P-WAVE SEISMIC ACQUISITION AND PROCESSING TEST NEAR THE PROPOSED CUP-McCOOK RESERVOIR, COOK COUNTY, ILLINOIS

by

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1.0 Introduction

1.1 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 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 constrains 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).

1.2 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) structures (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 need for drilling by an order of magnitude. While the seismic-reflection method shows fault locations and stratigraphic relationships, it can give only estimates of depth and does not explicitly identify lithologies without confirmation drilling.

1.3 This report displays and interprets seismic-reflection data acquired by the Kansas Geological Survey (KGS) on contract to STS Consultants to determine the feasibility of detecting a fault(s) inferred from two drill holes approximately 2000 ft apart in the Chicago area (Figure 1). A series of walkaway noise tests and a 2000 ft CDP seismic line were acquired along 67th Street between La Grange Road and the Des Plaines River (Table 1). The walkaway tests included three different sources and four analog low cut filter settings with a total apparent spread length of approximately 575 ft. The production CDP survey was conducted using the MiniSOSIE technique and consisted of a total of 127 stations each separated by 16 ft. The effects of cultural noise, a very attenuative near-surface, and low overall signal-to-noise ratios at this site inhibited the use of conventional high resolution seismic methods

(Steeples and Miller, 1990). The MiniSOSIE technique possessed the highest potential of obtaining useable CDP data at this site.

2.0 Geologic Setting

2.1 This shallow reflection survey was designed to image the contact between the shales of the Maquoketa Group and dolomites of the Galena Group, both of Ordovician age. The bedrock surface is buried beneath approximately 35 ft of fill and glacial drift at a boring located near station 124. Silurian dolomites make up the entire interval between the bedrock surface and the Ordovician shales at 350 ft. These dolomites within the upper 350 ft should be transparent on seismic data acquired for this survey. The contact between the Silurian and Ordovician at approximately 350 ft is sufficiently gradational on borehole BH-18 logs that it is unlikely energy reflected from that contact could be distinguished from background noise. From electrical logs of BH-18, the velocity/density contrast of the Scales shale basal contact represents the strongest potential reflector (at the resolution of this survey) between the bedrock surface and 460 ft of depth. Based on log data from BH-18, at 800 ft a second potential reflecting interface exists between the Platteville dolomites and the Ancell sandstone. The presence of faulting within the Maquoketa shales, displacement and size of any fault zone, and fractures within the Silurian dolomites represented the primary geologic targets of this seismic survey.

3.0 Data Acquisition

3.1 Walkaway data were acquired with both I/O's DHR-2400 and EG&G Geometric's 2401x seismographs. The Geometric's seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. The selected low cut filters have a 18 dB/octave rolloff from indicated -3 dB points. The 1/5 ms sampling interval resulted in a 5000 Hz sampling frequency for a record length of 307 m. The Geometrics 2401x is a 48 channel floating point seismograph.

3.2 Production data for this study were acquired on a 24-channel Input/Output DHR-2400 seismograph. The data were analog filtered, amplified, A/D converted (11 bits plus sign), and recorded on 9-track tape for future digital processing. The record length is 250 ms with a sampling interval of 0.5 ms. The 1/2 ms sampling interval equates to a sampling frequency of 2000 Hz and therefore an alias or

Nyquist frequency of 1000 Hz. A 250 Hz high cut filter with a 24 dB/octave rolloff acted as an anti-alias filter and reduced wind noise and higher modes of 60 Hz power line noise. For the production portion of the survey an 80 Hz analog low cut filter was used to shape the pre-amplified spectra, enhancing the higher frequency components of recorded energy.

3.3 A variety of field parameters and equipment were tested to insure optimization of recorded data. The sources for the testing included the downhole 50 caliber rifle (Steeples et al., 1987), the auger gun (Healey et al., 1991), and MiniSOSIE (Barbier et al., 1976, see Appendix B). The receivers for the entire study were Mark Products L-28E 40 Hz geophones wired three in series per string. The receivers were placed in a 3 ft in-line array to help attenuate source-generated air coupled wave.

3.4 The production seismic profile was preceded by an extensive series of tests. Proper matching of high- and low-cut filters for the acoustic characteristics and targets at this site, allowed optimization of each seismograph's dynamic range. Source-to-receiver offsets on walkaways ranged from 8 to 575 ft with receivers spaced at 8 ft intervals at the test site along the production line. At the test site within the forest preserve the source-to-receiver offsets ranged from 4 to 576 ft with receivers spaced on 4 ft intervals. Direct wave, refractions, ground roll, and air-coupled wave can be identified on the walkaway data. Reflections can be interpreted on data recorded with 100 and 140 Hz lowcuts on the 2401x at the forest preserve site and with 80 Hz lowcuts with data recorded on the DHR 2400 at the 67th Street site. All aspects of the testing were instrumental in fine-tuning the acquisition parameters and equipment for the CDP portion of this study and in determining the potential of several variations in the acquisition process.

4.0 Data Processing

4.1 Data processing was done on an Intel 80486-based microcomputer using *Eavesdropper*, a set of algorithms marketed by Interactive Concepts Incorporated. The processing flow was similar to those used in petroleum exploration (Table 2). 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.

4.2 The extremely variable near-surface resulted in severe static anomalies on CDP stacked data. First arrival energy was delayed on shots from the east end of the line. This delay implies either a decrease in near-surface velocity, an increase in depth to the bedrock surface, or both. Due to inherent pre-first arrival noise levels associated with the MiniSOSIE method it was not possible to correct for near-surface velocity irregularities using common-offset or refraction statics. Detailed knowledge of the bedrock surface and the material between the bedrock and the ground surface is necessary to properly interpret the structural and stratigraphic significance of reflecting events. In the case of this data set, relative displacement and the size of the fault zone can not be inferred without complete and accurate compensation for the weathered layer.

4.3 To analyze variations in the source wavelet with offset, the data were gathered into groups based on common source-to-receiver offsets. The data were not adjusted for non-vertical incidence, but were digitally filtered and AGC scaled. The resulting display format allows comparison of offset dependent effects and reduces the detrimental aspects of data stacking.

4.4 For most basic shallow, high-resolution seismic reflection data the processing steps/operations are a simple scaling down of establish petroleum based processing techniques and methods. However, processes such as deconvolution have basic assumptions that are violated by most shallow data sets. Due to non-conventional scaling (vertical and/or horizontal) many times migration appears to be necessary when in actuality geometric distortion may be simple scale exaggeration. Processing/processes used on data for this report has/have been carefully executed with no assumptions and with care not to create anything after an operation that was not present before.

5.0 Walkaway Noise Tests

5.1 Preliminary testing of parameters and equipment included the 50 caliber downhole rifle, 8 gauge auger gun, and earth compactors (Wackers) as sources and 50, 100, and 140 Hz low cut filters for the 2401x seismograph (Figures 2, 3, 4, 5, 6, 7, and 8) and 40 and 80 Hz low cut filters for the DHR 2400 seismograph (Figure 9). Walkaway noise tests allow the effects of variations in recording parameters to be observed and analyzed. The goal of the noise testing process is to change one variable at a time so optimal combinations and/or sequences of acquisition parameters and techniques can be determined for a particular geologic setting. Sixty Hz power line noise is evident on all filtered single shot records. The high apparent velocity, trace-to-trace coherency, and high dominant frequency characteristics of power line noise makes removal with a filter (digital or f-k) impractical. The direct wave has a strong presence from first arrival to the bottom of the record. The very repetitive nature of this arrival is a direct result of the very narrow bandwidth of the wavelet and extremely high acoustic impedance contrast at the bedrock surface. This high contrast channels the energy, creating a standing wave traveling within the weathered material. The narrow band nature of the energy makes both analog and digital filtering relatively ineffective. Ground roll is interpretable at offsets out to about 50 ft. The low frequency and velocity of the ground roll makes removal and/or avoidance possible without adversely affecting body wave energy. No potential reflection energy deeper than 50 msec can be confidently identified on walkaway data from the south side of 67th Street.

5.2 The source location was moved to both determine if an anomalous break in energy coherency that occurred 56 ft from the original source location was a near-surface effect and record forward and reverse first arrivals on the same record (Figures 4 and 5). After moving the source 56 ft into the line the apparent break in slope was no longer evident, suggesting it was the result of a localized near-surface irregularity and not an offset depend feature. The near-surface velocity is very consistent both forward and reverse, suggesting a relatively flat bedrock surface and/or consistent properties of near-surface materials at least beneath the walkaway area.

5.3 The source was moved off-line 15 ft to verify consistency in data quality recorded at this site (Figures 6 and 7). The extremely high apparent velocity of the first arrival is due to the 15 ft off-line offset. The combination of the power line noise and the relative nonconducive acoustic environment made recording high quality reflection data very difficult. No reflected energy can be readily interpreted on any of the single shot walkaways from the area south of 67th Street.

5.4 Walkaways from the parking area of the forest preserve north of 67th Street (Figure 1) show much more promise for single shot type sources (Figure 8). The power line noise is not evident on walkaways regardless of offset or low cut filter settings. The strong direct wave component is still interpretable on all filter settings. The bandwidth of the body wave energy is much broader and shifted toward the higher frequencies as evidenced by the "tighter" wavelet. An event (most likely a reflection) can be interpreted on 100 and 140 Hz lowcut data at about 90 ms, between approximately 192 ft and 325 ft of offset. The dominant frequency is in excess of 100 Hz and the apparent NMO velocity is approximately 2800 ft/sec. Testing in the forest preserve suggests that surface single shot techniques could be effective imaging the upper 400 ft in this area at locations with limited cultural activities and relatively undisturbed near-surface material.

5.5 Walkways recorded using the MiniSOSIE technique in the area south of 67th Street possess the highest signal-to-noise ratio and probability of recording useable data along the street (Figure 9). A reflection can be interpreted on 80 Hz low cut data at an offset of about 32 ft and time of 40 msec. This event could be from the bedrock surface and becomes a wide angle reflection at offsets greater than 240 ft. With the extremely noisy environment along the street, the recorded reflection and higher signal-to-noise ratio observed on the 80 Hz MiniSOSIE data strongly influenced the choice of recording equipment. The MiniSOSIE data have only subtle indications of power line noise. The direct wave component of the data is significantly less than on single shot gun records. The ground roll is much more pronounced on the MiniSOSIE data. The selected recording parameters were based on maximizing the potential of recording a reflection from approximately 300 ft of depth.

6.0 Results

6.1 Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. Many of the raw field files acquired for the production portion of the survey have a confidently identifiable reflection event at approximately 100 ms (Figure 10). The reflection has a dominant frequency of approximately 80 Hz and an apparent NMO velocity of approximately 9000 ft/sec. These would equate to an approximate depth to reflector of 450 ft and a vertical resolution potential of about 30 ft. The signal-to-noise ratio on the raw file is not sufficient to confidently identify reflections on most files.

6.2 Analysis of processed field files improves confidence in interpretations of CDP-stacked sections (Figure 10). Digital filtering, first arrival muting, appropriate trace balancing, bad trace editing, and surface consistent statics were key processes in improving the pre-stack appearance of reflections barely interpretable on raw field files (Figure 10). The reflection event indentifiable on some of the walkaway files at approximately 50 ms is not evident on most files recorded during the production portion of the study. This 50 ms event could be the bedrock reflection, however if average velocities postulated using interval velocities derived from refraction information are relatively close to accurate, the approximate depth to this reflector is between 50 and 100 ft. The lack of a potential geologic target at 50 to 100 ft and the speculative nature of the assigned average velocity predicate care and a conservative approach to interpretations of coherent energy arriving earlier than 70 ms on stacked data.

6.3 Coherent events can be interpreted across the entire CDP stacked section (Figure 11). The CDP stacked section possesses nominal 12-fold redundancy as a result of the 24 channel seismograph and recording geometry. Traffic on the north/south road (East Ave) at the east end of the line was sufficiently heavy that neither continuous acquisition across the road or under-shooting of the road was possible. The dominant frequency of most recorded reflection energy is between 50 and 100 Hz. The stacking velocity ranged from 6000 to 9000 ft/sec. Most of the apparent east dip of reflecting events is postulated (without any borehole information) to be the result of an increase in the thickness and/or decrease in velocity of the weathered layer (alluvial and glacial deposits). With the general dip in this area being 15 ft/mile, approximately 30 ft of the eastward dip identified on the 2000 ft seismic line must be related to either increased overburden thickness/ decreased overburden velocity or faulting/folding.

6.4 Faulting in the 100 ms reflection is interpreted on the stacked section between station numbers 164 and 181 (Figure 11). The fault zone is composed of a series of high-angle normal faults with approximately 10 ms (45 ft) of total displacement across the zone which was active post-Ordovician. Normal faulting interpreted in the 140 ms event beneath station 140 does not appear to have been active post-Ordovician. The chaotic zone between stations 130 and 143 at times between 100 and 150 ms makes confident correlation of beds across the pre-Silurian fault difficult. Structural features on the 100 ms event (some of which is interpreted here as faulting) are probably the result of folding, faulting, and static irregularities in near-surface material.

6.5 Data gathered according to common source-to-receiver offsets, digitally filtered, and AGC scaled allows diffractions generally associated with bed terminations to be confidently interpreted (Figure 12). Diffractions between station numbers 160 and 170 have apexes from 50 to 150 ms. These diffractions are very localized and closely correlate to faulting interpreted on CDP stacked data. In this geologic environment the most likely source of diffractions are faults and/or joints. Diffractions interpretable on the common offset section are not conclusive evidence for faulting, but they strongly support the proposed interpretation of the CDP stacked data.

6.6 The feasibility of using shallow reflection in residual areas with approximately the same near-surface material and cultural noise can be approximated with the data set collected along this highly commercialized area of 67th Street (Figure 13). A residential street was simulated to have 98 ft lots, 65 ft houses, and 22 ft driveways with data collected in grassy, front yards south of the paved street. The data collected along 67th Street from station 101 to the north/south road (East Ave) were modified so shots and receivers located on driveways were deleted. The resulting stacked section possesses structural and stratigraphic features very similar to the original stacked section (Figure 11). This suggests that in a residential neighborhood with similar noise levels and near-surface material as those encountered along 67th Street, the MiniSOSIE method of shallow seismic reflection could produce interpretable data.

7.0 Conclusions

7.1 Shallow seismic reflection can be used to delineate structural features present in the Ordivician shales at a depth of over 300 ft at this site along 67th Street. The noise level present along most of 67th Street was such that the MiniSOSIE method of recording was necessary to obtain useable information. Faults/fractures are interpretable on both CDP stacked and common offset gathered seismic reflection data between stations 160 and 180. It is not possible to unequivocally identify the seismically interpreted faulting along this line as the same faulting/fault responsible for the 60 plus ft of offset between two off-line boreholes. Assuming the effects of near-surface irregularities are minor, displacement in the 450 ft reflector is around 40 to 50 ft. If all the apparent general eastward dip interpretable on stacked data is the result of near-surface velocity anomalies, the fault displacement between stations 160 and 180 could be as little as 10 to 20 ft. Shallow seismic reflection in this area could easily reduce the number of boreholes necessary to confidently locate and quantify faulting by an order of magnitude.

The combination of apparent offset interpreted on the CDP stacked data and diffraction patterns observed on the common offset data set allow significant confidence in suggesting faults and/or joints are present along this line. The only source of diffracted energy not related to faulting or joints in this area would be subsurface irregularities such as boulders within the drift, extreme topographic undulations on the bedrock surface, or stratigraphic changes that horizontally alter the acoustic properties of the rock. The amplitude and well developed symmetric arrival patterns of diffractions interpreted on the common offset section are conclusive evidence of a (or series of) localized point source anomaly(s) such as faulting or joints. Relative strike-slip movement along the interpreted fault zone would result in diffraction patterns with no apparent bed displacement on the CDP stacked section. Theoretically, differentiating strike-slip faulting from a cluster of joints would in most cases be difficult. Any relative vertical component of faulting would be represented on a CDP stacked seismic section as bed displacement with associated diffractions. It is extremely unlikely but not impossible that the apparent eastward dip as interpreted on CDP stacked data is related to variations in the overburden. It is with a high degree of certainty that the irregularities in the reflections and presence of diffractions are interpreted as either joints or faults.

8.0 Recommendations

8.1 To verify the location of the fault zone and associated interpretation of the seismic data, confirmation boreholes should be drilled at locations 160 and 185. The horizontal distance between these locations is 400 feet. An uphole or downhole velocity survey is necessary to better quantify fault displacement. With uphole or downhole velocity information, the data could be reprocessed/reinterpreted to better define the fault location and relative displacement. The interpretation presented suggests faulting is probably distributed over a fault zone.

8.2 Any further seismic reflection work in the area should be done using Mini-SOSIE or some similar pulse-coded technique to avoid problems with pervasive cultural and 60 Hz noise that are present in much of the Chicago metropolitan area. The USGS office in Denver does contract MiniSOSIE work for other government agencies. Dr. Kaye Shedlock at (303) 236-1585 is the contact person.

8.3 Any regional study involving seismic reflection studies should be preceded by a series of short test lines to evaluate the value of seismic reflection in various parts of the study area. Low-lying areas along the river and other drainage avenues could be used to good benefit to maximize resolution by favoring high-frequency seismic energy. The possibility of shooting marine-type surveys in the river should be considered because of the better resolution that is normally achieved in such surveys. The USGS office in Connecticut does shallow marine surveys for other government agencies. Peter Haeni at (203) 240-3299 is the contact person.

9.0 References

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TABLE 1

112	sewer manhole cover
126	sewer manhole cover
between 128 & 129	C.E. Co. meter box
131	phone cable box
140	sewer manhole cover
155	sewer manhole cover
160	stop ahead sign
170	sewer manhole cover
185	large storm drain
187 & 188	over driveway
189	red fire hydrant at edge of driveway
202	at road on other side of Santa Fe Tr.
205	at road (Santa Fe Tr.)
217 & 218	over driveway-loading dock
227	end of line at driveway

Table 1) Shot map and tie points from a 2000 ft CDP seismic line. These points are along 67th Street between La Grange Road and the Des Plaines River.

TABLE 2

format from SEG2 to KGSEGY
preliminary editing (automatic bad trace edit with 10 msec noise window)
trace balancing (50 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 5,000 to 9000 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 40-70 150-225)
secondary editing (manual review and removal of bad or noisy traces)
CDP stack
amplitude normalization (AGC 150 msec)
display

* Normal Move Out correction:

station	time	velocity	time	velocity
104	65	5200	90	8100
124	65	5800	90	8100
135	70	6000	90	8100
155	75	6400	95	9100
167	80	6500	100	9100
177	80	5800	105	8100
182	80	5800	105	9100
192	85	5200	105	9100
202	80	5200	105	9100

Table 2) Processing flow for CDP stacked data in Figure 11. Parameters were determined by analysis for each prior step as well as through iterative analysis of particular operations.

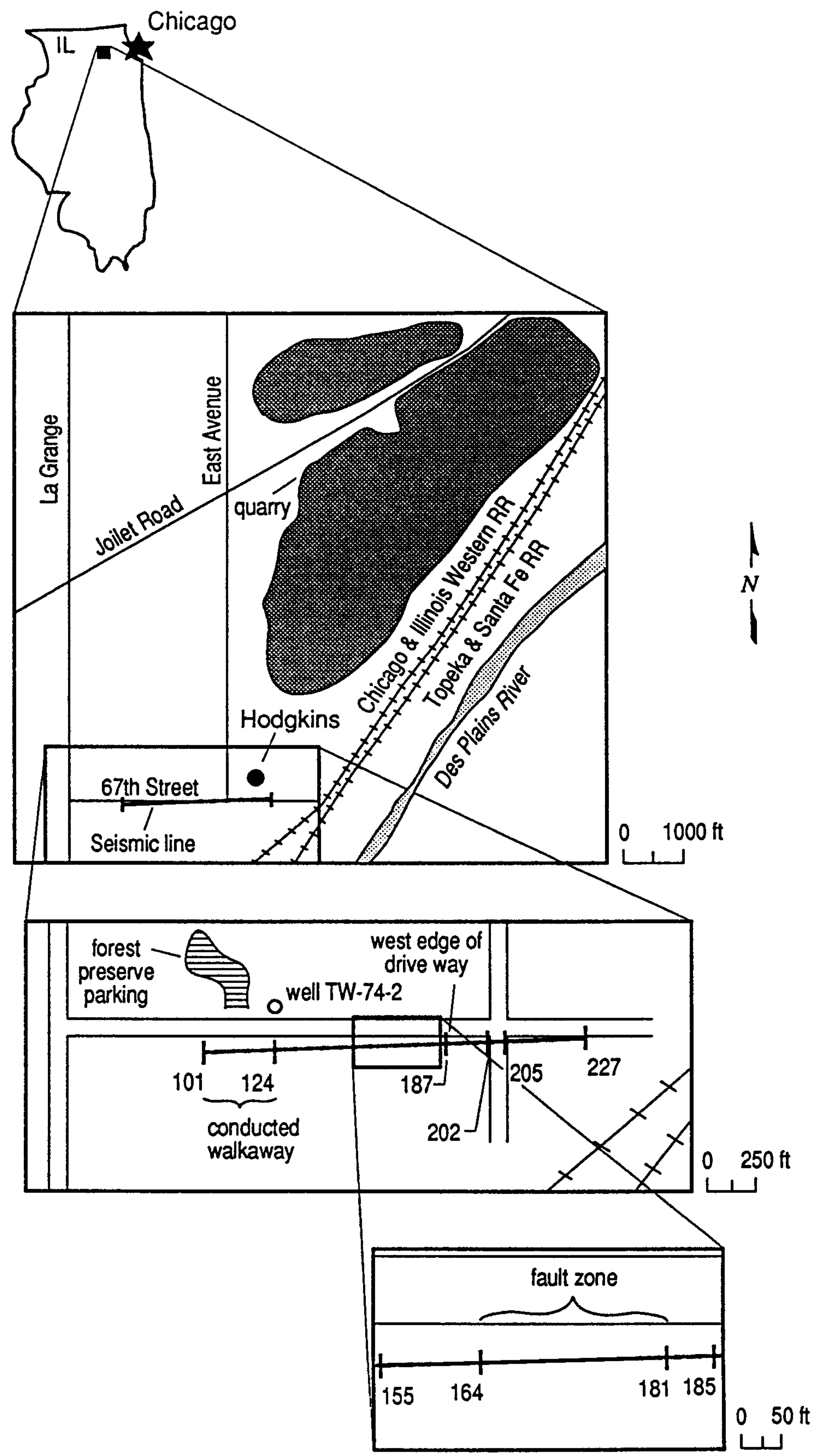

Figure 1) Site map of survey area. Station locations indicate key tie points along the line.

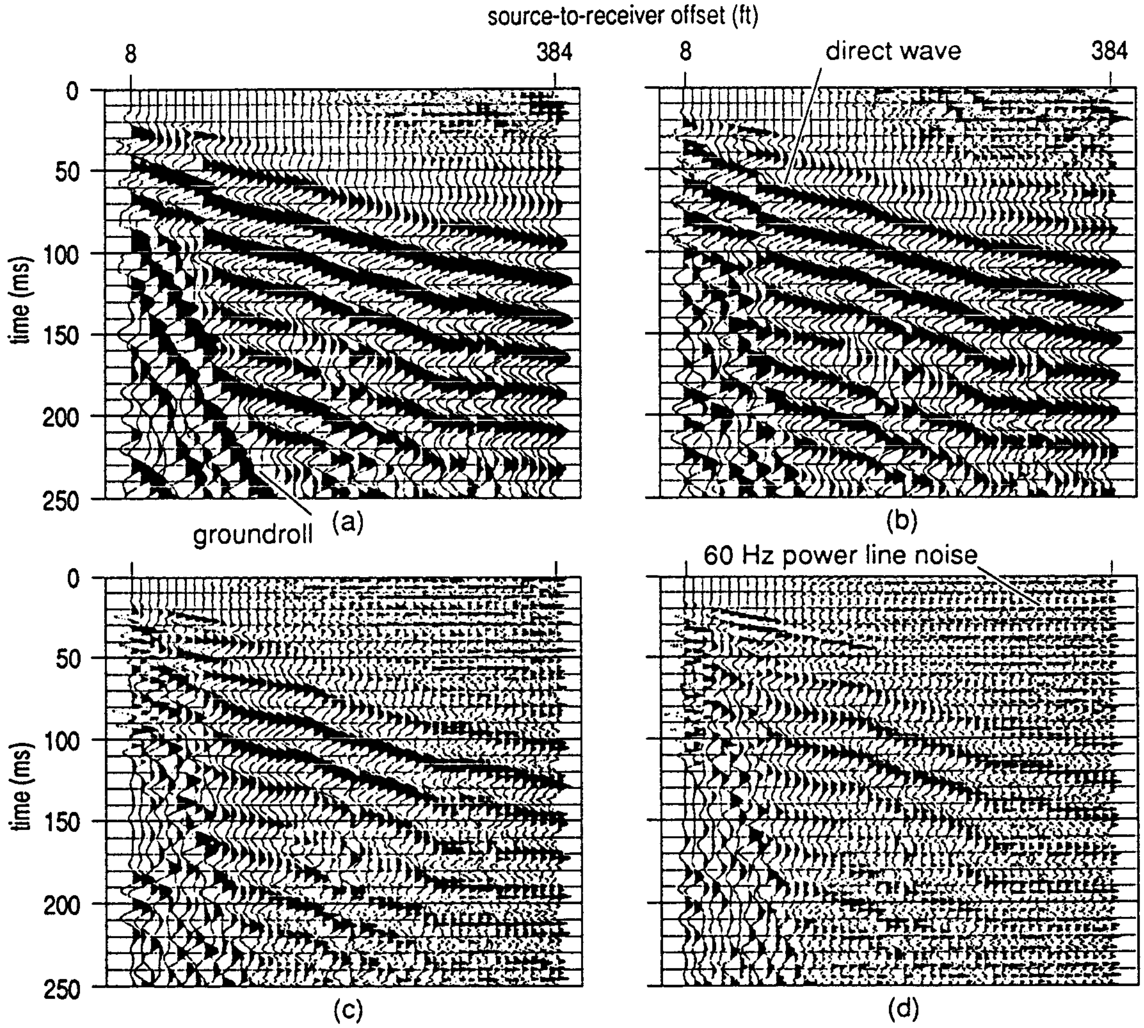

Figure 2) Walkaway noise tests with downhole 50 cal along 67th Street. Low cut filters ranged from a) out, b) 50 Hz, c) 100 Hz, to d) 140 Hz. Power line noise is evident on all data. An apparent near-surface anomaly resulted in some phase distortion on trace 8.

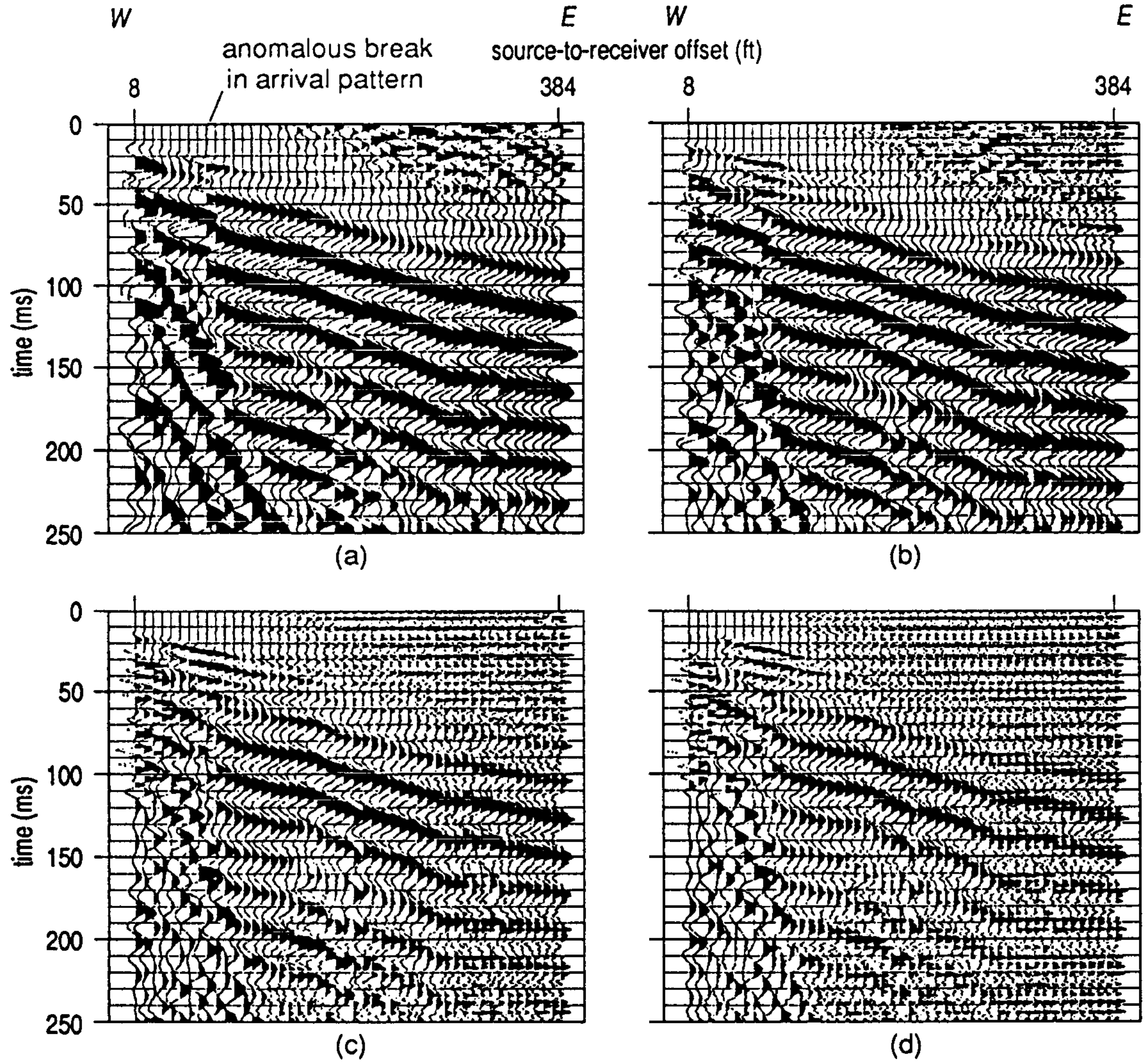

Figure 3) Walkaway noise tests with downhole 50 cal along 67th Street. Low cut filters ranged from a) out, b) 50 Hz, c) 100 Hz, to d) 140 Hz. Power line noise is evident on all data. An apparent near-surface anomaly resulted in some phase distortion on trace 8.

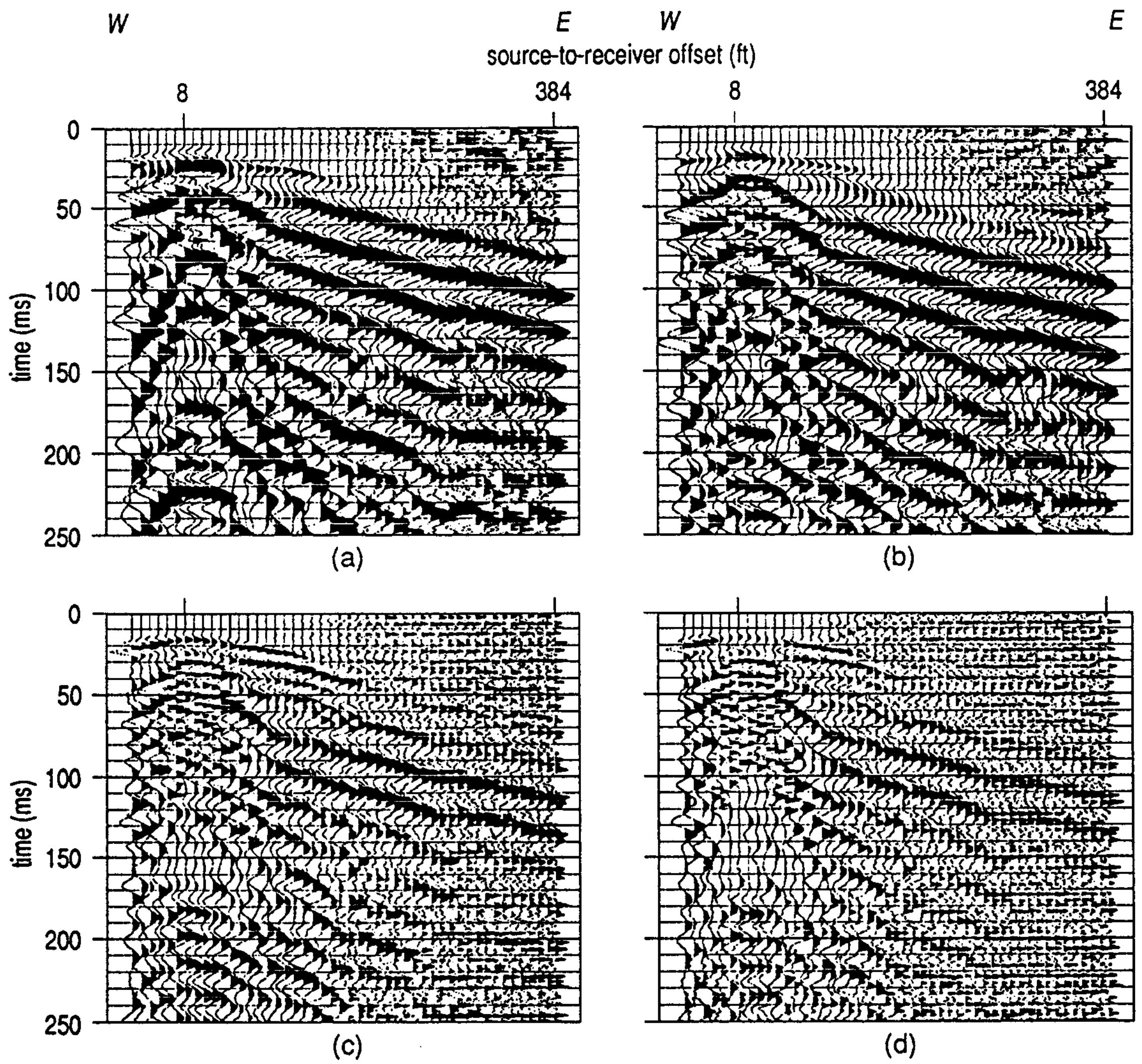

Figure 4) 8 gauge auger gun walkaway noise tests with the source location centered on trace 8 (56 ft) from shot location of figure 2. This asymmetric split-spread was tested with lowcuts including a) out, b) 50 Hz, c) 100 Hz, and d) 140 Hz.

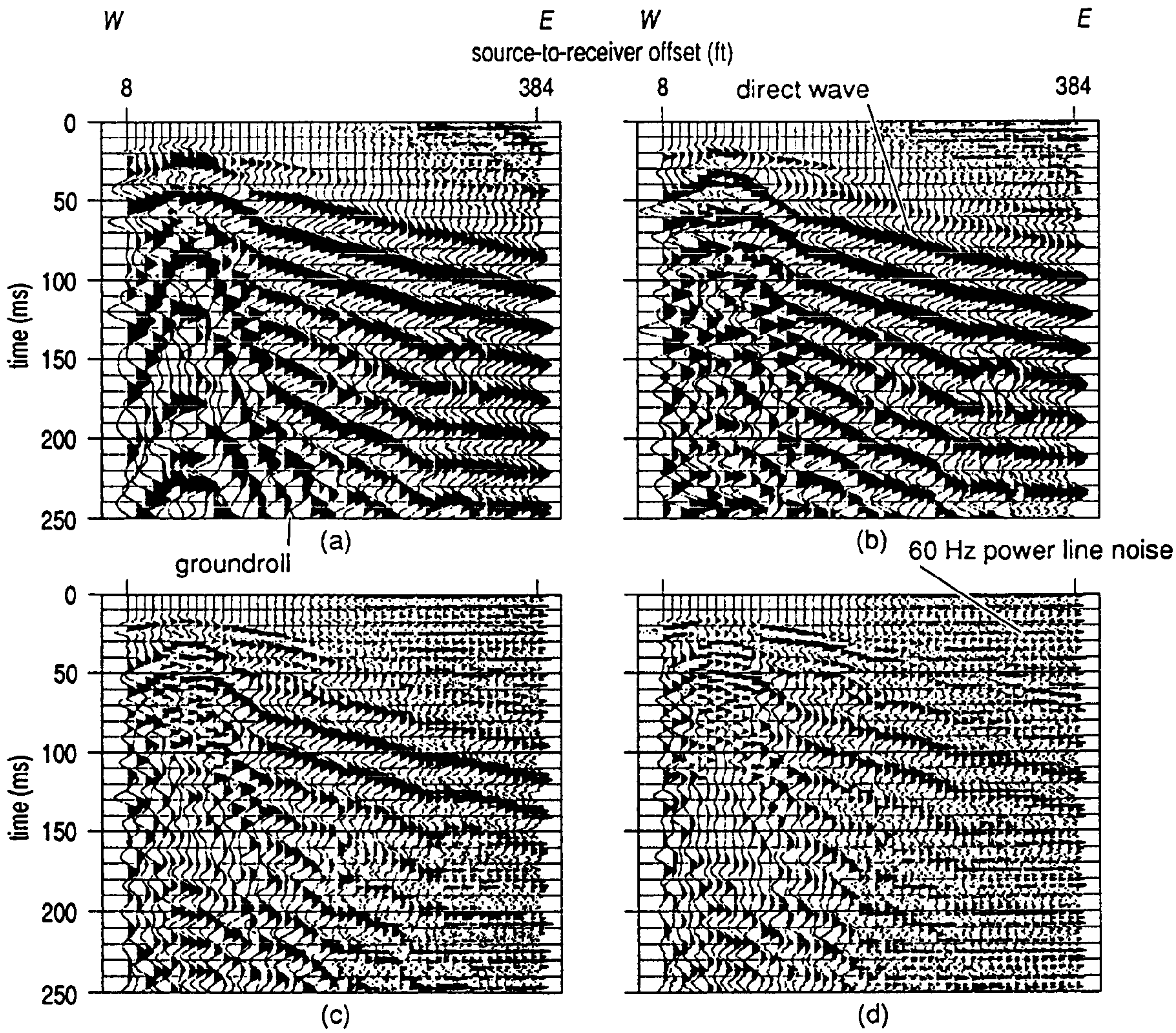

Figure 5) 50 cal walkaway noise tests with the source location centered on trace 8 (56 ft from original source location) on figure 2. This asymmetric split- spread was tested with lowcuts that included a) out, b) 50 Hz, c) 100 Hz, and d) 140 Hz.

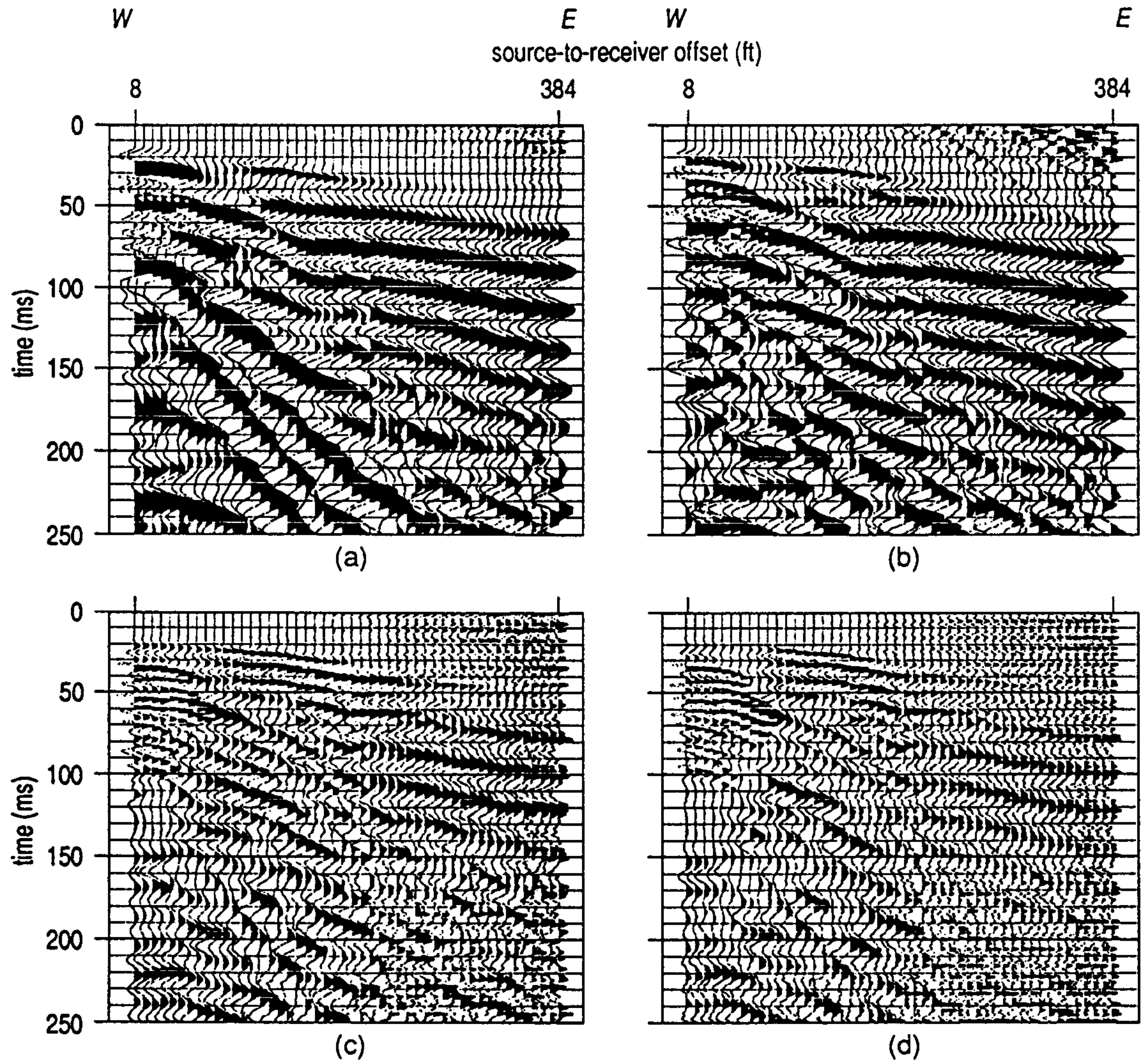

Figure 6) 8 gauge auger gun walkaway noise tests with the source location 15 ft off-line to the north relative to the original shot location of figure 2.This off-line spread was tested with lowcuts a) out, b) 50Hz, c) 100 Hz, and d) 140 Hz.

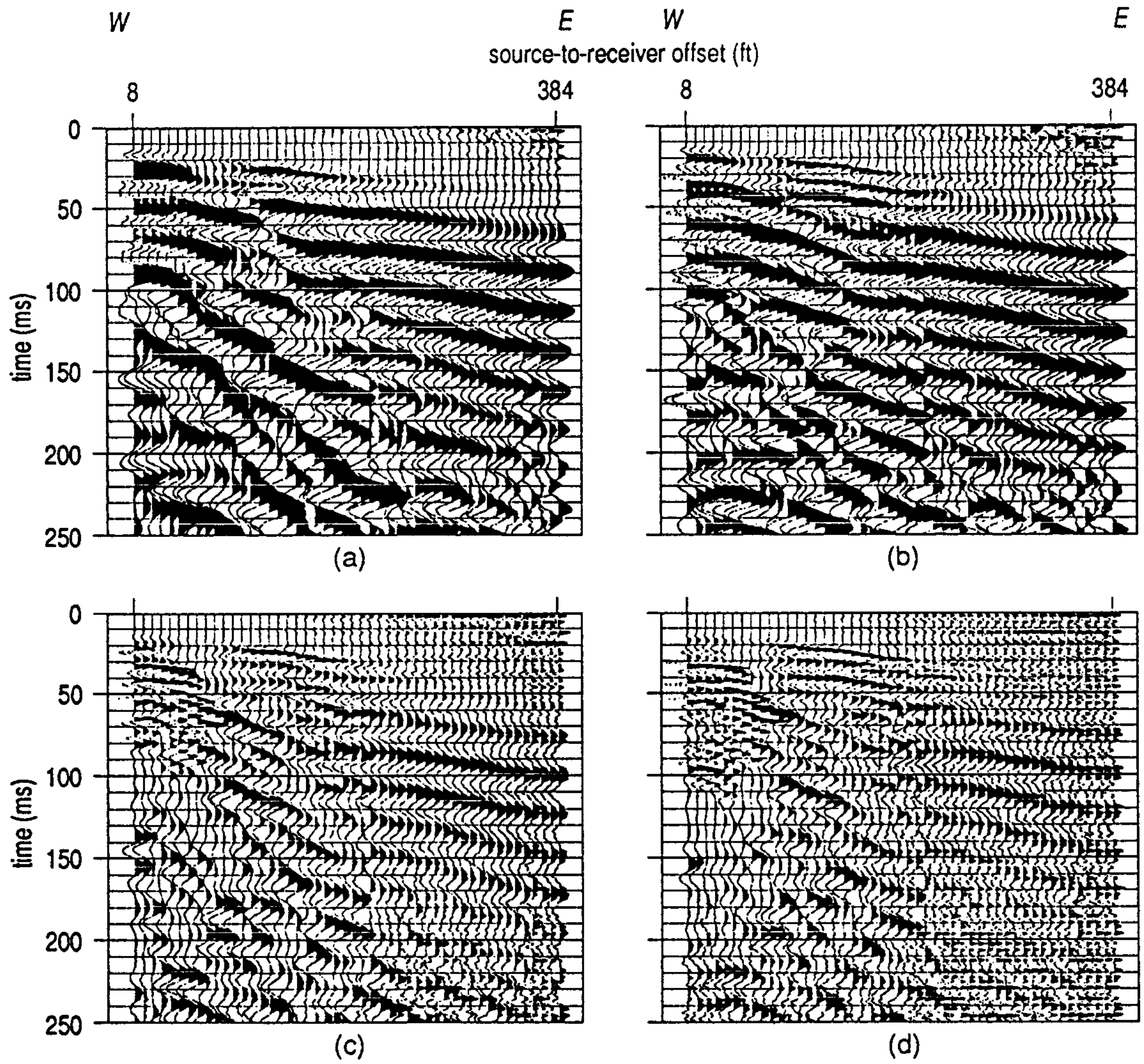

Figure 7) 50 cal walkaway noise tests with the source location off-line 15 ft compared to figure 2. This off-line asymmetric split-spread was tested with lowcuts that included a) out, b) 50 Hz, c) 100 Hz, and d) 140 Hz.

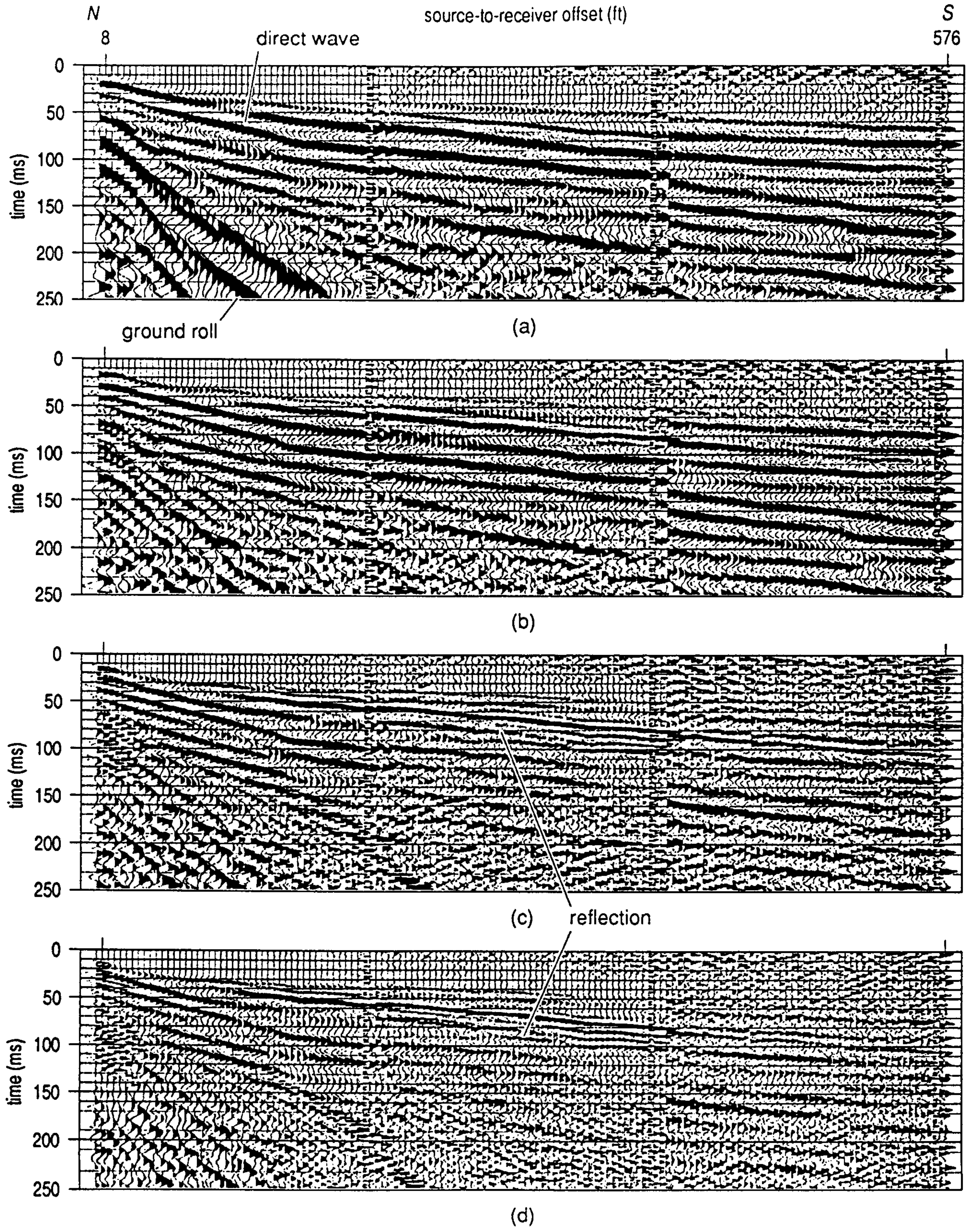

Figure 8) 8 gauge auger gun walkaway noise tests from the parking area of the forest preserve were acquired on 4 ft receiver spacing with a total spread length of over 575 ft. Lowcut filter tests include a) out, b) 50 Hz, c) 100 Hz, and d) 140 Hz. A reflection can be interpreted at about 240 ft source offset at about 90 ms.

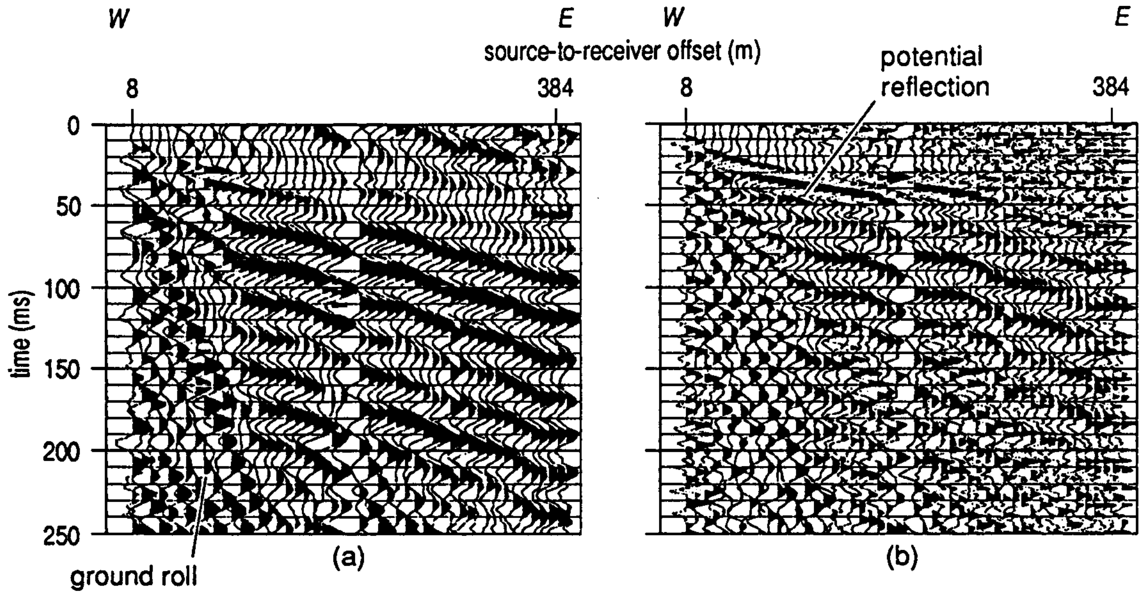

Figure 9) MiniSOSIE walkaway noise tests at the site along 67th Street. The walkaway spread included two different 24 channel spreads. The low cuts tested included a) 40 Hz and b) 80 Hz. A reflection can be interpreted at about 50 ms.

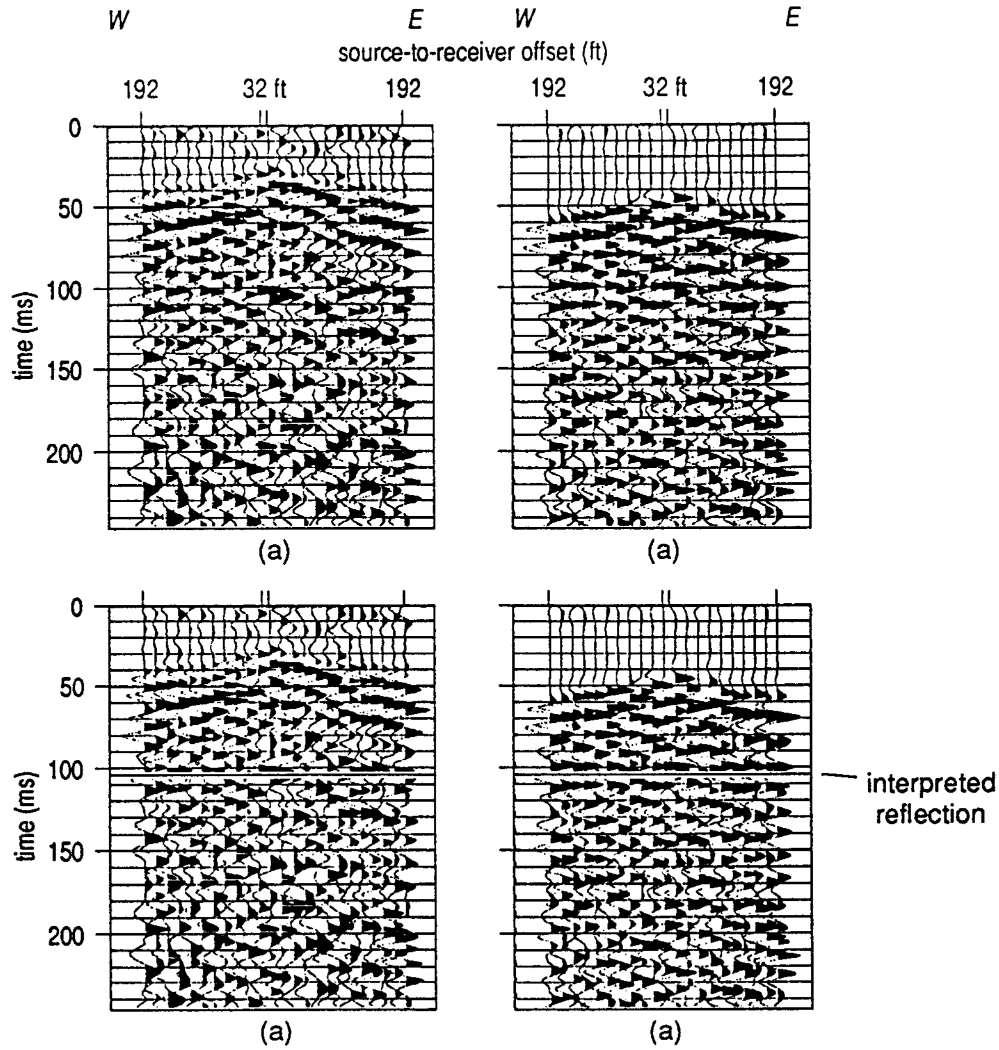

Figure 10) Split-spread field file from the production line a) with AGC b) is file a) filtered moved-out, scaled, and edited. Lower pair have the 100 ms reflection interpreted.

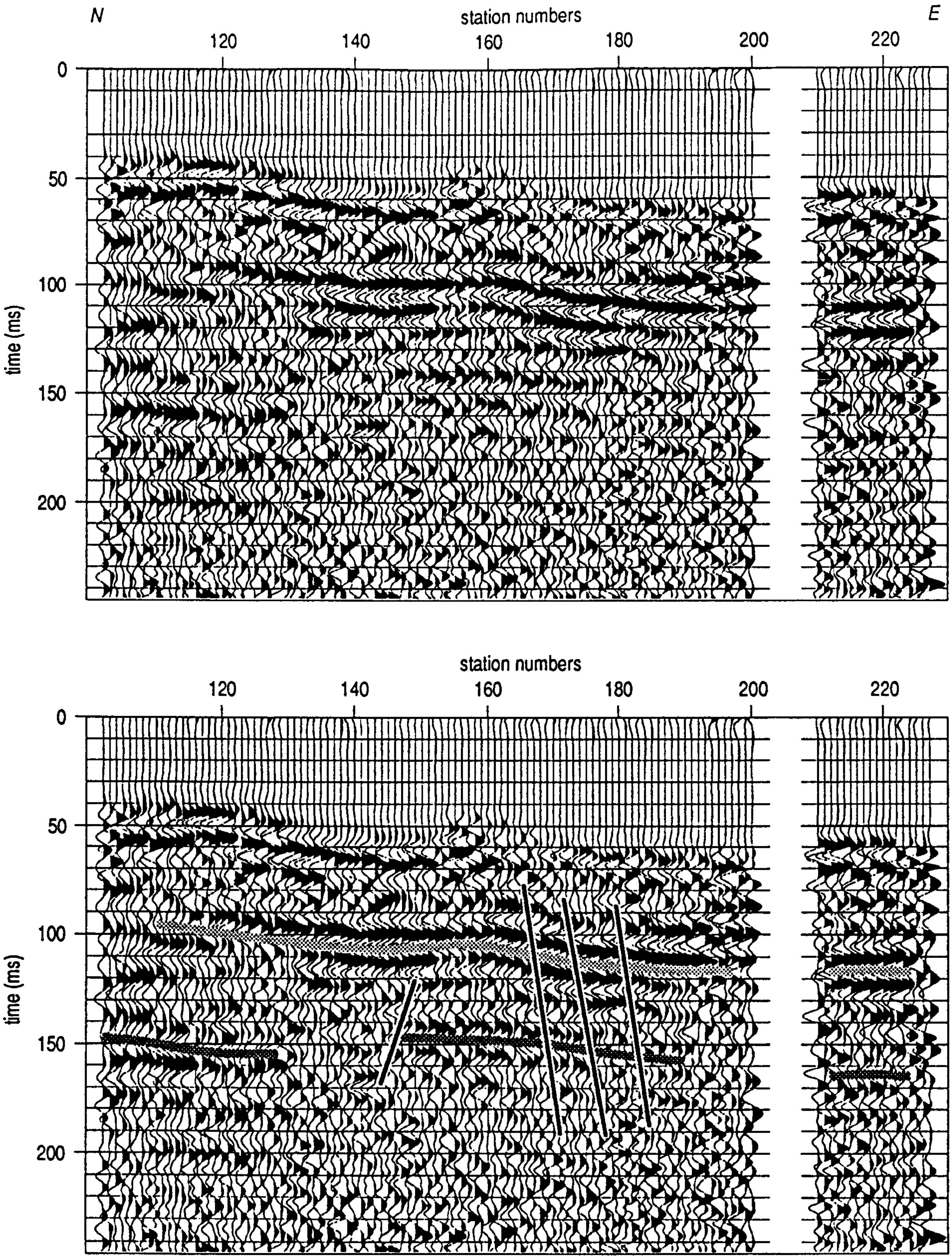

Figure 11) CDP stacked data a) with the reflection from 450 ft interpreted at 100 ms and a reflection from around 650 ft interpreted at around 140 ms b). The zone of faulting is indicated by the series of three apparent normal faults.

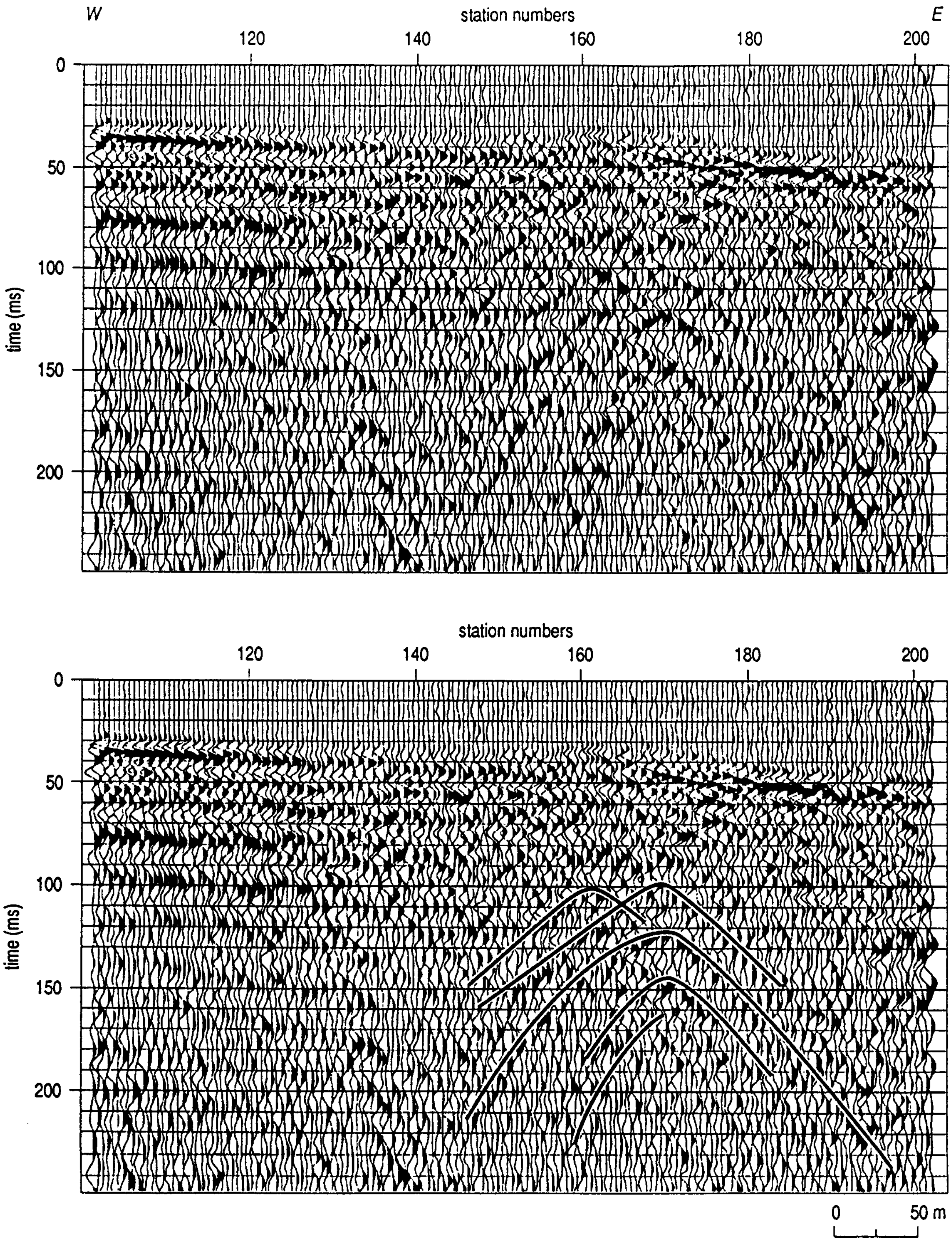

Figure 12) All traces with source-to-receiver offset of 97 ft filtered and scaled a) Diffraction b) interpretable on the common offset gather have apex from 165 to 175 at time from 50 to 140 ms.

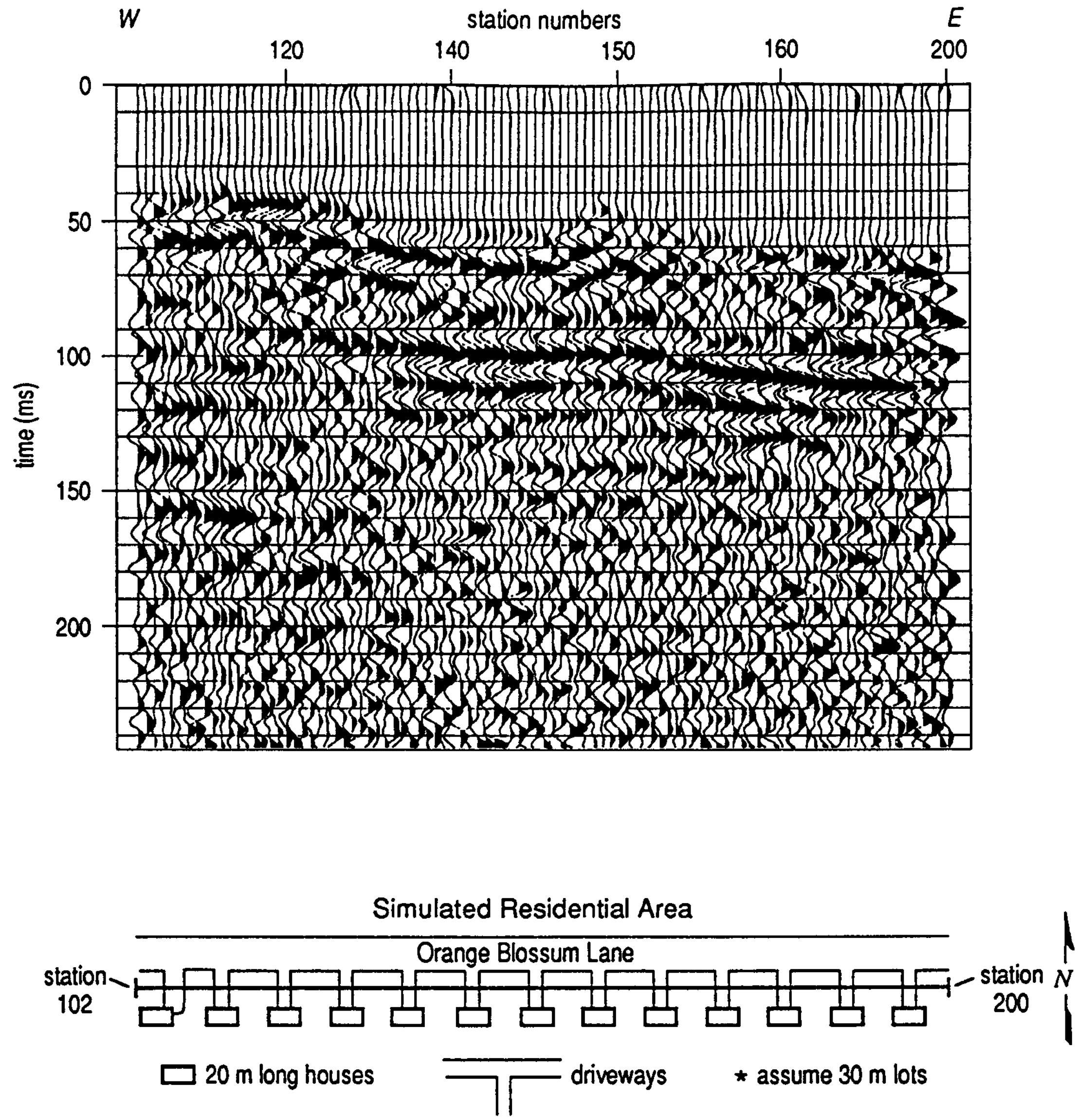

Figure 13) Data from figure 11 reprocessed deleting receiver and shot location that would have fallen on driveways of the simulated residential neighborhood. The data would have been interpreted almost identical to the stack section in figure 11.

APPENDIX A

3.46 Concepts of Seismic Reflection Prospecting

3.47 It is the purpose of this short appendix and the attached figures to describe basic principles and features of seismic reflection. The paper is intended primarily for those who have heard of seismic reflection but do not know how it works.

3.48 The seismic-reflection method is a powerful technique for underground exploration that has been in use for over 60 years. The revolution in microelectronics during the past ten years has resulted in the construction of new seismographs and microcomputers for data collection and processing that permit the cost-effective use of seismic reflection in a wide variety of applications that were not feasible previously.

3.49 Seismic-reflection techniques depend on the existence of discrete velocity and/or density changes in the subsurface. These discrete changes in either mass density or seismic velocity are known as acoustical contrasts. The measure of acoustical contrast is formally known as acoustic impedance, which is simply the product of mass density and the speed of seismic waves traveling within a material. In many cases, the acoustical contrasts occur at boundaries between geologic layers or formations, although man-made boundaries such as tunnels and mines also represent contrasts.

3.50 Compressional waves, or P-waves, are the most commonly used type of seismic wave for reflection prospecting. P-waves propagating through the earth behave similar to sound waves propagating in air. P-waves generate echoes (reflections) when they come in contact with an acoustical contrast in the air or under the ground. In the underground environment, however, the situation is more complex because energy that comes in contact with a solid acoustical interface can be transmitted across the interface or converted into refractions and/or shear waves as well as reflected waves.

3.51 Seismic reflection is sensitive to the physical properties of earth materials and is relatively insensitive to chemical makeup of both the earth materials and their contained fluids. The seismic-reflection technique involves no assumptions about layering or seismic velocity. However, no seismic energy will be reflected back for analysis unless acoustic impedance contrasts are present within the depth range of the equipment and procedures used. This is identical to the observation that sound waves in air do not echo back to an observer unless the sound wave hits something solid that causes an echo. The classic use of seismic reflections involves identifying the boundaries of layered geologic units. It is important to note that the technique can also be used to search for anomalies such as isolated sand or clay lenses and cavities.

3.52 The simplest case of seismic reflection is shown in Figure A-1. A source of seismic waves emits energy into the ground, commonly by explosion, mass drop, or projectile impact. Energy is radiated spherically away from the source. One ray path originating at the source will pass energy to the subsurface layer and return an echo to the receiver at the surface first. In the case of a single flat-lying layer and a flat-topographic surface, the path of least time will be from a reflecting point midway between the source and the receiver with the angle of incidence on the reflecting layer equal to the angle of reflection from the reflecting layer.

3.53 The sound receivers at the surface are called geophones and are essentially low-frequency microphones. The signals from the geophones are transmitted by seismic cables to the recording truck which contains a seismograph. The seismograph contains amplifiers that are very much like those on a stereo music system. The sounds from the earth are amplified and then recorded on digital computer tape for later processing and analysis. The purpose of the computer processing is to separate the echo sounds from other sounds to enhance them and to display them graphically.

3.54 In the real world, there are commonly several layers beneath the earth's surface that are within reach of the seismic-reflection technique. Figure A-2 illustrates that concept. The reader should note that echoes from the various layers arrive at the geophone at different times. The deeper the layer, the longer it takes for the echo to arrive at the geophone. The fact that several layers often contribute echoes to seismograms tends to make the seismic data more complex.

3.55 In the case of a multi-channel seismograph, several geophones detect sound waves almost simultaneously. Each channel has one or more geophones connected to it. Reflections from different points in the subsurface are recorded by various geophones. Note in Figure A-3 that the subsurface coverage of the reflection data is exactly half of the surface distance across the geophone spread. Hence, the subsurface sampling interval is exactly half of the geophone interval at the surface. For example, if geophones are spaced at 16-m intervals at the earth's surface, the subsurface reflections will come from locations on the reflector that are centered 8 m apart.

3.56 In Figure A-4 we have placed source locations and receiver locations in such a way that path S1–R2 reflects from the same location in the subsurface as path S2–R1. This is variously called a common-reflection point (CRP) or a common-depth point (CDP), depending upon the preference of the author. The power of the CDP method is in the multiplicity of data that come from a particular subsurface location. By gathering common midpoint data together and then adding the traces in a computer, the reflection signal is enhanced. Before this addition can take place, however, the data must be corrected for differences in travel time for the reflected waves caused by the differences in source-to-geophone distance. The degree of multiplicity is called CDP fold. A seismograph with 24 channels, for example, commonly is used to record 12-fold CDP data.

3.57 The seismic-reflection method is used to determine the spatial configuration of underground geological formations. Figure A-5 shows conceptually what we are trying to accomplish with such a survey. Note that the peaks of the seismic reflections have been blackened to assist in the interpretation. This example is a very simple version of typical near-surface geology that depicts a buried sand lens in a river valley. As the sand lens is moved to deeper layers below the surface, it becomes more difficult to detect, but the physical principles remain the same.

3.58 In an earlier part of this discussion, we briefly touched on the analogy between a seismograph and a stereo music system. A stereo music system has control knobs to enhance high frequencies (like a flute) or low frequencies (like a bass drum). A seismograph has similar capabilities in choosing the sound frequencies that are recorded. A seismologist selects the frequencies to be enhanced depending on the depth and size of the underground geologic features of interest.

3.59 In order to detect small geologic features, it is necessary to use a seismograph that can record and enhance the high-frequency sound waves. The use of high-frequency seismic waves in reflection seismology is known as "high-resolution" seismic exploration. As research and instrumentation developments allow recording higher and higher seismic frequencies, it is becoming possible to prospect for progressively smaller geologic targets.

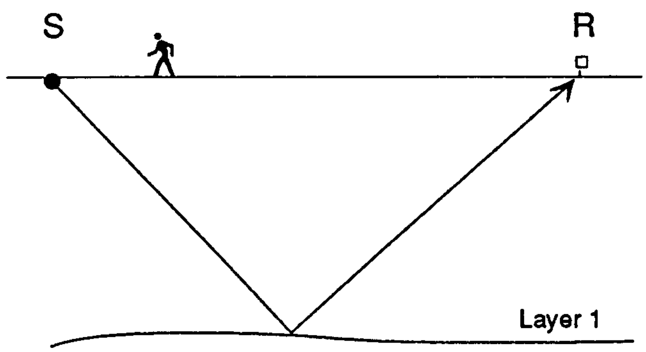

Figure A-1. Reflection from one layer

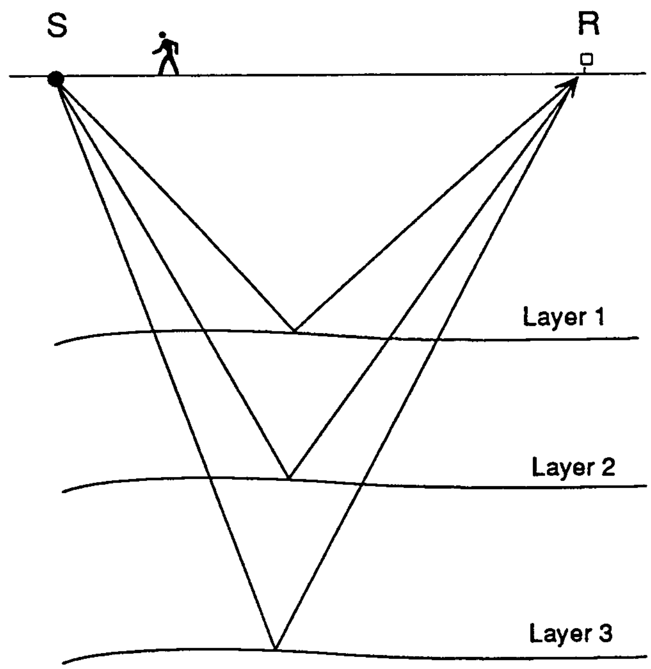

Figure A-2. Reflection from three layers

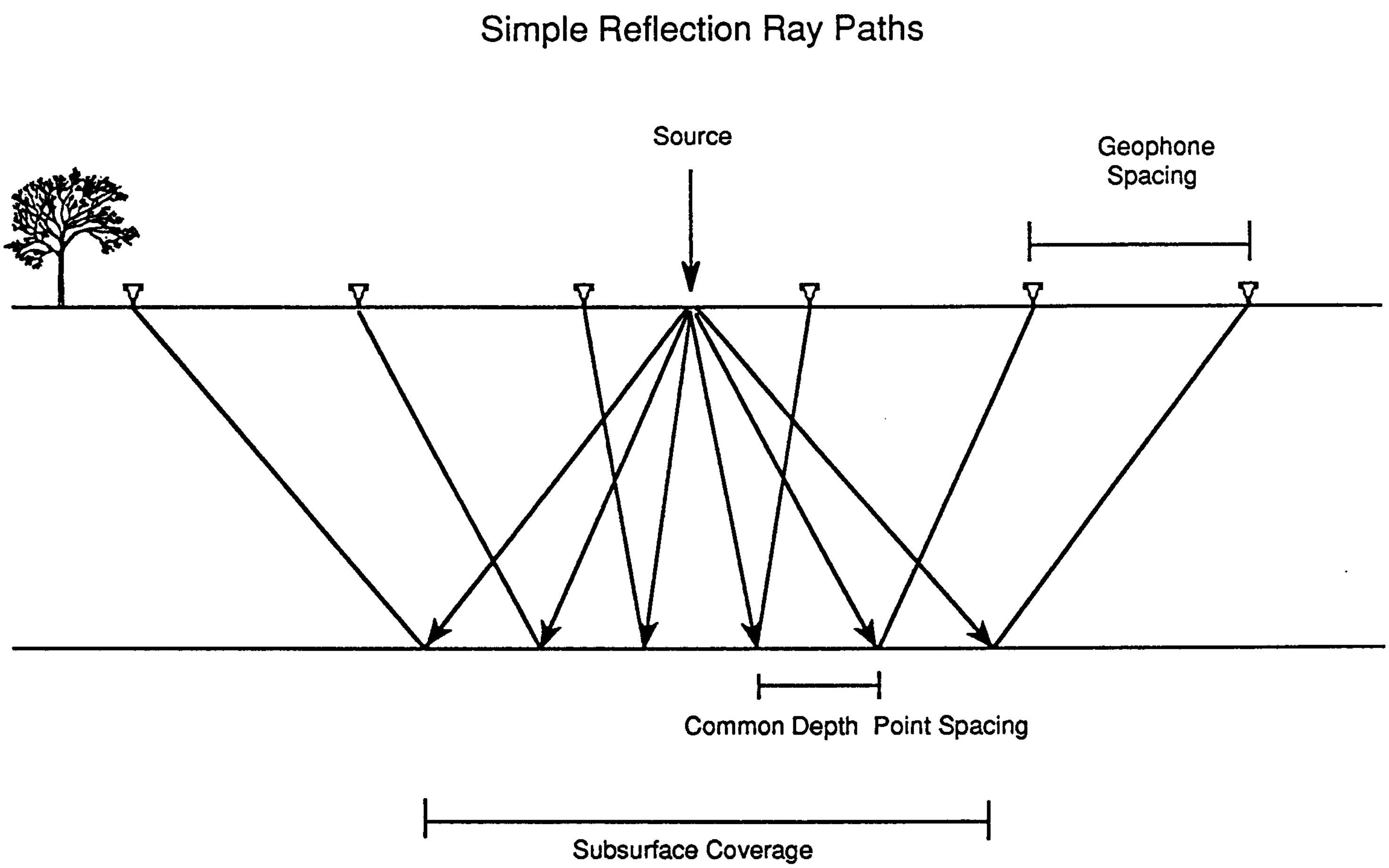

Figure A-3. Schematic drawing of seismic ray paths for a single shot with a six-channel reflection seismograph.

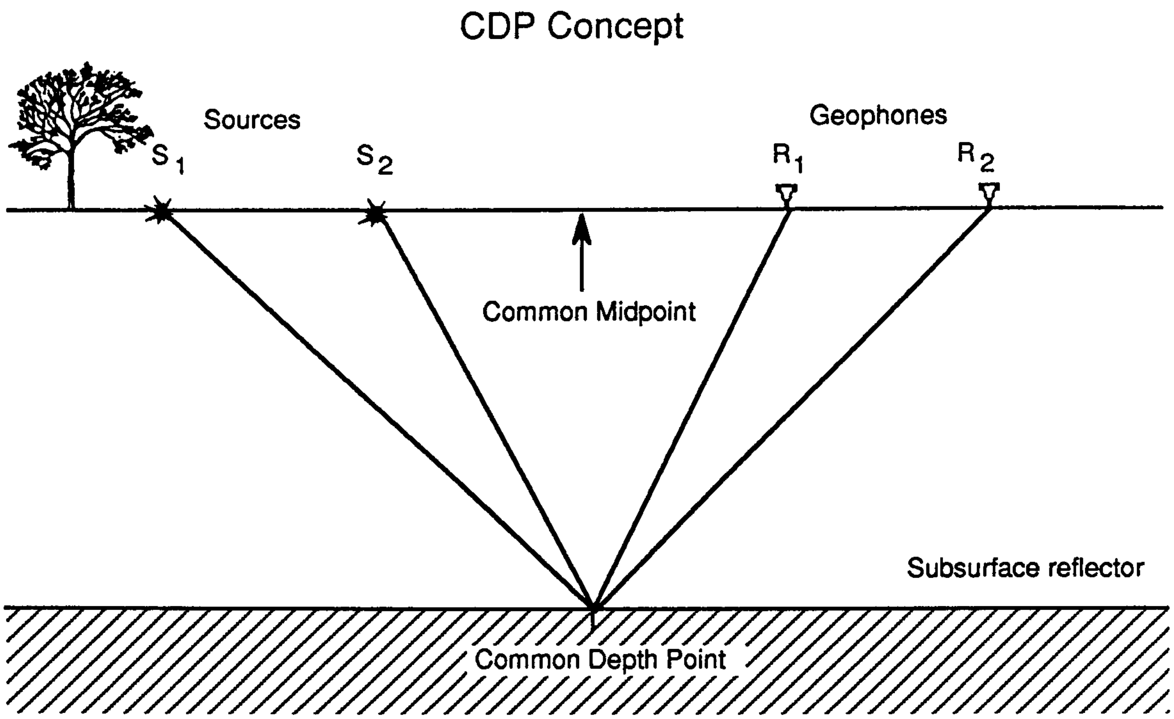

Figure A-4. The concept of Common Depth Point (CDP). Note that ray paths from two different shots (S_1 and S_2) reflect from a common point in the subsurface.

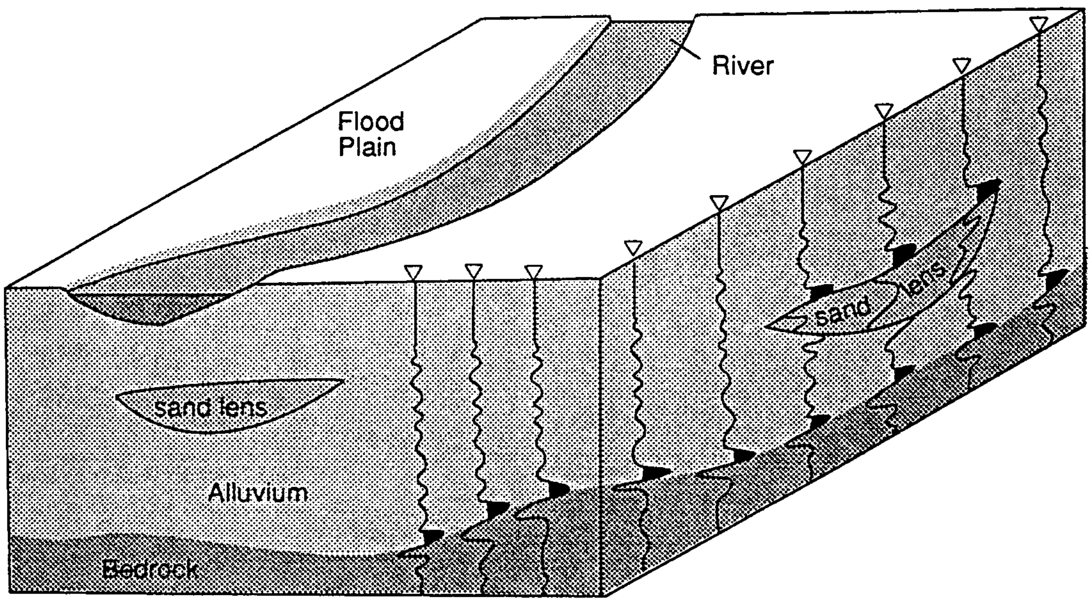

Figure A-5. Schematic showing a seismic section relating to real-world geology.

APPENDIX B

3.60 MiniSOSIE Recording Technique

3.61 Introduction

3.62 Most techniques and concepts described here are well documented in literature and are minor variations of work done in the geophysical industry for decades. The MiniSOSIE technique is an exception. The SOSIE technique was originally developed as a marine seismic source (Barbier and Viallix, 1973) and MiniSOSIE is its land adaptation. Most seismologists who see the technique in operation for the first time in the field don't immediately and intuitively understand how it can work, and we were also skeptical. Because MiniSOSIE is a relatively new (Barbier et al., 1976) and somewhat mysterious technique, we discuss it here. Understanding the MiniSOSIE method is important because of its unique application of fundamental geophysical principles and because it is a creative means of enhancing signal from a weak source. MiniSOSIE, or an adaptation of it, is a potential means of substantially improving shallow high resolution reflection seismology. Its weakness to date is related to limitations of the hardware that is licensed to use the method.

3.63 In the field, MiniSOSIE recording is done by summing signals from about 10 to 40 impacts per second from one or more civil engineering earth compactors known as Wackers (after the manufacturer of the most common earth compactors used). Typically, signals from 1,000 to 2,000 impacts are stacked at each shotpoint. The impacts are usually made along the seismic line over a linear segment equal to geophone group interval (i.e., a source array) rather than at a single point, and one to four Wackers are run simultaneously. Each Wacker has a transducer attached to its base plate and the transducer sends a time-break pulse by radio or wireline to the recording truck each time the Wacker base plate strikes the ground.

3.64 The mystery about MiniSOSIE is that typical seismic records are about 1s in duration, while the time between successive Wacker impacts is of the order of one-tenth of a second or less. Intuitively we know that the signals from successive impacts should interfere in an unpredictable and possibly noisy, if not destructive, manner. The key to the MiniSOSIE technique is overcoming this intuitive difficulty by having the seismograph perform a simple processing step in the recording truck during recording.

3.65 Real-time processing is done according to the following scheme:

3.66 Signal from a single impact = (source) * (earth function)

3.67 Signal from multiple impacts = (single impact) * (source input time series)

3.68 =(source) * (earth function) * (source input time series)

3.69 Recorded signal = (source) * (earth function) * (ACF time series) (1)

3.70 where "source" is the shape of an impulse pulse of energy transmitted into the Earth by an earth compactor impact, "earth function" is the reflection coefficient series of the earth and varies with geology, "source input time series" is the function defining the impact pattern of the impulses, "ACF time series" is the auto-correlation function of the time series of impulses from the Wacker base plates, and * is the convolution operator. This compares with conventional techniques (i.e., dynamite) where

3.71 Recorded signal = (source) * (earth function) (2)

3.72 Note that if "ACF time series" in equation (1) is a spike (i.e., an impulse or Dirac delta function), the recorded signals, equations (1) and (2), will be the same. MiniSOSIE acknowledges the fact that the auto-correlation function of a "random time series" is a spike and that convolution with a spike is essentially multiplication by unity. In essence, this is why MiniSOSIE works. The "random time series" is generated by randomly varying the engine speed (and, hence, the impact rate) of the Wackers. Correlation of the "signal from multiple impacts" and the "source input time series" is performed by the seismograph using a real-time processing procedure using a 20-bit micro-processor. The results are MiniSOSIE field data, equation (1), that look very much like dynamite field data, equation (2). Except for the unique energy source and the auto-correlation processing during recording, MiniSOSIE seismic recording is identical to conventional dynamite recording.

3.73 MiniSOSIE surveys have provided good high-resolution results at depths between 100 and 1,000 m in most localities (for example, Steeples et al., 1986; Miller at al., 1988). It is an especially good technique in areas of high ambient noise because most noise tends to cancel during the tens of seconds required to stack coherent signal from 1,000 or more Wacker impacts. This is particularly true for random noise (i.e., traffic and wind), but is also true for any noise type that does not correlate with the source input function (i.e., 60 Hz highline hum). Because the source input function is random, it is unlikely that any ambient noise source would synchronize with it.