GEOPHYSICS, VOL. 57, NO. 5 (MAY 1992); P. 693–709, 21 FIGS., 1 TABLE.

Field comparison of shallow seismic sources near Chino, California

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ABSTRACT

Data from a shallow seismic-source comparison test conducted in an area with a water-table depth in excess of 30 m and near-surface velocities less than 330 m/s were acquired from 13 different sources at a single site near Chino, California. The sources included sledgehammer, explosives, weight drop, projectile impacts, and various buffalo guns. A possible reflecting event can be interpreted at about 70 ms. At this particular test site, the lowly sledgehammer is among the best sources to provide data to see the possible reflection. Our previous work and that of our colleagues suggests that any source could dominate the comparison categories addressed here, given the appropriate set of site characteristics.

INTRODUCTION

Choosing a seismic source can be a pivotal decision for a successful shallow-reflection survey. To help provide basic information on source selection for shallow seismic surveys, the SEG Engineering and Groundwater Committee has conducted shallow source comparison tests in New Jersey (Miller et al., 1986) and California. This paper is a presentation of summary results from the tests near Chino, California. The data allow source characteristics specific to a dry near-surface geologic environment to be deduced and compared for each unique source. A more detailed version of this report (Miller et al., 1989) is available from the Kansas Geological Survey.

Application of seismic-reflection methods to engineering, groundwater, mining, and environmental problems has become increasingly popular over the last 10 years (Steeples and Miller, 1990; Jongerius and Helbig, 1988; Pullan and MacAulay, 1987; Birkelo et al., 1987; Hunter et al., 1984; Ruskey, 1981; Schepers, 1975). With the extremely site-dependent nature of shallow reflections, some particular source in a specific geologic setting can generate higher quality and more usable seismic energy than any other. To assist investigators with selection of the optimum seismic sources for particular applications, geologic conditions, and site logistics, a representative group of sources needs to be compared in a variety of geologic and hydrologic settings with consistent testing procedures and equipment.

In an attempt to quantify significant characteristics of some of the available shallow-seismic sources, a source comparison was conducted just above the tide line near the ocean in New Jersey during 1985 (Miller et al., 1986). The water table was within a meter of the ground surface. This comparison was orchestrated by the Geological Survey of Canada, Kansas Geological Survey, New Jersey Geological Survey, and U.S. Geological Survey. The New Jersey site was distinguished by the ease with which reflections at frequencies of about 300 Hz could be produced from depths of as much as several hundred feet.

Under the geologic conditions at that particular site, the main distinction among the 26 different sources and variations of sources tested was related to the total energy recorded for each source. Very little diversity in recorded seismic characteristics could be deduced from analysis of the data generated during that extensive series of tests. Those data suggest that at such an excellent seismic-data site, source selection is critical only in relation to total energy necessary to image the geologic target.

After the New Jersey source comparison, it was decided that a second source comparison was needed at a site where seismic-reflection information was more difficult to obtain. During November, 1988, a group of shallow-seismic source owners, in cooperation with the Geological Survey of Canada, California Division of Mines and Geology, Kansas Geological Survey, and U.S. Geological Survey, gathered at a site approximately 40 km east of Los Angeles near Chino, California, to participate in this second source comparison

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(Figure 1) (Miller et al., 1989). The test results are summarized in this paper.

GEOLOGIC SETTING

The geologic conditions at the site near Chino, California, were less conducive for the propagation of high-frequency seismic energy than at the New Jersey site. Previous studies in 1985 by the Kansas Geological Survey and the U.S. Geological Survey identified the Chino site as fair-to-poor with respect to recording shallow-seismic reflections. The observed surface and very shallow near-surface material consisted of a thin layer of dry soil overlying loosely compacted, unsorted material with grains ranging in size from clay particles to pebbles. The cultural noise was limited to an occasional car or light plane passing within a predesignated unacceptable distance from live geophones. The recording of data for this test was halted if obvious levels of cultural noise were observed on AGC-plotted field files. The site was unobstructed by surface barriers that could possibly act as reflecting surfaces for source-generated airwaves. The site was easily accessible to vehicles.

FIELD PROCEDURES

There are many factors to consider in a source evaluation. The New Jersey tests primarily addressed the questions of energy, frequency content, and signal-to-noise ratio. Other factors significant to selection of the optimum source relate to source wavelet, portability, cost (both initial and per shotpoint), site preparation requirements, cycle time, repeatability, environmental damage, and safety.

This experiment was designed to be as consistent as possible with the New Jersey tests. Each source was operated in undisturbed soil, and the total source area used was about 4 m sq. By keeping the source area small, differences in near-surface conditions and variations in raypaths were kept small. One improvement in the California tests was to avoid trees and other objects that could echo air-coupled waves back to the geophones during the record length (250 ms).

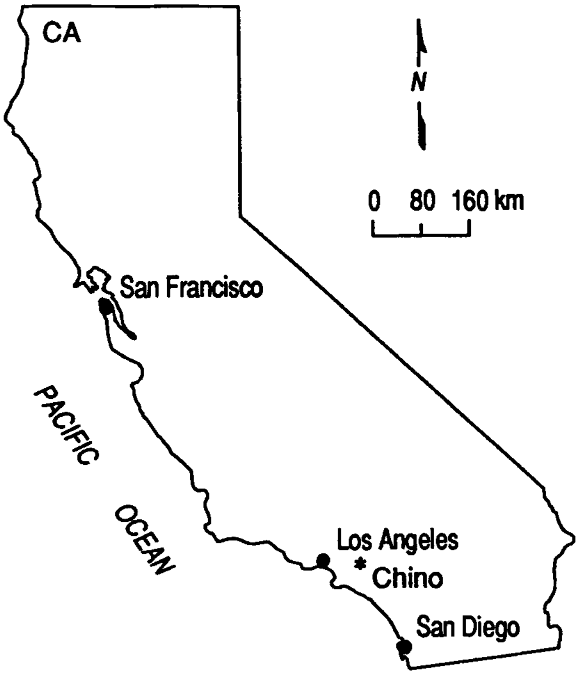

FIG. 1. Location map of Chino, California.

An Input/Output, Inc. DHR 2400 seismograph digitally recorded the data on half-inch magnetic tape in 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 was 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 DHR system was used because of its relatively high instantaneous dynamic range, and it is no longer manufactured, so any apparent endorsement of new instrumentation could be avoided.

Receiver offsets were determined after a series of noise tests conducted the first day of the comparison. The nearest geophone to the source area was 8.5 m and the receiver interval was 0.5 m. 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 line. The geophones were firmly planted and left in place throughout the tests.

Each individual source configuration had a unique undisturbed spot on the ground, resulting in as many source offsets as sources tested. The source area was small enough that offset variations were less than 2 m from the nominal 8.5 m offset to the nearest geophone.

Each source was fired on, into, or within previously undisturbed ground. The time-break system for all sources was a 10 Hz geophone planted within 20 cm of the source. All field parameters, except for analog low-cut (high pass) filters and amplifier gains, were held constant for each source. Each source was recorded with no low-cut filtering (open), 110 Hz low-cut filtering, or 220 Hz low-cut filtering. The analog filters have a 24 dB per octave roll-off from the selected -3 dB point of 110 or 220 Hz. The fixed gain amplifiers were adjusted with each shot to nearly maximize use of the 12-bit A/D converters. The intent of the amplification process was to maintain a minimum of at least one 8-bit digital word on all traces with no word using the full 11 bits (relative plots in the field were used to verify that no signal was clipped). The total surface area disturbed during the two days of testing was less than 16 m^2.

GENERAL INTERPRETATION OF SEISMOGRAMS

Based on water-well information from the California Division of Mines and Geology, the depth to the water table about 1 km from the Chino test site was in excess of 30 m at the time of the source comparison. Little other information on the shallow subsurface geology or structure is available. A simple model of the upper 10 to 15 m of the subsurface (Figure 2) was used to produce a time-distance plot displaying the arrival times of various refraction and reflection events.

The first arrival on all the seismograms (as evidenced in Figures 7 through 17) is the airwave (between 25 and 60 ms). On the unfiltered records, the amplitude of the airwave is small in comparison to later arrivals, and its presence may not be apparent in all cases. Ground roll is prominent on unfiltered records (high-amplitude, low-frequency energy) arriving after 50 ms on the nearest-to-source trace and after 120 ms on the farthest-to-source trace. Ground-roll energy is attenuated on records with a 110 Hz or 220 Hz analog low-cut filter.

The first post-airwave coherent event on the records (between 45 and 70 ms) is interpreted to be a refraction from the top of the second layer in the model (Figure 2). The hyperbolic event between 60 and 110 ms is interpreted to be the wide-angle reflection from the layer 1/layer 2 interface estimated to be approximately 3 m below the ground surface. There is considerable interference in this portion of the seismogram, so the interpretation of coherent events within a 50 ms time window beginning at about 30 ms is somewhat speculative.

There does appear to be reflection information on the unprocessed filtered field files between 65 and 75 ms at source-to-receiver offsets between 8 and 15 m. The reflection event can best be observed on data acquired with 220 Hz analog low-cut filters. According to the model and a least-squares velocity fit to the hyperbola, this reflection is from an interface approximately 11 m below the ground surface. The shot offset and geophone spacing used during the source comparison were chosen so as to best define this reflection event.

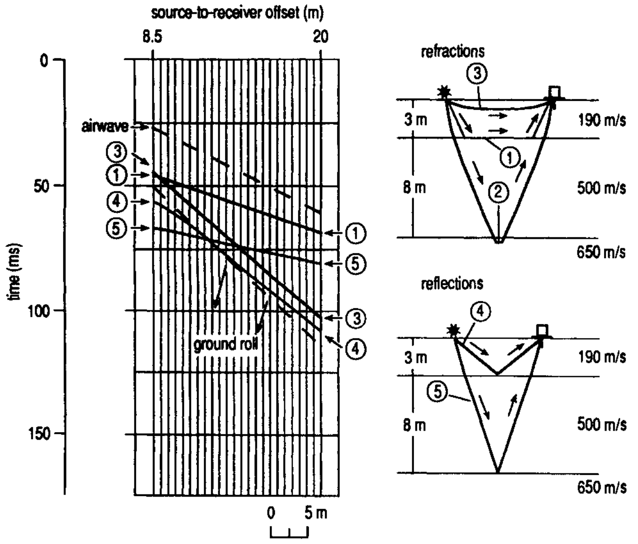

FIG. 2. Time/distance plot with approximate arrival times for various coherent events indicated at the appropriate source-to-receiver offset. The velocity/depth model used to generate the time-distance plot was determined from refraction arrivals on walkaway noise tests and is diagramed on the right side of the figure. Each significant body-wave arrival has been identified with a number that correlates to the geologic model diagramed on the right of the figure. The refraction path labeled 2 on the right would not appear as an arrival for the given source/receiver geometry. This velocity of 650 m/s at the base of the model was observed on far offsets during experiments prior to selecting the optimum offsets.

RESULTS

The participants brought and tested a total of 23 sources or variations of sources (Table 1) (Figure 3). Photographs of the sources can be found in Miller et al. (1986). The downhole rifle configuration was not included in the New Jersey source test, so it is illustrated in Figure 5. Eleven primary types of sources were tested (Figure 4) with variations including wet holes, dry holes, types of gun powder, amounts of gun powder, type of projectile, weight of projectile, and draw-back on rubber band. The various shells used by the gun sources in this test, the downhole capsules, and cage chamber are shown in Figure 6. The photographs of the various sources can be used to assess characteristics such as relative portability, site preparation, and to some degree, safety.

The bar graphs (Figure 3) allow comparisons of relative total amplitude recorded for various sources. All bar graphs used in this paper represent amplitude values (for the indicated source, with the indicated recording parameters) that are the sum of the absolute value of all samples from each of the 24 traces after an amplitude correction to 42 dB of gain. Each amplitude bar has been divided into two parts: total recorded amplitude excluding air-coupled wave (stippling) and air-coupled wave (black). To avoid contamination from trigger-generated noise (high-amplitude and high-frequency spikes), only the 920 samples of each trace between 20 and 250 ms were used in the amplitude calculation. The intent of the bar graph is to allow a relative ordering of sources according to total recordable energy at this site. Total amplitude is not necessarily related to the signal-to-noise (S/N) ratio of the recorded data.

Relative amplitudes of the eleven most commonly used shallow seismic source configurations are compared at all filter settings used in this test (Figure 4). It is hoped that this comparison will allow the reader to gain a better appreciation of relative energy output of these different sources at the particular frequency bands. It must be kept in mind that these data were obtained at one particular site, and different results may be expected under different site conditions.

Unprocessed seismograms and analysis of raw data from each of the eleven primary sources are shown in Figures 7 through 17. Data recorded with each of the three filter settings are displayed in variable-area wiggle-trace plots 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. These plots allow the reader to make trace-to-trace and file-to-file comparisons of wavelet characteristics, relative energy, and spectral content.

Recorded energy, which varied by more than an order of magnitude both trace-to-trace and source-to-source, required gain adjustments during recording and display of the data. Seismograms in Figures 7 through 21 have been amplitude corrected. Each trace within any seismogram has been amplified according to the dB indicated along the x-axis of the seismogram. The amplification is generally divided into two parts (partly by coincidence and partly by design) on each seismogram. The first part includes the 17 traces nearest the source, and the second part includes the far 7 traces (channel numbers 18 to 24). These dB values account for all gain from the input to the preamp of the seismograph

Table 1. Source characteristics

Source	Variation Tested	Site Preparation	Manufacturer/ Supplier/ Price[1]
General			
1) 10 kj spark pak		Dug hole 0.5-m deep and 0.3 m in dia., lined with trash bag and poured in water and salt.	Geomarine Systems $>15,000
Weight Drop			
2) 7.3 kg hammer onto steel plate		Seated steel plate with several impacts.	Hardware store $<500
3) Bison Elastic Wave Wave Generator (EWG) (accelerated weight drop)	a) full extension of rubber band before release. b) extend rubber band 0.5 m before release. c) extend rubber band 0.25 m before release.	Seated 2.6 cm steel plate with several impacts.	Bison Instruments $5,000-$15,000
Surface Projectile			
4) surface .30-06-cal. rifle, silenced	a) shot 180-gram bullet into undisturbed ground. b) shot 180-gram bullet into water-filled hole.	none Poured water into bullet hole from previous shot.	Custom, $<500
5) Betsy Seisgun M3, 8-ga.	a) undisturbed dry area 3-oz lead slug. b) shot 3 oz into wet hole.	Fired into undisturbed ground. Poured water into hole from dry shot of Betsy.	Betsy Seisgun $5,000–$15,000
6) downhole .30-06-cal. rifle	shot into wet hole, 180 grain projectile.	Poked 1/3 m deep hole with 2.3 cm shaft and poured in water.	Custom, $500-$5,000
7) downhole .50-cal. rifle	a) dry hole b) wet hole	Auger drilled 0.05 m hole 0.66 m deep. Poured water in previous dry shot hole; placed condom on end of barrel.	Assembled by Kan. Geol. Surv. from parts manufactured by Texas Gun & Machine Co. $500-$5,000
Downhole Gun/Explosive			
8) .410 Buffalo gun/wet hole	1/5-oz lead slug FED F412-RS	Auger drilled 0.05 m hole 0.66 m deep, loaded gun in hole, poured in water; one-person secured gun.	Betsy Seisgun $500-$5,000
9) 12-ga. Buffalo gun/wet hole	a) 1-oz lead slug REM SP12-Mag. b) Black powder only (blank) WIN VW12BL, 165 grain. c) black powder only (blank) w/PVC liner WIN VW12BL, 165 grain.	Same as source 8.	Betsy Seisgun $500-$5,000
10) 8-ga. Buffalo gun/wet hole	a) powder only (blank) 250-grain REM R8BL. b) 3-oz lead slug REM 3-oz Pb. c) powder only (blank) w/ PVC liner 250-grain REM R8BL.	Auger drilled 0.05 m hole 0.66 m deep, loaded gun in hole, poured in water, held in place by ATV*, compression detonation rubber mallet.	Betsy Seisgun $500-$5,000
11) 8-ga. Betsy Cage gun downhole	powder only (blank) 250-grain REM R8BL	Same as source 8.	Betsy Seisgun $500-$5,000
12) 8-ga. downhole capsules	a) 500-grain high voltage electric detonation. b) 220-grain high voltage electric detonation.	Auger drilled 0.05-m hole 0.66-m deep, loaded capsule, tamped water, and dirt on capsule.	Betsy Seisgun $<500
13) Explosives 200 grains PETN.	1.25 m det. cord	Same as source 12.	$<500

*All terrain vehicle (ATV).

[1] Prices have been given in terms of the following ranges:

$<500
$500-$5,000
$5,000-$15,000
$>15,000

FED = Federal
REM = Remington
WIN = Winchester

through the final analog display. All data can be directly compared, if consideration is given to the indicated total gain.

Spectral characteristics of each of the eleven primary sources or source configurations tested are presented in amplitude-versus-frequency plots above the associated wiggle-trace seismograms in Figures 7 through 17. Two spectra for each seismogram are superimposed on each amplitude-versus-frequency plot. One spectrum represents the averages of all 24 traces (starting time was 20 ms to avoid the effects of near time-zero spikes associated with the time break). Since the airwave is the first arrival and is well separated from later events on all the records, the second spectrum was calculated after removal of the air-coupled wave. The area between the two curves (stippling) is attributed to the air-coupled wave. On some of the records obtained with the 220 Hz low-cut filter, the air-coupled wave is a major component of the total recorded energy. All traces used to calculate the spectra were corrected to 42 dB of gain prior to spectral analysis allowing direct source-to-source comparisons of recorded frequency content.

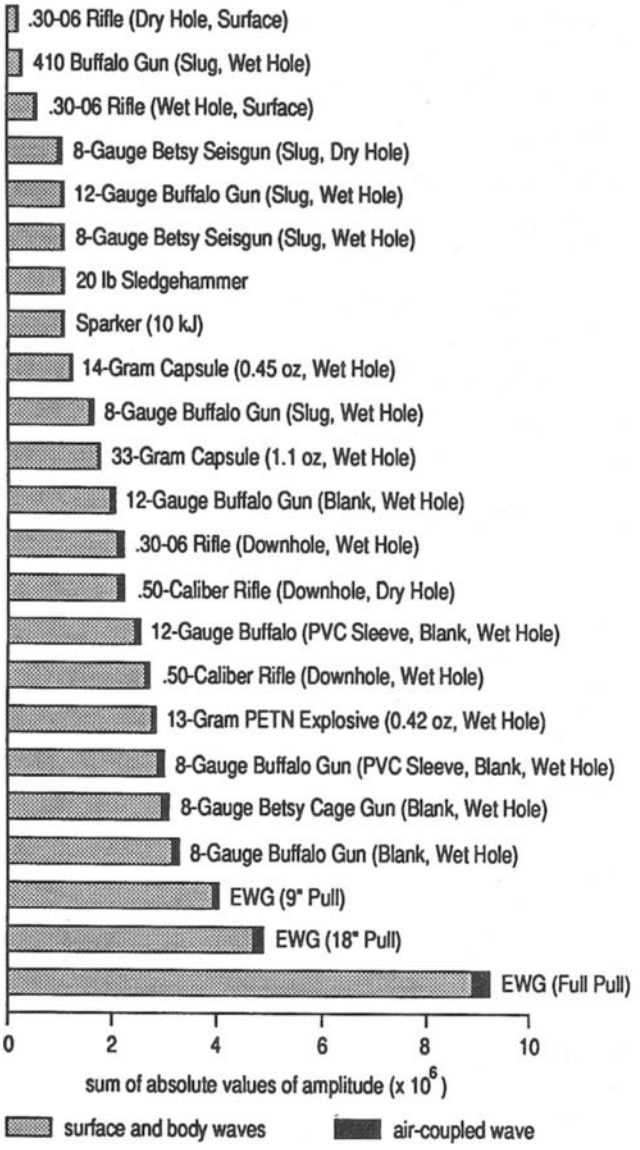

FIG. 3. This bar graph allows amplitude comparisons from the 23 sources and configurations of sources recorded with the seismograph's analog low-cut filters out (open). The length of the stippled bar indicates the sum of the absolute value of all traces after each individual trace was gain-corrected to 42 dB. The total recorded air-coupled wave is represented by the black end of the bar.

Data recorded at this site with the elastic wave generator (EWG) possess unique noise characteristics (Figure 9). The EWG requires continuous use of a 4-cycle gasoline engine to power its hydraulic lift mechanism. The frequency spectra of energy recorded during this test from any single EWG shot contain high-frequency engine noise. The 220 Hz low-cut filter data with the EWG have identifiable engine noise on the seismogram and spectra. Contamination of recorded seismic energy by the EWG's high-frequency engine noise should be considered during comparisons with all other sources used in this study.

Figures 18 through 21 are comparisons of like or similar sources, varying specific parameters or configuration. Seismograms and graphs are identified with alpha characters (Figures 18 through 21). Parts (a, b, c) and (d, e, f) of each figure are the variable area wiggle-trace display of the two similar source configurations for comparison at the three low-cut filter values. The (g, h, i) parts are bar-graph comparisons of whole trace amplitude for the two source configurations at the same three low-cut filter settings. The intent of Figures 18 through 21 is to highlight particular characteristics of each source and source configuration that may be significant to shallow-reflection or refraction surveys at this site or sites similar to this one.

The downhole shotguns are capable of firing either a black powder blank or a metallic slug (Figure 18). Both configurations have been used at various times on shallow seismic surveys. Seismograms obtained using the 8-gauge downhole shotgun with 3 oz slugs (a, b, c) are displayed over seismograms of the black powder blanks (d, e, f). Absolute value bar graphs (g, h, i) show that the black powder loads (lower bar) generate almost triple the total recordable amplitude of the lead slug (upper bar). At this site more energy can be recorded with less environmental impact and expense with blank loads than with lead projectiles.

Figure 19 is a comparison of surface-versus-downhole firing of the .30-06 rifle. Recorded seismic energy levels were increased from four to ten times when the .30-06 rifle was converted from a silenced surface source to a water-stemmed downhole source. Lowering the energy origination point below the ground surface clearly increases the total energy recorded, and in this case, increases the amount of recorded air-coupled wave.

Downhole sources (i.e., explosives, shotguns, and rifles) are generally lowered down small diameter boreholes, backfilled with material, and detonated. Investigators have used a variety of materials to backfill loaded boreholes in hopes of containing the energy and reducing the air-coupled wave. Comparison at this site of the two most popular configurations of downhole shooting (water-filled versus air-filled) suggests water-stemming reduces the air-coupled wave by as much as one-third and increases the recorded seismic energy from one-fifth to almost double (Figure 20). A water stem improves the coupling of seismic energy and decreases the recorded source-generated air-coupled wave.

For certain applications the downhole black powder capsule has become a popular alternative to high explosives. At this site, an approximately equivalent amount of black powder (encased in a heavy-walled PVC capsule) yielded less than one-half the recorded seismic energy of high explosives (Figure 21). The high explosive generated more recordable seismic energy than black powder capsules and from twice to four times the ratio of seismic energy to air-coupled wave.

Increased levels of recorded air-coupled waves generally associated with larger energy downhole sources at this site are probably related to insufficient water head/hole depth to contain the energy. Data recorded with the 110 or 220 Hz low-cut filters possessed a lower signal-to-air-wave ratio than either data recorded with no low cuts or data recorded from less energetic sources (Figure 4). The apparent dependence of the air-coupled wave on low-cut filtering is a result of the increased gaining after low-cut filtering and the high-frequency characteristics of the air-coupled wave.

(text continues p. 707)

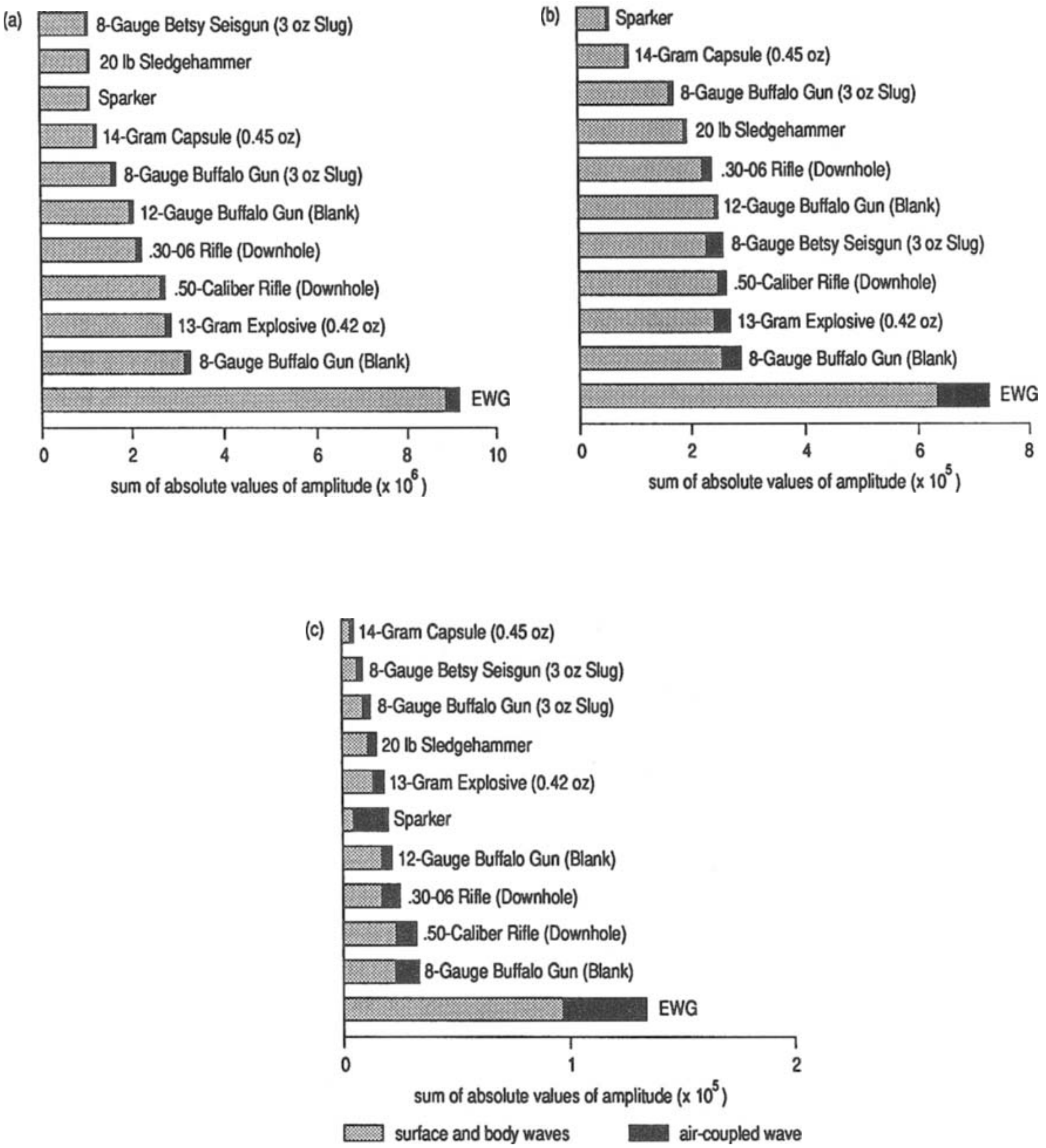

FIG. 4. (a) This bar graph compares the amplitudes of the recorded seismic energy of the 11 (Figures 7 through 17) more commonly used shallow seismic sources with the seismograph's analog low-cut filters out (open). (b) Same as (a), except the seismograph's analog low-cut filters were set at 110 Hz. (c) Same as (a), except the seismograph's analog low-cut filters were set at 220 Hz.

FIG. 5. Photograph of downhole configuration of the .50-caliber rifle.

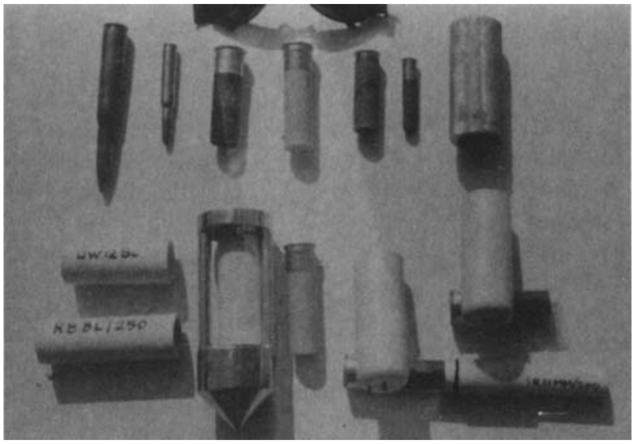

FIG. 6. Photograph of shotgun shells, rifle shells, capsules, and cage gun.

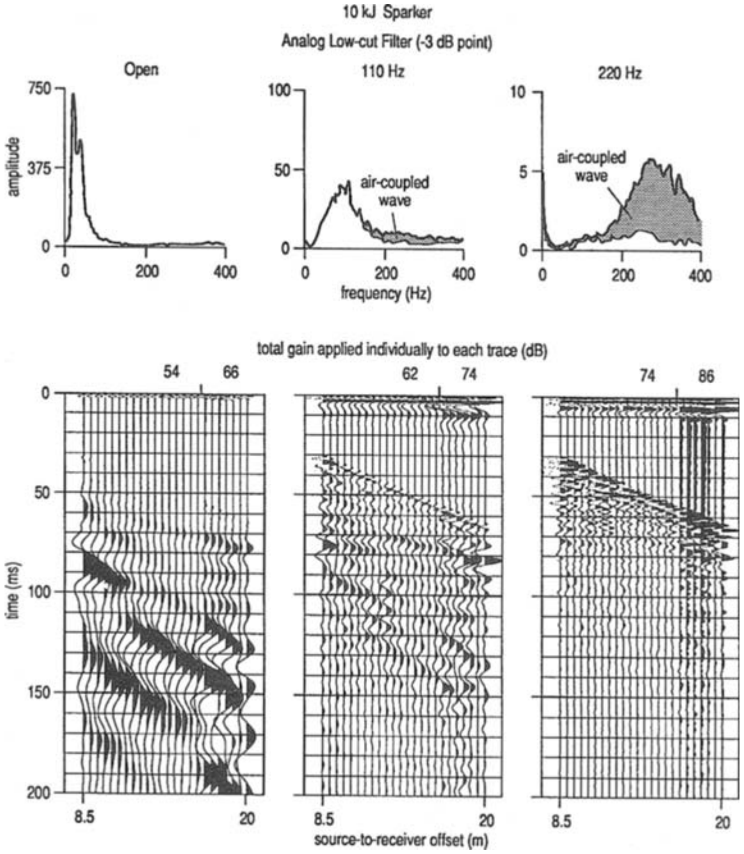

FIG. 7. 10 kJ Sparker immersed in a saltwater solution contained in a dug hole approximately 50 cm deep and 75 cm in diameter. The hole was lined with a plastic bag to contain the salt-water solution. The same hole was used for all the shots recorded with the sparker.

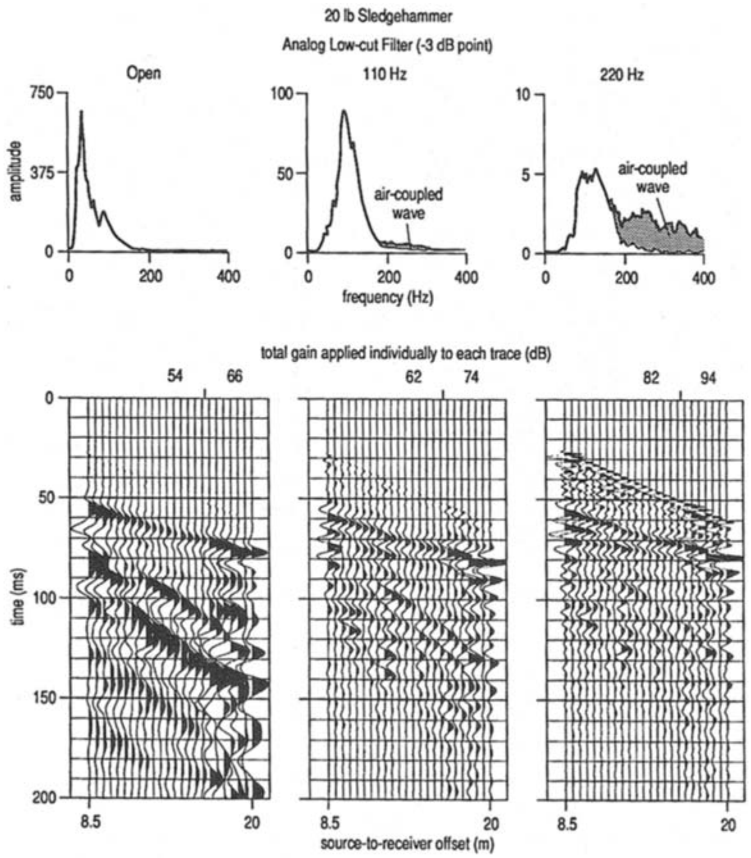

FIG. 8. Single impact on an approximately 10-lb steel plate with a 20-lb sledgehammer. The steel plate was seated with several impacts with the sledgehammer. The location of the seated steel plate was the same for all shots recorded with the sledgehammer.

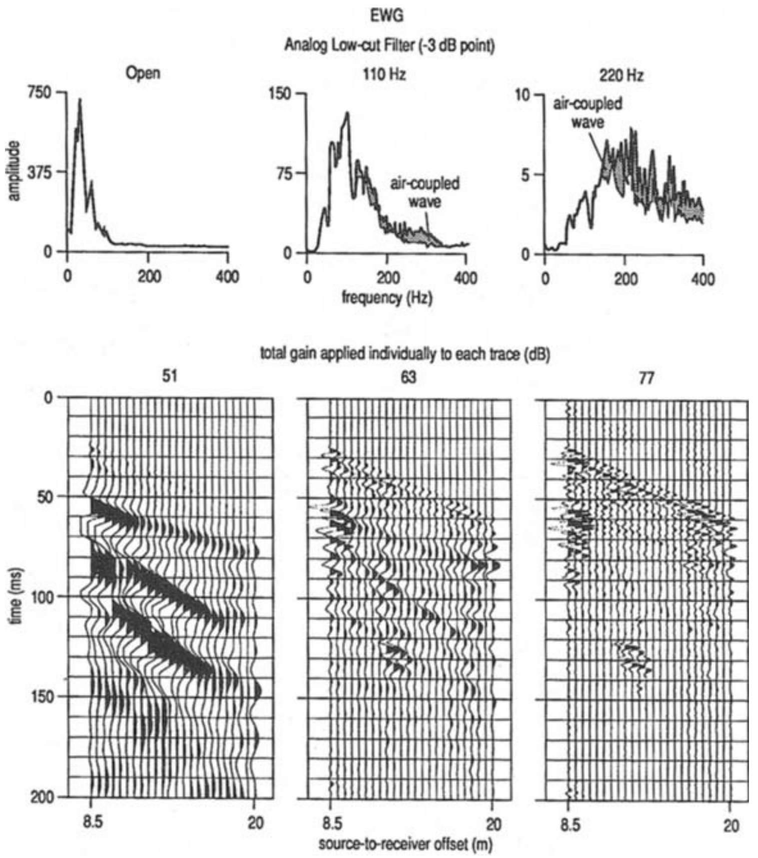

FIG. 9. The elastic wave generator (EWG) is a weight-drop source. Prior to firing, the steel pad was seated with several blows. Data were recorded while the 4-cycle gasoline engine was running. Contamination of the recorded data by engine noise is evident (see discussion in text).

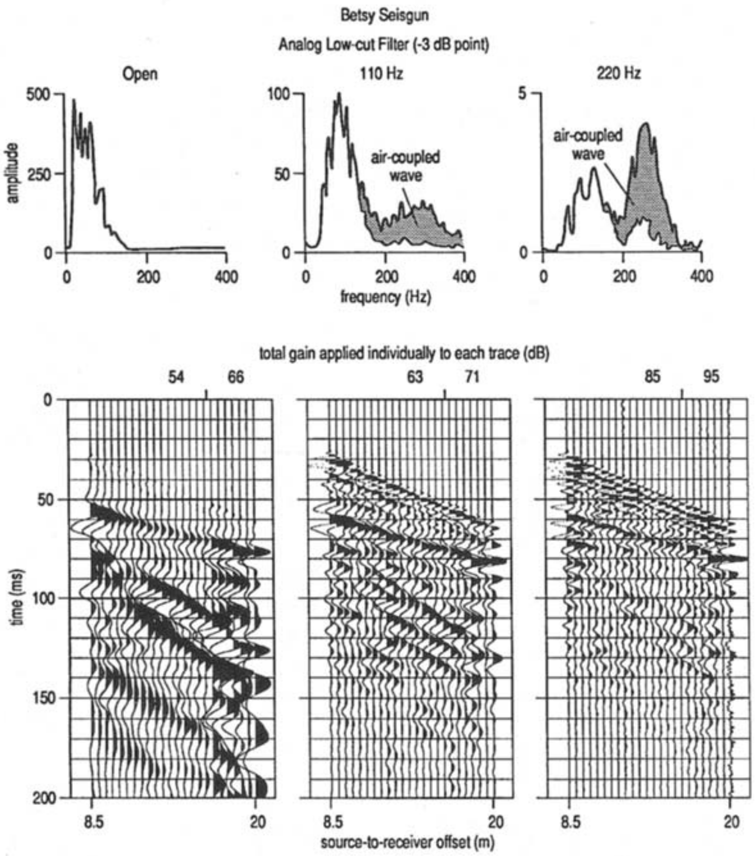

FIG. 10. An 8-gauge Betsy Seisgun fired into a 50-cm hole filled with water. The Betsy was firing a 3-oz lead slug. A new hole was used for each shot.

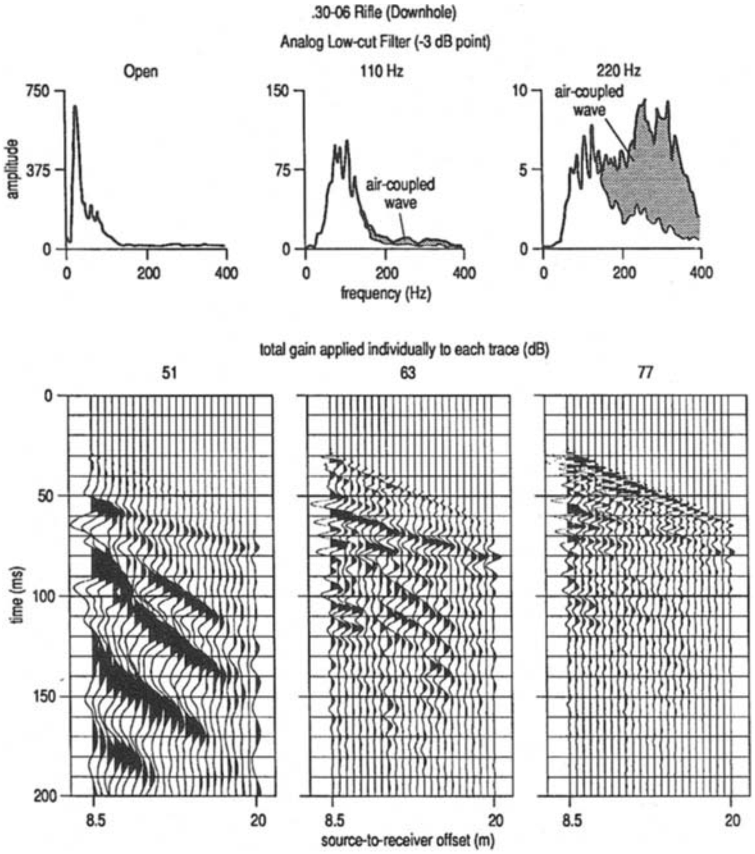

FIG. 11. Downhole .30-06 rifle firing a 180-grain projectile into a 50-cm deep water-filled hole. Approximately 25 cm of the gun barrel was submerged in the water-filled hole. The water was kept out of the gun barrel with a standard pre-lubricated condom covering the end of the barrel. A new hole was used for each shot.

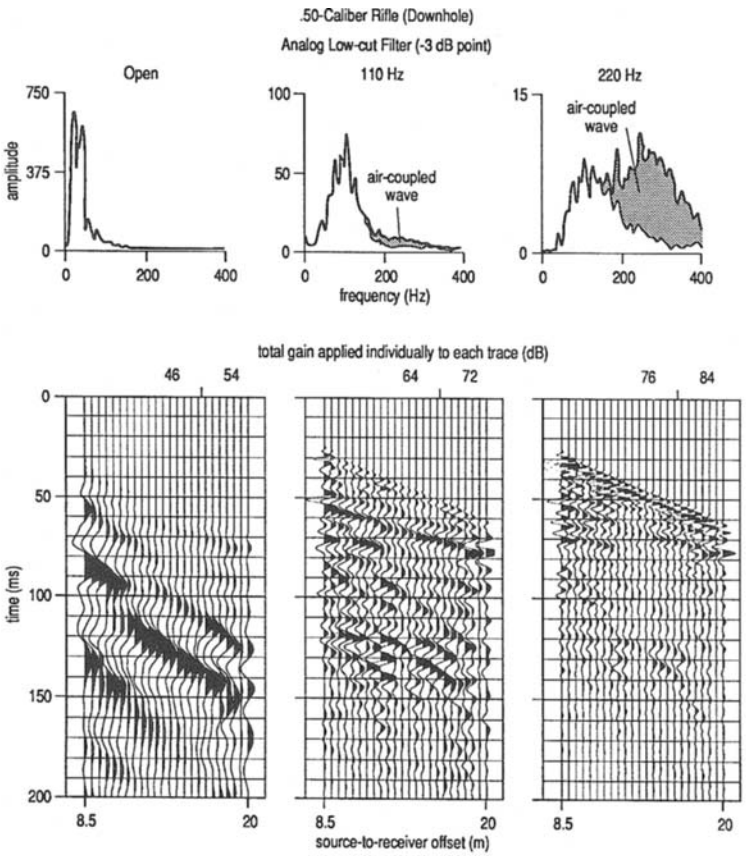

FIG. 12. Downhole .50-caliber rifle firing a 750-grain projectile into a water-filled hole. Approximately 50 cm of the rifle barrel was submerged in the water-filled hole. A standard pre-lubricated condom was used to keep water out of the rifle barrel. A new hole was used for each shot

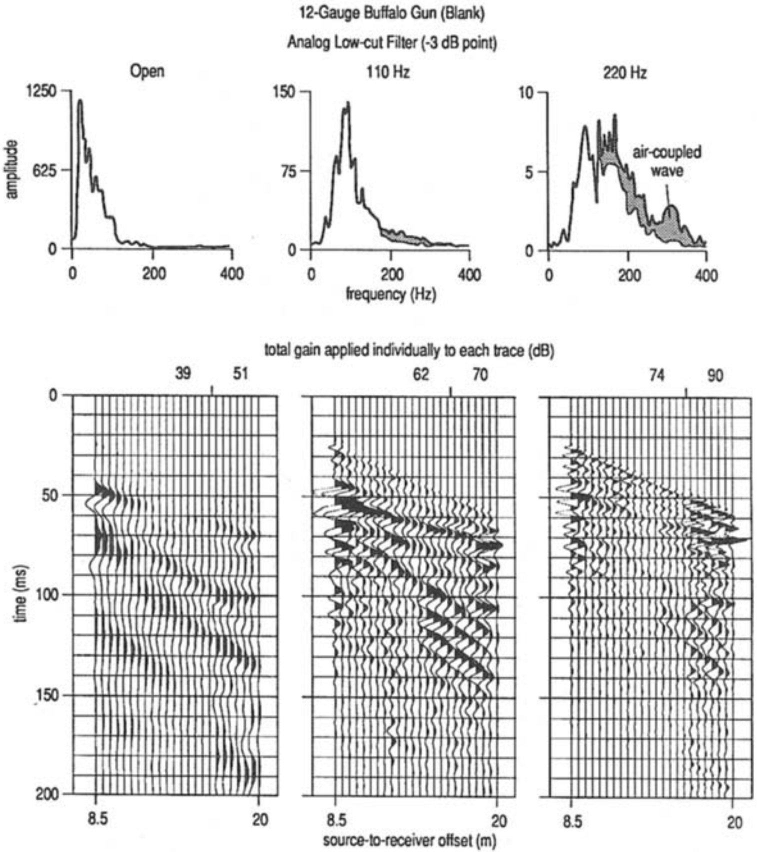

FIG. 13. A 12-gauge buffalo gun fired into a water-filled hole at a depth of approximately 0.8 m. The buffalo gun was compression-fired using a rubber mallet to strike the firing pin at the top of the gun approximately 1 m above the ground surface. The 12-gauge shell was a magnum load of black powder with no projectile (blank). A new hole was used for each of the three recorded shots.

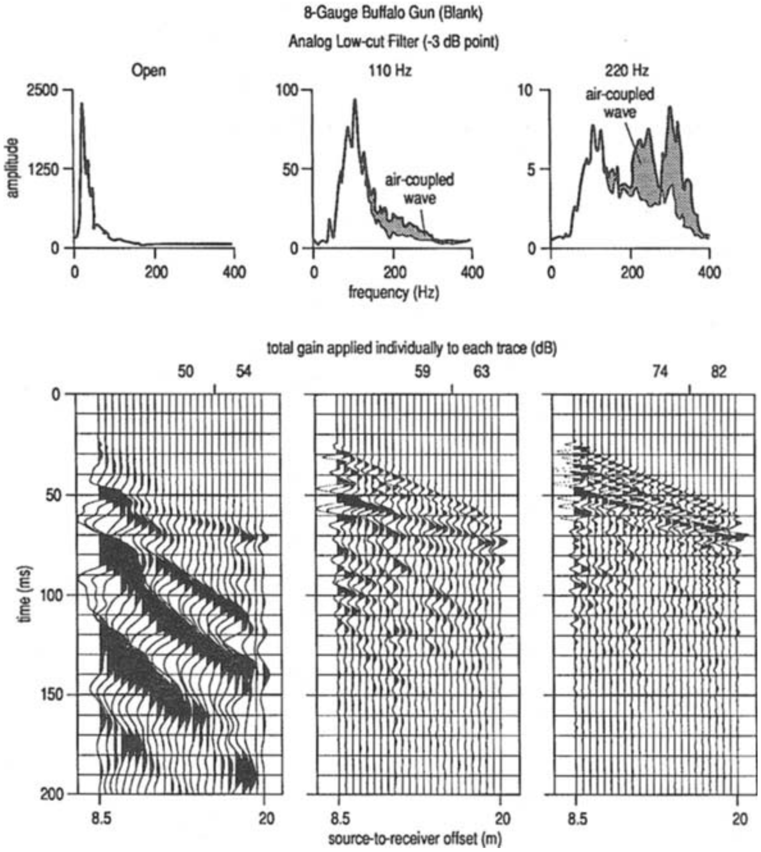

FIG. 14. An 8-gauge buffalo gun fired into a water-filled hole at a depth of approximately 0.8 m. The buffalo gun was compression-fired using a rubber mallet to strike the firing rod exposed at the top of the gun approximately 1 m above the ground surface. The 8-gauge shell was a black-powder blank round (i.e., no projectile). A new hole was used for each of the three recorded shots.

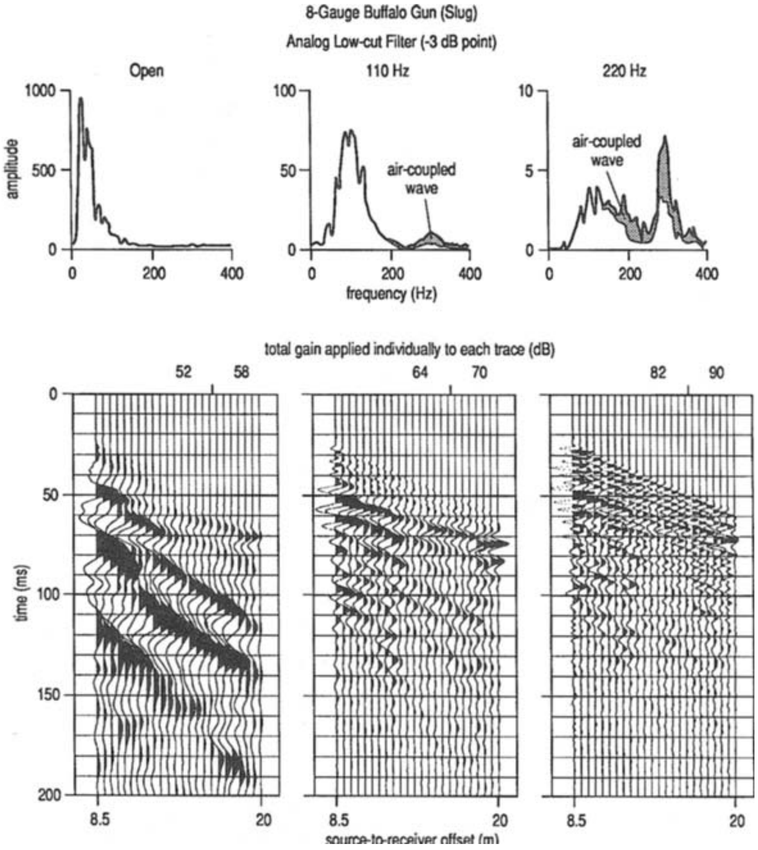

FIG. 15. An 8-gauge buffalo gun fired into a water-filled hole at a depth of approximately 0.8 m. The buffalo gun was compression-fired using a rubber mallet to strike the firing rod exposed at the top of the gun approximately 1 m above the ground surface. The 8-gauge shell was a 14-grain load firing a 3-oz projectile. A new hole was used for each of the three recorded shots.

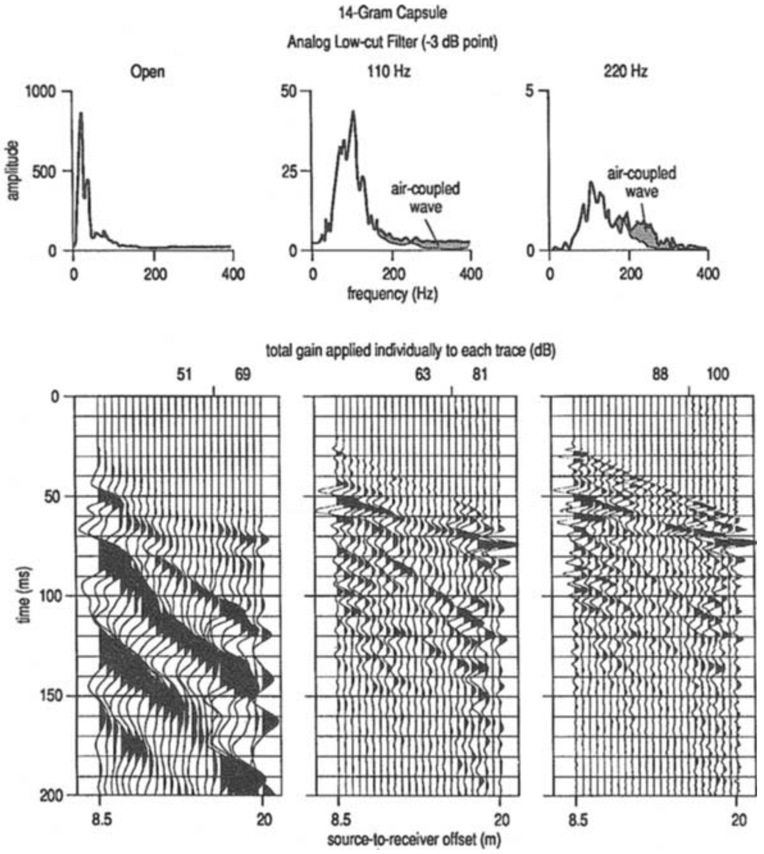

FIG. 16. A 14-gram black powder 8-gauge capsule. This 8-gauge electrically detonated blank shotgun shell was encased in a PVC housing, buried, and detonated with a standard seismic blasting box. The stemming material for the 0.8-m holes included water and dirt. A new hole was used for each of the three recorded shots.

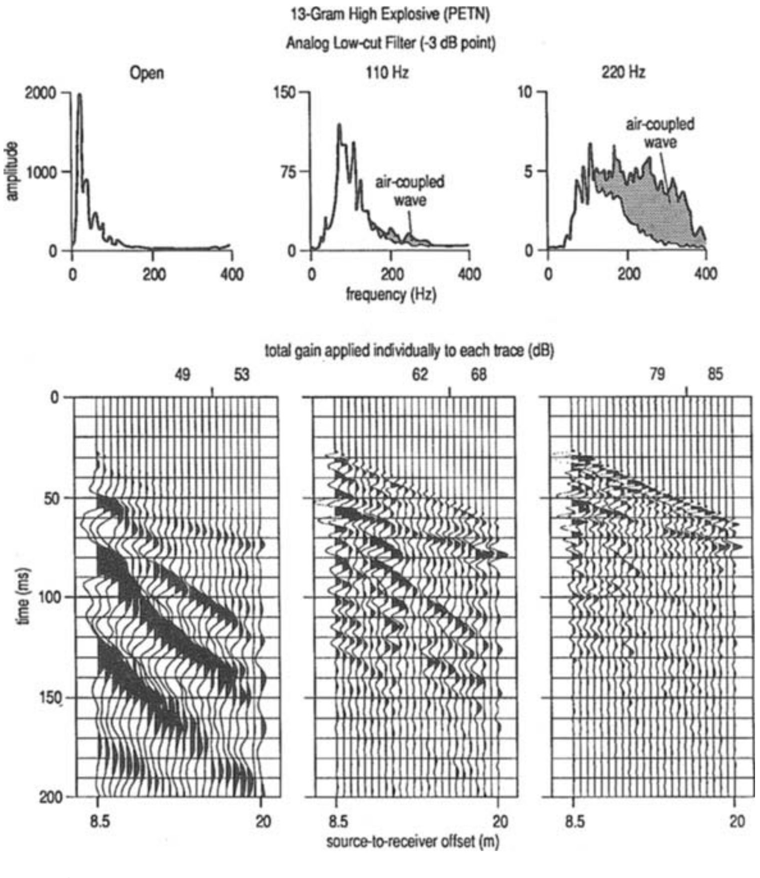

FIG. 17. A charge of 13 grams of PETN with 1.2 m of Det Cord. The charge was placed at the bottom of a 0.8-m hole and stemmed with water and dirt. A new hole was used for each shot. Each shot was fired electrically with a standard seismic blasting box.

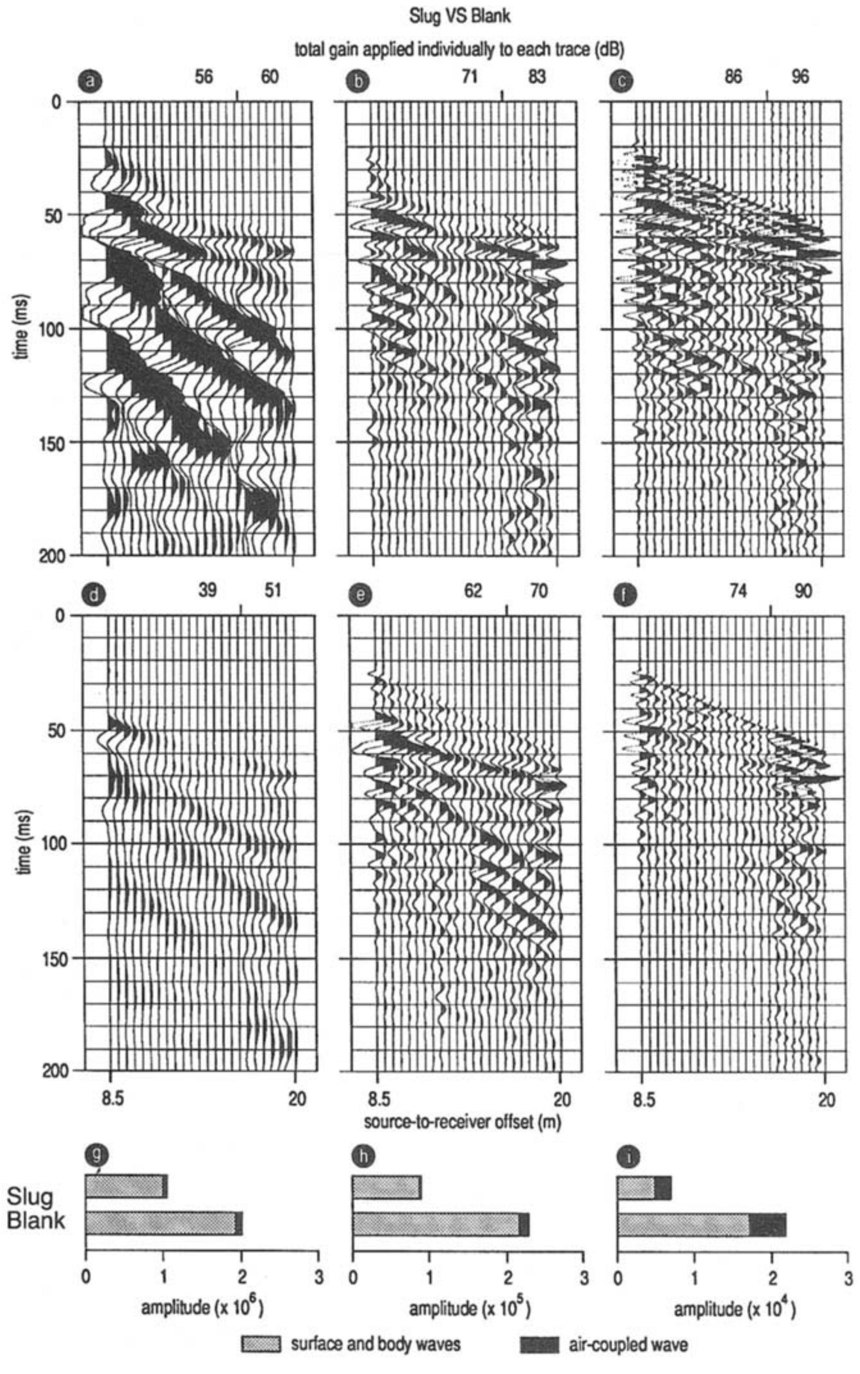

FIG. 18. An 8-gauge downhole shotgun comparing black powder blanks (d, e, f) with 3-oz lead slugs (a, b, c). The bar graphs (g, h, i) suggest blank loads transfer as much as three times more recordable seismic energy to the ground. The overall quality of the interpreted seismic reflection at around 55 ms (ignoring the amplitude difference) is consistent regardless of load.

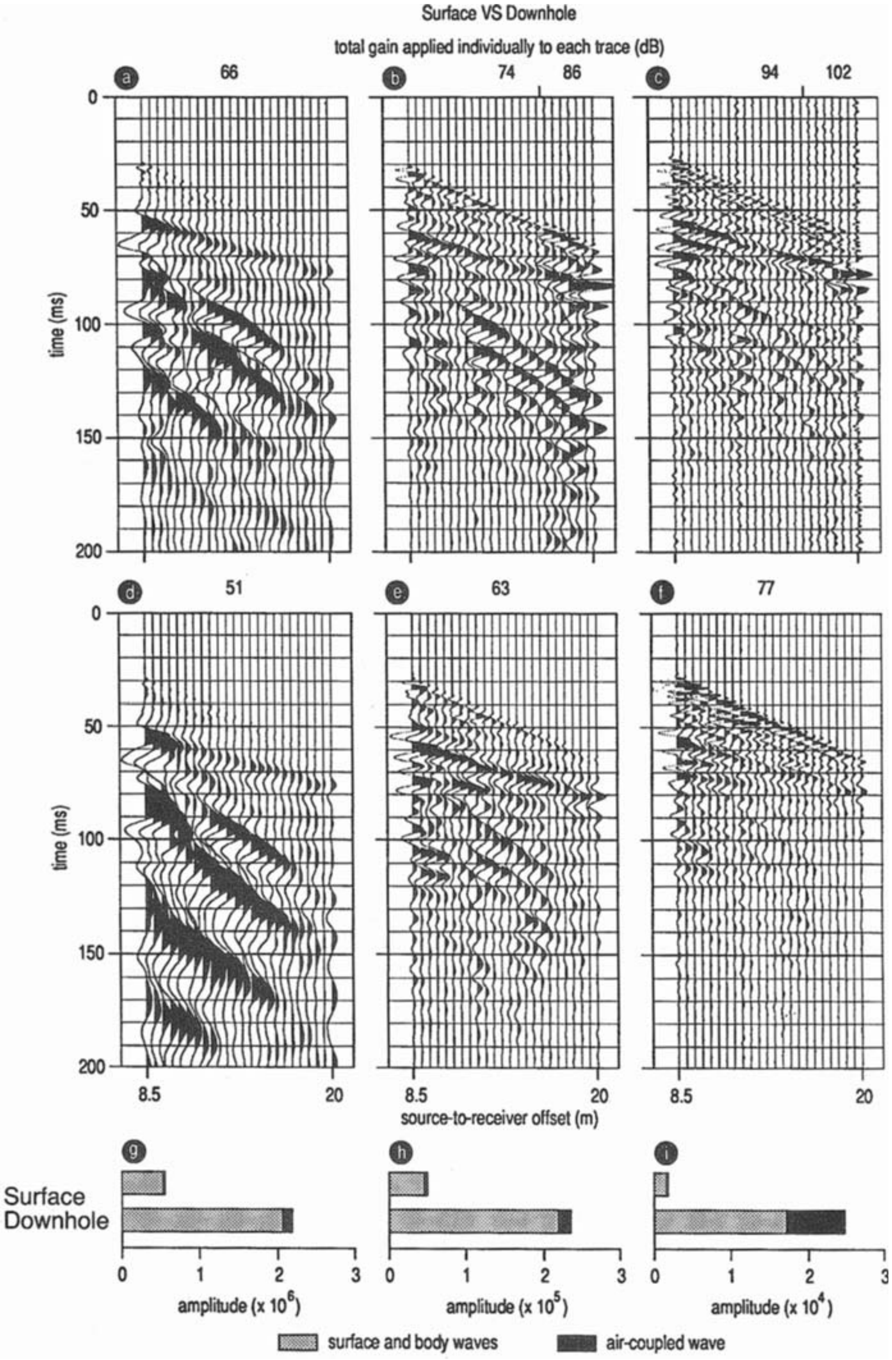

FIG. 19. Downhole (d, e, f) versus surface (a, b, c) firing of the .30-06 rifle. The quality of the reflection at 55 ms and the total recorded energy are increased by as much as ten times when the gun barrel was lowered down a 30-cm water-filled hole. The dominant frequency of the reflection event on 220 Hz low-cut filter data is increased by at least 10 percent by lowering the energy source point under water and below the ground surface.

These observed increased air-coupled wave levels are probably related to energy containment limitations of 50-cm augered holes at this site.

CONCLUSIONS

The relative energy strengths exhibited by the various seismic sources are similar to the relative strengths shown by Miller et al. (1986) at the New Jersey test site. It is apparent that the choice of source is more important for good quality results at the California test site than at the New Jersey test site. It is also apparent that the 55 and 70 ms reflections at the California site could be detected almost as well with a sledgehammer as with any other of the sources tested.

To lure owners of the various seismic sources to the test site, the organizers agreed not to publish conclusions that would prejudice one commercial source over another. As a

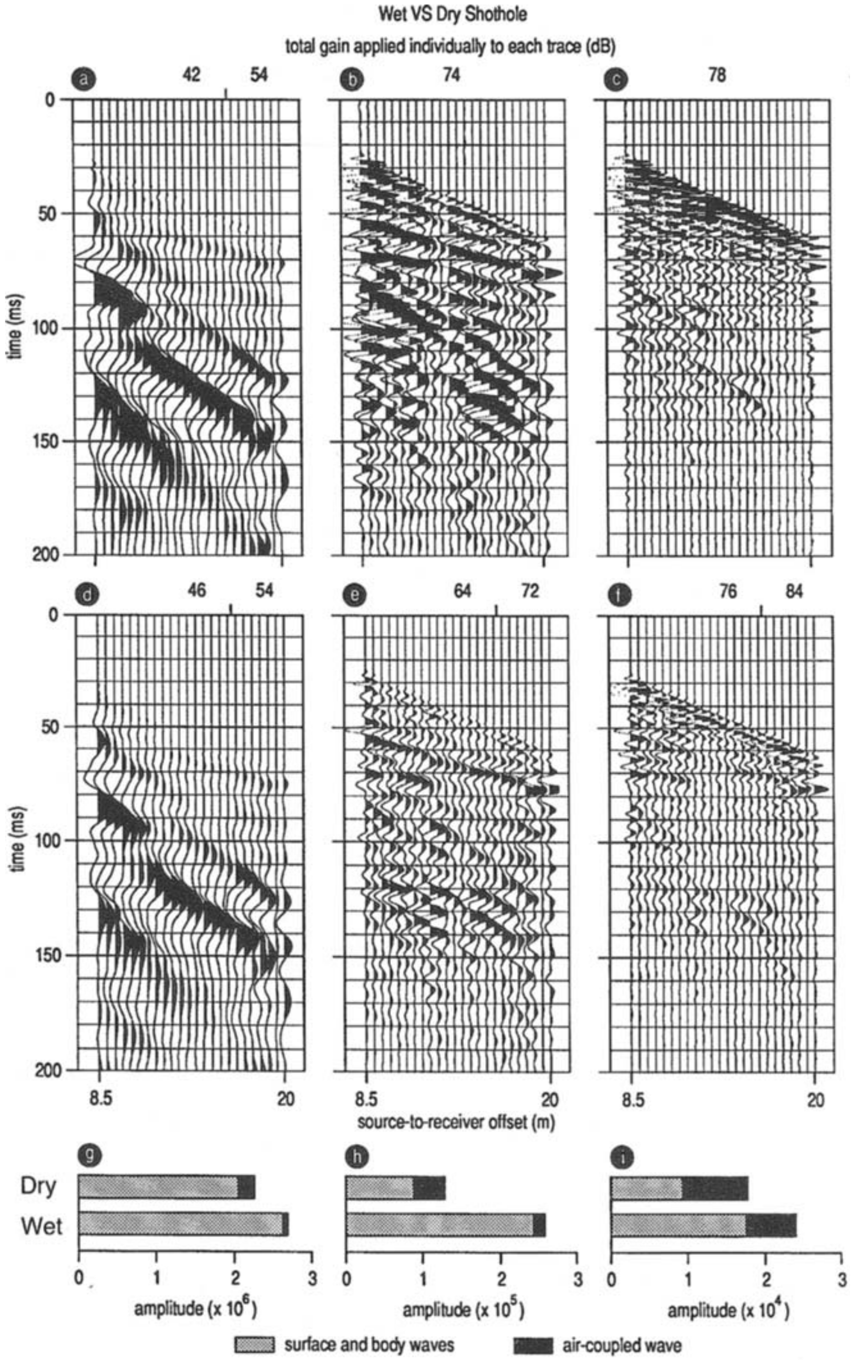

FIG. 20. Stemming shallow shot holes with water (d, e, f) versus air (a, b, c) reduces recorded air-coupled wave and increases the relative high-frequency content of the spectra. Recorded seismic-energy-to-airwave-noise ratio is increased by almost threefold and the recorded seismic-energy levels experience a twofold increase on data recorded with a 220 Hz low-cut filter when the hole was stemmed with water instead of air.

result, the reader should develop judgments based on the presentation of data within this paper and other tests published in the literature such as Miller et al. (1986) and Pullan and MacAuley (1987). The intent of this report is to present significant comparative data from an area with a relatively deep water table and very slow near-surface velocity. The presentation of data in this paper should allow at least general comparisons with data acquired in an area with a shallow (1–3 m) water table and a much higher near-surface velocity (Miller et al., 1986).

In the authors' experience, it is wise to bring at least two or three possible sources to any new site where shallow reflection surveys are contemplated or planned. The relatively new science of shallow seismic reflection is sufficiently immature so that surprises often occur in the selection of an optimum source for a particular site. At a bare minimum, a

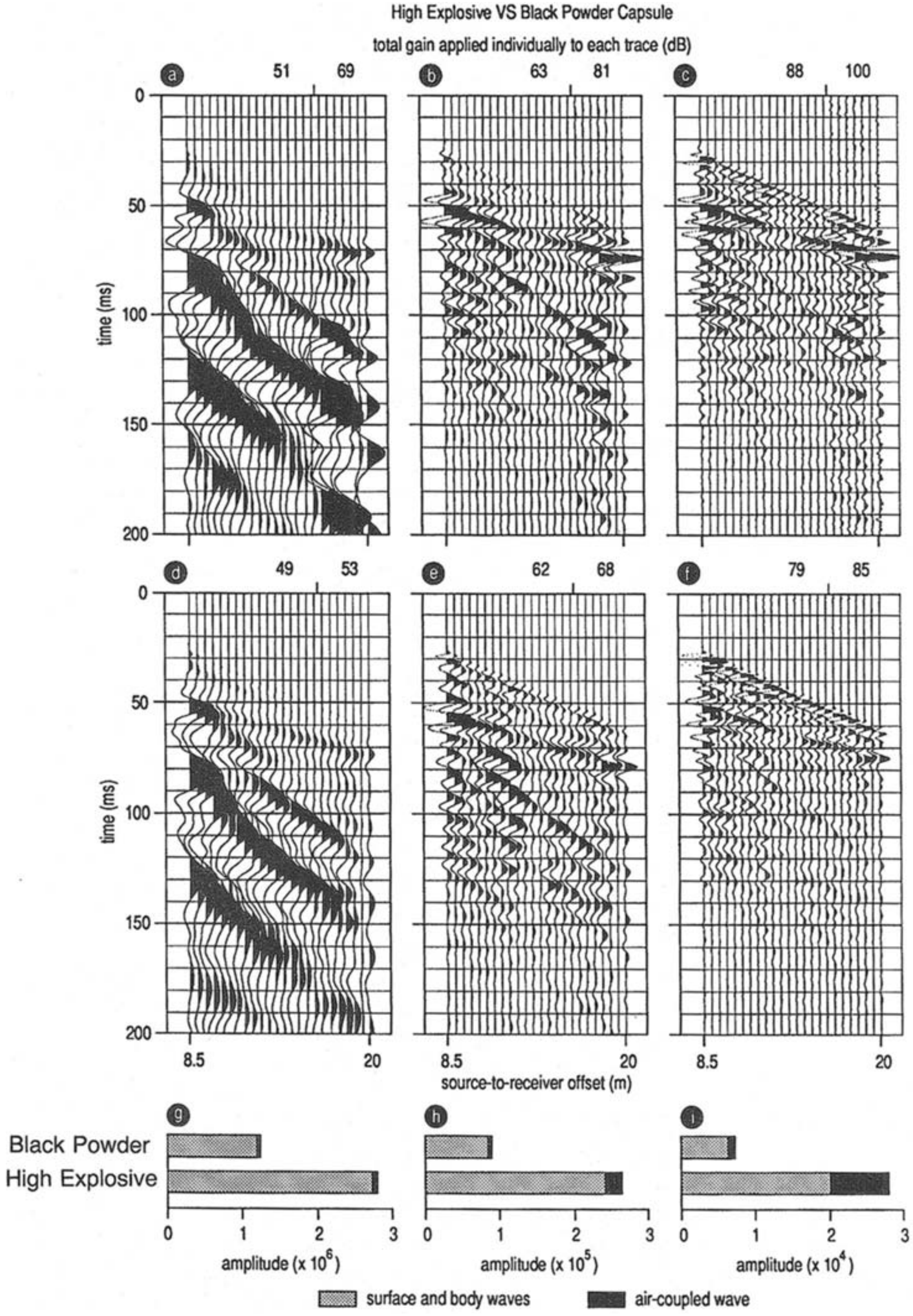

FIG. 21. An equivalent weight of high explosives (d, e, f) yields more than twice the recordable seismic energy of black powder capsules (a, b, c). The high explosive produced a higher percentage of air-coupled wave to high-frequency seismic energy (i). The reflection event (after gain adjustment) is of similar overall quality with either the capsules or the high explosives.

sledgehammer and some other source should be tested before performing an extensive shallow reflection survey at a site with a relatively deep water table.

Choosing the seismic source for a shallow-reflection survey can be a pivotal decision for the engineering geophysicist. We hope that the data presented here will prove useful to the engineering geophysics community.

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