Field comparison of shallow seismic sources

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GEOPHYSICS. VOL 51 . NO. 11 I (NOVEMBER 19861: P. *2067-2092. 30* FIGS..1, TABLE.

GEOPHYSICS. VOL. 51. NO II (NOVEMBER 1986L P. 2067-2092. 30 FIGS., I TABLE

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ABSTRACT

Choosing a seismic source for a shallow reflection survey can be the most pivotal decision for the engineering geophysicist. The intent of this paper is to present data that will assist in selection of a shallow seismic source best meeting the goals within the constraints of specific projects, particularly in areas where the water table is near the surface. The data were collected (and displayed as seismograms and amplitude spectra) for 15 different shallow seismic sources in October, 1985 at a single site in New Jersey; they show the different characteristics of each source. Considering the almost three orders of magnitude difference in total source energy between the largest and smallest source, we chose a display format that presented the data as objectively as possible, while still allowing direct comparisons. Two strong reflections at about 100 and 130 ms probably mark the top and bottom of a clay unit 80 m below the surface at this site. Our previous work and that of our colleagues suggests that, given a specific set of site characteristics, any source could dominate the comparison categories addressed here.

INTRODUCTION

The use of seismic reflection methods in engineering, mining, and groundwater applications has increased rapidly during the past five years (Doornenbal and Helbig, 1983; Hunter et al., 1984; Steeples, 1984; Ruskey, 1981). For these applications, a wide variety of sources have been developed by numerous investigators. During October of 1985, personnel from the Geological Survey of Canada, Kansas Geological Survey, New Jersey Geological Survey, and U. S. Geological Survey organized a field comparison of the most commonly used shallow reflection seismic sources at the Brigantine National Wildlife Refuge in New Jersey. This paper summarizes the major results of this field comparison. We have attempted to display the data objectively and leave all judgments of the relative merits of the sources to the reader.

A complete data compilation from this experiment will be available as an open-file report from the U.S.G.S., the Geological Survey of Canada, or the New Jersey Geological Survey. Data tapes in SEG-Y format are available from the Kansas Geological Survey.

In many cases, the choice of an energy source is critical to the success of a shallow reflection profiling project. The data presented here indicate only the relative quality of sources at one site in a particularly favorable environment. Pullan and MacAulay (1985) show that the quality of seismic signals from various seismic sources is strongly site-dependent.

There are many factors to consider in a source evaluation. This experiment primarily addresses the questions of *energy* and *frequency content.* From the data presented, the reader can also compare the *source wavelets,* the relative *portability,* an order-of-magnitude *cost,* and *site preparation* requirements of the various sources. This paper does not address the questions of source *repeatability, cycle time* between shots, *environmental damage,* or *safety* requirements.

Direct comparisons of sources is difficult because the source signature depends upon environmental conditions at and below the surface as well as on the recording and processing parameters (for example, single shots versus vertical stacking of small, repetitive high-frequency sources). Environmental conditions and recording parameters affect not only the amplitude of the energy reflected from an acoustical boundary, but also the spectral content. To compare sources, all possible variables must be held constant.

The purpose of this experiment was to record signal from various shallow seismic sources at a favorable site, while holding field parameters constant. This method yields data in a format that facilitates direct comparison of sources.

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GEOLOGIC SETTING

The Brigantine National Wildlife Refuge is located approximately 8 km north of Atlantic City. New Jersey along the Atlantic coast. The New Jersey Coastal Plain comprises unconsolidated interbedded sand, clay, and silt of Quaternary to Cretaceous age. The total thickness of these sediments along the New Jersey coast can be as much as 1 800 m (Owens and Sohl, 1969).

The predominant reflecting horizon at the source comparison site is the top of a bluish-gray diatomaceous clay bed 80 m below sea level: This clay is within a sequence of marine sands and clays of Miocene age (Isphording and Lodding, 1969). Within this 88 m thick diatomaceous clay unit is a laterally continuous medium-to-coarse-grained sand layer 12 m thick. The diatomaceous clay is overlain by a fine-to-medium-grained gray, micaceous sand of the same age. The dip of the diatomaceous *clay* layer is approximately 0.5 degrees to the southeast. The comparison site was 0.8 m above both mean sea level and the water table. The site's unsaturated zone was composed of medium-to-coarse-grained sand and some gravel.

FIELD PROCEDURE

An Input/Output, Inc. DHR 2400 seismograph recorded the data digitally on half-inch magnetic tape in modified SEG-Y format and also analogically on paper. The record length was 250 ms with a sample interval of 1/4 ms. The recording start time was electronically delayed 20 ms to optimize the time window of the records. 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 dynamic range of 72 dB. Total system response as a function of frequency using various low-cut filter settings is shown in Figure 1.

Participants from the four geologic surveys involved and other groups brought a total of 26 different sources or variations of sources for testing. Data from 15 sources are presented for comparison. Eleven additional variations of these

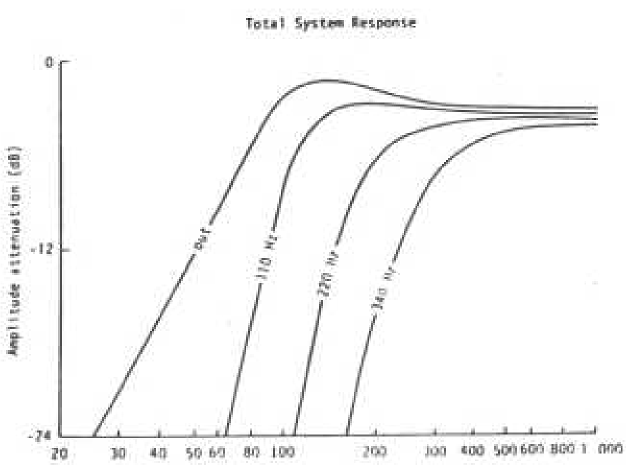


Fig. I. The entire recording system's analog response to signal using the indicated low-cut filtering- The response curve is affected by both the 100 Hz geophones and the pre-amp analog filtering

sources, such as changes in ballistic load, hammer weights, and wet-versus-dry shotholes, will be included in the open-file reports. Each source was tested using four different low-cut filter settings and two different source-to-closest-receiver offsets. Although only close-offset data are included here, the open-file reports will include all the data. All other field parameters were held constant except the analog pre-amplification which was adjusted as necessary to maintain digital word sizes between 7 and 10 bits. Low-cut filter settings included open. 110 Hz, 220 Hz, and 340 Hz, where each setting had a 24 dB/octave rolloff below these -3 dB points.

Receiver offsets ranged from 20 m for the nearest to 135 m for the longest, with a group interval of 5 m, for the data presented here. Each of 24 seismograph channels was connected to a single, undamped 100 Hz Mark Products L-50 geophone with a 0.14 m spike firmly planted in the ground. Geophone plants were left fixed throughout the tests. The time break was provided by voltage from a geophone placed within 0.5 m of the individual sources.

Each source was fired on, into, or within previously undisturbed ground. Each source was fired four times at each of the two offsets. An area of approximately 12 m^2 was altered by the sources tested.

RESULTS

During the recording period, signal obtained consisted of: seismic reflections and refractions; surface waves (ground roll); air-coupled waves (air blast); instrument noise; cultural noise (visitors walking on line); and air-coupled, randomly arriving source echoes. The reflections and refractions are obvious. They are convincing evidence that this is an excellent seismic recording site. Surface waves can be clearly identified on the first eight traces by their high amplitude and long wavelength. The air-coupled wave cuts through the time section from the origin (the source) to 90 m (trace 15) from the shotpoint. The most noteworthy characteristic of the air blast is its very high-frequency wavelets. Instrument noise affects all traces equally when the signal gain is equivalent (which is the case for spectra calculations). All visible cultural noise was from human motion on or near the line and is observable on only a few of the seismograms. Finally, the air-coupled, randomly arriving source echoes appear as high-frequency chatter trailing the air blast on the first 15 traces. It results from interaction of the source air blast with the trees and brush that line the road. The data from any shot could include any combination of the noises just described, at intensity levels dependent upon source characteristics and cultural activity at the time of that shot.

The results of the source field test are presented in the following format:

(1) Shallow-source physical data—to show approximate cost. site preparation, and general description (Table 1).

(2) Variable-area wiggle-trace plots—to show the signatures of reflected wavelets from a strong reflector (Figures 2-16). A variable-area wiggle-trace plot is an analog representation of the digital data with positive responses shaded as a visual aid.

(3) Amplitude spectra plot—to compare the frequency-versus-amplitude content of the ground roll

Table 1. Physical source information.

Source	Description of Source	Site Preparation	Manufacturer/Supplier	Cost Estimate
1. Piezoelectric	Piezoceramic transducer stack with high-voltage discharge impulse; 1 kV power supply vehicle transported.	Impact plate set on ground.	One of a kind built by Southwest Research Institute, San Antonio, TX.	$5 000 - $15 000
2. 10 kJ Spark Pak (ES-2705)	Consists of control unit, energy storage units (5 kJ up to max of 20 kJ), and transducer; operates off a 1 kW generator.	0.5 m hole dug in ground; some water poured in, garbage bag placed in hole and filled with salt water.	Geomarine Systems, Inc., Cold Spring, N.Y.	>$15 000
3. Sledge Hammer	7.3 kg hammer striking a steel plate of roughly equivalent weight.	Plate set in dirt roadbed with one or two swings of hammer.	Locally available materials.	<$500
4. Silenced 03A3 30-06 Rifle	Modified 30-06 rifle with portable silencing device, fired into ground.	One or two shots fired into dirt roadbed; hole filled with water; data recorded from wet hole shot.	Experimental model built by Betsy Seisgun, Inc., Tulsa, OK.	$500 - $5 000
5. 12-ga. Buffalo Gun	1 m iron water pipe with coupler plus nipple chamber on one end; firing rod dropped down pipe detonates 12-ga. shell below ground surface.	0.04 m hole augered 1 m into ground; shot loaded; gun placed in hole; hole filled with water.	Locally available materials.	<$500
6. 10-ga. Buffalo Gun	Same as above, but uses 10-ga. shells.	Same as above (5).	Locally available materials.	<$500
7. 8-ga. Buffalo Gun	1 m iron water pipe with machined end piece to hold electrically detonated 8-ga. shell; detonation below ground by a high-voltage explosives blaster.	Same as above (5).	Experimental model built by Del Selin, Gunsmith, Vernon, B. C., Canada	<$500†
8. Betsy Seisgun M3 8-ga.	8-ga. industrial gun on portable base; fires percussion or electrically detonated shells (lead or iron slugs) into ground.	One or two shots fired into dirt roadbed; hole filled with water; data recorded from shot fired into wet hole.	Betsy Seisgun, Inc., Tulsa, OK.	$5 000 - $15 000
9. Silenced 50-cal. Rifle	50-cal. single-shot, bolt-action, sport rifle bolted to truck-mounted silencing device, fired into ground.	Same as above (8).	One of a kind built by Kansas Geological Survey	$500 - $5 000
10. Brutus	136 kg weight drop raised by a gasoline powered hydraulic pump; trailer mounted.	Plate set on roadbed by dropping weight drop several times.	Built by E.J. Dickerson, Consulting Geophysicist, Midland, TX	$5 000 - $15 000
11. Dynasource (VAWD) (WDA-T885)	Vacuum assisted 45 kg weight drop; compressor powered by a gasoline motor; trailer mounted.	Same as above (10).	EG&G Mount Sopris Instruments, Delta, CO	$5 000 - $15 000
12. Elastic Wave Generator	114 kg weight drop accelerated by industrial elastic bands; reset by electric winch; trailer mounted.	Same as above (10).	Bison Instruments, Minneapolis, MN	$5 000 - $15 000
13. Primary Source	Compressed air accelerated 136 kg weight drop mounted on 2-ton truck with hydraulic positioning control.	Same as above (10).	Shear Wave Technology, Inc., Northville, MI	>$15 000
14. Mini-Primacord	0.1 m, 200-grain Primacord detonated inside 0.013 m sq. tubing 1 m below surface by standard explosives blaster.	1 m by 0.013 m sq. tubing pounded into ground with sledge hammer; primacord pushed to bottom of tubing and tamped with sand or dirt.	Locally available materials.	<$500†
15. Explosives 114 g Thermex "ANFO"	Two-component explosive, mixed on site; ammonium nitrate and nitro-methane detonated by a seismic blasting cap and standard explosives blaster.	0.1 m hole augered approx. 1 m into ground; cap and explosives placed at bottom of hole and hole packed in.	Thermex Energy Corp., Dallas, TX	<$500†

* The cost of each source is given as one of the following ranges: <$500, $500-$5 000, $5 000-$15 000, >$15 000. The estimates are in U.S. dollars as of December 1, 1985.

† These values do not include the cost of the blaster.

and reflected wavelets in this geologic setting (Figures 2-16).

(4) Relative energy bar graph—to compare the relative amounts of ground roll and reflected energy produced by the various sources (Figure 17).

(5) Photograph of source—to show relative portability (Figures 18-29).

Shallow seismic sources physical data

A cost estimate, site preparation, physical description, and name of manufacturer for each seismic source are shown in Table 1.

Variable-area wiggle-trace display

The field records are displayed in true-amplitude wiggle-trace variable-area format. Four wiggle-trace records are presented on the right sides of Figures 2-I6. The four records for each source correspond to analog low-cut filter settings of open, 110, 220, and 340 Hz. Because the total energy varied by more than an order of magnitude, gain variations between sources during recording were necessary. Each field record is annotated with the amplification factor (the sum of both the field and display amplification) needed to produce a visible waveform plot. The reader should consider the amplification factor when comparing different sources.

(continued *p. 2085)*

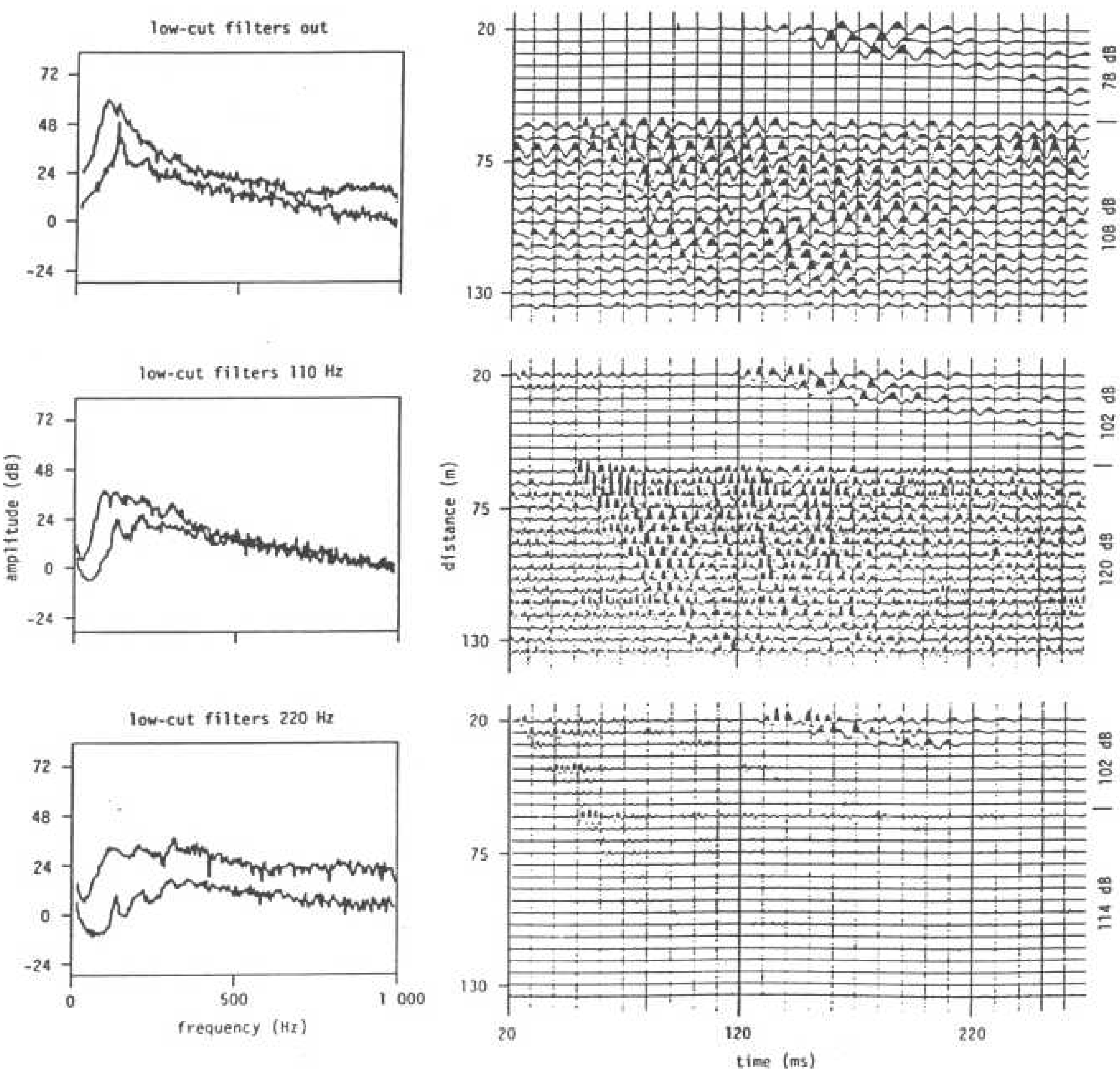


FIG. 2. Stack of 20 single piezoelectric shots recorded at each of the indicated low-cut filter settings. No stack of 20 shots was recorded with low-cut filters out.

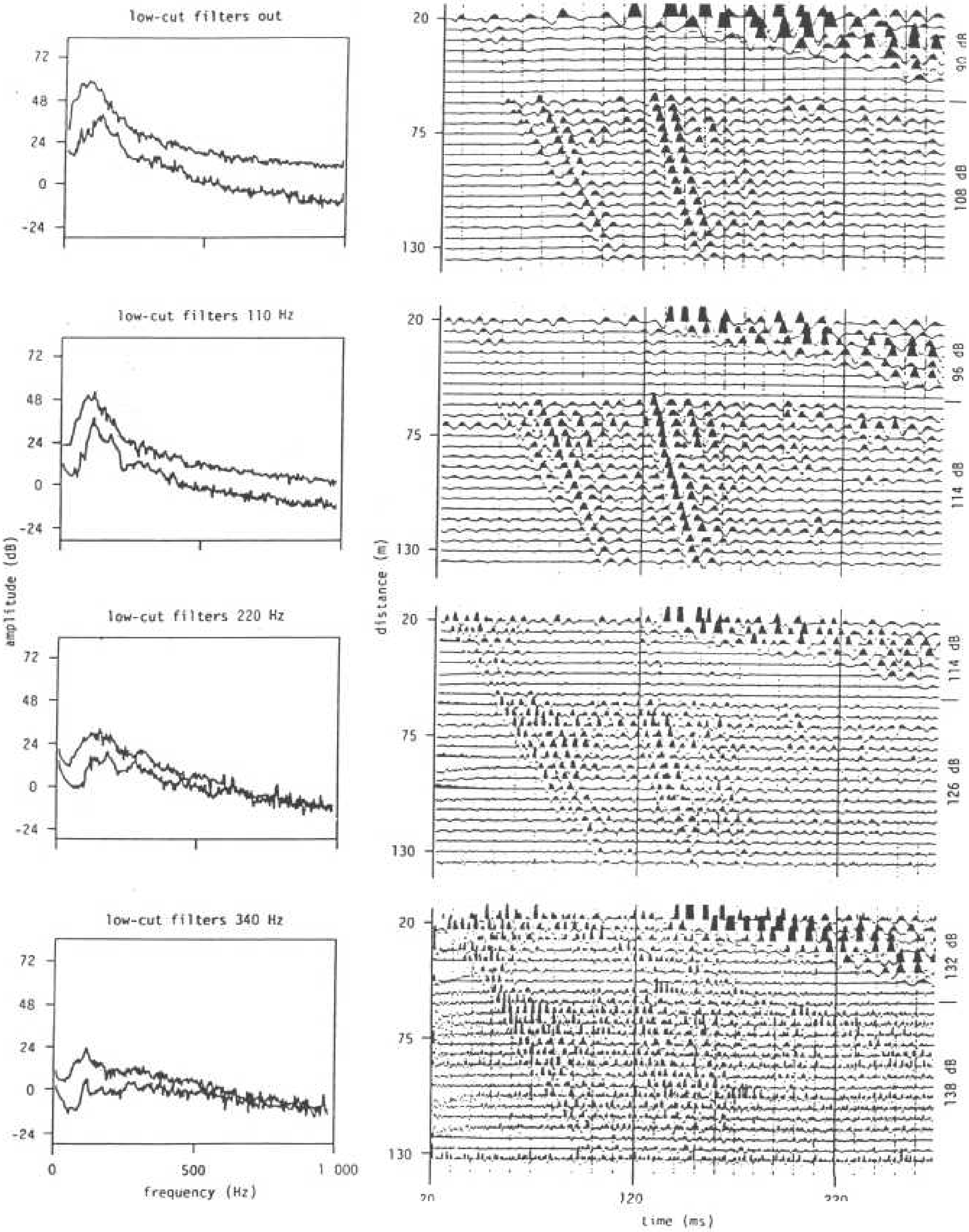


FIG. 3. Single shot at each of the indicated low-cut filter settings using the 10 kJ Spark Pak unit. Observable on some traces of the 220 Hz and 340 Hz low-cut data is a slight bias. This resulted from an electronic imbalance in the amplifier modules.

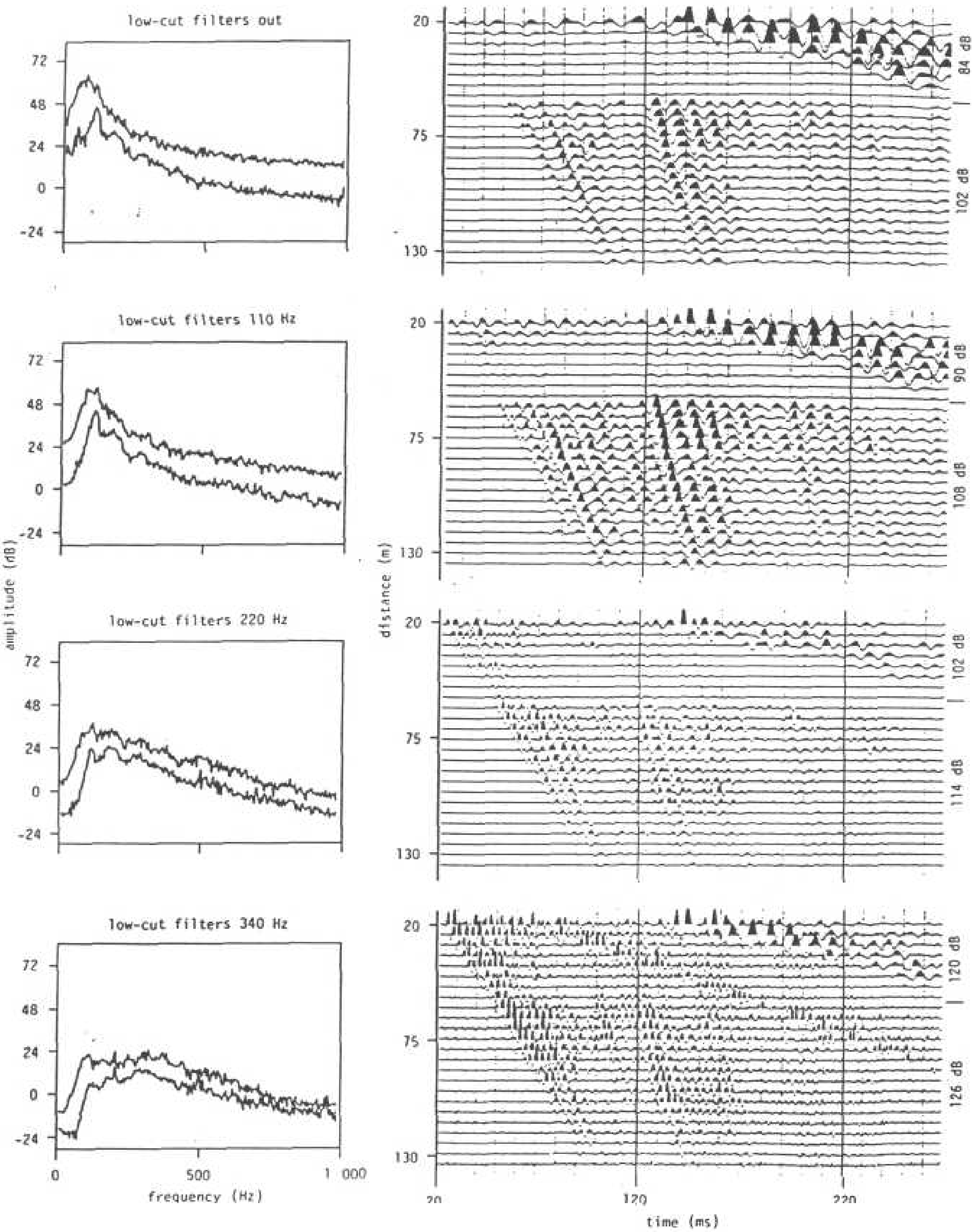


FIG. 4. 7.3 kg sledge hammer impacting a seated 0.03 m steel plate.

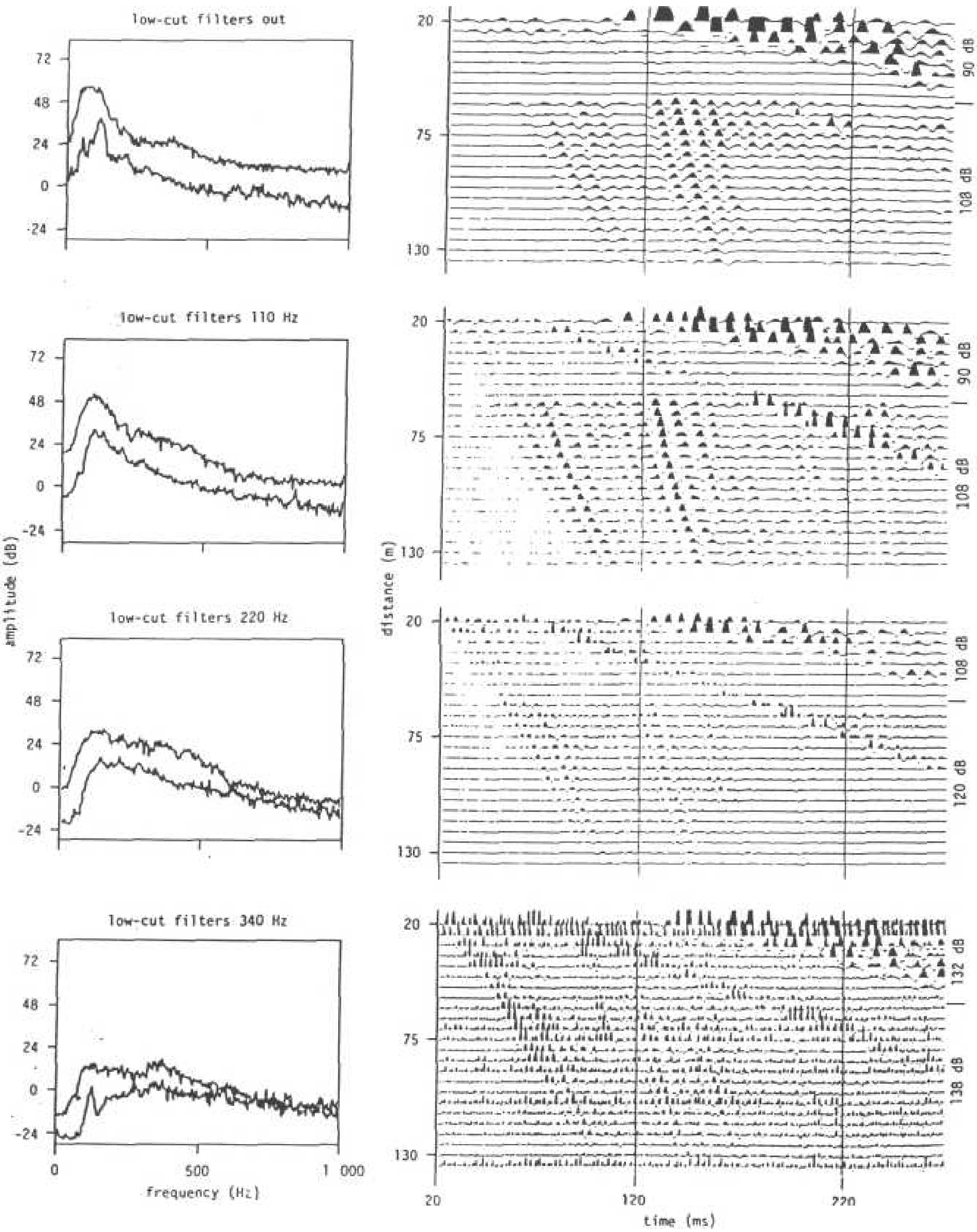


FIG. 5. Silenced 30-06 rifle firing a 180 grain bullet into a wet hole.

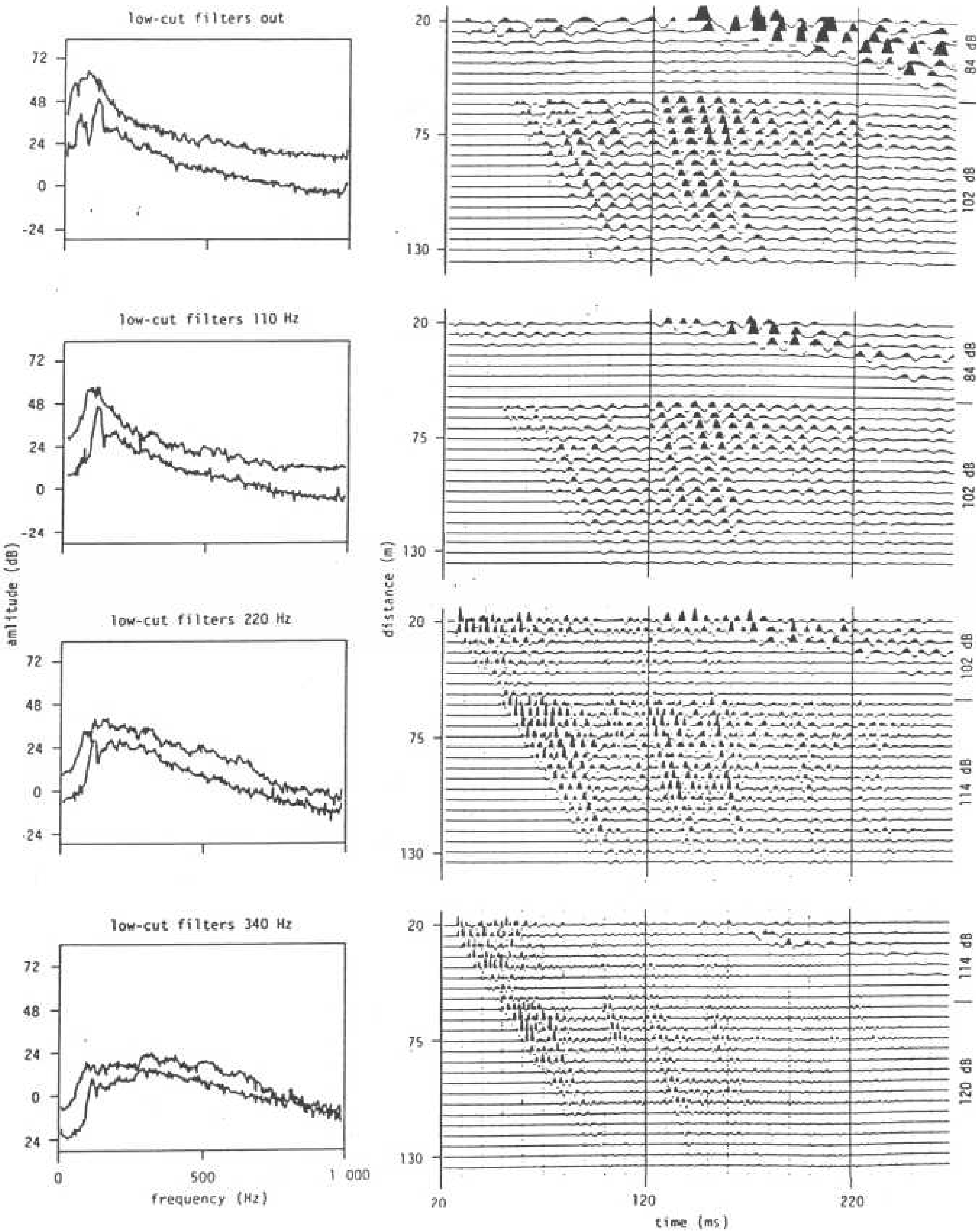


FIG. 6.12-gauge Buffalo gun firing a buckshot load.

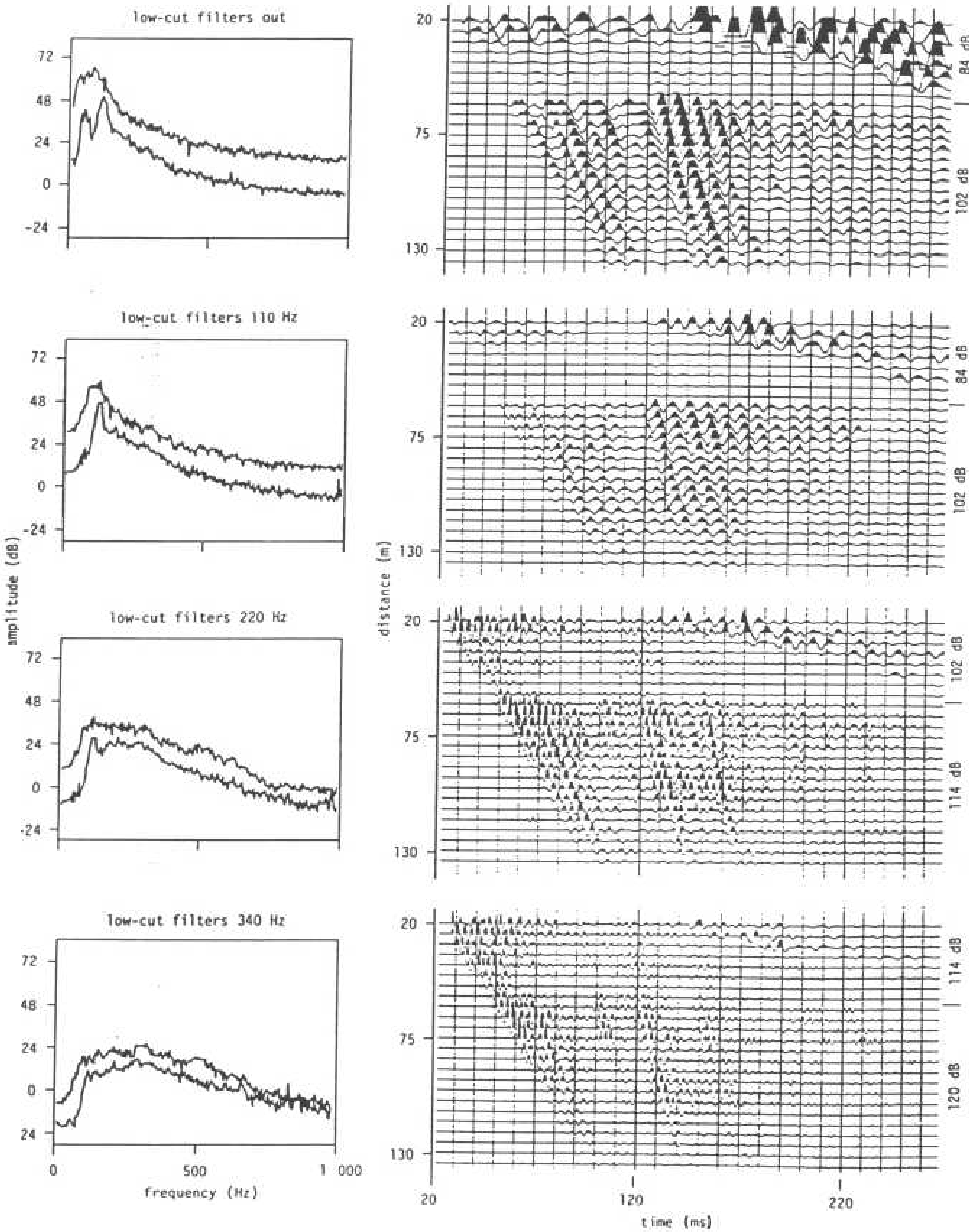


FIG. 7. 10-gauge Buffalo gun firing buckshot.

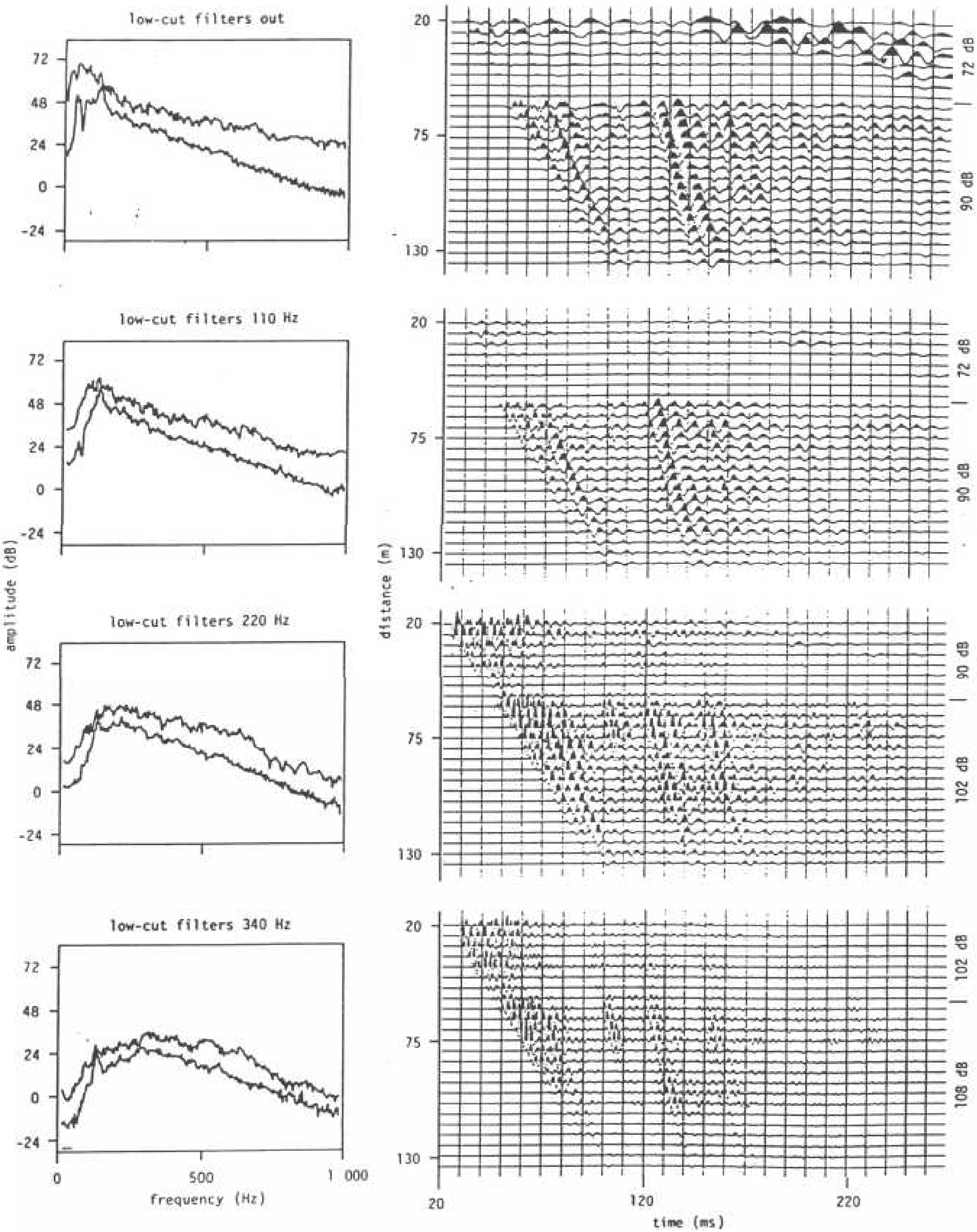


FIG. 8. 8-gauge Buffalo gun firing a 3 oz. lead slug.

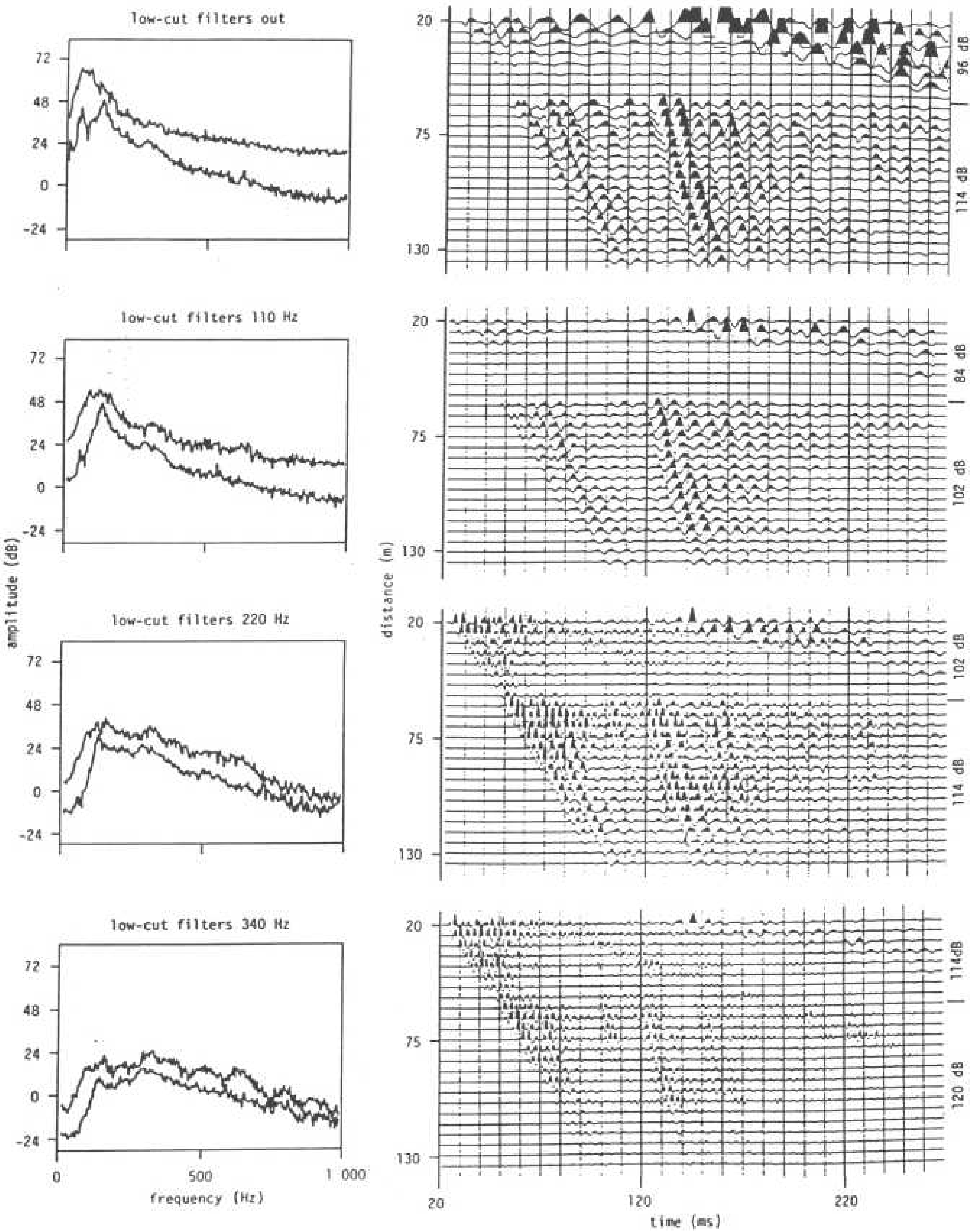


FIG. 9. 8-gauge Betsy Seisgun firing a 3 oz. iron slug into a wet hole.

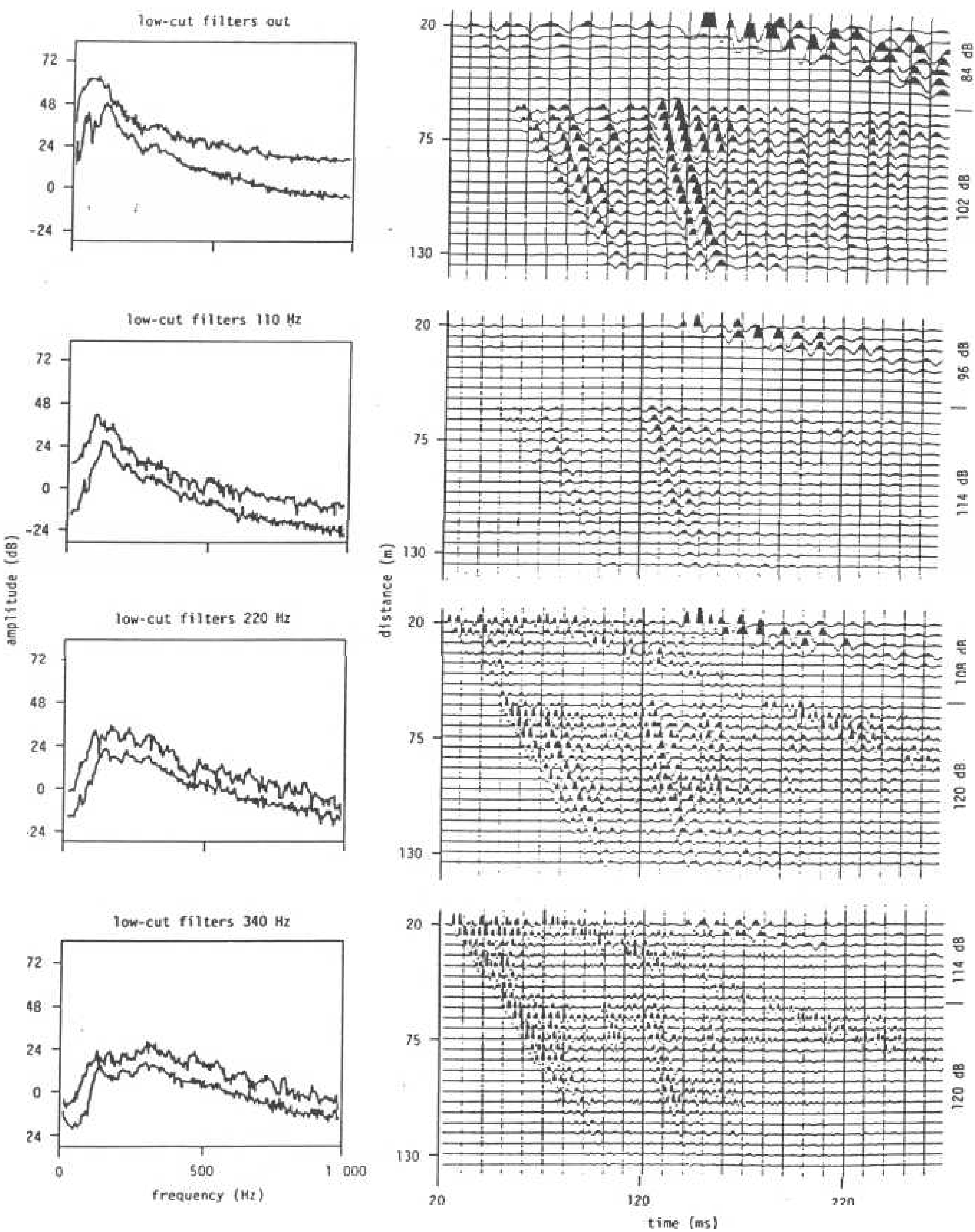


Fig . 10. Silenced 50-caliber rifle firing a 750 grain ball load into a wet hole.

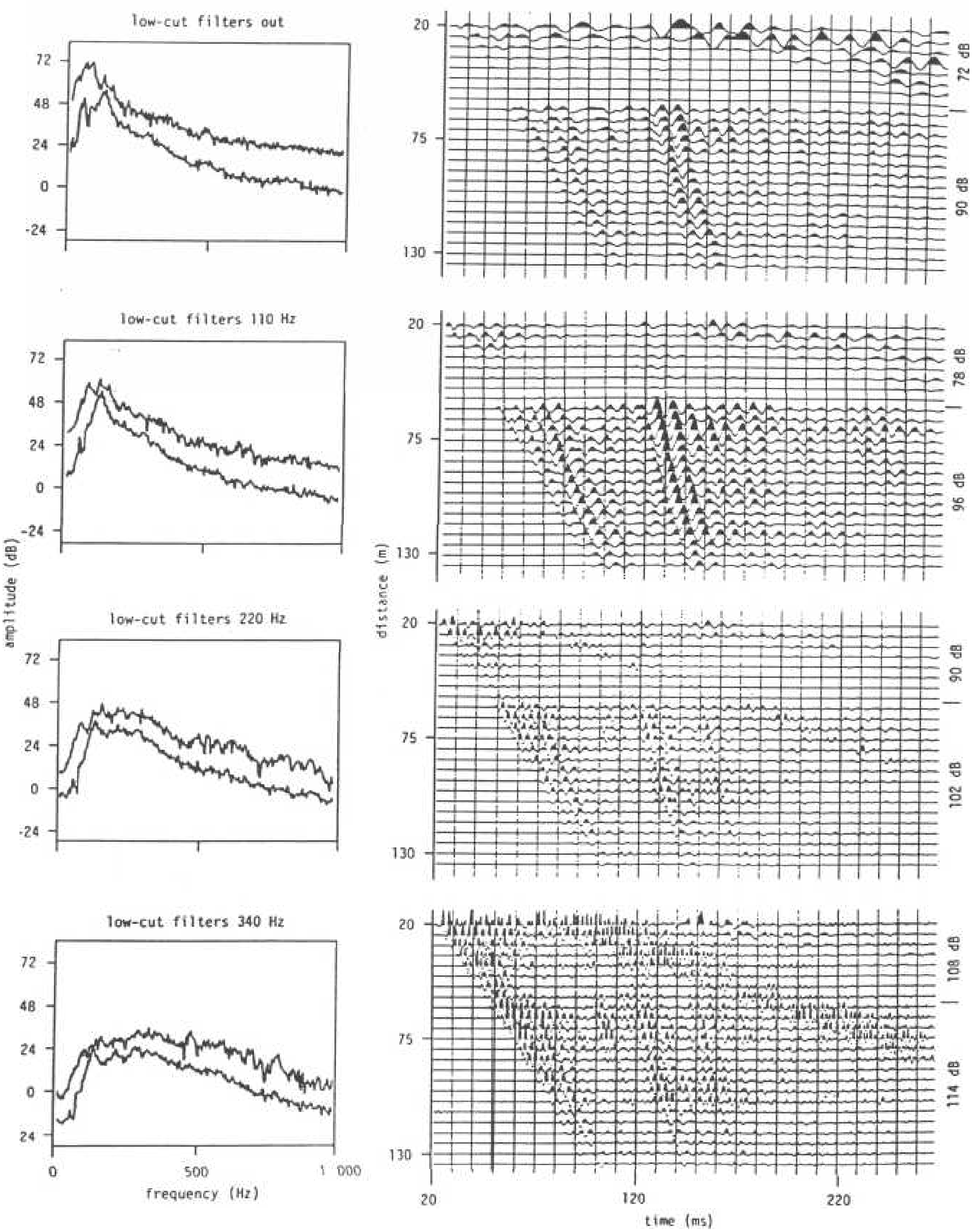


FIG. 11. Brutus, a 136 kg weight drop.

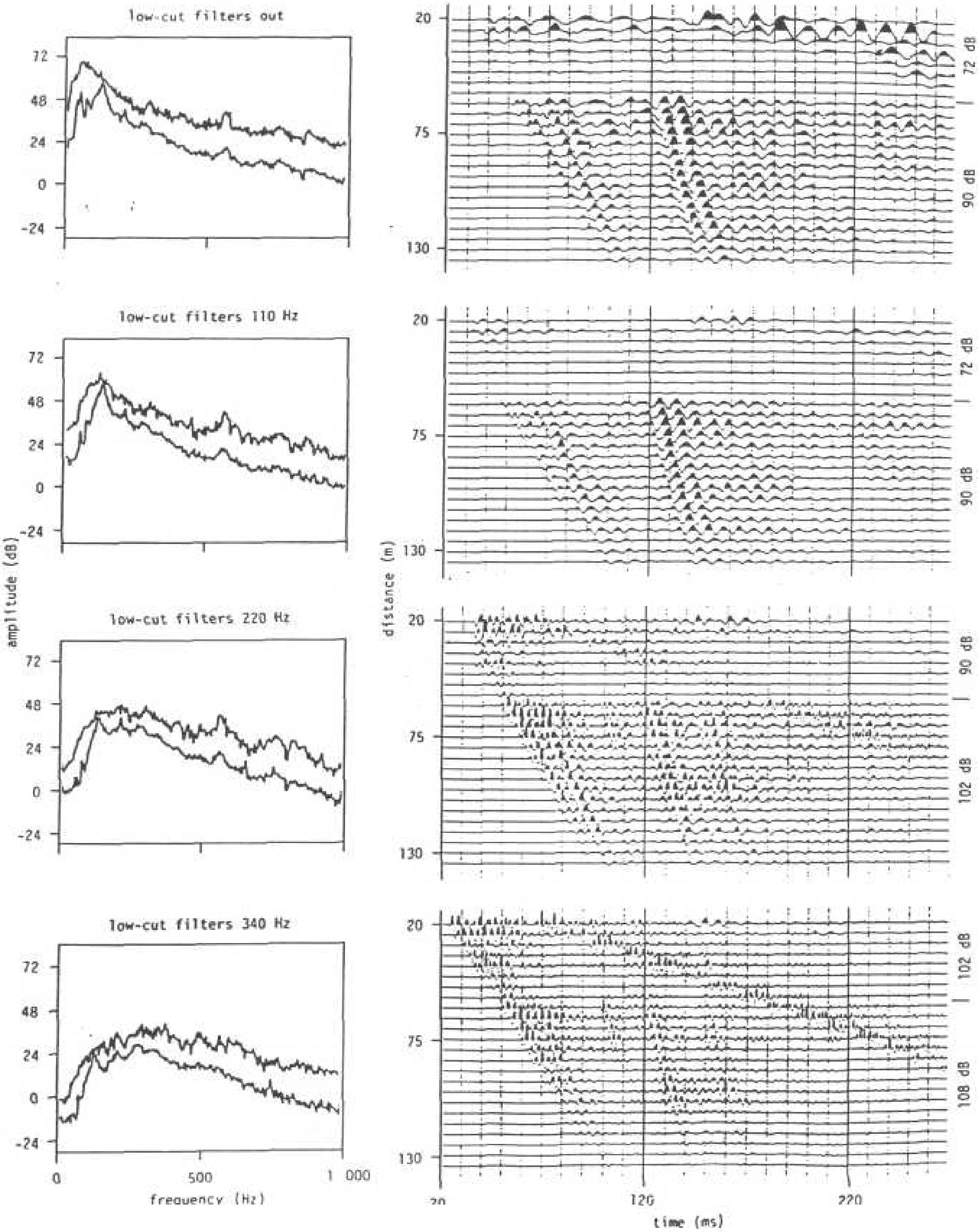


FIG. 12. Dynasource, a vacuum-assisted 45 kg weight drop.

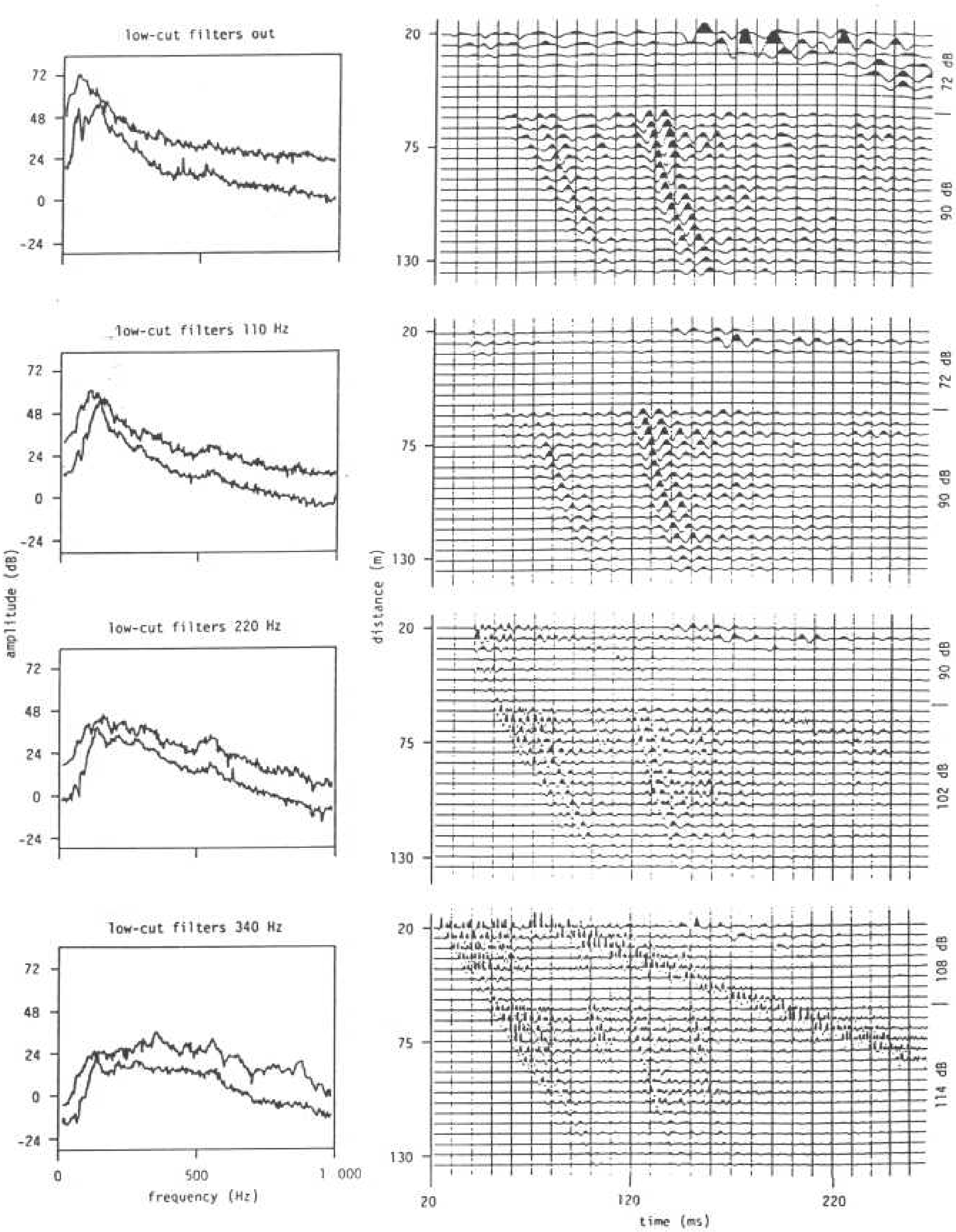


FIG. 13. Elastic Wave Generator, a rubber band-assisted 114 kg weight drop.

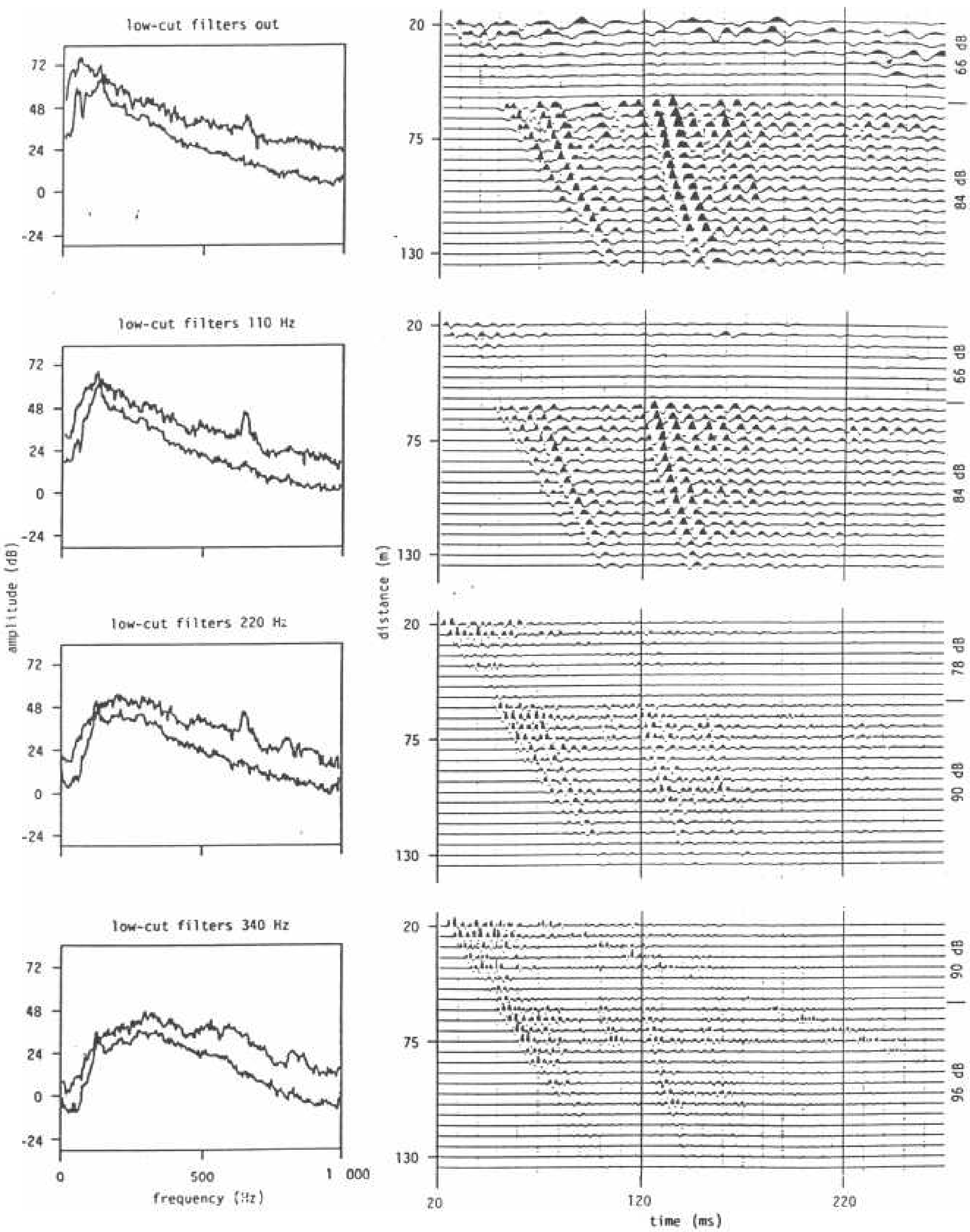


FIG. 14. Primary Source, a 136 kg compressed air-assisted weight drop.

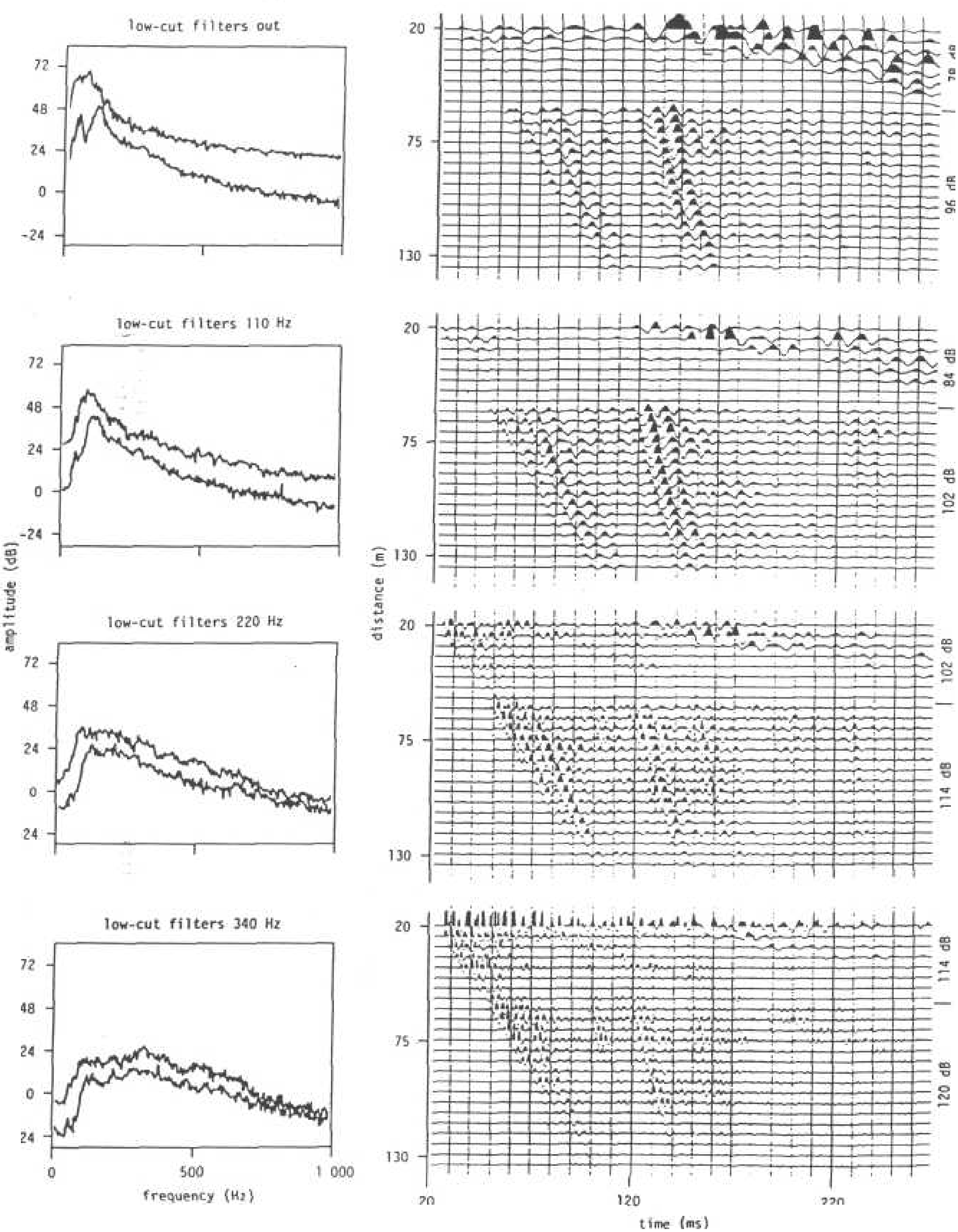


FIG. 15. Mini-Primacord, a 0.1 m long 200 grain Primacord detonated below the ground surface.

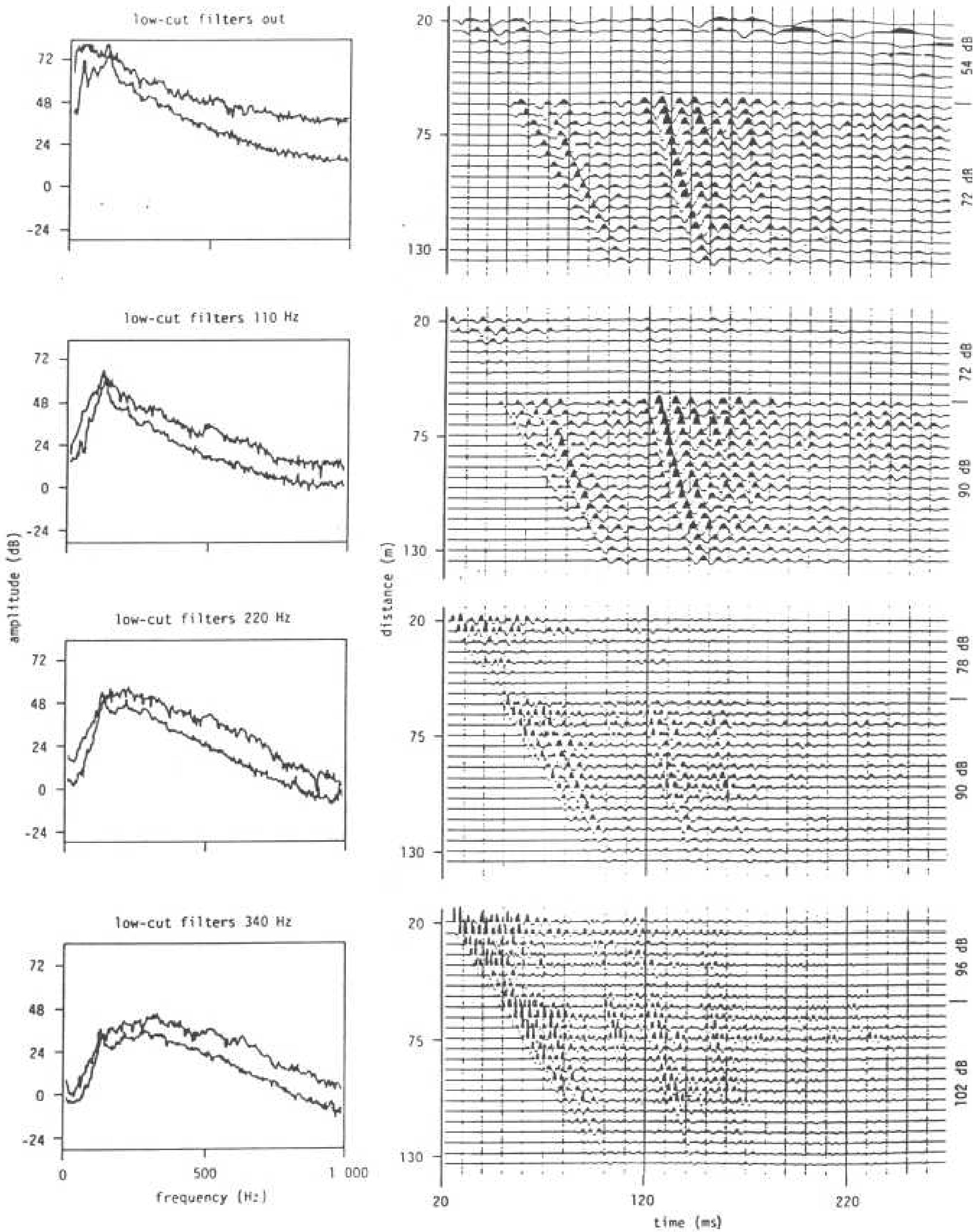


Fig. 16. 114 g of a two component explosive detonated by a blasting cap 1 m under the ground surface.

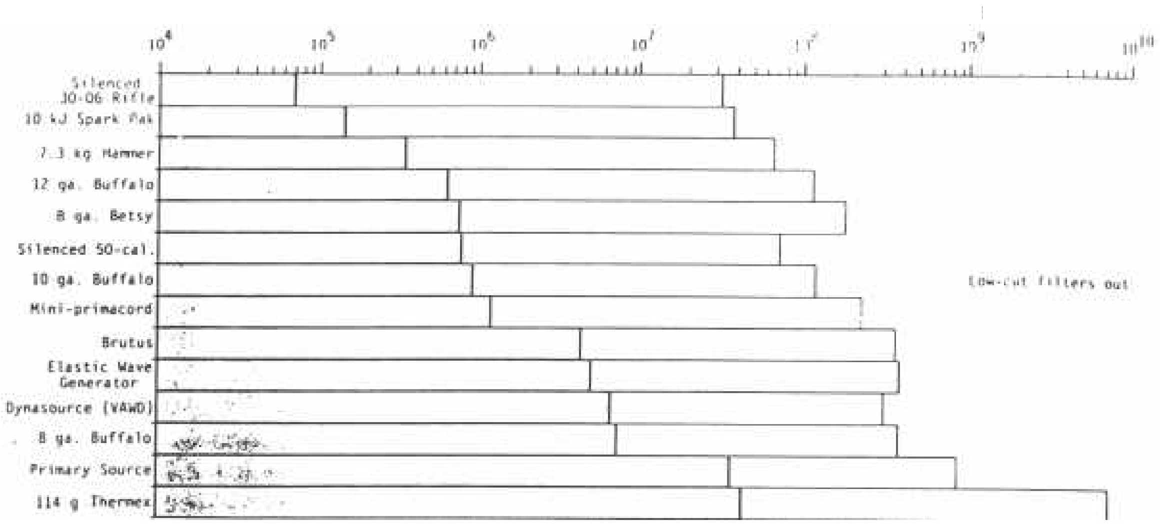


FIG. 17. Relative energy bar graph compares ground roll energy (traces 1-8) (the open bar) and reflection energy (traces 9-24) (the solid bar) with low-cut filters out. The energy from the piezoelectric source is not plotted on this bar graph due to the extremely low energy output of a single shot.

Fig . 18. Piezoelectric

On all records. one gain setting is used for traces 1 to 8 where ground roll is the predominant event, whereas higher gain is used to display traces 9 to 24 which contain mainly reflected energy land in some cases a ground-coupled air wave). The gain setting for the far traces was chosen as the closest increment of 6 dB that brought trace 9 to full scale without clipping. The difference between the display gain setting for traces 1 to 8 and that for traces 9 to 24 has been held constant for each filter value. The display gain for the near traces is 18 dB lower than that for the far traces on the unfiltered and 110 Hz low-cut records. 12 dB lower for the 220 Hz low-cut data, and 6 dB lower on the 340 Hz low-cut records. The piezoelectric source generated such low energy that equating gain separations with the other sources was not possible.

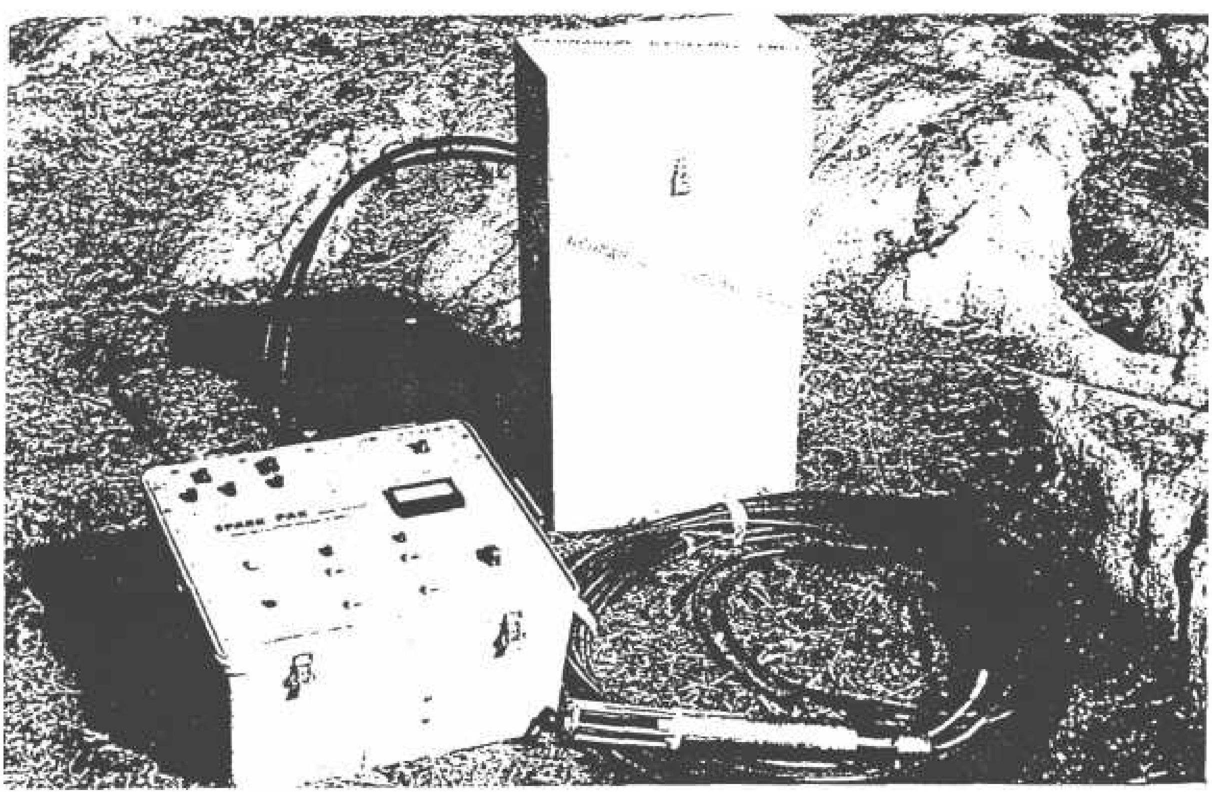
Enough gain to show the reflections clearly on all 24 traces would result in severe clipping of the ground-roll signal on the first eight traces. The resultant display of the data allows some minor clipping of ground roll, but gives a hint of reflector visibility on the close traces. The clipping occurred only on plotting and not on the original digital data on tapes.

Amplitude spectra

Two spectra are superimposed on one plot for each source at each filter value. and they are shown to the left of the respective wiggle-trace record on Figures 2-16. The average spectrum for the first eight traces (the upper curve) was calculated by summing each individual trace spectrum (traces 1-8) and dividing by eight. The second average (the lower curve) spectrum. which represents primarily the reflected wavelet frequency content. was calculated by summing the individual trace spectra for traces 9 to 24 and dividing by 16. Averaging yields a spectrum that retains the major highs and lows of each individual (race spectrum. but reduces the spikiness and, hence, smooths the spectrum. The spectra from different sources and different filter values max' be directly compared because the amplification factors (field gain plus display gain) for all traces were adjusted to 78 dB before spectral analysis and all spectra are plotted on the same scale.

The amplitude spectra are presented in a format for direct comparison of the ground roll and seismic reflection energy. However, since ground roll and seismic reflections are not the only arrivals on the seismic traces, the spectrum that results from a fast Fourier transform will not indicate only ground roll or reflection frequency. As a result, certain peculiarities can be observed on the spectral overlays.

Detailed inspection of the spectra is necessary to understand each source's frequency characteristics. The dominant frequency bands of ground roll and reflection energy can be easily compared. The dominant frequencies for both wave types are within the high-amplitude humps centered below 400 Hz on the spectra plots (the average of traces 1-8 primarily representing ground roll is the top curve; the average of traces 9-24 primarily representing reflections is the bottom curve. The contribution of the source air blast to each average spectrum can he seen on both curves. The air blast's dominant frequencies are contained within the humps at about 6(X) Hz. The apparent amplitude difference between the upper and lower curves at 600 Hz results from averaging individual trace spectra with unequal ratios of air blast to total signal. Because the air blast arrival is observable only on the first 15 traces. the upper curve (traces 1-8) will have an average amplitude almost four times greater than that of the lower curve (traces 9-24) within the dominant frequency band of the air blast. Beyond 600 Hz the majority of the energy is either instrument noise or high-frequency chatter previously identified as air-coupled, randomly arriving source echoes. Instrument noise is equivalent across all 24 channels, therefore any difference in spectral amplitude (above about 700 Hz) is the result of the echoes that follow (in time) the air blast. As mentioned, arrival of the air blast is not present on any trace beyond trace 15; therefore, its associated echo will not influence an individual trace spectrum between traces 16 and 24. This nonsymmetric distribution of echoes from the air blast results in average spectral amplitudes (above 700 Hz) 12 to 24 dB greater for the first eight traces than for the last sixteen traces.



Fu.. 19. 10 kJ Spark Pak

Relative energy bar graph

To obtain an estimate of the relative amounts of the two major types of seismic energy recorded for each source, the relative energy" was computed by summing the squares of the amplitude coefficients (amplitude coefficients are the individual values depicting the amount of signal at particular frequencies) of each of the two spectra for the unfiltered data. For each source, two energy levels arc shown in a bar graph in Figure 17: ground-roll energy (open bar) and reflection energy (solid bar). The ratios of ground roll to reflection energy shown here have been influenced by the low-cut filtering effects of the 100 Hz geophones (approximately 6 dB per octave) (Figure I).

The relative energy bar graph gives a clearer understanding of the wiggle-trace display problems encountered here. Gaining differences both in the field and on the true amplitude plots can be better` appreciated by knowing that the total relative energy difference between the largest and smallest source was approximately three orders of magnitude.

Photographs of shallow seismic sources

The relative portability of each source can he ascertained from Figures 18-29.

DISCUSSION

Choosing the seismic source for a shallow reflection survey can be the most pivotal decision of the engineering geophysicist. The intent of this paper is to assist in selection of a shallow seismic source to meet the goals within the constraints of specific projects, particularly in areas where the water table is near the surface. We hope the results presented here prove useful to the engineering geophysics community and that they lead to similar tests in other locations.

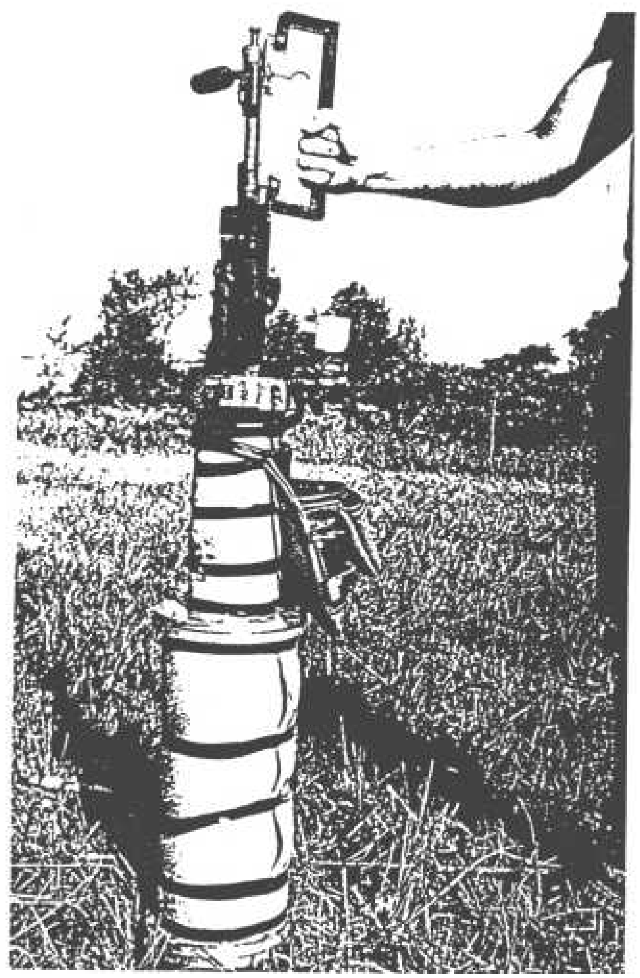


Fig 20 7 3 kg sledge hammer Fig 21. Silenced 30-06 rifle

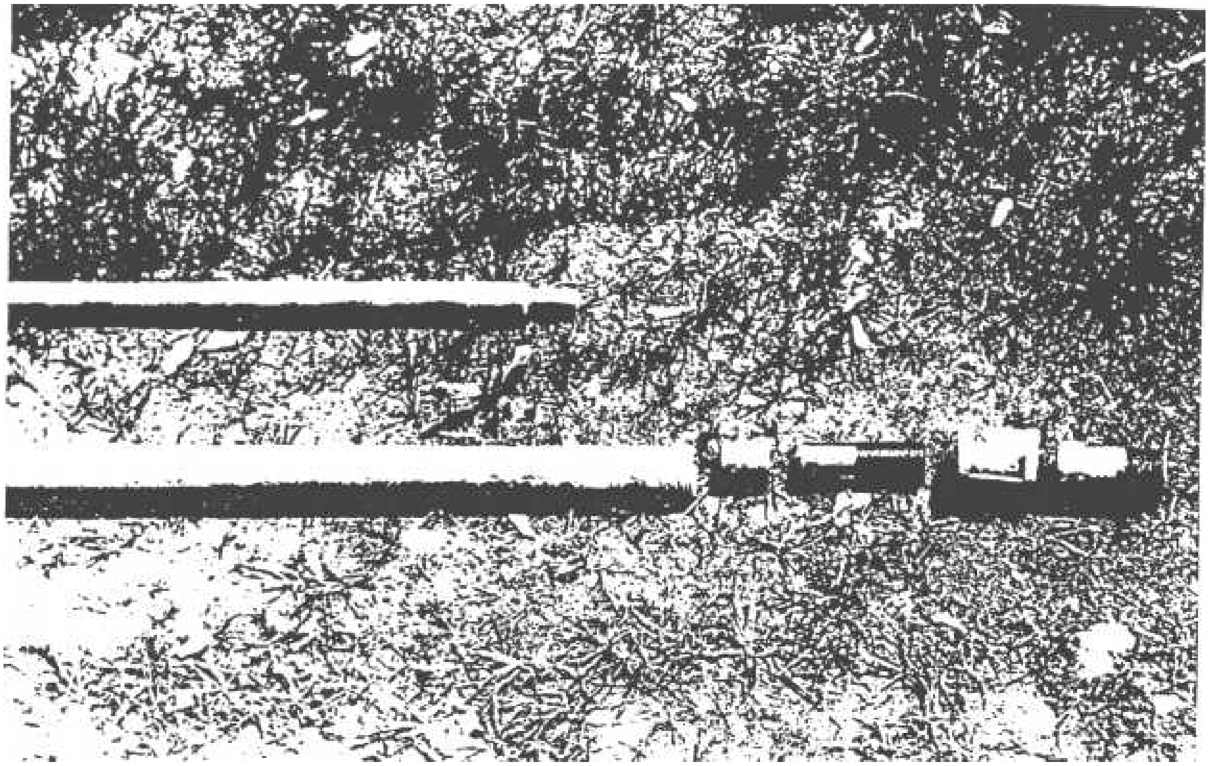


FIG. 21 10- and 12-gauge buffalo gun

FIG. 23. 8-gauge buffalo gun

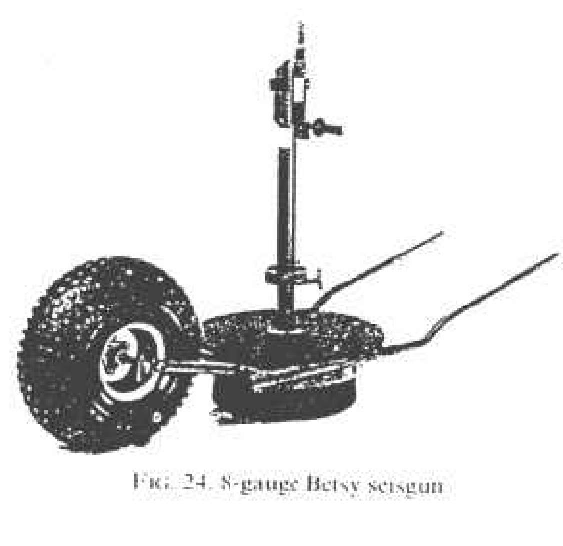


FIG. 24. 8-gauge Betsy seisgun

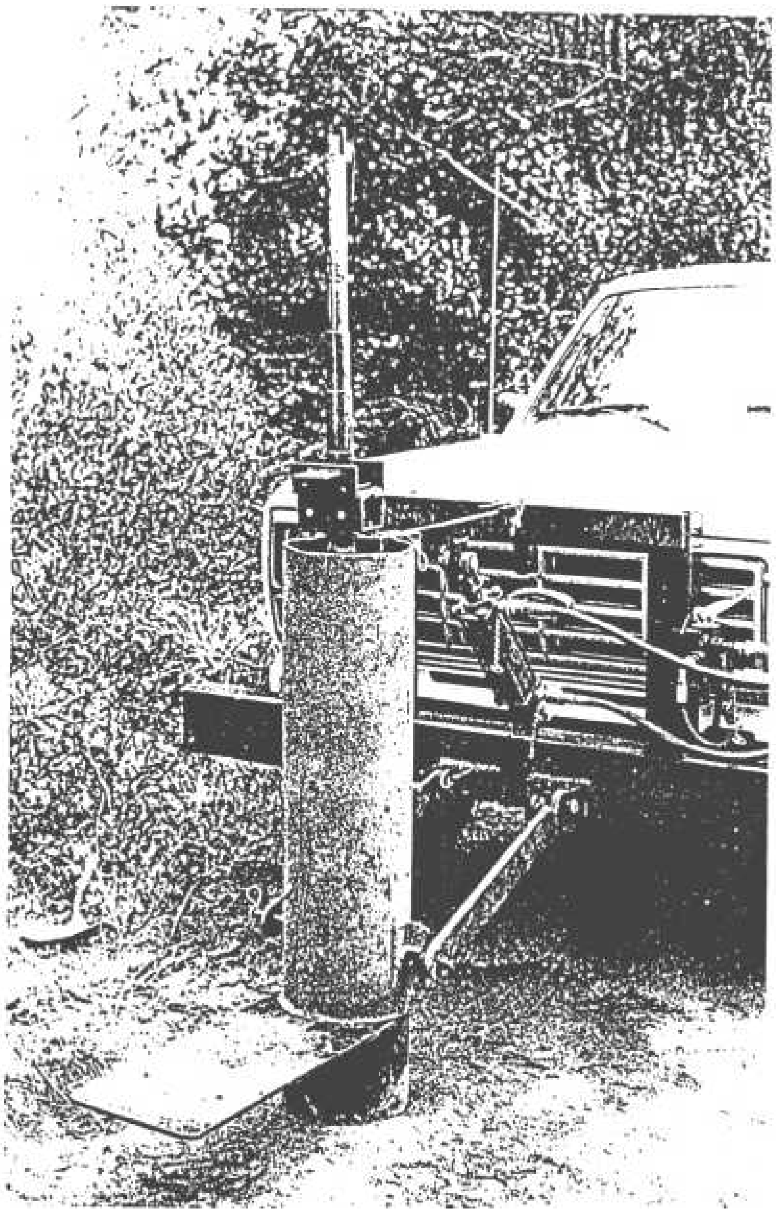
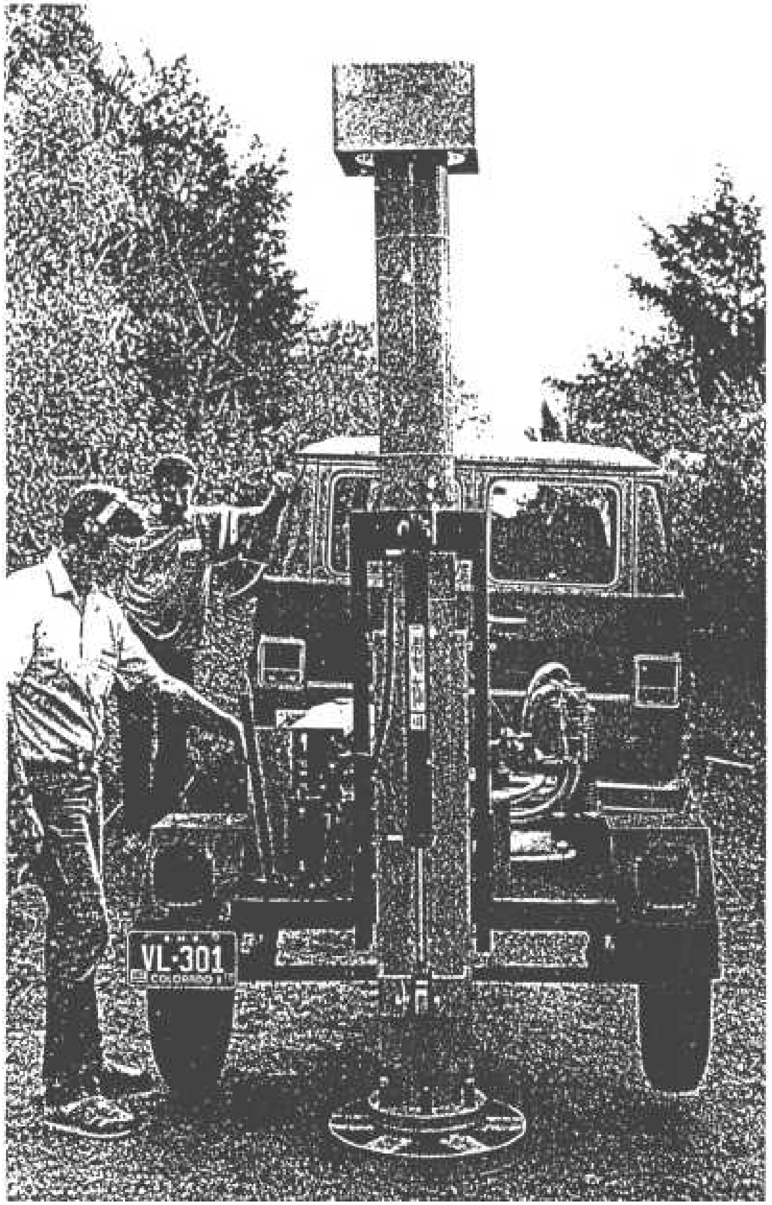


FiG. 25. Silenced 50-caliber rifle

FIG. 26. Brutus



. 27. Dynasource

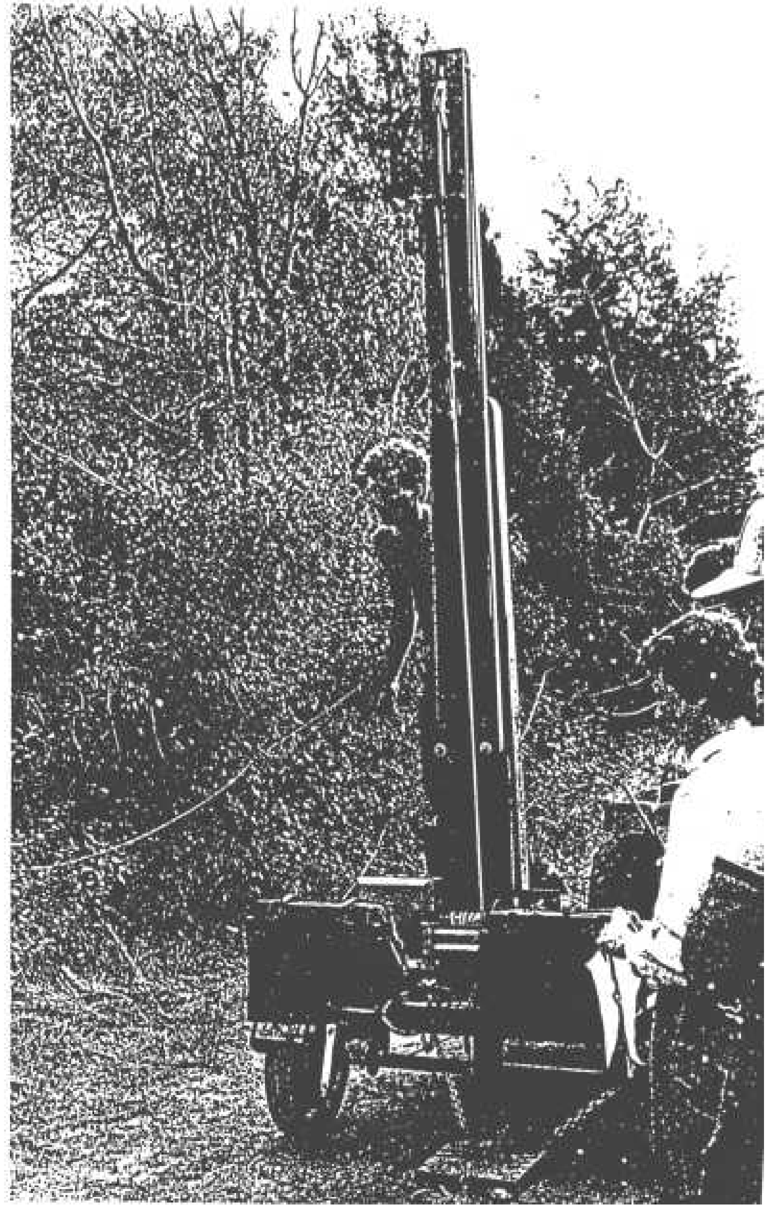


FIG. 28. Elastic Wave Generator

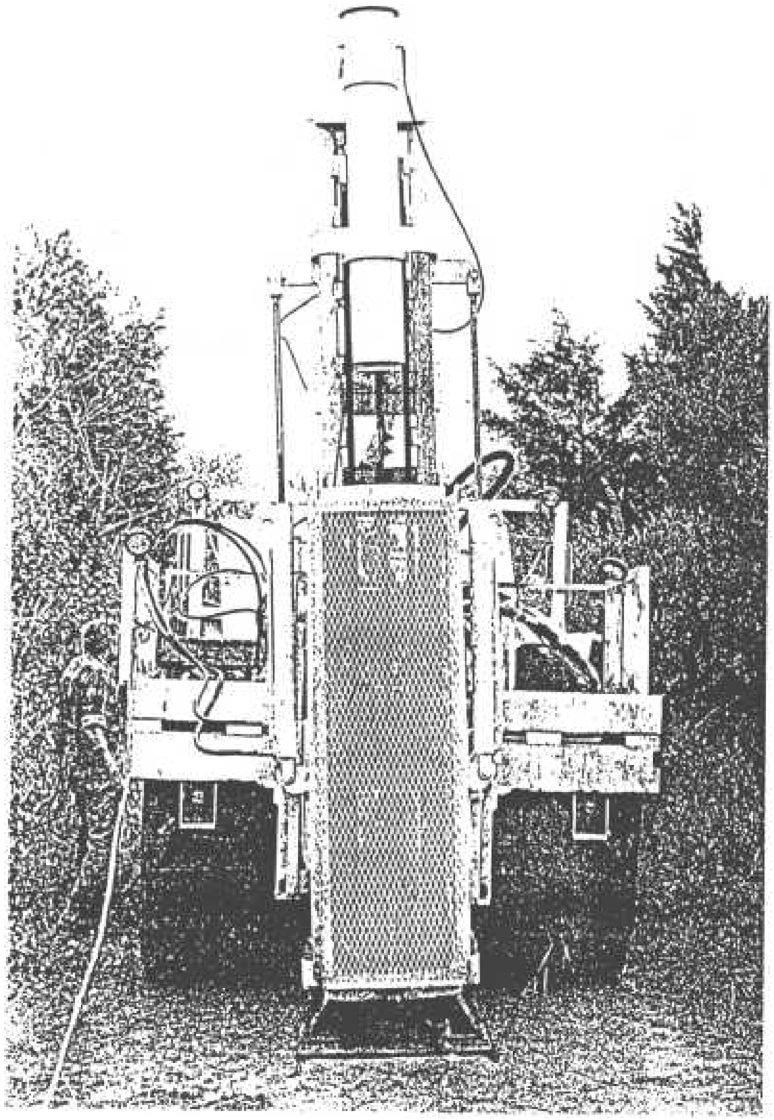


FIG. 29. Primary source

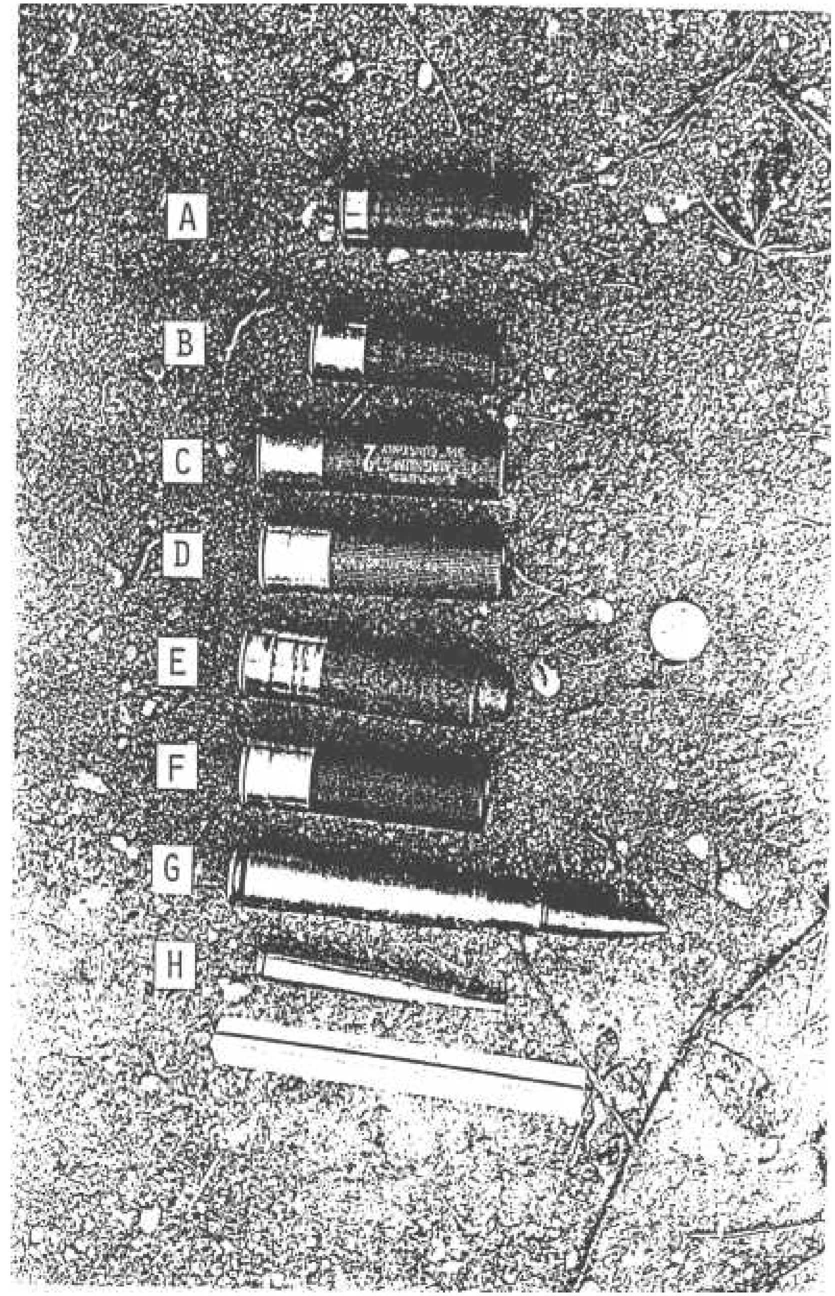


FIG. 30. Some of the shells used by gun sources during the source comparison: (A) 12-gauge blank, (B) I2-gauge buckshot, (C) 8-gauge buckshot, (D) 8-gauge lead slug 3 oz., (E) 8-gauge iron slug 3 oz., (F) 8-gauge electric detonation 3 oz lead, (G) 50-caliber 750 grain ball, (H) 30-06 180 grain.

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REFERENCES

Doornenbal, J. C., and Helbig, K., 1983, High-resolution reflection seismics on a tidal flat in the Dutch Delta—acquisition, processing, and interpretation: First Break, May, 9-20.

Hunter, J. A., Pullan, S. E., Burns, R. A., Gagne, R. M., and Good, R. L., 1984, Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph—Some simple techniques: Geophysics, 49, 1381-1385.

Isphording, W. C., and Lodding, W., 1969, Facies change in sediments of Miocene age in New Jersey, in Subitsky, S., Ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guide book of excursions: Rutgers Univ. Press, 7-13.

Owens, J. P., and Sohl, N. F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, in Subitsky, S., Ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guide book of excursions: Rutgers Univ. Press, 235-259.

Pullan, S. E, and MacAulay, H. A., 1985, A new source for engineering seismic surveys: Presented at the 55th Ann. Mtg., Soc. Explor. Geophys, Washington, D. C., 168-170.

Ruskey, F., 1981, High-resolution seismic methods for hardrock mining: in Premining Investigations for hardrock mines, Bureau of Mines Information Circular IC-8891, 4-28.

Steeples, D. W., 1984, High-resolution seismic reflections at 200 Hz: Oil and Gas J., Dec. 3, 49, 86-92.