

## Field comparison of shallow *P*-wave seismic sources near Houston, Texas

Richard D. Miller\*, Susan E. Pullan‡, Don W. Steeples\*\*, and James A. Hunter‡

### ABSTRACT

A shallow *P*-wave seismic source comparison was conducted at a site near Houston, Texas where the depth to the water table was approximately 7 m, and near-surface materials consisted of clays, sands, and gravels. Data from twelve different sources during this November 1991 comparison are displayed and analyzed. Reflection events are interpretable at about 40 ms on some 220-Hz analog low-cut filtered field files, and at 60 ms on most 110- and 220-Hz analog low-cut filtered field files. Calculations and local water well information suggest the 40-ms event is from the top of the water table. Subsurface explosive sources seem to possess the highest dominant frequency, broadest bandwidth, and recorded amplitudes and, therefore, have the greatest resolution potential 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

Choosing a seismic source can be a pivotal decision for a shallow-reflection survey. Comparison data with consistent testing procedures and equipment are needed from a representative group of sources in a variety of geologic and hydrologic settings. In an attempt to quantify the significant characteristics of some of the more popular shallow *P*-wave seismic sources, the Source Comparison Subcommittee of the SEG Engineering and Groundwater Committee, active since 1985, has published the results from two previous source comparisons in New Jersey and California in *GEOPHYSICS* (Miller et al., 1986; 1992). During November 1991, a group of shallow-seismic *P*-wave source owners, in

cooperation with the Geological Survey of Canada and the Kansas Geological Survey, gathered at a golf course approximately 40 km southwest of Houston (near Richmond, Texas) to continue testing low energy, shallow seismic sources (Figure 1), and the results from these tests are summarized in this paper.

Total recorded energy is the characteristic that distinguished the 26 different sources and variations of sources tested at the New Jersey site. The upper several hundred meters of material at this site consisted of unconsolidated interbedded Quaternary sands, clays, and silts. The water-table depth was about one meter. Very little diversity in recorded signal was evident after analyzing the data generated during those tests. The New Jersey data suggest that at an excellent seismic-data site, optimum source selection is critical in relation to total energy necessary to image the geologic target but has little bearing on resolution potential.

Geologic conditions at the California site were less conducive to the propagation of high-frequency seismic energy than the New Jersey site. The characteristics of shallow-seismic reflections were fair to poor at the California site. The water table was in excess of 30 m, and the near-surface velocity (about 310 m/s) was less than the speed of sound in air (330 m/s). Data from the 13 different sources varied most notably in signal-to-noise ratio and reflection coherency and lacked the range of total recorded energy and resolution potential observed at the New Jersey site. A probable reflection event was interpreted at about 70 ms. The geologic unit responsible for this event, speculated to be 11 m deep, is not known. At the California site, surface impact sources produced the most coherent reflection events with the highest collective signal-to-noise ratio of all source types tested. Little difference in spectral properties was observed among the various sources.

The 1991 Texas experiment was designed to be as consistent as possible with the 1985 New Jersey and 1988 California tests, primarily addressing the questions of en-

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\*Kansas Geological Survey, 1930 Constant Ave., Campus West, Lawrence, KS 66047.

‡Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8.

\*\*Formerly Kansas Geological Survey, Lawrence, KS 66047. Presently Department of Geology, University of Kansas, 120 Lindley Hall, Lawrence, KS 66045.

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ergy, frequency content (resolution potential), and signal-to-noise ratio. Other factors significant to the selection of the optimum source, but covered in much less detail, relate to source wavelet, portability, cost (both initial and per shot point), site-preparation requirements, source cycle time and repeatability, environmental damage and constraints, and safety requirements.

### Houston, Texas site

The Texas site was selected based on the premise that it would be more conducive to the propagation of high-frequency energy than the California site but less than the New Jersey site. Unfortunately, limited geologic or hydrologic information was available prior to data acquisition. The water table in a domestic well adjacent to this site was approximately 7 m deep with alternating clays, sands, and gravels in the upper 30 m. The lithological contacts and the water table represented potential reflecting horizons.

The acoustic properties of the near-surface at the Texas site were unknown prior to initial walkaway tests. The observed surface and very shallow near-surface material observed during the two-day test consisted of a layer of vegetation overlying fine-grained sands with rapidly increasing compaction or hardness to depths of at least 1 m. The site was sufficiently remote that cultural noise was not a concern. The only sources of noise outside occasional wind gusts were spectators and source owners in the staging area. Data were recorded only when noise levels were low. The site was unobstructed by surface barriers that could potentially act as reflecting interfaces for source-generated, air-coupled

waves, it was easily accessible to vehicles, and allowed a very consistent recording environment.

### FIELD PROCEDURES

An Input/Output, Inc. DHR 2400 seismograph recorded the data digitally on half-inch magnetic tape in modified SEG-Y format and also on paper (Table 1). Analog-to-digital (A/D) conversion on this 24-channel seismograph is 11 bits plus sign. The low-cut (high-pass) filters each possess a 24-dB per octave roll-off from the selected  $-3$  dB point of 110 or 220 Hz. The amplifiers have a factory noise specification of 120 nV root-mean-square (rms), providing a fixed gain instantaneous dynamic range of 72 dB. Use of this recording instrument for both the New Jersey and California tests was the primary basis for its selection at the Texas test.

Source-to-receiver offset and station spacings were determined after a series of walkaway noise tests conducted the first day of the comparison (Table 1). The geophones were firmly planted and left in place throughout the comparison. All field parameters except analog low-cut (high-pass) filters and selected amplifier gains were held constant for each source. Data were recorded for each source with (1) no low-cut filtering, (2) 110-Hz low-cut (high-pass) filtering, and (3) 220-Hz low-cut (high-pass) filtering. The fixed gain amplifiers were adjusted to nearly maximize the 12-bit A/D converters for each shot. The intent of the amplification process was to maintain a minimum of at least one 9-bit digital word on all traces with no word exceeding 11 bits. Relative amplitude plots in the field were used to verify that no signal was clipped.

Twelve primary types of sources were tested with variations including hole saturation, amounts of explosive, type/weight of projectile, and drawback on rubber band (Table 2). Pictures of all sources tested at the Texas site have been previously published (Miller et al., 1986; 1992) with the exception of the Auger gun and the USGS Rotator (Figures 2 and 3, respectively). Each of the twelve sources was fired on, into, or within previously undisturbed ground. The total surface area disturbed during testing was less than 16 m<sup>2</sup>. Because of the required size of the source area, source-to-nearest and furthest receiver distances were not the same for all sources. However, of the 24 source-to-receiver offset distances recorded for each source, 15 offset distances were consistent for all sources. To allow representative comparisons, only the 15 source-to-receiver offset distances (7.5–14.5 m) common to all sources were used for analysis (spectral and amplitude) comparisons.

Repetitive stacking of many of the source types tested here is representative of actual field acquisition scenarios.

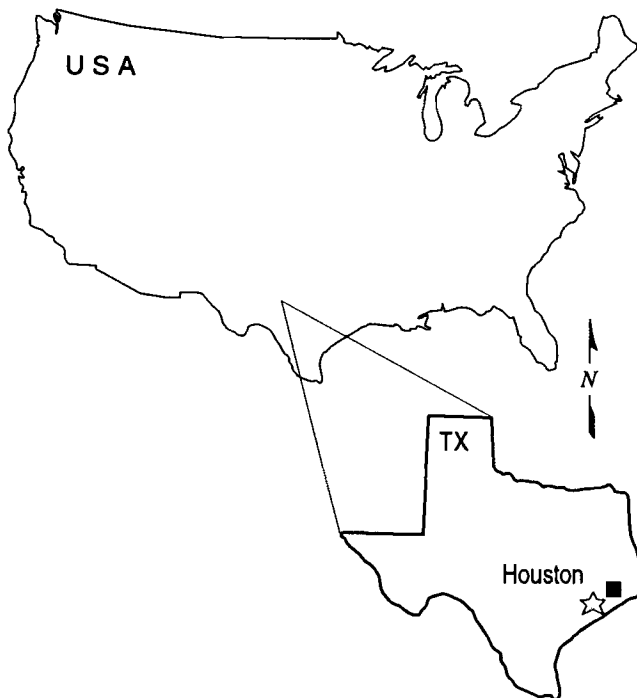


FIG. 1. Site map indicating the location of the source comparison near Houston, Texas.

Table 1. Acquisition parameters and equipment.

1	I/O DHR-2400 12-bit, fixed gain 24-channel seismograph
2	3-L28E 40 Hz Mark Products geophones per group, planted beneath sod layer
3	1/4 ms sample interval, 1000 samples per trace
4	0.5 m receiver station spacing
5	Analog low-cuts: out, 110, and 220 Hz
6	Minimum source area offset = 3 m
7	Total source area 4 m × 4 m

To allow comparison of signal-to-noise ratios, to maintain a uniform basis for comparing total source energy, and to avoid adversely affecting any source's spectral properties through vertical stacking, as many pre-recorded impacts as necessary were allowed, but only a single shot was recorded for analysis. It is worth noting that in most environments, the stacking of weight-drop style sources usually increases the signal-to-noise ratio and total recorded energy.

RESULTS

Relative amplitudes

The bar graphs (Figure 4) allow comparisons of relative total amplitude and, to a limited degree, the amount of air-coupled wave recorded for the various sources. The effects of low-cut (high pass) filtering are evident when comparing the relative amplitude values for the various sources. Relative amplitude bar graphs (used in this paper)

represent the sum of the absolute values of all samples from the 15 traces with equivalent offset distances after uniform adjustment to 50 dB of total applied gain. The 220-Hz low-cut filter amplitude bar graph has been divided into two parts: total amplitude of seismogram (stippling plus black), and total amplitude of seismogram excluding the air-coupled wave (black). The intent of the bar graph design is to allow a relative ordering of sources according to total recorded energy and to get a qualitative understanding of the percentage of air wave. Comparison of bar graphs associated with different low-cut (high-pass) filters should allow a greater appreciation of relative energy output in particular frequency bands (as a result of the low-cut filters' preferential attenuation of certain frequencies). The bar graphs need to be used in conjunction with the time sections since total amplitude is not necessarily related to the signal-to-noise (S/N) ratio or spectral properties of recorded data.

Table 2. Description and variation of sources and site preparation requirements.

Source	Variation tested	Site preparation	Manufacturer/supplier/price*
<b>Weight Drop</b>			
1) 9.1 kg hammer onto steel plate		Seated steel plate with several impacts.	Hardware store \$<500
2) Bison EWG IV Generator (accelerated weight drop)	a) high energy 1 m drop	Seated 2.6 cm steel plate with several impacts.	Bison Instruments \$>15,000
3) USGS Rotator	b) low energy 0.46 m drop		
	100 rpm setting	Steel plate seated by single impact.	Custom USGS/EPA \$>15,000
<b>Projectile</b>			
4) surface .30-06-cal. rifle silenced	shot into wet hole, 180-grain bullet	Used 3 cm shaft to poke 1/3 m deep hole, and water poured in.	Custom \$<500 Ks. Geol. Survey
5) downhole .30-06-cal. rifle	shot into wet hole, 180-grain projectile	Auger drilled 5 cm hole 0.6 m deep and water poured in.	Custom \$<500 Ks. Geol. Survey
6) Betsy Seisgun M3 8-gauge	shot 3 oz slug into wet hole	Same as Source 5.	Betsy Seisgun \$5,000-\$15,000
7) .50-cal. rifle downhole	a) dry hole	Auger drilled 5 cm hole 0.66 m deep.	Assembled by Ks. Geol. Survey
	b) wet hole	Poured water in virgin augered shot hole and placed condom on end of barrel.	Mfg by Texas Gun & Machine \$500-\$5,000
<b>Downhole Explosive</b>			
8) 8-ga. auger gun	300-grain black powder blanks	Screwed hollow-stem auger 0.66-m deep into ground.	Custom, Ks. Geol. Survey, not incl. loader \$500-\$5,000
9) 8-ga. downhole buffalo gun	a) black powder (blank) 300-grain, wet hole	Auger drilled 5 cm hole 0.66 m deep, loaded gun in hole, poured in water (wet shots), compression detonation using rubber mallet.	Betsy Seisgun \$500-\$5,000
	b) black powder (blank) w/PVC casing 300-grain, wet hole		
	c) black powder (blank) 300-grain, dry hole		
10) 12-ga. downhole buffalo gun	black powder (blank) 165 grain, wet hole	Same as source 9.	Betsy Seisgun \$500-\$5,000
11) Explosives	30 grams of high explosive	Same as source 5.	Explosive dealers \$<500 incl. blast box
12) Seismic blasting cap		Same as source 5.	Same as source 11.

\*Prices have been given in terms of the following ranges: \$<500, \$500-\$5,000, \$5,000-\$15,000, and \$>15,000.

### Seismograms and spectra

Unprocessed seismograms, total applied gain, and spectral analyses of raw data from each of the 12 primary sources and configurations are displayed in Figures 5 through 18. Data recorded with each of the three filter settings are presented in variable-area wiggle-trace and amplitude spectra plots. The variable-area wiggle-trace plots are analog representations of the digital data, with positive amplitude values shaded as a visual aid. Any wavelet clipping observed on wiggle trace plots is present only on display (with the exception of the data recorded with low-cut filters out using the EWG and 30 grams of high explosives). Clipped signal on close offset traces from the two more energetic sources occurred in the analog portion of the system. Annotation and display style of the data allow readers to make trace-to-trace and file-to-file comparisons of wavelet characteristics, relative energy, and spectral content.

Total energy varied by an order of magnitude both trace-to-trace and source-to-source, requiring gain adjustment during recording and display of the data. Displayed seismo-

grams have been amplitude corrected (Figures 5 through 18). Each trace within any seismogram has been gained by the amplification value (dB) indicated along the top of the figure. The amplification is generally divided into two parts on each seismogram. This division is usually governed by the high-amplitude direct-wave arrival. The displayed amplitude values account for all gaining from the pre-amp of the seismograph to final analog display. Direct comparisons can be made if consideration is given to the indicated total gain and source-to-receiver offset.

Spectral characteristics of each of the 12 sources or configurations are presented in relative amplitude-versus-frequency plots above the associated variable-area, wiggle-trace seismograms (Figures 5 through 18). Each spectrum represents the total of all samples from the appropriate 15 traces. Two spectra are superimposed on the 220-Hz low-cut, amplitude-versus-frequency plots to quantify the approximate relative amount of air wave to other high-frequency source-generated energy. On some records the air-coupled wave is a major component of the total recorded energy. All traces used to calculate the spectra were corrected to 50 dB of gain prior to spectral analysis



FIG. 2. The 8-gauge Auger gun with Case 1825 skid steer loader.

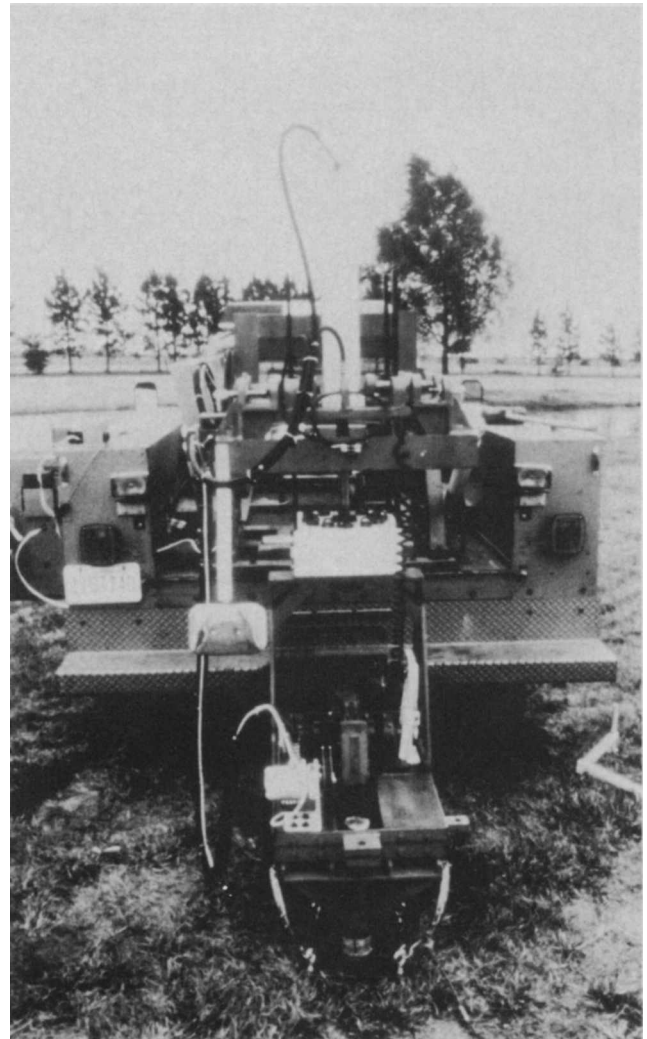


FIG. 3. USGS Rotator mounted on 1 ton truck.

allowing direct source-to-source comparisons of recorded frequency content.

DISCUSSION

Reflection events are interpretable on some raw field data at approximately 40 and 60 ms (Figure 19). Deeper events are present on a few records. Reflections can best be observed on data acquired with 220-Hz analog low-cut filters. First-arrival information is interpreted as refractions with linear velocities of about 350 m/s. The reflection with a zero-intercept time of approximately 40 ms is from a depth of about 7 m using a calculated normal moveout (NMO) velocity of 390 m/s. The reflection with an origin time of about 60 ms was determined to be from a depth of about 14 m using a calculated NMO velocity of 470 m/s. These velocities and calculated depths were based on a least-squares fit of a hyperbolic curve to the interpreted reflection arrivals.

Reflected energy is more coherent and can be interpreted with more confidence on data recorded using downhole explosive sources than projectile or weight-drop sources.

The data collected with 220-Hz low-cut filters using the seismic blasting cap or 30 grams of high explosives possess the highest signal-to-noise ratio, broadest spectrum, and highest dominant frequency of any source or configuration tested. Downhole black powder sources followed high explosives in the quality of shallow reflection signal recorded; the only significant difference between the two was the clarity (signal-to-noise) of the 40-ms event. The spectral properties of the high explosives and downhole black powder sources were similar; however, the relative amplitudes of recorded data were significantly different. At this site, weight-drop sources produced the poorest shallow seismic reflection records. Coherent reflection arrivals are visible on far offset channels of weight-drop records when the impact force was sufficiently high to overdrive close offset channels of the recording system.

Comparison of 220-Hz low-cut spectral plots reveals the approximate percentage of air-coupled wave to other energy recorded for each source. Removal of the air-coupled wave from seismograms prior to spectral analysis required some degree of subjective interpretation. An air-coupled wave is interpretable on all 220-Hz data, with the exception of the encapsulated 8-gauge buffalo gun (Figure 14), as a high amplitude, high-frequency event arriving soon after the much weaker first arrivals. Downhole placement and confinement of subterranean sources obviously results in a lower percentage of air-coupled wave to other source-generated energy (Figures 8 and 9, 13 and 15). The smaller subterranean sources have a lower percentage of air-coupled wave and slightly higher dominant frequency (Figures 13 and 16, 17 and 18). Only general comparisons should be made of the two spectra displayed for each source with 220-Hz low-cut filters.

Because of the subjectivity in interpreting the air-coupled wave, seismically significant characteristics of a source at this site can be determined from direct comparison of like sources. A decrease in dominant frequency and increase in the depth of energy penetration result from an increase in the relative energy output of explosive sources (Figures 20 and 21). Percentage of reflected-to-other-recorded-energy decreases without confinement; i.e., no water stem (Figure 22). Characteristics of reflected energy recorded using 8-gauge sources change with only subtle modifications in downhole configuration (Figure 23). Projectile sources generated more direct wave and slightly less coherent reflection signal than the downhole explosive sources (Figure 24). The more energetic the weight-drop source, the higher the signal-to-noise-ratio on more distant outside channels and the greater the number of over-driven inside seismograph channels (Figure 25). A water-confined downhole explosive charge seemed to represent the optimum configuration and source type for this site.

OBSERVATIONS AND CONCLUSIONS FROM THREE SITES

Choosing the seismic source for a shallow-reflection survey can be a pivotal decision. This report presents results from an area with a moderate water-table depth and low near-surface velocity. Data from this study can be compared directly with data acquired in an area with a water table very  
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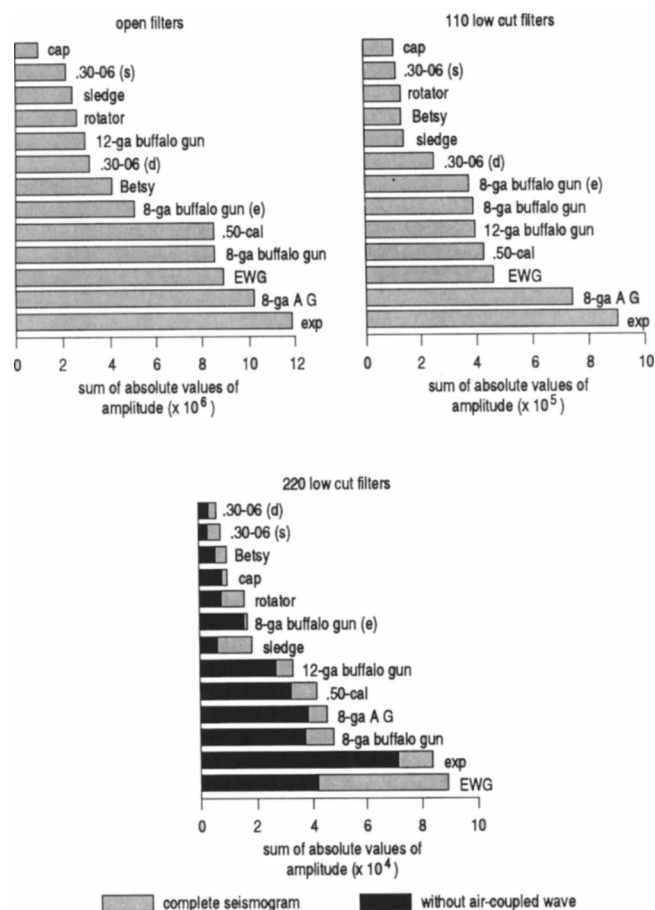


FIG. 4. Sum of the absolute values of amplitudes for the fifteen offsets that were identical for each source at each of the indicated low-cut filter settings. (d) = downhole; (s) = surface; (e) = encapsulated; buffalo gun = downhole firing rod; exp = high explosive (30 grams); AG = auger gun; sledge = 9.1-kg sledge hammer; EWG = elastic wave generator.

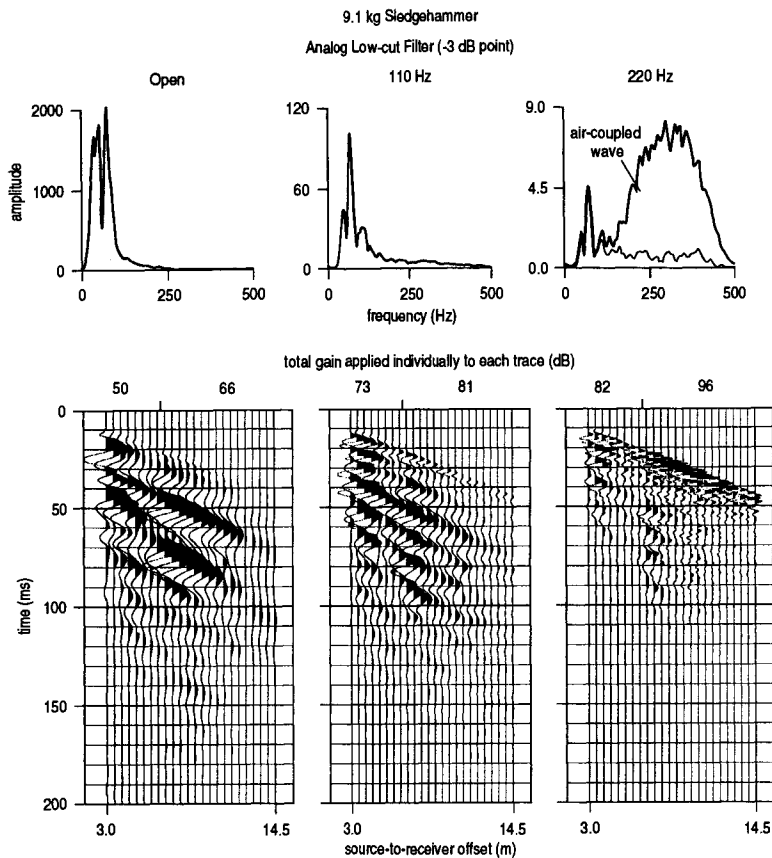


FIG. 5. The 9.1-kg hammer impacting seated steel plate of approximately the same weight.

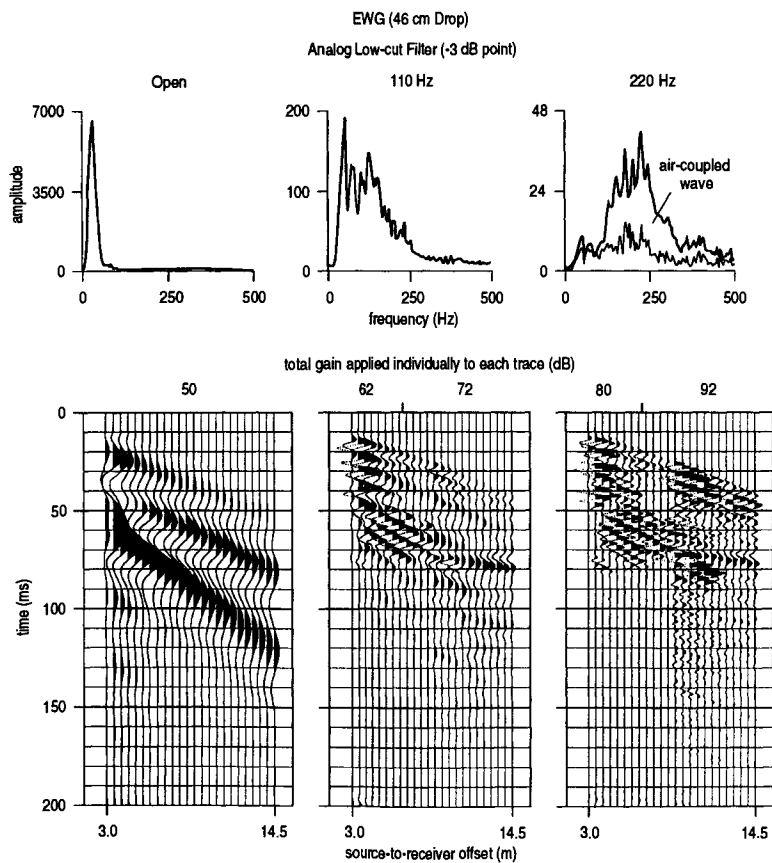


FIG. 6. Bison Elastic Wave Generator IV (EWG) with a 0.46-m acceleration onto a seated steel plate. The high energy noise after the first breaks on the inside 12 traces of the 220-Hz low-cut record is most likely the effect of overdriving the analog portion of the seismograph. The spectrum of the 200-Hz low-cut data with air wave removed also has the analog circuit artifacts removed.

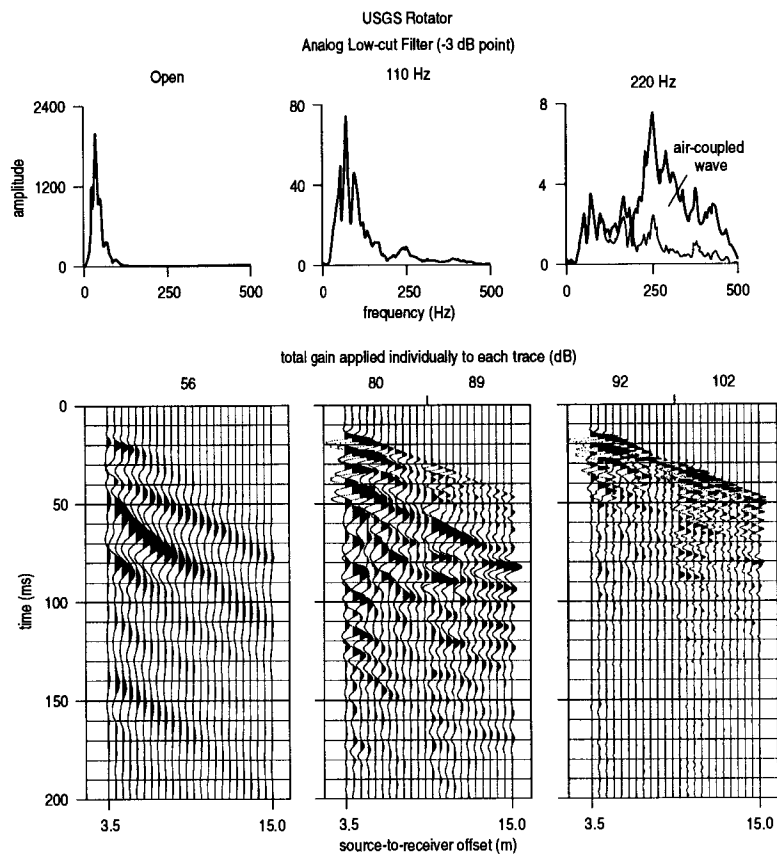


FIG. 7. USGS Rotator vertically impacting a seated steel plate following rotational weight acceleration up to 100 rpm.

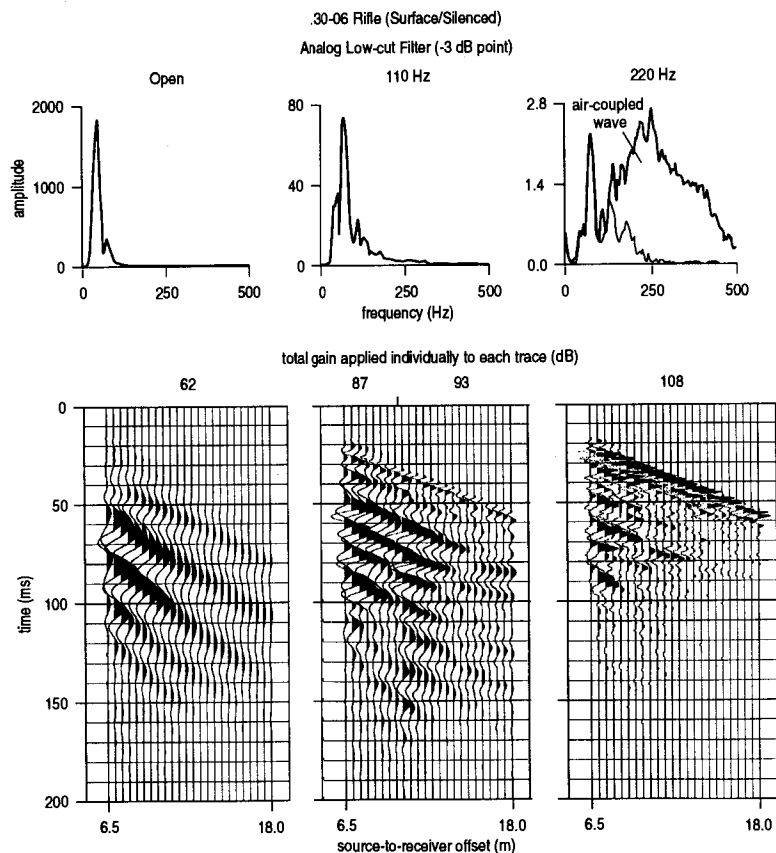


FIG. 8. Surface .30-06 with silencer fired into a water filled hole approximately 0.3 m deep.

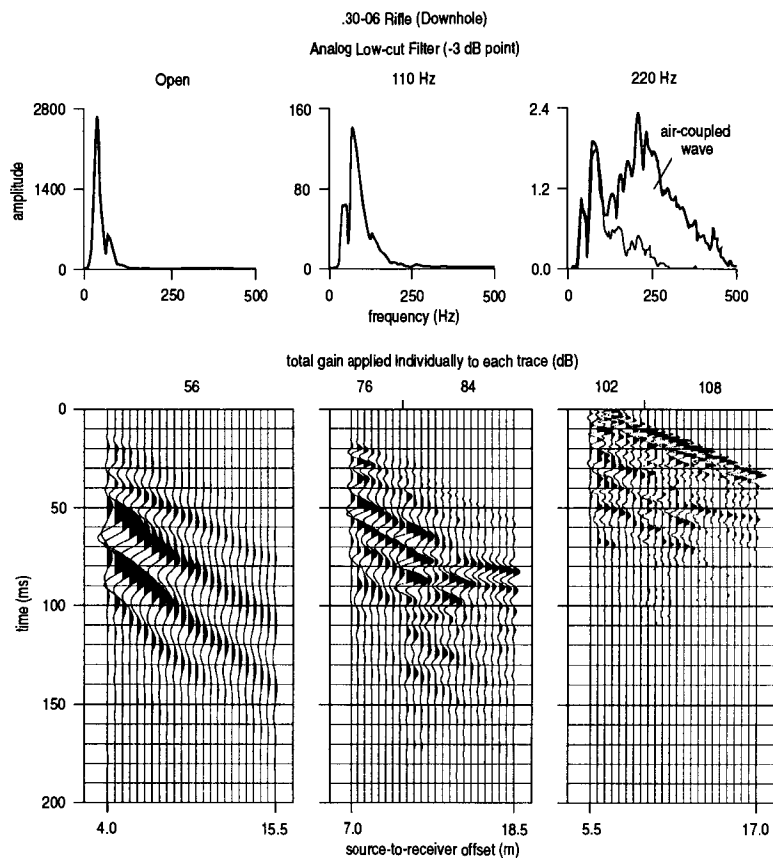


FIG. 9. Downhole .30-06 rifle fired into a water filled hole approximately 0.6 m deep. A delayed trigger resulted in the time shift observed on the 220-Hz low-cut record.

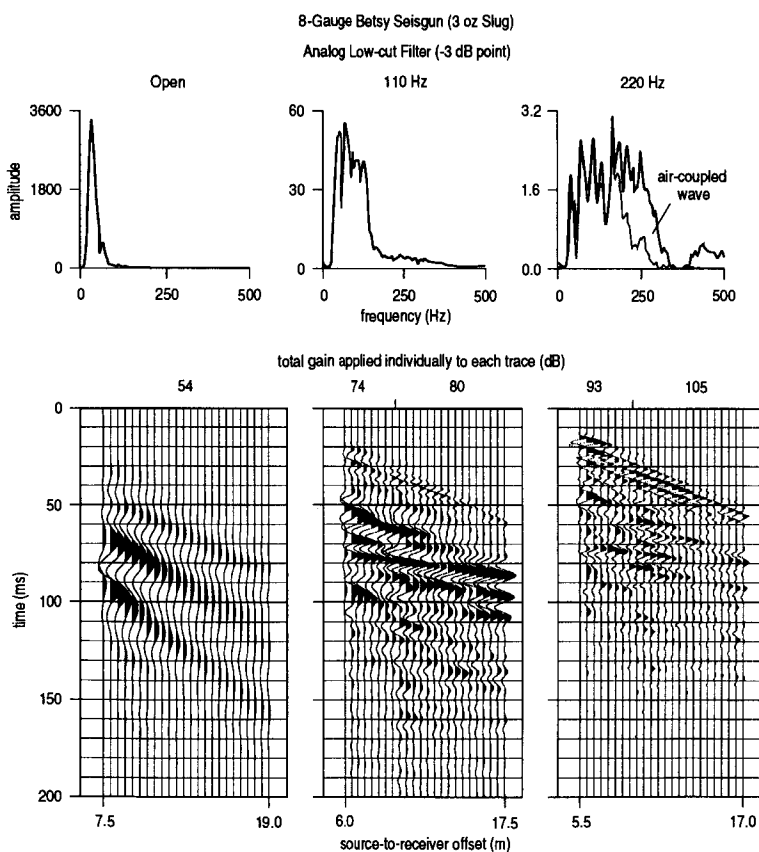


FIG. 10. Betsy Seisgun M3, 8-gauge firing a 3-oz lead projectile into a 0.6-m water-filled hole.



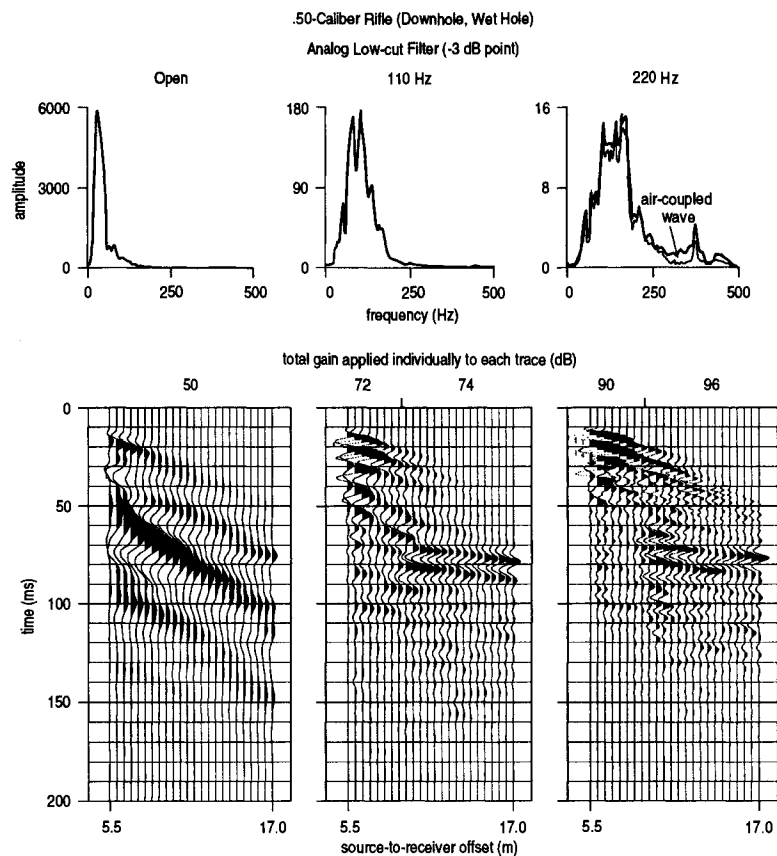


FIG. 11. Downhole .50-caliber rifle firing a 750-grain ball load projectile into a water-filled 0.6-m deep hole.

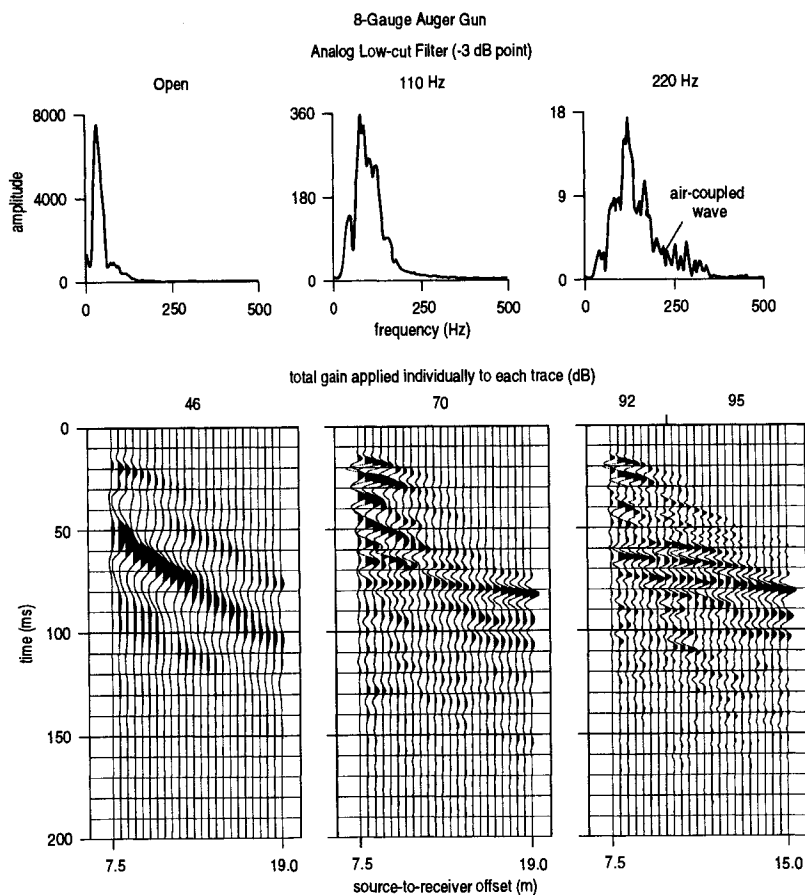


FIG. 12. Auger gun detonating a 300-grain black powder load at base of a 0.6-m deep screw hole filled with water.

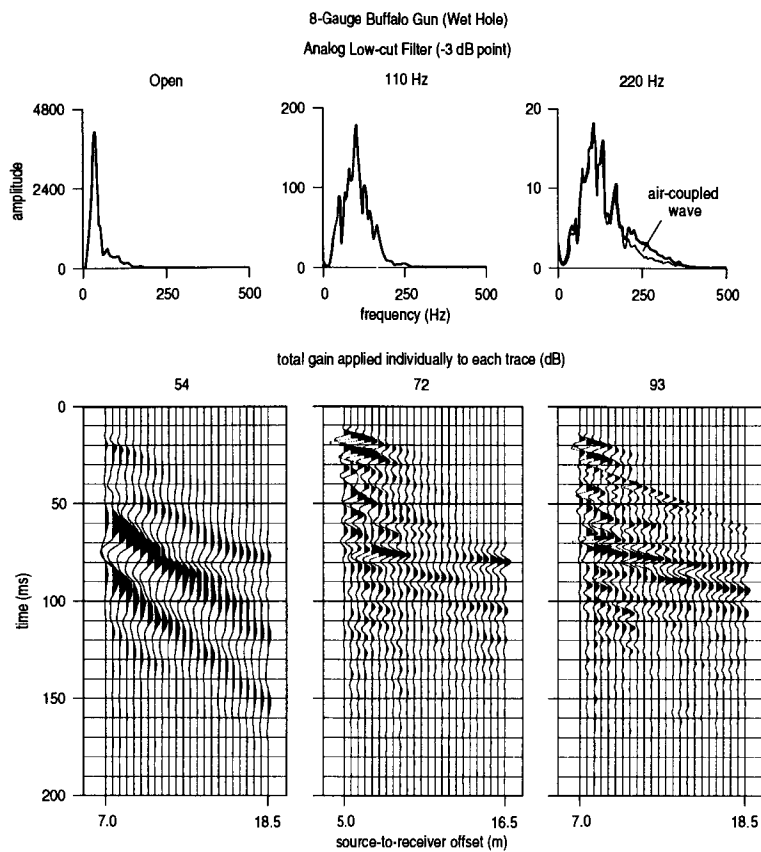


FIG. 13. The 8-gauge buffalo gun detonating a 300-grain black powder load at the base of a 0.6-m deep hole filled with water.

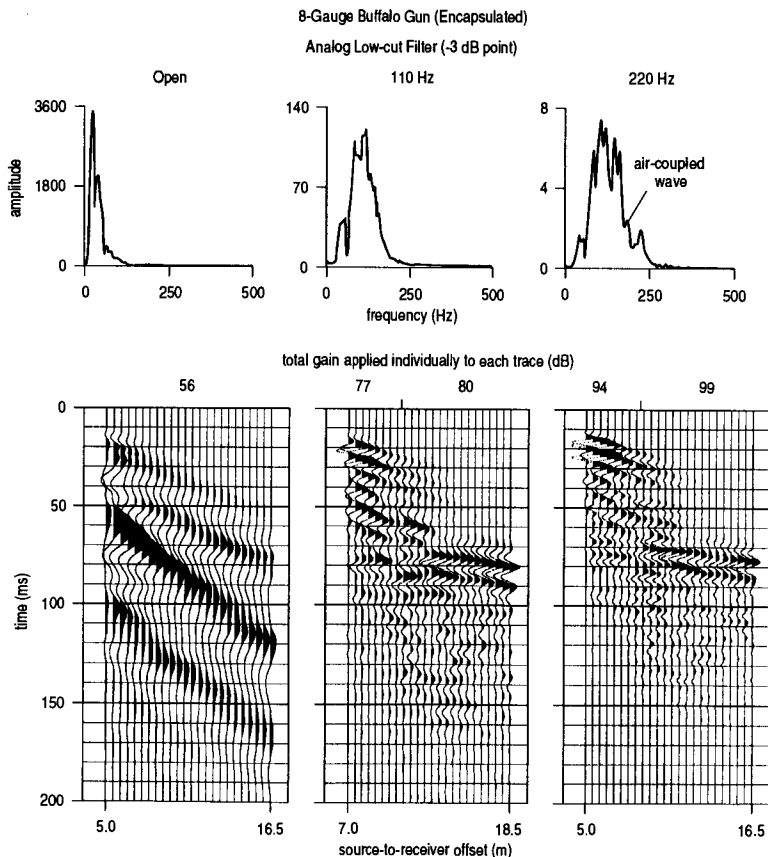


FIG. 14. The 8-gauge buffalo gun detonating a 300-grain PVC encapsulated black powder load at the base of a 0.6-m deep hole filled with water.

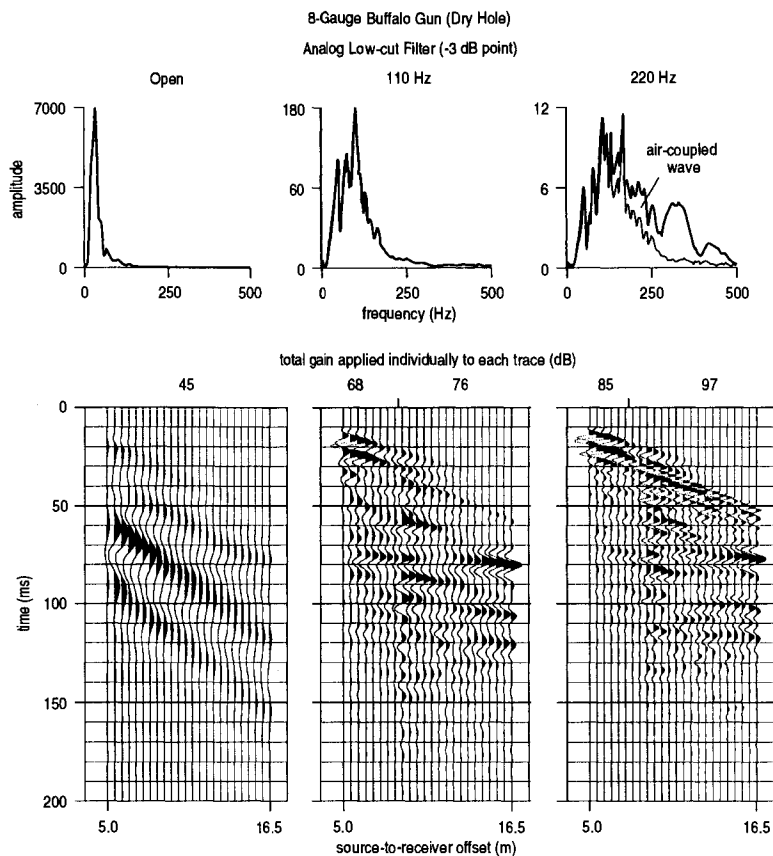


FIG. 15. The 8-gauge buffalo gun detonating a 300-grain black powder load at the base of a 0.6-m deep hole.

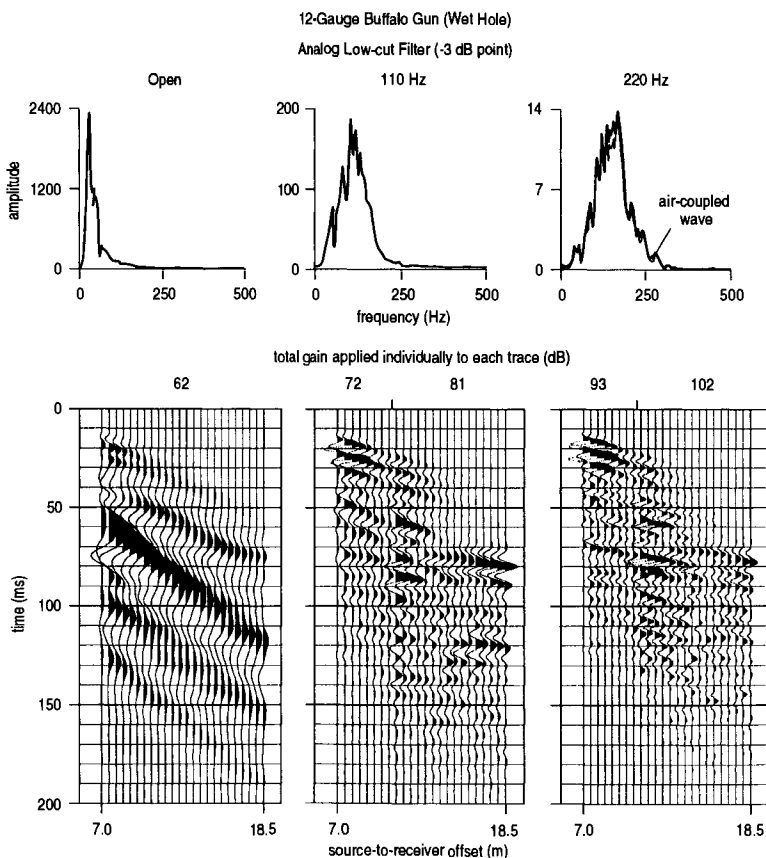


FIG. 16. The 12-gauge buffalo gun detonating a 165-grain black powder load at the base of a 0.6-m deep water-filled hole.

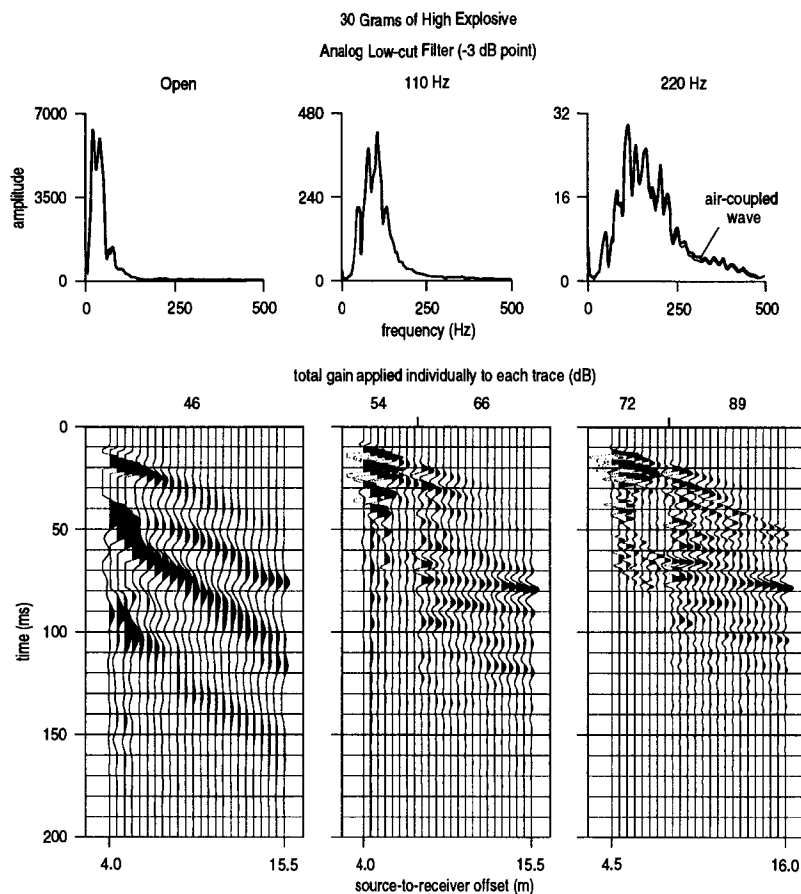


FIG. 17. Thirty grams of high explosives detonated at the base of a 0.6-m deep water-filled hole. Clipping the data set resulted from over-driven amplifiers during acquisition.

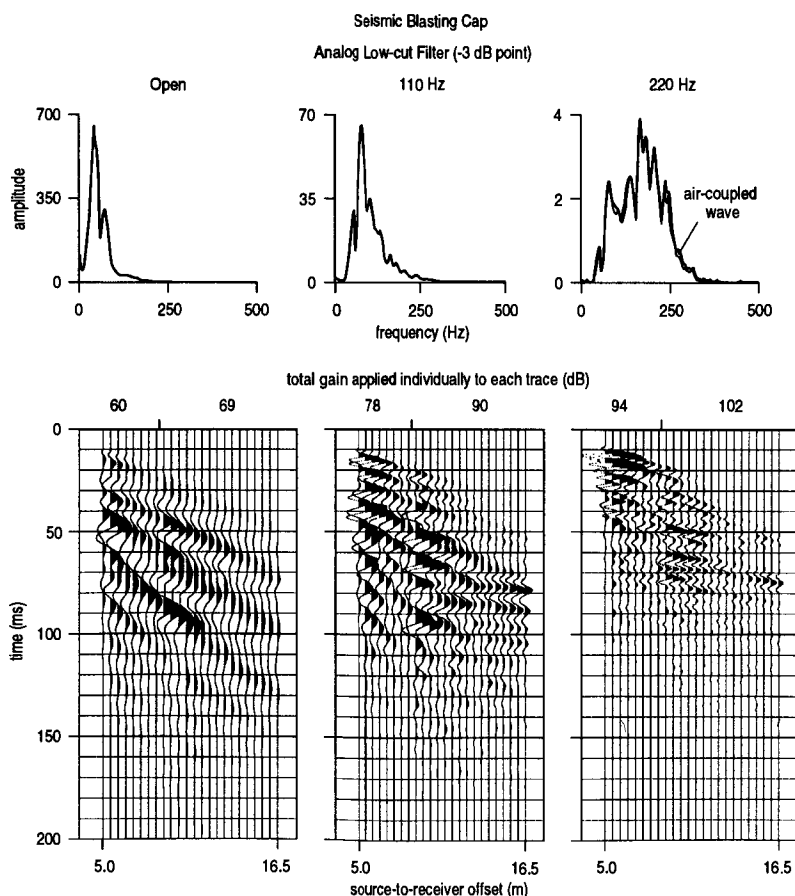


FIG. 18. Seismic blasting cap detonated at the base of a 0.6-m deep water-filled hole.

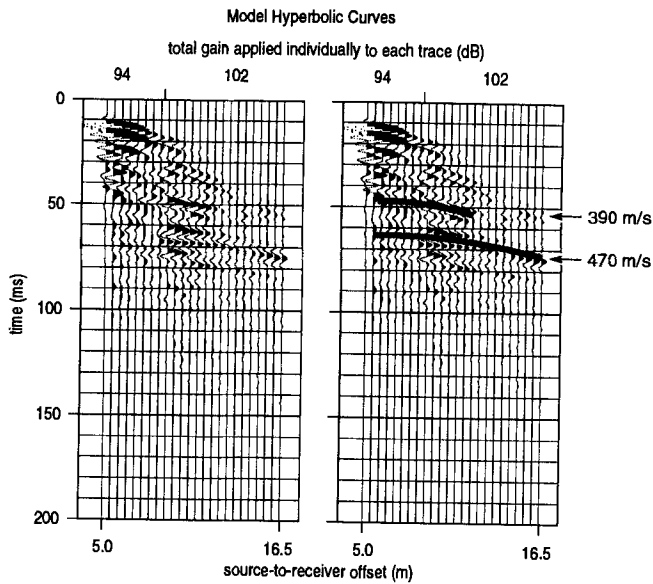


FIG. 19. Seismogram with curves overlaid representing 390 m/s for the 40-ms event and 470 m/s for the 60-ms event. The uninterpreted seismogram is presented for comparison and reader judgment.

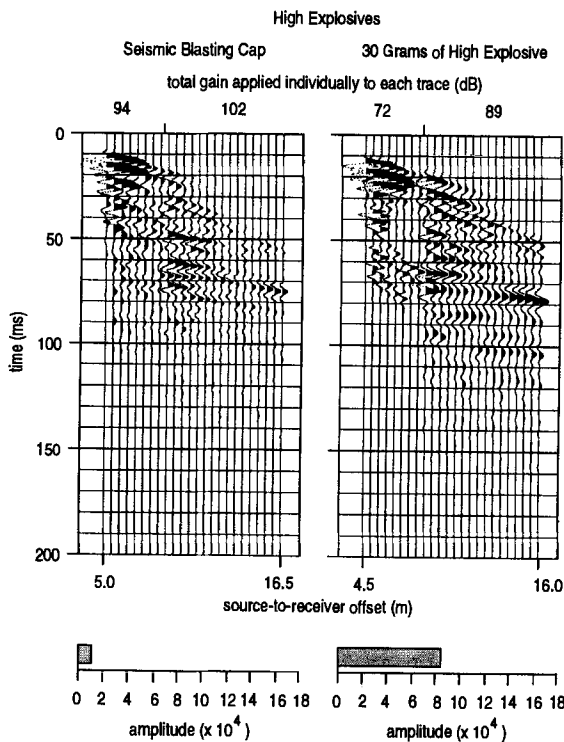


FIG. 20. Comparison of the high explosive sources with 220-Hz low-cut filters. The cap produced the highest dominant frequency reflection of any source tested.

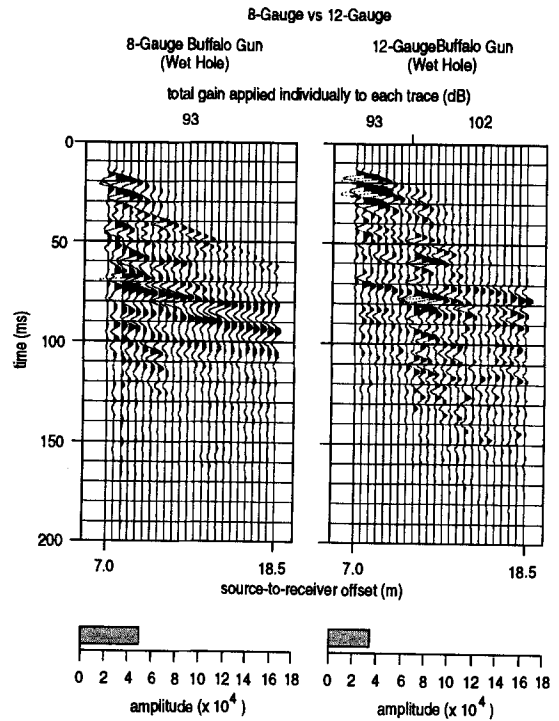


FIG. 21. Comparison of 8- and 12-gauge buffalo guns (300 versus 165 grains of black powder) with 220-Hz low-cut filters. Essentially no air-coupled wave is observable on the 12-gauge record and the dominant frequency is slightly higher. The 8-gauge record possesses a stronger, more coherent, but lower frequency signal.

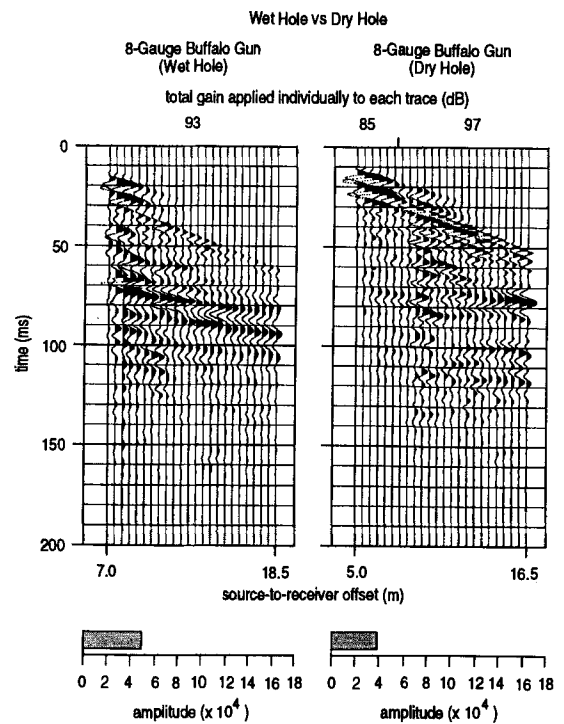


FIG. 22. Comparison of wet versus dry hole with 8-gauge buffalo gun and 220-Hz low-cut filters. The air-coupled wave is much lower in amplitude and the signal-to-noise ratio is much higher when the source is detonated in a water-filled hole.

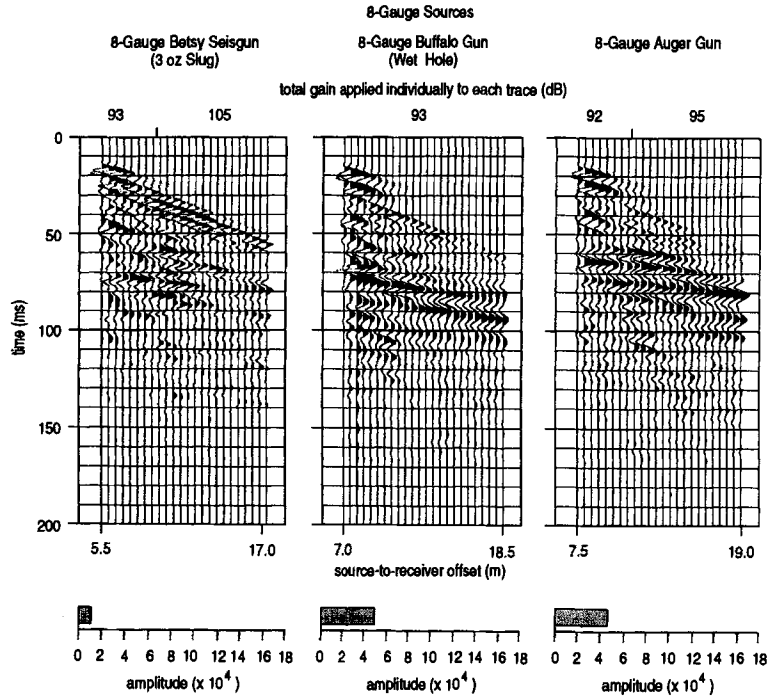


FIG. 23. Comparison of the 8-gauge sources tested with 220-Hz low-cut filters. The Betsy Seisgun produced a surprisingly high-frequency reflection record but lacked in recorded amplitude and possessed an increased amount of air-coupled wave. The 8-gauge buffalo gun produced a very high amplitude reflection record with reflection events interpretable back to trace 1. The Auger Gun seemed to produce a reflection record with a slightly higher signal-to-noise ratio than the buffalo gun.

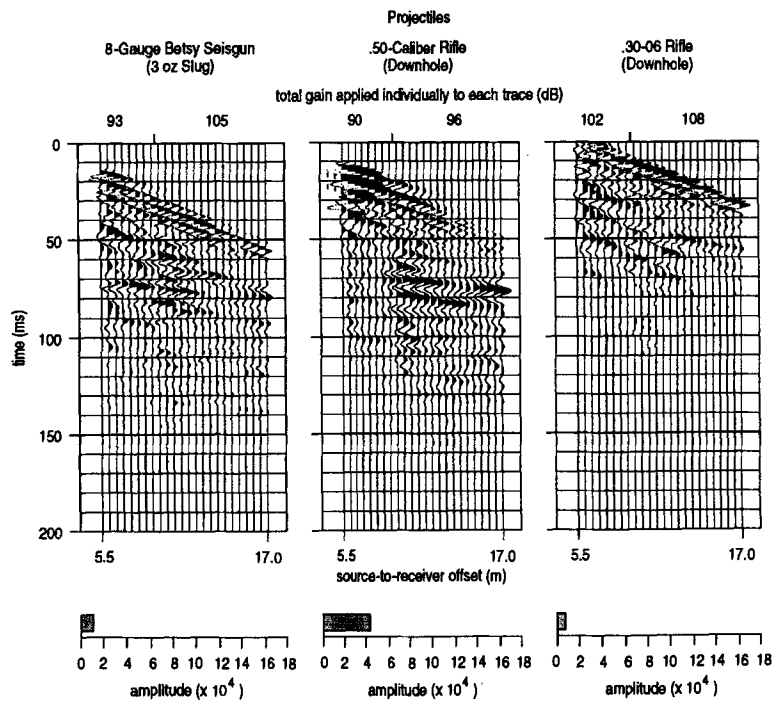


FIG. 24. Comparison of projectile sources. The Betsy Seisgun record exhibits a high dominant frequency and relatively good coherency on most events across several traces. The .50-caliber downhole record possesses a much higher amplitude, signal-to-noise ratio, and reflection coherency, with less air-coupled wave and a similar frequency content. In spite of the time break delay resulting in the time shift observed on the downhole .30-06 data, a reflection event can be interpreted on the far offset traces.

near the surface and a much higher near-surface velocity (Miller et al., 1986), and data acquired in an area with a deep water table and a very low-velocity, near-surface layer (Miller et al., 1992).

Comparison of published results from the three shallow source tests conducted by the source comparison subcommittee of the Engineering and Groundwater Committee of SEG yields some potentially useful "rules of thumb" and

general selection criteria (Table 3). Data acquired with downhole explosive sources at sites with a shallow water table and fine-grained sediments are most likely to possess the highest frequencies and broadest bandwidth. Sites with dry unsorted near-surface conditions with a hard ground surface represent situations where weight drop sources seem to excel. Projectile sources are relatively effective when the near-surface is dry and hard. In areas with a very deformable

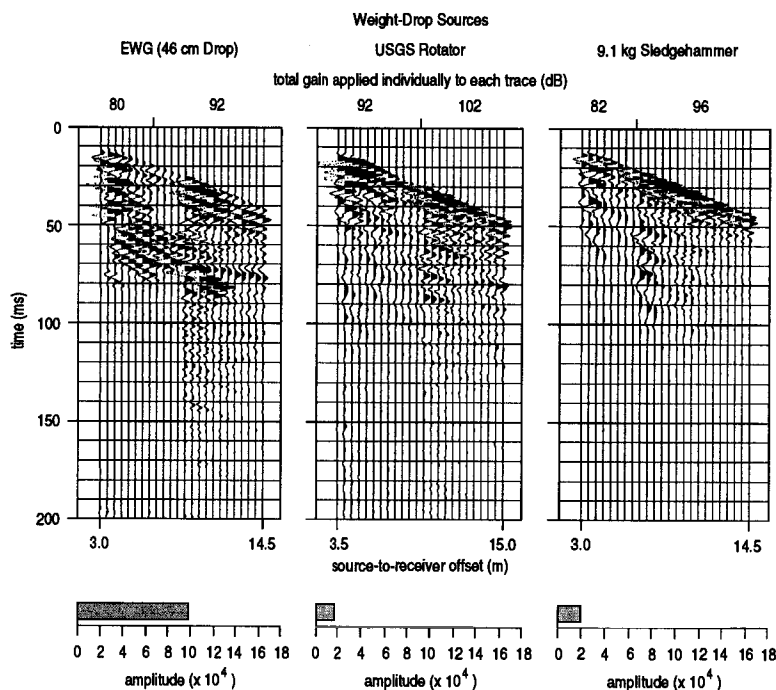


FIG. 25. Comparison of weight-drop sources with 220-Hz low-cut filters. The low energy EWG record possesses the highest quality reflection signal at offsets greater than 9 m. The high energy noise after the first breaks on the inside 12 traces of the EWG are most likely the effects of overdriving the analog portion of the seismograph. The outside 12 traces seem to have been recorded with no artifacts. Comparing the three weight-drop sources at the longer offset, the EWG possesses highest signal-to-noise ratio.

Table 3. Summary of source comparisons.

	New Jersey	California	Texas
Water table	0.8 m	>30 m	7 m
Target depth	80 m clay	11 m	7 m/15 m
<b>General geology</b>			
Grain size	fine to medium	fine to coarse	fine
Sorting	well	poor	medium to well
Material type	sand, clays, gravels	sands and gravels	sands, clays, gravels
Average velocity	1600 m/s	320 m/s	390-470 m/s
Drilling	firm/moist	hard/loose	firm/dry
Best source for target and conditions	Downhole, high explosive	Sledgehammer/weight drop	Downhole, explosive
Primary positive characteristic of best source	Highest frequency with broadest bandwidth	Most coherent reflected energy	Highest frequency, most coherent
Best alternate source	Subsurface projectile/weight drop	Projectile	Projectile
Worst source for site and conditions	Surface projectile	Downhole explosive	Weight drop

near-surface, downhole source placement seems to be important. The following "rule of thumb" represents a reasonable conclusion based on comparison data from three unique sites:

If the near-surface is saturated and fine-grained, try to use downhole sources. If it is hard and dry, weight drop sources should be a top choice. Always try to bring several types of sources, but your first choice should be based on near-surface conditions, site restrictions, and target of interest.

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