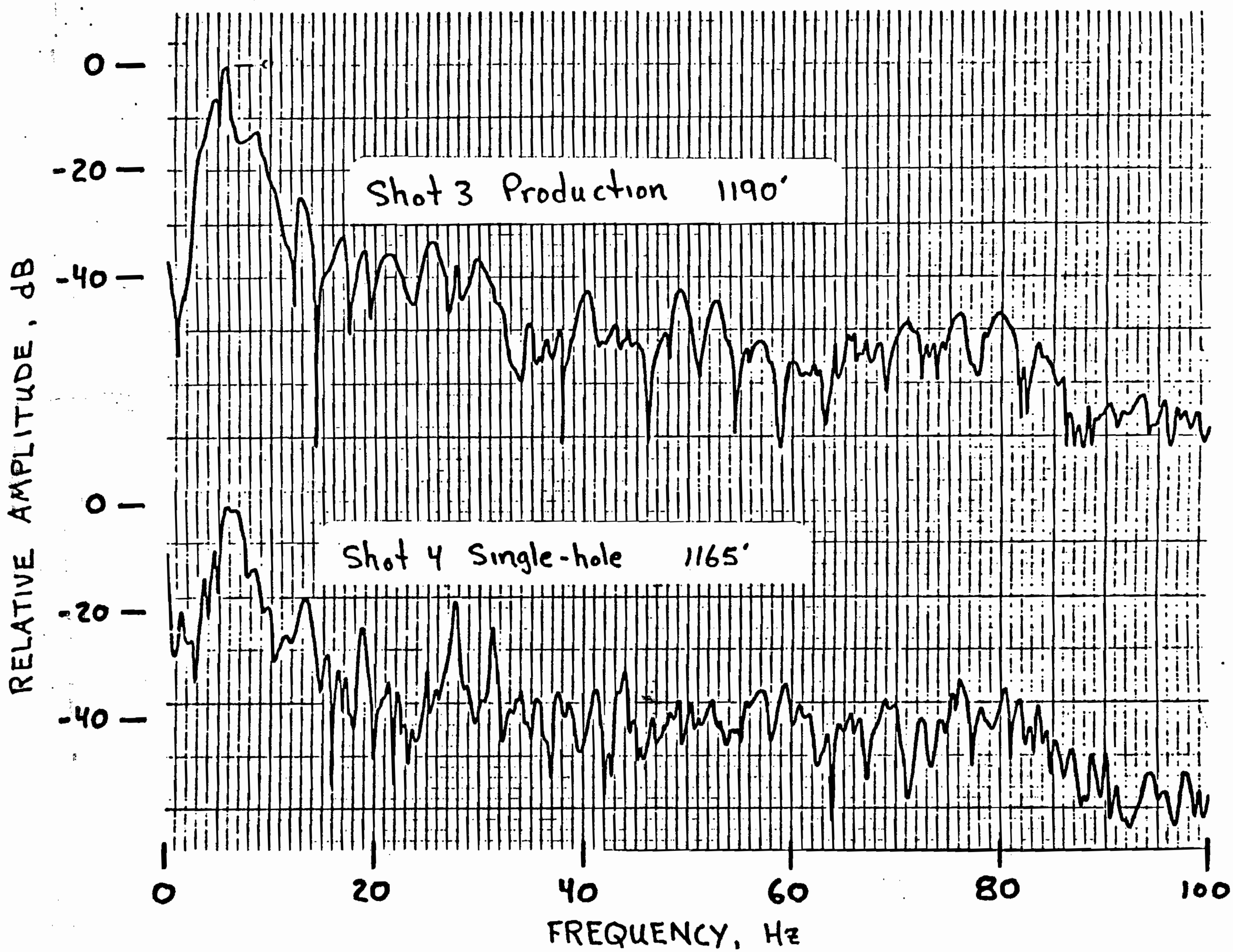
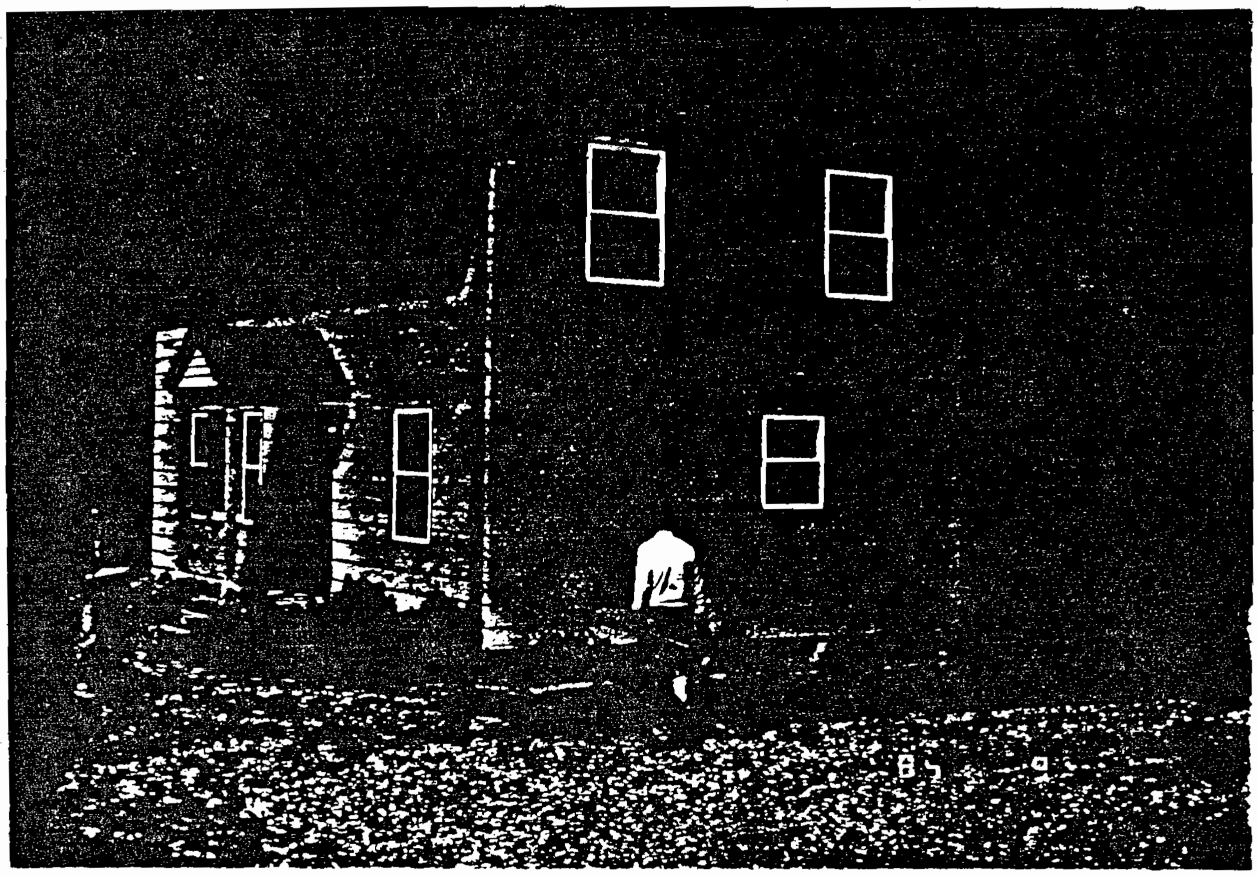


Figure 59. Frequency spectra comparing production shot and single-hole shot frequency content of recorded vibrations in the far-field.



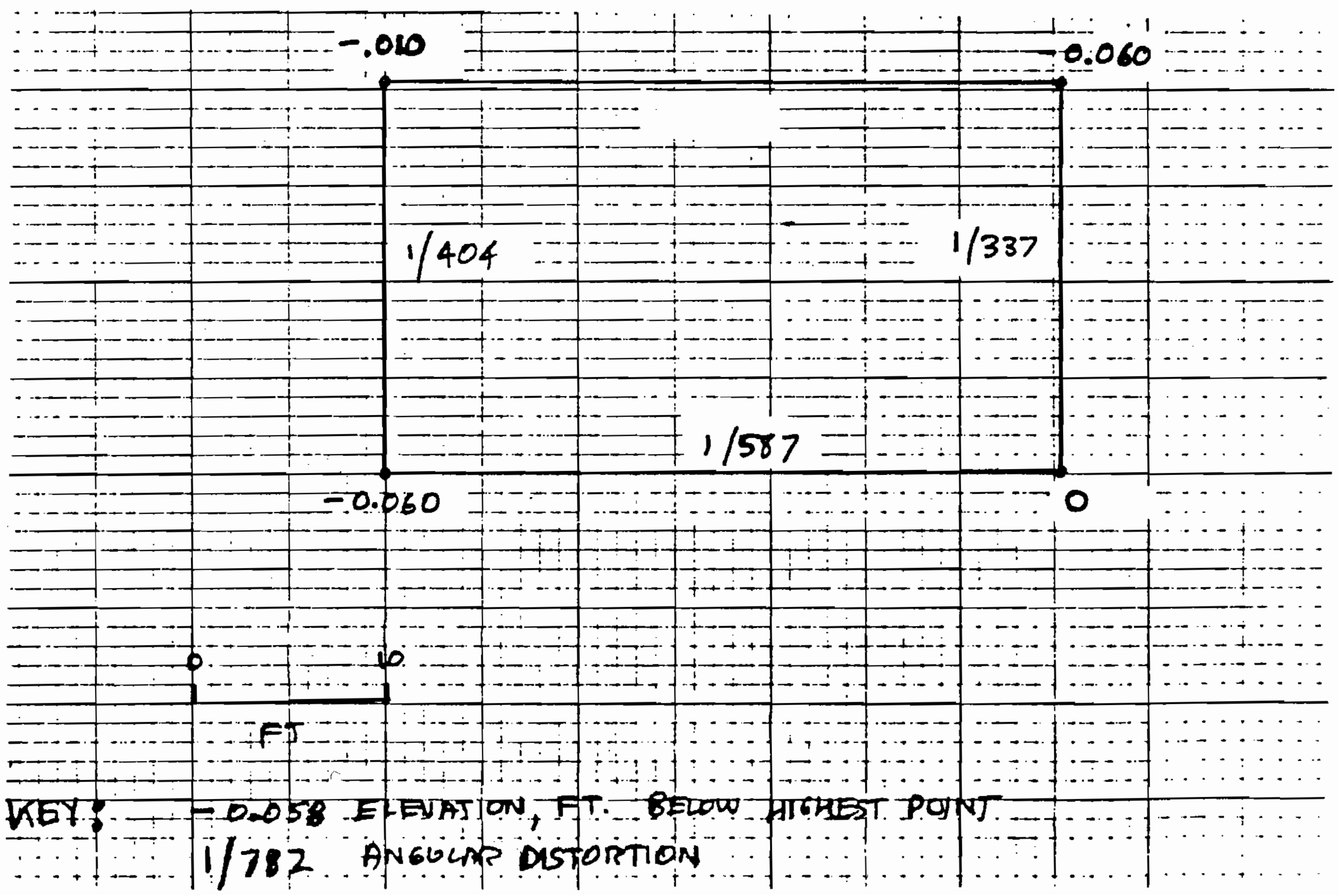
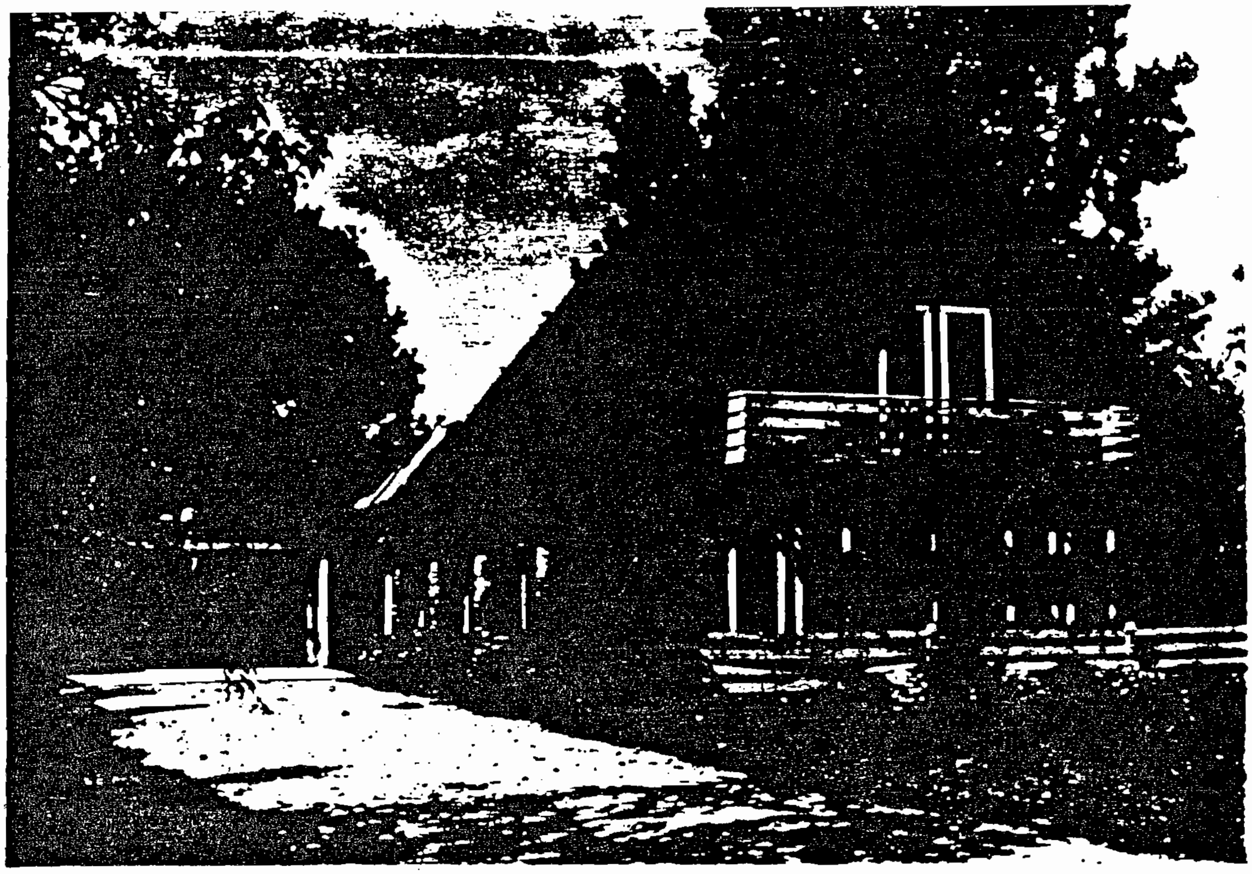


FIGURE 60. - Ahlemeyer house and level loop survey.



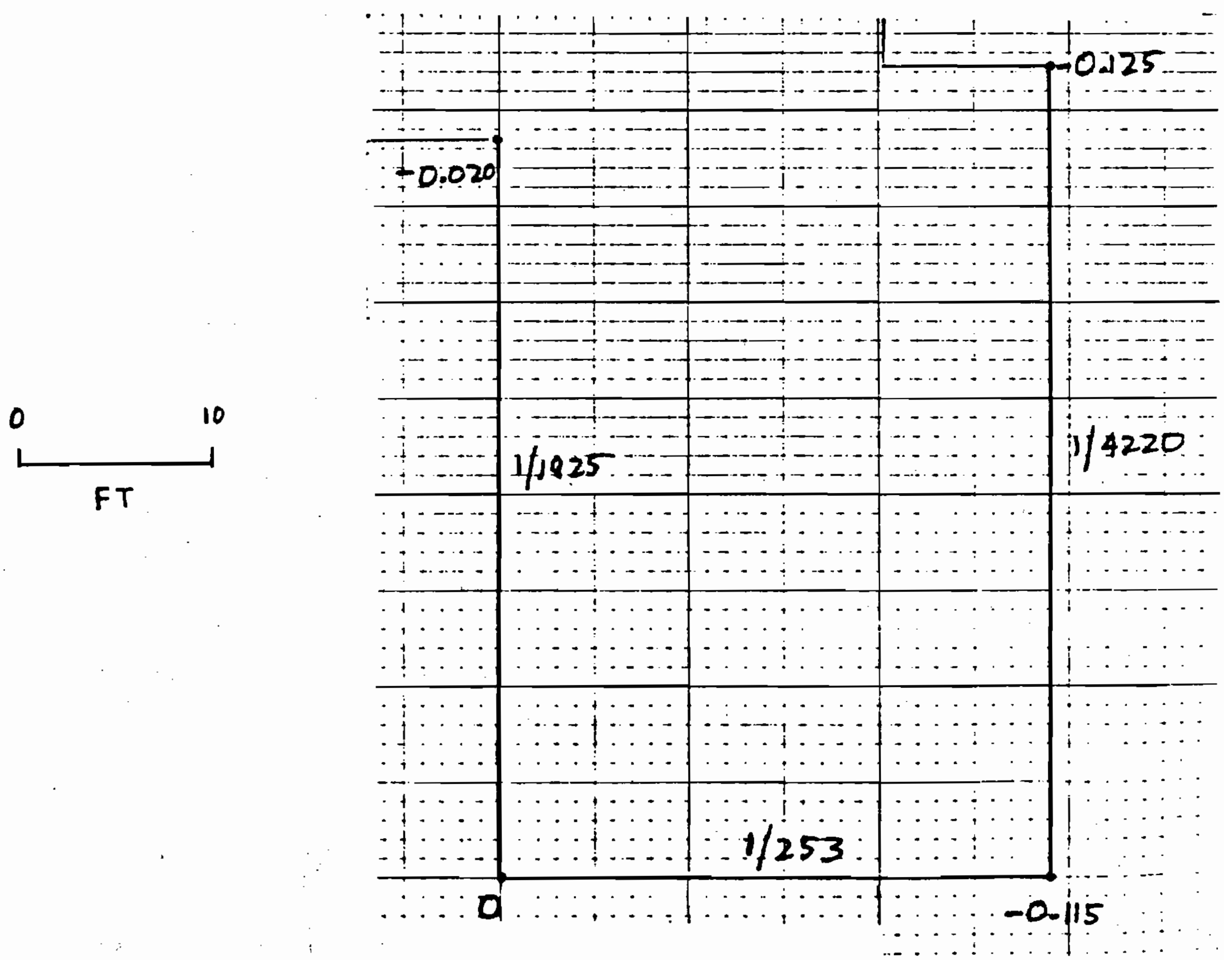
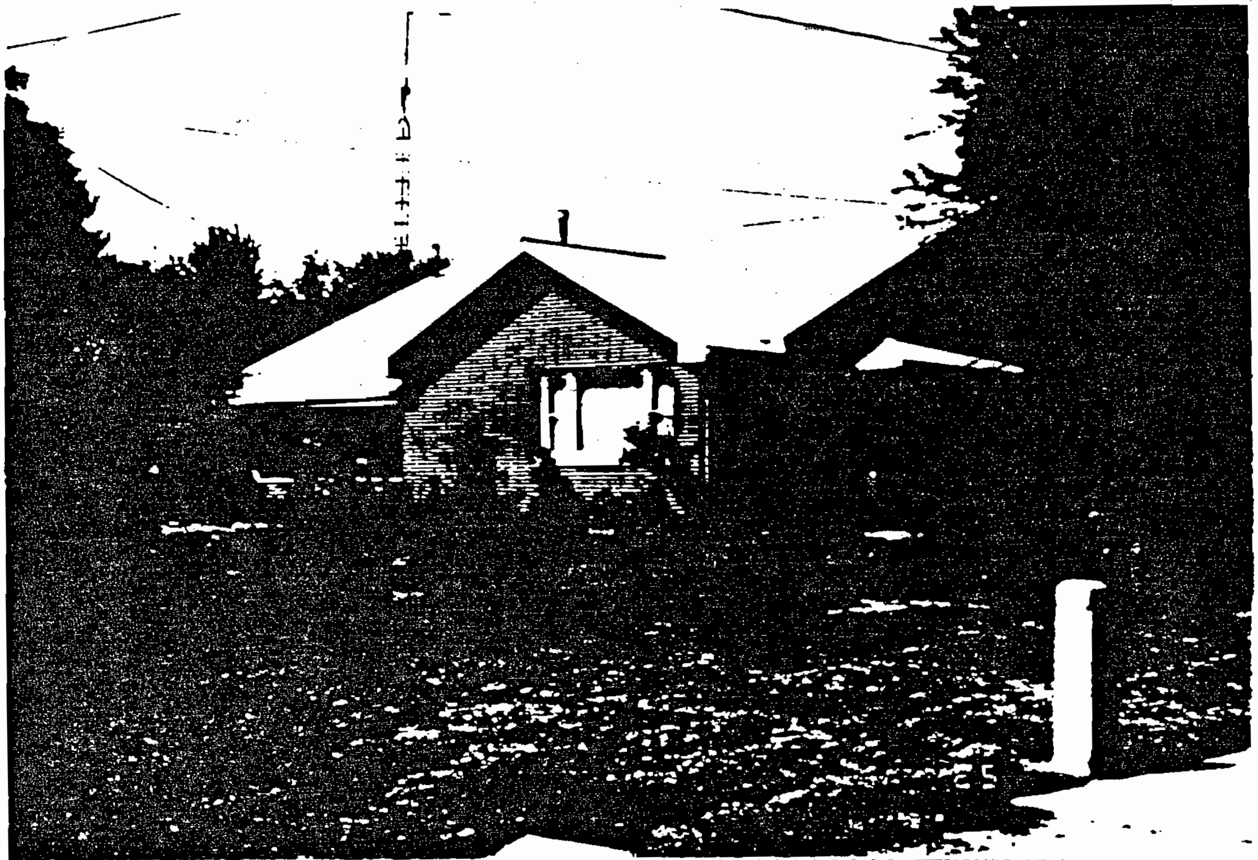


FIGURE 61. - Albrecht house and level loop survey.



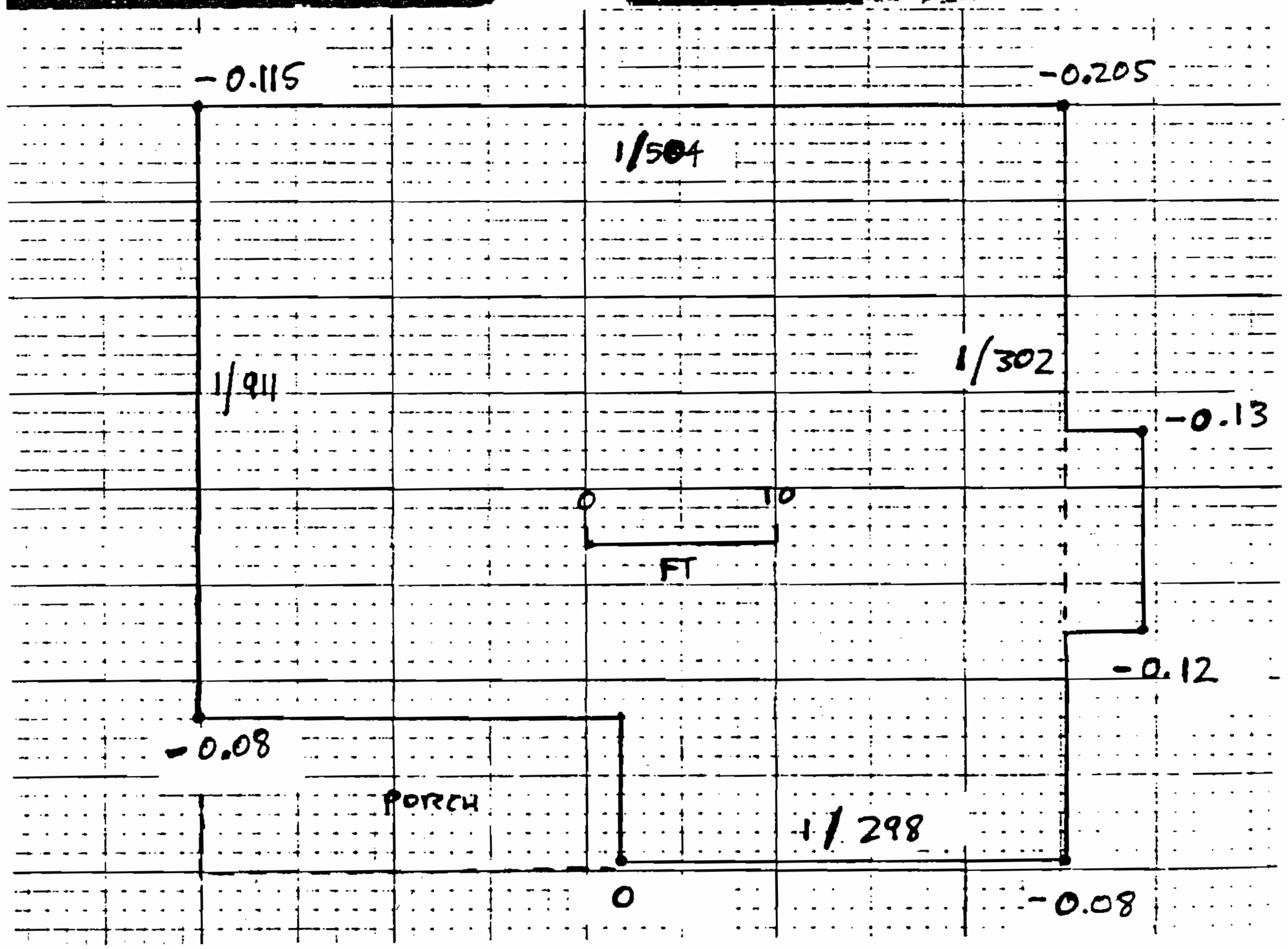


FIGURE 62. - Erna Finger house and level loop survey.

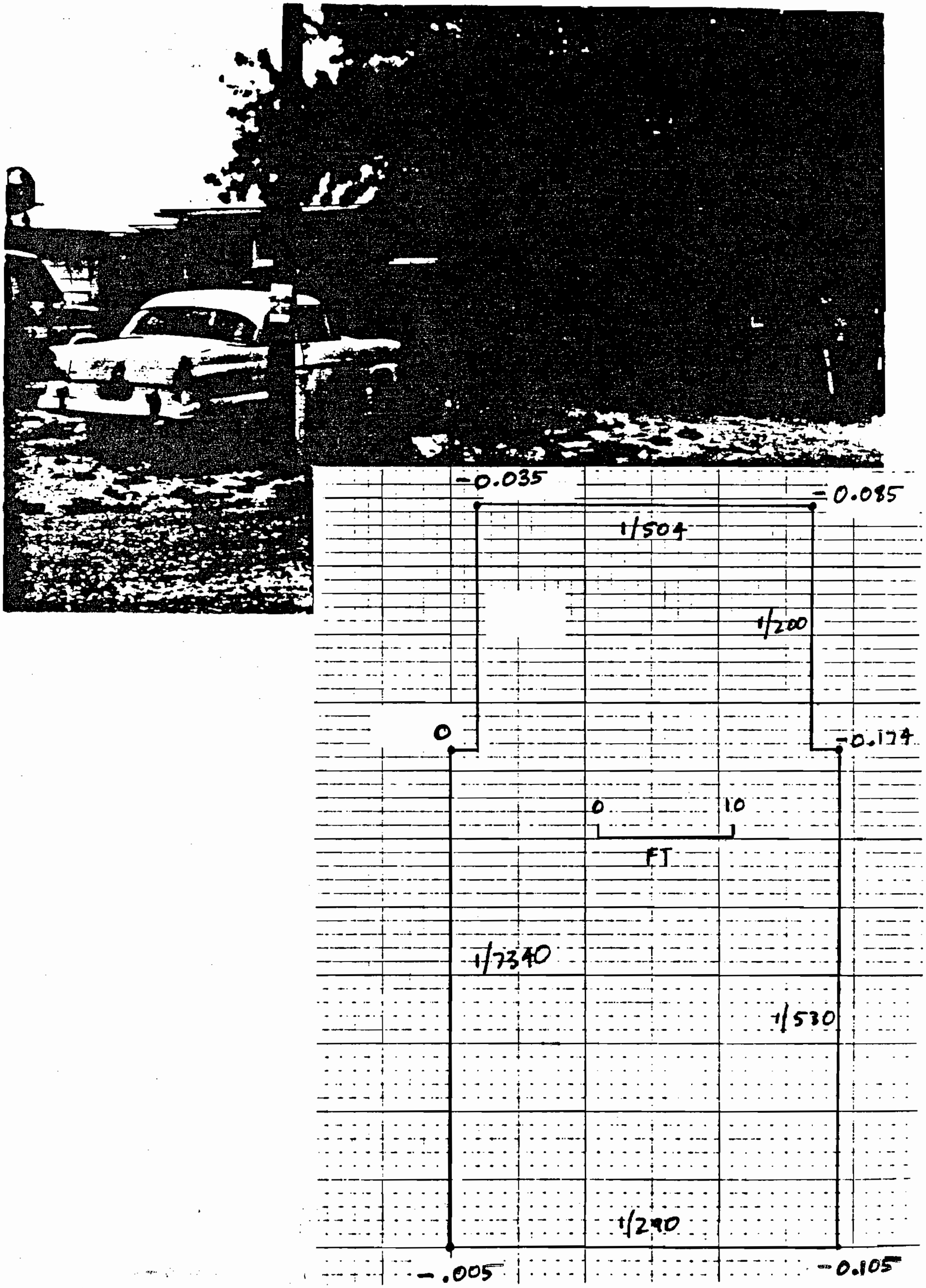
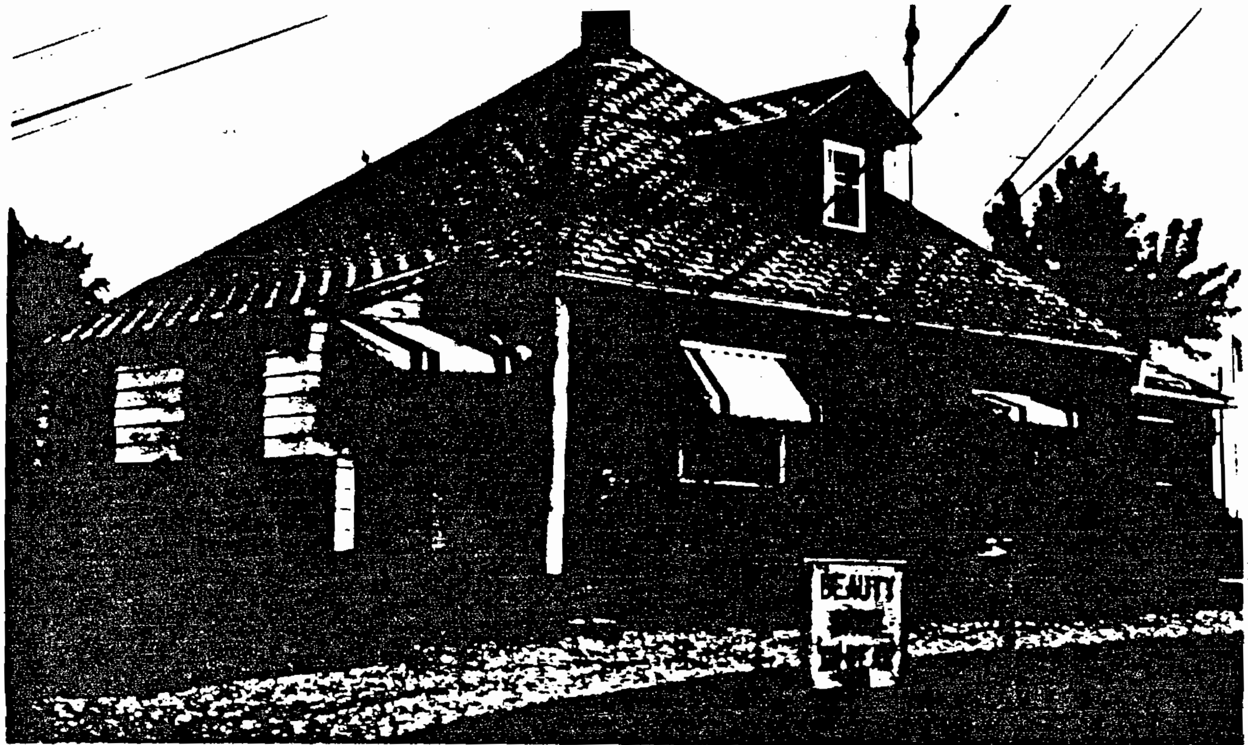


FIGURE 63. - Otto Finger house and level loop survey.



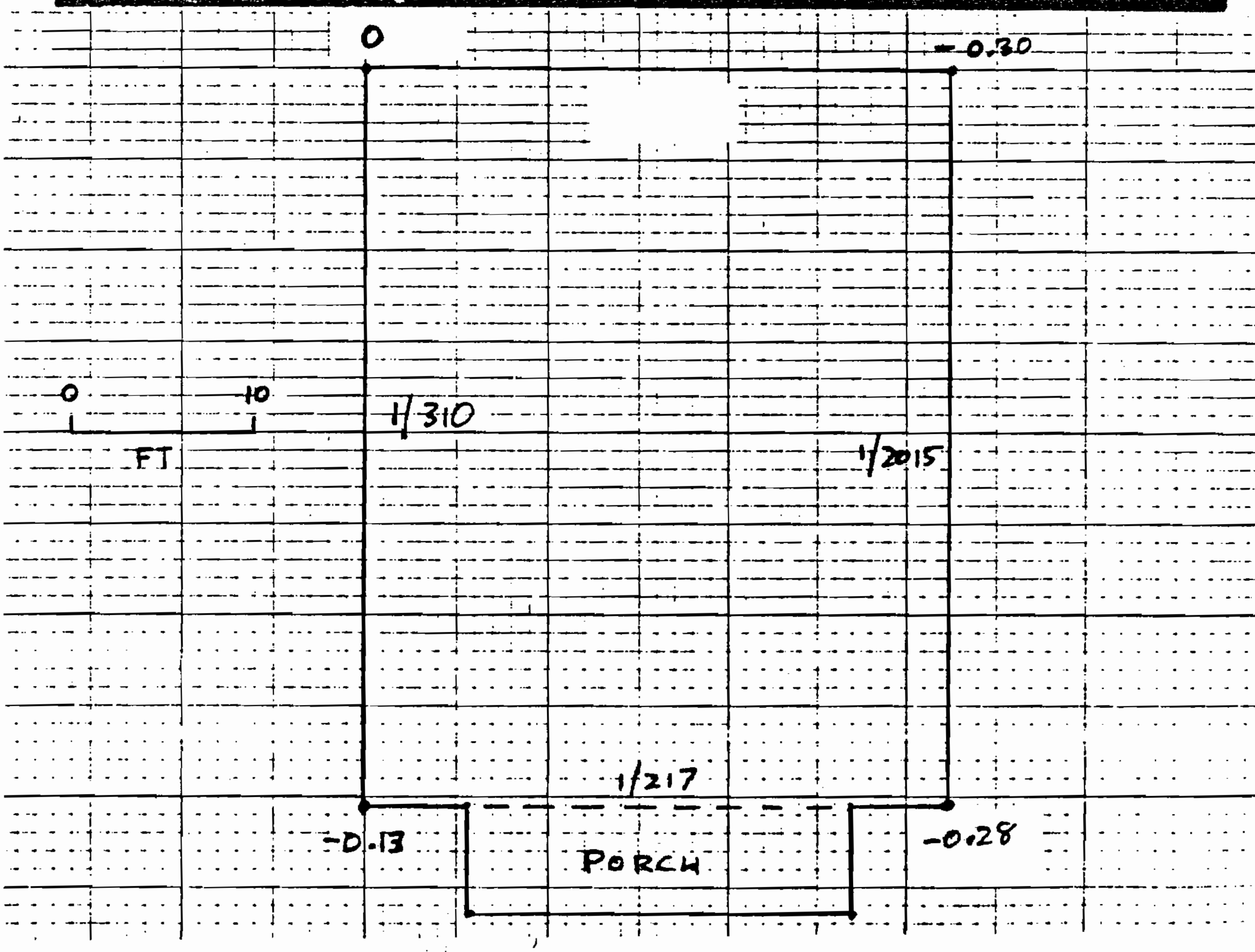


FIGURE 64. - Jovanovich house and level loop survey.

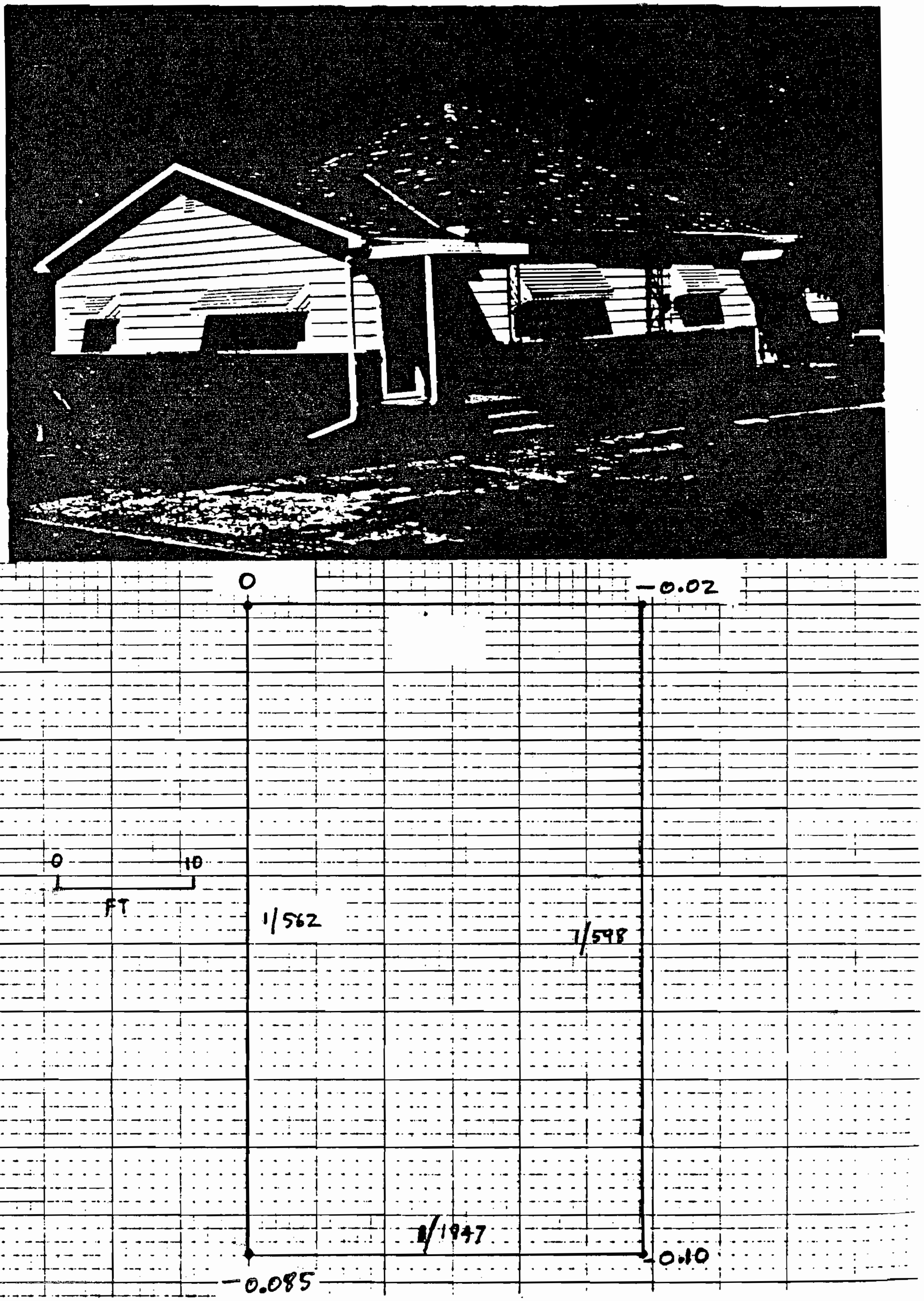


FIGURE 65. - Marietta house and level loop survey.

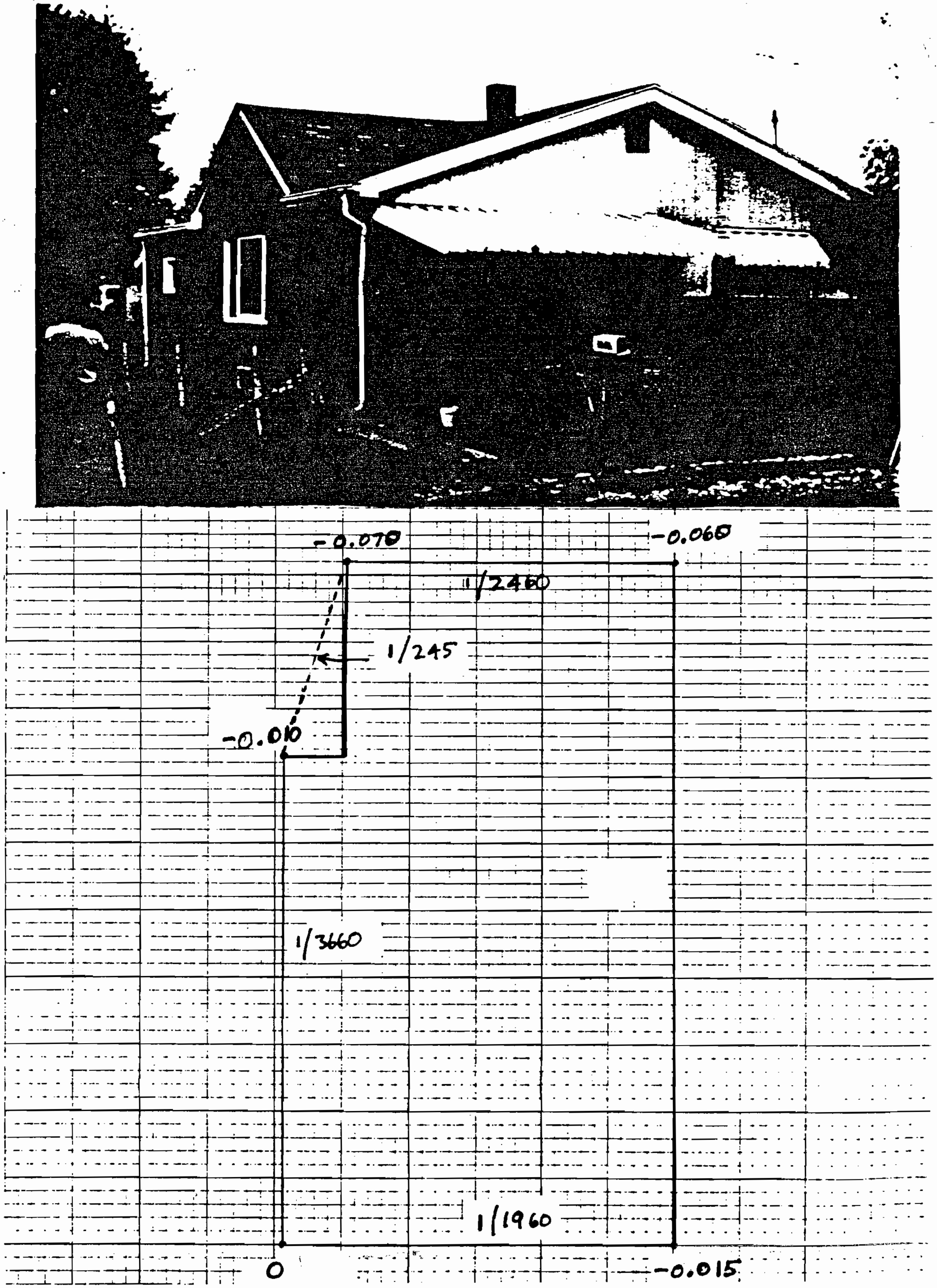


FIGURE 66. - Skorich house and level loop survey.

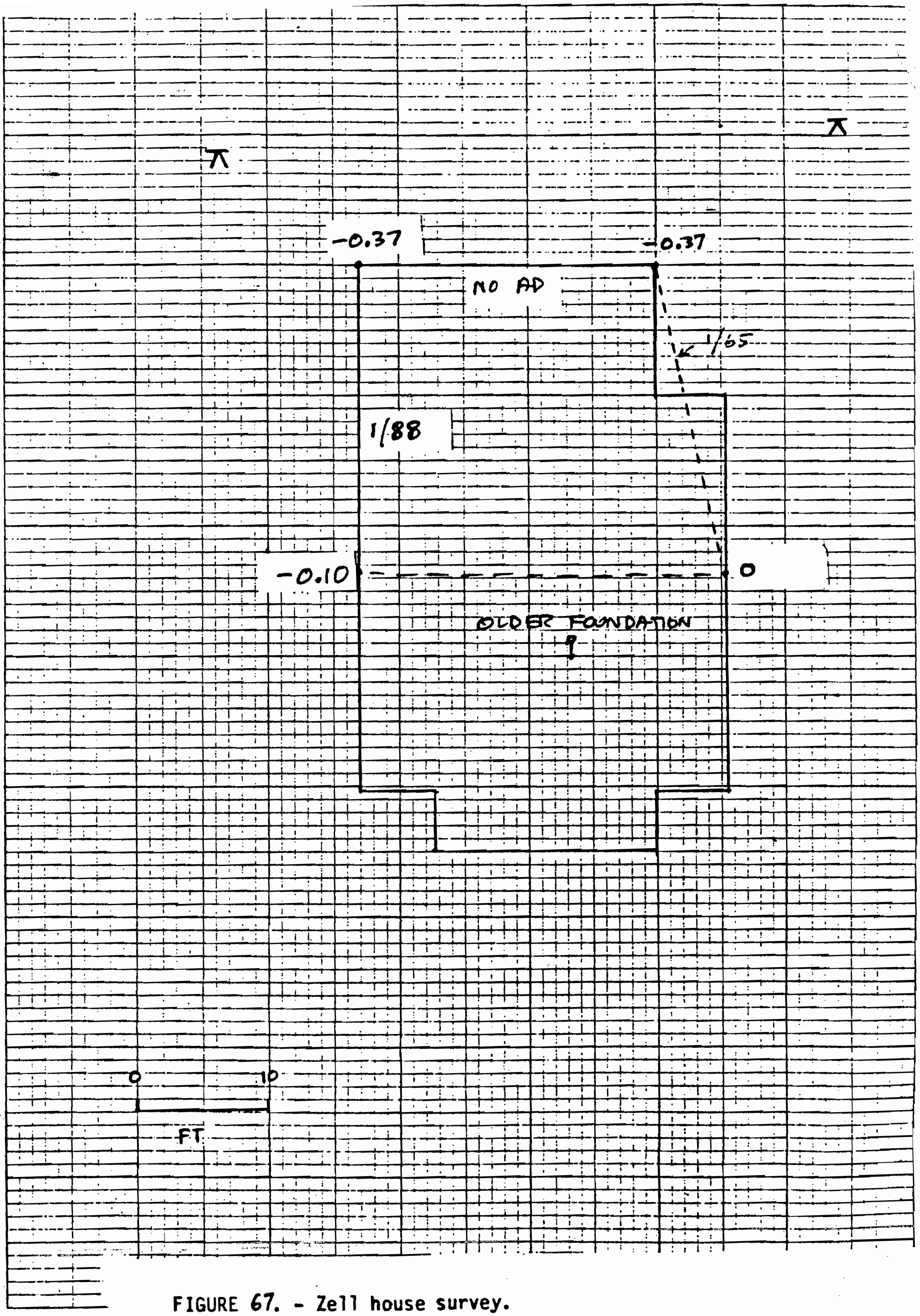


FIGURE 67. - Zell house survey.