INVESTIGATION OF THE SLEDGEHAMMER AS A SHALLOW SEISMIC SOURCE

by

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INTRODUCTION

This report summarizes the results of experiments intended to determine critical variations in seismic data quality associated with changes in the weight and energy of sledgehammer impacts on an assortment of plates with different weights, surface areas, thickness, and composition. The experiments were performed at three sites in the Lawrence, Kansas, area, each with different near-surface conditions. Uniformity and consistency in the testing process was critical and allowed derivation of some conclusions consistent for the three Kansas sites and presumed to be good rules-of-thumb for other sites.

Seismic surveying has been an effective means of imaging acoustic interfaces of the earth's subsurface since the early 1930's. Development of shallow-seismic techniques began with refraction in the early-1950's (Stam, 1962) with reflection following in the mid-1950's (Pakiser, 1956). Improvements in techniques and equipment have allowed delineation of increasingly more complicated geology and resolution of thinner beds. The need for greater resolution at shallow depths (< 30 m) is the principle catalyst spurring the development of high-frequency, low-energy sources for shallow-reflection applications. The wide variety of seismic sources presently used for shallow-seismic applications has resulted from the vast number of applications, targets, resolution and economic requirements, and, of course, personal preference (Miller, et al., 1986).

Application of seismic methods to engineering, ground water, mining, and environmental problems has become increasingly popular over the last 15 years (Steeples and Miller, 1990; Lankston, 1990; Miller and Steeples, 1990; Pullan and Hunter, 1990; Gochioco and Cotten, 1989; Miller et al., 1989; Jongerius and Helbig, 1988; Pullan and MacAulay, 1987; Birkelo et al., 1987; Hunter et al., 1984; Ruskey, 1981; Schepers, 1975). With the extreme site-dependent nature of shallow reflections, each source may have a specific geologic setting where it can generate higher quality seismic energy than any other. In some settings, several approximately equivalent energy sources can generate equally good recorded seismic signals requiring source selection to be based on criteria such as economics, repeatability, portability, safety, and efficiency.

Sources for shallow seismic surveys were almost exclusively limited to explosive charges until the late 1950's when improvements in acquisition equipment allowed the recording of signal from low energy weight-drop sources. The sledgehammer represents the most simplistic and economical of all weight-drop sources. At most sites, however, the economics of the sledgehammer generally do not out-weigh the higher reflection frequencies and reduced surface-wave energy produced by explosive and projectile sources. The lack of highly repeatable impacts from a sledgehammer inhibits CMP (CDP) processing and vertical stacking in high-frequency data areas where the signal-to-noise ratios are low. At some sites, the sledgehammer can be a repeatable, high-frequency source equivalent or nearly equivalent to projectile or explosive sources (Miller et al., 1986; Miller, et al. 1989). A significant economic and, in some cases, time saving is possible at sites where the sledgehammer is an acceptable source.

The sledgehammer source configuration consists of a hammer and a plate. Maximizing the sledgehammer source requires appropriate matching of both the source and plate to the survey objectives. Laboratory experiments using conservation of momentum, collision theory, and the coefficient of restitution have shown that source characteristics are maximized when the weight of the hammer is equivalent to the weight of the plate (steel) (Mereu, 1962). Verification of laboratory results and determination of critical surface area versus thickness of plates and effects of various types of plate materials would improve the selection of sledgehammer source configurations at many locations. At some sites, slight improvements in the quantity of useable seismic energy from a sledgehammer source could eliminate the need for explosive or projectile sources, greatly reducing the expense of and environmental constraints on shallow-reflection surveys.

GEOLOGY

The three test sites were all located within 1 km of the city limits of Lawrence, Kansas (Figure 1). Each site had a different type of material present in the upper few meters. The near-surface materials present at each of the three test sites are uniformly underlain by a geologic sequence of deeper flat-lying Paleozoic rocks overlying the Precambrian surface to a depth of around 800 m. Pennsylvanian units consisting of cyclic sequences of marine and non-marine strata comprise about half of the total Paleozoic rocks. The three test sites have bedrock surfaces that consist of either Lawrence or Stranger Formation limestone, sandstone, or shale (Figure 2).

The first test site is located on the University of Kansas campus on a grassy untended field. The Lawrence formation outcrops at the site with near-surface material consisting of a typical soil profile underlain by sandy-shale sediments. A strong reflection representing the top of the Stanton limestone has been present on most seismic data recorded in this area at approximately 85 ms (Knapp and Watney, 1987). This site has classically been a good high-frequency area with strong reflection events present from 40 ms to depths in excess of 300 ms.

The second test site is located about 500 m south of the city limits of Lawrence on a grassy mowed lawn immediately south of a small farm pond (Figure 1). The near-surface at site 3 represents the transition from the weathered shaley, soil profile present at the first test site and the sandy alluvial deposits present at site 3. Borehole information suggests a strong reflector should be present 33 m deep at the base of the Tonganoxie sandstone. The reflection should arrive at about 40 ms two-way time. Data quality at this location will be enhanced by the relatively compacted near-surface and shallow water table.

The third site is located approximately 500 m north of the city limits of Lawrence within the Kansas River valley on a heavily travelled sand and gravel roadway within the bounds of an industrial sand dredging operation (Figure 1). The upper 10 cm consists of a wet compacted river sand underlain by a compacted gravel layer. The process of compaction has predominantly occurred over the last decade by heavy-equipment travel. Beneath the gravel layer are river-valley alluvial deposits down to bedrock at a depth of approximately 20 m. The edge of the dredge pond is within 50 m of the line with a static water level less than 2 m below the elevation of the test line. Bedrock reflections in the Kansas River valley generally occur at approximately 50 to 80 ms two-way time (Steeples and Knapp, 1982).

FIELD PROCEDURE

An Input/Output, Inc. DHR 2400 24-channel seismograph recorded the data digitally on half-inch magnetic tape in a modified SEG-Y format and also on paper. The record length was 250 ms with a sample interval of 1/4 ms. Analog-to-digital (A/D) conversion is 11 bits plus sign. The amplifiers have a factory noise specification of 120 nV root-mean-square (rms), providing a fixed-gain instantaneous dynamic range of 72 dB. The gain levels were selected to maintain a word size of at least 9 bits but less than a full 11, therefore maximizing recorded information without clipping. Time zero was provided by a 10-Hz geophone placed within 0.2 m of the hammer/plate contact point. The DHR 2400 is a step down from the new crop of state-of-the-art engineering seismographs with 15+ bit A/D conversion and floating-point amplifiers, but with its available dynamic range and fixed-gain amplification, it is very competitive for target-oriented studies.

The individual 24-channel field files used in this investigation were acquired after analysis of a series of walkaway-noise tests performed at each of the three sites. Field geometries were selected for each site, individually, to optimize recorded reflection energy. All the data were recorded with 24 dB per octave analog low-cut filters with a -3 dB-point of 110 Hz. Recording all the data with consistent analog filters allowed direct comparison of source configurations and site specific spectral properties. The receivers were 3-40 Hz L28E Mark Products geophones damped to 0.65 of critical, on 0.14 m spikes, wired in series, and spaced 0.25 m apart perpendicular to the survey lines. The geophones were firmly planted and left in place throughout all the tests at each site. All data used for comparison in this study were acquired at each site within about a 6-hour time window.

Individual site geometries were:

SITE 1

source-to-nearest-receiver	30 m
receiver station spacing	1.22 m
target reflector depth	100 m

SITE 2

source-to-nearest-receiver	17 m
receiver station spacing	0.6 m
target reflector depth	20 m

SITE 3

source-to-nearest- receiver	13.5 m
receiver station spacing	0.6 m
target reflector depth	30 m

Critical to meaningful comparisons of subtle variations in hammer/plate configurations is consistency and repeatability in the amount of energy delivered to the plate and in coupling of individual plate to the ground. An All Terrain Vehicle (ATV)-mounted swing arm was designed to deliver consistent and accurate sledgehammer blows to plates with surface areas as small as 0.02 square meters (figure 3). The hitting machine can deliver blows from various size sledgehammers with impact energy dependent on the selected swing arm length (Table 1). The apparatus is fully portable and repeatable within ± 0.04 J for any single impact.

Ten different plates and 3 different hammers represented the comparison repertoire, each with either different total weight, surface area, and/or material (Table 2). The plates were all cylinders and constructed of a solid piece of either mild steel or aluminum. The hammers were all standard off-the-shelf sculptured cylindrical steel weights on the end of oak handles. The same set of 10 plates and 3 hammers was used at each of the three sites.

All recorded impacts followed a consistent pre-shooting sequence. At each site a source area approximately four square meters was cleared of vegetation and debris. Before each impact, a plate was seated in virgin spots within the source area with a single impact from the hitting machine. Six impacts were recorded with each plate. Each impact possessed a unique amount of total energy (three different hammers and two different swing arms). The progression within the source area for each new plate location was toward the nearest-to-source area receiver. This uniform shooting procedure minimized the chance of observed variations being the result of inconsistent experimental procedure.

Table 1

Impact Energy Levels of Source Combos

Weight of hammer [kg (lb)] plus handle extension apparatus at impact

Hammer	1 m Extension	3 m Extension
3.6 (8)	5.0 (11)	7.7 (17)
5.4 (12)	7.7 (17)	9.5 (21)
9.1 (20)	10.4 (23)	12.7 (28)

Mean velocity (m/s) prior to impact of sources

Hammer	1 m Extension		3 m Extension	
kg	$\bar{x}$	σn*	$\bar{x}$	σn*
3.6	5.6	0.09	8.5	0.29
5.4	5.5	0.05	8.5	0.04
9.1	5.4	0.07	8.2	0.14

*σn = standard deviation; n = 12 to 15

Kinetic Energy — K.E. = (1/2) (m) (v^2)

Hammer (kg)	1 m Extension	3 m Extension
3.6	78 J	278 J
5.4	116 J	343 J
9.1	152 J	427 J

Table 2

IMPACT PLATE SPECIFICATIONS

Weight (kg)	Thickness (cm)	Radius (cm)	Surface Area (cm^2)
2.72	2.54	13.18	545
10.88	10.16	13.18	545
1.36	0.64	18.73	1102
2.72	1.27	18.73	1102
5.44	2.54	18.73	1102
10.88	5.08	18.73	1102
21.77	10.16	18.73	1102
2.72	0.64	26.43	2195
10.88	2.54	26.43	2195
1.81 *	2.54	18.73	1102

* Aluminum

DATA PROCESSING

Data processing was done on an Intel 80486-based microcomputer using a proprietary set of algorithms (Eavesdropper) developed by the Kansas Geological Survey (Somanas et al., 1987). The data are all displayed and analyzed in field file format and/or as amplitude spectra. Adjustments for variations in recording gain and time zero were made to individual data files as necessary in accordance to observers' notes and visual data inspection. All records within any comparison grouping are displayed in a relative amplitude format with equivalent gain. All adjustments were made and data are displayed to enhance observable variations resulting from differences in plate dimension and/or weight and hammer energy.

RESULTS

Data are displayed to enhance differences in recorded data consistent with variations in plate weight, plate surface area, and/or hammer weight. The data from each site were grouped in three sets according to (1) constant source energy and plate surface area with changing plate weights, (2) constant source energy and plate weight with a changing surface area, and (3) constant surface area and plate weight and changing source energy. Spectra for all field files were generated to determine dominant frequency and any subtle frequency dependence on plate weight, surface area, and/or hammer energy.

K.U. Campus Site—The primary reflection present at 85 ms on all recorded data has a dominant frequency of about 120 Hz. Refractions represent the first arrivals on records at this source-to-nearest offset distance. The refractions have a significant amount of ring down to a two-way time of approximately 55 ms. The reflection event at 80 to 85 ms is coherent across all 24 traces. Lower frequency arrivals on the close traces at 80 ms are surface waves. On files where the air-coupled wave is identifiable, it appears as a high-frequency linear arrival at approximately 85 ms on trace 1, and 170 ms on trace 24. The reflection event is easily interpretable on most records.

The 1.36 kg, 18.73 cm plate produced more recordable seismic energy than any other 18.73 cm plates regardless of the impact energy, followed closely by the 10.88 kg plate. Data recorded with the 21.77 kg plate resulted in a drop of 30 to 75 percent in amplitude compared to other 18.73 cm plates impacted with equivalent energy. The data from the 21.77 kg plate was approximately equivalent in amplitude to data recorded with no plate (hammer impacting the ground surface). The signal-to-noise ratio for data recorded with the 10.88 kg, 18.73 cm plate, independent of source energy, was about 20 percent higher than any other plate with the same surface area.

Recorded amplitudes are, in general, about 30 percent greater for equivalent hammer weights and plate configurations when the velocity is increased from around 5.5 m/s with the 1-m extension to approximately 8.5 m/s with the 3-m extension. Increasing the surface area from 545 cm^2 to 1102 cm^2 while maintaining a consistent total weight, increases the recorded amplitudes of both 5.4 and 9.1 kg hammer impacts on 3-m extensions by 300 percent. Increasing the surface area from 1102 cm^2 to 2195 cm^2 without changing the plate weight increases the recorded amplitudes of the 5.4 and 9.1 kg hammers on 3-m extensions by 25 to 30 percent. The 9.1 kg hammer on the 1-m extension experienced a 100 percent increase with a surface area increase from 1102 cm^2 to 2195 cm^2. Increasing the surface area of the plates for either the 3.6 or the 5.4 kg hammers with the 1-m extension increased the recorded amplitude from 10 to 15 percent.

The sledgehammers generated approximately one-half the total recorded amplitude and a dominant frequency of about 10 percent higher than the downhole .30-06. A drop in the dominant frequency of 20 to 40 Hz is observed when the surface area of the plates are increased from 545 cm^2 to 1102 cm^2. The dominant frequency of the recorded data seems to be independent of the number of impacts; therefore, seating the plate has no effect on the dominant frequency at this site. The amplitude is affected by the process of seating the plate; a 30 percent increase in recorded amplitude can be observed after seating the plate with 2 uniform impacts.

Snodgrass Ranch Site—Several reflections are interpretable on the raw field files. The event at 45 ms is the highest frequency and most coherent of the three interpretable events above 100 ms. The air-coupled wave is faintly visible across the 24 trace files. The ground roll first arrives at approximately 110 ms on the near-traces . The dominant frequency of the 45 ms reflection is approximately 200 Hz. Body waves and air waves are the only other seismic energy present in the upper 100 ms on all files.

The files recorded with lower impact energy have higher reflection-to-noise ratio and dominant frequency. The data recorded with 1.36 kg, 18.73 cm plate possess the largest recorded amplitudes of all the 18.73 cm plates for equivalent impact energy. Increasing the surface area from 545 cm^2 to 2195 cm^2 results in a 25 percent increase in recorded amplitudes for the same impact energy and plate weight. Impacting the ground without a plate results in about a 20 percent drop in recorded amplitude. The plates with lesser weight generate higher recordable amplitudes regardless of surface areas.

Tripling the impact energy doubles the recorded amplitudes. A uniform increase in recorded amplitude regardless of plate weight or surface area requires a 2 times greater increase in impact energy with the higher velocity, 3-m extension than the low velocity, 1-m extension. Recorded amplitudes are equivalent when a 1-m extension is used with a 20-lb hammer representing 152 J, and a 3-m extension is used with a 12-lb hammer representing 343 J. More recordable energy is generated from three 1/3-full impacts than from one full impact.

Data recorded using the 26.43 cm plate possess 15 percent higher amplitudes than data recorded with the 18.73 cm plate. The 18.73 cm plate produces 10 percent more recordable energy than the 13.18 cm plate. This surface-area dependence is consistent for all energy levels and plate weights (i.e., 6 and 24 lb) except when the 3-m extension is used in conjunction with the 10.88 kg plate when the 7" plate appears to excel. In most cases, increasing the surface area seems to increase the recorded amplitude while maintaining a consistent dominant frequency.

Sand Pit Site—A reflection from bedrock can be identified at approximately 45 ms on most field files. Reflections from within the Paleozoics—one at 70 ms and one a approximately 130 ms—can also be interpreted on most records. The high frequency, linear air-coupled wave first appears on the near-trace at approximately 50 ms. Surface wave is the highest-amplitude, lowest-frequency event on the records. The curved arrival below 210 ms is an out-of-the-plain reflection, probably of the air-wave off one of the many sand piles near the line. The dominant frequency of the reflection is slightly in excess of 100 Hz.

The heavier plates are much more sensitive to changes in surface area than the lighter plates. Recorded amplitudes are relatively consistent for the 2.72 kg plates regardless of surface area with lower energy impacts. An amplitude increase of between 10 and 20 percent was observed with higher energy impacts on the heavier plates when the plate surface area was increased from 545 cm^2 to 2195 cm^2. An amplitude decrease of between 5 and 40 percent is observed with lower energy impacts on the heavier plates when the plate surface area increased from 545 cm^2 to 2195 cm^2. When the lowest energy impacts (78 J) were used, changes in the weight of the 18.73 cm plates made no difference in the recorded amplitudes. The 1.36 kg plate produced 10 to 30 percent higher recorded amplitudes with low-energy impacts than any other 18.73 cm plate. The 21.77 kg plate produced 5 to 30 percent higher recorded amplitudes with higher energy impacts than any other 18.73 cm plate.

Reflection amplitudes, regardless of the source energy, are greater with the 13.18 cm plates than either the 18.73 cm or the 26.43 cm for the 2.72 kg plates. The 1-m extension on the 9.1 kg hammer impacting the 1.36 kg plate generates approximately the same level of recordable energy as the 3-m extension with either the 3.6 or 5.4 kg hammer. Recorded amplitudes double when impact energy is tripled. No difference is observed in total recorded amplitude for data recorded at the lowest impact energy (78 J) regardless of plate configuration. The amplitude of the high-frequency air wave is less for files with equivalent total recorded amplitude with the 3.6 kg hammer. Air-wave-to-reflection ratio is 2 to 3 times greater for equivalent impact energy on a 26.43 cm plate compared to a 13.18 cm plate. There seems to be no spectral dependence on plate configuration or hammer energy.

The signal-to-noise ratio of the aluminum plate is slightly higher than other plates at this site. In comparison to all the 18.73 cm plates, the aluminum plate generates approximately equivalent levels of recordable energy for lower impact energy. For high-impact sources, the aluminum plate generates slightly less than or equal recordable amplitudes to the 21.77 kg plate. The reflection amplitudes are visibly higher with the aluminum plate than with any other 18.73 cm plate regardless of the impact energy.

CONCLUSIONS

No single "rule of thumb" is clearly evident from these studies of sledgehammers and plates. However, several key observations potentially significant to shallow seismic applications where a sledgehammer is the source of choice can be made.

1) There appears to be no spectral dependence on plate weight, surface area, or on plate seating.

2) Aluminum seems to be a reasonable alternative to steel. Weight is not a consideration in hammer/site/plate matching.

3) For a fixed amount of energy available per shotpoint, several smaller hits result in more recorded seismic energy than one large hit.

4) Larger surface area plates (within the limits of the plates tested here) seem to increase the amount of recorded seismic energy.

5) Plate weights between 1/7 and 1/4 the hammer weight seem to perform the best at meduim to compacted sites.

6) There seems to be no all-incompassing correlation between hammer weight and plate weight.

7) A heavy hammer delivering a lower velocity impact converts a higher percentage of kinetic energy to recordable seismic energy.

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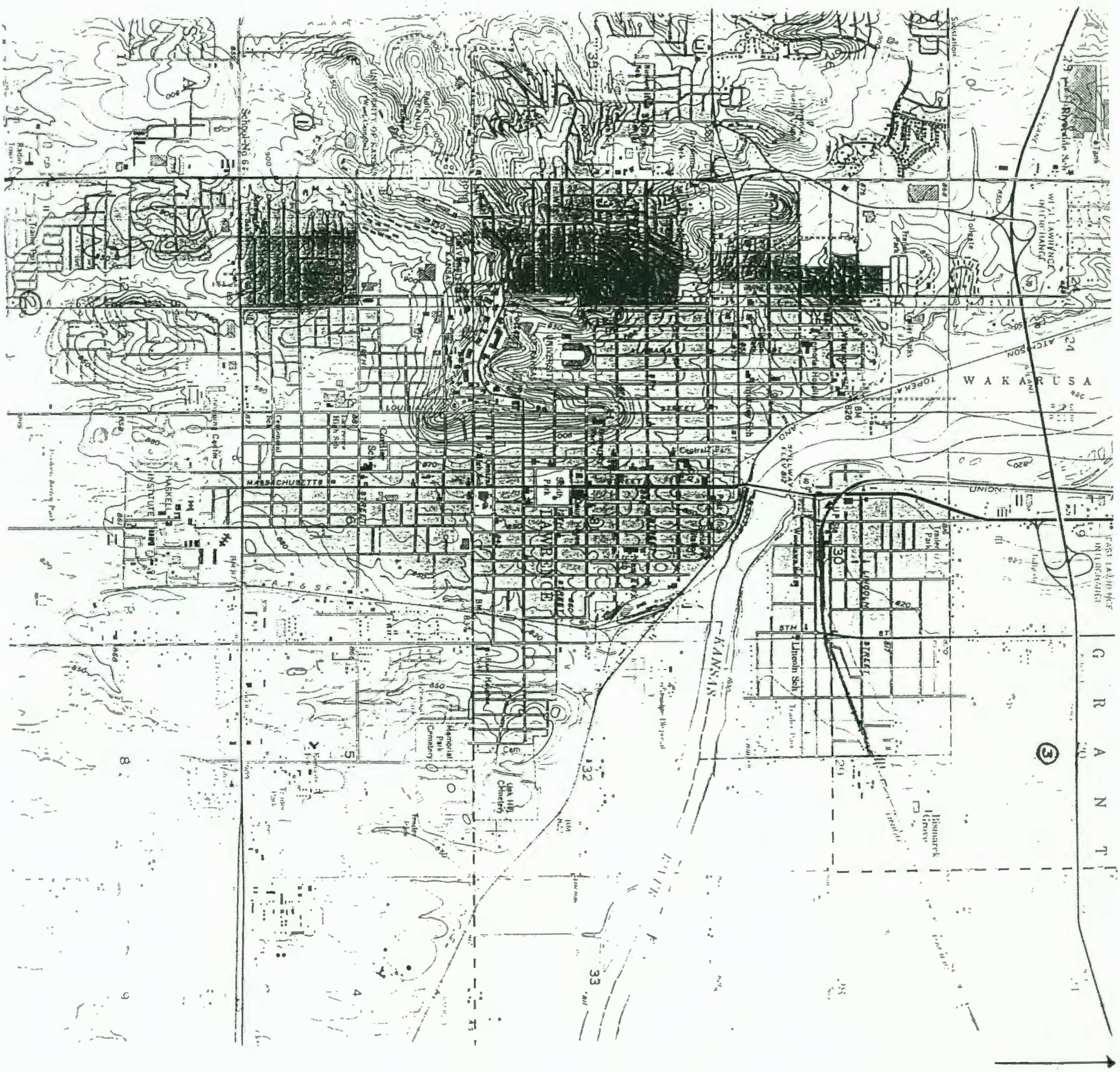
FIGURE CAPTIONS

FIG. 1. General map of Lawrence and surrounding areas indicating the location of the three test sites. Site 1 is the KU Campus, site 2 is the Snodgrass Ranch, and site 3 is the Sand Pits.

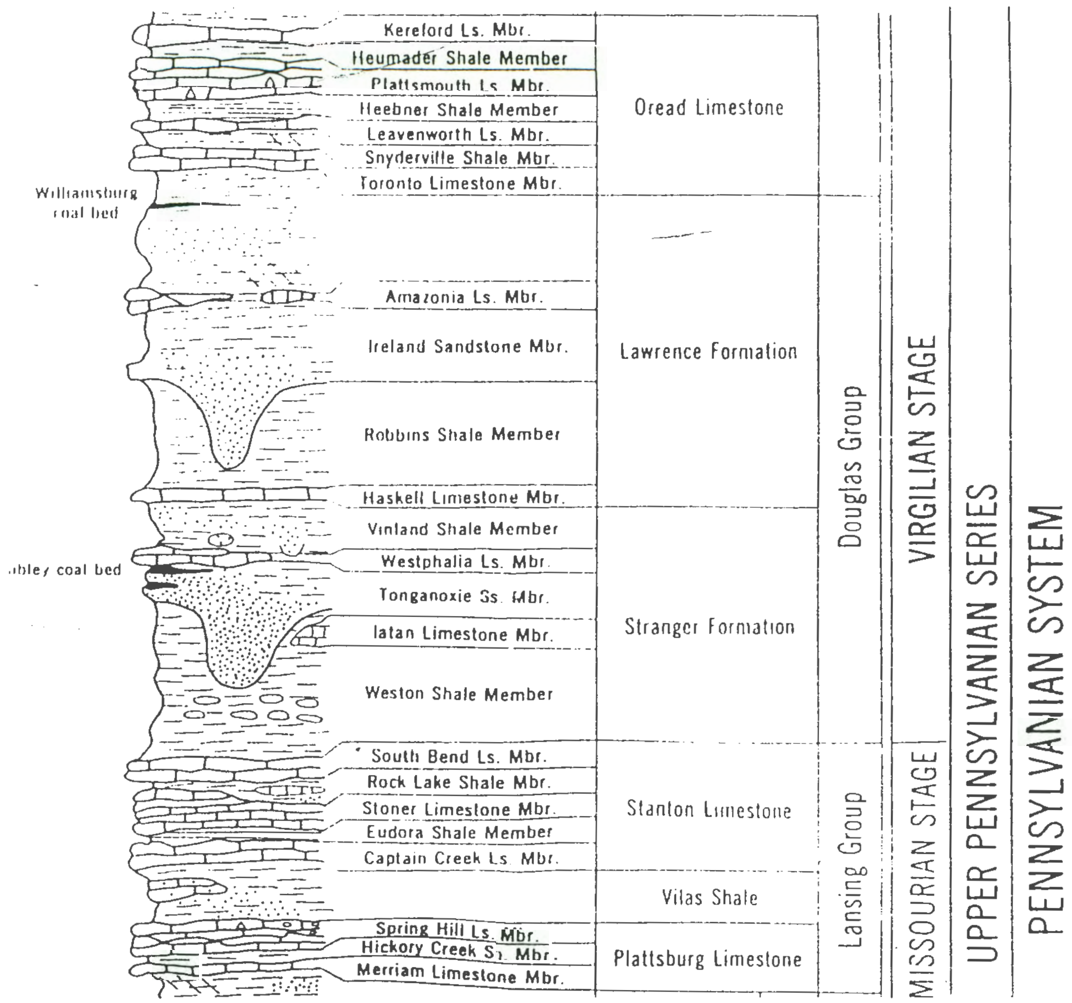
FIG. 2. Stratigraphic sequence for the study areas.

FIG. 3 Schematic diagram of the hitting machine designed to deliver a consistent, accurate impact with a sledgehammer.



WAKARUSA
MASSACHUSETTS
HASKELL INSTITUTE
LAWRENCE
KANSAS
UNION
TOPEKA
ATCHISON
Central Park
Lincoln Sch.
Memorial Park Cemetery
GRANT

FIGURE 1



Kereford Ls. Mbr.
Heumader Shale Member
Plattsmouth Ls. Mbr.
Heebner Shale Member
Leavenworth Ls. Mbr.
Snyderville Shale Mbr.
Toronto Limestone Mbr.
Oread Limestone
Williamsburg coal bed
Amazonia Ls. Mbr.
Ireland Sandstone Mbr.
Robbins Shale Member
Lawrence Formation
Haskell Limestone Mbr.
Vinland Shale Member
Westphalia Ls. Mbr.
Tonganoxie Ss. Mbr.
Iatan Limestone Mbr.
Weston Shale Member
Stranger Formation
South Bend Ls. Mbr.
Rock Lake Shale Mbr.
Stoner Limestone Mbr.
Eudora Shale Member
Captain Creek Ls. Mbr.
Stanton Limestone
Vilas Shale
Spring Hill Ls. Mbr.
Hickory Creek Sh. Mbr.
Merriam Limestone Mbr.
Plattsburg Limestone
Douglas Group
Lansing Group
VIRGILIAN STAGE
MISSOURIAN STAGE
UPPER PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM

FIGURE 2

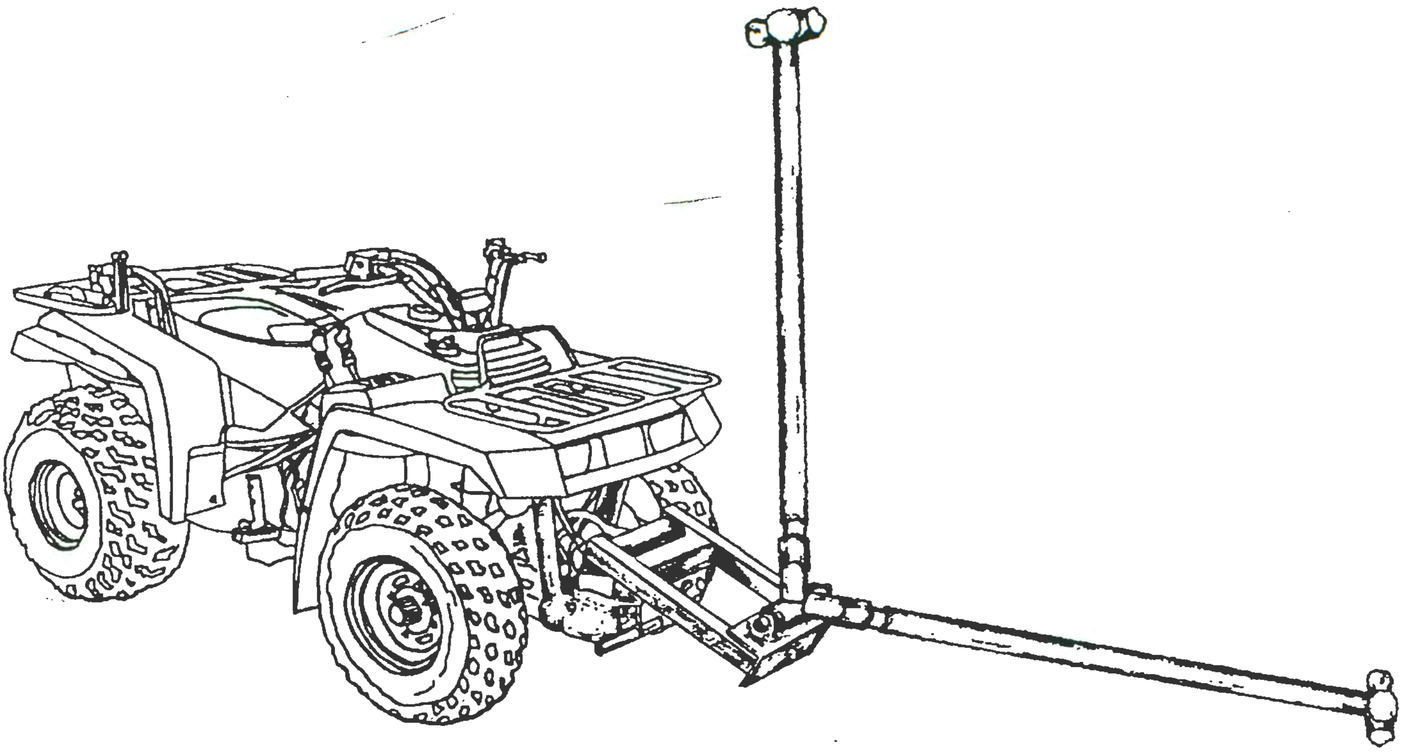


FIGURE 3

APPENDIX A

K. U. CAMPUS SITE

APPENDIX A FIGURE CAPTIONS

FIG. 1. Unprocessed field plots of K.U. campus site showing comparison of common surface area (0.05 m^2) plates for various hammer weights (3.6, 5.4, and 9.1 kg) and plate weights (2.7 and 10.9 kg), 1-meter hammer handle extension.

FIG. 2. Same as Figure 1 except for 3-meter extension.

FIG. 3. Same as Figure 1 except for surface area of plates (0.22 m^2).

FIG. 4. Same as Figure 1 except for surface area (0.22 m^2) and 3-meter hammer handle extension.

FIG. 5. Field files of various plate weights (1.36, 2.72, 5.44, 10.88, 21.77 kg) for common source energy (1-meter handle extension, 3.6 kg hammer) and plate surface area (0.11 m^2).

FIG. 6. Same as Figure 5 except for 5.4 kg hammer.

FIG. 7. Same as Figure 5 except for 9.1 kg hammer.

FIG. 8. Same as Figure 5 except for 3-meter handle extension.

FIG. 9. Same as Figure 5 except for 3-meter handle extension and 5.4 kg hammer.

FIG. 10. Same as Figure 5 except for 9.1 kg hammer and 3-meter handle extension.

FIG. 11. Comparison of raw field plots showing effect of plate surface area changes (0.05, 0.11, and 0.22 m^2) for 3-meter handle extension, 3.6 kg hammer, and various plate weights (2.72 kg and 10.88 kg).

FIG. 12. Same as Figure 11 except for 5.4 kg hammer weight.

FIG. 13. Same as Figure 11 except for 9.1 kg hammer weight.

FIG. 14. Same as Figure 11 except for 5.4 kg hammer weight and 1-meter handle extension.

FIG. 15. Same as Figure 11 except for 3.6 kg hammer weight and 1-meter extension.

FIG. 16. Same as Figure 11 except for 9.1 kg hammer weight and 1-meter extension.

FIG. 17. Comparison of raw field files, K.U. campus site, for constant plate surface area and weight (0.11 m^2, 1.36 kg), and various hammer weights (3.6, 5.4, and 9.1 kg) and handle extension (1 and 3 meters).

FIG. 18. Same as Figure 17 except for plate weight (2.72 kg).

FIG. 19. Same as Figure 17 except for plate weight (5.44 kg).

FIG. 20. Same as Figure 17 except for plate weight (10.88 kg).

FIG. 21. Same as Figure 17 except for plate weight (21.77 kg).

FIG. 22. Same as Figure 17 except hammer source directly strikes the ground; no plate used.

APPENDIX A

PART I

SOURCE CONSTANT

CHANGE PLATE WEIGHT

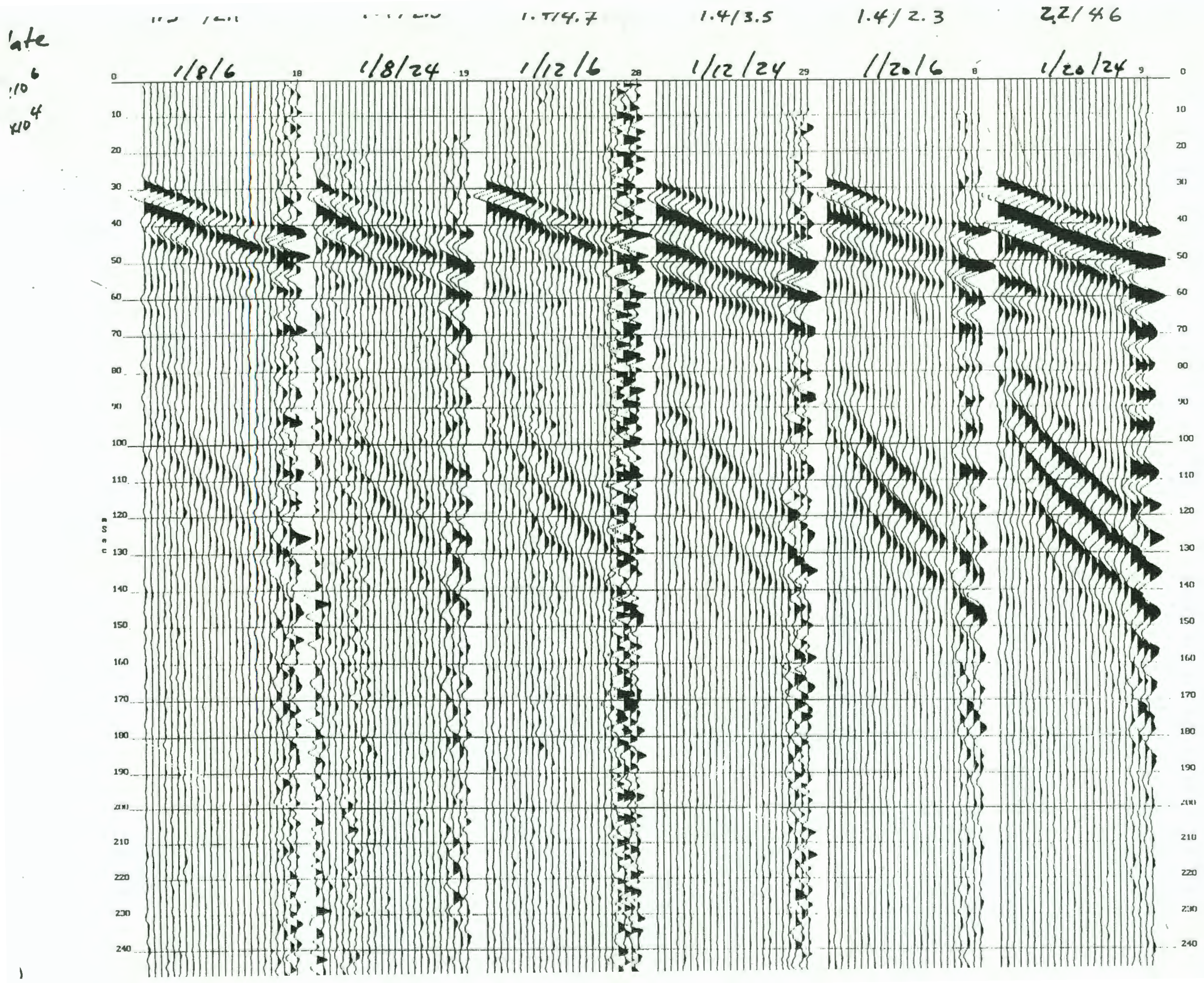
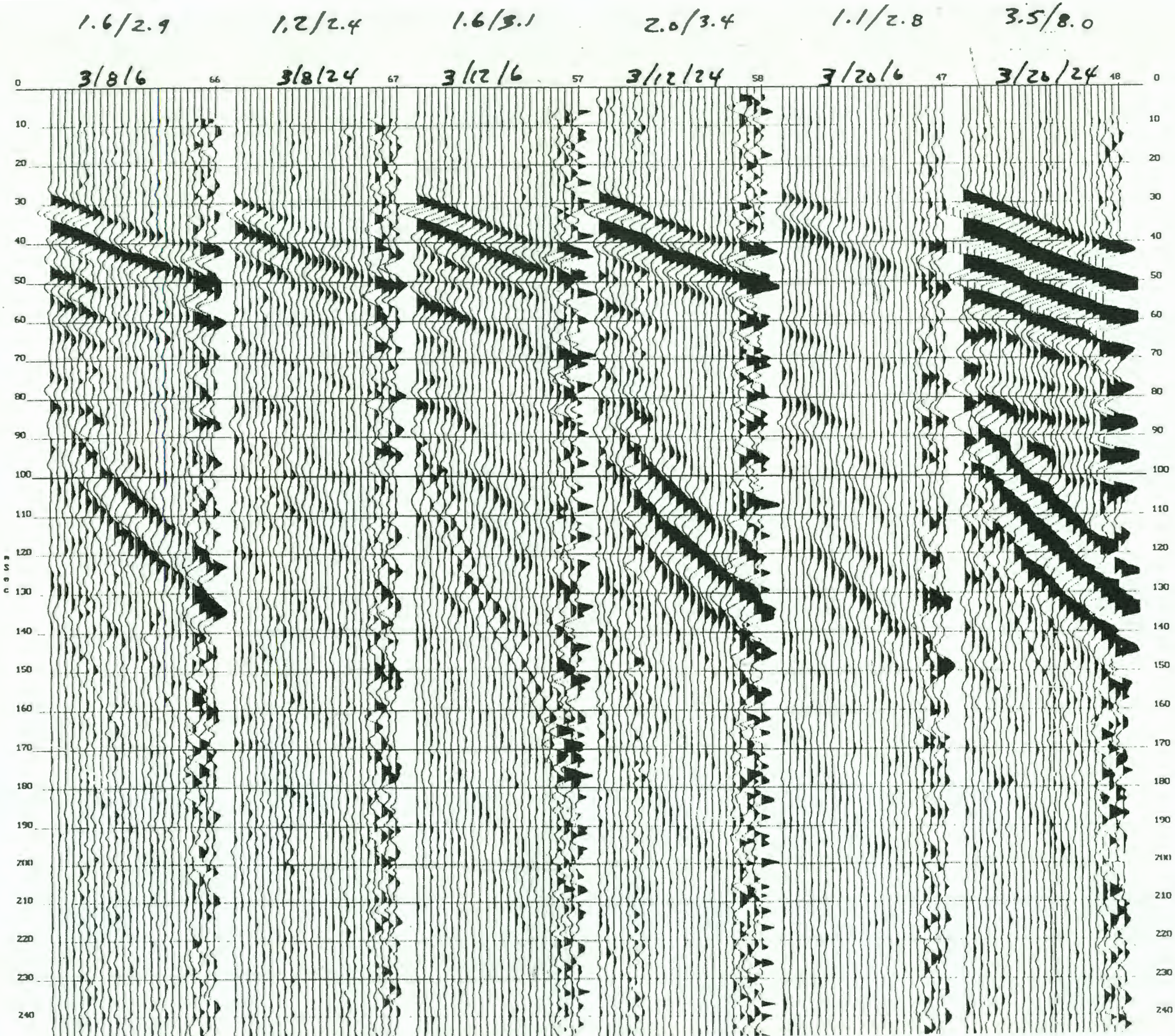

1.4/4.7
1.4/3.5
1.4/2.3
2.2/4.6
1/8/6
1/8/24
1/12/6
1/12/24
1/20/6
1/20/24

Plate)

x10^6
10^4

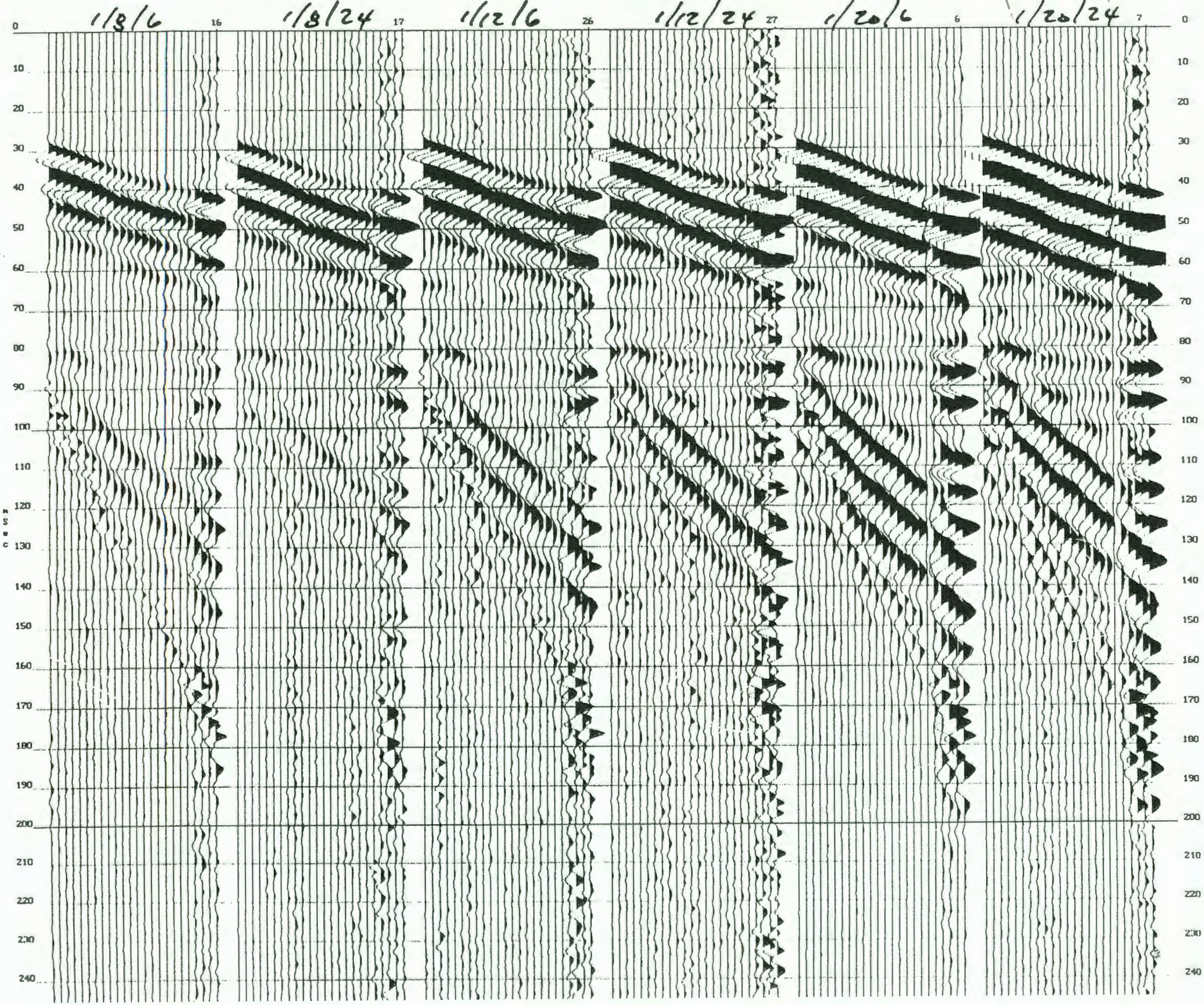


late

x10^6

x10^4

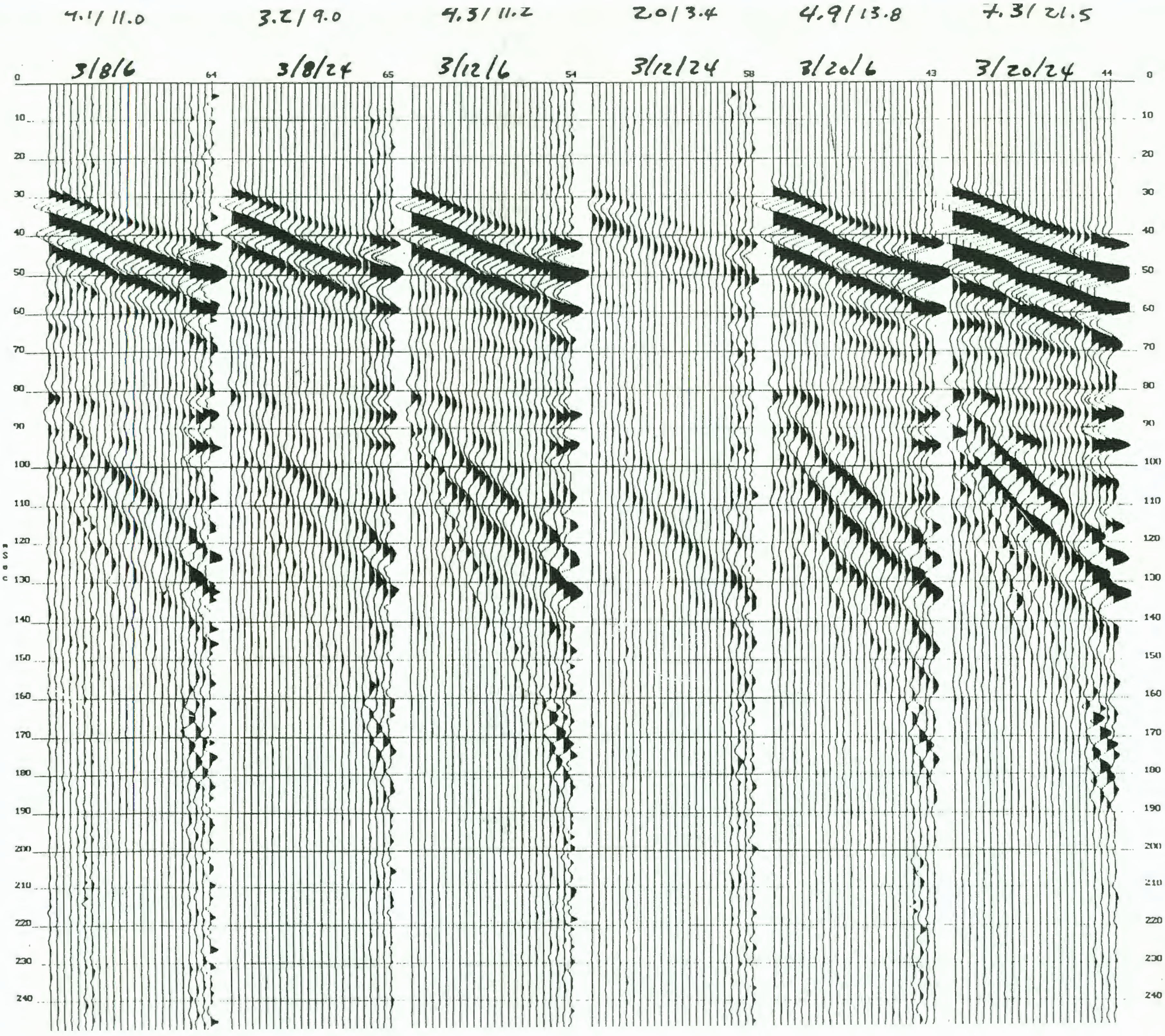
2.2/5.8 3.5/7.6 4.0/10.2 4.4/11.5

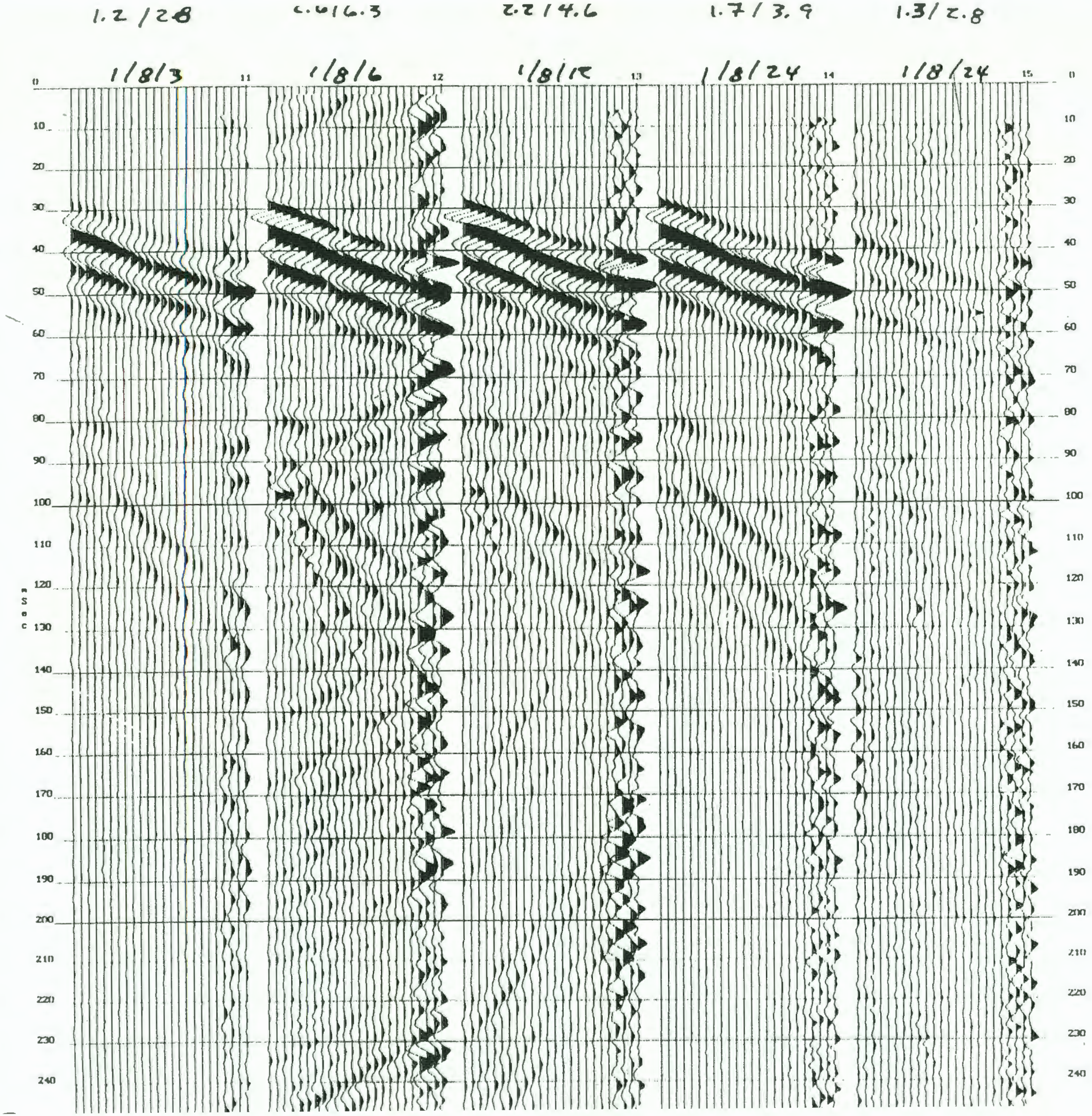


" plate)

$x10^6$

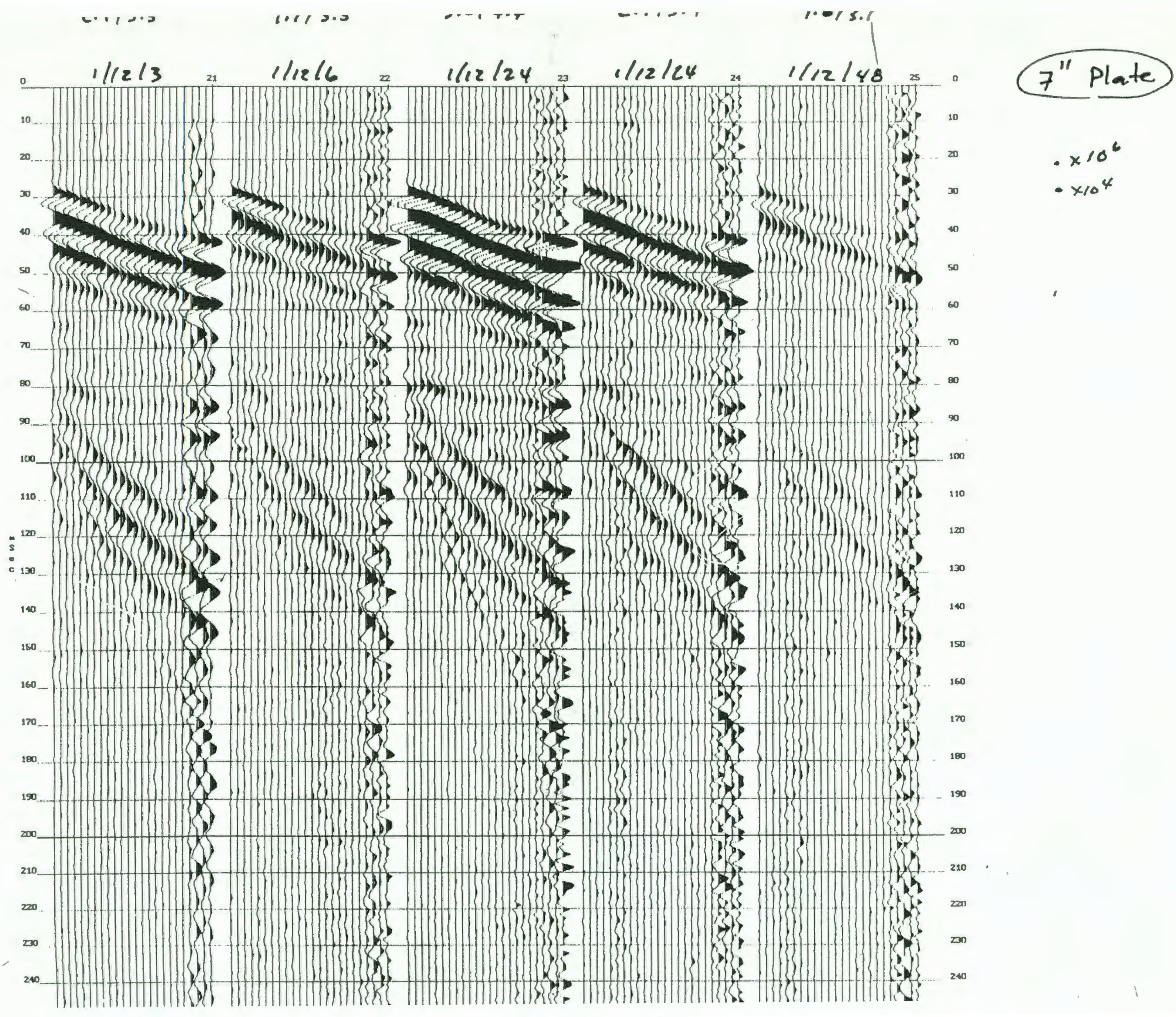
$x10^4$ -

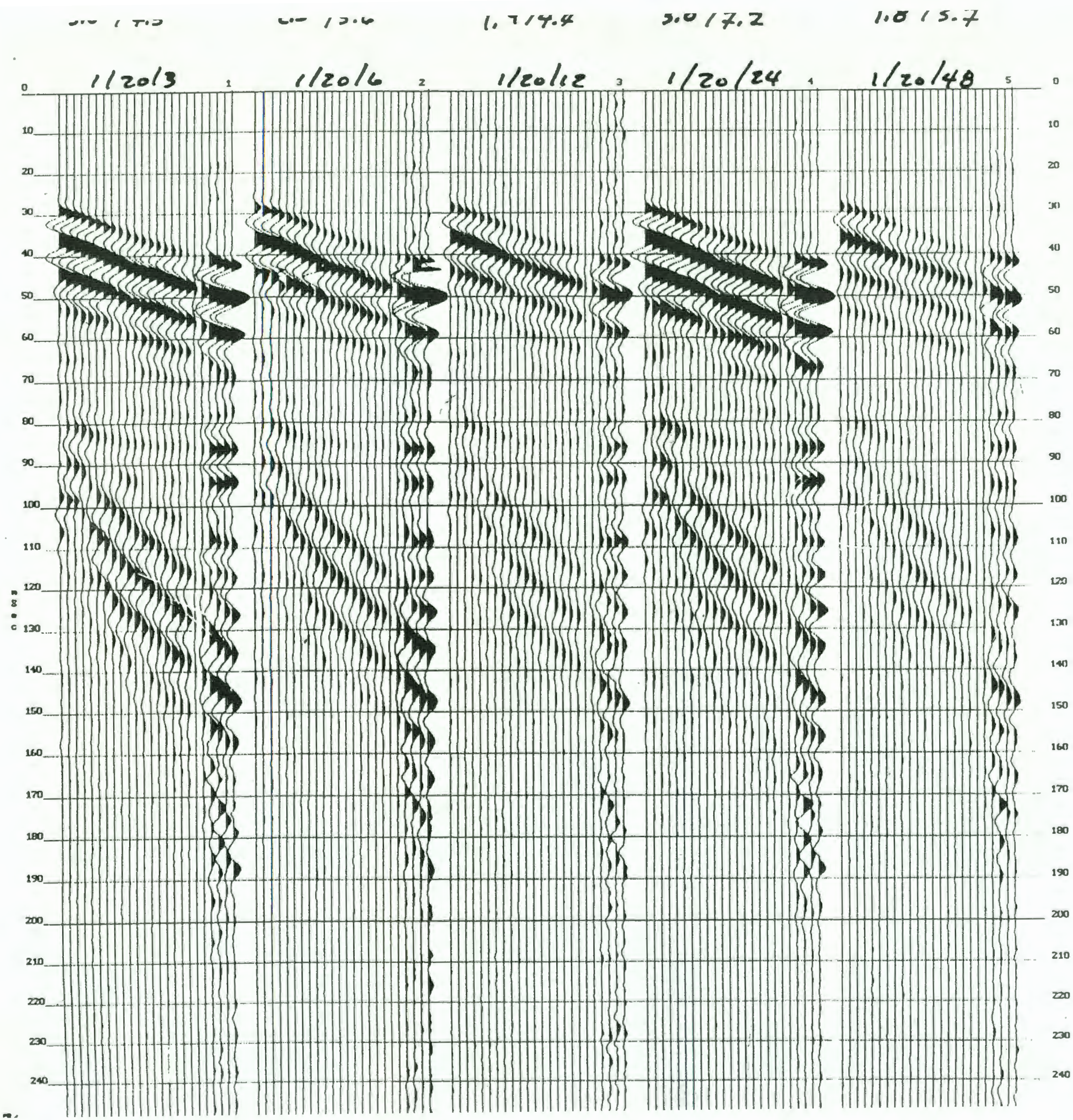




7" plate

• ×10⁶
• ×10⁴

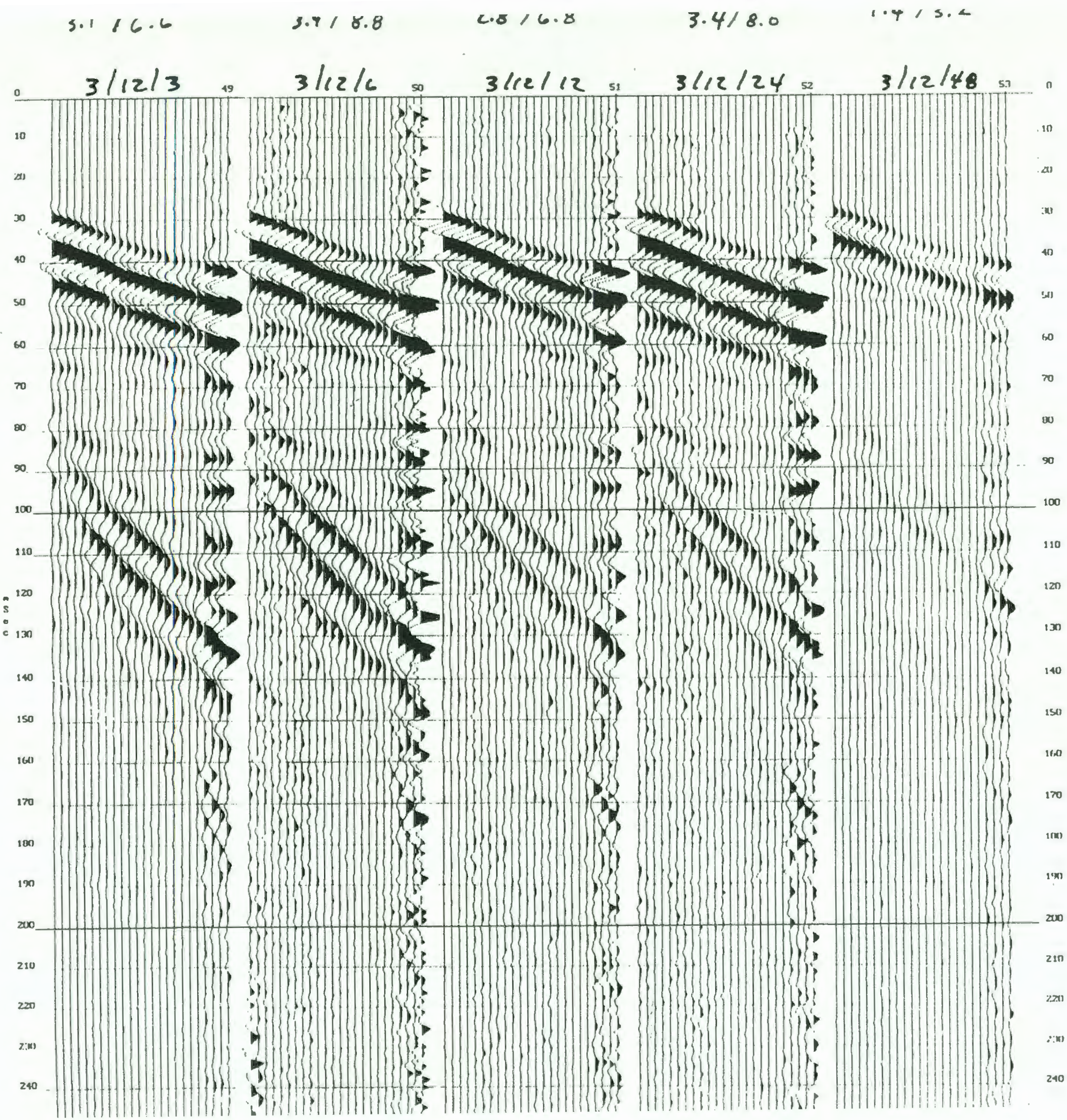

1/12/3
1/12/6
1/12/24
1/12/24
1/12/48
21
22
23
24
25
msec
7" Plate
• x10^6
• x10^4



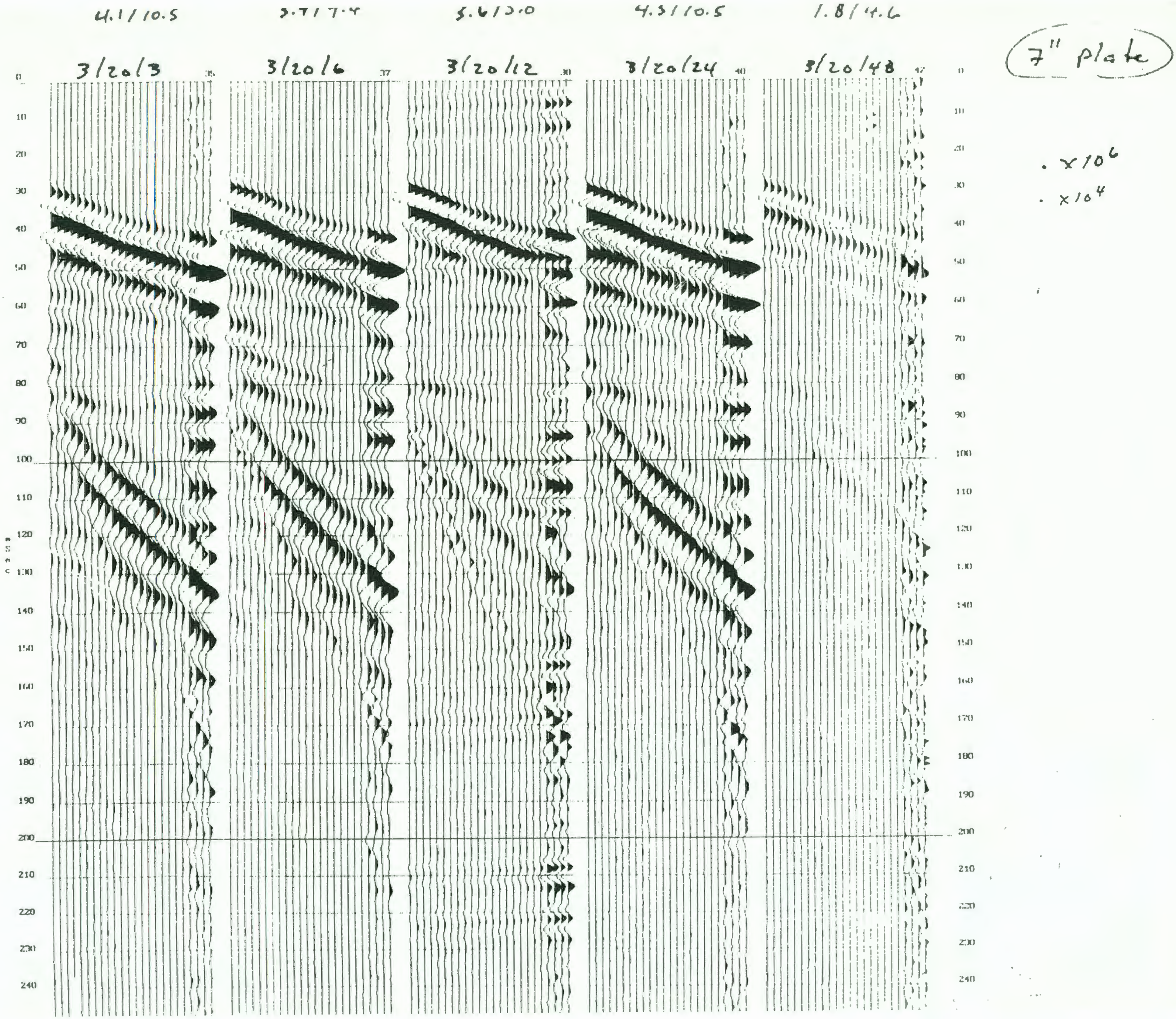
7" plate

· x10^6
· x10^4

7" plate



· x10^4
· x10^5



4.1/10.5
4.3/10.5
1.8/4.6
3/20/3
3/20/6
3/20/12
3/20/24
3/20/48
7" plate
x10^6
x10^4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

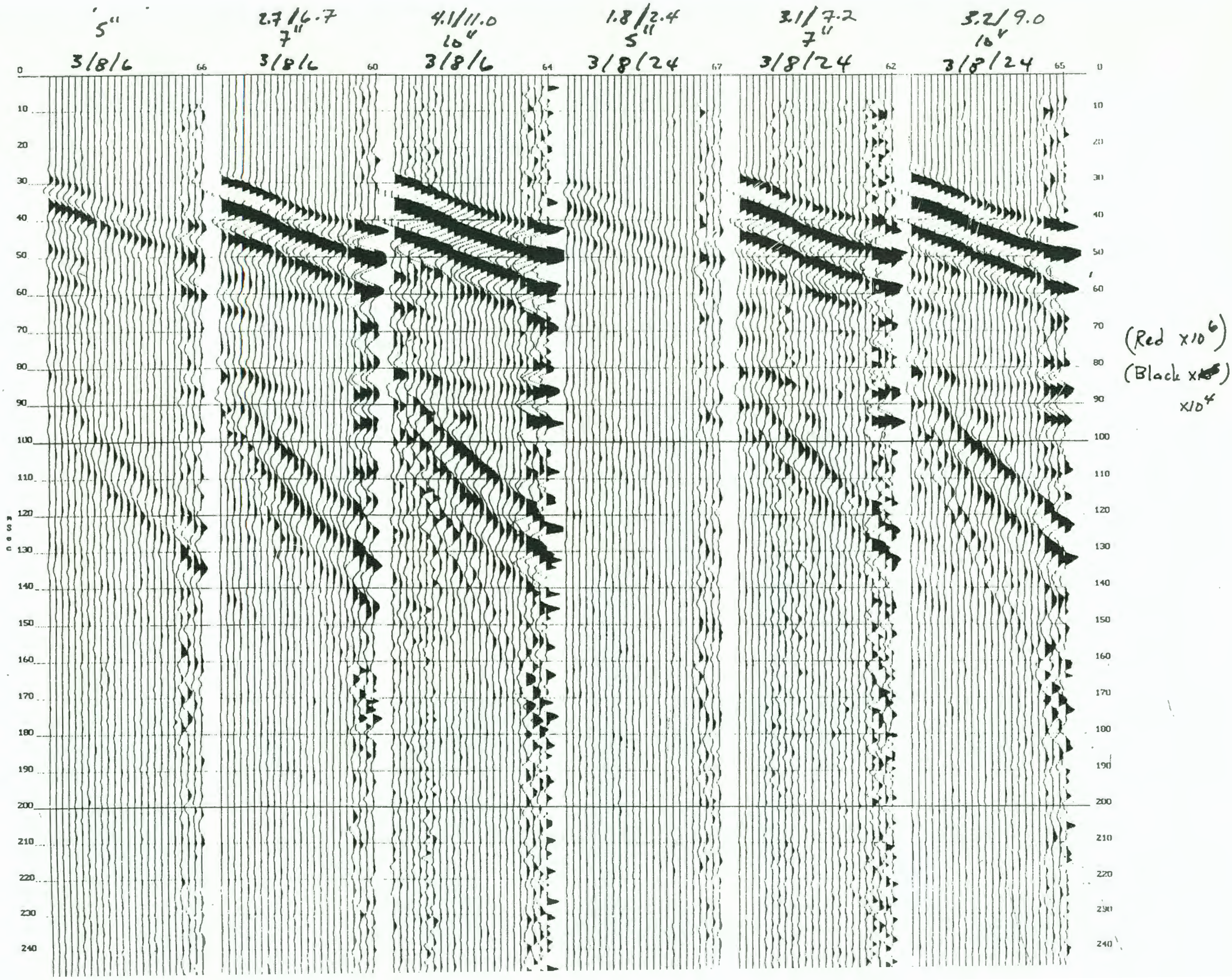
APPENDIX A

PART II

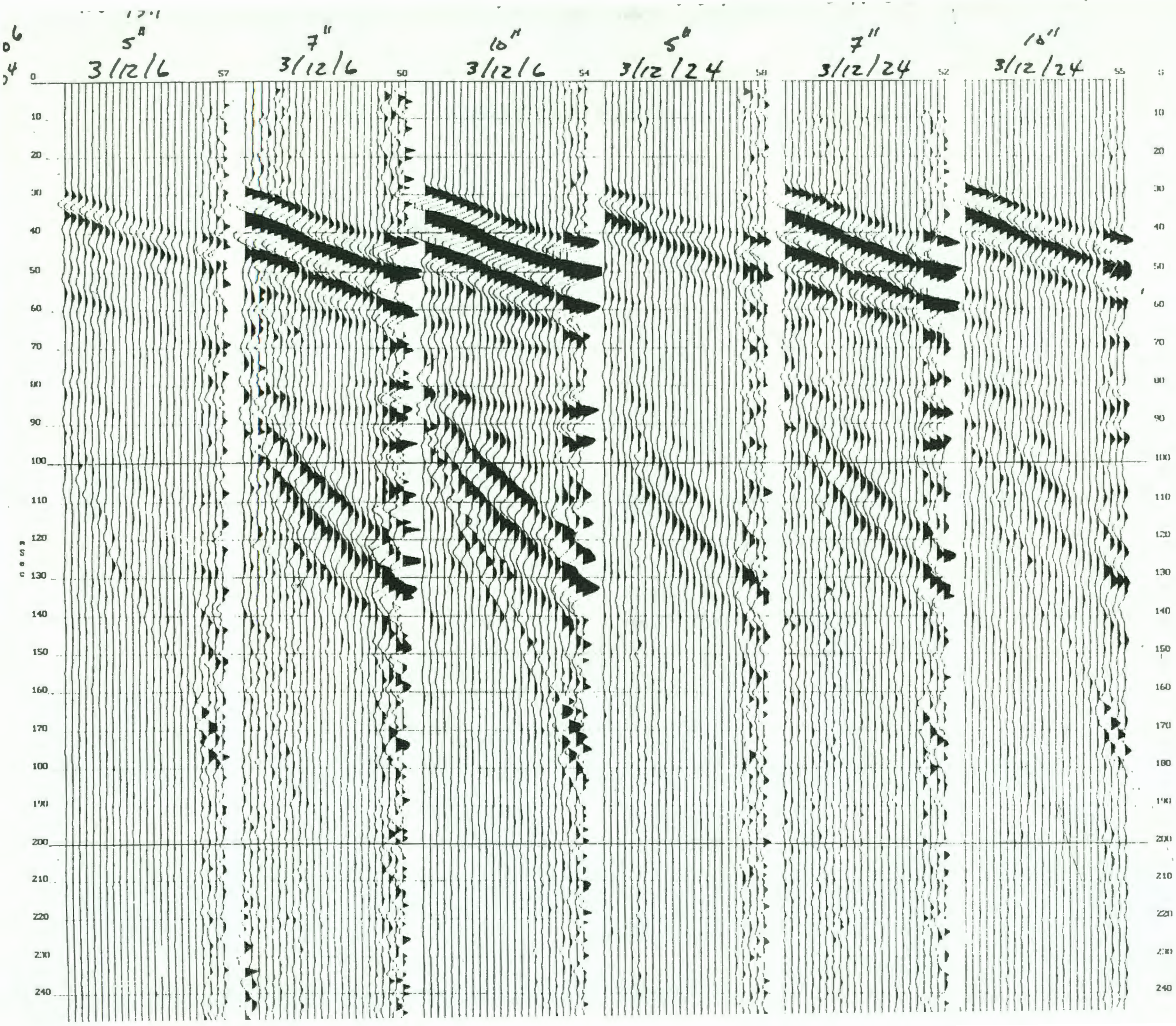
SOURCE CONSTANT

PLATE WEIGHT CONSTANT

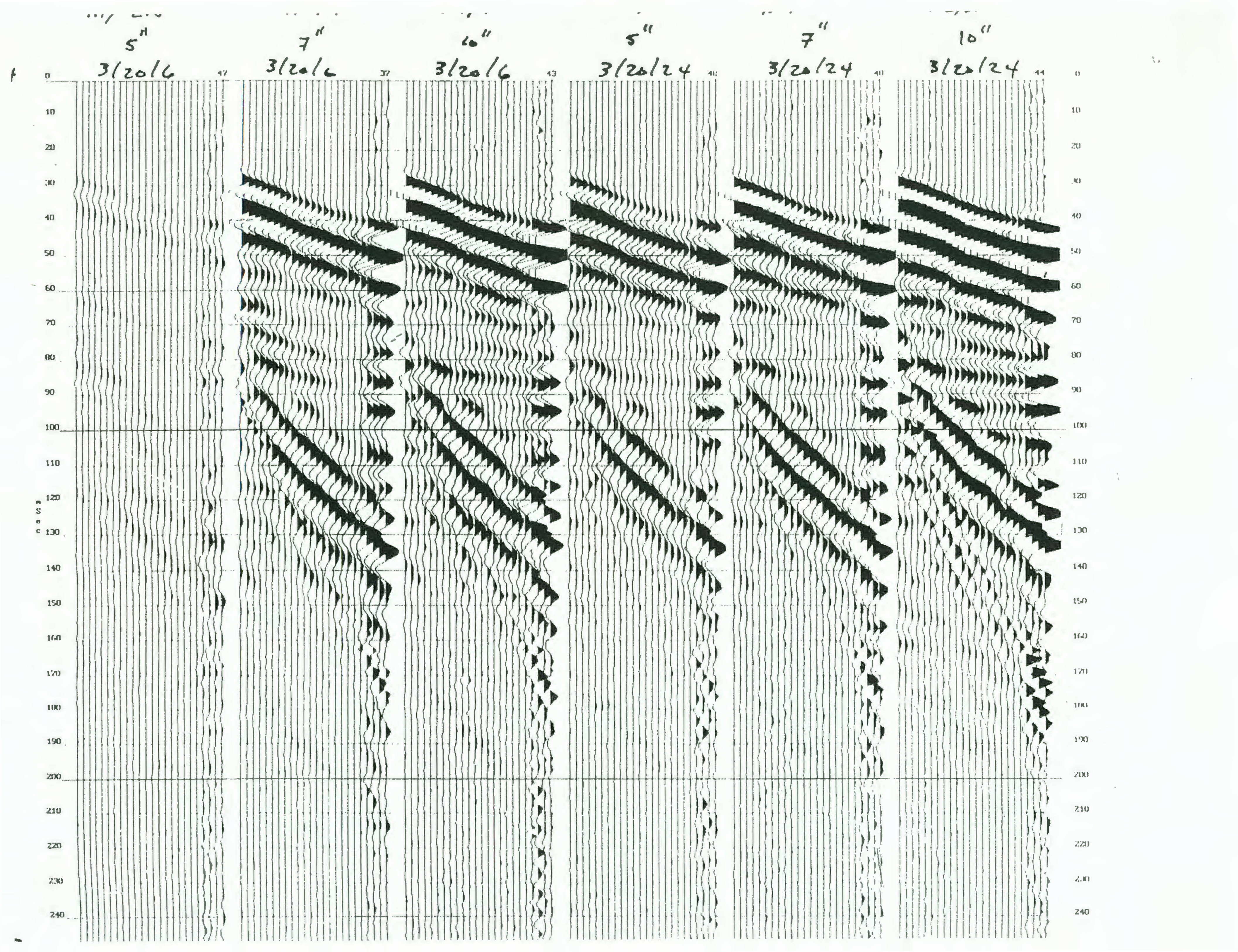
VARY PLATE SURFACE AREA



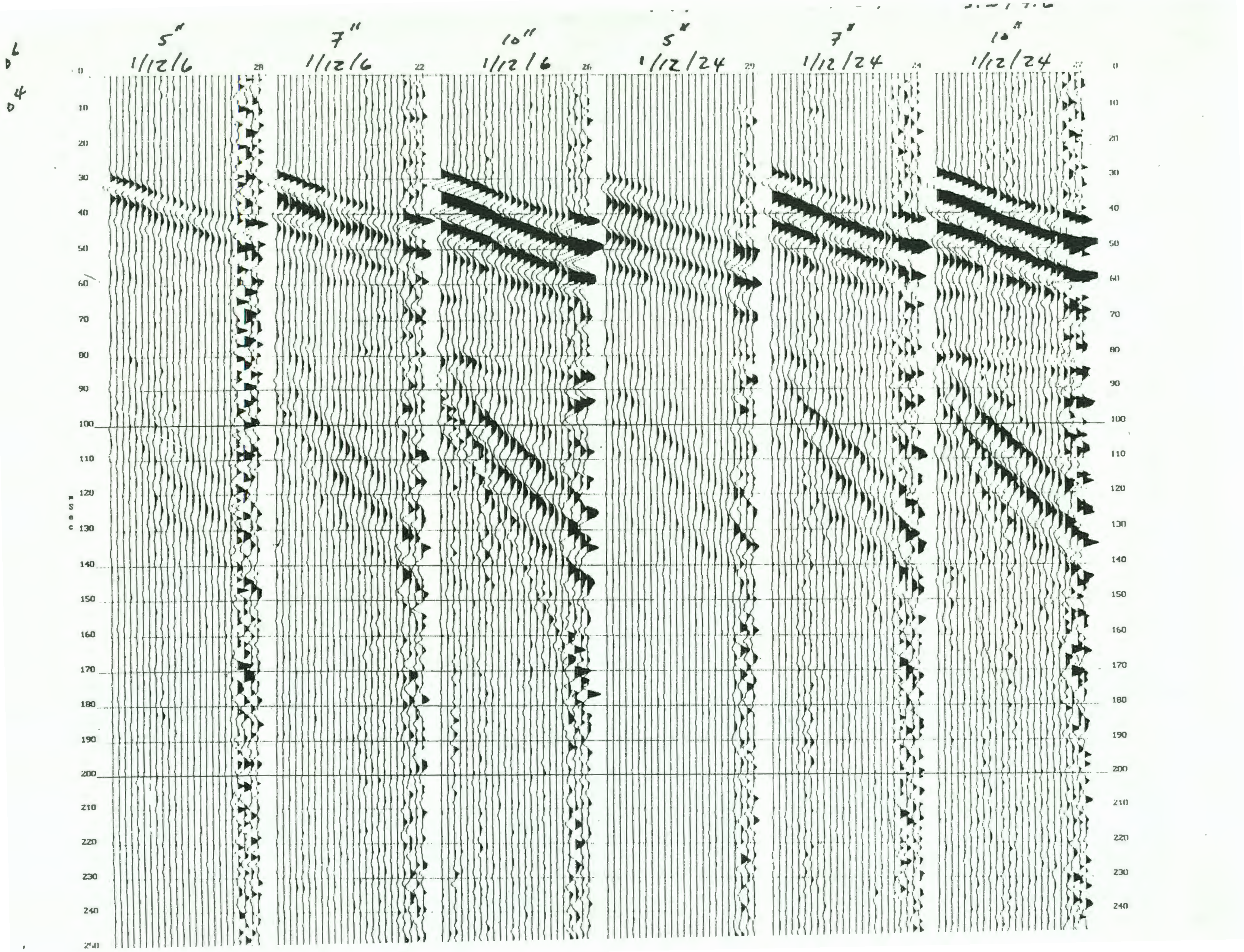
5"
3/8/6
2.7/6.7
7"
3/8/6
4.1/11.0
10"
3/8/6
1.8/2.4
5"
3/8/24
3.1/7.2
7"
3/8/24
3.2/9.0
10"
3/8/24
(Red x10^6)
(Black x10^4)
msec



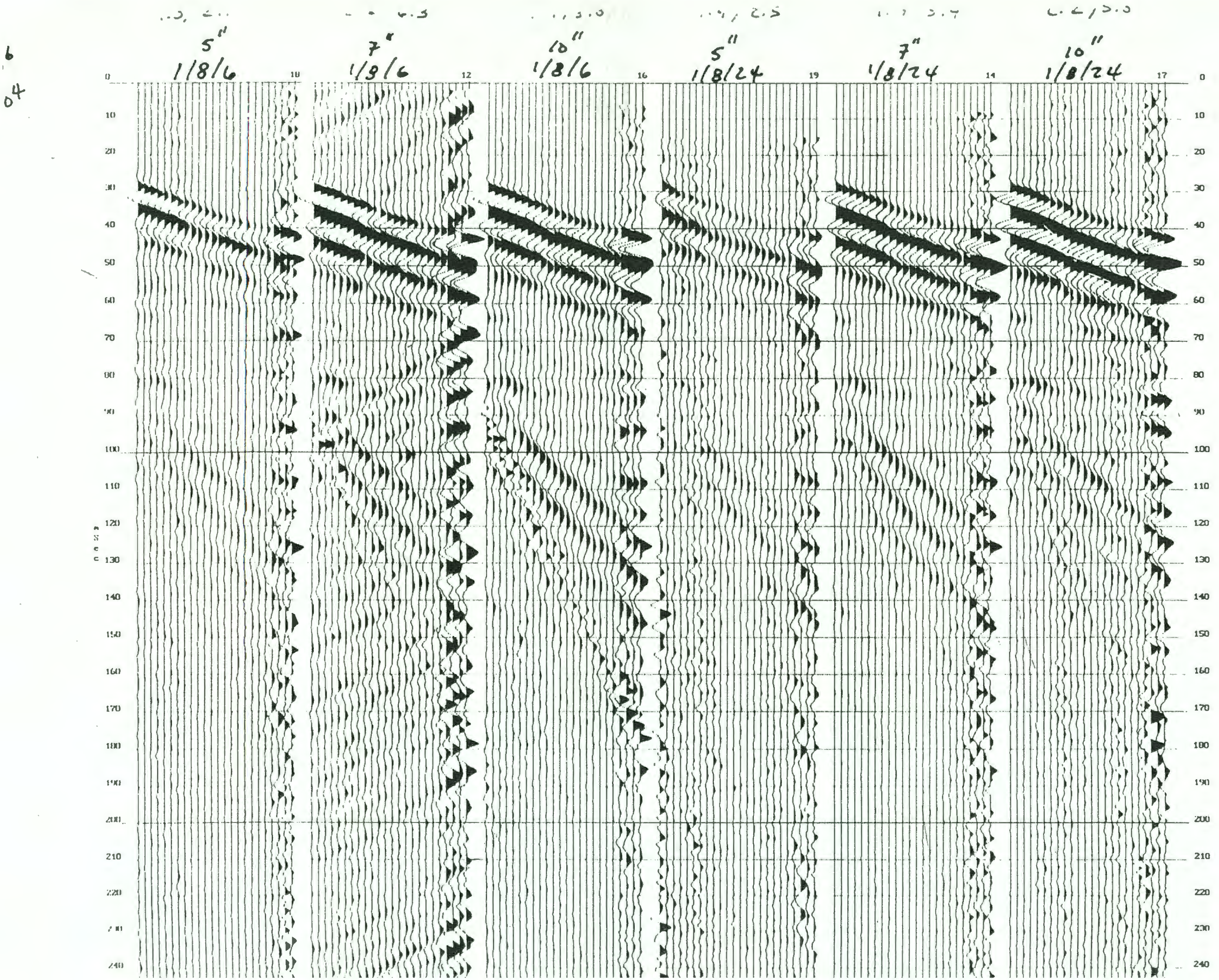
5" 3/12/6
7" 3/12/6
10" 3/12/6
5" 3/12/24
7" 3/12/24
10" 3/12/24
0
57
50
54
58
52
55
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240



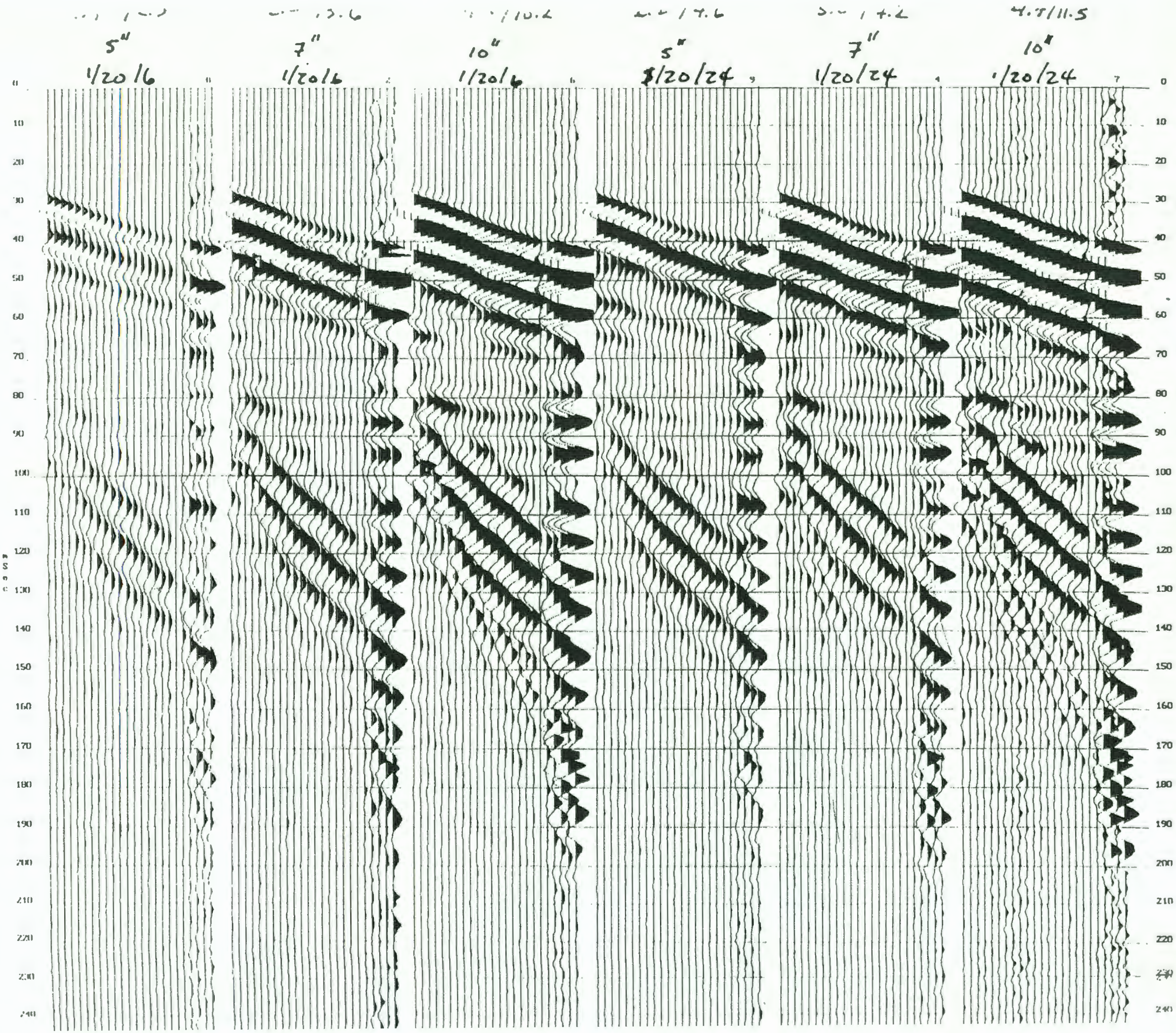
5"
7"
10"
5"
7"
10"
3/20/6
3/20/6
3/20/6
3/20/24
3/20/24
3/20/24
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240



5"
1/12/6
7"
1/12/6
10"
1/12/6
5"
1/12/24
7"
1/12/24
10"
1/12/24


6
04
5"
1/8/6
7"
1/9/6
10"
1/8/6
5"
1/8/24
7"
1/8/24
10"
1/8/24
0
10
12
16
19
14
17
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

10^6
10^4



5"
1/20/6
7"
1/20/6
10"
1/20/6
5"
1/20/24
7"
1/20/24
10"
1/20/24
4.7/11.5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

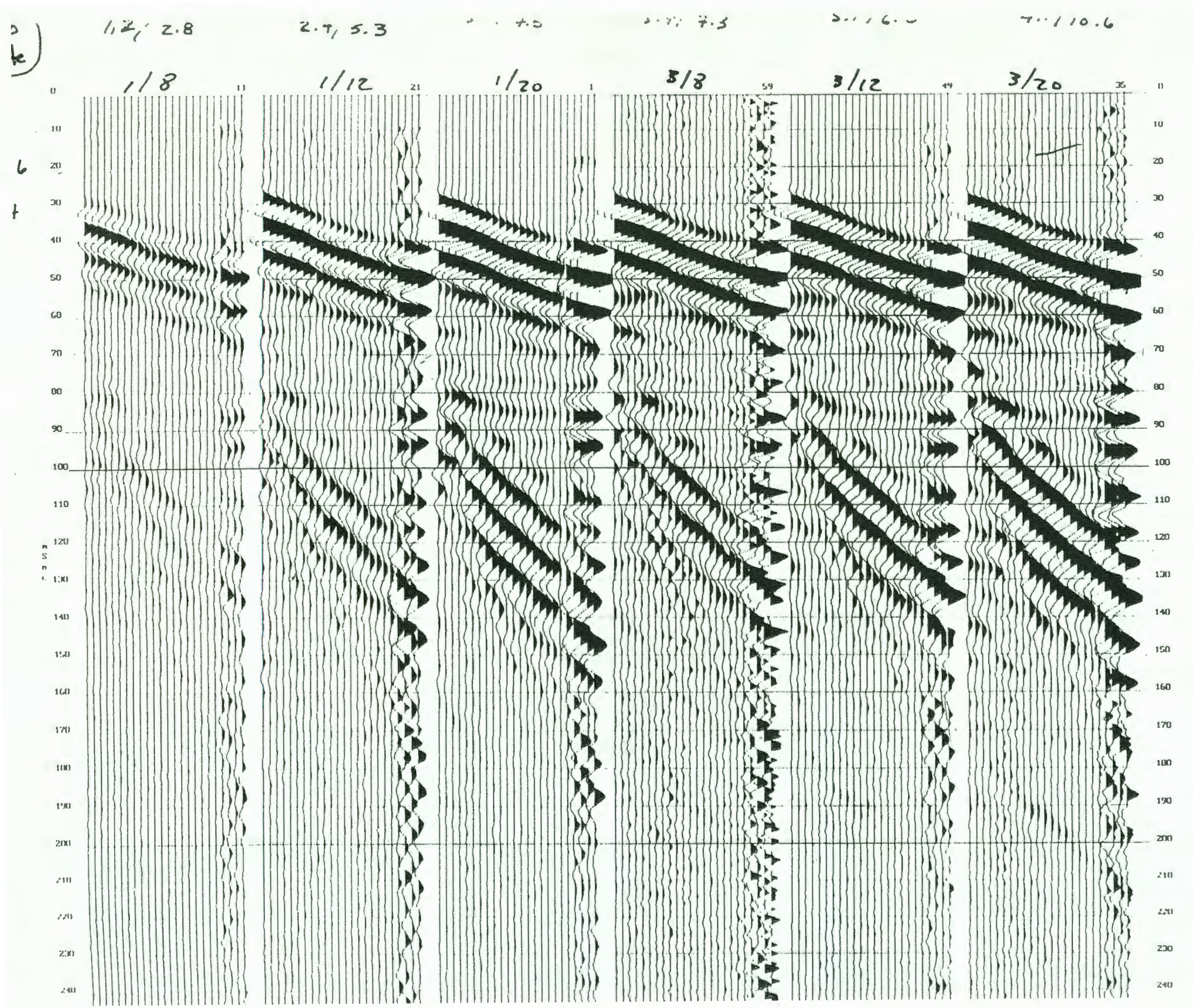
APPENDIX A

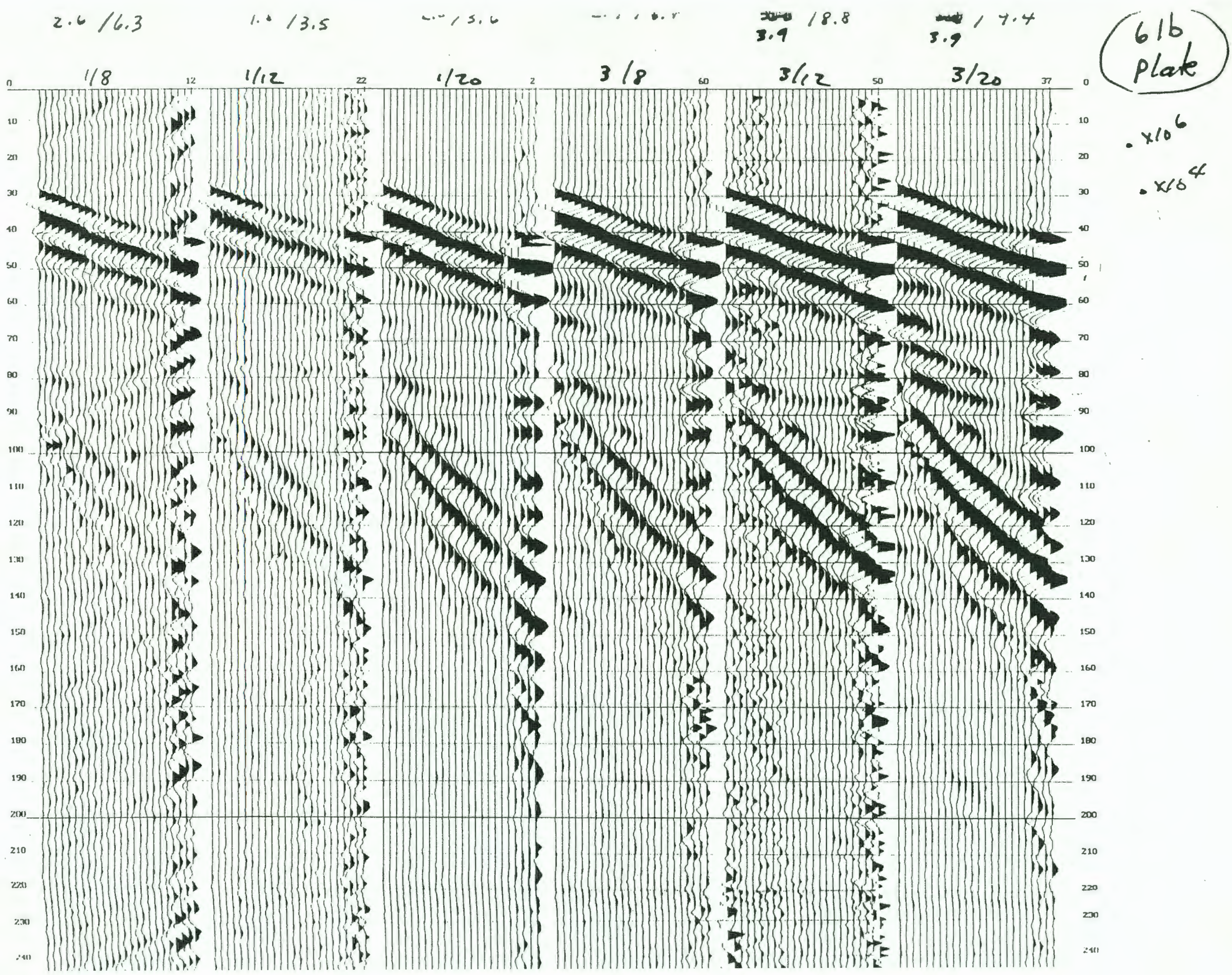
PART III

PLATE CONSTANT

(Both S.A. & weight)

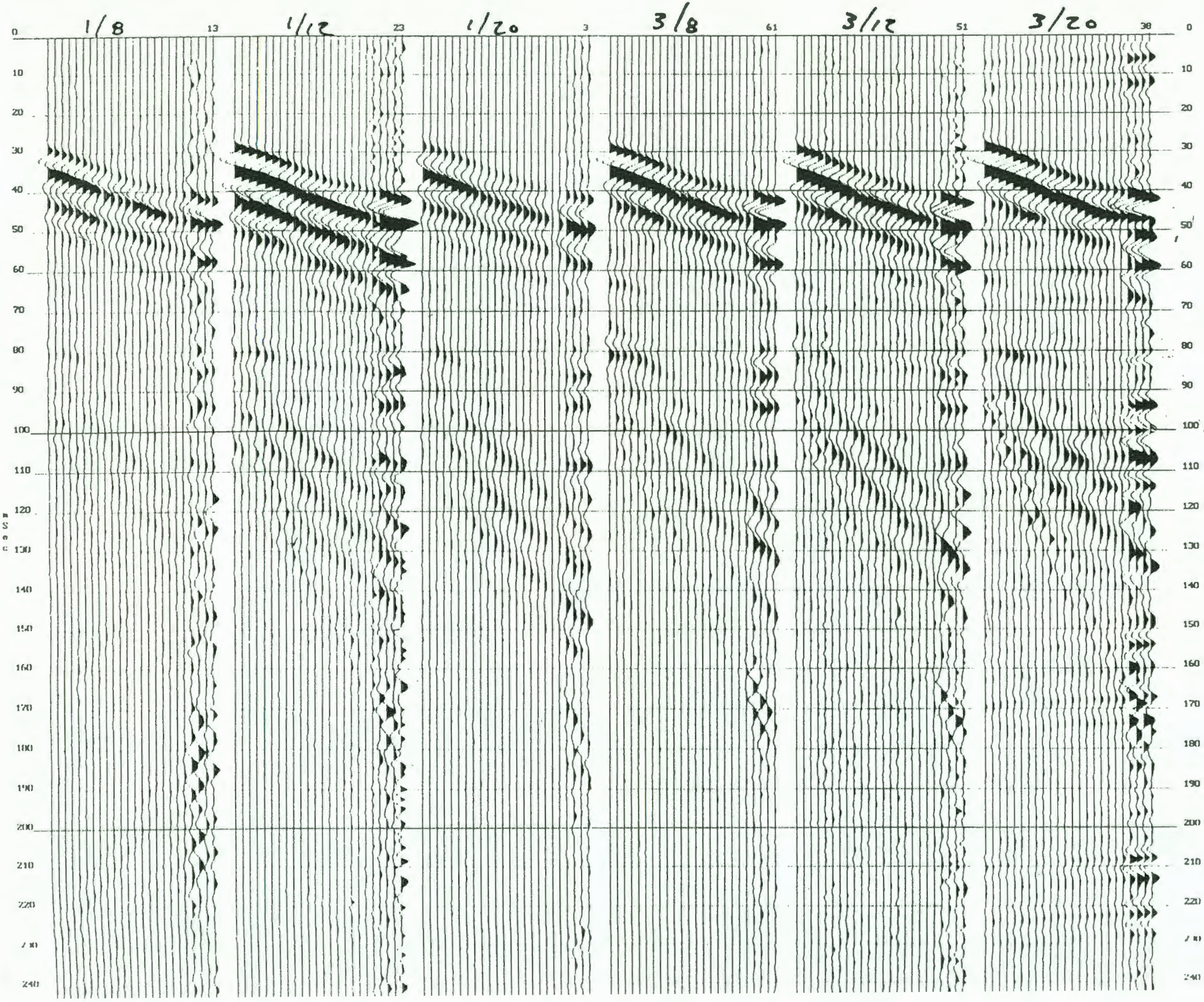
VARY SOURCE ENERGY


1.2, 2.8
2.4, 5.3
1/8
1/12
1/20
3/8
3/12
3/20
11
21
1
59
49
35
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

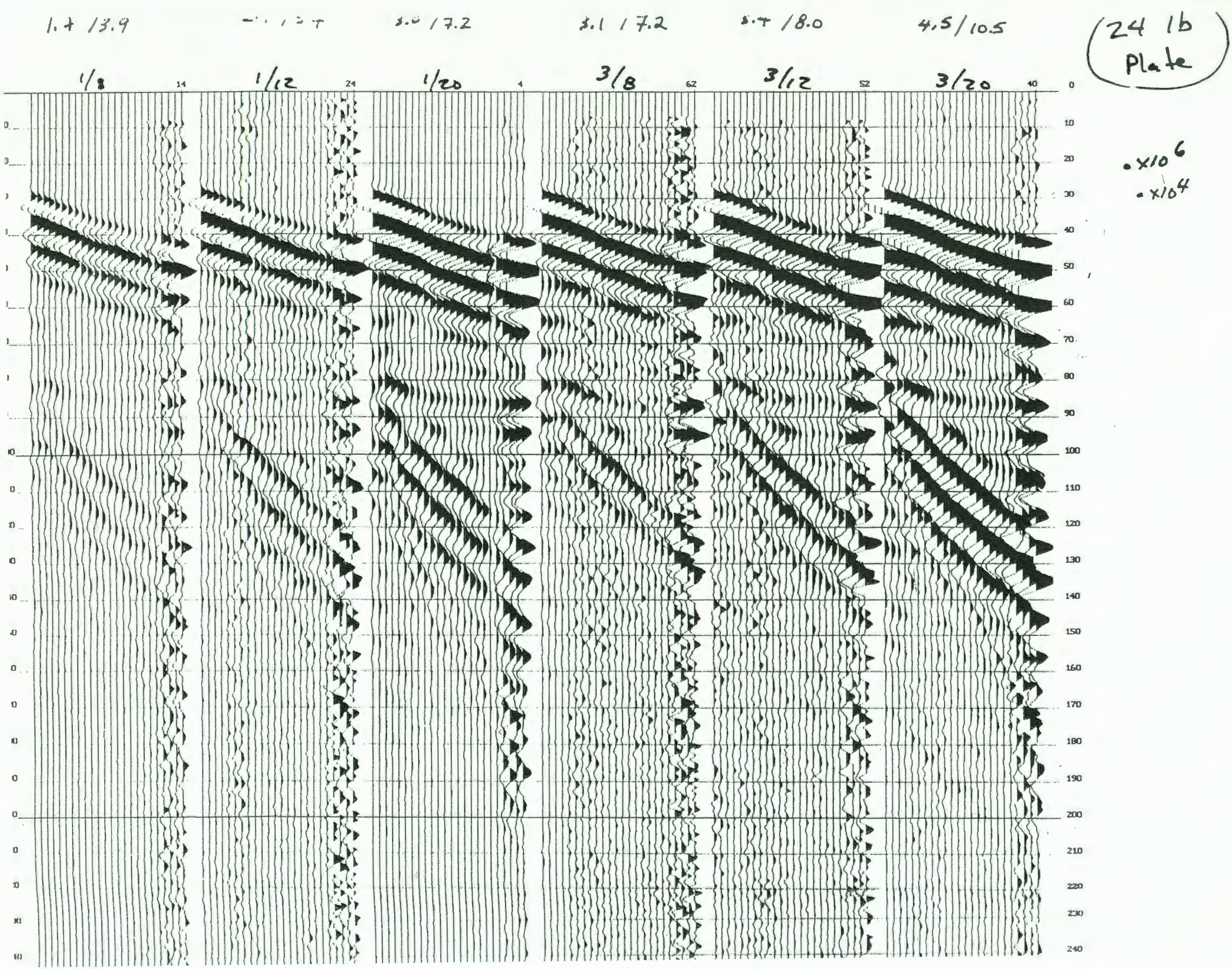


2.6 /6.3
/13.5
/18.8
3.9
3.9
61b
plate
1/8
1/12
1/20
3/8
3/12
3/20
0
12
22
2
60
50
37
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

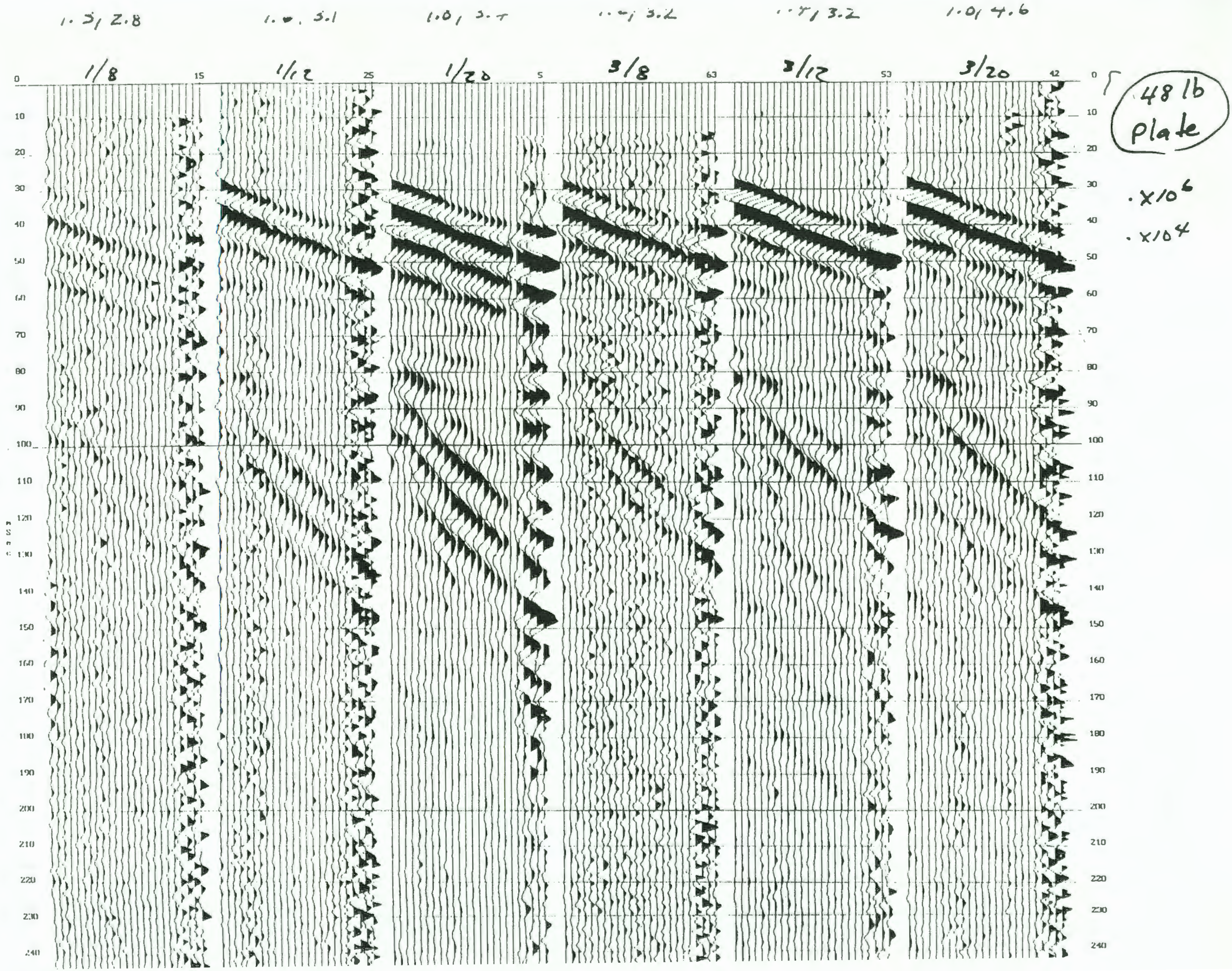
12 1b
Plate

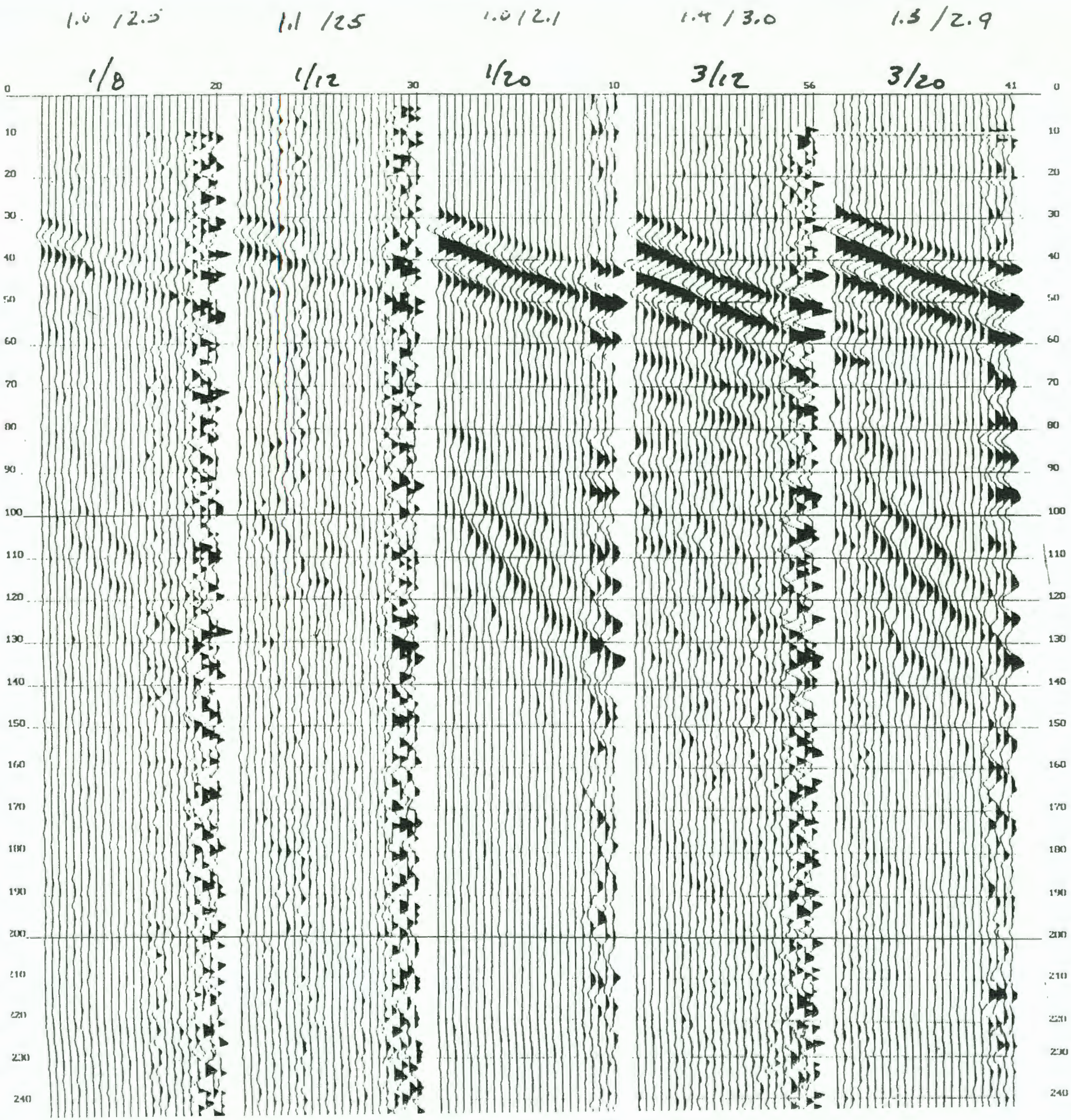


. x10^6
. x10^4



4.5/10.5
24 lb Plate
1/8
1/12
1/20
3/8
3/12
3/20
14
24
4
62
52
40
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
x10^6
x10^4


1.5, 2.8
1/8
1/12
1/20
3/8
3/12
3/20
48 lb plate
.x10^6
.x10^4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240



No plate

$\cdot \times 10^6$

$\cdot \times 10^4$

(For Comparison
Noise survey (ff 46)
1.0/2.1)

3/8 No plate → Not recorded.

APPENDIX B

SNODGRASS RANCH SITE

APPENDIX B FIGURE CAPTIONS

FIG. 23. Field plots of constant handle extension (1 meter) and plate surface area ($0.05\ m^2$). Various plate weights (2.72 and 10.88 kg) and hammer weights (3.6, 5.4, and 9.1 kg) are shown. SNODGRASS RANCH SITE.

FIG. 24. Same as Figure 23 except for 3-meter handle extension. 'M' indicates a manual swing.

FIG. 25. Same as Figure 23 except for surface area of plate ($0.11\ m^2$).

FIG. 26. Same as Figure 23 except for 3-meter handle extension. 'M' indicates a manual swing.

FIG. 27. Field plots of common source energy (manual swing 5.4 kg hammer) showing comparison of plate weight (1.36, 2.72, 5.44, 10.88, 21.77 kg) for constant plate surface area ($0.11\ m^2$).

FIG. 28. Same as Figure 27 except for 1-meter handle extension, 3.6 kg hammer.

FIG. 29. Same as Figure 27 except for 1-meter extension, 5.4 kg hammer.

FIG. 30. Same as Figure 27 except for 1-meter extension, 9.1 kg hammer.

FIG. 31. Same as Figure 27 except for 3-meter extension, 3.6 kg hammer.

FIG. 32. Same as Figure 27 except for 3-meter extension, 5.4 kg hammer.

FIG. 33. Same as Figure 27 except for 3-meter extension, 9.1 kg hammer.

FIG. 34. Constant source energy (3-meter extension, 3.6 kg hammer) and plate weight (2.72 kg) for various surface areas (0.05, 0.11, $0.22\ m^2$). SNODGRASS RANCH SITE.

FIG. 35. Same as Figure 34 except for 5.4 kg hammer weight.

FIG. 36. Same as Figure 34 except for 9.1 kg hammer weight.

FIG. 37. Same as Figure 34 except for 1-meter handle extension.

FIG. 38. Same as Figure 34 except for 1-meter handle extension and 5.4 kg hammer weight.

FIG. 39. Same as Figure 34 except for 1-meter extension and 9.1 kg hammer.

FIG. 40. Same as Figure 34 except for manual swing.

FIG. 41. Seismogram comparison of constant source energy (3-meter extension, 3.6 kg hammer) and plate weight (10.88 kg) for various surface areas (0.05, 0.11, 0.22 m^2). SNODGRASS RANCH SITE.

FIG. 42. Same as Figure 41 except for 5.4 kg hammer weight.

FIG. 43. Same as Figure 41 except for 9.1 kg hammer weight.

FIG. 44. Same as Figure 41 except for 1-meter extension.

FIG. 45. Same as Figure 41 except for 1-meter extension and 5.4 kg hammer weight.

FIG. 46. Same as Figure 41 except for 1-meter extension and 9.1 kg hammer weight.

FIG. 47 Same as Figure 41 except for manual swing.

FIG. 48. Seismogram comparison of constant plate weight (1.36 kg) and surface area (0.11 m^2) for various hammer weights (3.6, 5.4, and 9.1 kg) and handle extension (1 and 3 meters). SNODGRASS RANCH SITE.

FIG. 49. Same as Figure 48 except for (2.72 kg) plate weight.

FIG. 50. Same as Figure 48 except for (5.44 kg) plate weight.

FIG. 51. Same as Figure 48 except for (10.88 kg) plate weight.

FIG. 52. Same as Figure 48 except for (21.77 kg) plate weight.

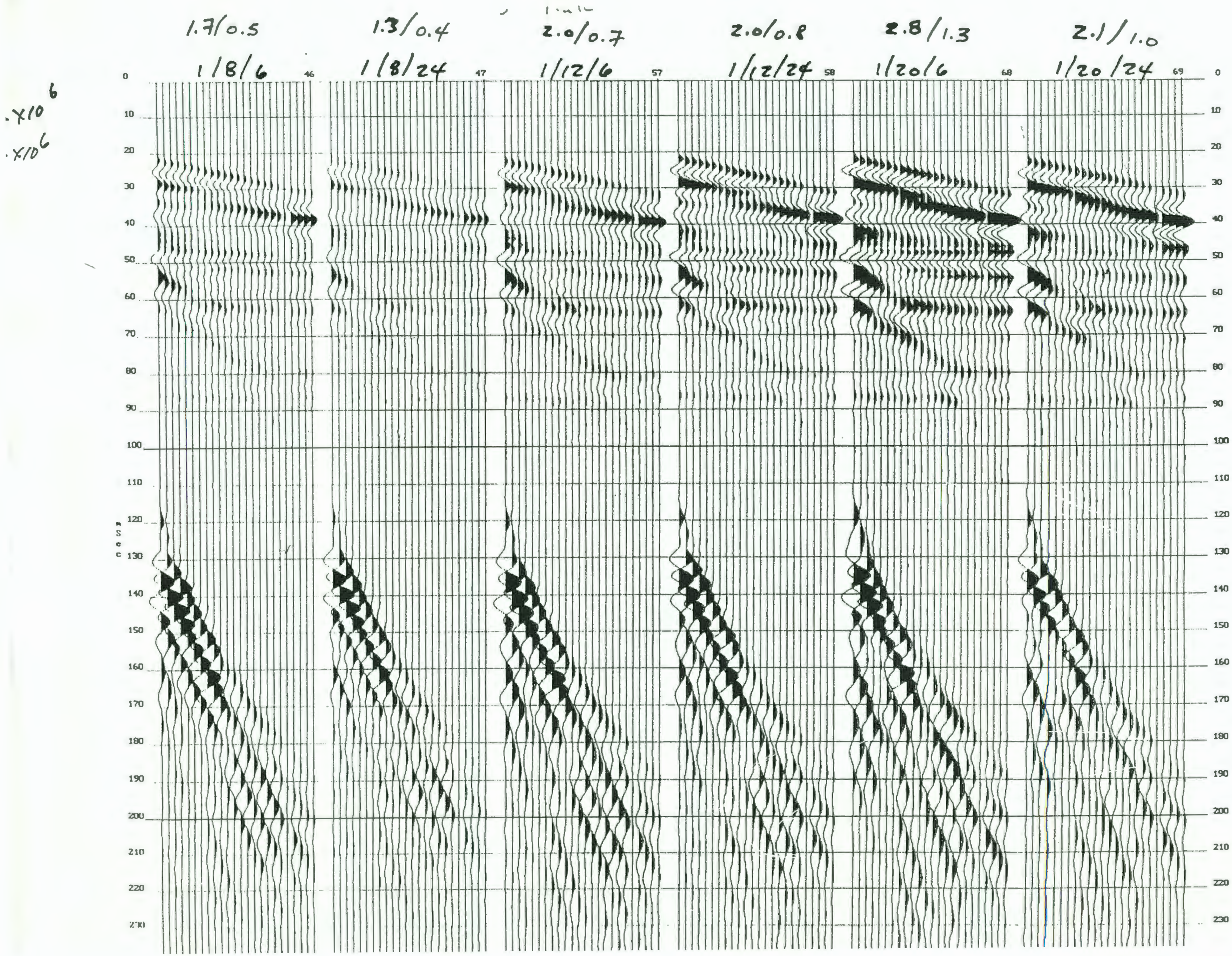
FIG. 53. Same as Figure 48 except no plate was used.

APPENDIX B

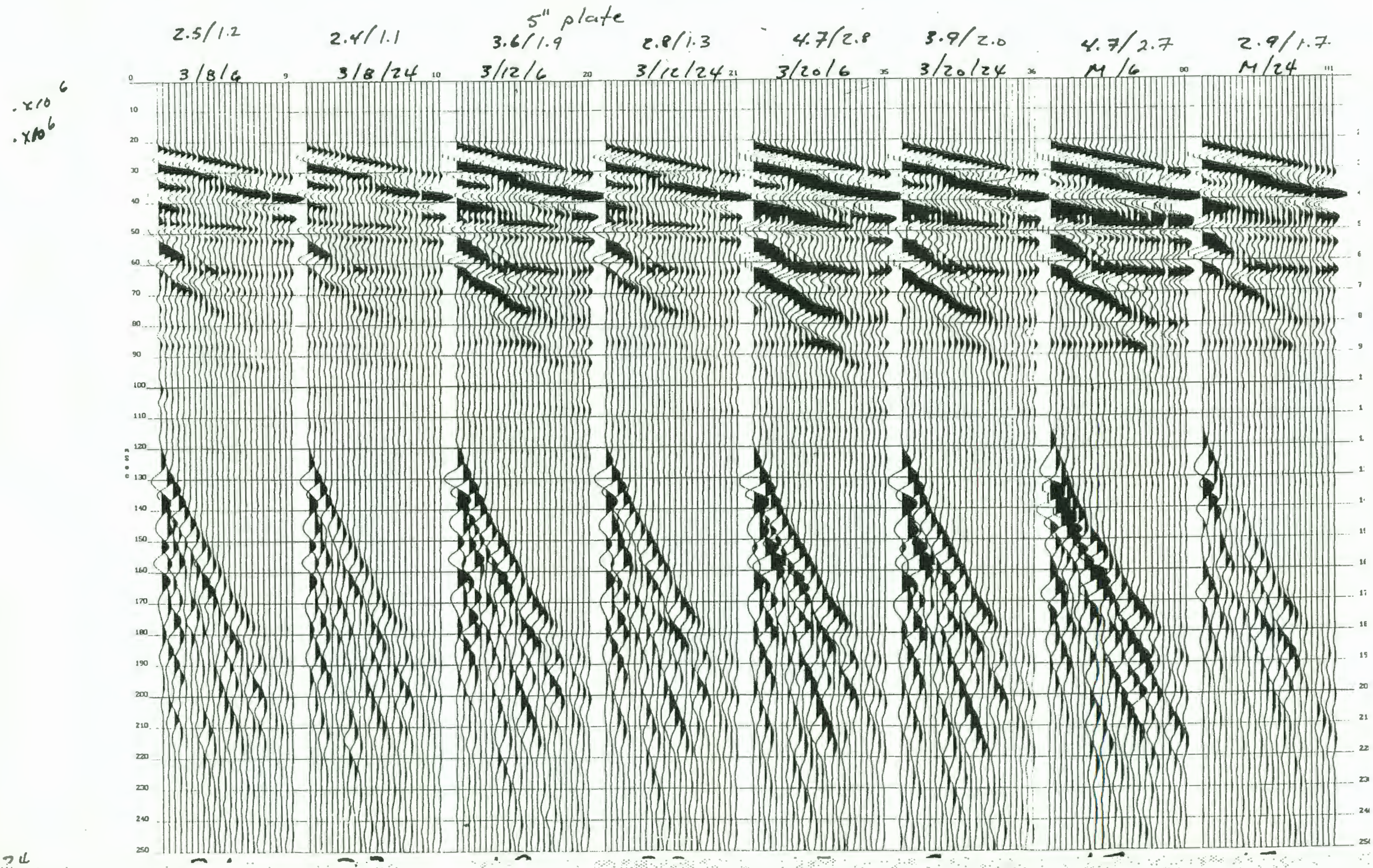
PART I

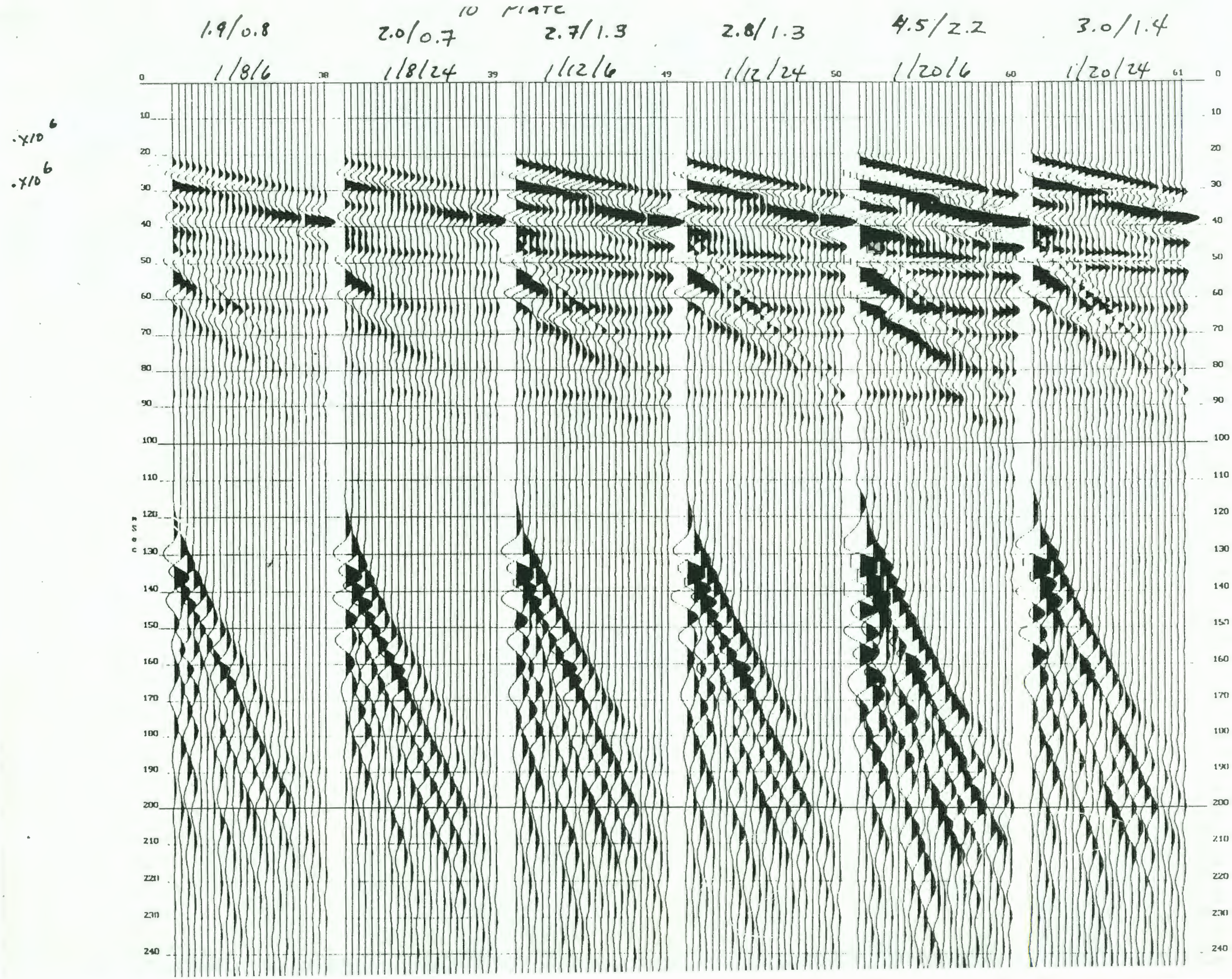
SOURCE CONSTANT

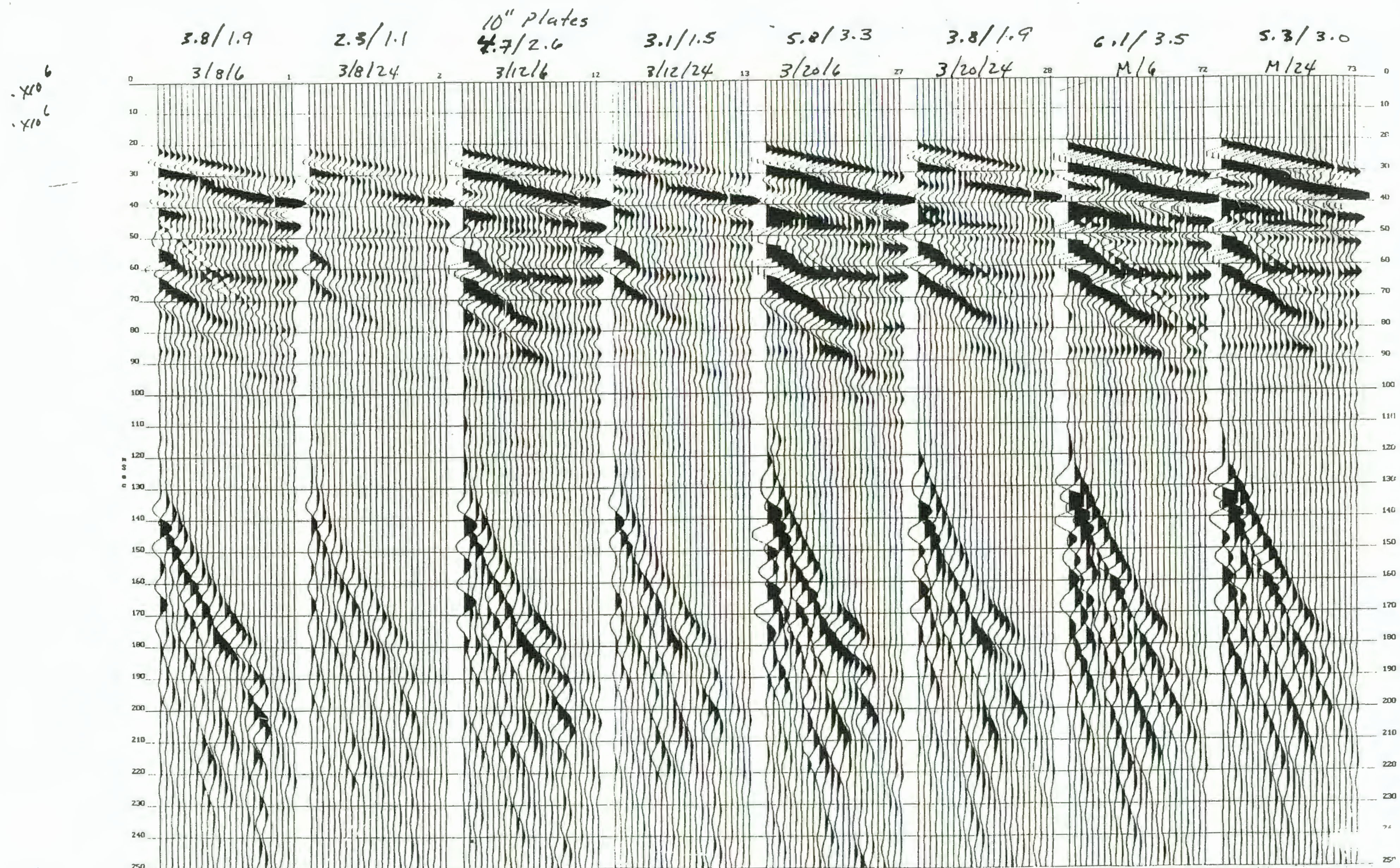
CHANGE PLATE WEIGHT

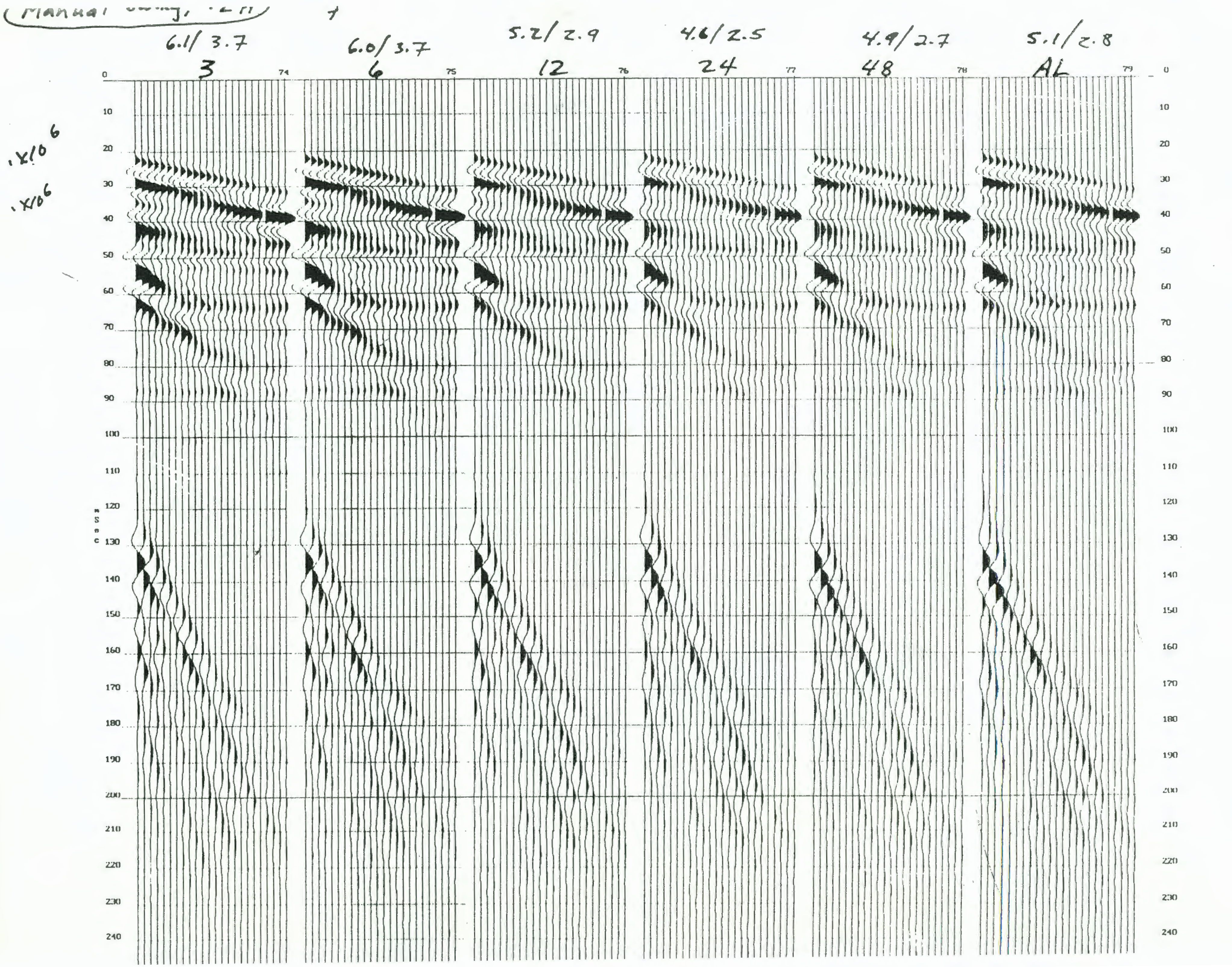


.x10 6
.x10 6
1.7/0.5
1.3/0.4
2.0/0.7
2.0/0.8
2.8/1.3
2.1/1.0
1/8/6
46
1/8/24
47
1/12/6
57
1/12/24
58
1/20/6
68
1/20/24
69
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230

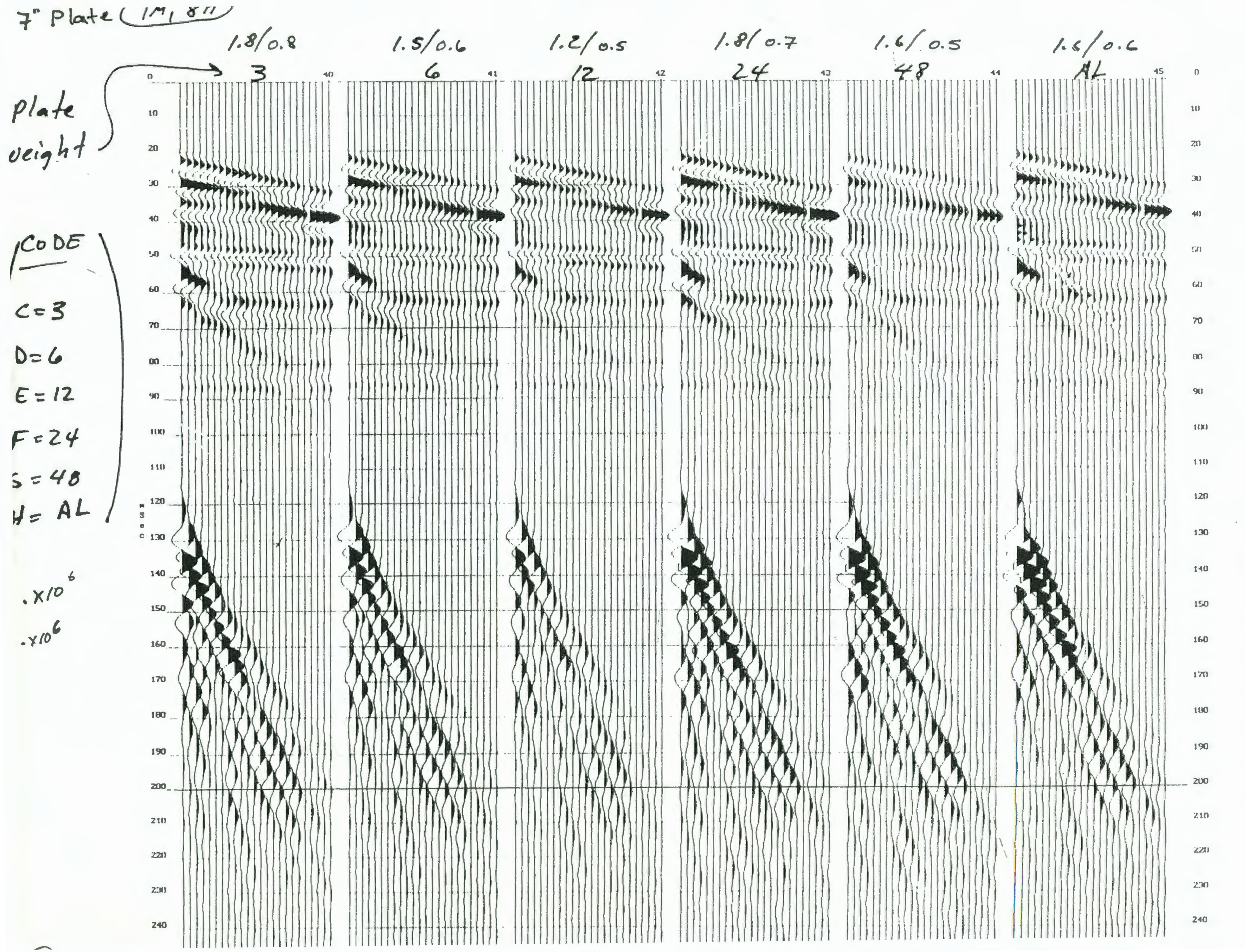

5" plate
2.5/1.2
3/8/6
2.4/1.1
3/8/24
3.6/1.9
3/12/6
2.8/1.3
3/12/24
4.7/2.8
3/20/6
3.9/2.0
3/20/24
4.7/2.7
M/6
2.9/1.7
M/24
.x10^6
.x10^6
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

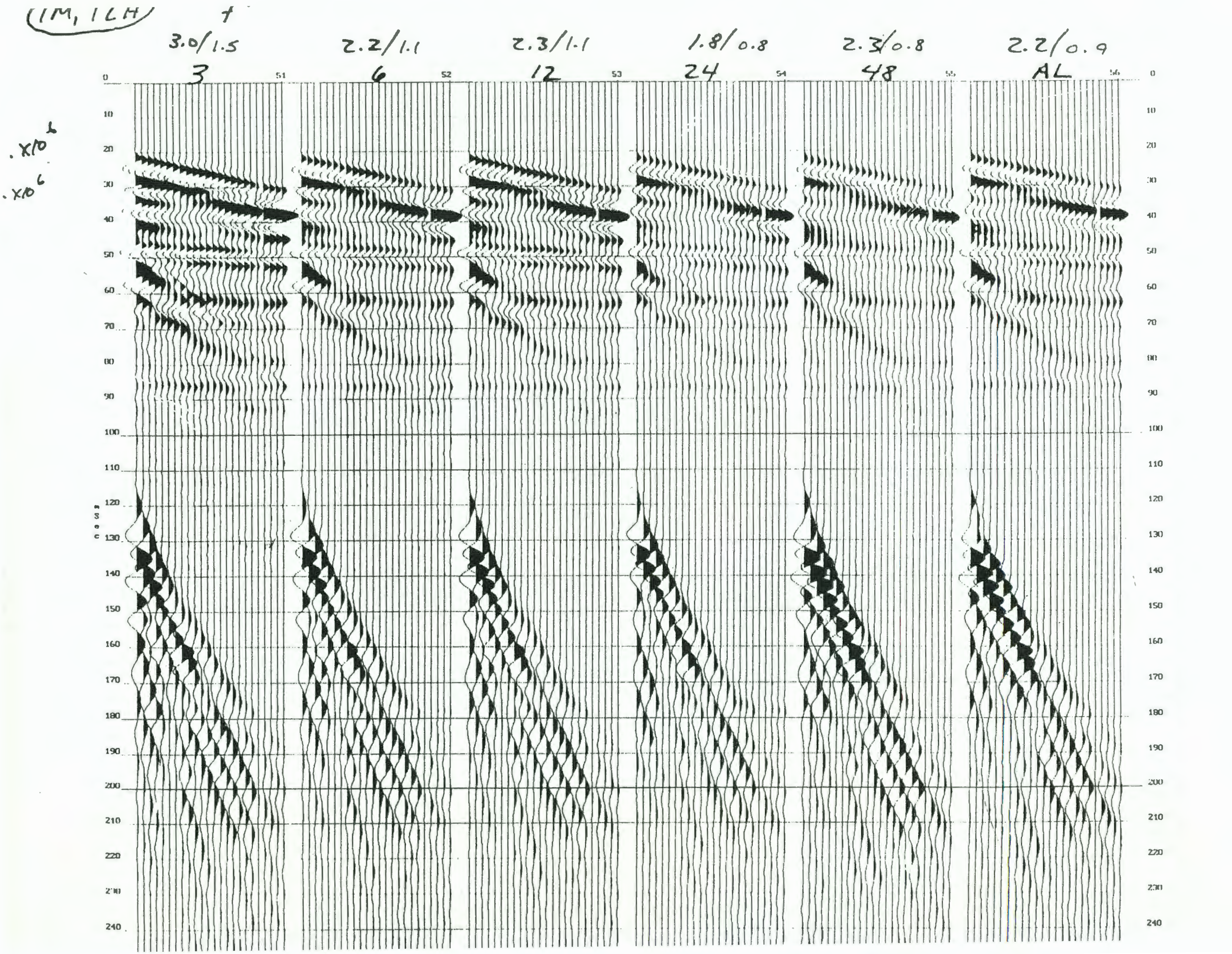

1.9/0.8
2.0/0.7
2.7/1.3
2.8/1.3
4.5/2.2
3.0/1.4
1/8/6
1/8/24
1/12/6
1/12/24
1/20/6
1/20/24
0
38
39
49
50
60
61
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240


·x10^6
·x10^6
10" plates
3.8/1.9
3/8/6
2.3/1.1
3/8/24
4.7/2.6
3/12/6
3.1/1.5
3/12/24
5.8/3.3
3/20/6
3.8/1.9
3/20/24
6.1/3.5
M/6
5.3/3.0
M/24
76

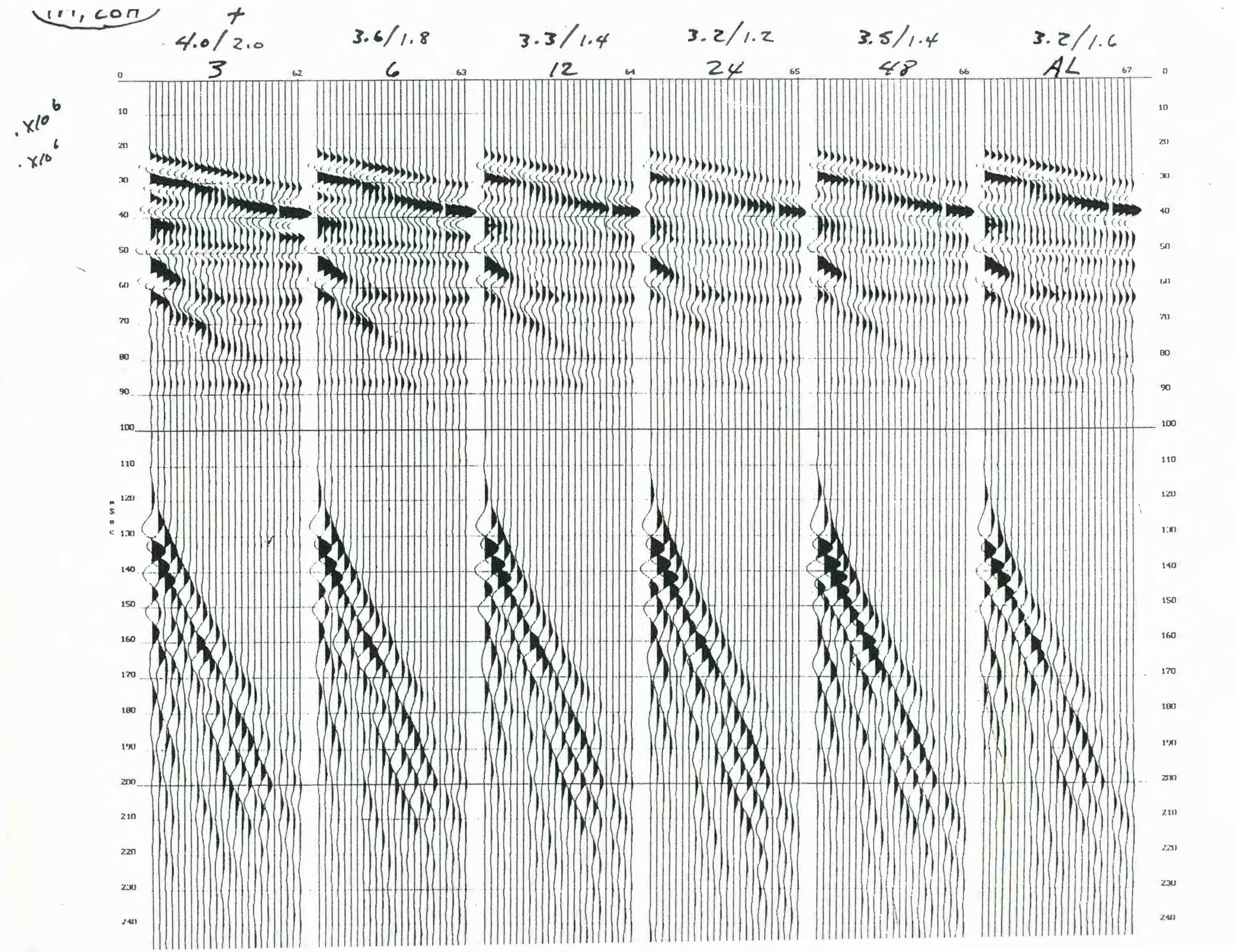


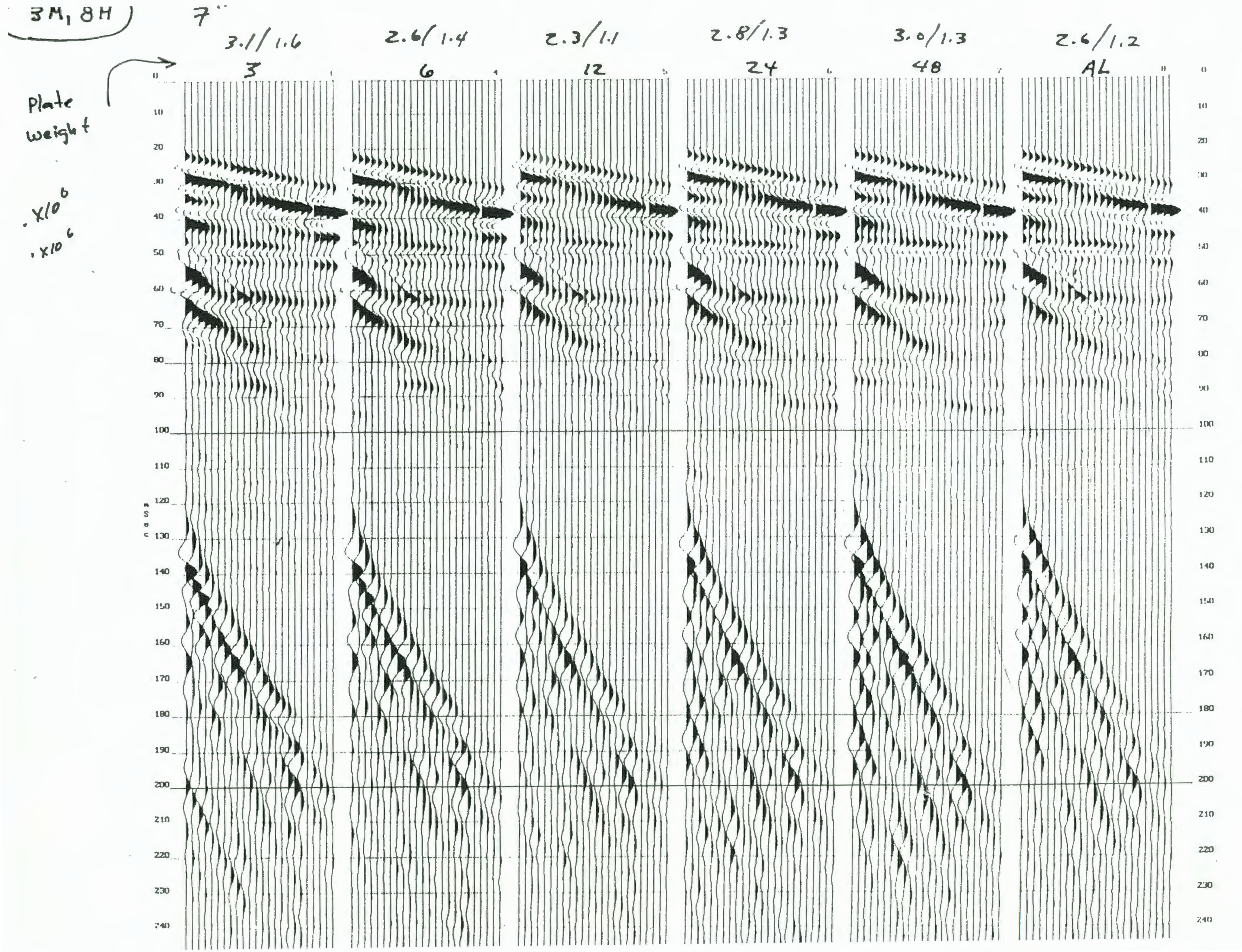
6.1/3.7
6.0/3.7
5.2/2.9
4.6/2.5
4.9/2.7
5.1/2.8
3
6
12
24
48
AL
.x10^6
.x10^6
msec


7" Plate
1.8/0.8
1.5/0.6
1.2/0.5
1.8/0.7
1.6/0.5
1.6/0.6
3
6
12
24
48
AL
0
40
41
42
43
44
45
plate weight
CODE
C=3
D=6
E=12
F=24
= 48
H= AL
.x10^6
.x10^6
msec
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

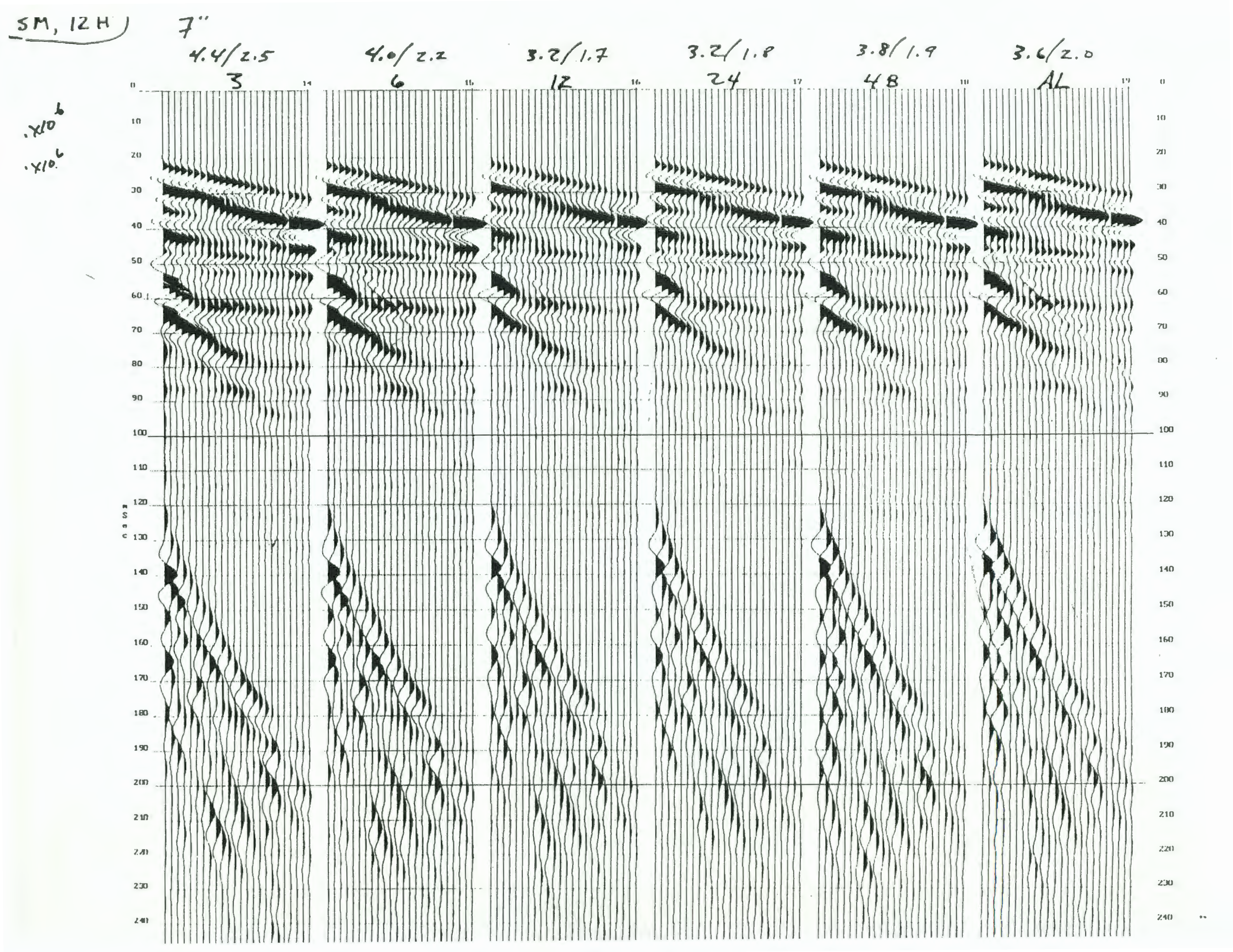


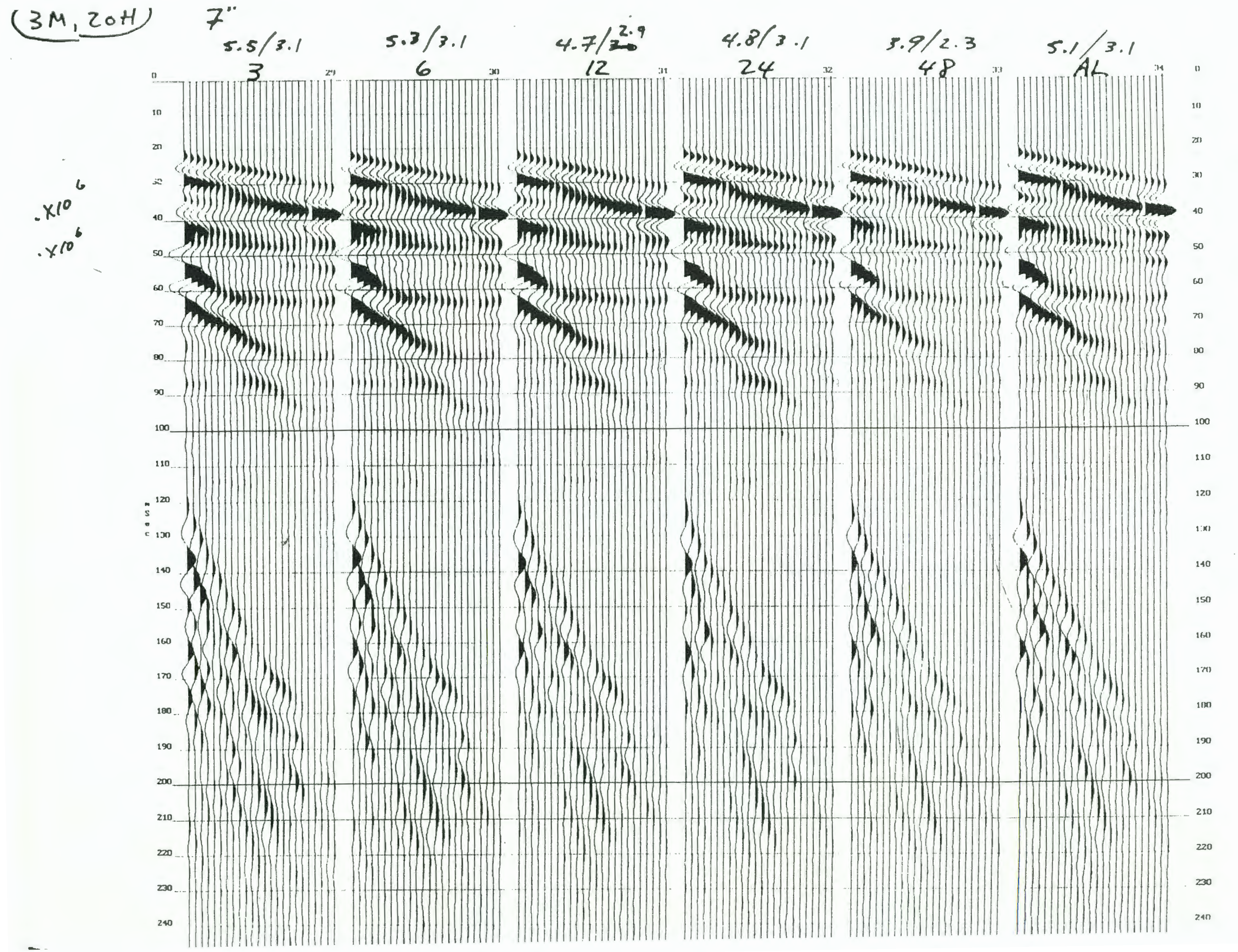
(IM, ILH)
3.0/1.5
2.2/1.1
2.3/1.1
1.8/0.8
2.3/0.8
2.2/0.9
3
6
12
24
48
AL
.X10^6
.X10^6
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240


4.0/2.0
3.6/1.8
3.3/1.4
3.2/1.2
3.5/1.4
3.2/1.6
3
6
12
24
48
AL
62
63
64
65
66
67
.X10⁶
.X10⁶
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240


3M, 8H
7"
Plate weight
.x10^6
.x10^6
3.1/1.6
2.6/1.4
2.3/1.1
2.8/1.3
3.0/1.3
2.6/1.2
3
6
12
24
48
AL
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

SM, 12H 7"





(3M, 20H)
7"
5.5/3.1
3
5.3/3.1
6
4.7/2.9
12
4.8/3.1
24
3.9/2.3
48
5.1/3.1
AL
.X10^6
.X10^6

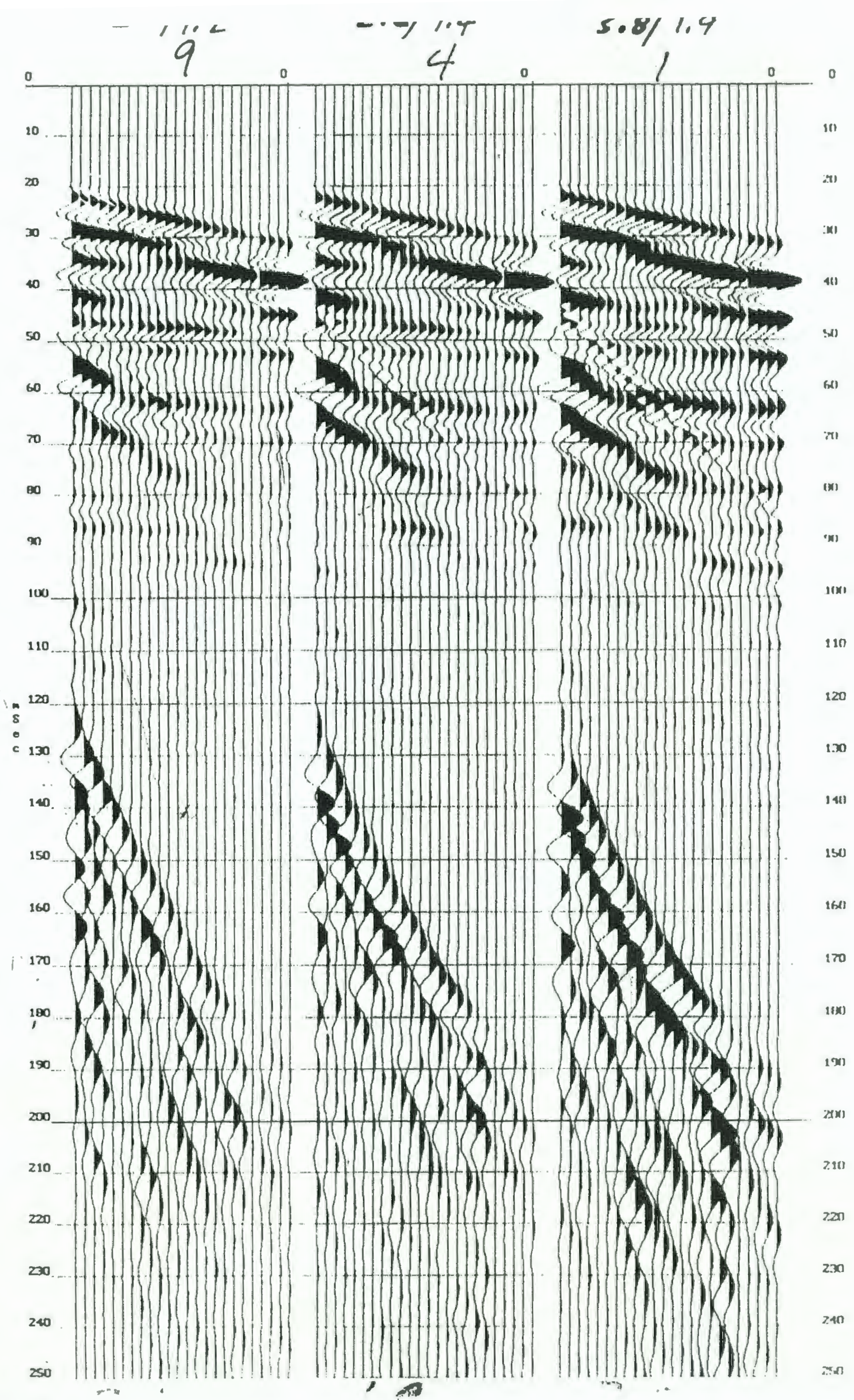
APPENDIX B

PART II

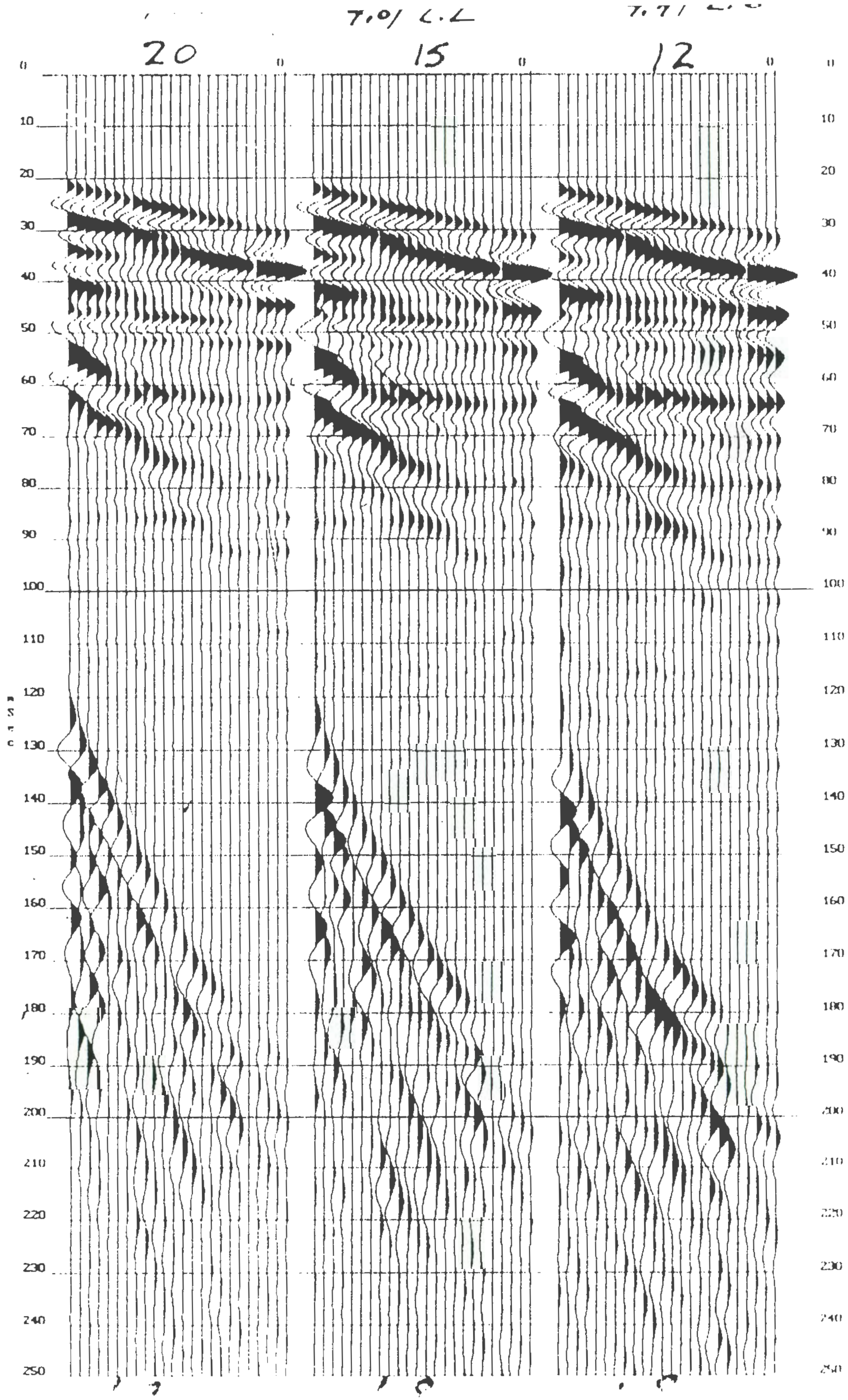
SOURCE CONSTANT

PLATE WEIGHT CONSTANT

VARY PLATE SURFACE AREA

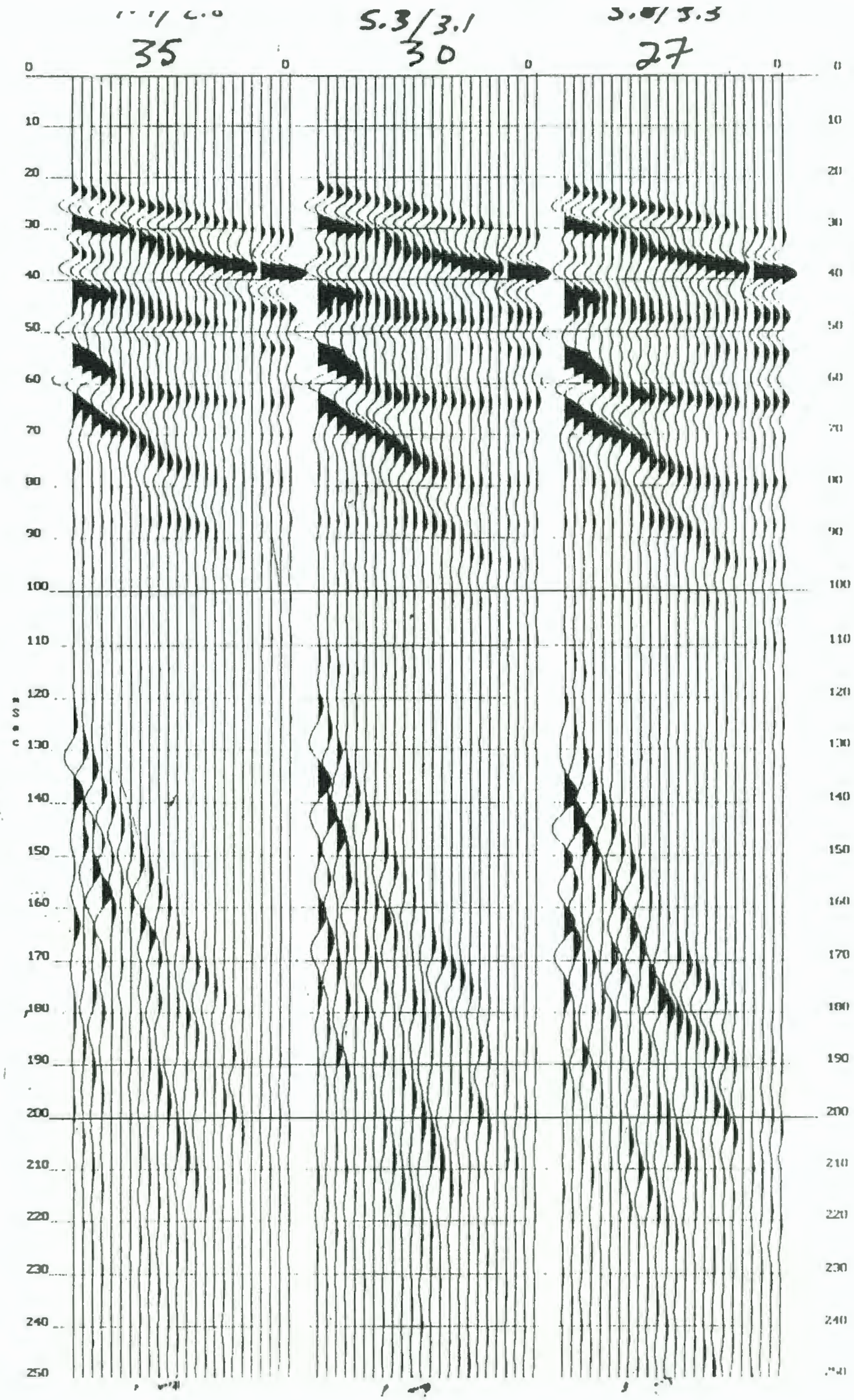


.x10^6



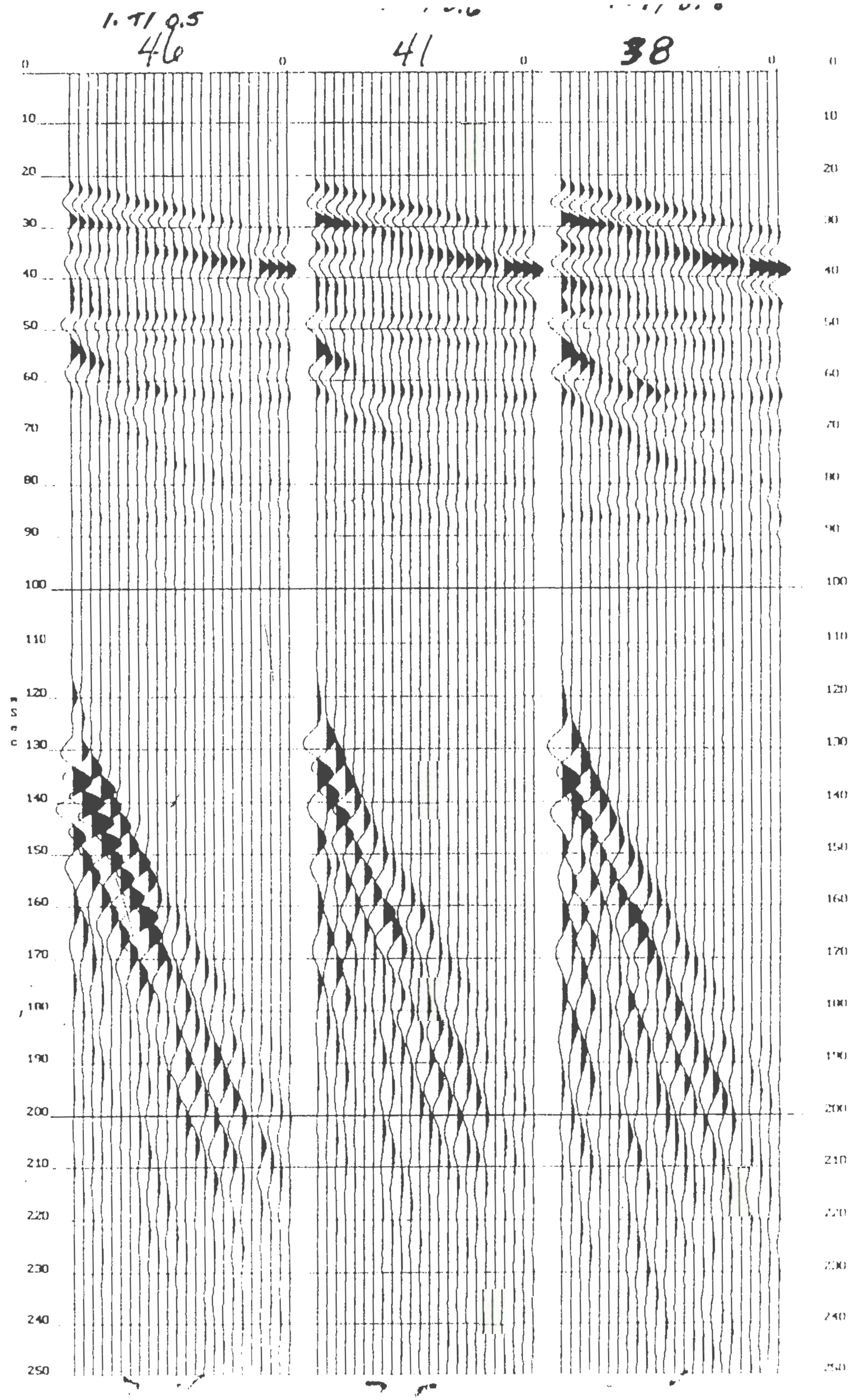
.x10^6

.x10^6


5.3/3.1
35
30
27
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

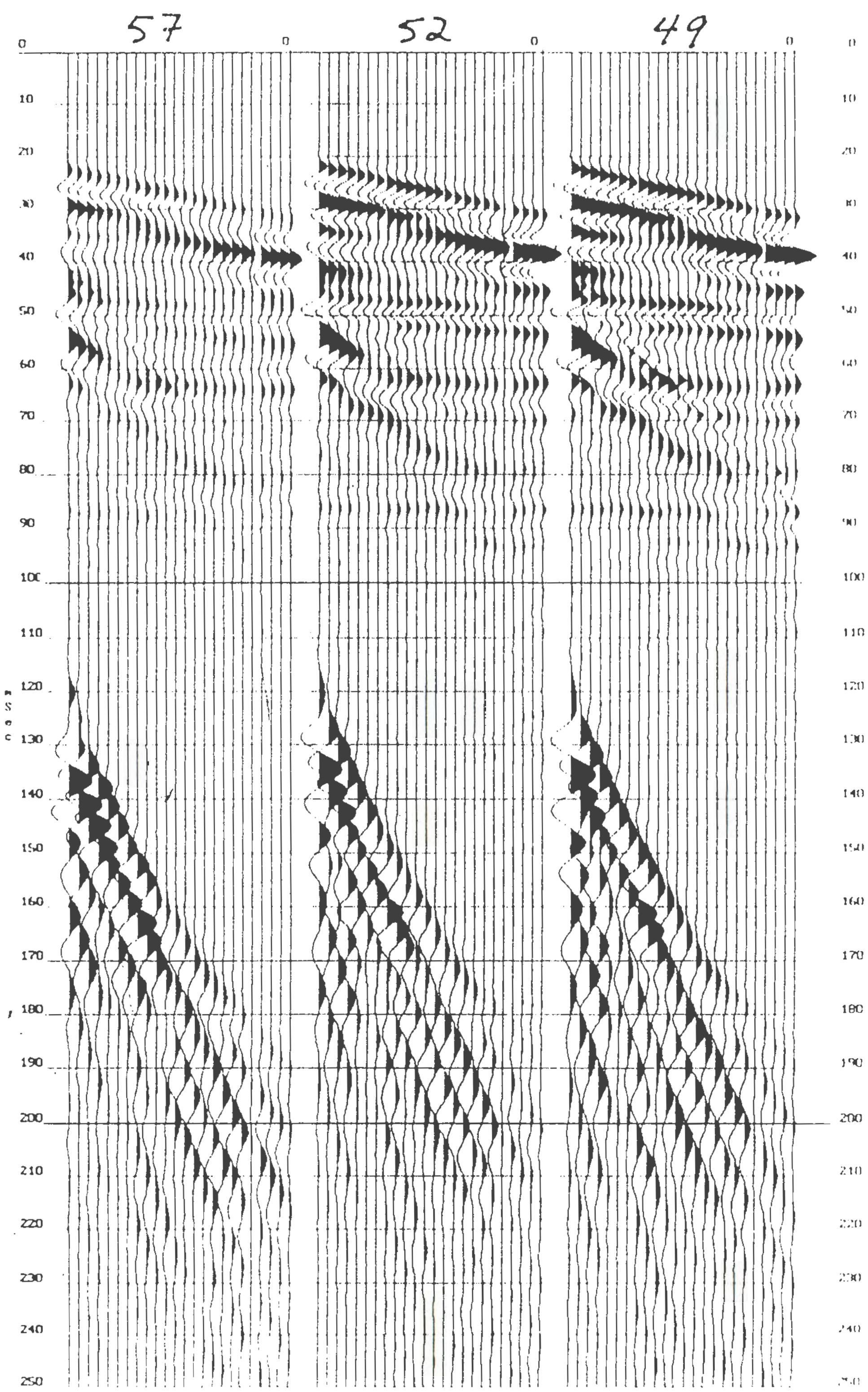
. x10^6

. x10^6


1.T/0.5
46
41
38
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

. x10^6

. x10^6

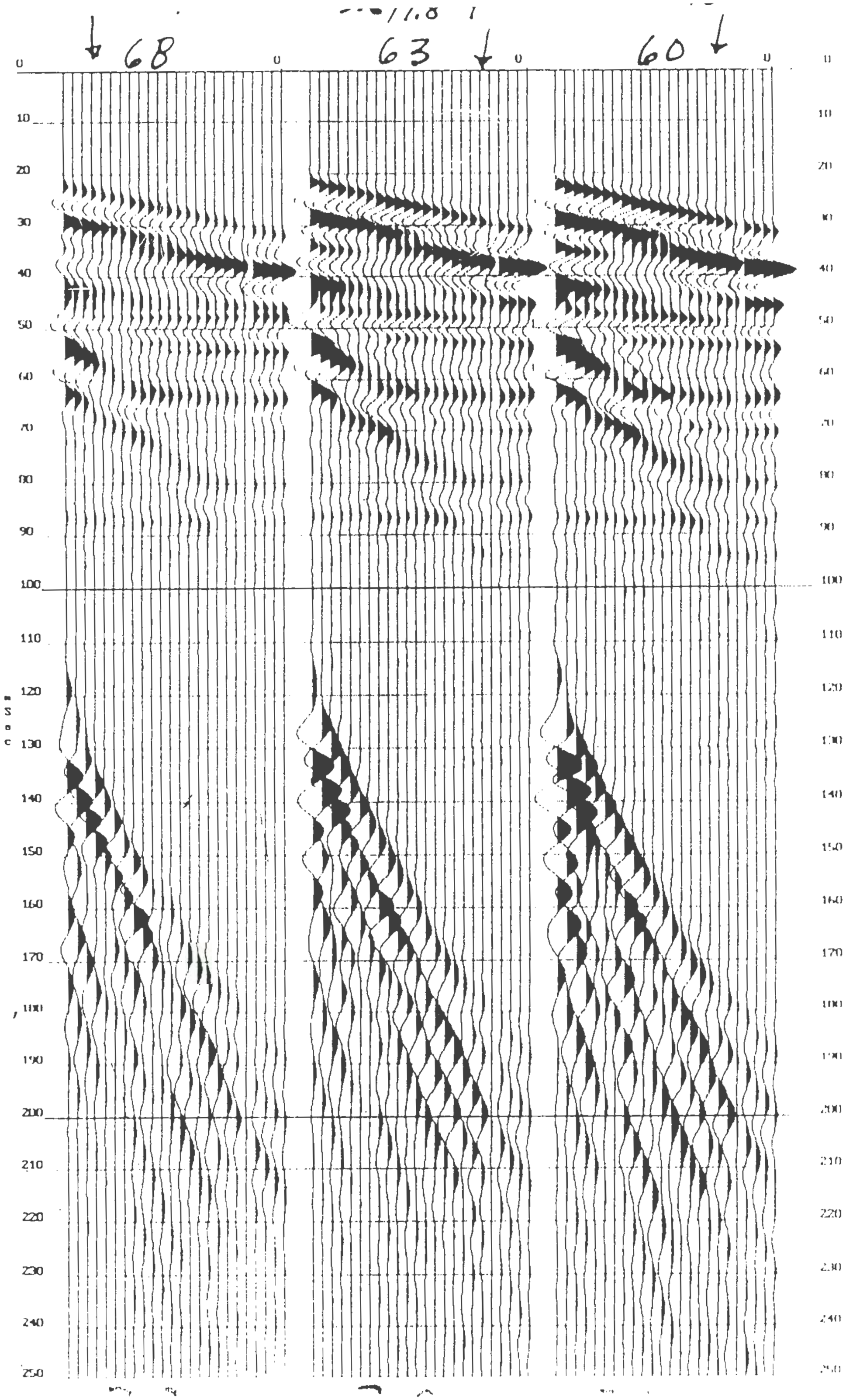


57
52
49
0
0
0
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

. x10^6

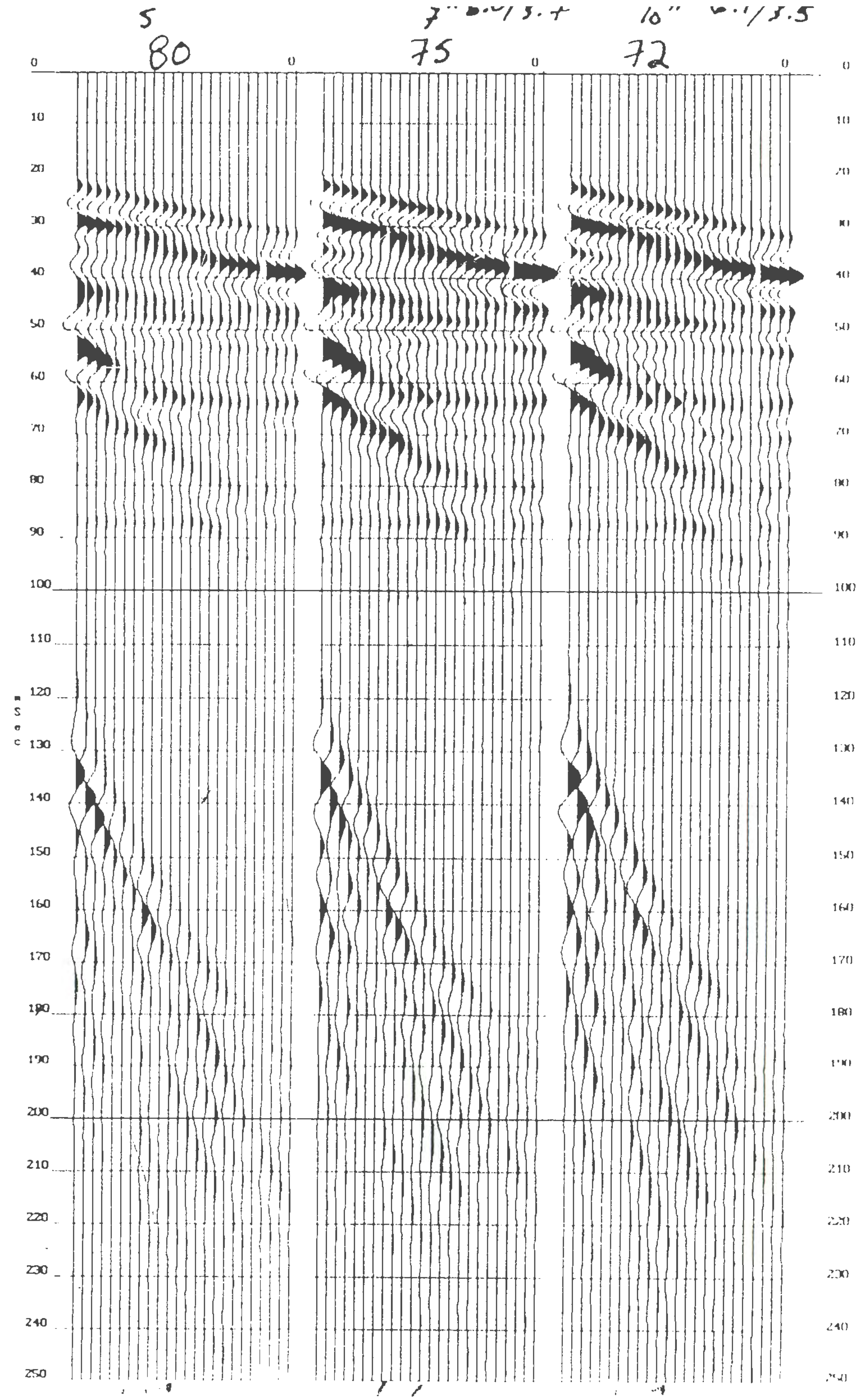
. x10^6

28



· x10⁶

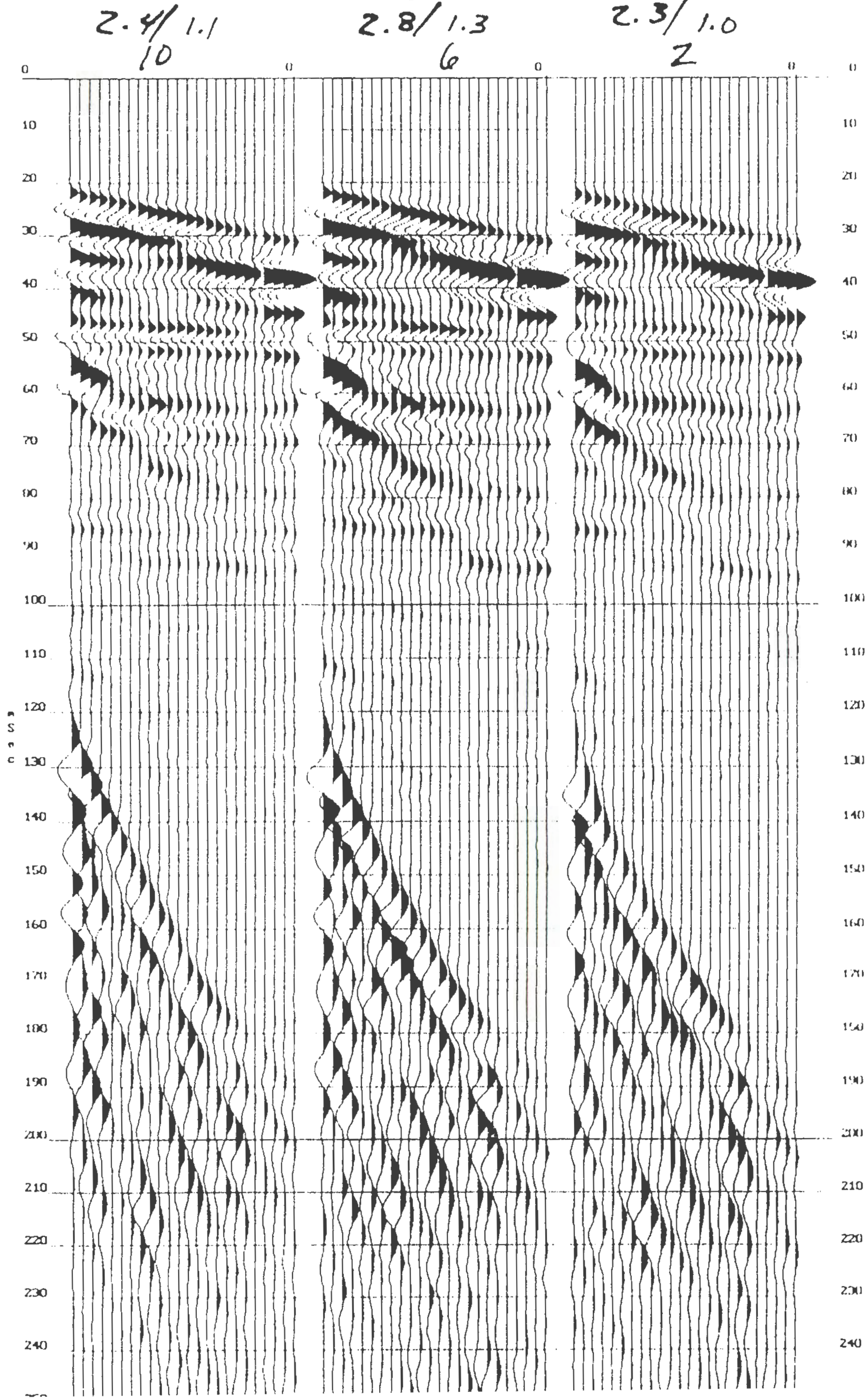
· x10⁶


5
80
75
72
10"
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
msec

x10^6

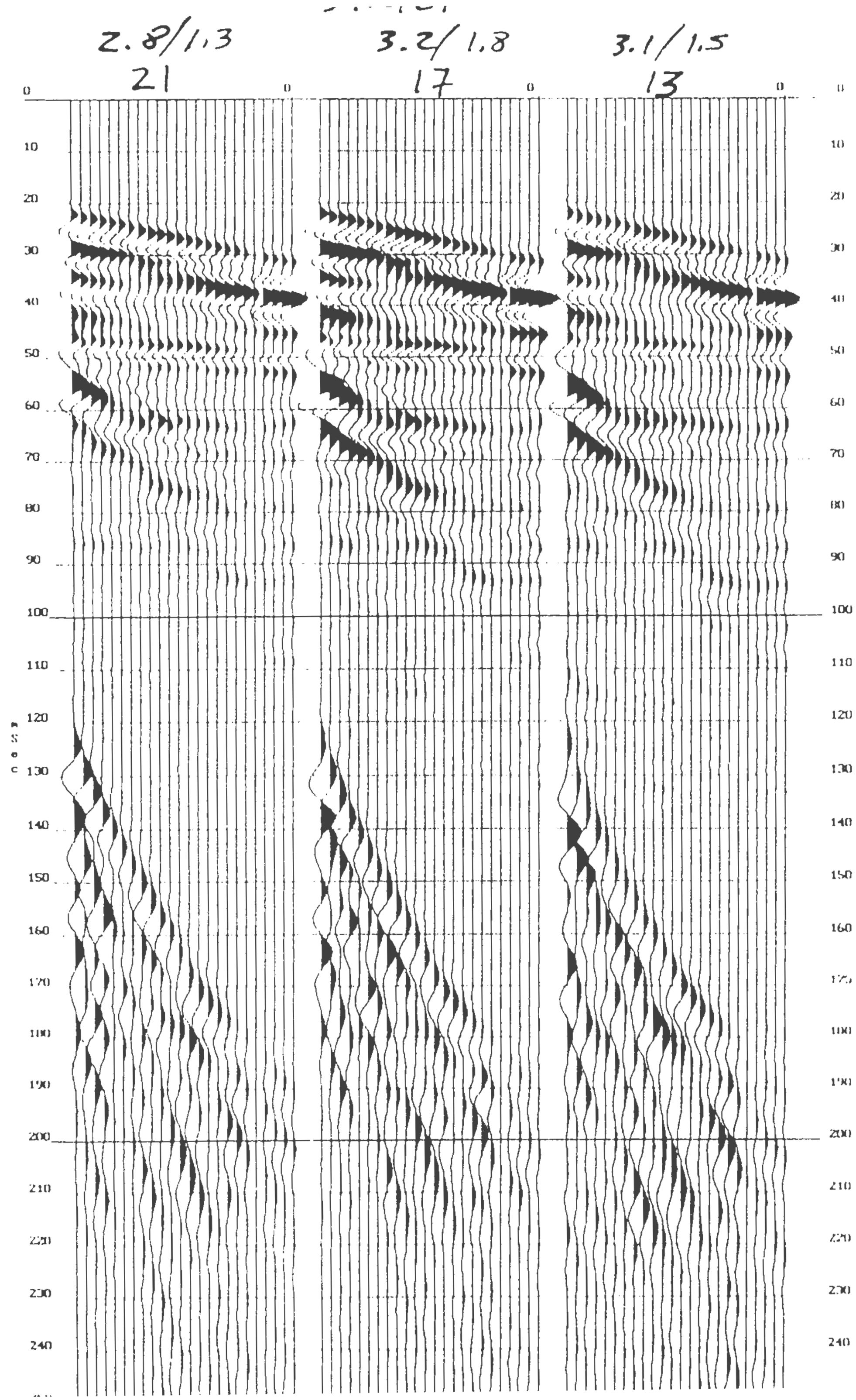
. x10^6

[redacted]

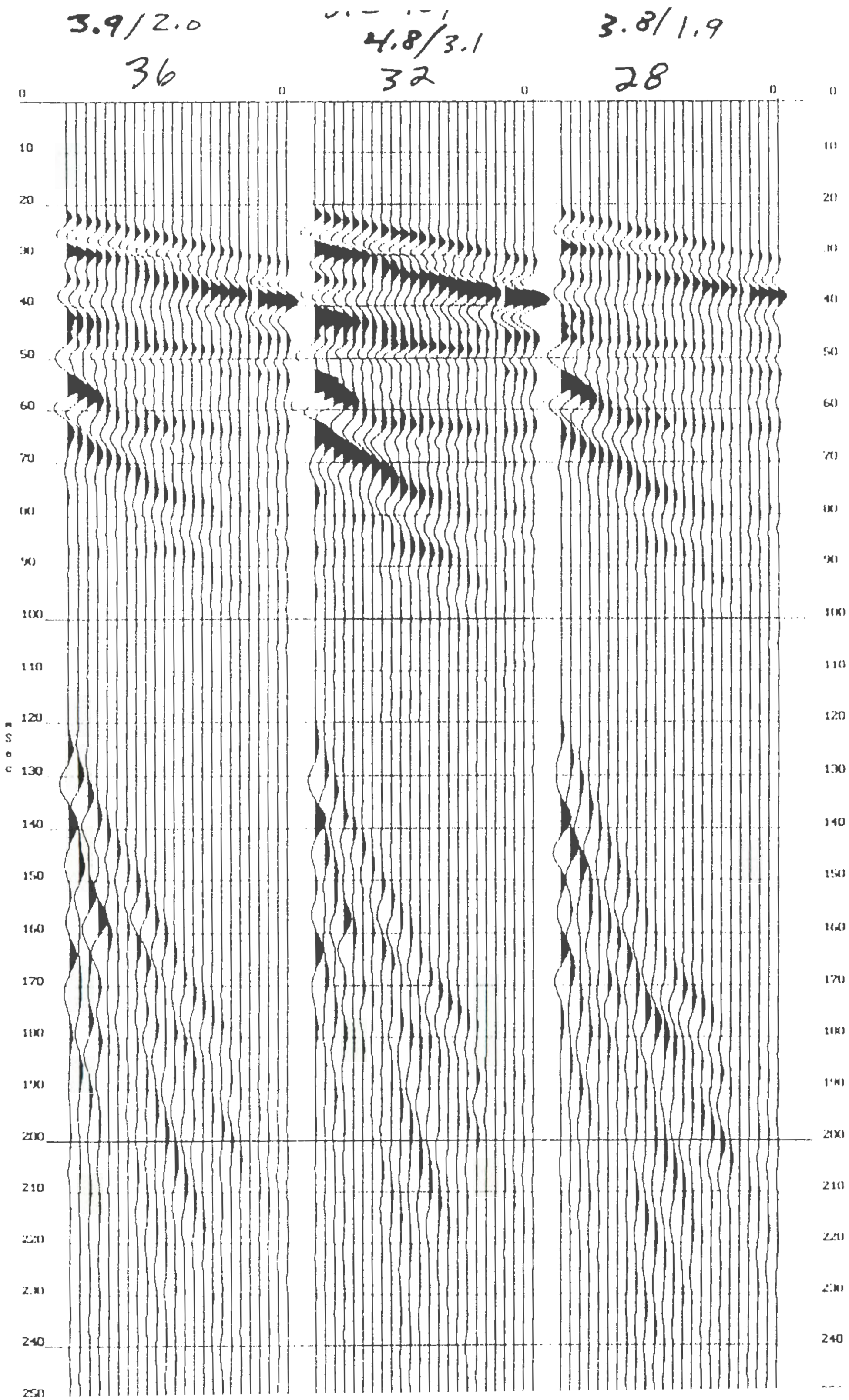


.x10^6

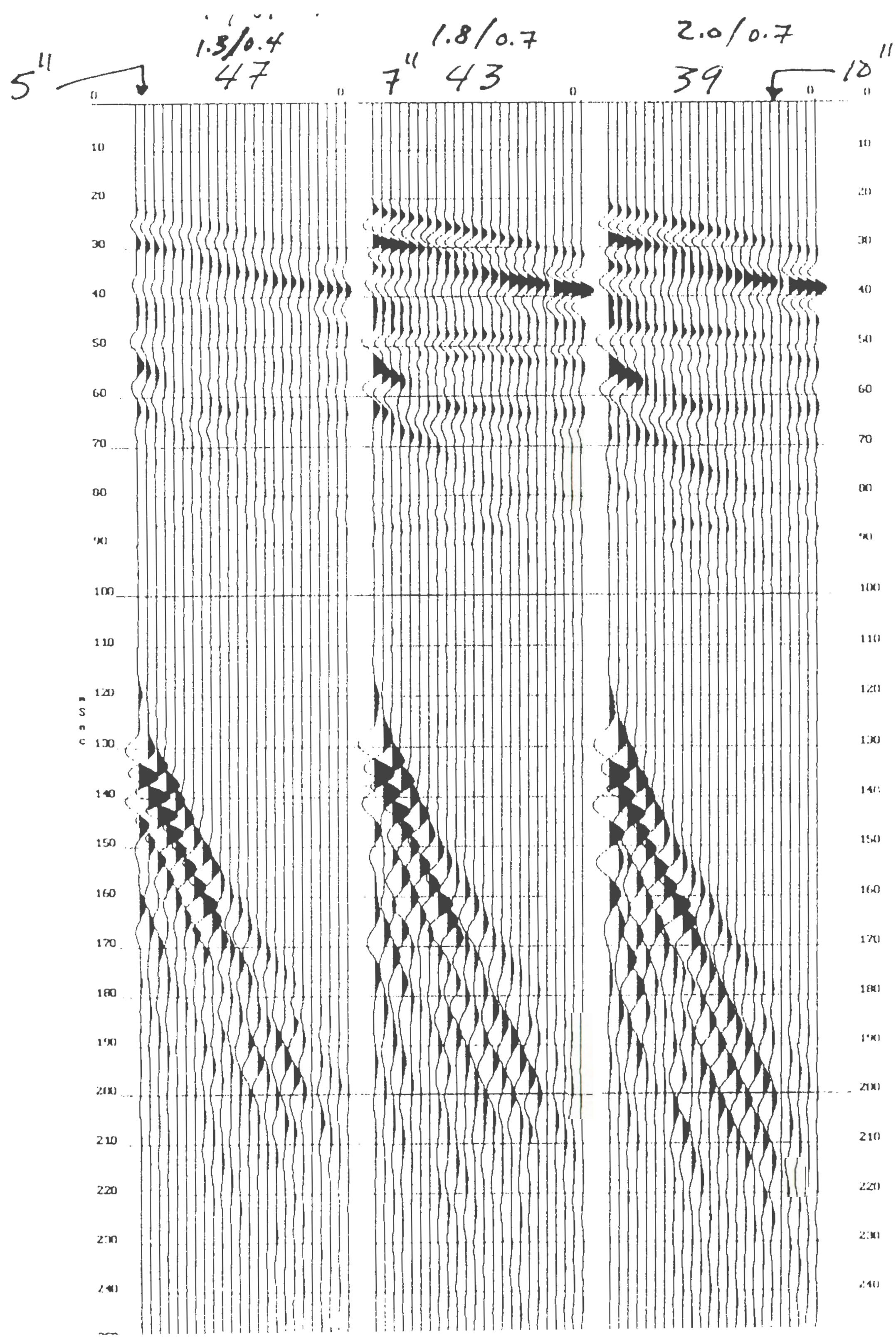
.x10^6


2.8/1.3
3.2/1.8
3.1/1.5
21
17
13
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

.x10^6
.x10^6

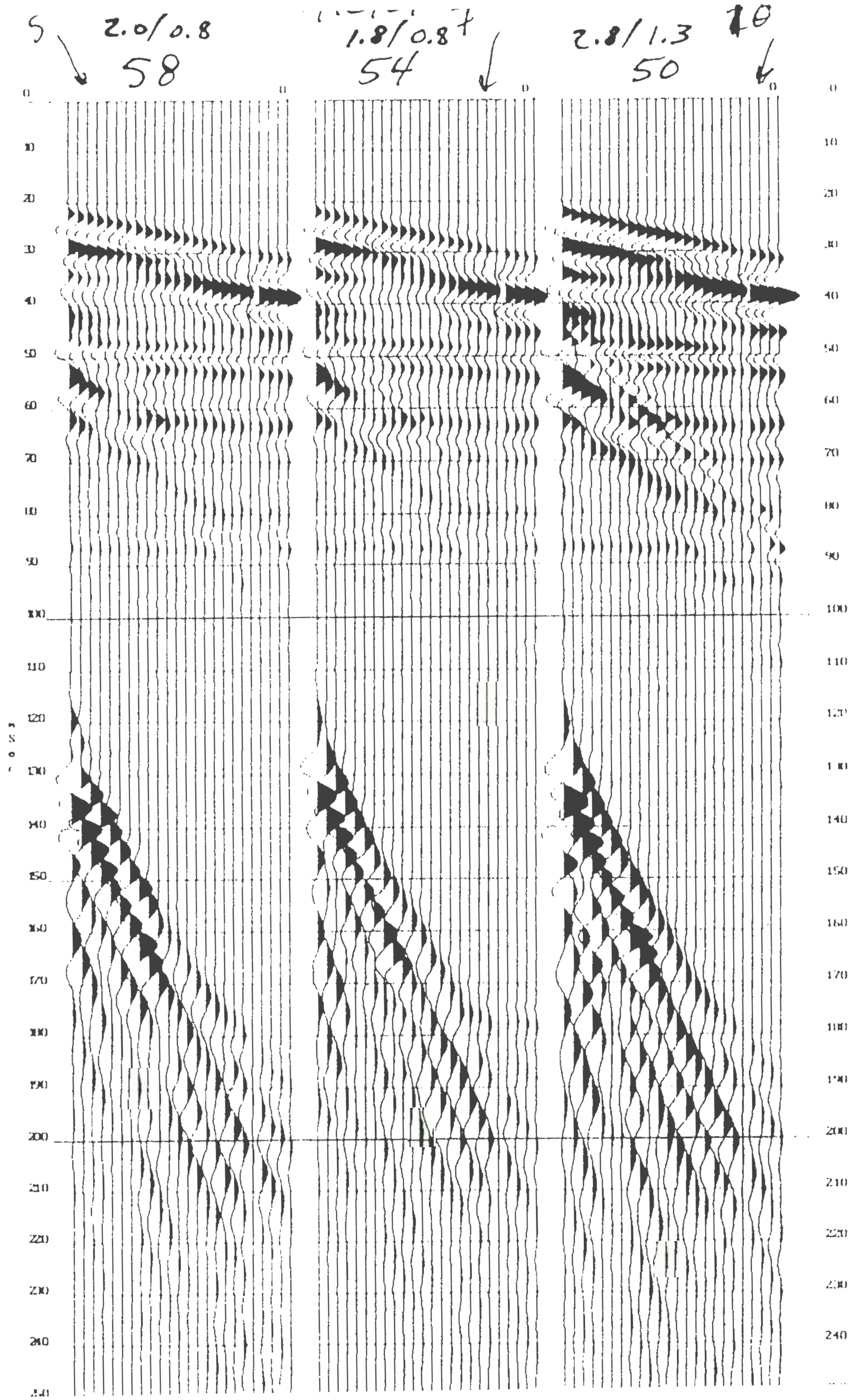

3.9/2.0
36
4.8/3.1
32
3.8/1.9
28
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

. x10^6
. x10^6


1.3/0.4
1.8/0.7
2.0/0.7
5"
47
7"
43
39
10"
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

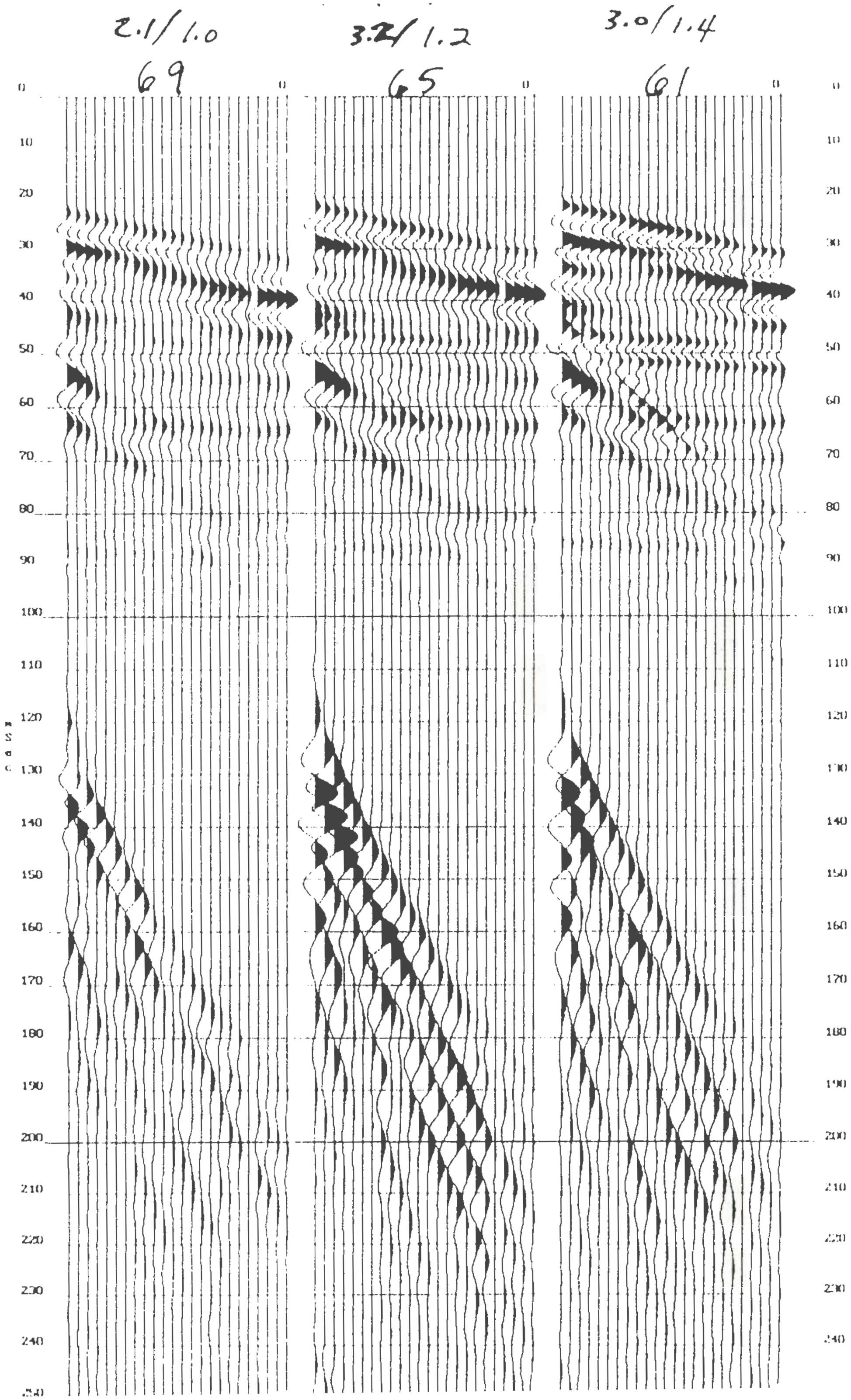
.x10^6

.x10^6



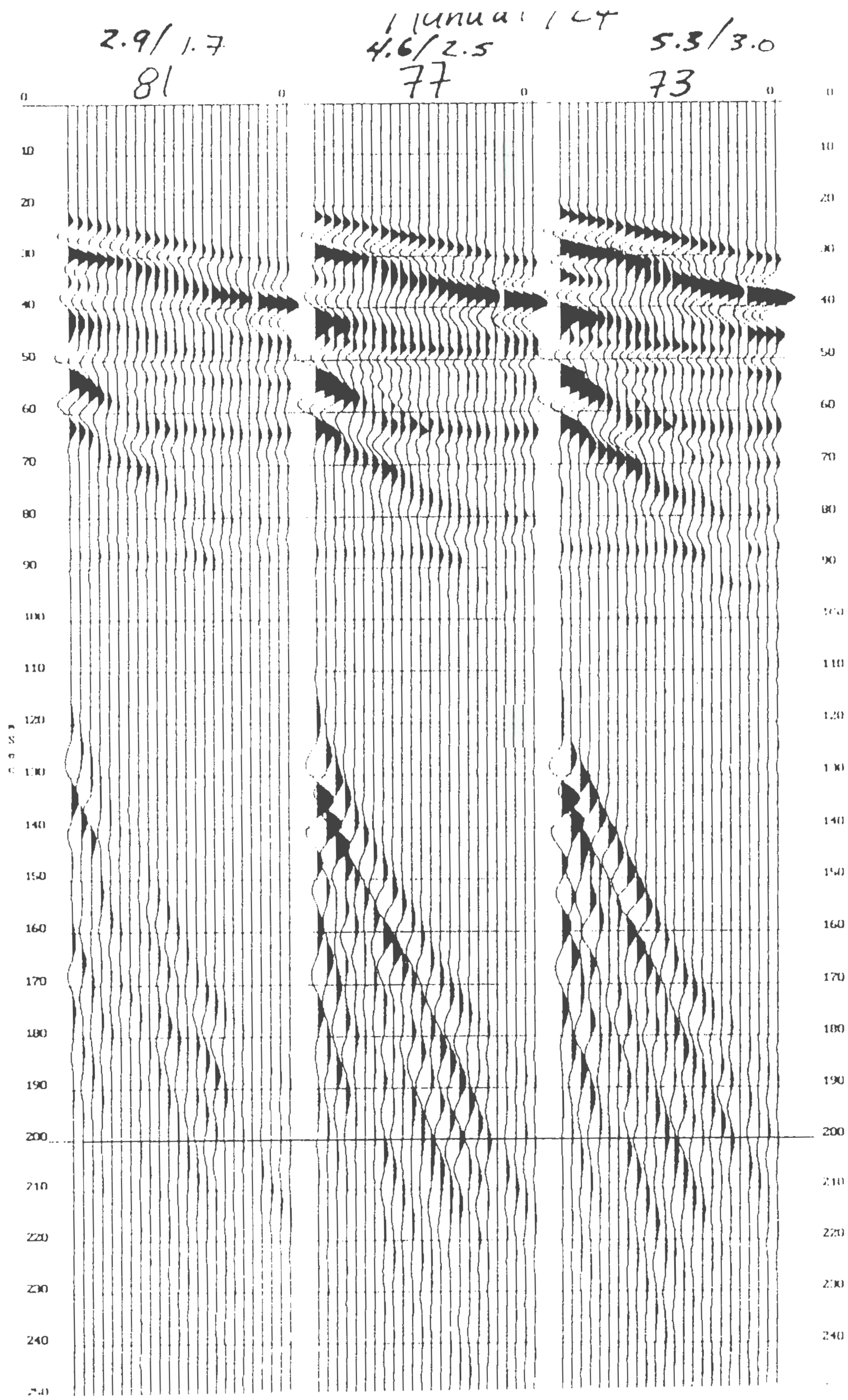
. x10 6

. x10 6


2.1/1.0
69
3.2/1.2
65
3.0/1.4
61
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

.x10^6

.x10^6



.x10⁶

.x10⁶

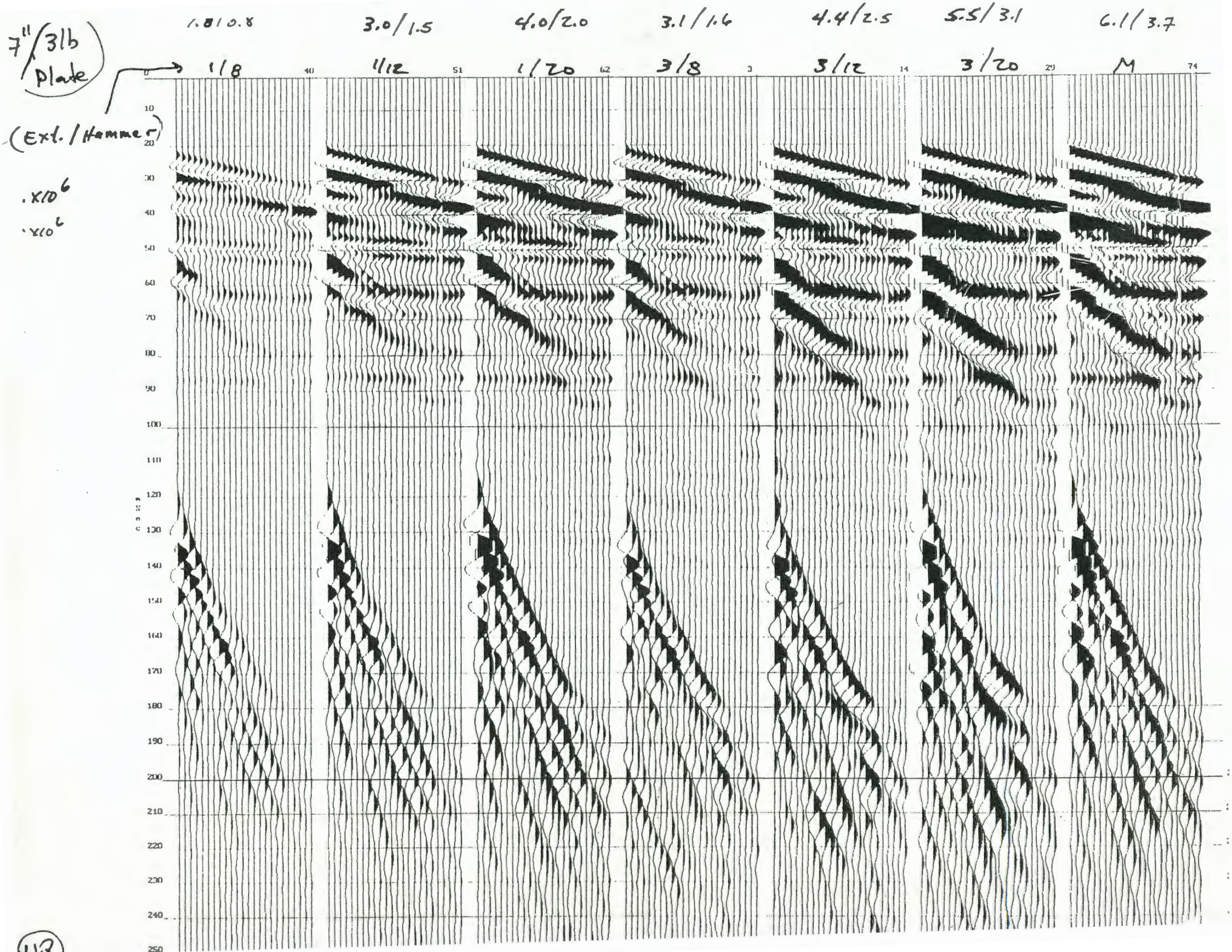
APPENDIX B

PART III

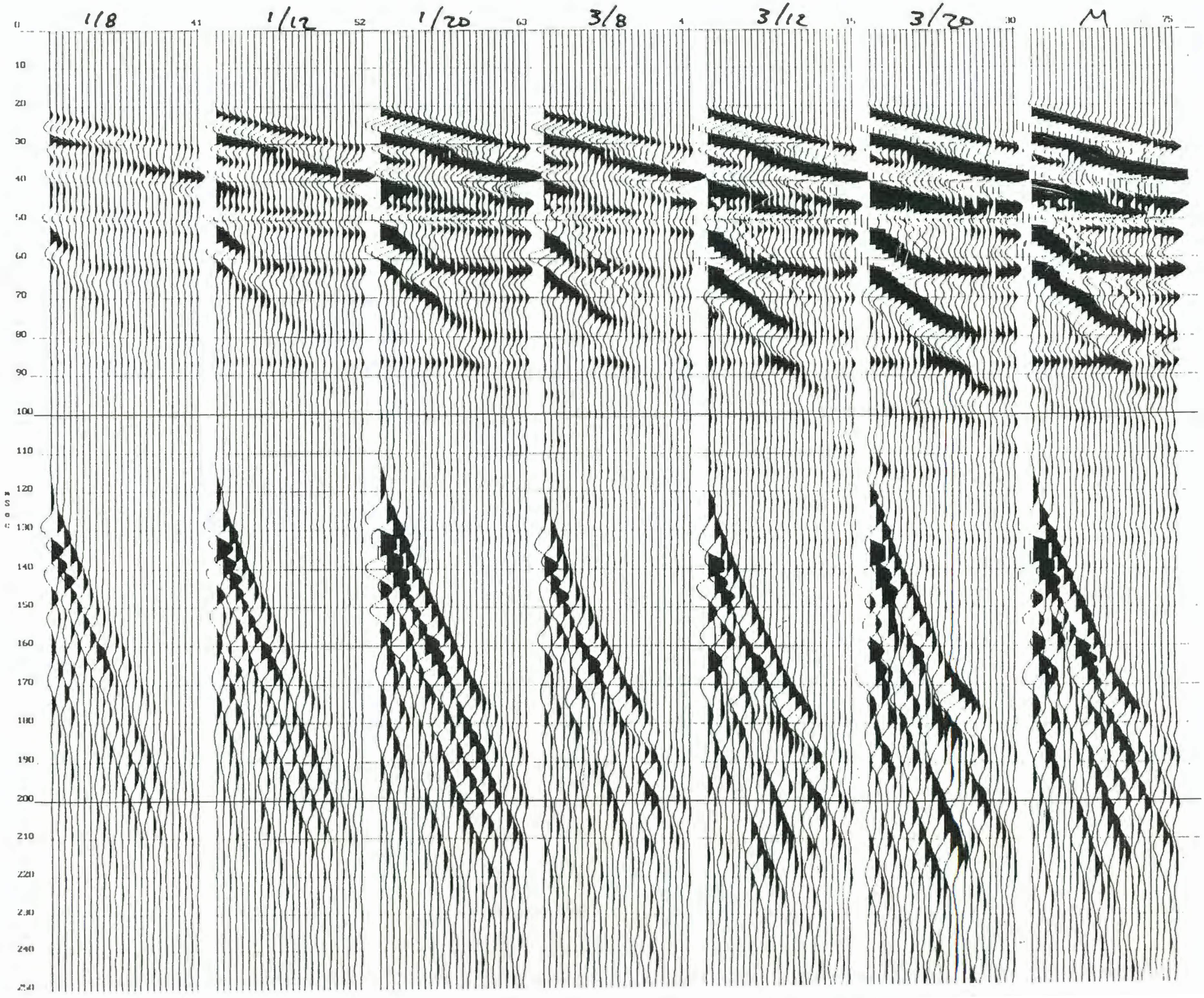
PLATE CONSTANT

(Both S.A. & weight)

VARY SOURCE ENERGY


7"/3lb Plate
(Ext./Hammer)
.x10^6
.x10^6
1.8/0.8
3.0/1.5
4.0/2.0
3.1/1.6
4.4/2.5
5.5/3.1
6.1/3.7
1/8
1/12
1/20
3/8
3/12
3/20
M
0
40
51
62
3
14
29
74
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

6 lb plate


1/8
1/12
1/20
3/8
3/12
3/20
M
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

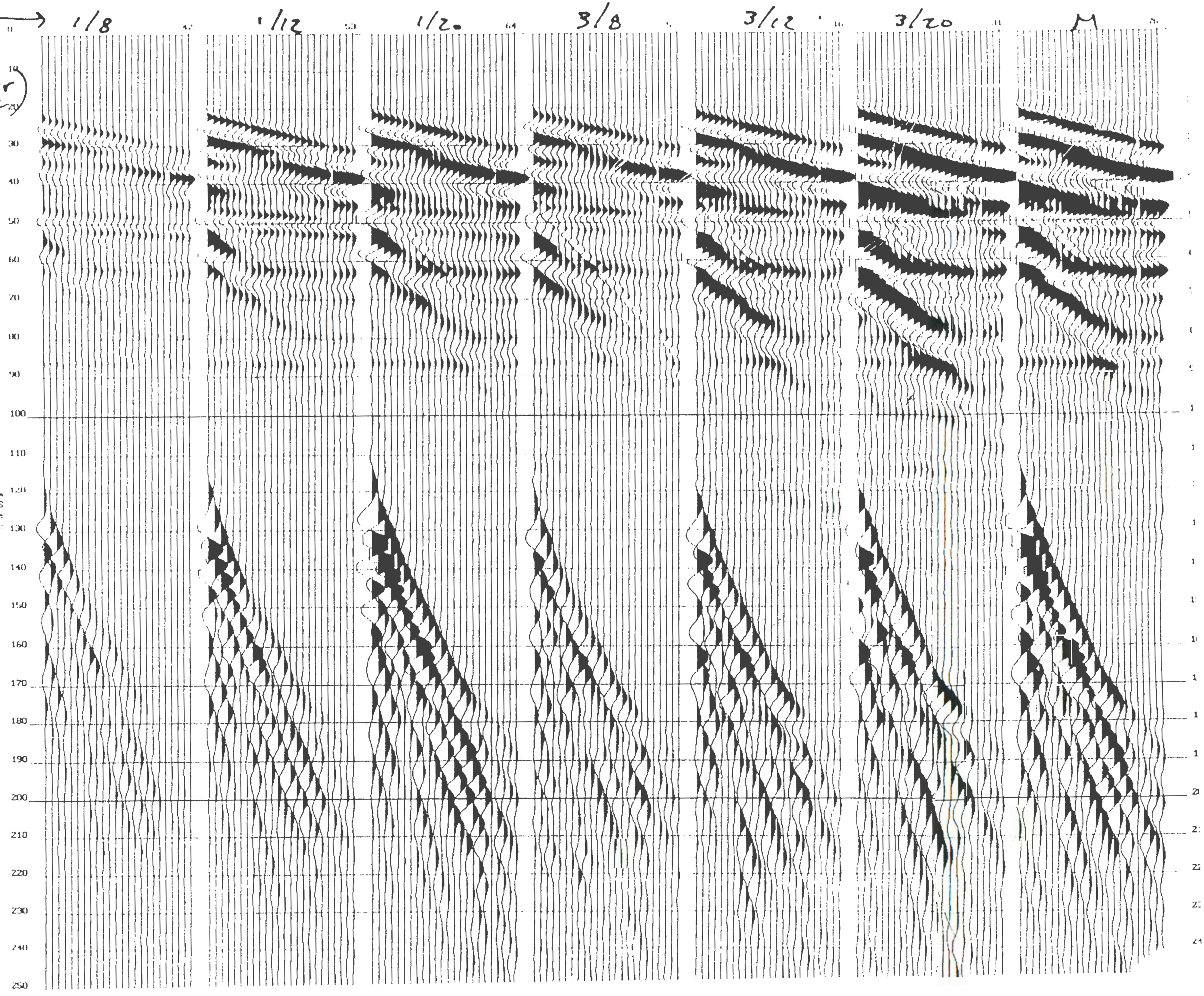
.1a

7" / 12 lb (plate)

5xt. / Hammer weight

•X10^6

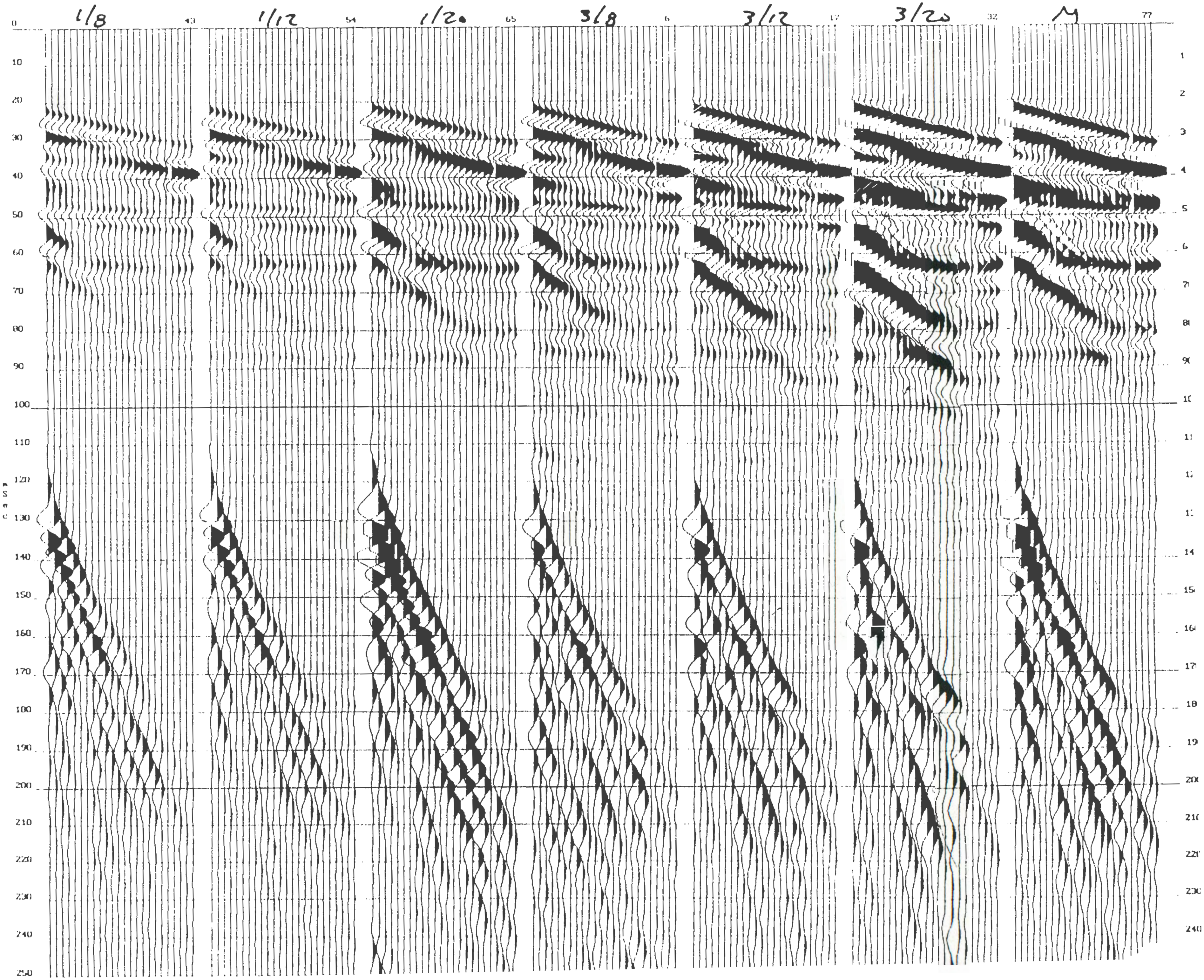
•X10^6



50

(plate

.X10^6
.x10^6

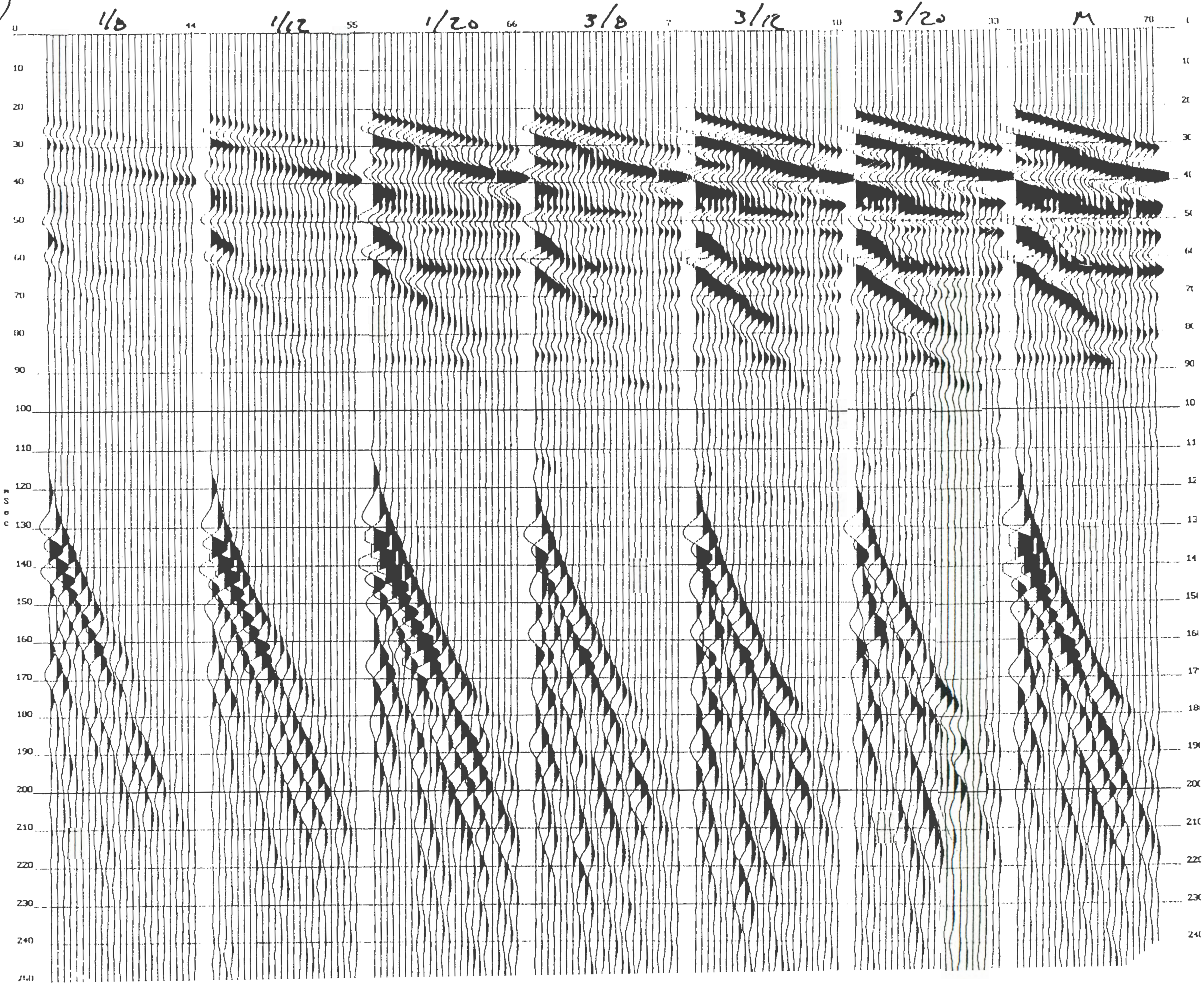


41

1" (48 lb plate)

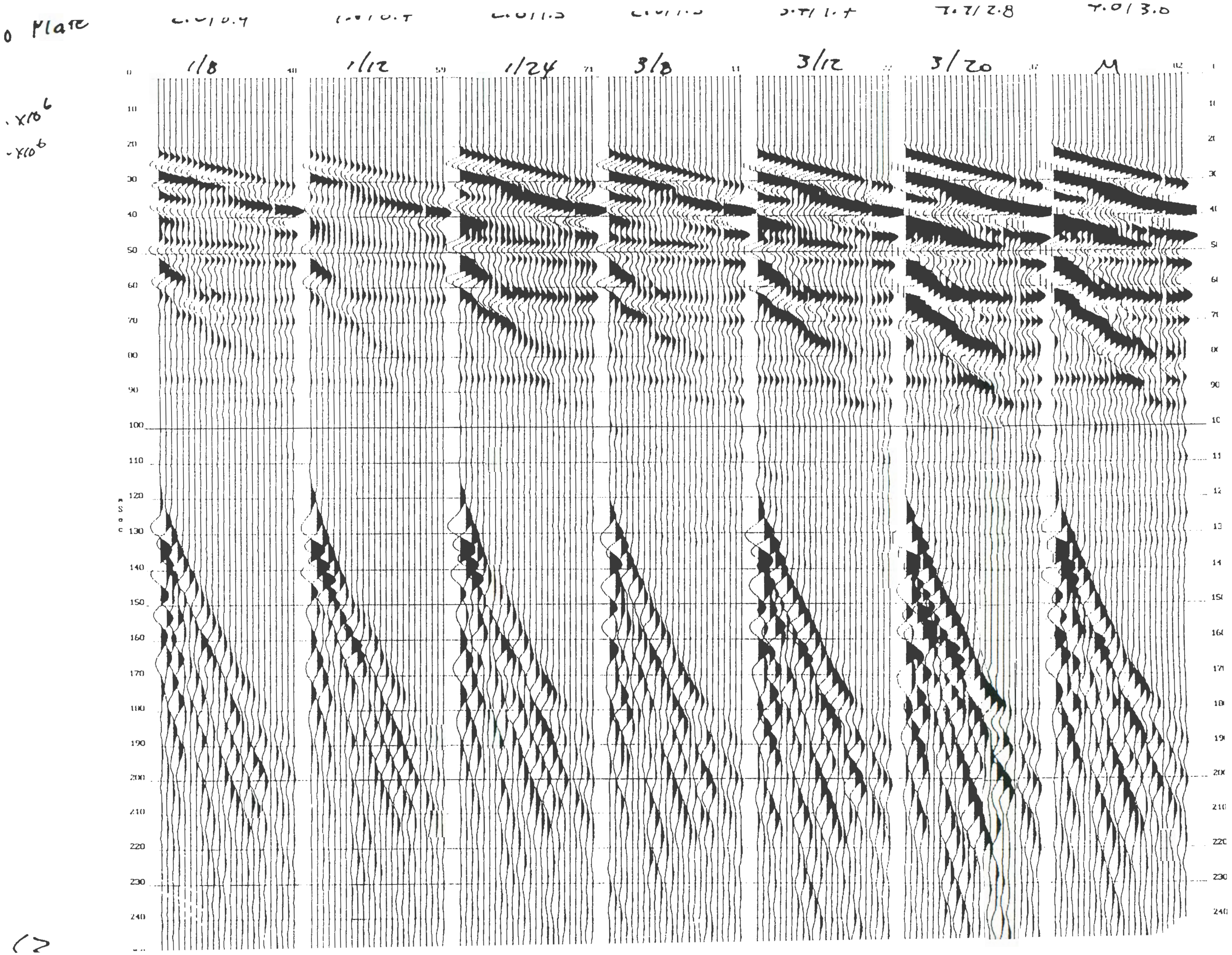
x10^6

x10^6



57

Jo Plate


1/8
1/12
1/24
3/8
3/12
3/20
M
4.7/2.8
4.0/3.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
msec

APPENDIX C

SAND PIT SITE

APPENDIX C FIGURE CAPTIONS

FIG. 54. Field files showing comparison of common surface area (0.05 m^2) plates, various plate weights (2.72 and 10.88 kg), and hammer weights (3.6, 5.4, and 9.1 kg), 1-meter handle extension. SANDPIT SITE.

FIG. 55. Same as Figure 54 except for 3-meter extension.

FIG. 56. Same as Figure 54 except for plate surface area (0.22 m^2).

FIG. 57. Same as Figure 54 except for plate surface area (0.11 m^2) and 3-meter extension.

FIG. 58. Seismograms of common surface area plates (0.11 m^2) and constant source energy (1-meter extension, 3.6 kg hammer) for various plate weights (1.36, 2.72, 5.44, 10.88, and 21.77 kg). SANDPIT SITE.

FIG. 59. Same as Figure 58 except for (5.4 kg) hammer weight.

FIG. 60. Same as Figure 58 except for (9.1 kg) hammer weight.

FIG. 61. Same as Figure 58 except for 3-meter extension.

FIG. 62. Same as Figure 58 except for 3-meter extension and (5.4 kg) hammer weight.

FIG. 63. Same as Figure 58 except for 3-meter extension and (9.1 kg) hammer weight.

FIG. 64. Field files showing comparison of constant impact energy (1-meter extension, 3.6 kg hammer) and plate weight (2.72 kg) for various plate surface areas (0.05, 0.11, and 0.22 m^2).

FIG. 65. Same as Figure 64 except for (5.4 kg) hammer weight.

FIG. 66. Same as Figure 64 except for (9.1 kg) hammer weight.

FIG. 67. Same as Figure 64 except for 3-meter extension.

FIG. 68. Same as Figure 64 except for 3-meter extension and (5.4 kg) hammer weight.

FIG. 69. Same as Figure 64 except for 3-meter extension and (9.1 kg) hammer weight.

FIG. 70. Same as Figure 64 except for (10.88 kg) plate weight .

FIG. 71. Same as Figure 64 except for plate weight (10.88 kg) and hammer weight (5.4 kg).

FIG. 72. Same as Figure 64 except for plate weight (10.88 kg) and hammer weight (9.1 kg).

FIG. 73. Same as Figure 64 except for plate weight (10.88 kg) and 3-meter extension.

FIG. 74. Same as Figure 64 except for source (3-meter extension, 5.4 kg hammer) and plate weight (10.88 kg).

FIG. 75. Same as Figure 64 except for source (3-meter extension, 9.1 kg hammer) and plate weight (10.88 kg).

FIG. 76. Seismograms showing comparison of constant plate surface area (0.11 m^2) and weight (1.81 kg) for various hammer weights (3.6, 5.4, and 9.1 kg) and extensions (1 and 3 meters). Aluminum Plate. SANDPIT SITE.

FIG. 77. Same as Figure 76 except for steel plate (1.36 kg).

FIG. 78. Same as Figure 76 except for steel plate (2.72 kg).

FIG. 79 Same as Figure 76 except for steel plate (5.44 kg).

FIG. 80. Same as Figure 76 except for steel plate (10.88 kg).

FIG. 81. Same as Figure 76 except for steel plate (21.77 kg).

FIG. 82. Same as Figure 76 except hammer struck the ground directly; no plate used.

APPENDIX C

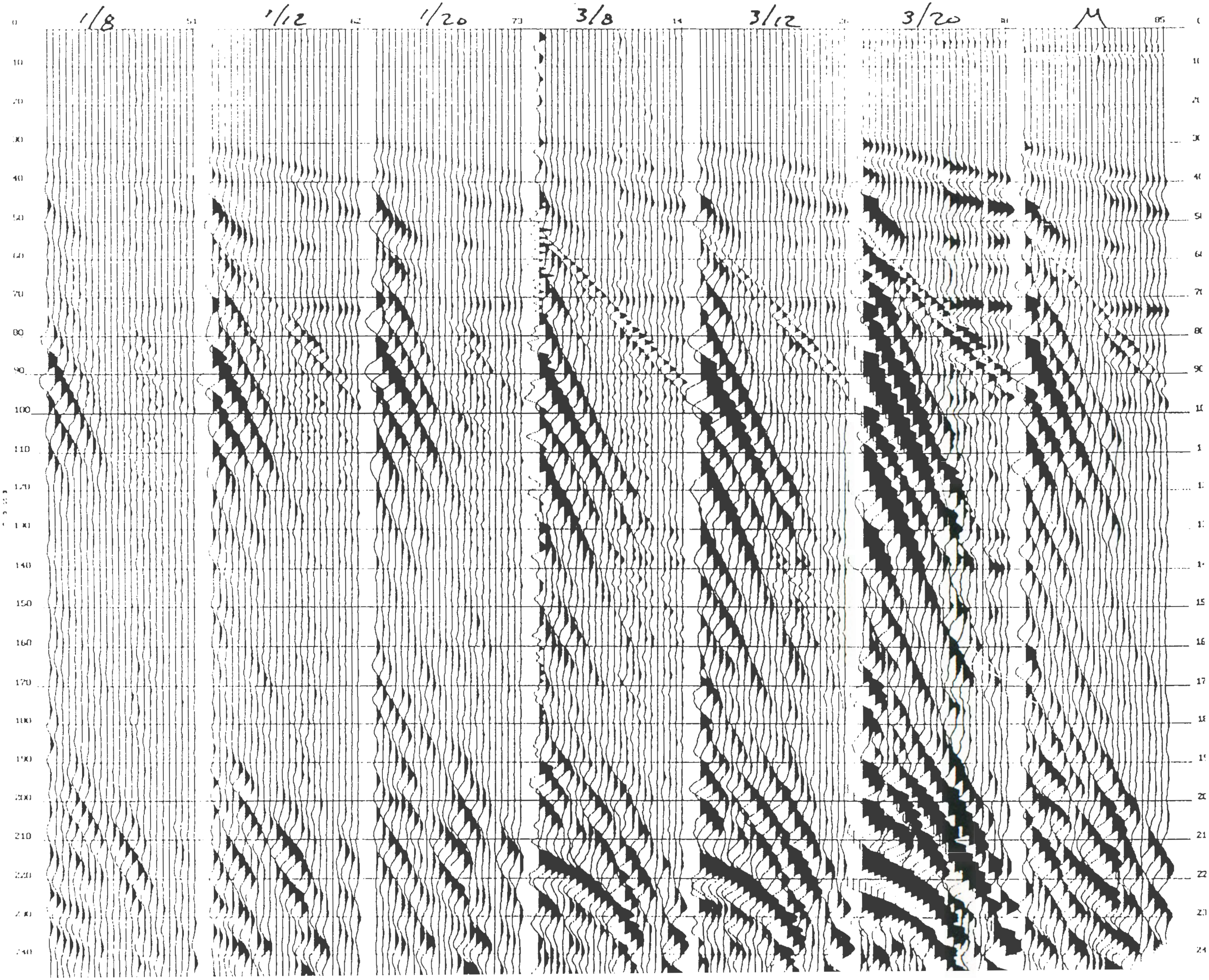
PART I

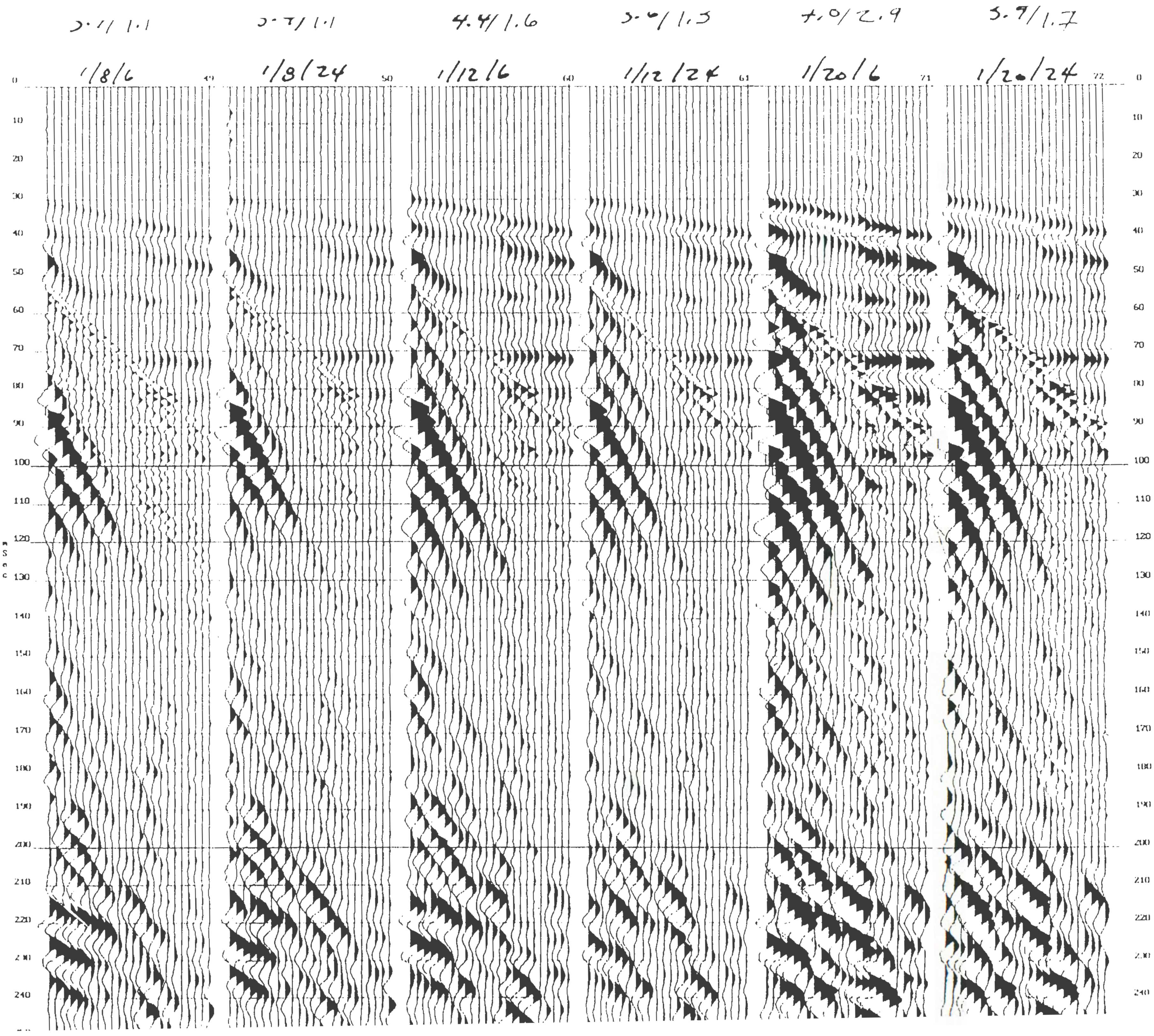
SOURCE CONSTANT

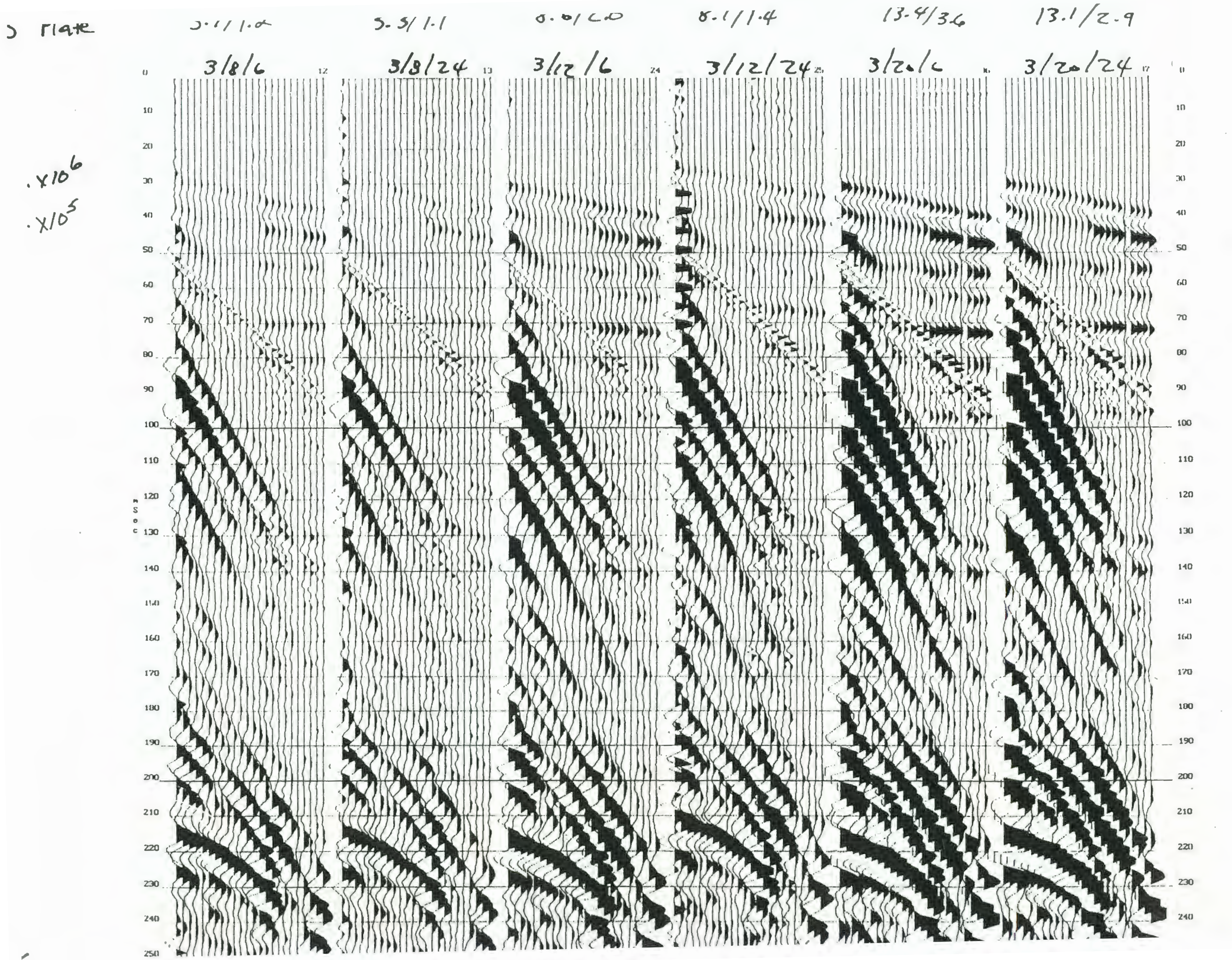
CHANGE PLATE WEIGHT

late

. x10^6
. x10^5



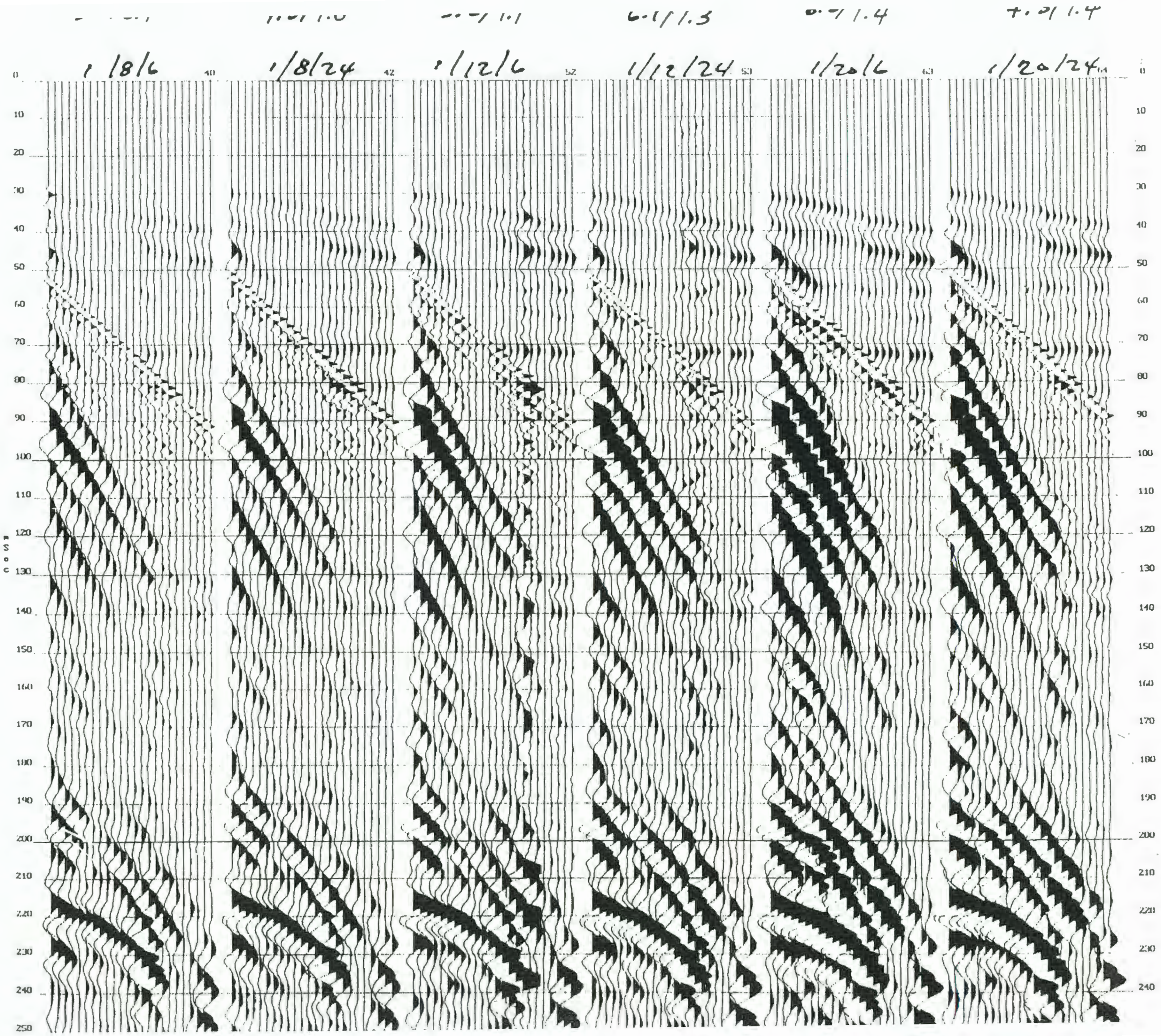

4.4/1.6
5.9/1.7
1/8/6
1/8/24
1/12/6
1/12/24
1/20/6
1/20/24
.X10^6
.X10^5


3/8/6
3/8/24
3/12/6
3/12/24
3/20/6
3/20/24
.x10^6
.x10^5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

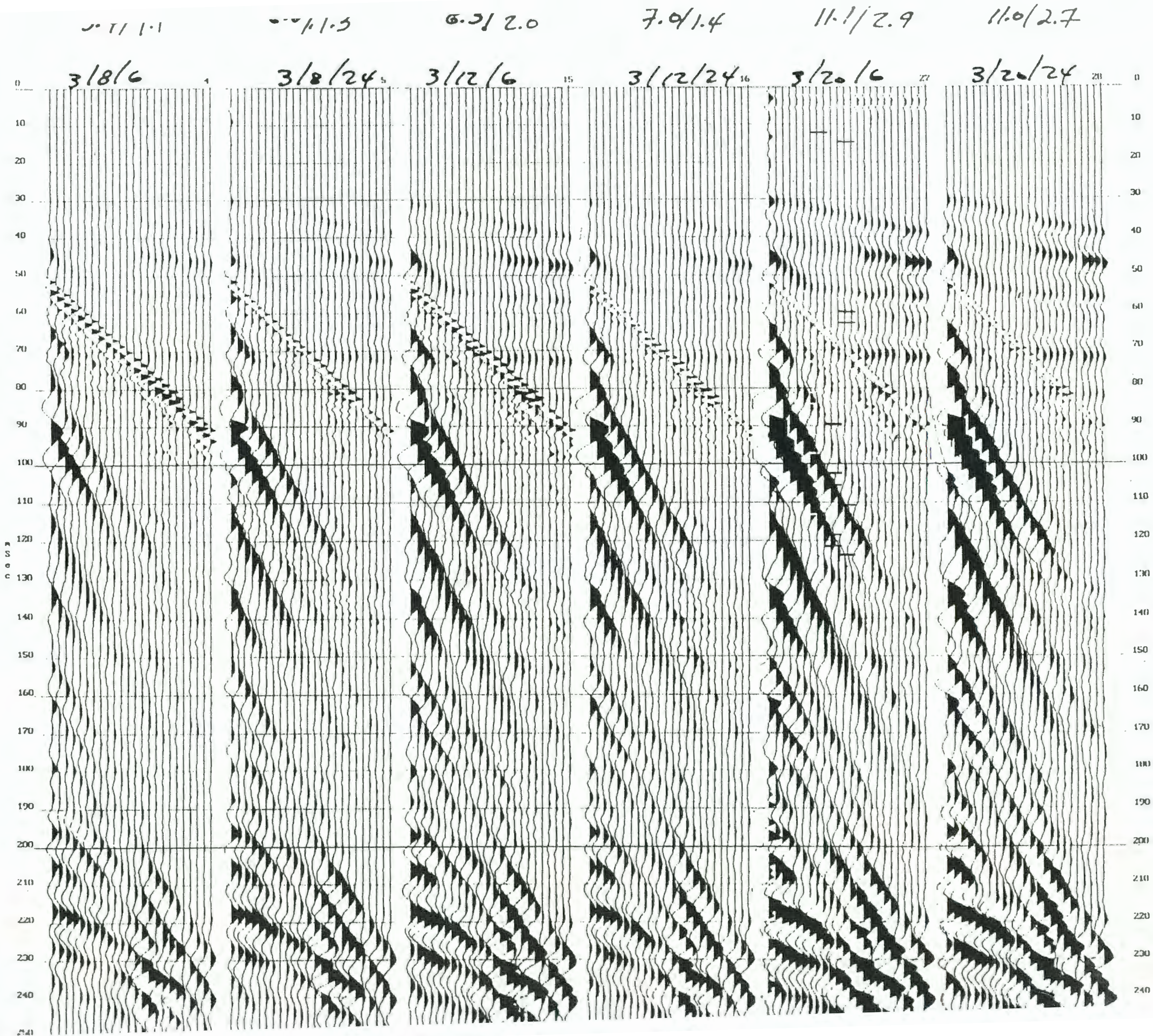
"Plate

.x10^6

.x10^5



10 plate



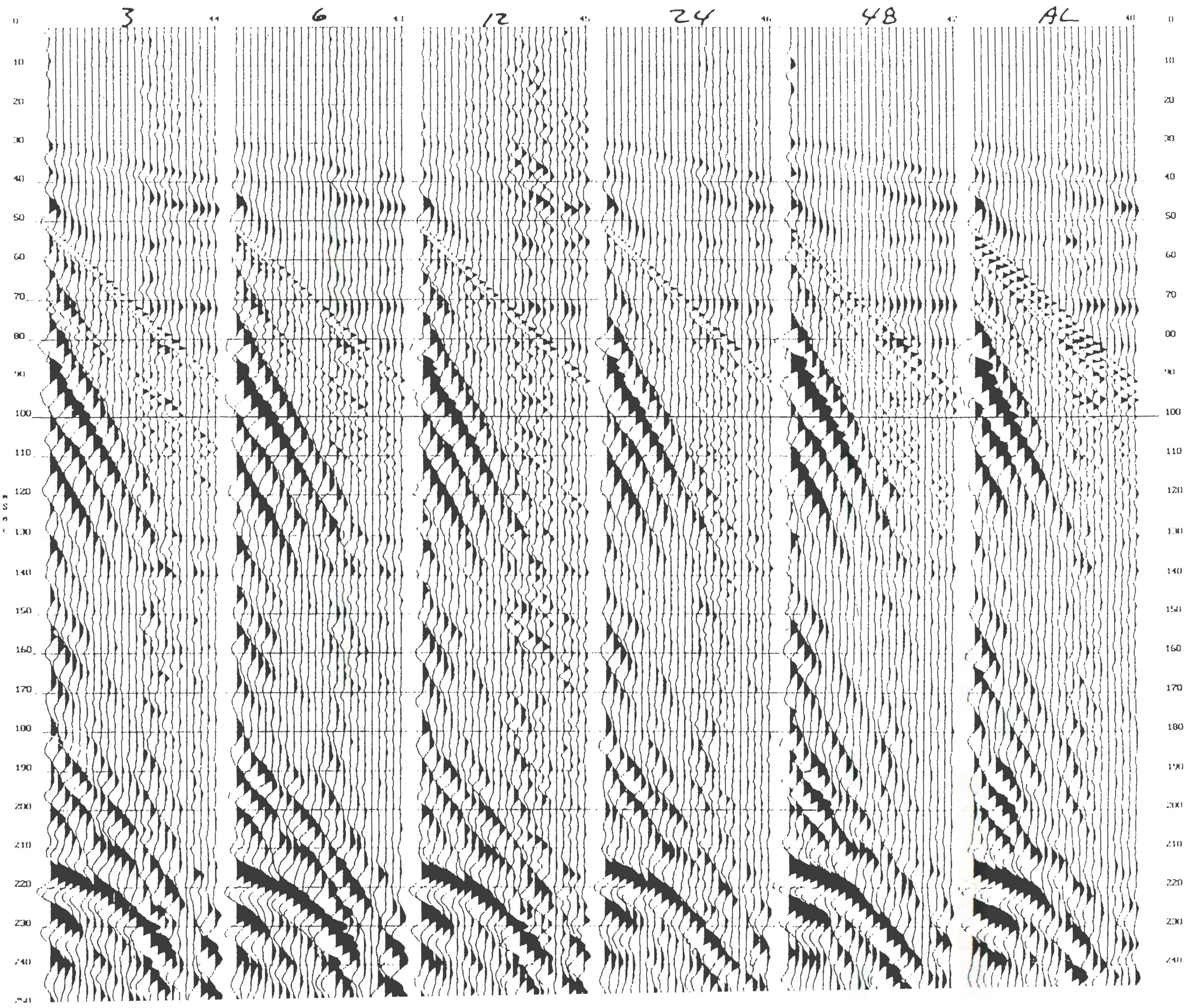
6.3/ 2.0
7.0/1.4
11.1/2.9
11.0/2.7
3/8/6
3/8/24
3/12/6
3/12/24
3/20/6
3/20/24
. X10^6
. X10^5
msec
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

3.6/1.1 3.0/0.9 3.6/1.1 3.6/1.1

(1/8)

.x10^6

.x10^5



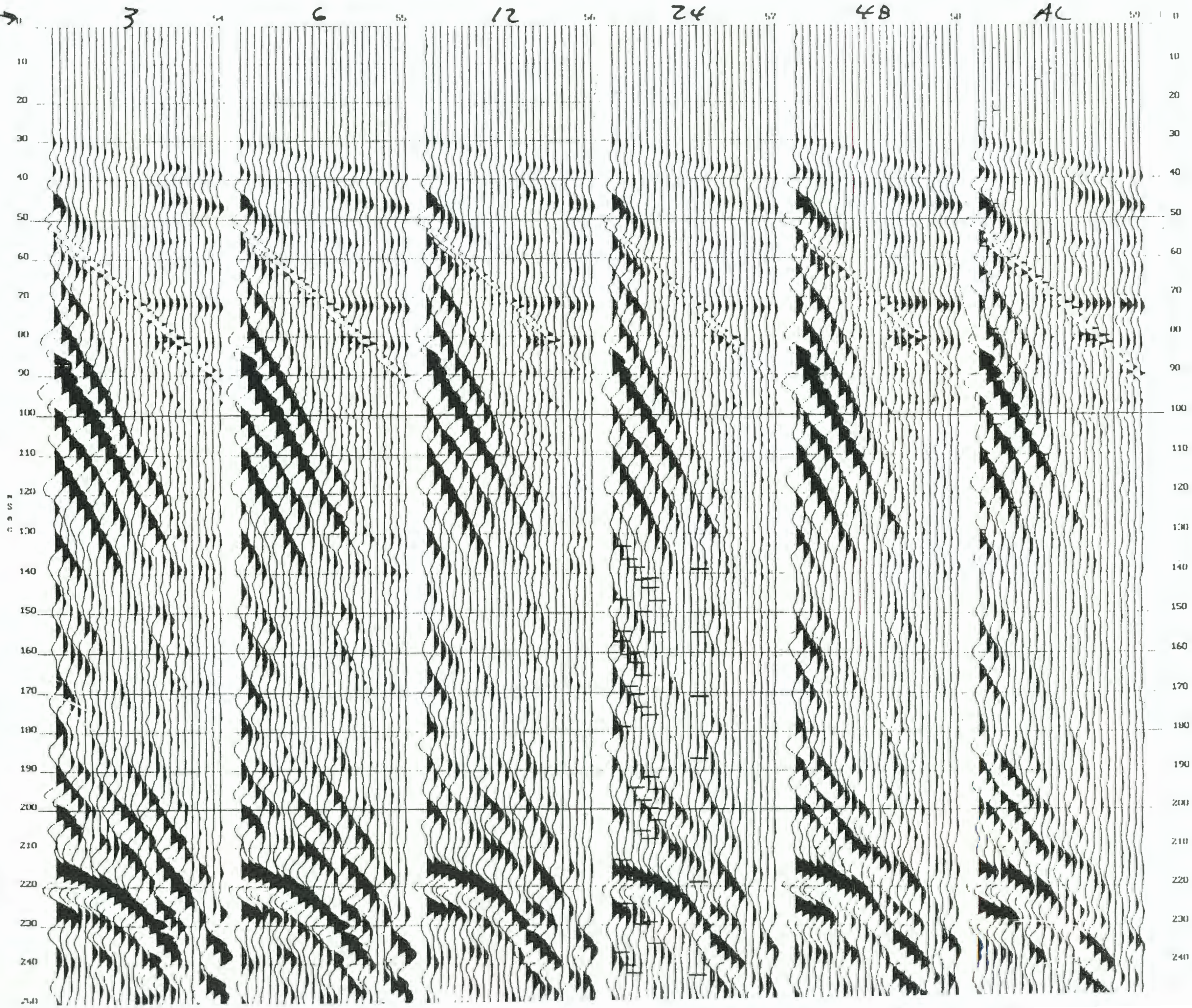
7 plate

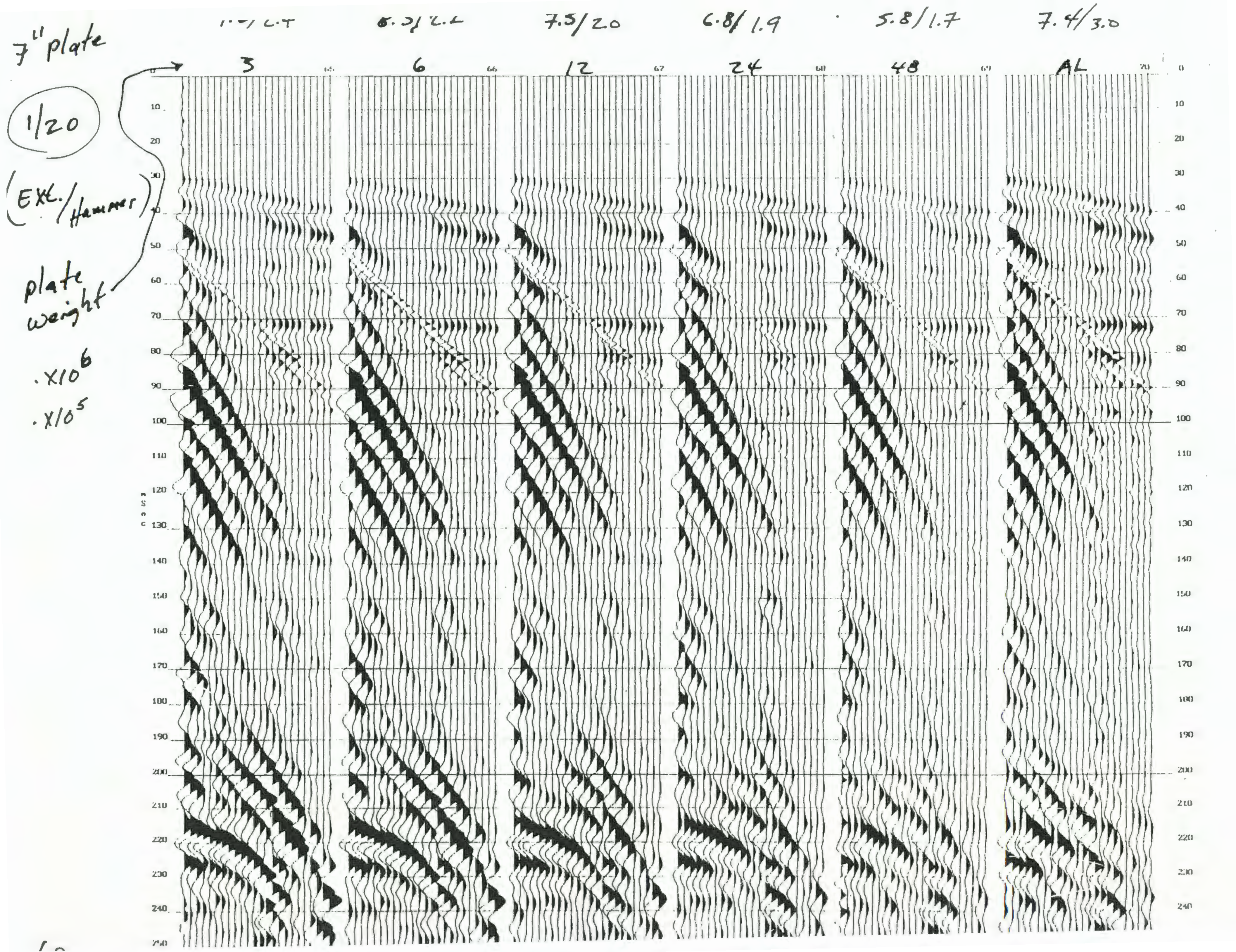
1/12

plate weight (lbs)

$.x10^6$

$.x10^5$



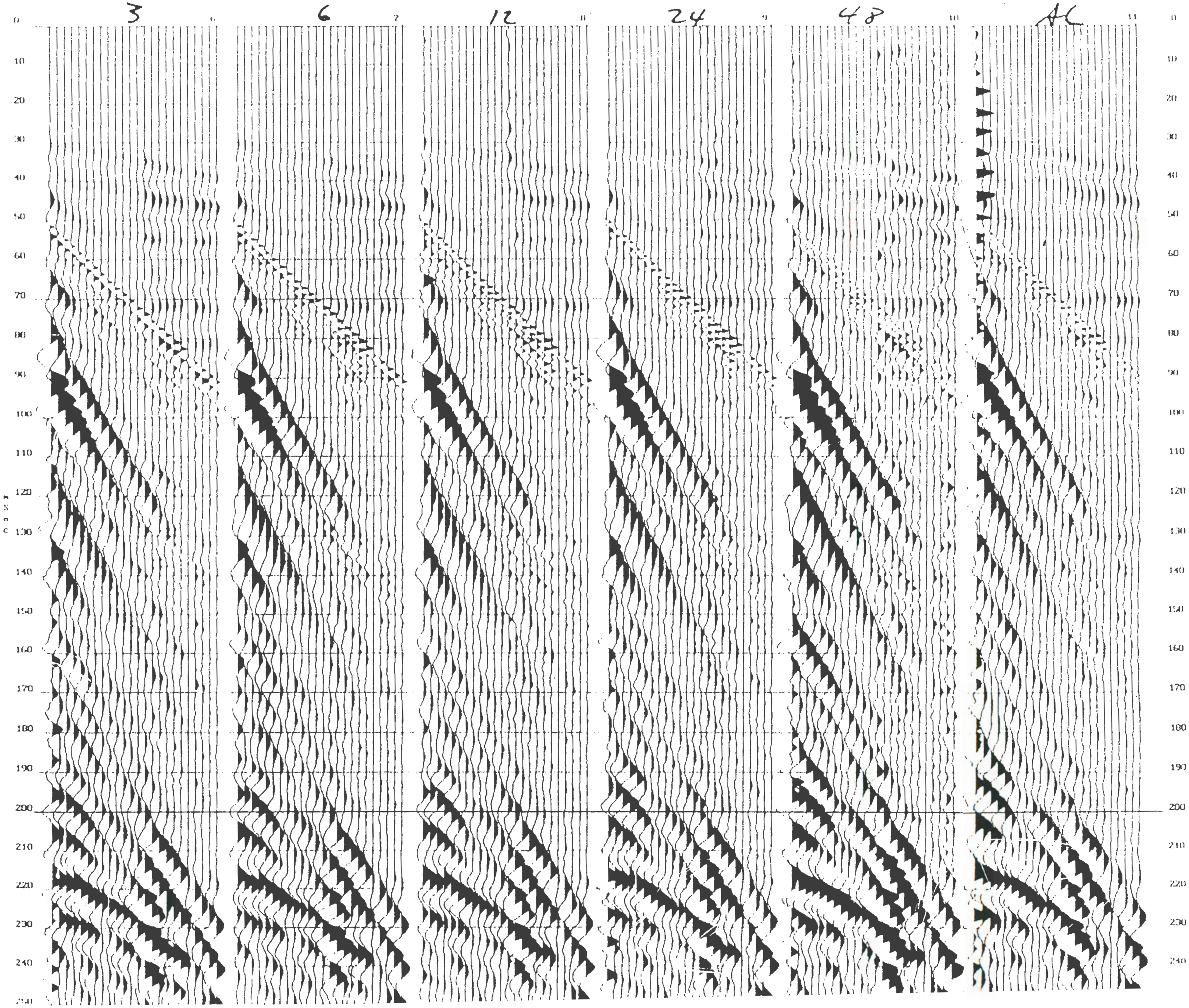


7" plate
1/20
(EXC./Hammer)
plate weight
.X10^6
.X10^5
7.5/20
6.8/1.9
5.8/1.7
7.4/3.0
3
6
12
24
48
AL
msec

7 Mar

3/8

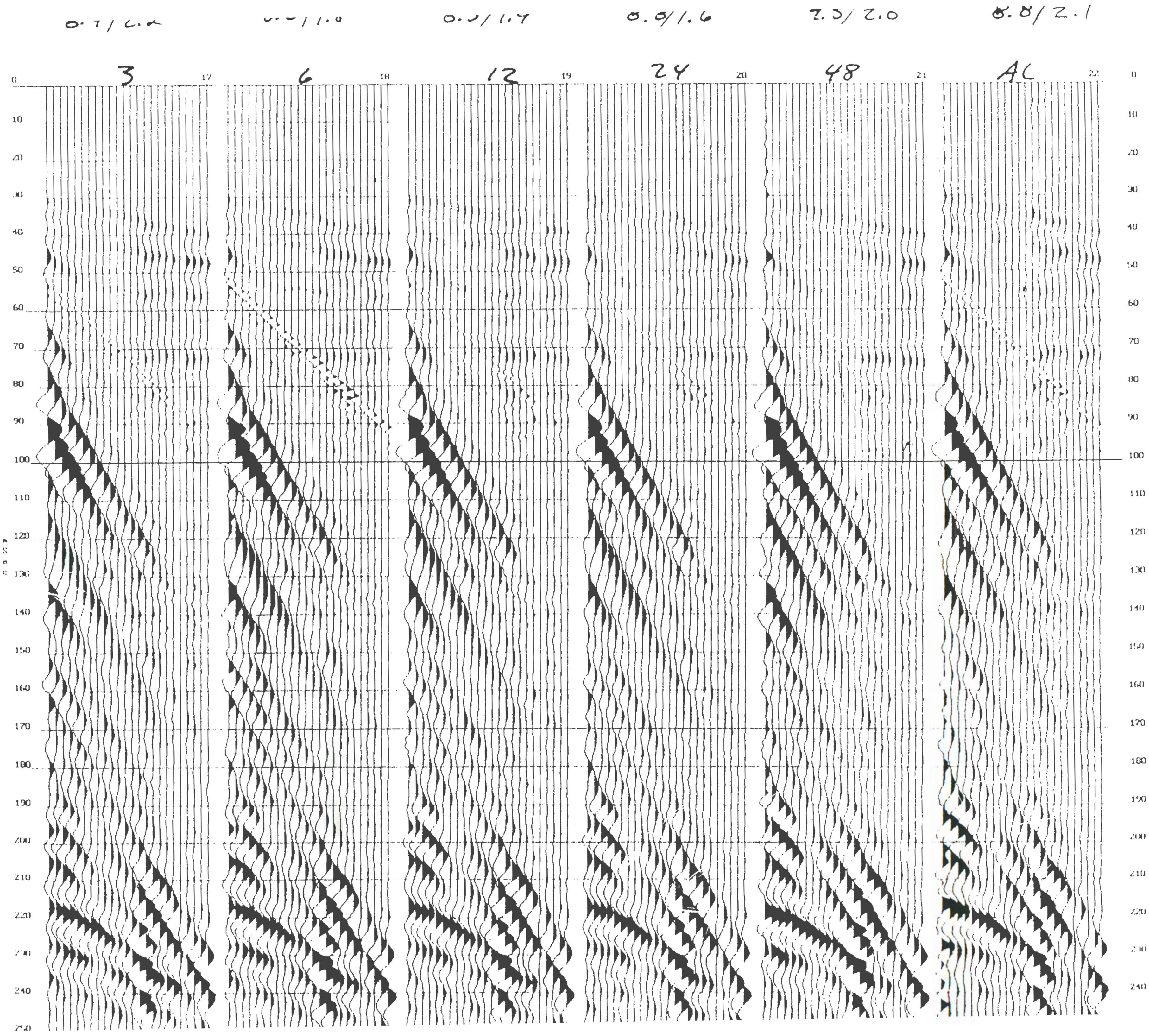
.x10^6



7" Plate

3/12

.x10^6

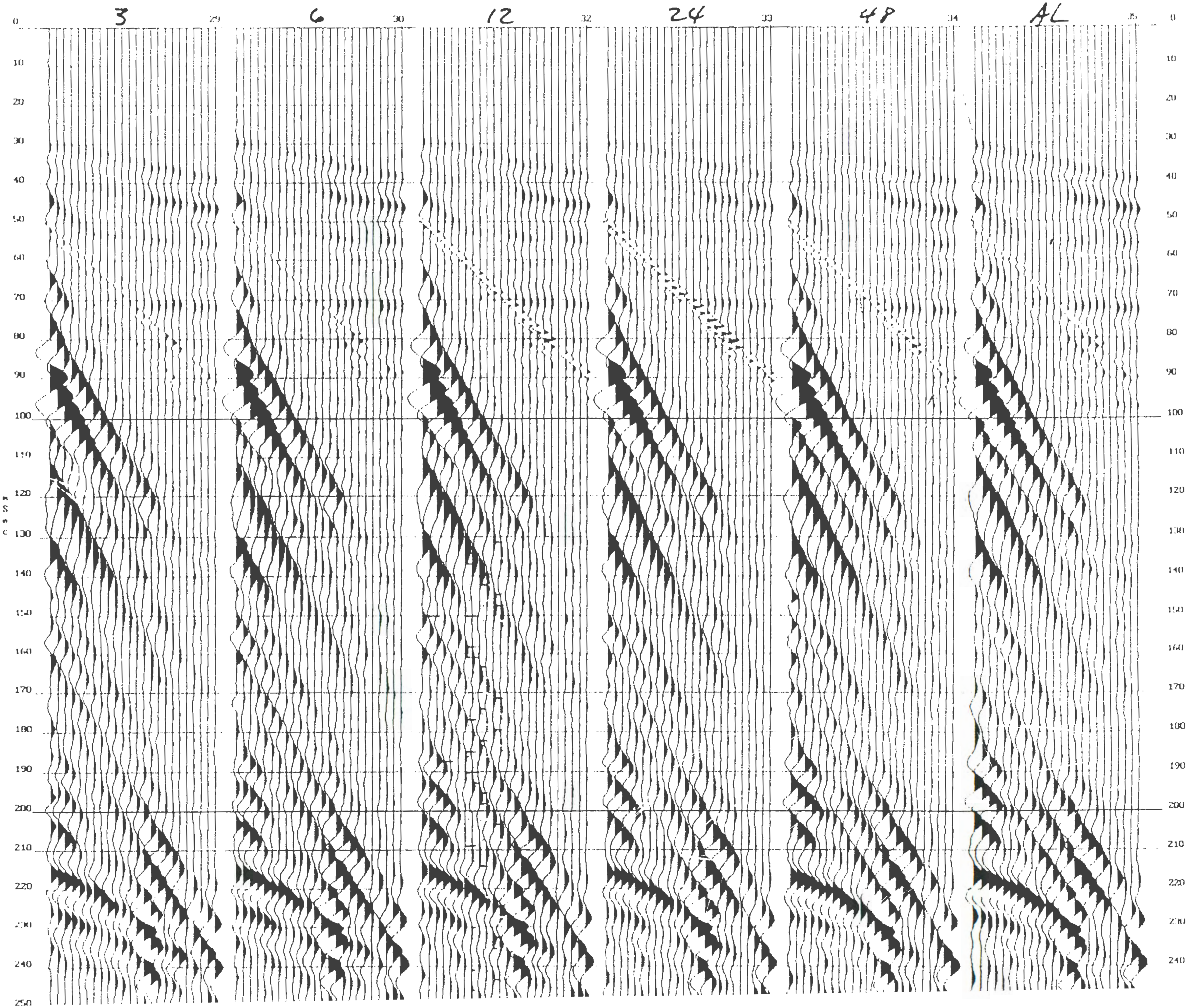


7 plate

(3/20)

.x10^6

11.7/2.4 12.5/3.2 12.7/2.9 12.4/2.4 13.1/2.8 13.6/3.4



APPENDIX C

PART II

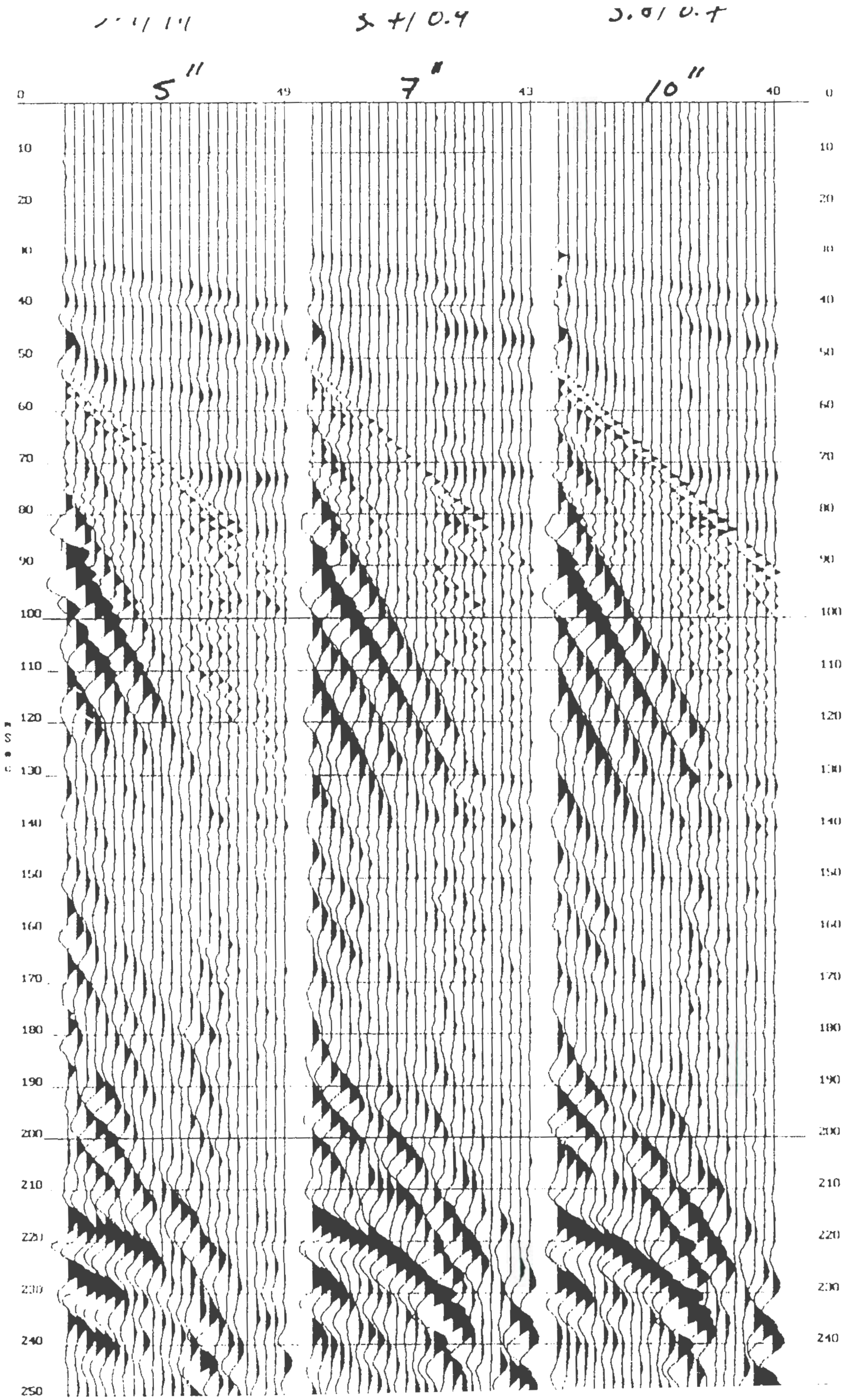
SOURCE CONSTANT

PLATE WEIGHT CONSTANT

VARY PLATE SURFACE AREA

1/8/6

.x10^6
.x10^5

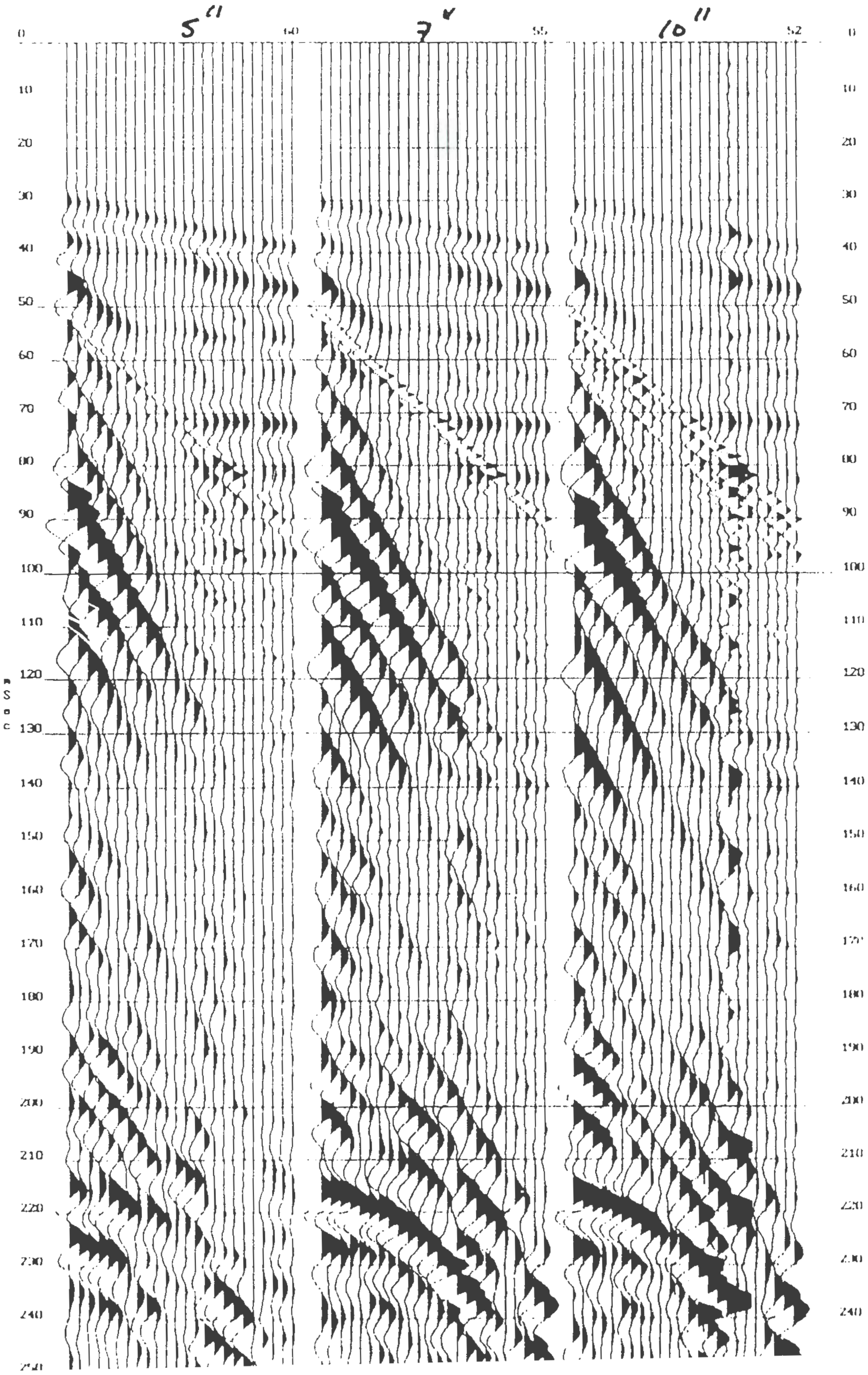


1/8/6

(1A)

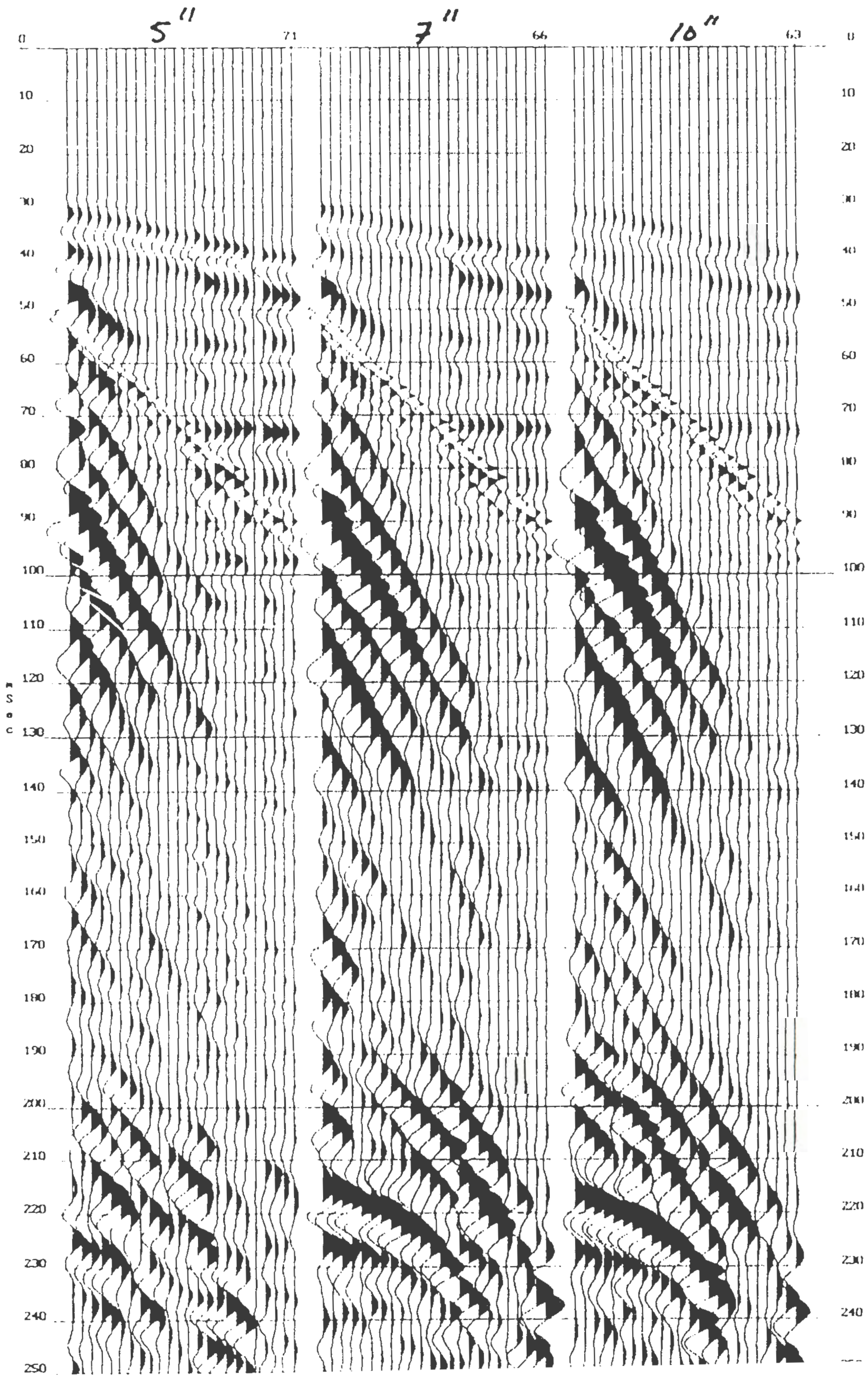
7.T//1.6 -.7//1.5 5.6//1.1 1/12/6

1/12/6



.x10^6
.x10^5

1/20/6

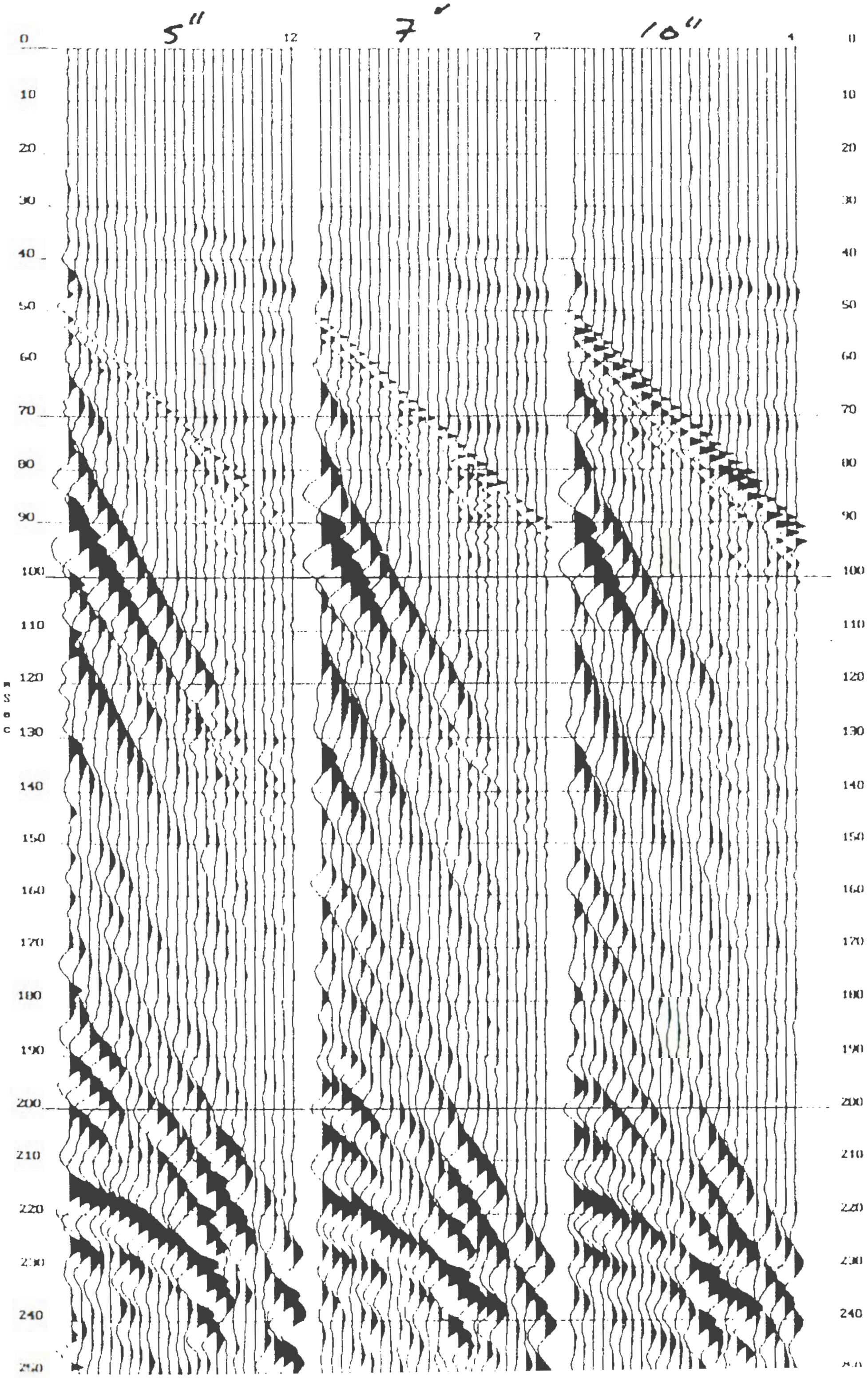


[redacted]

1/20/6

· $x10^6$

· $x10^5$



5"
12
7"
7
10"
4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250

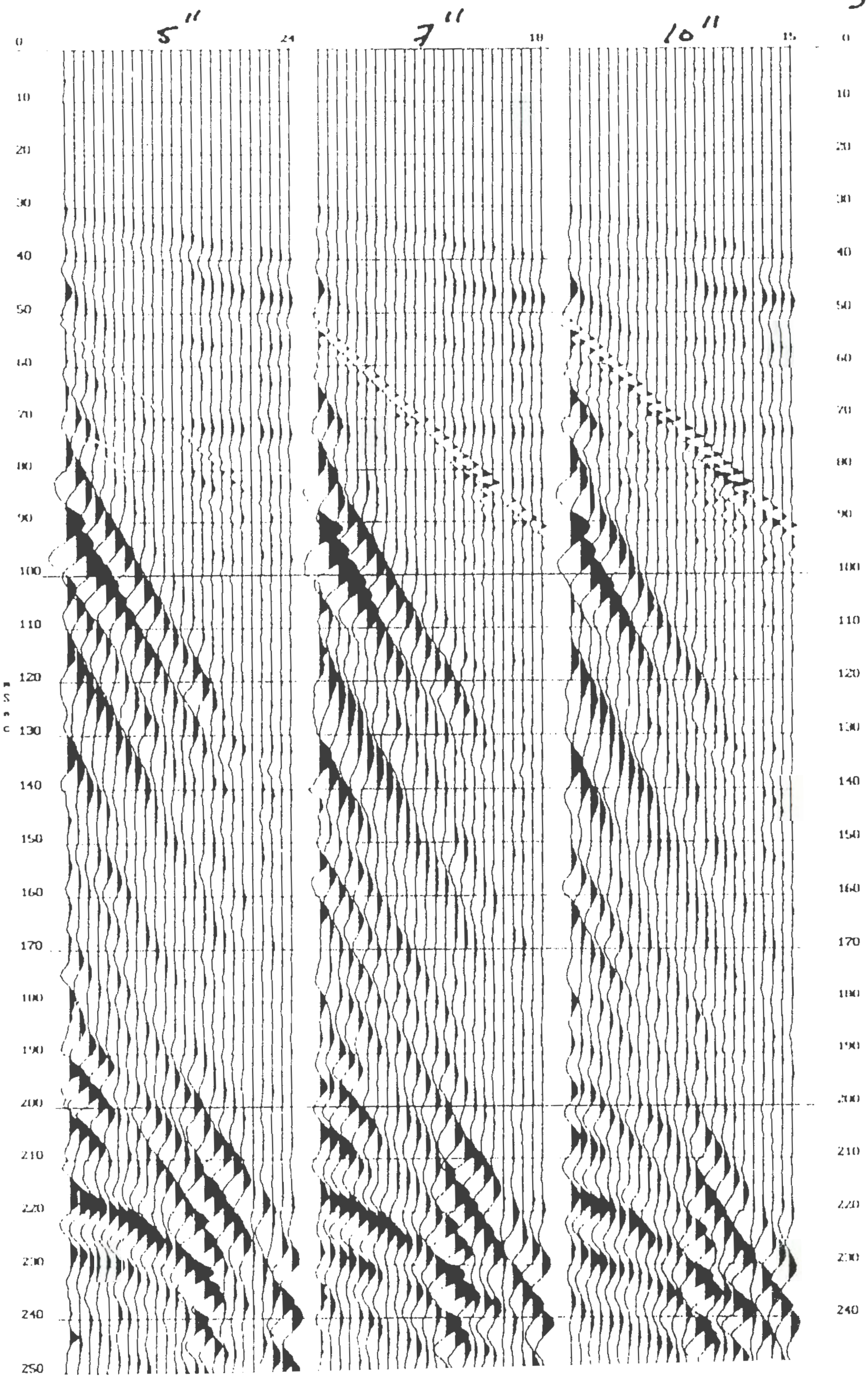
0.- •/2.0 0.0/1.0 0-5/2.0

[redacted]

3/12/6

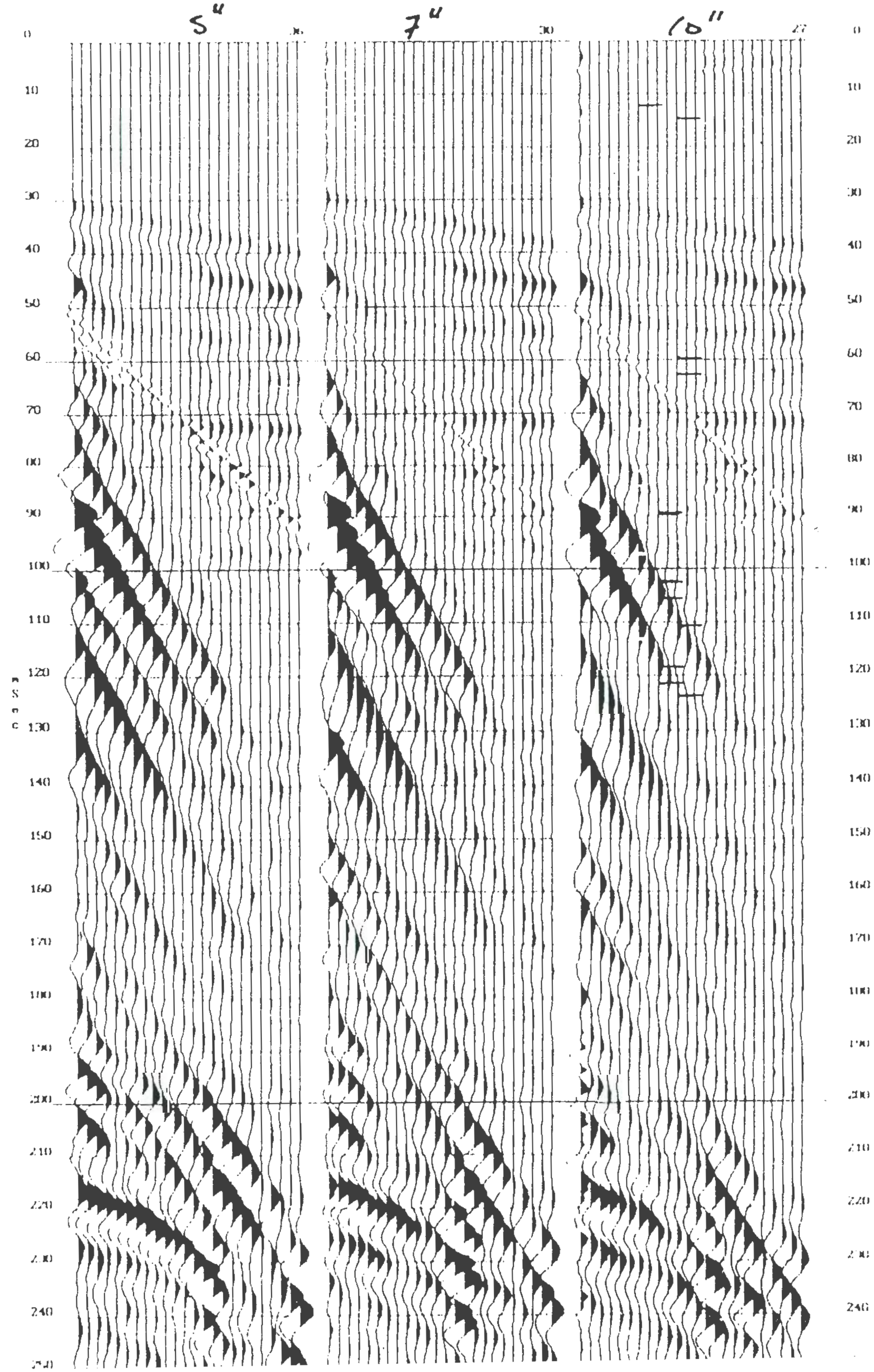
.x10^6

.x10^5



10.1/3.0 10.2/3.2 11.1/2.9 3/2016

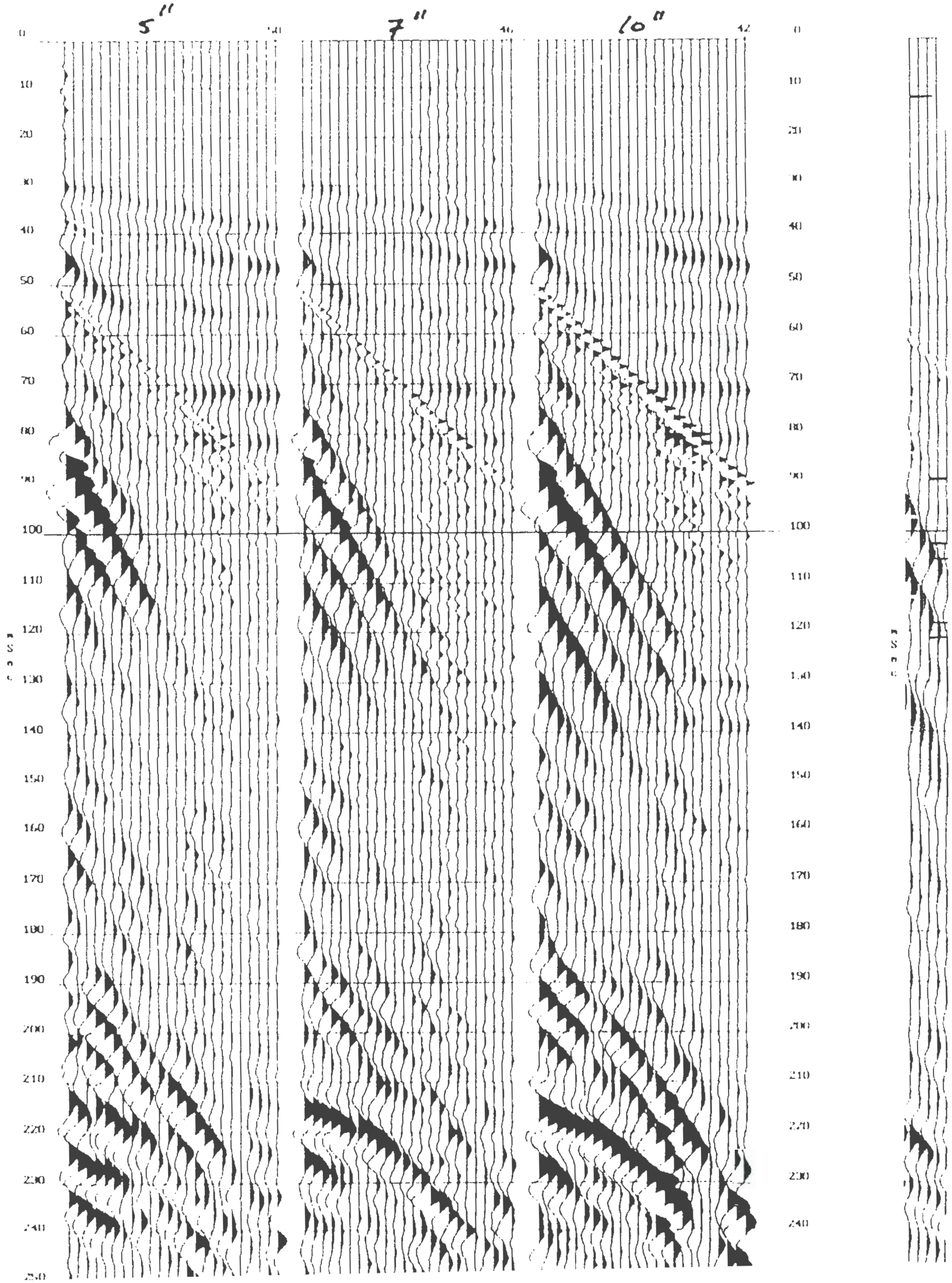
.x10⁶
.x10⁵



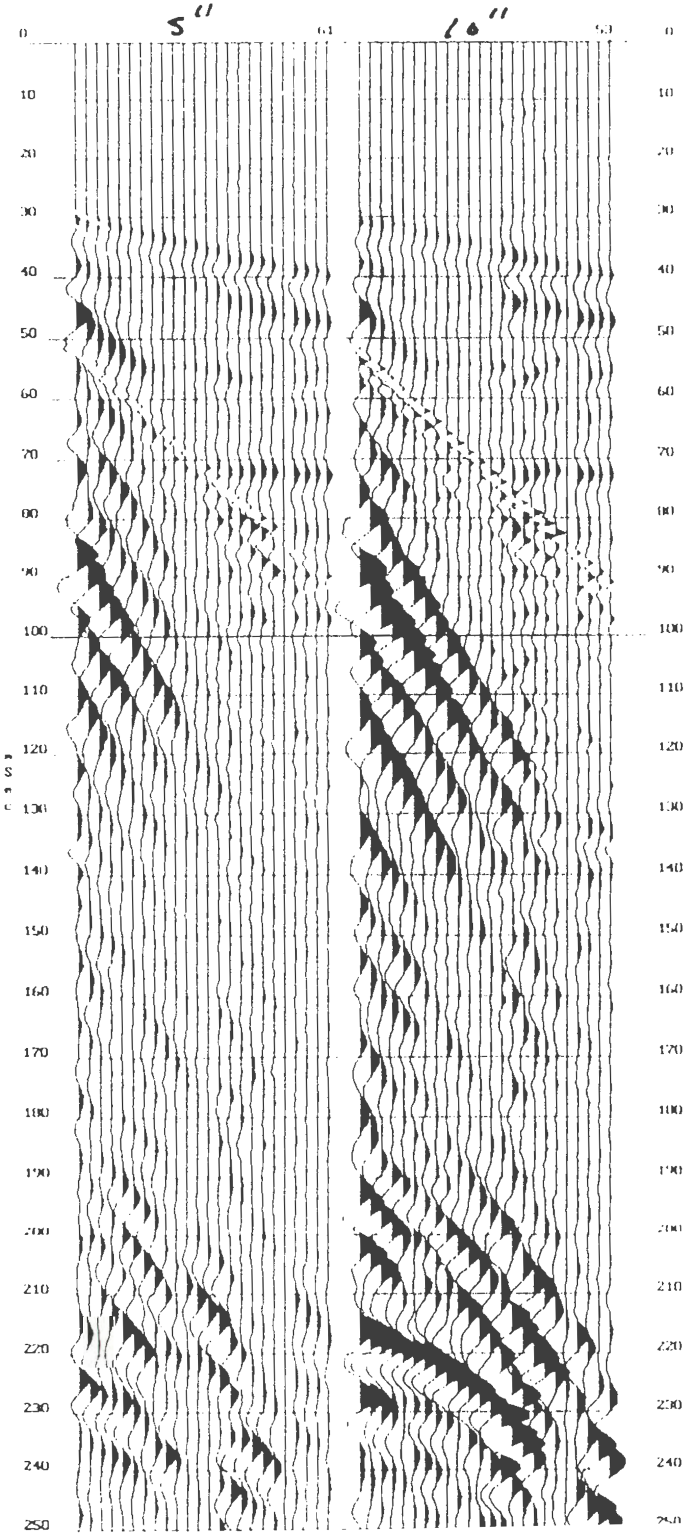
1/8/24

$.\times10^{6}$

$.\times10^{5}$



— / 1.3   1/12/24

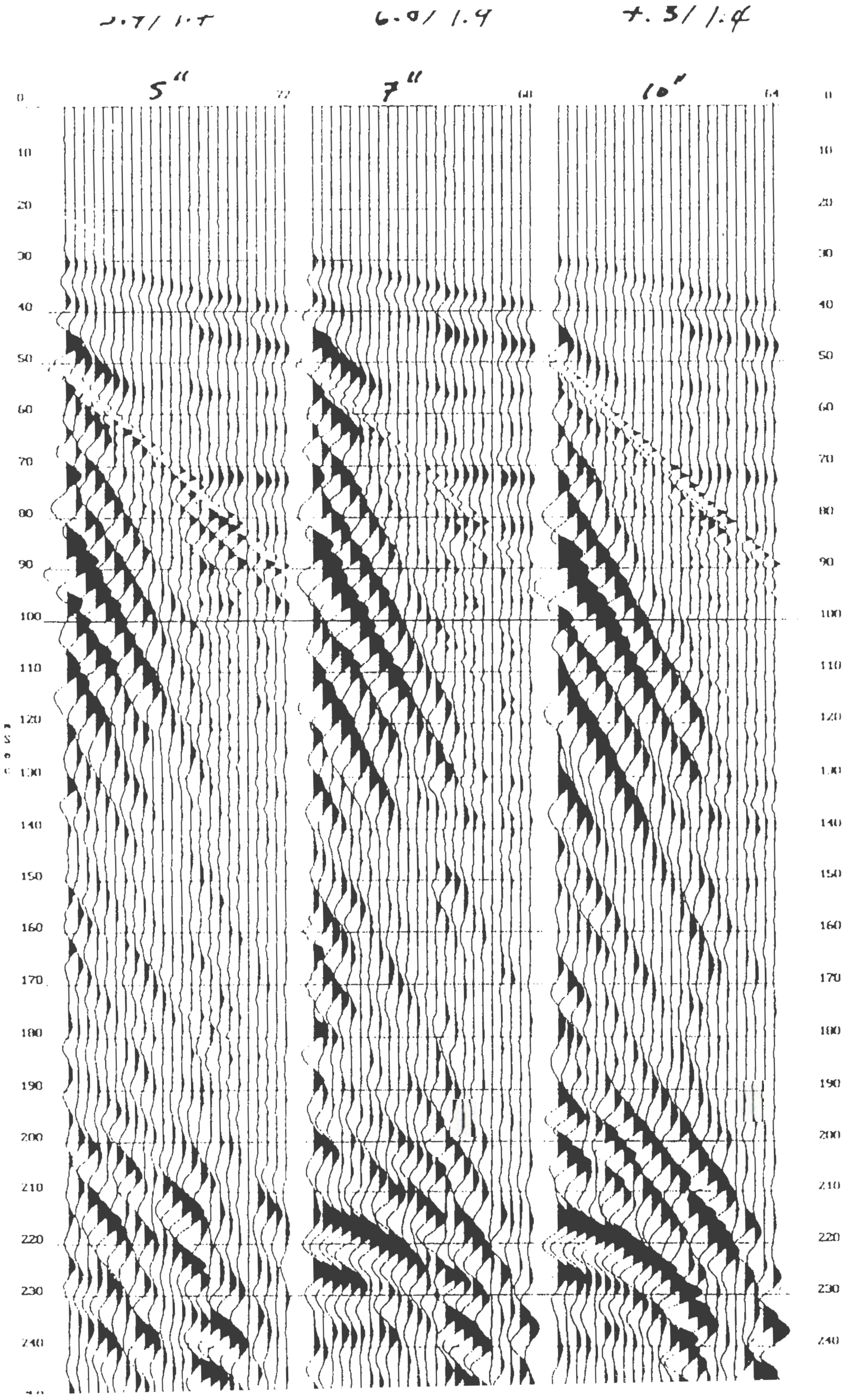


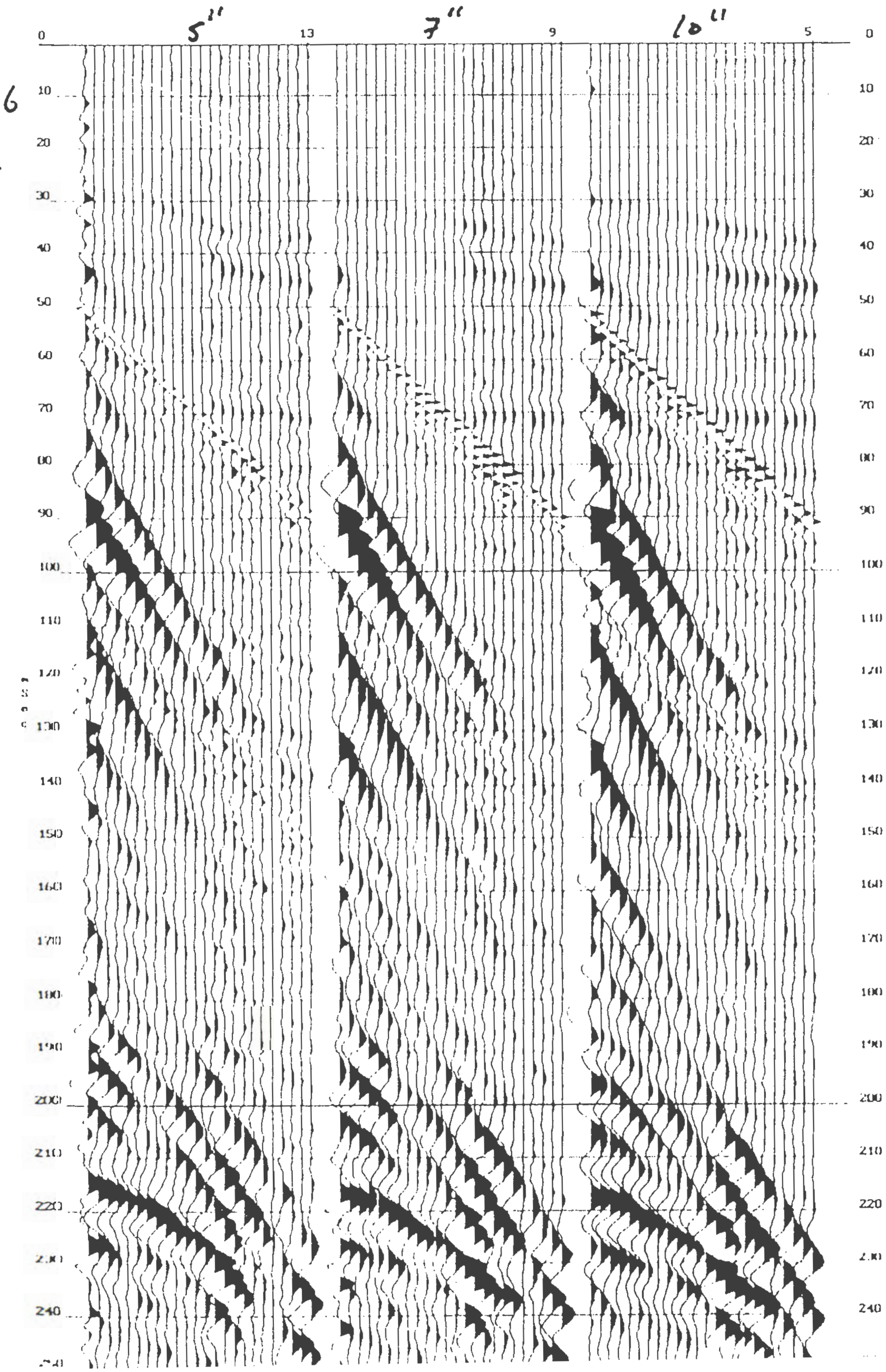
.x10^6

.x10^5

* 7" plate out due to spikes on record.

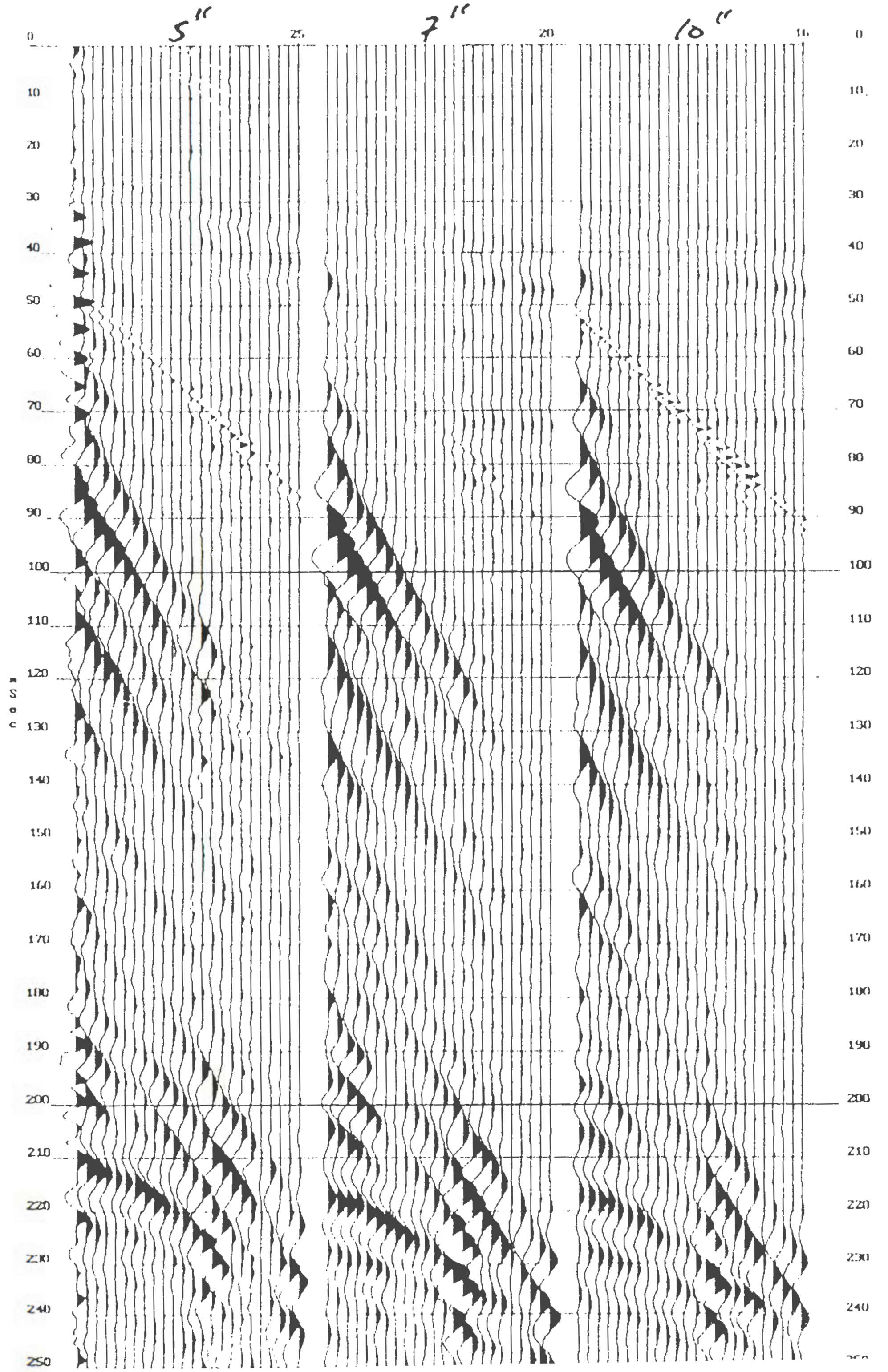
11


6.0/1.4
5"
7"
10"
1/20/24



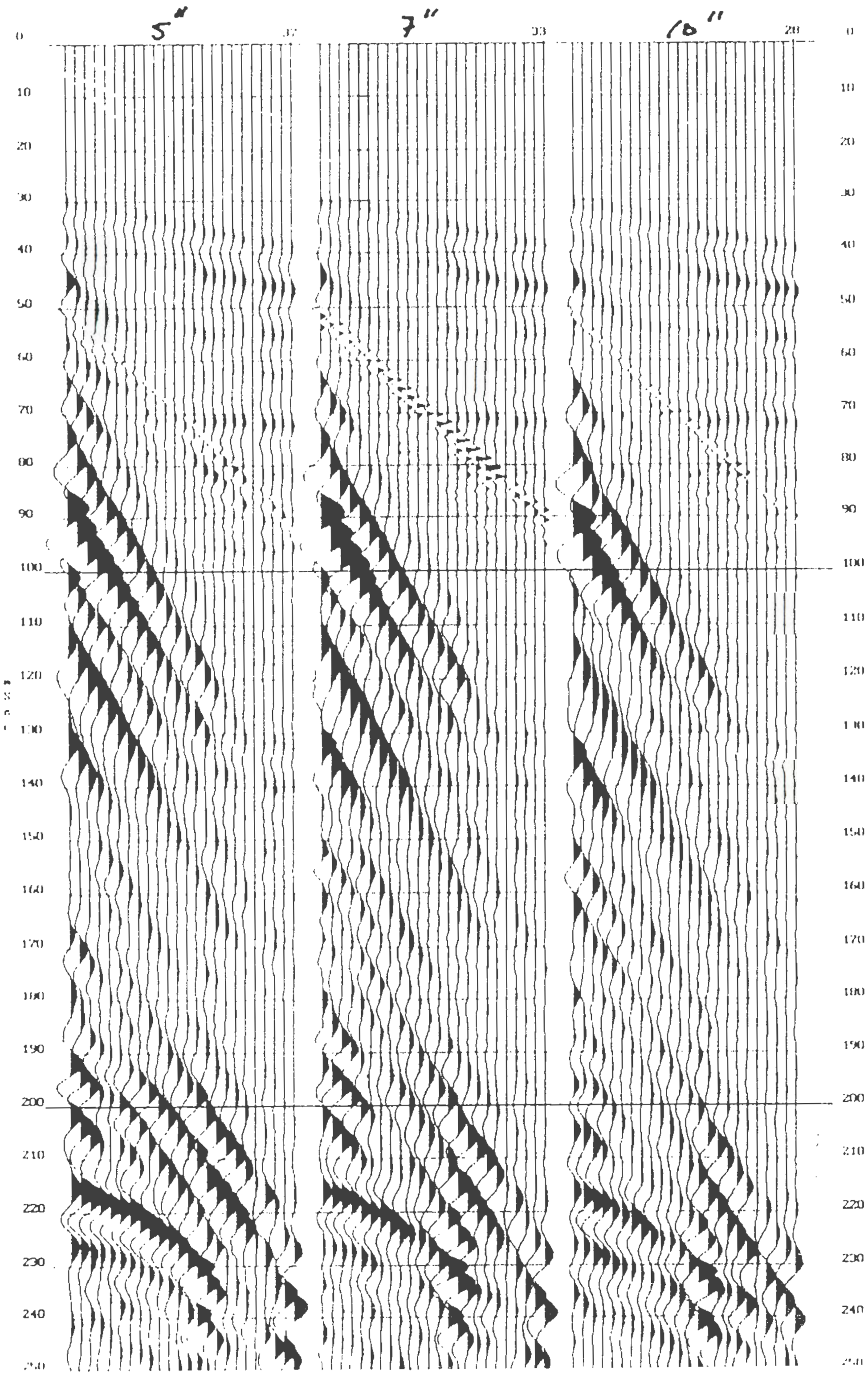
5"
7"
10"
0
13
9
5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

0.4/1.4 0.?/1.6 1.?/1.4 3/12/24



.x10^6

.x10^5


5"
7"
10"
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

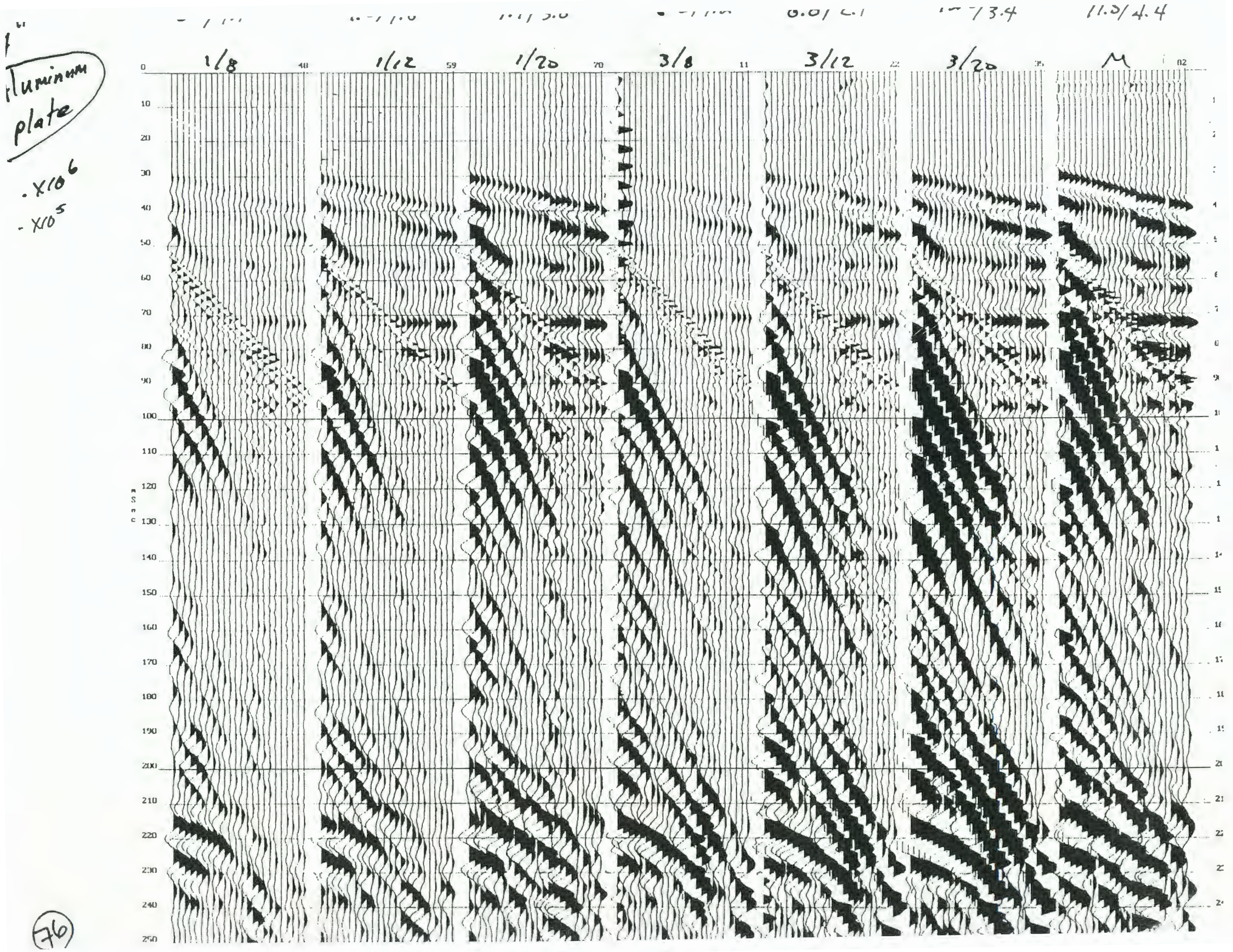
APPENDIX C

PART III

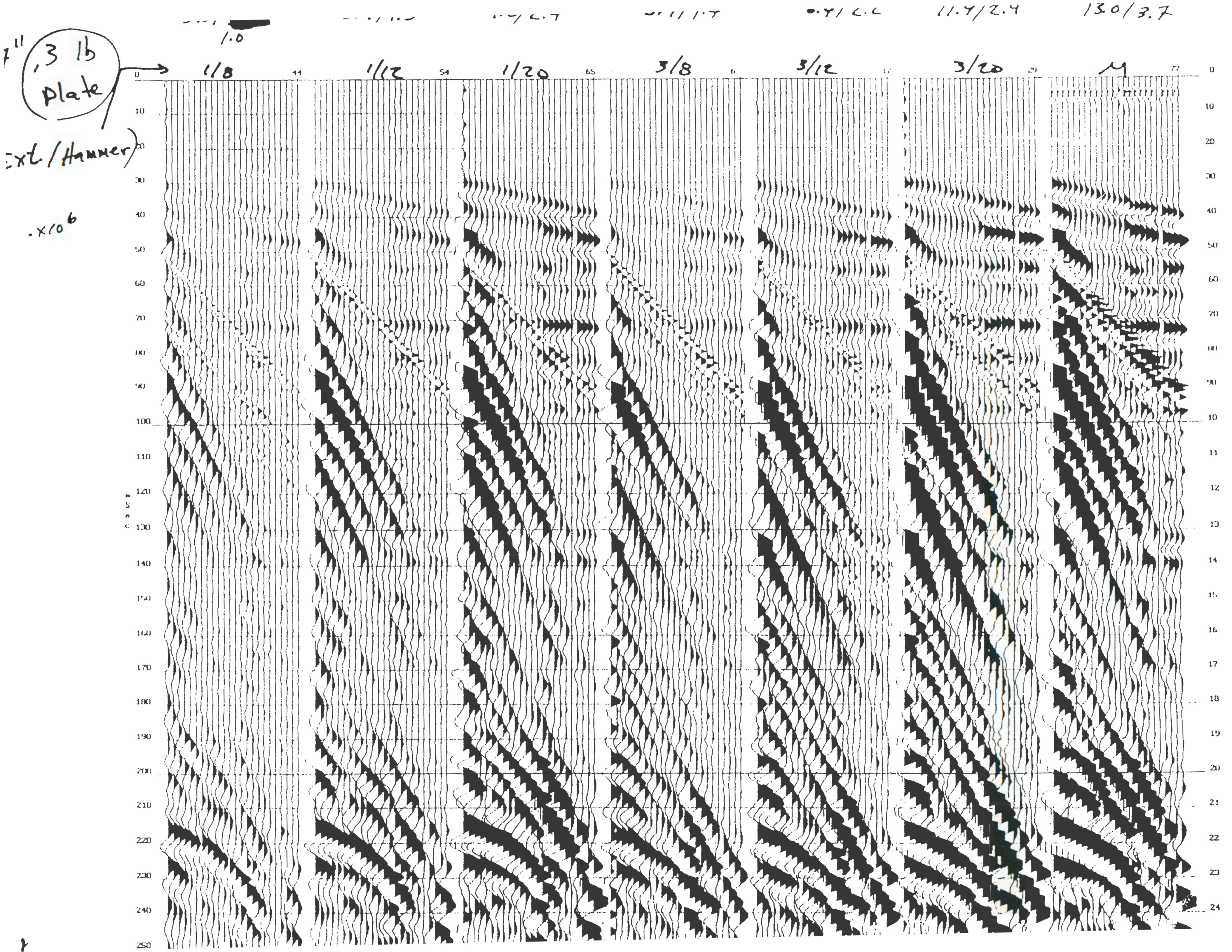
PLATE CONSTANT

(Both S.A. & weight)

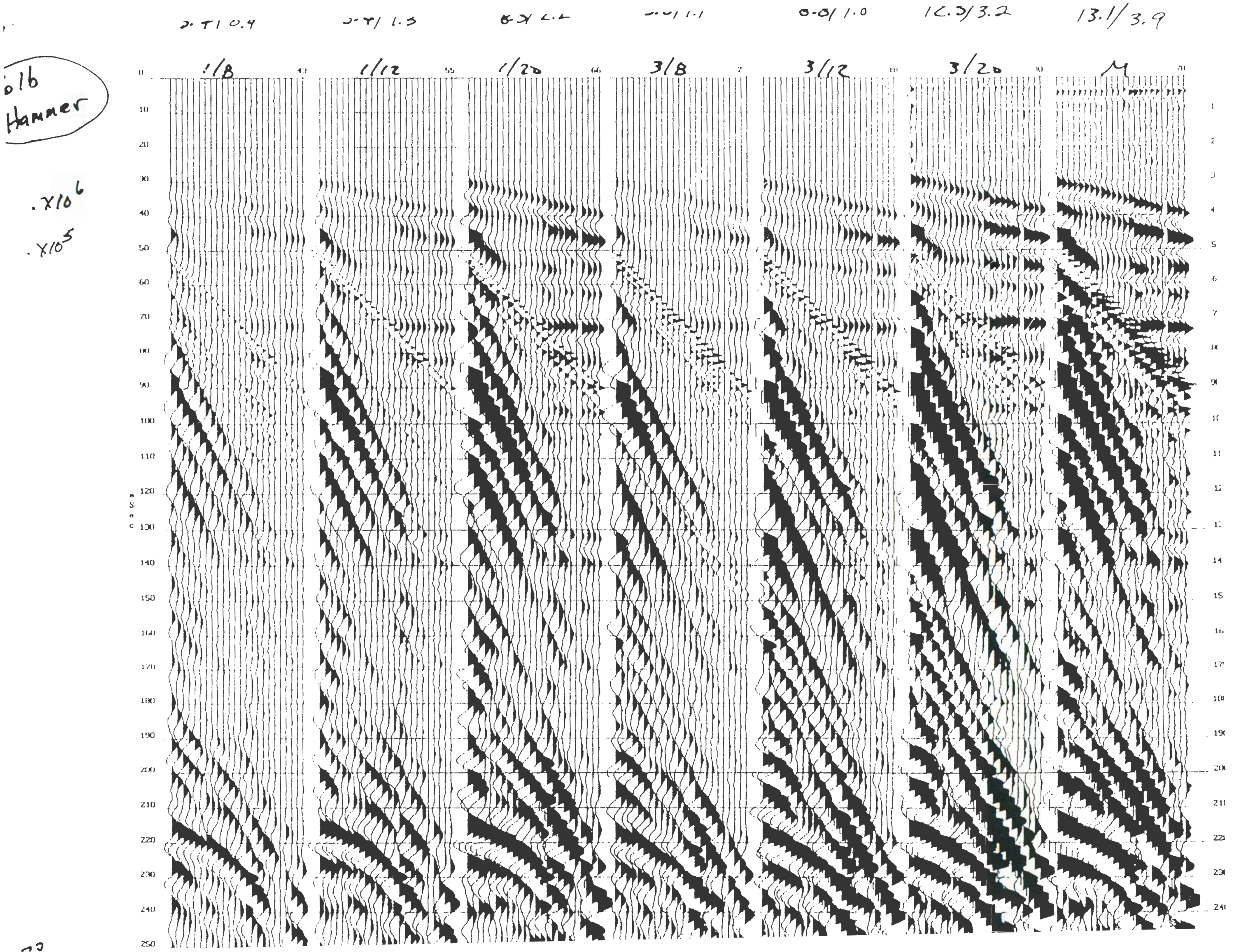
VARY SOURCE ENERGY



Aluminum plate
·X10^6
·X10^5
1/8
1/12
1/20
3/8
3/12
3/20
M
11.0/4.4
76



1.0
11.4/2.4
13.0/3.7
,3 lb
plate
Ext./Hammer
.x10^6
1/8
1/12
1/20
3/8
3/12
3/20
M

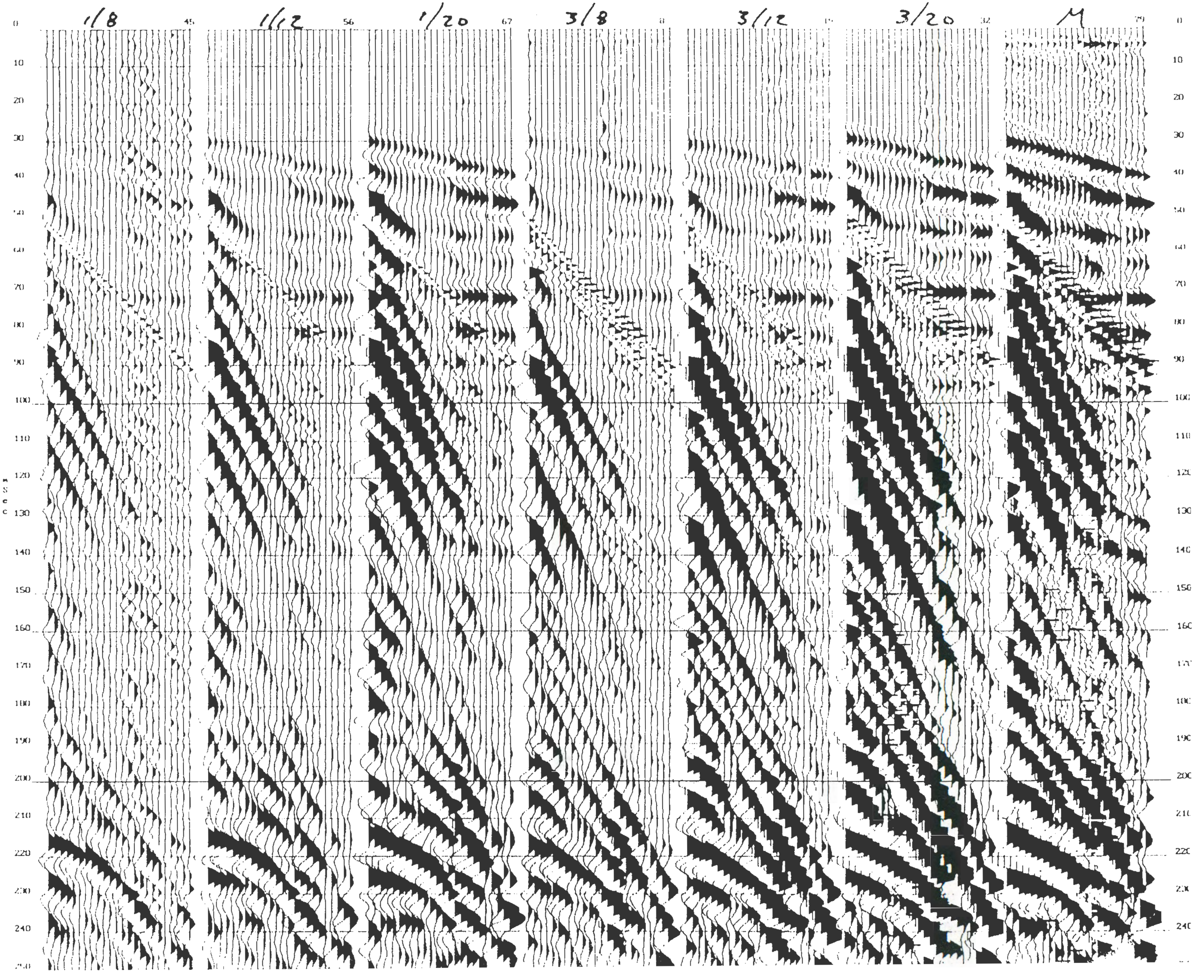


Hammer
1/8
1/12
1/20
3/8
3/12
3/20
M
12.5/3.2
13.1/3.9

216 late

.x10^6
.x10^5

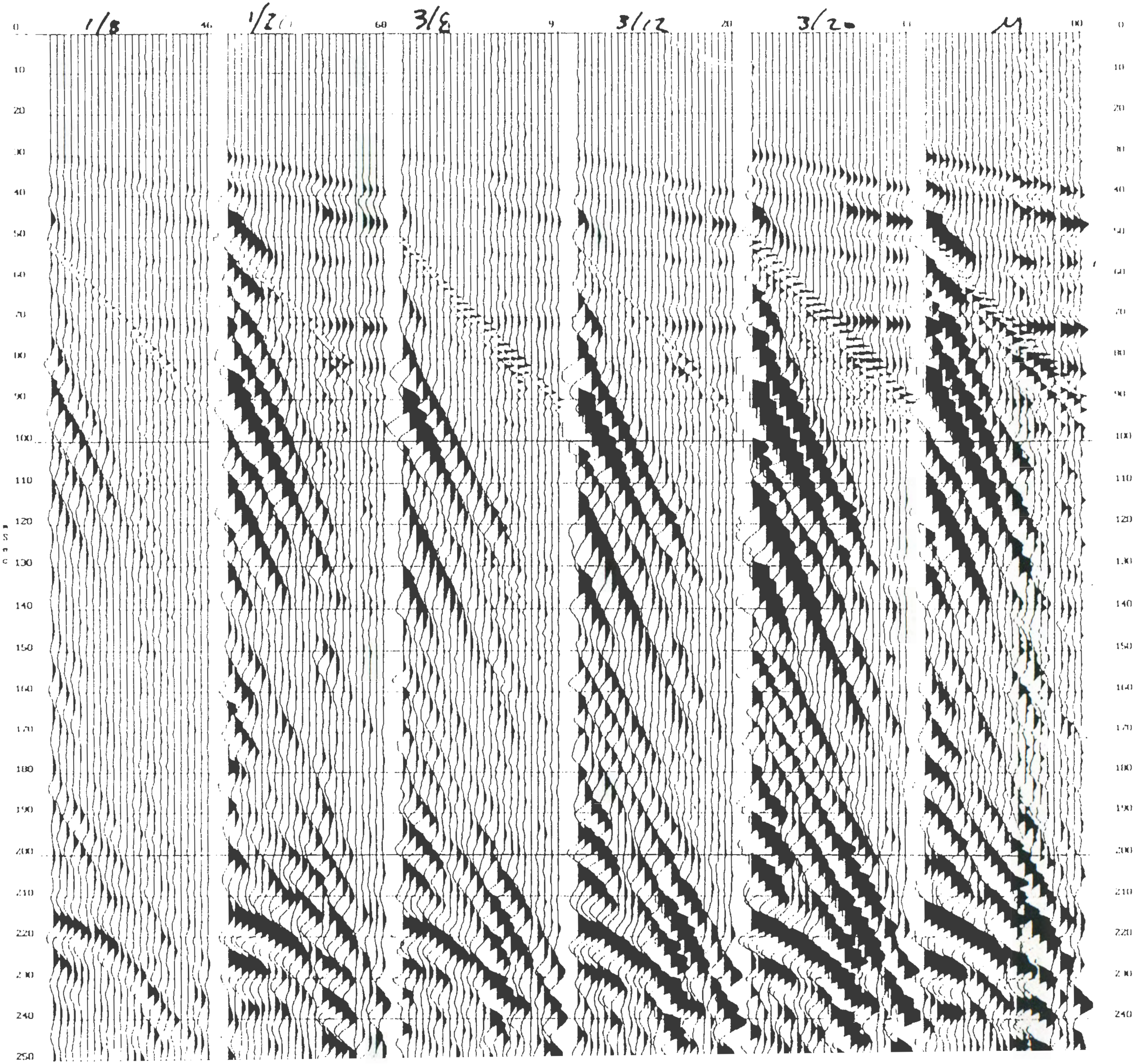
14.6/3.9



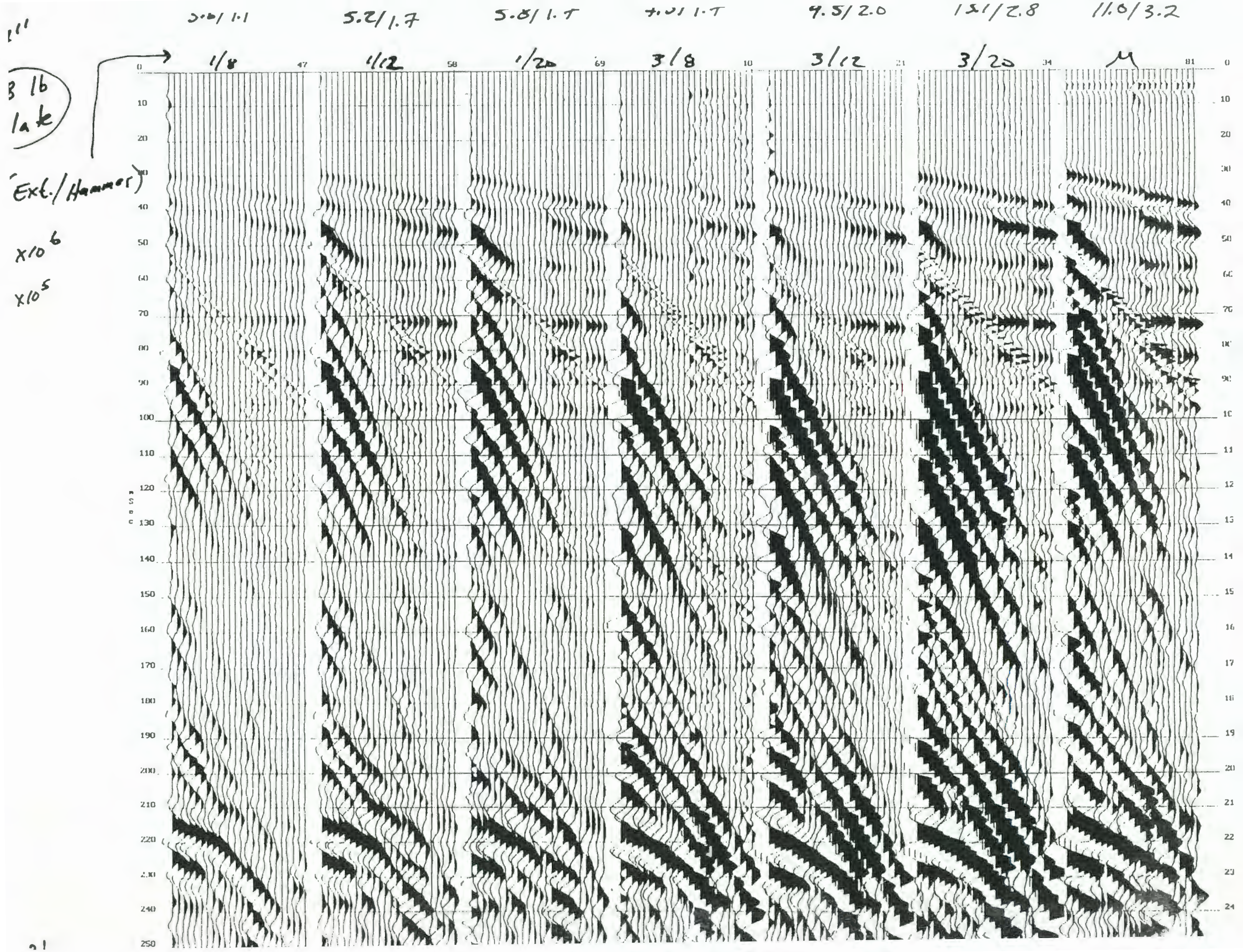
4 lb plate

x10^6

.x10^5



on



5.2/1.7
9.5/2.0
11.0/3.2
1/8
1/12
1/20
3/8
3/12
3/20
M
Ext./Hammer)
x10^6
x10^5
0
10
20
40
50
70
90
100
110
120
130
140
150
160
170
190
200
210
220
240
250

ate

. x10^6

. x10^5