SHALLOW SEISMIC REFLECTION SURVEY AT THE SOUTHERN CLEAN FUELS COAL LIQUEFACTION FACILITY NEAR WILSONVILLE, ALABAMA

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Introduction

Seismic-reflection surveys have been extensively used for more than 60 years to image the subsurface for petroleum exploration. The successful use of the technique in shallow engineering applications, however, depends on several key conditions. First and foremost is the existence of acoustic velocity and/or density contrasts between geologic units in the subsurface. The second relates to the ability of the near-surface to propagate high-frequency seismic signal. Finally, the acquisition parameters and recording equipment must be compatible with the proposed target, resolution requirements, and environmental constraints of the survey. The application of shallow, high-resolution seismic reflection methods to specific geologic situations or problems requires a thorough understanding of the basic principles (Appendix A).

Shallow high-resolution seismic-reflection profiles can be useful in characterizing shallow structures and extending features identifiable in outcrop and surface excavation into the upper several hundred meters of the subsurface. High-resolution seismic reflection has only recently developed as a practical and effective method for identifying shallow (<100 m) faults and structure (Goforth and Hayward, 1992; Miller et al., 1990; Treadway et al., 1988; Myers et al., 1987; Miller and Steeples, 1986). The shallow seismic-reflection technique is inexpensive (relative to drilling) and can often decrease the number of drill holes needed by an order of magnitude. While the seismic-reflection method can accurately show fault locations and stratigraphic relationships, it can give only estimates of depth and it does not explicitly identify specific lithologies.

This report displays and interprets seismic-reflection data acquired by the Kansas Geological Survey (KGS) and Oak Ridge National Laboratory (ORNL) on contract to Southern Clean Fuels (SCF). The purpose of this study was to image the shallow subsurface at SCF's coal liquefaction plant near Wilsonville, Alabama (Figure 1). A series of walkaway noise tests and three high resolution CDP seismic lines (500 to 800 ft each) were acquired around the facility. The walkaway tests included three different sources and four analog low-cut filter settings. The CDP survey was conducted using the 8-gauge Auger Gun and consisted of approximately 500 stations on three lines with station spacings of 4 ft. Cultural noise, a very attenuative near-surface, and low overall signal-to-noise ratios at this site affected the overall data quality.

Data Acquisition

Data for this study were acquired on a 48-channel EG&G Geometrics 2401x seismograph. The seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. Analog filters have an 18 dB/octave rolloff from the selected -3 dB points. The 1/2 ms sampling interval resulted in a 2000 Hz sampling frequency for a record length of 250 msec and a 1000 Hz Nyquist frequency. A 250 Hz high-cut filter with a 24 dB/octave rolloff acted as an anti-alias filter and to reduce wind noise and higher modes of 60 Hz power line noise. The Geometrics 2401x is a floating point seismograph.

Walkaway data were acquired with a variety of field parameters and equipment to optimize production data. The sources for the testing included the downhole 50-caliber rifle (Steeples, et al., 1987), and the 8- and 12-gauge auger gun (Healey et al., 1991). The receivers for the entire study were Mark Products L-28E 40 Hz geophones wired in series with three geophones per string. The station spacing for the walkaways was 2 ft. The resulting walkaway spreads possessed 96 traces with offsets ranging from 2 ft to 288 ft (two source locations were occupied).

Direct wave, refractions, ground roll, and air-coupled wave can all be identified on the walkaway data (Figures 2-7). Reflections can be interpreted on data recorded with 100 Hz low-cut filters. All aspects of the testing were necessary to properly fine-tune the acquisition parameters and equipment for the CDP portion of the study.

The production portion of the survey included three separate lines with station spacings of 4 ft. The source for the CDP data was the 8-gauge auger gun. The three geophones were placed in a 3 ft in-line array to help attenuate source-generated air coupled wave. The seismograph was configured to focus on reflections from the upper 250 msec with average velocities from 2000 to 6000 ft/sec. 50 Hz analog low-cut filters were used to shape the pre-amplified spectra, enhancing the higher frequency components of the recorded energy. The primary target of the survey was the bedrock surface and strata in the upper 400 ft.

Data Processing

Data processing was done on an Intel 80486-based microcomputer using *Eavesdropper*, a set of commercially available algorithms. The processing flow was similar to those used in petroleum exploration (Table 1). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, extra care during muting operations, and lack of deconvolution.

For most basic shallow, high-resolution seismic reflection data the processing steps/operations are a simple scaling down of established petroleum-based processing techniques and methods. However, processes such as deconvolution have basic assumptions (Yilmaz, 1987) that are violated by most shallow data sets. Migration is another operation that, due to non-conventional scaling (vertical and/or horizontal), many times may appear to be necessary when in actuality geometric distortion may be simple scale exaggeration (Black et al., 1993). Processing/processes used on data for this report has/have been carefully executed with no *a priori* assumptions and with care not to create anything during a processing operation that was not present before.

Diffracted energy is present on all three CDP stacked sections (Figures 8-10). The application of a post-stack f-k (Stolt) migration resulted in a drastic decrease in the usefulness of coherent arrivals (Figures 8-10). Pre-stack full waveform migration was not applied to the data, and is unlikely to have improved the interpretability of the unmigrated CDP stacked sections. F-k filtering was applied to the data to remove diffracted energy with arrival curvature in the reverse or negative direction and independently to remove the diffraction curves with positive curvature. Neither f-k filtering approach was successful in suppressing the diffracted energy. F-k domain operations had little effect on the high amplitude diffracted energy arrivals on CDP stacked sections.

Results

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. A few of the digitally filtered field files acquired during the production portion of the survey have reflection events identifiable between 50 and 125 msec. The reflections have a dominant frequency of approximately 50 Hz and an apparent NMO velocity of approximately 4000 ft/sec. These would result in an approximate depth to the reflector of between 100 and 300 ft. The signal-to-noise ratio on the raw field files is not sufficient to confidently identify reflections on most files.

Analysis of processed field files improves confidence in interpretations of CDP-stacked sections. Digital filtering, first arrival muting, appropriate trace balancing, bad trace editing, and correlation statics were key processes in improving the pre-stack appearance of coherent events barely interpretable on raw field files. The coherent events identifiable on some of the filtered files possess an arrival pattern inconsistent with the classic hyperbolic moveout of a reflection. This is no doubt related to the complex geology and predicates care and a conservative approach to interpretations of coherent energy on stacked data.

Coherent events can be interpreted across all the CDP stacked sections (Figures 8-10). The stacked sections possess nominal 24 CDP fold as a result of the 48 channel recording system and the recording geometry. Only lines 1 and 2 tie in the subsurface, at CDP 886 on line 1 and CDP 440 on line 2. The fold drop near the end of line 1 inhibits a confident tie. There is some indication of a correlatable set of events between 40 and 90 msec. The extreme curvature of most of the events and the lack of consistent source wavelet characteristics minimized accurate correlation of events from line to line.

The near-surface conditions were poor. Line 1 possessed significant topographic relief. The near-surface material included hard packed gravelly fill on the west end of line 2 and north end of line 1, organic residue on the south end of line 1, and a tight clay overlain by a hard packed gravel road across all of line 3. The dominant frequency of body wave energy and the very cyclic, ringy nature of most arrivals on field files is consistent with this very difficult near-surface.

The dominant frequency of most recorded reflection energy is between 50 and 100 Hz. The stacking velocity ranged from 4000 to 6000 ft/sec. The very complicated nature of the geology as implied by borings in the area is evident on the field files as well as the CDP stacked sections. Severe muting and pre-stack processing resulted in a relatively narrow optimum window both in time and horizontally in offset distance.

Examination of the coherent stacked arrivals reveals several apparent diffractions on all the stacked sections (Figures 8-10). Modelling of a zero incident diffraction arrival from six point sources at different depths results in a set of curves that nearly perfectly overlay the diffraction-looking events on stacked sections (Figure 11). The high amplitude and frequency content makes removal by filtering impossible. F-k migration proved ineffective in collapsing the diffraction arrivals. The migration operation gave the data a 'wormy' look that inhibited extraction of any useful geologic information. Within the diffracted energy are hints of primary reflections. F-k filtering was used to remove the steep part of diffraction curves from both the CDP stacked and unstacked data (Figure 12). The steeply dipping events were removed, but the resulting section, possessing only flat lying or gently dipping events, was not consistent with the geologic setting and could not be traced back to hyperbolic events on gathers. The overwhelming diffraction on many parts of the seismic line and the severe dip of potential reflectors on lines 1 and 3 makes the extraction of reflections that are coherent across the entire line not feasible on these data.

The diffraction energy can be used to assist with interpretations of contacts and faulting along the lines. The diffraction patterns with apex at CDP 860 on line 1 and 430 on line 2 are probably from the same feature. Faulting is the most likely source of this diffracting event. The diffraction with apex at CDP 720 could be from the geologic contact inferred from drilling between a shale on the north and a limestone on the south. This same interpretation could be made of the diffraction event on line 3 with an apex at CDP 350. A secondary diffraction interpreted on line 3 with an apex at CDP 460 has arrivals with a different curvature than the model and the other interpreted diffractions. We speculate that the source of this scattered energy is out of the plane of the reflection survey and could be the large strike-slip fault inferred from drill data and outcrop studies to run sub-parallel to seismic line 3. The various sources of the diffracted energy are a bit speculative, but the diffractions as interpreted on the stacked section likely represent geologically significant features.

The CDP stack of line 1 possesses two strong diffraction events and some indication of a primary reflection on the southernmost end of the line. Due to low fold and obvious interference from scattered energy, it is not possible to place a great deal of confidence on that identification. As well, some indication of reflected energy is interpreted on the northernmost end of line 1 beneath the high amplitude diffraction at CDP 860. The event has significant static problems but does appear to be a genuine reflection arrival.

The CDP stack of line 2 possesses a single strong diffraction event that correlates relatively well to the diffraction on the north end of line 2. Some evidence exists to suggest coherent reflection arrivals are present on the east end of line 2. The stacked events do not possess the characteristic curvature but do seem to possess unique arrivals. The event interpreted between 90 and 130 msec on line 2 is speculative beyond CDP 290 where its arrival is strongly influenced by the diffraction. This line was acquired parallel to strike with some indications of folding in the primary reflections interpreted on the east end. This folding is consistent with outcrop studies from the southernmost end of the facility.

The CDP stack of line 3 possesses at least two strong diffraction events. The diffraction with apex at CDP 350 has the highest amplitude and most closely matches the diffraction model. This close match to the model suggested that the model parameters closely approximate the geologic situation. The model possesses vertically incident energy and several point sources at different depths. This strongly supports the suggestion that this diffraction is probably from the contact between the limestone and shale as opposed to a fault plane crossing the seismic line at an oblique angle. The second diffraction with similar curvature is at a time depth of approximately 120 msec and not fully developed. The diffraction-looking event interpreted at CDP 460 possesses unique curvature inconsistent with the model. This suggests the diffracting source is most likely out of the plane of the survey or extremely shallow with an associated low velocity. Some indications of primary reflections are interpreted on the northernmost end of the line. These events are definitely distorted by the arrival of the high amplitude diffracted energy.

Conclusions

The data collection occurred in a culturally noisy area that had undergone significant near-surface disruption during construction of the facility's road and utility system. These factors contributed to decreased data quality. Despite the problems in data collection, some indications of seismic reflections are present along portions of lines 1 and 2. This leads us to believe that reflected energy may be present along other parts of the lines also, but if those reflections are present, they are obscured by large amplitude diffractions. The diffractions are diagnostic of abrupt changes in lithology, most likely faults in a geologic environment such as this field site. While the apices of the diffractions give clues to the location of the faults, no information can be extracted about the amount or direction of displacement on the faults. Diffractions could not be successfully removed by migration despite several attempts during the processing of the data.

Recommendations

The seismic reflection and diffraction interpretations should be integrated into what is already known about the site. At a minimum, the seismic data can be used to select new drilling sites to confirm or refute the suggested specific locations of the faults on the seismic sections.

It might also be possible to analyze the surface waves and the refractions to refine the diffraction and reflection interpretations. No attempt was made to process or interpret either the refractions or the ground roll. The near-surface disturbances from construction affect the refractions and the ground roll much more than the reflections or diffractions and therefore any interpretation inconsistent with the reflection data presented here should be cautiously incorporated into the overall geologic interpretation of this site. Geophone offset distances from the source may not be long enough for meaningful geologic interpretations based on refractions and ground roll.

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TABLE 1

Processing flow

format from SEG2 to KGSEGY
preliminary editing (automatic bad trace edit with 10 msec noise window)
trace balancing (40 msec window)
first arrival muting (detailed trace by trace mutes based on arrival identification)
surgical muting (removal of air coupled wave based on trace-by-trace arrival)
assign geometries (input source and receiver locations)
sort into CDPs (re-order traces in common midpoints)
velocity analysis (whole data set analysis on 100 ft/sec increments)
spectral analysis (frequency vs amplitude plots)
NMO correction (station dependent ranging from 4,000 to 6,000 ft/sec)
surface consistent statics (2 msec max shift with 9 trace pilot, 2 iterations)
residual statics (1 msec max shift with 7 trace pilot)
digital filtering (bandpass 50-90 200-275)
secondary editing (manual review and removal of bad or noisy traces)
CDP stack
amplitude normalization (AGC 50 msec with 20 msec delay)
display

Table 1. Processing flow for CDP stacked data. Parameters were determined by analysis for each prior step as well as through iterative analysis of particular operations.

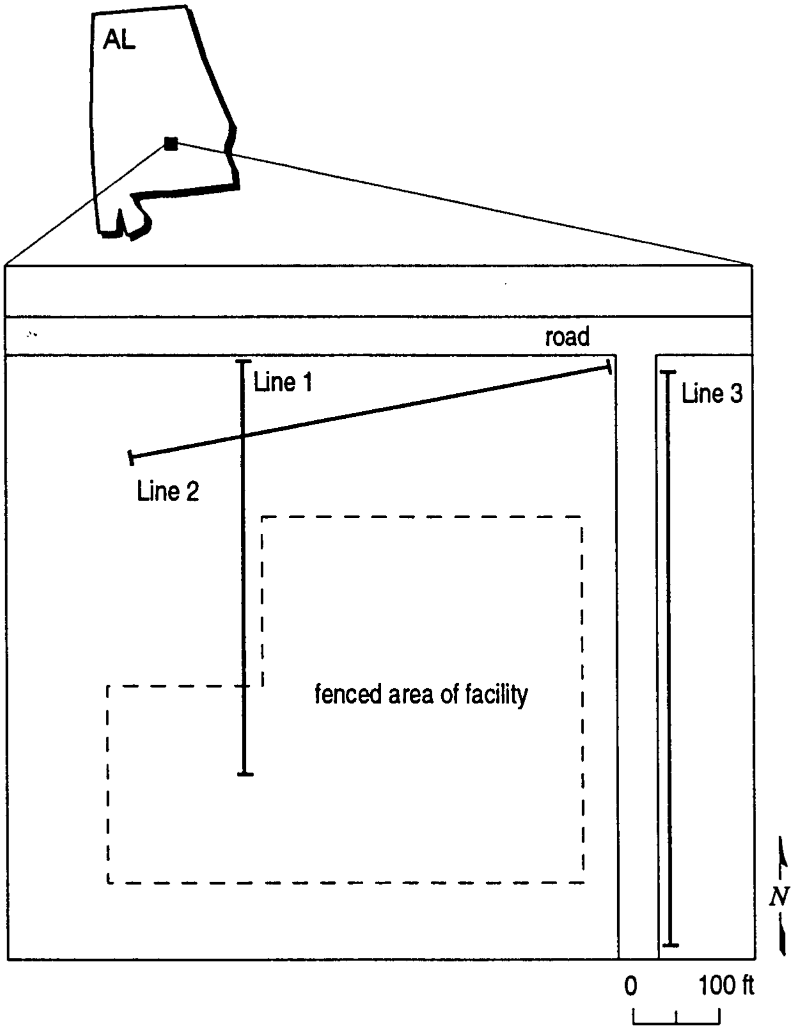


Figure 1. Site map indicating the approximate relative locations of the seismic lines.

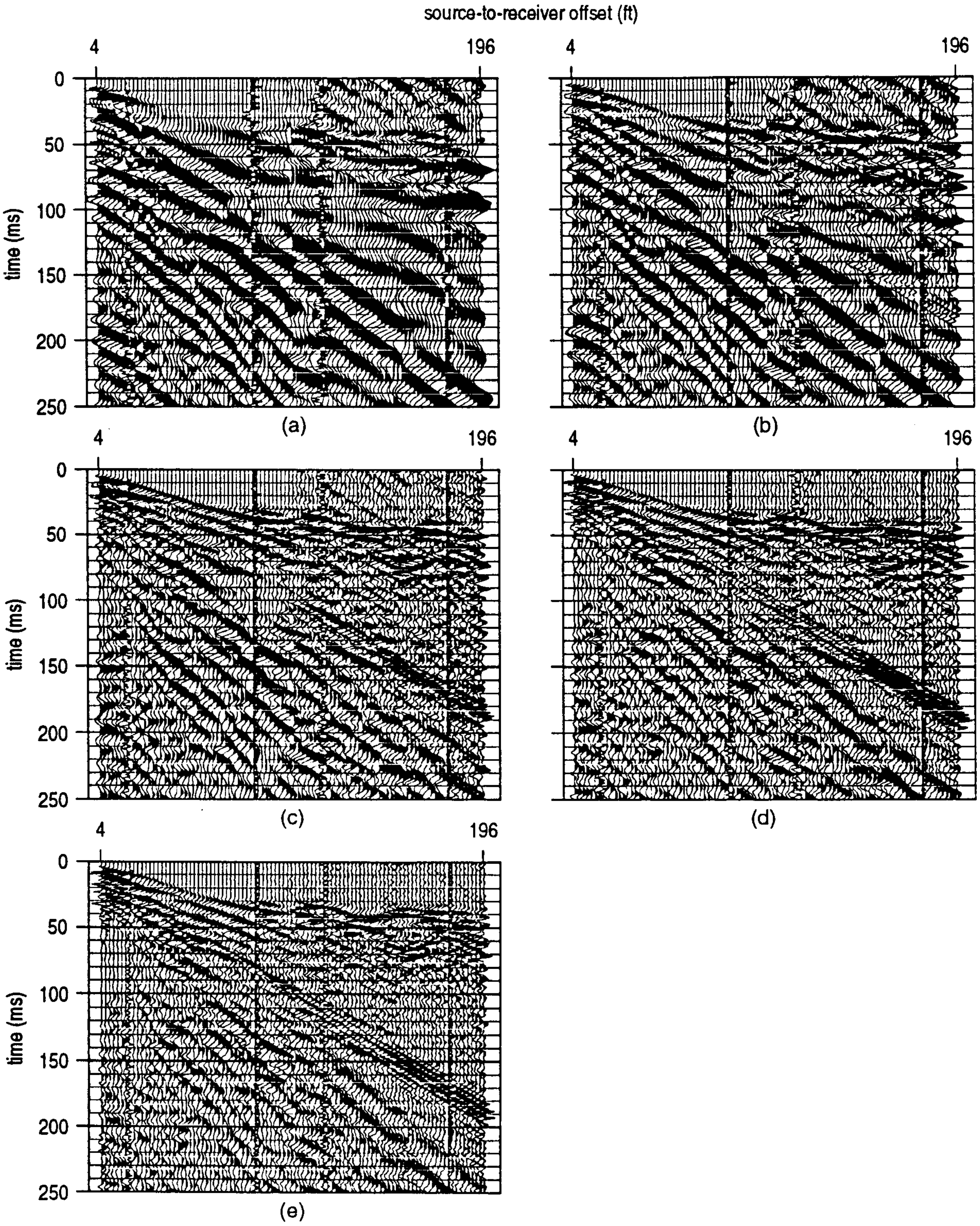


Figure 2. Walkaway noise tests using downhole 50 cal source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

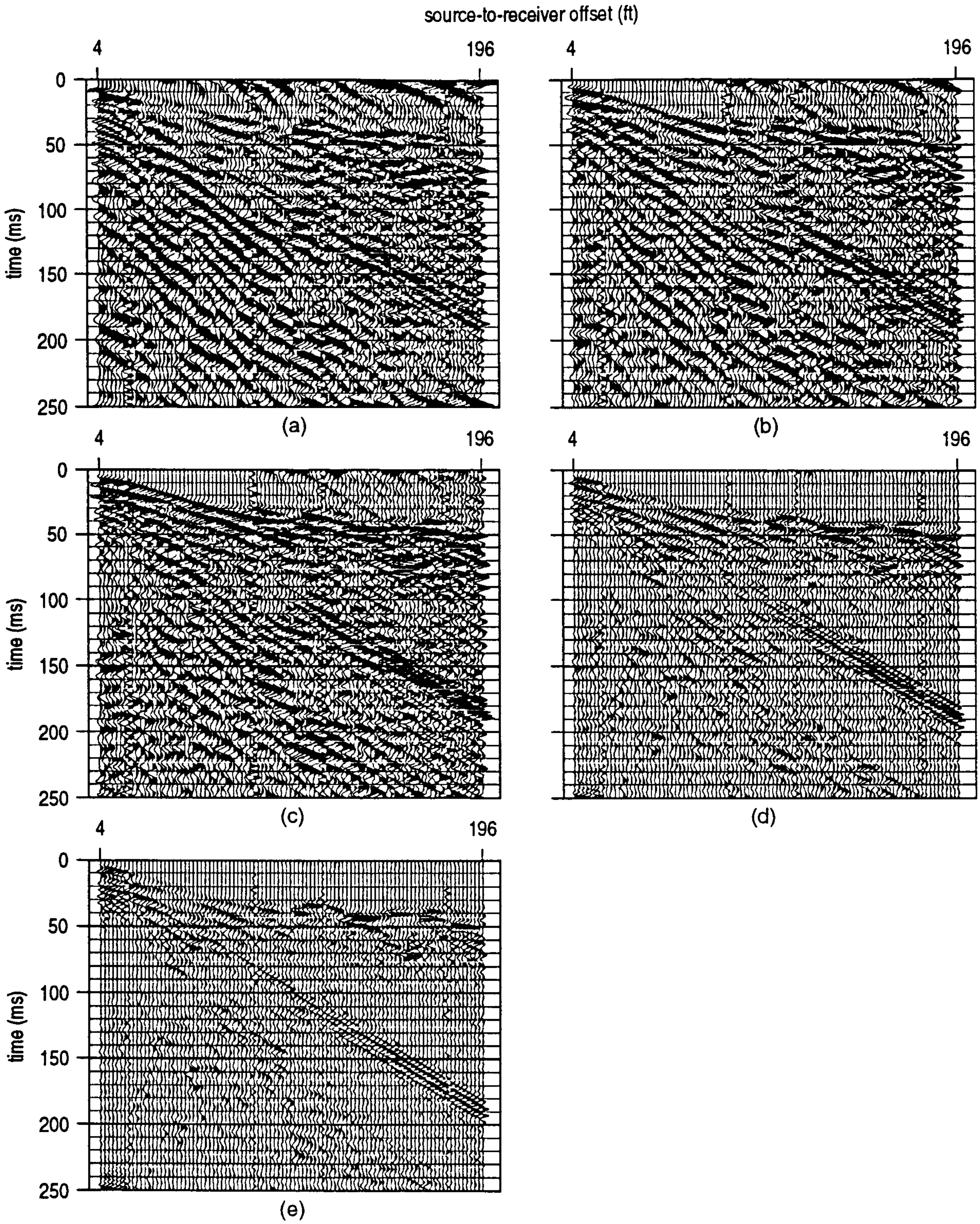


Figure 3. Digital bandpass filter applied to walkaway noise tests using downhole 50 cal source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

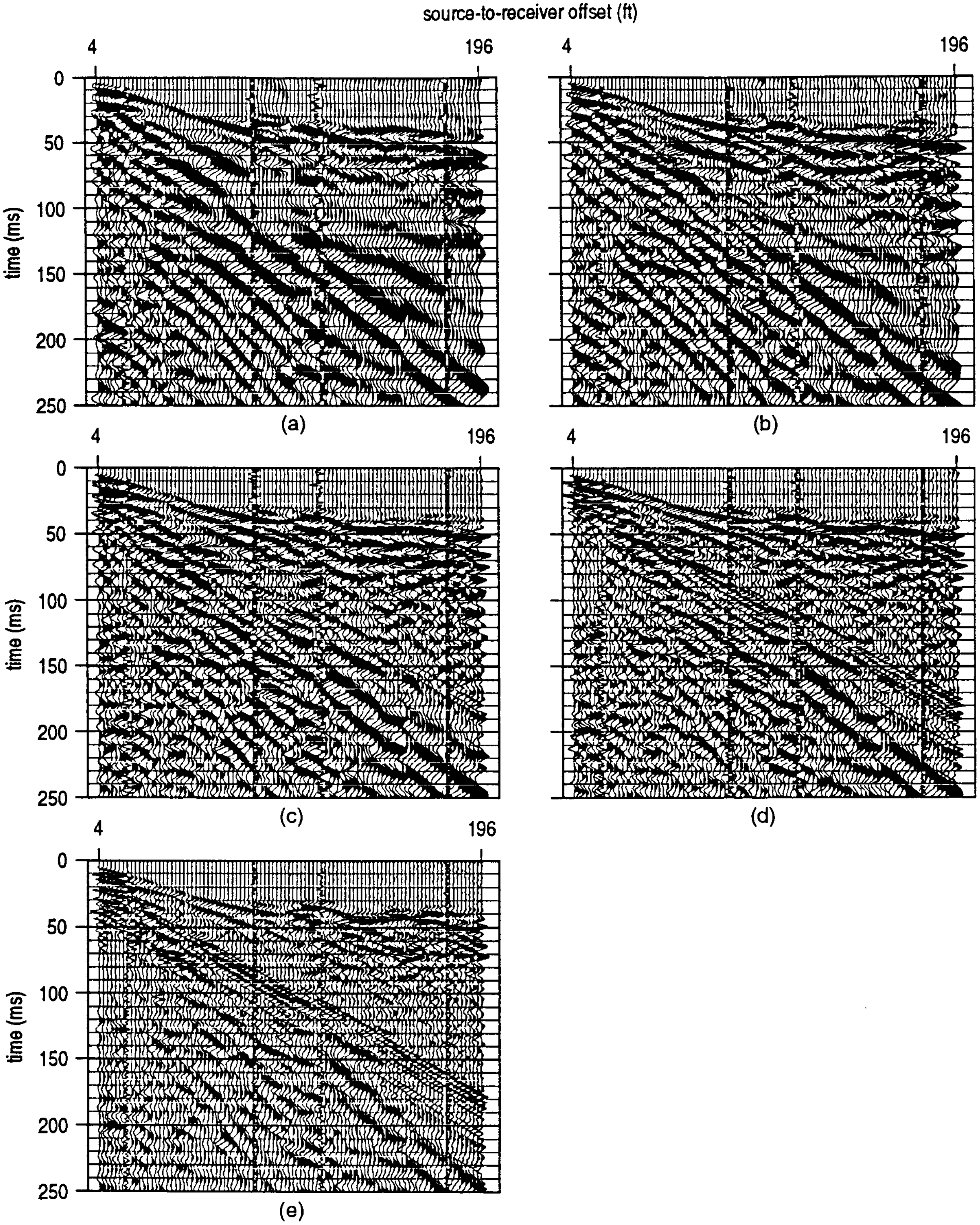


Figure 4. Walkaway noise tests using 8-gauge Auger gun seismic source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

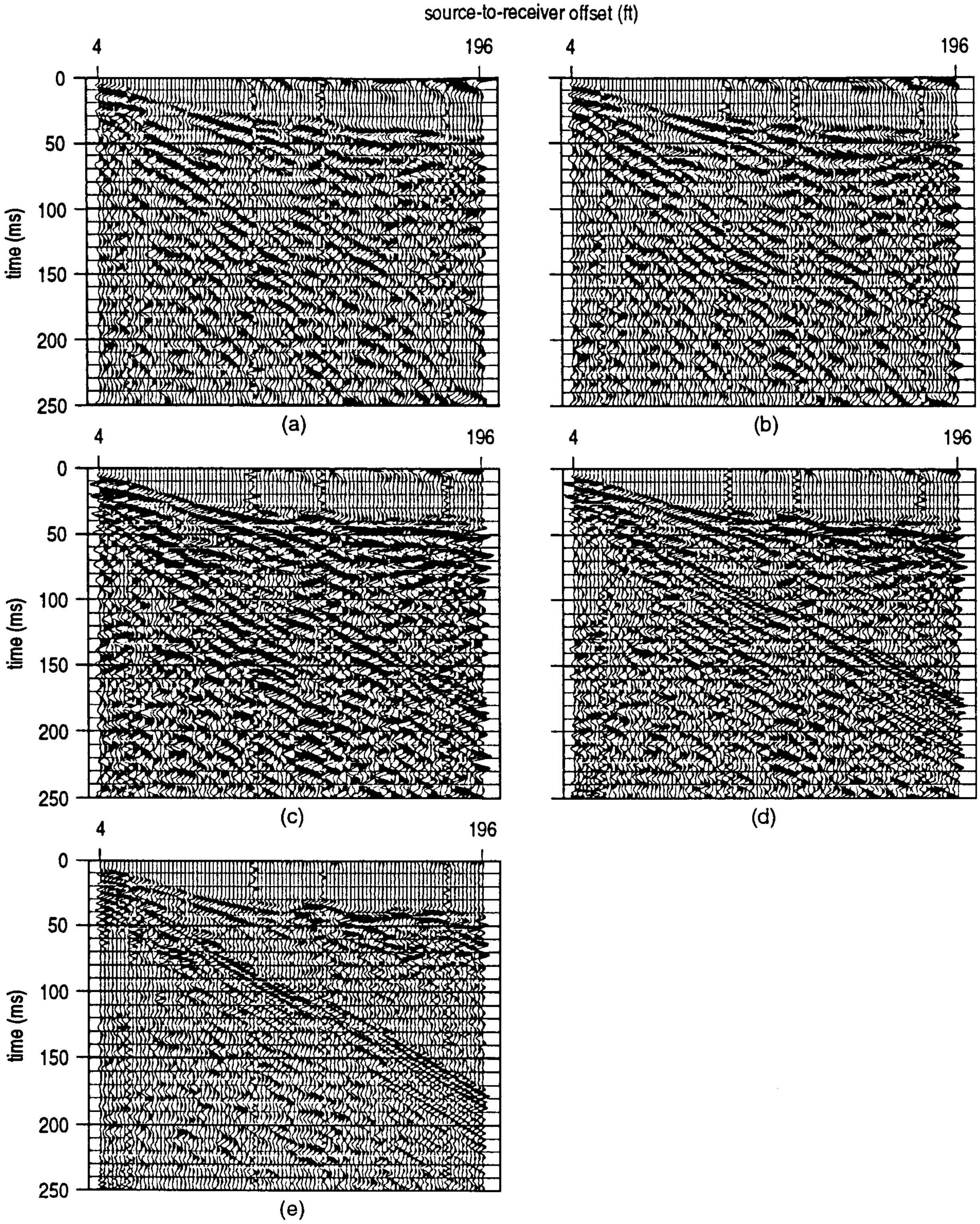


Figure 5. Digital bandpass filter applied to walkaway noise tests using 8-gauge Auger gun seismic source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

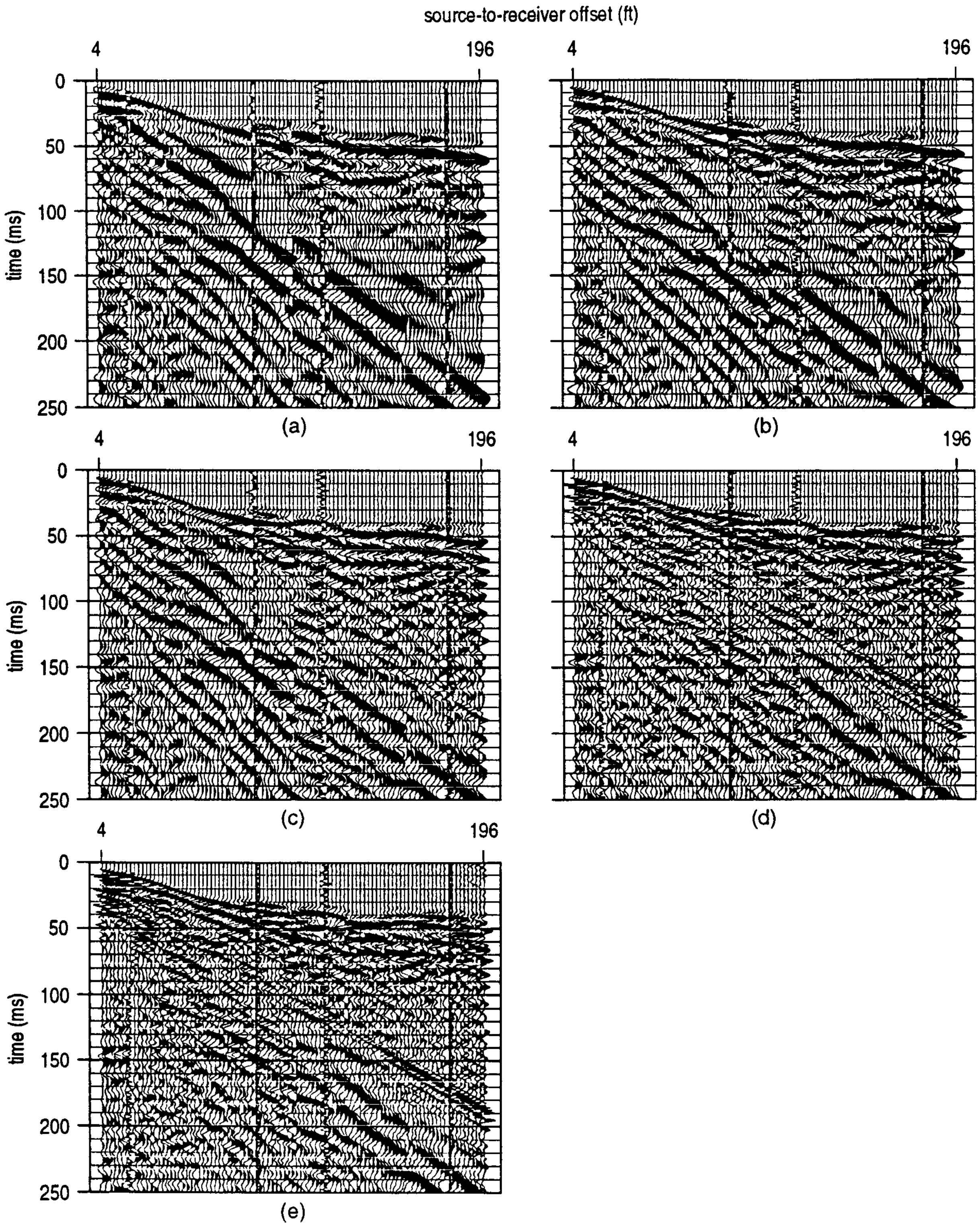


Figure 6. Walkaway noise tests using 12-gauge Auger gun seismic source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

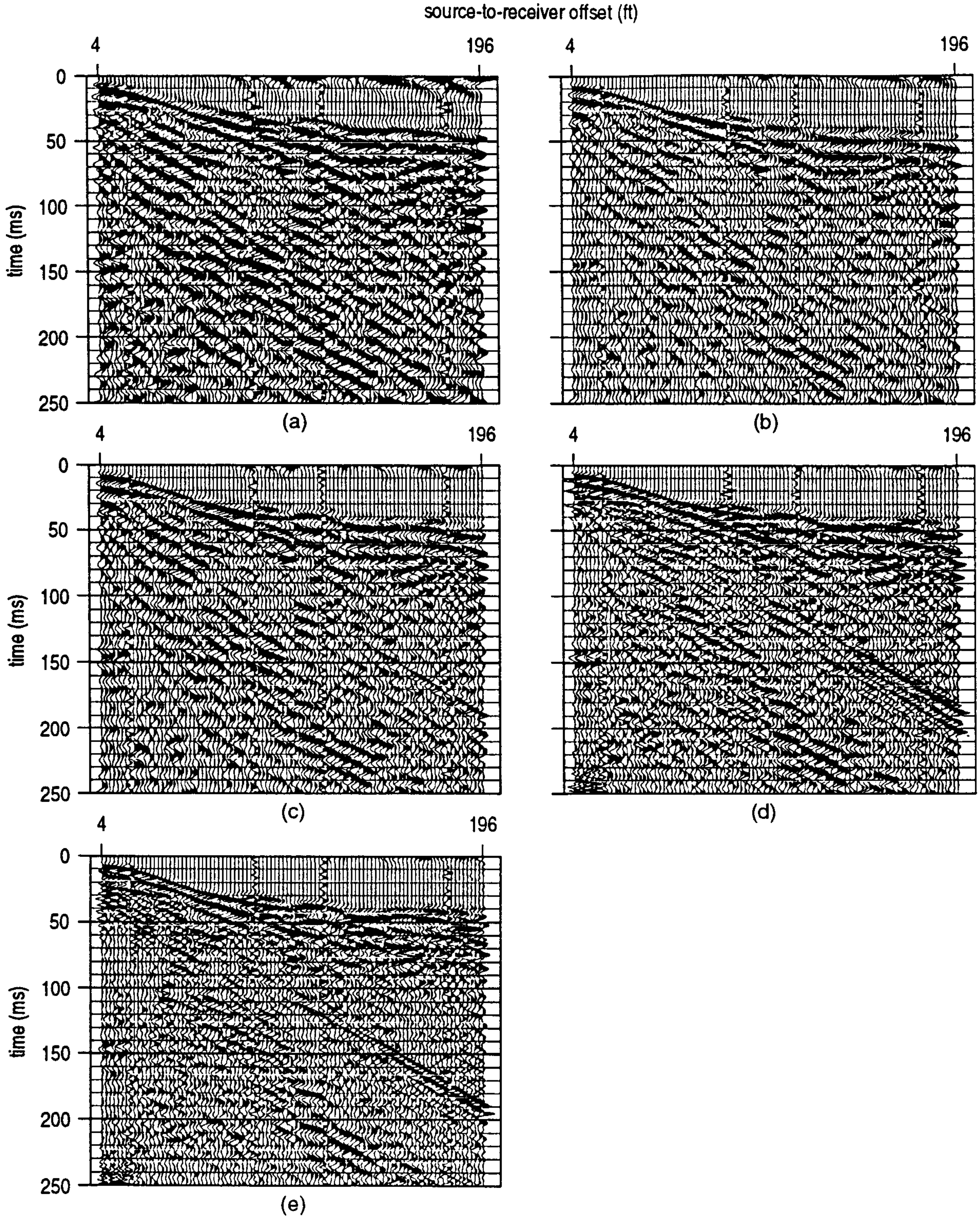


Figure 7. Digital bandpass filter applied to walkaway noise tests using 12-gauge Auger gun seismic source. Analog low-cut filter tests included settings with -3 dB points of (a) out, (b) 50 Hz, (c) 100 Hz, (d) 140 Hz, and (e) 200 Hz.

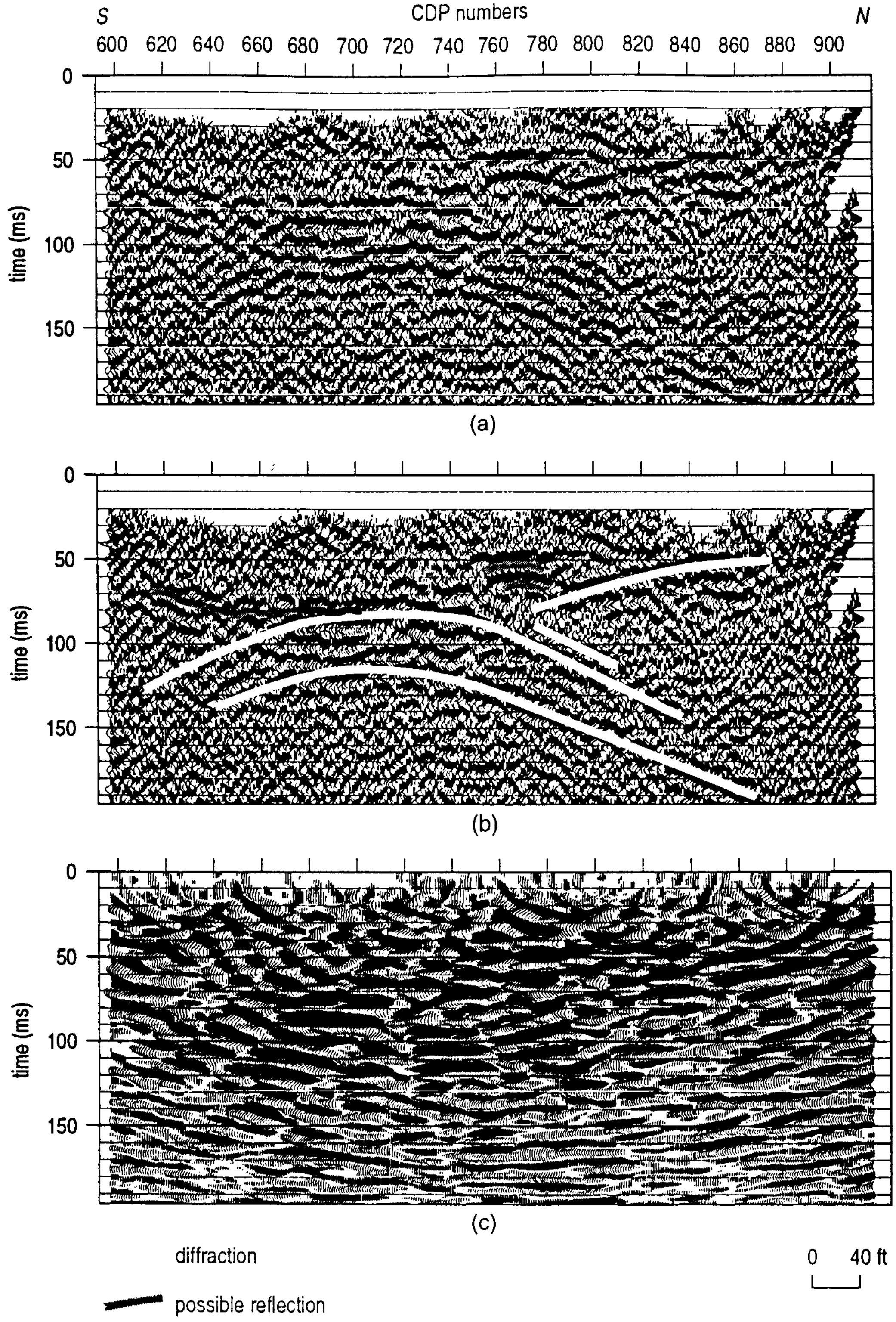


Figure 8. CDP stacked seismic section for line 1. The data are dominated by apparent large amplitude diffractions. It is possible that coherent energy arriving at the extreme north and south ends of the line could be interpreted as reflections. The CDP stacked data (a) was interpreted (b) and migrated with a post-stack Stolt migration assuming a constant velocity of 4500 ft/sec (c).

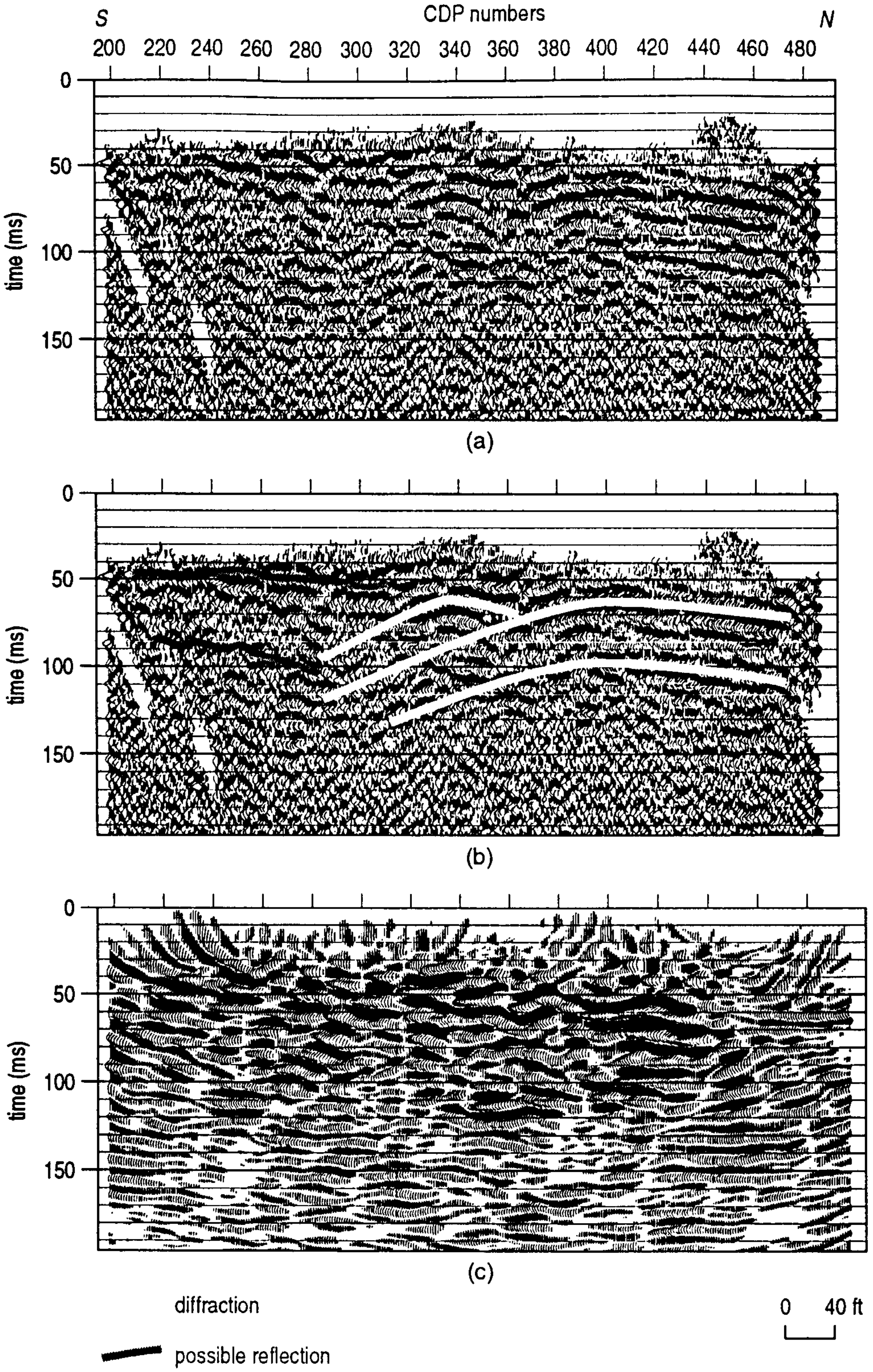


Figure 9. CDP stacked seismic section for line 2 (a). Possible reflections and diffractions are interpreted (b). Stolt migration at a constant velocity of 4500 ft/sec adversely affected the data quality (c).

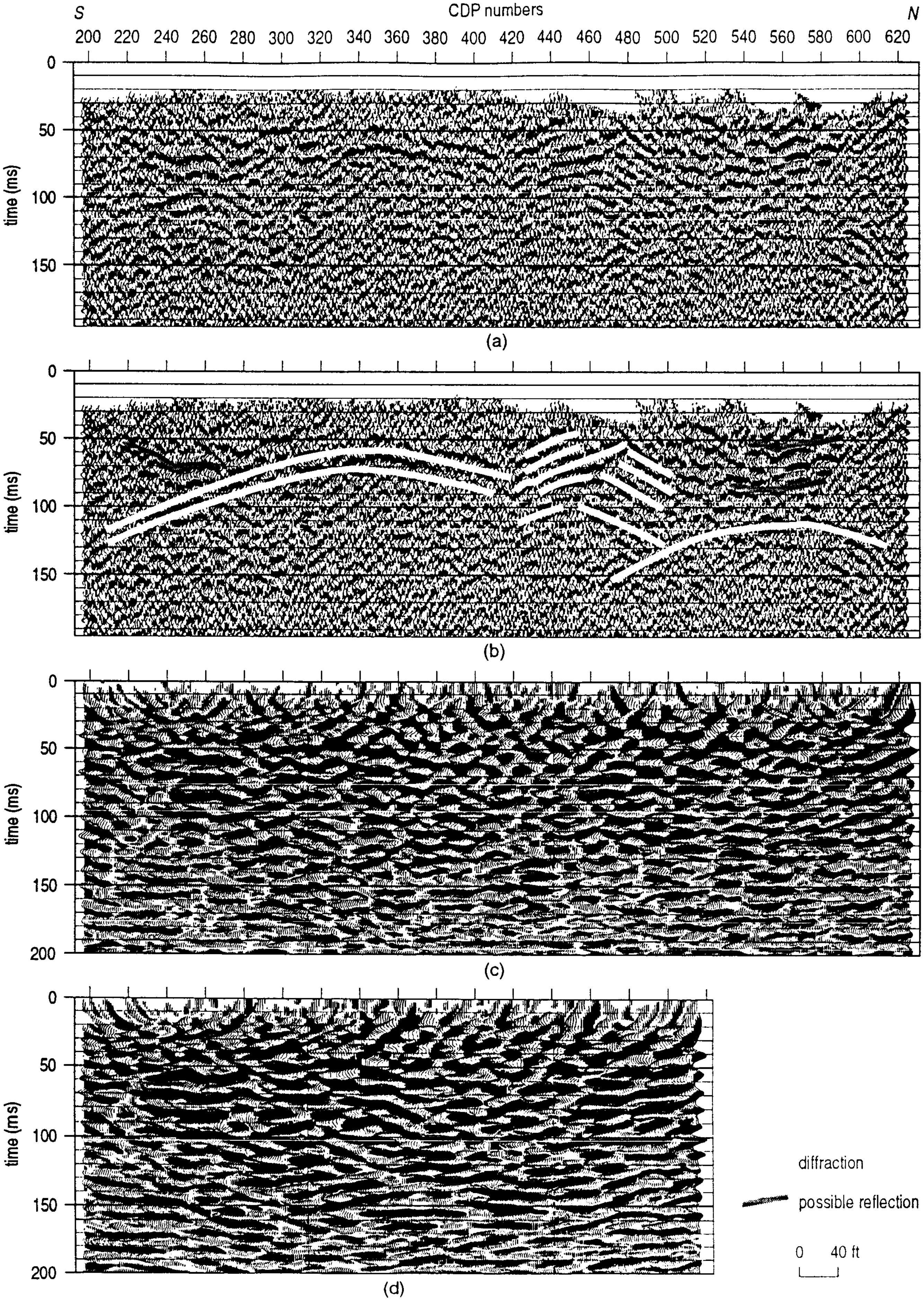


Figure 10. CDP stacked seismic section for line 3 (a). Possible reflections and diffractions are interpreted (b). Stolt migration at velocities of 4500 ft/sec (c), and 5000 ft/sec (only first 300 CDP migrated for this velocity) (d).

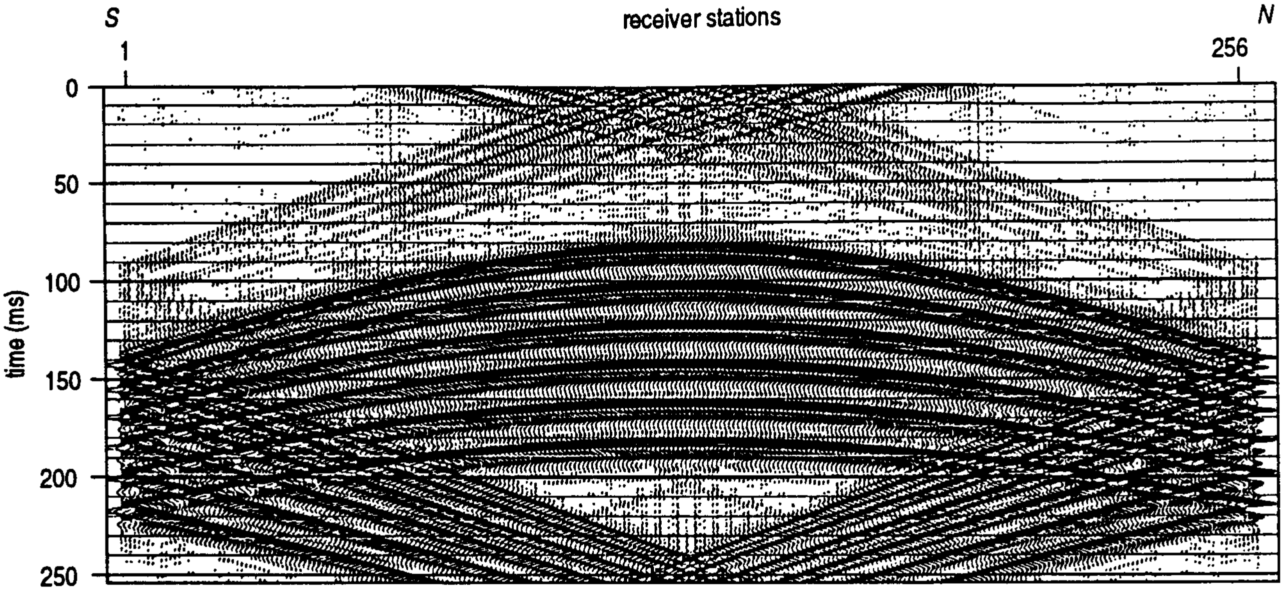
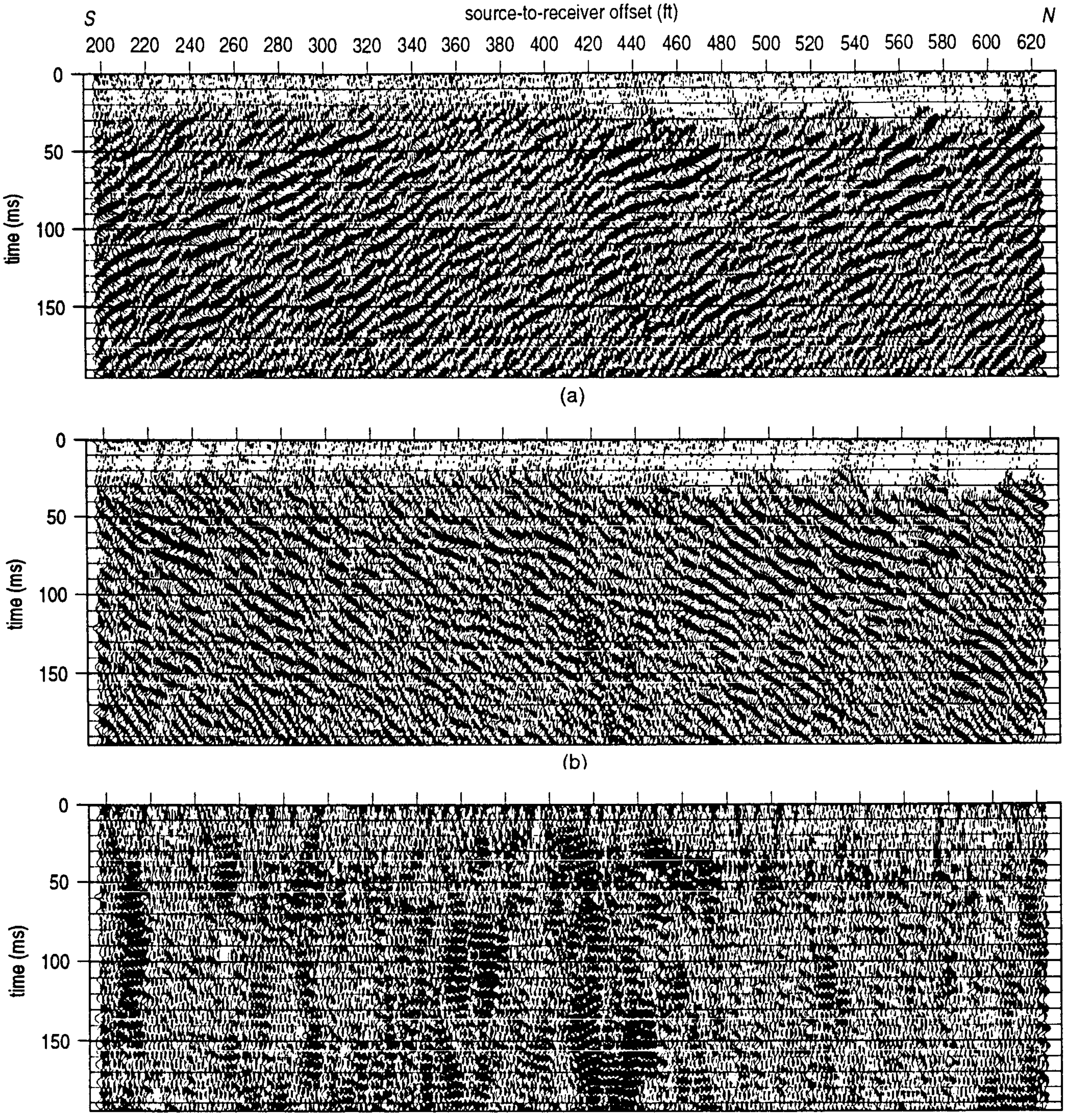


Figure 11. Diffraction model for a series of point sources located at various depths below the center of the figure.



(a)

(b)

(c)

Figure 12. F-k filtering on the CDP stacked section of line 3. The positive slope removal resulted in negative-only coherent arrivals (a) as the negative slope removal resulted in positive-only coherent arrivals (b). The forward and reverse steep-slope removal result in a stacked section (c) with little or no dipping events and only flat-lying coherent arrivals at very shallow time.

Appendix A
BASIC PRINCIPLES AND CONCEPTS OF PRACTICAL SHALLOW SEISMIC REFLECTION PROFILING

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Abstract

Seismic reflection is a powerful geophysical exploration method that has been in widespread use in the petroleum industry for more than 60 years. This paper addresses some basic principles of the method and its application at depths shallower than 30 m. Since 1980 the shallow-reflection technique has been increasingly used for engineering and environmental problems such as mapping bedrock beneath alluvium and delineating intra-alluvial features near hazardous waste sites, detecting voids in coal and karst, defining the top of the saturated zone, and mapping shallow faults. New applications will be added with improved resolution and increased cost-effectiveness.

Introduction

It is the purpose of this tutorial paper to describe, to those who have heard of seismic reflection but are not familiar with how it works and/or its potential applications, some of the basic principles of seismic reflection and their significance, as applied to shallow engineering, mining, and environmental projects. The seismic reflection method is a powerful technique for underground exploration that has been in use since the 1920s (Waters, 1987; Dobrin, 1976; Coffeen, 1978; Telford et al., 1976; Sheriff, 1978). The use of seismic reflection surveys for imaging targets shallower than 30 m has only been available since the early 1980s. The technique is rapidly finding new applications in characterizing the geologic, hydrologic, and stratigraphic conditions within three to 30 meters of the earth's surface. As research and development continues, higher and higher seismic frequencies will be attainable, allowing practical prospecting for progressively smaller geologic targets.

Seismic-reflection techniques depend on the existence of discrete seismic velocity and/or mass density changes in the subsurface, known as acoustic impedance contrasts. Mathematically, acoustic impedance is simply the product of mass density and acoustic wave velocity. Acoustic impedance contrasts occur at natural boundaries between geologic layers, although man-made boundaries such as tunnels and mines also represent contrasts. The classic use of seismic reflection is to identify the boundaries of layered geologic units; however, the technique can also be used to search for localized anomalies such as sand/clay lenses and cavities.

Compressional waves (P-waves) propagating through the earth behave similarly to sound waves propagating in air. When sound waves (voices, explosions, horns, etc.) come in contact with a wall, cliff, or building (all acoustic contrasts), it is common to hear an echo. When a P-wave comes in contact with an acoustical contrast underground, echoes (reflections) are also generated. P-wave reflections can be thought of as sound wave echoes from underground acoustic impedance contrasts. In the underground environment the situation is more complex because some P-wave energy impinging on a solid acoustical interface can also be transmitted across the interface, refracted at the interface, and/or converted to other types of seismic waves at the interface.

Seismic methods are sensitive to the physical properties of earth materials and relatively insensitive to the chemical makeup of contained fluids in earth materials. Electrical methods are sensitive to contained fluids and to the presence of magnetic or electrically conductive materials. The measurable physical parameters upon which the seismic methods depend are quite different than the important physical parameters for electrical and magnetic methods. In the world of shallow geophysics, there are similarities among seismic reflection, seismic refraction, and ground-penetrating radar. There are also similarities with cross-hole seismic tomography and vertical seismic profiling. The similarities with electrical and potential fields methods are substantially less.

The work of Jim Hunter and Susan Pullan and their colleagues at the Geological Survey of Canada (Hunter et al., 1984; Pullan and Hunter, 1985) and Klaus Helbig (Doornenbal and Helbig, 1983; Jongerius and Helbig, 1988) and his students at the University of Utrecht in The Netherlands has been instrumental in developing shallow seismic reflection techniques. In particular, the simple data manipulation and display of Hunter's optimum window-common offset makes it a cost-effective method of imaging the shallow subsurface in areas conducive to seismic reflection.

Shallow Seismic Reflection Fundamentals

The simplest case of seismic reflection is a single layer over an infinitely thick medium (Figure A-1). Seismic energy induced into the ground from a point is radiated spherically away from that point in much the same fashion in three dimensions as waves from a pebble tossed into a still pond radiate outward in two dimensions (Figure A-2). An arbitrarily large number of ray paths can be traced outward from the seismic energy source. One particular ray path will direct energy to a subsurface layer, reflect from that subsurface layer, and return as an echo to the ground surface first, following Fermat's principle of least travel time. In the case of a single flat-lying layer and a flat topographic surface (Figure A-1), the path of least time will be from the energy source to a reflecting point mid-way between the source and the receiver, and then back to the receiver. The incident angle of the down-going ray will be equal to the angle of reflection of the up-going ray from the subsurface layer.

Commonly several layers beneath the earth's surface are targeted by a single seismic reflection survey (Figure A-3). Seismic data are more complex when several layers are involved. Seismic energy can be converted from one wave type to another at layer interfaces. The simple one-layer case (Figure A-1) becomes slightly more complicated when considering all the possible raypaths and wave conversions. The apparent complexity of a seismogram directly relates to the variety of types of seismic waves and their associated characteristic velocities and travel paths. Complexity is often increased as well by the presence of seismic energy that has bounced more than one time off layers in the subsurface (multiple reflections). Reflected energy from successively deeper and deeper boundaries appears on a seismic trace at greater and greater time.

Expanding the multilayer case of Figure A-3 to multiple receivers allows travel path versus arrival time determinations and comparisons (Figure A-4). Rays reflected from different points in the subsurface are recorded by receivers appropriately spaced on the ground surface. The distance between these subsurface reflecting points is exactly half the distance between receivers, providing a closer subsurface sampling interval than the surface receiver spacing. The recording of multiple receiver/channel locations for each individual shot allows determinations of apparent velocity (travel path/arrival time) and apparent reflector dip.

Source and receiver locations can be placed so that path S1–R2 reflects from the same location in the subsurface as path S2–R1 (Figure A-5). The subsurface point that is in common for both source and receiver pairs is called a common-reflection point (CRP) (Mayne, 1962), a common-depth point (CDP), or a common-midpoint (CMP), depending upon the preference of the author (Figure A-5). The power of the CDP method is in the redundancy in sampling of a particular subsurface location. By gathering traces in a computer according to CMP and time-adjusting them for different travel-path lengths, traces with the same CMP can be added to enhance the reflection signal. The degree of redundancy or multiplicity of data at a particular point is known as "CDP fold." A 24-channel seismograph, for example, is typically used to gather 12-fold CDP data. From a theoretical standpoint, signal-to-noise ratio of reflections improves proportionally to the square root of the CDP fold. For shallow reflection data in particular, it is important to remember that 1-fold of good data is better than many-fold of bad or marginal data.

The seismic-reflection method is generally used to determine the spatial configuration of underground geological interfaces. Displaying all the CDP stacked traces consistent with their spatial locations results in a reflection-time cross-section of a portion of the earth (Figure A-6). The peaks of the seismic reflections (wiggles) are generally blackened to assist in interpretation. This schematic example (Figure A6) is a very simple version of typical near-surface geology that depicts a buried sand lens in a river valley. Resolving a fixed size target becomes more difficult with increasing depth below the ground surface, but the physical principles remain the same. Resolving power is a linear function of increasing the frequency and bandwidth of the seismic reflection data.

Obtaining high quality shallow seismic reflection data is still somewhat of an art where an individual's ability improves with experience. Improving the quality of shallow reflection data is dependent on careful, meticulous procedures based on sound scientific observation and theory, step-by-step data analysis, stringent quality control during all aspects, and avoiding invalid assumptions during the acquisition, processing, and/or interpretation of shallow reflection data.

Practical Shallow Reflection Surveying

Seismic reflection surveys routinely involve three basic parts: acquisition, processing, and interpretation. A variety of selectable parameters and methods are possible at each of these three distinct stages. Pronounced differences exist between shallow and conventional seismic reflection techniques during the acquisition and processing stages. The basic principles of interpretation for both shallow and conventional seismic reflection are consistent, except for scale differences. The underlying theoretical basis for the seismic reflection method is consistent for both conventional and shallow applications.

Acquisition

The basic instrument for seismic studies is a seismograph, which is analogous to a stereo music system. The better the music system, the more detail the listener can ascertain from subtle background instruments. Likewise, the better a seismograph's dynamic range, the more the potential for distinguishing subtle geologic features. A stereo music system has variable controls to enhance high frequencies (like a flute) or low frequencies (like a tuba). A seismograph has similar selective capabilities for emphasizing recorded sound frequencies. A seismograph that can record and enhance high-frequency sound waves is necessary to detect small geologic features. The use of high-frequency seismic waves (>80 Hz) in reflection seismology is known as "high-resolution" seismic exploration (Sheriff, 1991). A stereo system also has an amplifier volume control where a seismograph has amplifier gain control, either fixed (selectable) or floating point (automatic). Selection of the frequencies to be enhanced and the amplifier gain necessary to maximize the recorded relevant geologic information depends on the depth and size of the underground geologic features of interest and the acoustic properties of the near-surface material.

Receivers for detecting reflected acoustic signals in the ground are called geophones, which are very specialized microphones similar in principle to those used in voice recording. The operation of a geophone is based on the voltage induced in a coil of wire when it moves through a magnetic field. For most geophones a magnet is rigidly attached within the geophone case. A coil of wire mounted on a spring surrounds the magnet. When the case experiences movement, the coil moves relative to the magnetic field (set up by the magnet), which in turn induces a voltage proportional to the velocity of the ground motion. Selection of the appropriate geophone for a particular survey should be based on dominant frequency and amplitude of the signal.

The most site dependent part of the acquisition system is the acoustic energy source. A wide variety of sources have been developed and are in routine use on shallow seismic reflection projects. As a human voice is a source of acoustic energy, so is an explosion, a book dropped onto the floor, a car horn, or an electric razor.

The method of generating and transmitting acoustic energy into the ground is what determines the quality of a source at any particular site. There are basically two types of sources: impulsive and vibratory. Impulsive sources are the predominant type of shallow seismic source while vibratory sources are the predominant conventional seismic source. The frequency-limited nature of vibratory sources is what has held them to very limited used on shallow reflection surveys. Most shallow reflection surveys employ weight drop (accelerated) or explosives as the source of acoustic energy.

Processing Shallow Reflection Data

The purpose of acquiring and processing seismic reflection data in a CDP format is to enhance reflections at the expense of everything else. There are a wide variety of filtering, display, and static correction techniques that can be employed to improve the quality of the reflections. Discussion here will have to be limited to only those techniques that are necessary to understand the fundamentals of CDP processing. There are many places in the scientific literature to obtain more details (Waters, 1987; Yilmaz, 1987; Robinson and Treitel, 1980).

Raw seismic data are in a field file or shot gather format with each seismograph channel or seismic trace for a particular shot ordered according to channel number (Figure A-7). The number of seismic traces within each shot gather is equal to the total number of seismograph channels. Prior to the gathering or sorting of the data into a CDP format, dead or unacceptably noisy traces are removed and the location of each station is defined in three dimensions. CDP gathers from a simplistic point of view, is a collection of seismic traces that have a common midpoint in the subsurface.

Before stacking (adding) seismic traces with equivalent subsurface sample points it is necessary to compensate for different travel-path lengths (arrival time of the reflection) and localized variability in the near-surface material. The arrival pattern of reflection wavelets across receivers with linearly increasing distance from the source is a hyperbolic function (Figure A-8). This hyperbolic arrival pattern or normal moveout curve is a result of the non-linear increase in travel path for a ray traveling down to a reflector and back to the surface with a linear increasing in distance from source to receiver.

To properly correct for different ray path lengths the average velocity above the reflector must be known (Figure A-9). The simplest procedure to determine the seismic velocity for good seismic-reflection data is to fit a hyperbola (X^2,T^2) to the data. The degree of curvature of the hyperbola or normal moveout curve of the reflection arrival (assuming horizontal surfaces) is dictated by the average seismic velocity above the reflector, depth to the reflector, and distance between geophones.

Once corrected, the data emulate what would be observed with zero distance between shot and geophone, known as zero-offset (vertical incidence). Proper time adjustment to correct for offset allows traces with common midpoints to be directly added without sacrificing any wavelet properties. The correct velocity gives the highest frequency and the best coherency on the stacked data (Figure A-10).

Variations in the velocity and thickness of the near-surface material cause errors known as statics, which uncorrected can produce apparent geologic structures that have no geologic significance. Static variations are most commonly determined using cross-correlation techniques such as surface consistent statics, residual statics, common offset statics, and refraction statics. Correcting static variations is accomplished through whole-trace time shifts representative of variability in the near-surface, generally in a relatively localized area.

A variety of filtering, scaling, display, and analysis techniques much less significant to the understanding of shallow data CDP processing are routinely used to improve overall data quality. The basics of CDP processing discussed here should provide a general understanding what is most significant to the generation of high-quality stacked sections.

Interpretation

Seismic reflection data can be displayed in a variety of forms including CDP stacked section, shot gather (field file), CDP gather, and common offset section, to name a few. Data displayed in any of these formats have features that require special considerations when trying to interpret the significance of the wiggles. First and foremost, with shallow reflection data not every wiggle necessarily has special geologic significance. Noise is present on any seismic data set and overly optimistic interpretations that draw meaning from every wiggle will eventually lead to misinterpretations. CDP stacked sections are corrected to represent vertically incident time arrivals and, therefore, of all the data display formats, CDP stacked data most closely equate to a geologic cross-section. Common offset data are similar to CDP in the similarity to a geologic cross-section. However, common offset data generally are not corrected from non-vertical travel paths and conversions from time to depth must compensate for the increased time of arrivals. Data in either shot gather or CDP gather format are generally ordered according to distance from shot to receiver. In this arrangement a single reflecting interface will be recorded at ever-increasing times at longer offsets. Interpretations based on shot or CDP gathered data are generally limited to approximate reflector depths and occasionally the inference (in a qualitative sense) of faulting or dipping beds. Seismic reflection data are almost always displayed relative to two-way travel time, which can be converted in a general sense to depth if velocity is known.

Seismic reflection data in a CDP stacked or common offset format can be thought of as the time equivalent to a highway road cut where geologic units are exposed for viewing. The accuracy of the conversion of a time seismic reflection section to a depth geologic cross-section is dependent on how well the average velocity from the surface to each reflector is known. The wiggles on a reflection seismogram represent amplitude (loudness from a sound wave perspective) of an echo that arrived at the geophone at a particular time. That time, when multiplied by the average seismic velocity within the earth, equates to twice depth. If the travel time of an acoustic pulse from the surface to a variety of depths in the subsurface can be determined from borehole geophones, conversion of time to depth can be very accurate. If, on the other hand, no borehole seismic velocity information is available, the NMO velocity must be used to approximate depth. NMO or stacking velocity is always 0-20% greater than the real average velocity. Reflector depths estimated from NMO or stacking velocities cannot be more than 20% deeper than the actual reflecting interface.

The nature of seismic energy is responsible for the representation of recorded signal in the form of a wave (wiggle) (Figure A-11). Extracting discrete geologic boundaries or anomalies from the series of wiggles present on seismic data requires the actual or inferred removal of the source wavelet or characteristic sound of a source. Seismic data recorded using the perfect source (flat frequency spectrum from zero to infinity) have spikes that represent each acoustic impedance contrast with the height of a spike directly related to the acoustic impedance contrast at the interface. Unfortunately, since no perfect source exists, the spikes of the perfect source are spread out in time and become waves whose appearance or characteristics are related to the unique spectral properties of the actual source. The narrower the bandwidth of the source the farther from a spike and the 'ringier' the reflection wavelets become. In some cases a reflection may be represented by a wavelet with as many as three zero crossings (3 positive and 3 negative deflections). The interpretation of seismic data requires a good understanding and working knowledge of the source wavelet for a particular source and experience with distinguishing interference between wavelets from two closely spaced reflectors.

Conclusion

Seismic reflection is a powerful geophysical tool for exploration of the subsurface. Applications of the technique to engineering, environmental, and groundwater problems has only recently become cost effective. As with any geophysical technique as long as the basic principles and limitations are understood and no assumptions are made shallow seismic reflection can provide subsurface continuity not possible by any other means at some locations.

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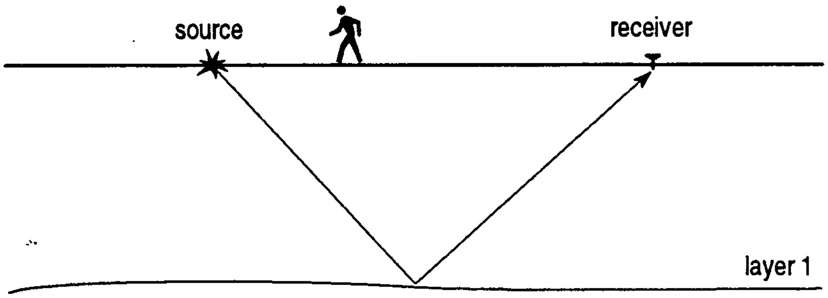

Figure A-1. Reflection from one subsurface layer. The angle of incidence of the downgoing ray is equal to the angle of reflectance of the upgoing ray.

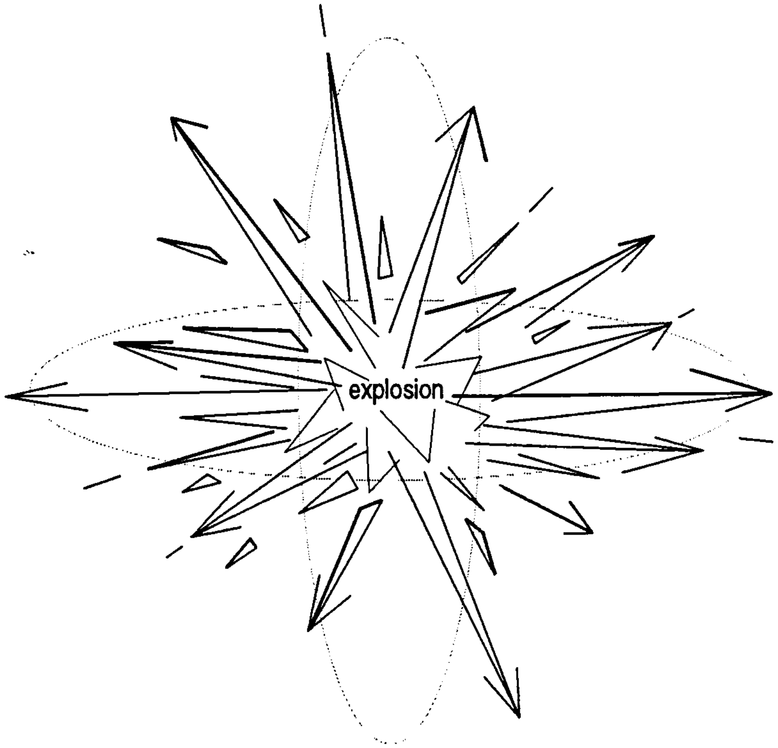

Figure A-2. Computer simulation of energy radiating out from a pebble dropped in a pond.

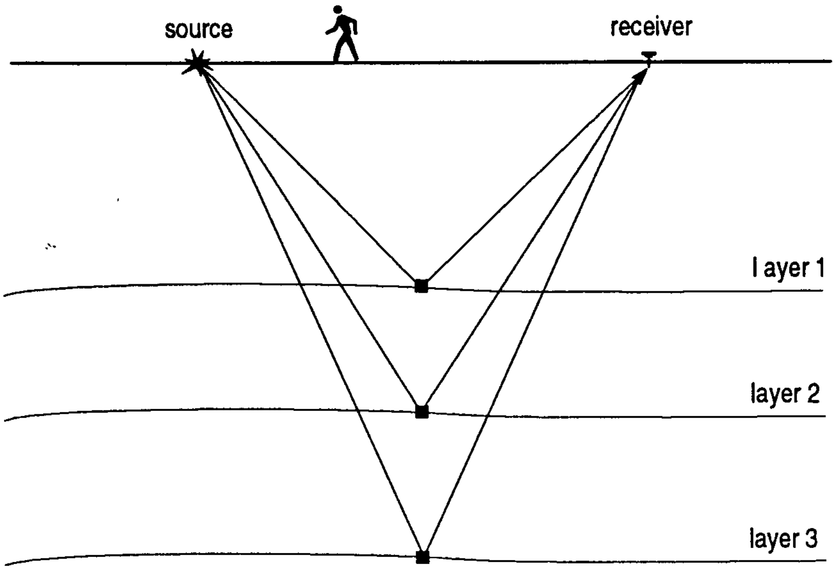

Figure A-3. Reflection from three subsurface layers. The angle of incidence is different for each layer/ray but the reflecting points are vertically equivalent.

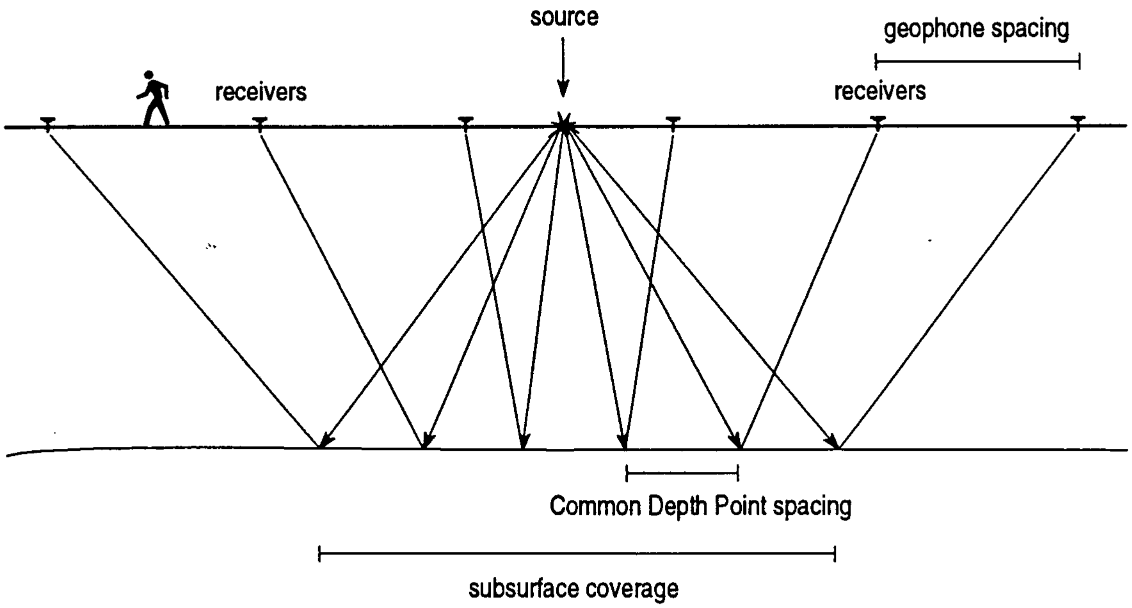

Figure A-4. Schematic drawing of seismic ray paths for a single shot with a six-channel reflection seismograph.

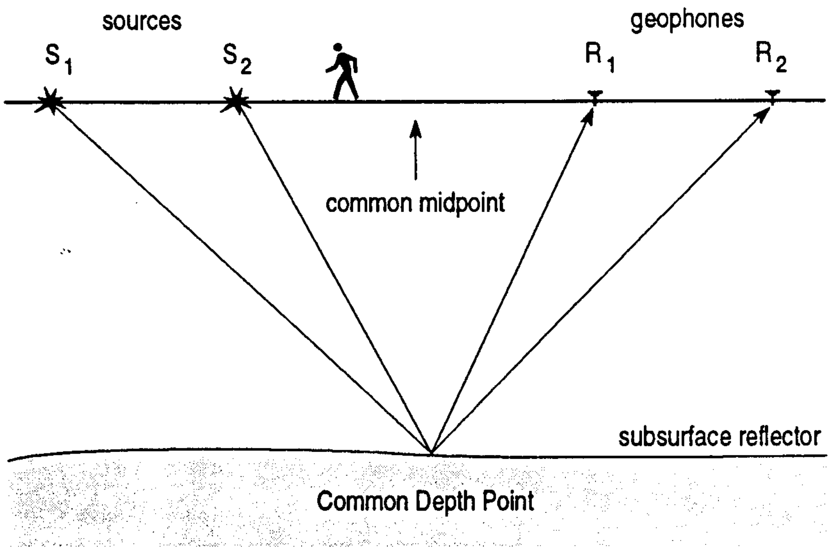

Figure A-5. The concept of Common Depth Point (CDP). Note that ray paths from two different shots (S_1 and S_2) reflect from a common point in the subsurface.

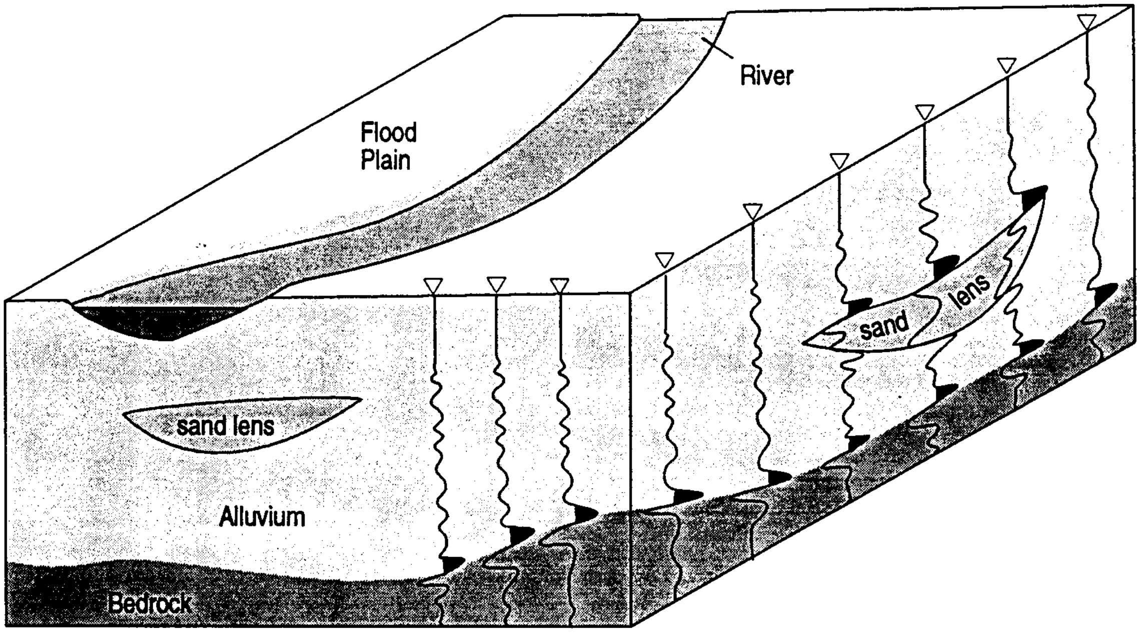

Figure A-6. Schematic showing a seismic section relating to real-world geology.

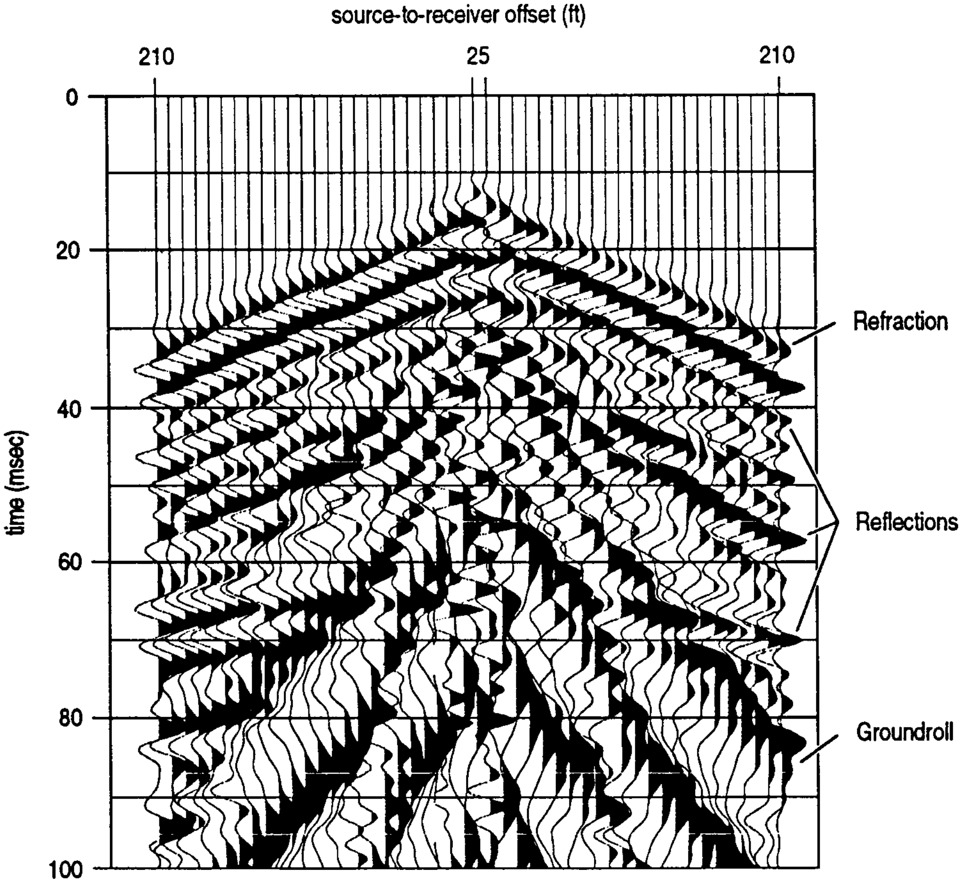

Figure A-7. 48 channel field file acquired in a split-spread format. The source is located between two sets of 24 channels.

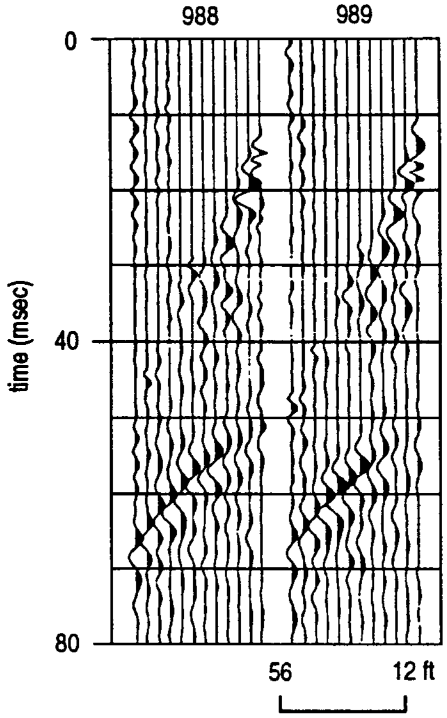

Figure A-8. Two CDP gathers from a 24 channel seismograph. The hyperbolic curvature of the reflection arrival is easily identified.

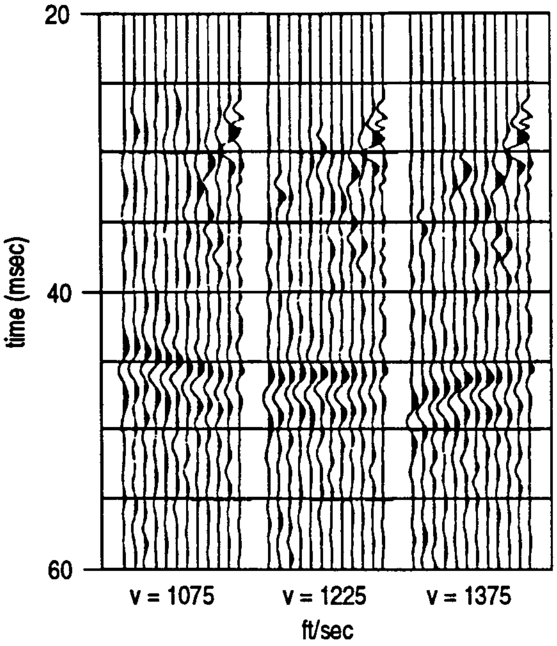

Figure A-9. CDP gathers from Figure A-8 moved out at various velocities.

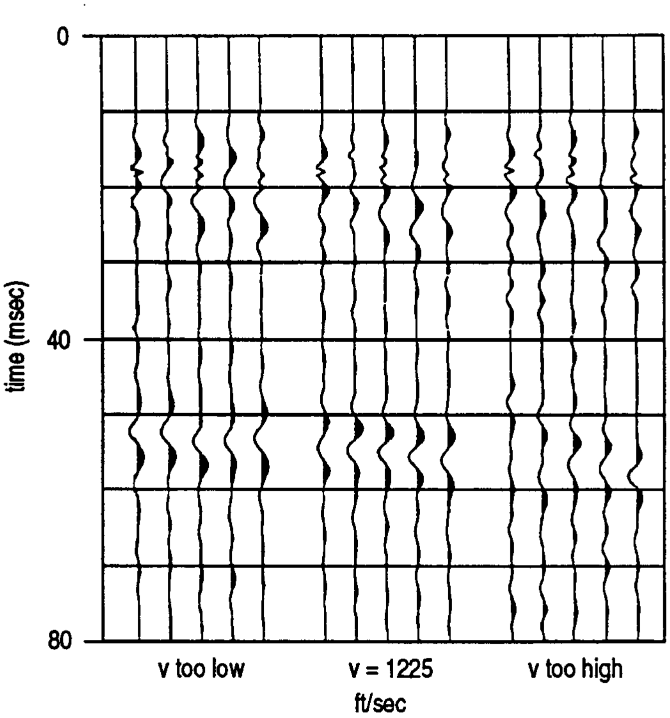

Figure A-10. The effects of an improper stacking velocity.

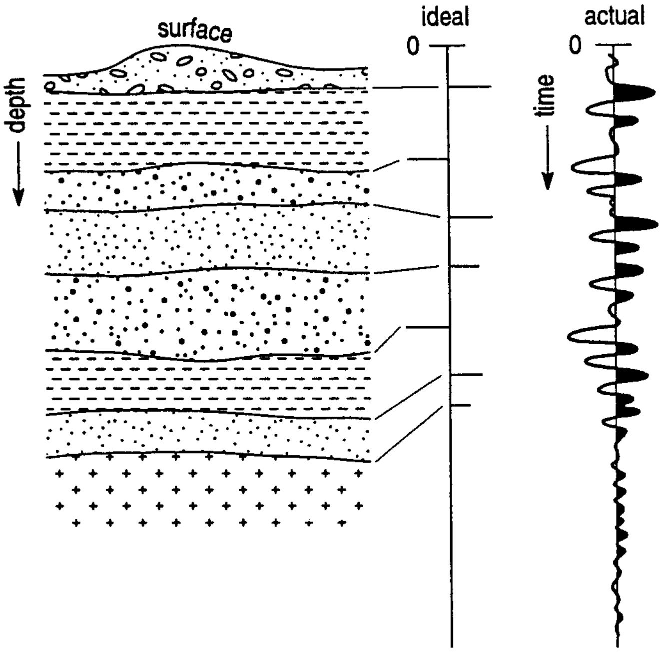

Figure A-11. Actual seismic trace (with simulated noise) that would result from a reflection survey over the geologic model. The spike or ideal trace represents the acoustic impedance contrasts at each interface.