FEASIBILITY OF SHALLOW SEISMIC REFLECTION METHODS NEAR THE RWMC AT THE IDAHO NATIONAL ENGINEERING LABORATORY (INEL)

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INTRODUCTION

This report presents the common depth point (CDP) processed seismic reflection data we collected south of the RWMC and our interpretation of the data (Fig. 1). It also includes our conclusions and recommendations for future use of the shallow-reflection technique as a tool to assist with subsurface geologic interpretation of the area around the RWMC. The general format of the first four sections of this paper is technical, but directed at engineers, geologists, physicists, and others with general technical backgrounds. Appendix A was written to give a basic overview of the seismic-reflection method to those unfamiliar with seismology. Appendix B is the geophysically technical portion of this report intended to specifically describe the procedures and steps followed from acquisition through processing.

Detailed knowledge of shallow subsurface layers is often needed to evaluate waste sites. Identifying contaminant migration paths in the subsurface assists in developing effective monitoring procedures. Data possessing the necessary detail for mapping of shallow structures has generally come from extensive drilling programs which are both time consuming and expensive. High-resolution seismic-reflection profiling has been used to image surfaces as shallow as 3 m and resolve beds as thin as 1 m in a variety of near-surface geologic settings (Doornenbal and Helbig, 1983; Birkelo et al., 1987; Myers et al., 1987; Branham and Steeples, 1988; Miller et al., in press). The seismic reflection technique has the potential to produce the necessary detail to allow identification of structural extremes in an intra-layered basalt/sand environment as shallow as 10 m.

The use of seismic-reflection techniques to map shallow layers in the repetitive basalt/sand environment of the eastern Snake River Plain has been successful in the 75- to 450-m depth range (Miller et al., 1988). Using conventional seismic-reflection techniques, separating reflections shallower than about 30 m from other energy arriving in the early portions of the seismogram has been difficult in any geologic environment (Steeples and Miller, 1986). The amplitude of shallow-reflected energy at commonly recorded frequencies, when present, is usually smaller than the amplitudes of unwanted noise, particularly ground roll, refractions, air-coupled waves, and direct waves. Detection of shallow-reflection events on seismograms requires closely-spaced source-to-receiver geometries, severe analog low-cut filtering, a suitable high-frequency seismic source, and a seismograph with quiet amplifiers and A/D conversion into a large digital word (Knapp and Steeples, 1986a,b). These criteria allow a minimum of unwanted noise energy to be recorded which, in turn, allows identification of variable and/or subtle shallow reflectors obscured when using more common seismic-reflection procedures.

GEOLOGIC SETTING

The study area is located within the central/eastern Snake River Plain between Arco and Idaho Falls, Idaho. The Snake River Plain is a depression which is filled with several thousand meters of basalt, rhyolite, and sediments of late Cenozoic age. In some areas within the Snake River Plain, as much as 1 km of interbedded basalt and sediments lies on top of older, rhyolitic volcanic rocks (Walker, 1964). The basalt flows in the upper 150 m of the eastern Snake River Plain are mostly compound pahoehoe flows, 3-to-5-m thick, interbedded with numerous, usually thin, layers of sediments. These sediments are mostly clay and sand with occasional gravel and loess deposits.

The seismic data were collected along one 500-m long line extending from about 50 m south of the SDA perimeter fence to approximately 50 m south of well 88 (Fig. 1). Well 88 is located at station number 129 (CDP 258) at the south end of the line. The surface material along the 500-m-long line varied from fine sand to basalt with a modest stand of sage brush. The multiple basalt outcrops along the line represented a potential problem maintaining consistent source and receiver coupling to the ground. Due to the rough and variable surface terrain, the geophones were planted in the base of the road ditch and the source was fired on the road shoulder nearest the geophones. This allowed for consistent source- and receiver-coupling to ground from station to station and minimized site logistic problems associated with the outcropping basalt.

RESULTS

The key to interpreting true geologic structures or stratigraphy from processed CDP shallow seismic data is the clear identification of reflection energy on raw, unprocessed field files. The hyperbolic time-distance moveout of reflection energy can be identified on most field files across the entire line (Fig. 2). The raw field file from near well 88 has several relatively strong reflection arrivals. The event at approximately 55 msec is interpreted as a reflection from the sedimentary layer at about 30 m on the geophysical logs of well 88 (Fig. 3). Due to the extreme variability of the geology along the line, correlating that reflection event from field file to field file is impossible over a horizontal distance of more than about 30 m. The velocity, apparent structure, and general reflection character of the seismic data on the raw field files lack lateral consistency. The general variability in the raw data emphasizes the need for care during the computer processing of data.

The dominant frequency of much of the raw data is easily in excess of 150 Hz. Using a one-forth wavelength minimum vertical resolution criterion (Widess, 1973) and a normal moveout velocity of 1000 m/sec, vertical bed resolution is on the order of 1.7 m. The horizontal sampling interval was 0.5 m, providing over 15 samples within the first Fresnel zone, surpassing the suggested 4 sample minimum of Knapp and Steeples (1986b). Minor distortion in interpreted geologic structure can occur in some situations as a result of oversampling the first Fresnel zone (Myers et al., 1987). The geologic setting, in association with the characteristics of the seismic data, suggests that the effects of the defocusing of reflected seismic energy as a result of oversampling, could cause some minor smoothing of interpreted geologic structure at this site.

The geologic cross-section, derived from the refraction information, was used to correct the inconsistent thickness/average-velocity of the near-surface layer (Fig. 4). A total of over 70 reversed refraction shots were recorded to generate the interpreted cross-section. The very short wavelength undulations (less than approximately 30 m) in the refraction-derived bedrock surface were smoothed in order to concentrate the refraction static operation on the long wavelength static inconsistencies. The average interval velocity of the weathered layer was calculated to be approximately 500 m/sec overlying an approximately 2000 m/sec bedrock. The refraction data indicates a maximum slope on the bedrock surface on the order of 11 degrees.

The processing flow of the reflection data involved separating out the high-confidence reflection information identifiable on field files from noise and questionable reflections. The result of this flow was three CDP stacked sections for both shot one and two—one with predominantly noise, one with reflections only, and then a rejoined reflections-and-noise section. The rejoining process was necessary to insure that contributions from subtle reflection information, not easily identifiable on the raw field files, were considered during the interpretation process. The interpretation process involved coordination of all the CDP stacks into a geologic cross-section that was consistent with all the reflection information.

Two .50-caliber rifle shots were fired into the same hole and recorded separately at each station location. The second shot was recorded in hopes of boosting the total recorded energy and increasing the dominant frequency. In some near-surface environments, the seismogram of the second shot fired into the hole of the first will possess as much as 6 dB greater reflection information and 20 Hz higher dominant frequency. Increases on the order of 10 Hz in dominant frequency and 3 dB in total source energy were observed at this site. Increases on this order, in this marginal seismic reflection environment, were deemed worthy of the two-shot procedure.

The stacked reflection-only sections of shots one and two are relatively consistent (Figs. 5 and 8). Correlating the two stacked sections (shots #1 and #2), a coherent reflector can be identified at about 40 msec that traverses the entire section. The relatively consistent and unique stacking velocity of this coherent event allows it to be interpreted by either velocity or phase. Slight horizontal frequency variations noticable in the reflection wavelet at various places across the line,result from a combination of inconsistent source-and-receiver coupling to the ground and nearly instantaneous variations in the near-surface material. The geophysical logs of well 88, which tie to the line at CDP 257, suggest an approximately 3-to-4-m thick sedimentary layer at about 30 m. The highlighted reflector correlates to the sedimentary unit identifiable on the logs on the basis of stacking velocity and calculated approximate depth.

The stacked sections (Figs. 7 and 10), with the reflection and noise portions processed separately and then recombined, were correlated with the reflection-only stacks (Figs. 5 and 8) to more accurately interpret the reflection data. The reflection-only data were a critical guide for maintaining a consistent interpretation and reducing the possibility for cycle skipping or misidentification in low signal-to-noise areas. Many subtleties not observable on the reflection-only stacks were interpreted using this correlation process. Correlating the two data sets also more clearly indicated areas where more processing work was necessary. The overall effect of the correlation process was to improve the confidence in the final interpreted sections.

The stacked reflection sections are all of sufficient quality to confidently interpret the sedimentary layer at 30 m (Figs. 5, 7, 8, 10, 11, 12). The acquisition and processing of this entire data set was focused on recording and enhancing the sedimentary layer reflector identified on field files at about 50 msec. (This reflection occurs at about 40 msec after static correction on the stacked sections.) The obvious reflections present on the stacked sections are restricted to a relatively narrow time window between about 30 and 70 msec. This narrow time-window appearance of the data is due to the very precise acquisition and processing parameters and the limited dynamic range and number of acquisition channels of the seismograph.

The apparent major long-wavelength synclinal structure and the multiple localized structural lows observable in the 40-msec-deep sedimentary layer, are either real geologic features or processing artifacts (Fig. 12). The long-wavelength synclinal structure located between CDP's 250 and 860 has a maximum relative depth of about 15 m. The multiple apparent localized structural lows, generally are no more than 20 to 30 m across, have a maximum relative depth of no more than 10 m. Any structure interpretable on the stacked sections that appears to mimic the refraction-derived bedrock map and the stacked refraction arrivals on the processed noise sections are probably artifacts of the refraction statics process. In order to simplify the refraction statics process sufficiently to make it a practical tool, it was necessary to assume that the near-surface velocity (weathered layer) was consistent horizontally. This assumption in such an acoustically variable area may not be physically valid and has probably resulted in incorrect time compensation for the weathered layer at various places along the line. Direct extrapolation of time on the seismogram to depth on the geologic cross-section is strongly influenced by the refraction-statics operation. Structural interpretations directly from the seismograms cannot be confidently made without additional drill information.

Frequency and phase anomalies at several places on the seismogram inhibit attempts to confidently correlate the sedimentary reflector across the line (Fig. 12). Between CDP 350 and 400 and 625 and 700, the reflection frequency varies as much as 25%, making correlating through the area spectulative. Abrupt horizontal variations in phase angle of as much as 120 degrees in correlated reflection arrivals are observable at CDP's 200, 525, 770, and 975. Either near-surface variations or changes in the geology at or near the depth of the reflector are responsible for these phenomina. Without drilling information, confident determination of the geology in these areas, and therefore the source of the phase and frequency distortion, cannot be identified.

Much of the slightly disjointed appearance of the reflector is a result of the extreme fluctuation in the stacking velocity from point to point. The overall coherency and the consistent appearance of the event on all the various processed sections supports the overall geologic interpretation.

CONCLUSIONS

1. The seismic-reflection method was successful in detecting a 3-to-4-m-thick sedimentary layer at 30 m of depth within a thick basalt/sand sequence. Extreme lateral variations in velocity and geology were evident on the seismic data making absolute depth calculations impossible. Associated with and possibly related to the velocity variability was the substantial variation in thickness of the near-surface unconsolidated layer.

2. Based on refraction calculations, the near-surface unconsolidated layer varies in thickness from zero to approximately 8 m. While the seismic surveys of this report were not designed to detect reflections from the base of the near-surface layer, it would be possible to detect them with shot and geophone intervals of about 1/4 m.

3. The frequency of the seismic data was higher than expected, which helps resolution. We had not expected to obtain frequencies above 100 Hz, but substantial energy is present in the 150- to 200-Hz range.

4. On some of the intermediate processed sections (not shown), there are hints of a deeper reflection at about 65 msec. This is about the right time for the sedimentary layer at 70-m depth seen in well 88. It may be feasible to map that reflector with a seismic-reflection survey designed to look deeper than 30 m.

5. The reflections that are easily visible on some of the field files are of exceptional quality. The extreme variation in quality and seismic character of the field files along the seismic line is uncommon for such short distances. We attribute this to the complicated composite depositional structure of the basalt flows.

6. This seismic survey was designed specifically to map the sedimentary reflector at a depth of about 30 m. We were successful in that effort. It would be possible to design surveys to examine deeper or shallower reflectors, if necessary.

7. We recommend that shallow seismic reflection be used in conjunction with a limited drilling program to help evaluate geologic structure and stratigraphy in and near the RWMC at INEL.

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FIGURE CAPTIONS

Figure 1 Site map indicating the approximate location and orientation of 500-m-long seismic reflection line and associated refraction profile. The location of well 88 is also indicated on the map. Base map was provided by EG&G.

Figure 2 Raw field files from various places along the seismic line. The cross-section of the surface topography on the top of the figure has the approximate surface locations of the shots fired for the included field files. From a seismic character point of view, the field records appear to have been recorded at geologically unrelated sites. These seismograms clearly indicate the magnitude of the variability in the near-surface.

Figure 3 Graph of well construction and geophysical logs for well 88. Provided by EG&G.

Figure 4 This interpreted cross-section was derived from refraction data. A dipping 2-layer model was used to formulate the cross-section. The actual values used to remove the effects of the near-surface unconsolidated sediments were approximately a 30-m running average of the plotted values.

Figure 5 The 12-fold CDP stacked data of shot #1 displayed here are the result of a severe surgical mute extracting only the high confidence reflection data at each location. The surface-consistent statics tables as well as the velocity function were formulated using this data set.

Figure 6 These 12-fold CDP stacked seismic data are what remained of shot #1 after the reflection data were extracted. The processing flow used on these data was identical to that used on the data in Figure 5.

Figure 7 This is the result of combining the two data sets (Figs. 5 and 6). This 12-fold stack possesses reflection information that was processed independently of the noise. This final stacked section had its processing parameters designed around true reflection energy.

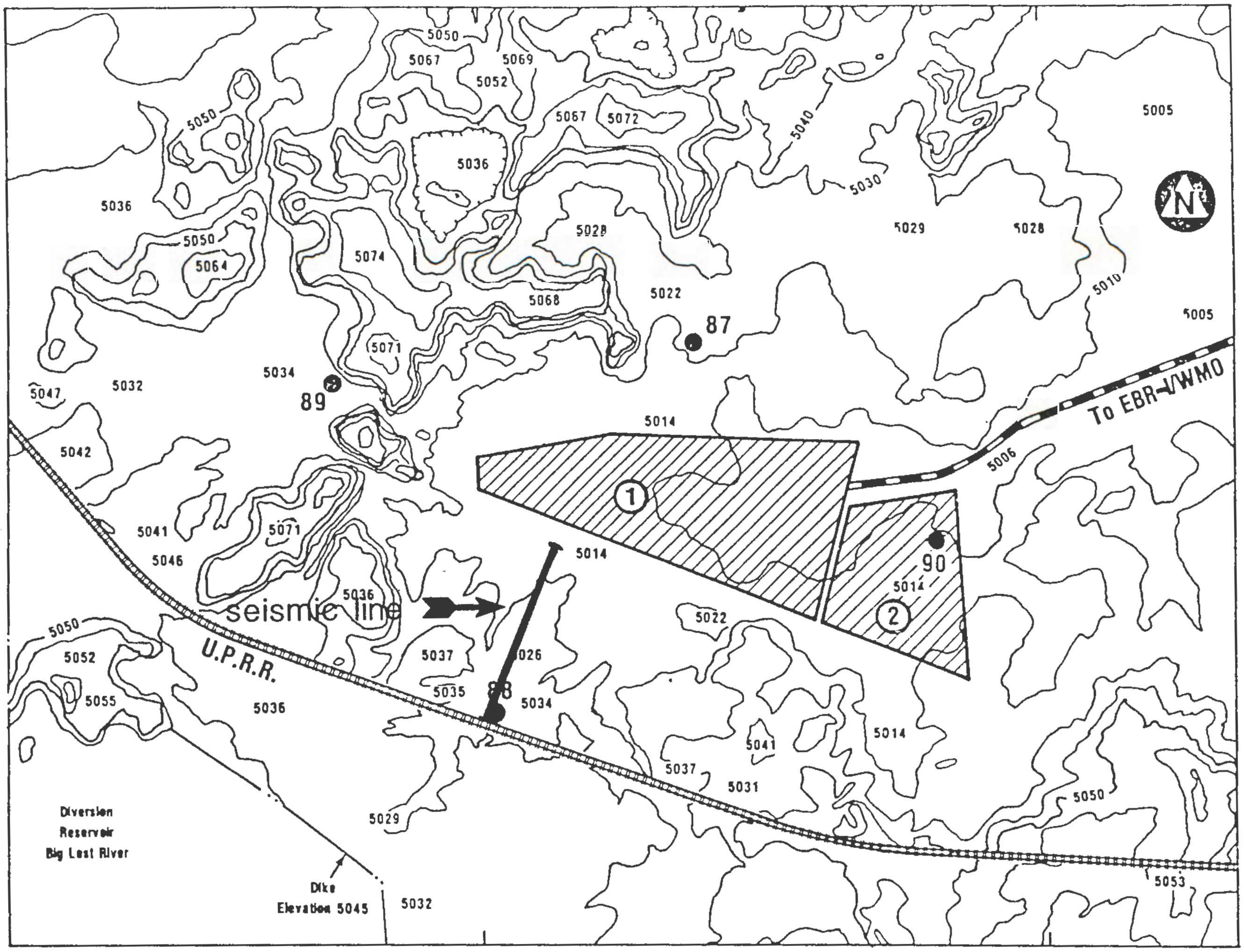
Figure 8 The 12-fold CDP stacked data of shot #2 displayed here are the result of a severe surgical mute extracting only the high-confidence reflection data at each location. The surface-consistent statics tables and the velocity function were formulated using this data set.

Figure 9 These 12-fold CDP stacked seismic data are what remained of shot #2 after the reflection data was extracted. The processing flow used on these data was identical to that used on the data in Figure 8.

Figure 10 This is the result of combining the two data sets (Figs. 8 and 9). This 12-fold stack possesses reflection information that was processed independently of the noise. This final stacked section had its processing parameters designed around true reflection energy.

Figure 11 This is the result of combining all data from shots 1 and 2, without residual statics correction.

Figure 12 These are the data of Figure 11 after a residual static correction. The lower half of the figure shows our interpretation of the top of the sedimentary layer. The residual static process was done after CDP stack, and time-shifts were limited to 2 msec, which is about 1/3 of the period of the dominant wavelets. The residual static process was done for cosmetic purposes to emphasize our interpretation of the data.



0 1000 2000 feet

Notes: Contour Interval 10 feet. Datum is Sea Level.
Observation Well (•) and number (87,88,89, and 90)
Tapping the Snake River Plain Aquifer

① Subsurface Disposal Area (SDA)

② Transuranic Storage Area (TSA)

Figure 1

Radioactive Waste Management Complex

Topography

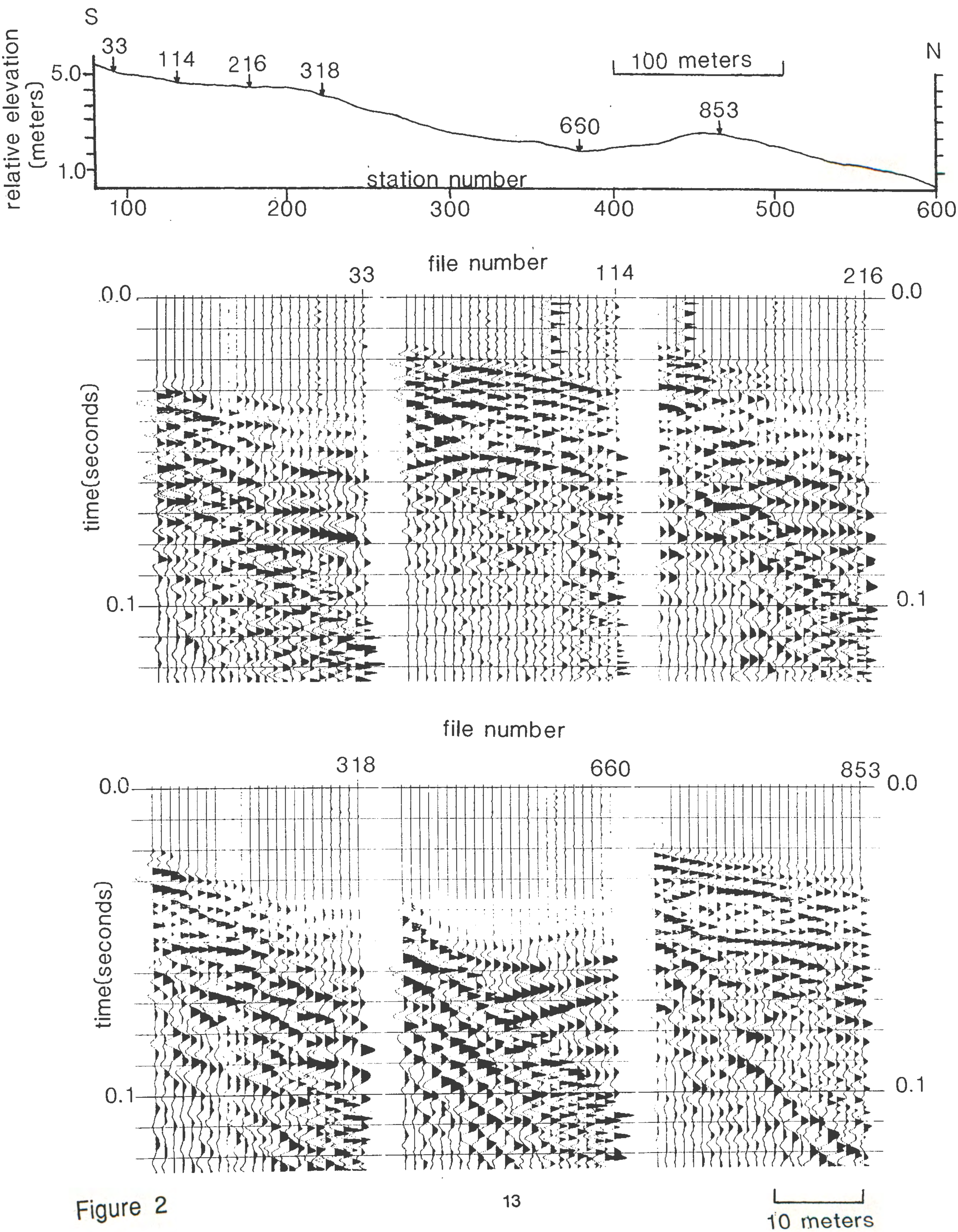

S
N
33
114
216
318
660
853
100 meters
relative elevation (meters)
5.0
1.0
station number
100
200
300
400
500
600
file number
33
114
216
0.0
0.1
time(seconds)
file number
318
660
853
0.0
0.1
time(seconds)
10 meters

Figure 2

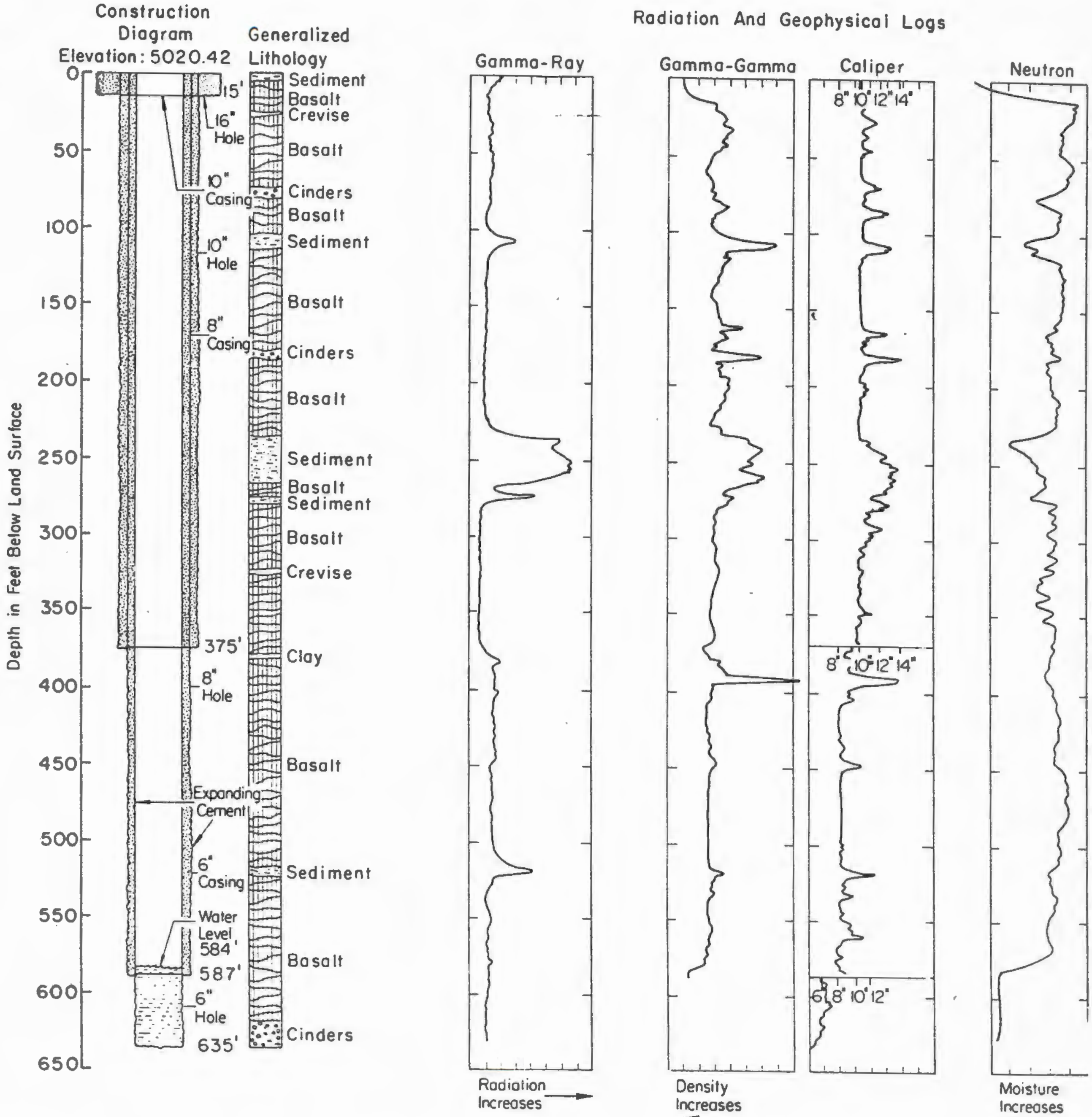


Figure 3 Graphs showing well construction, geology, and geophysical logs for well 88.

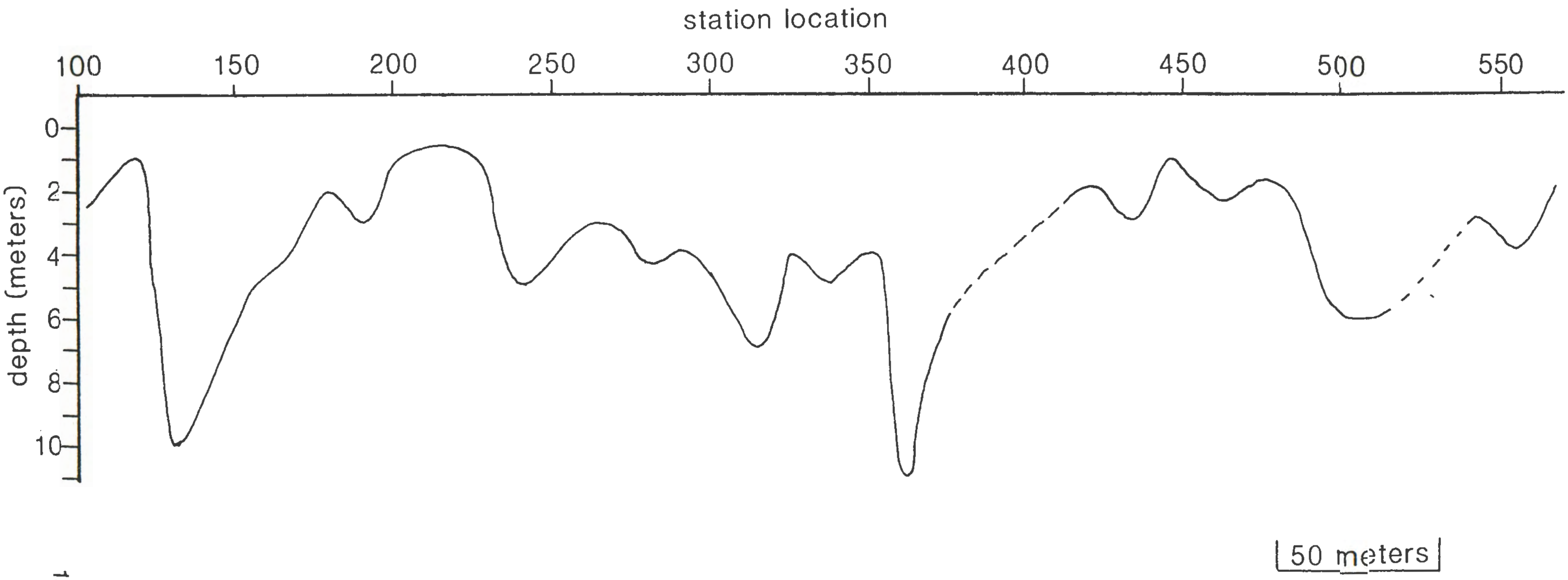

station location
100
150
200
250
300
350
400
450
500
550
depth (meters)
0
2
4
6
8
10
50 meters

Figure 4

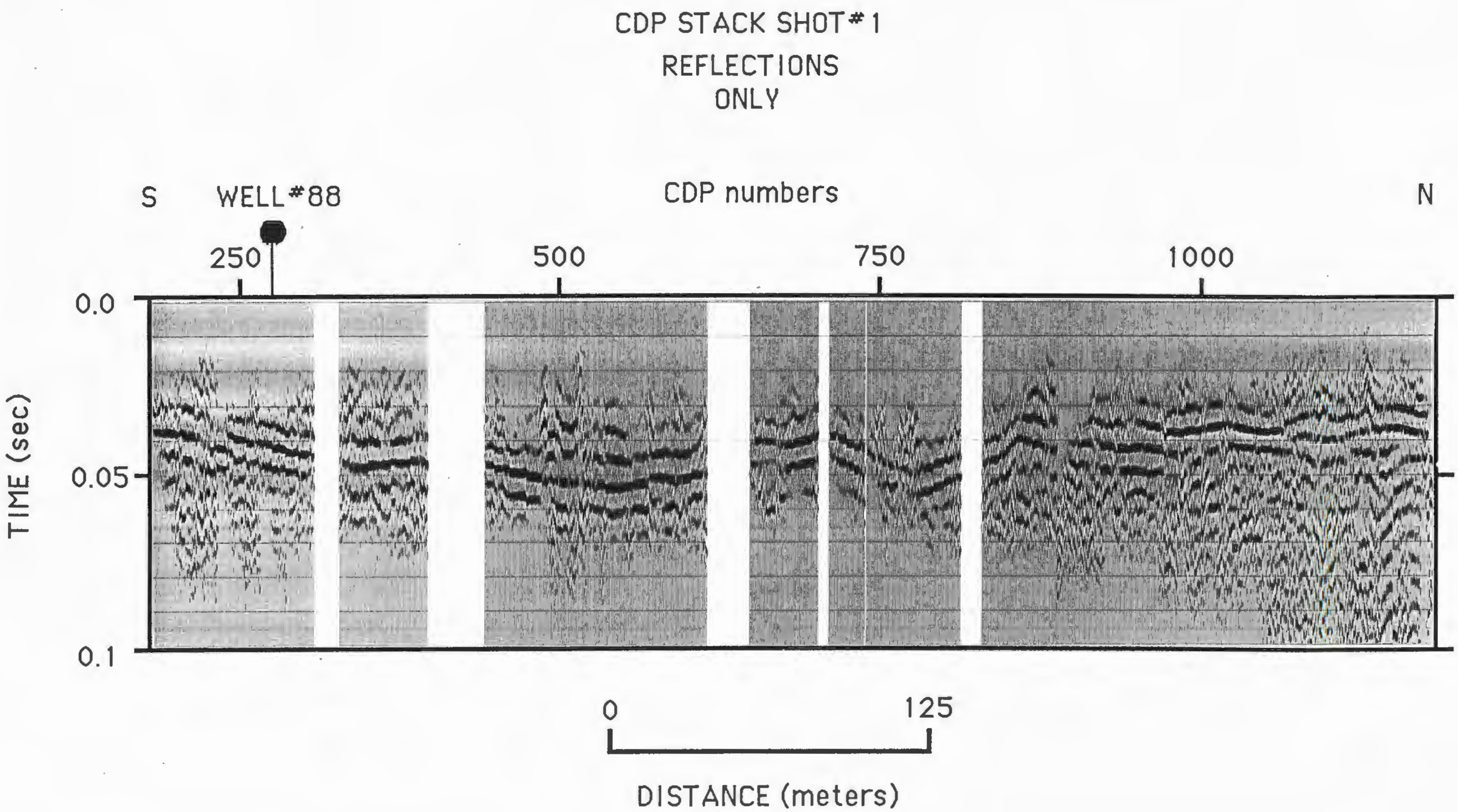

CDP STACK SHOT#1
REFLECTIONS
ONLY
S
WELL#88
CDP numbers
N
250
500
750
1000
0.0
0.05
0.1
TIME (sec)
0
125
DISTANCE (meters)

Figure 5

CDP STACK SHOT # 1
NOISE AFTER
REFLECTIONS
REMOVED

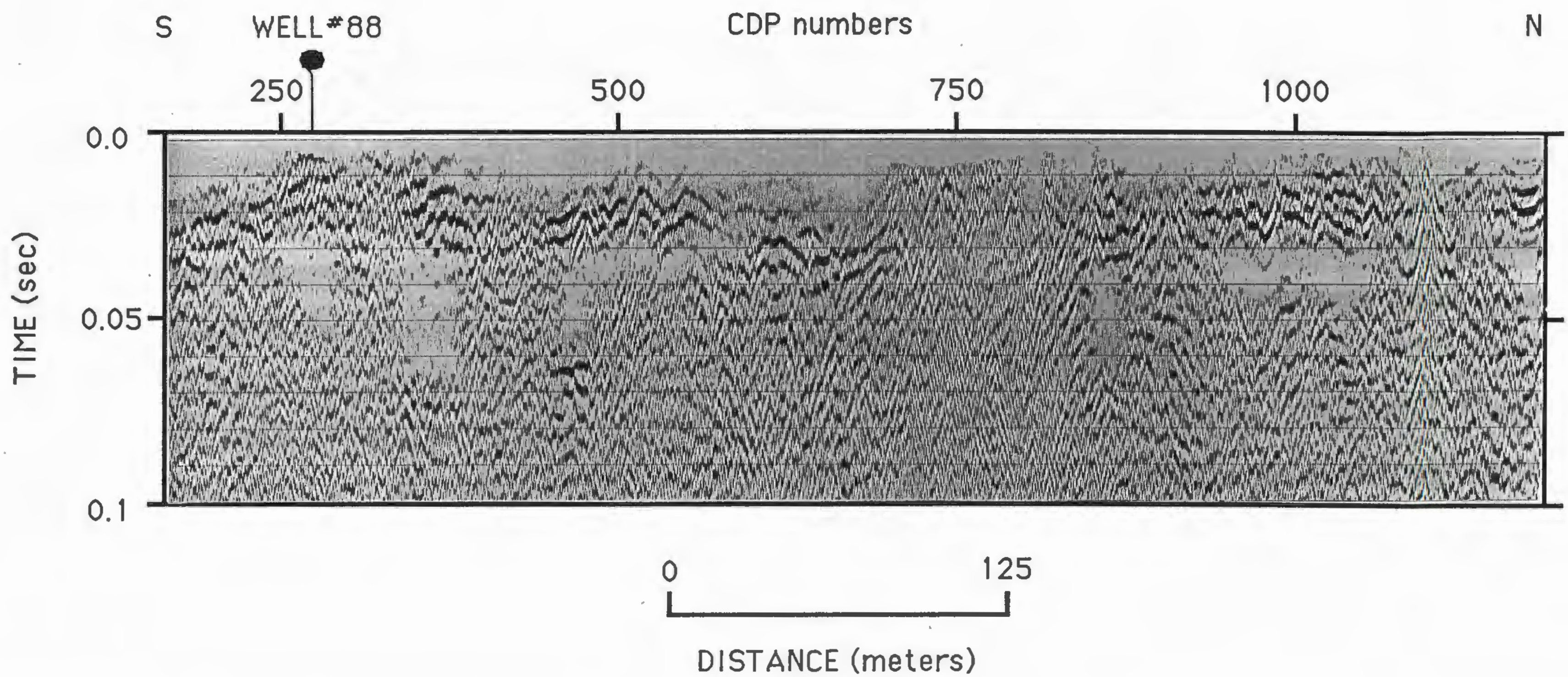


Figure 6

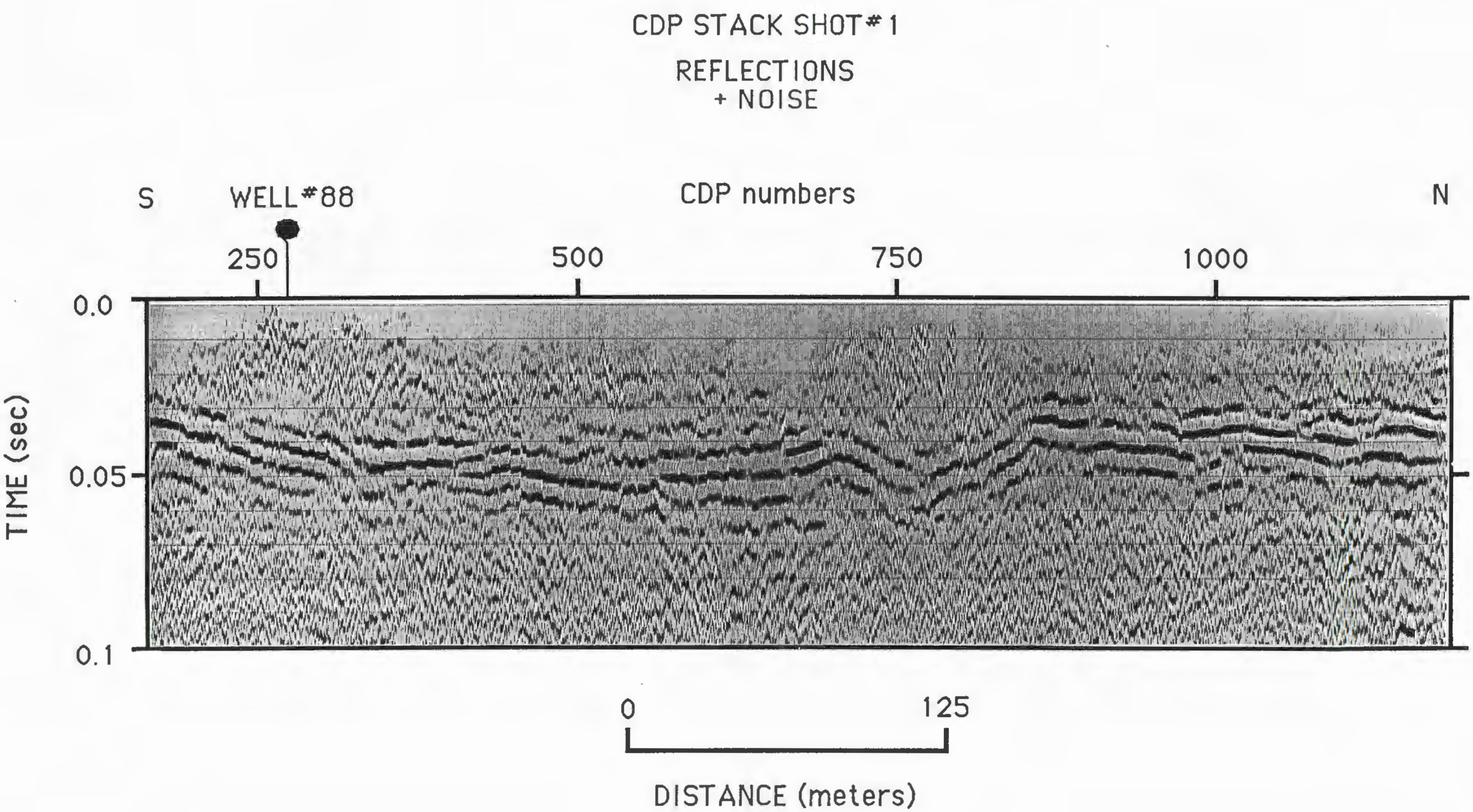
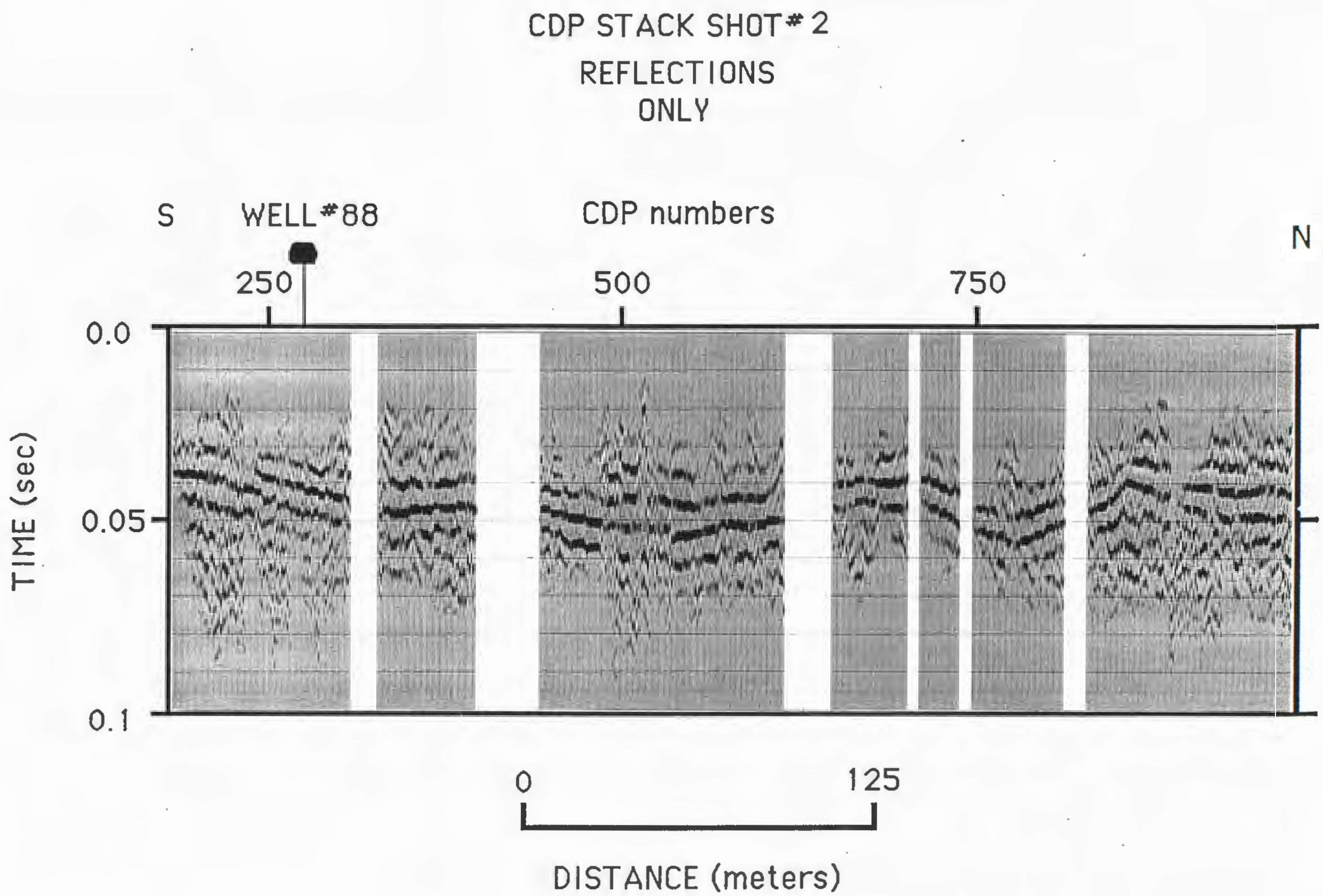

CDP STACK SHOT#1
REFLECTIONS
+ NOISE
S
WELL#88
CDP numbers
N
250
500
750
1000
0.0
0.05
0.1
TIME (sec)
0
125
DISTANCE (meters)

Figure 7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REFLECTIONS
ONLY
S
WELL#88
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750
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0.05
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TIME (sec)
0
125
DISTANCE (meters)

Figure 8

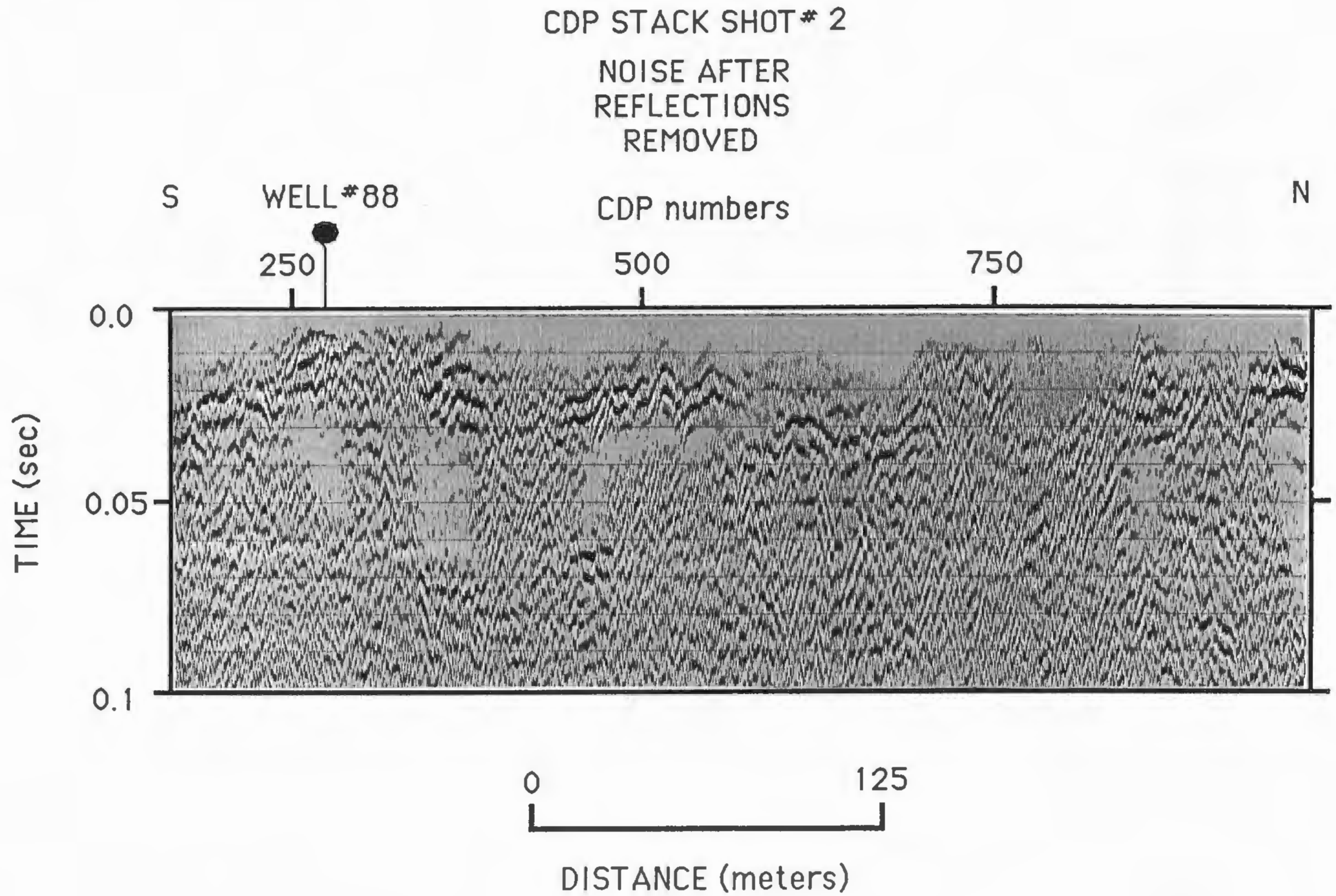

CDP STACK SHOT # 2
NOISE AFTER
REFLECTIONS
REMOVED
S
WELL # 88
CDP numbers
N
250
500
750
0.0
0.05
0.1
TIME (sec)
0
125
DISTANCE (meters)

Figure 9

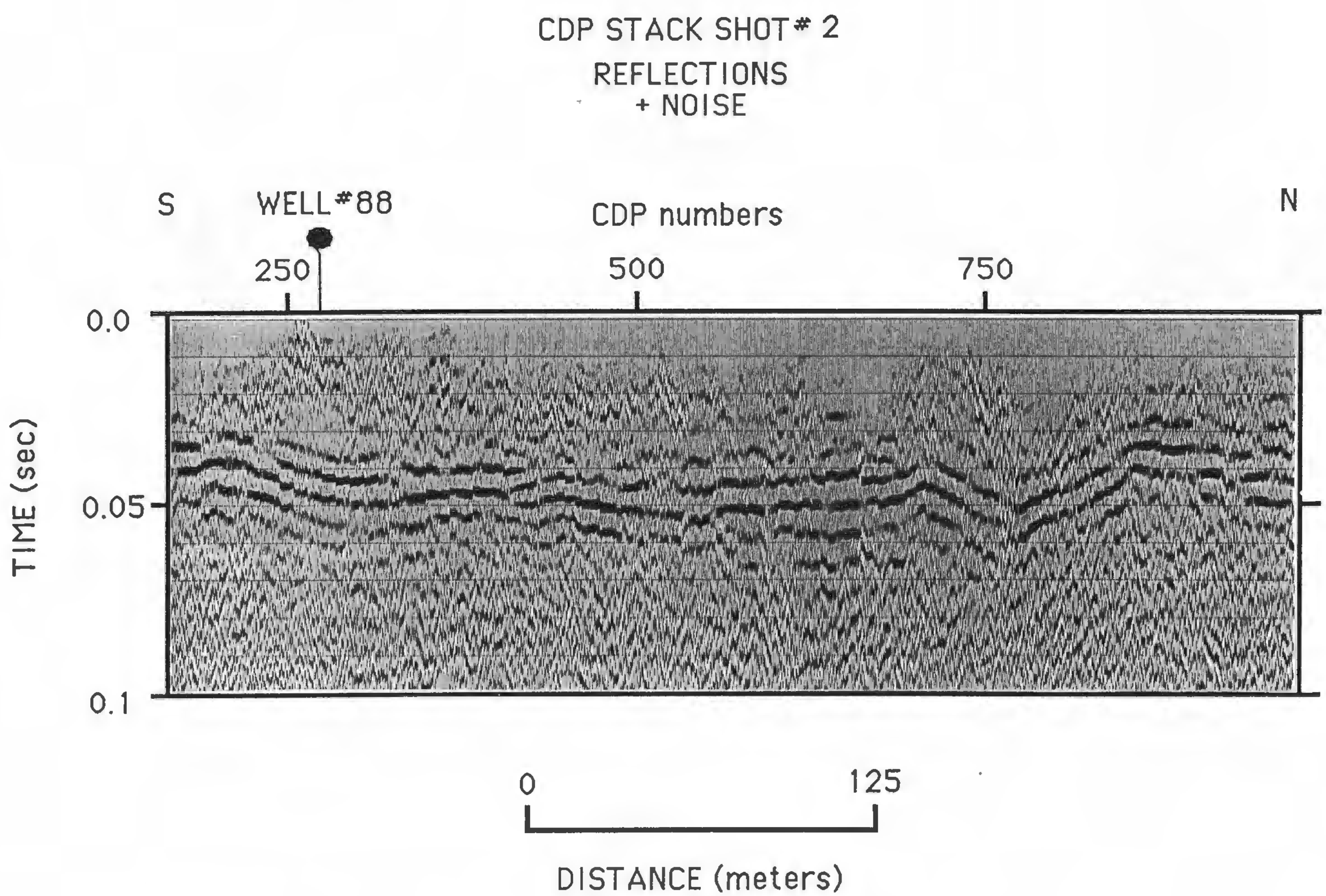

CDP STACK SHOT# 2
REFLECTIONS
+ NOISE
S
WELL#88
CDP numbers
N
250
500
750
0.0
0.05
0.1
TIME (sec)
0
125
DISTANCE (meters)

Figure 10

CDP STACK SHOT#1 + SHOT#2

REFLECTIONS
+ NOISE

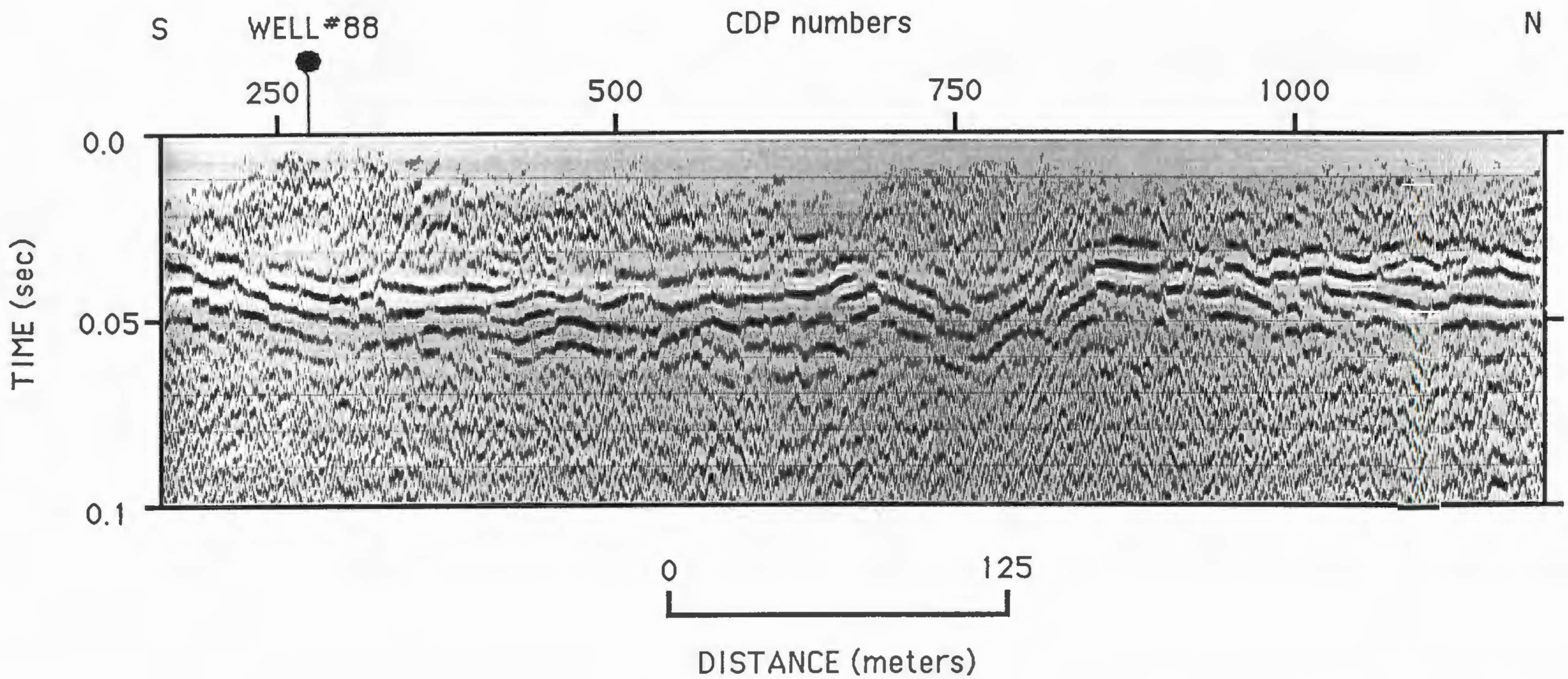


Figure 11

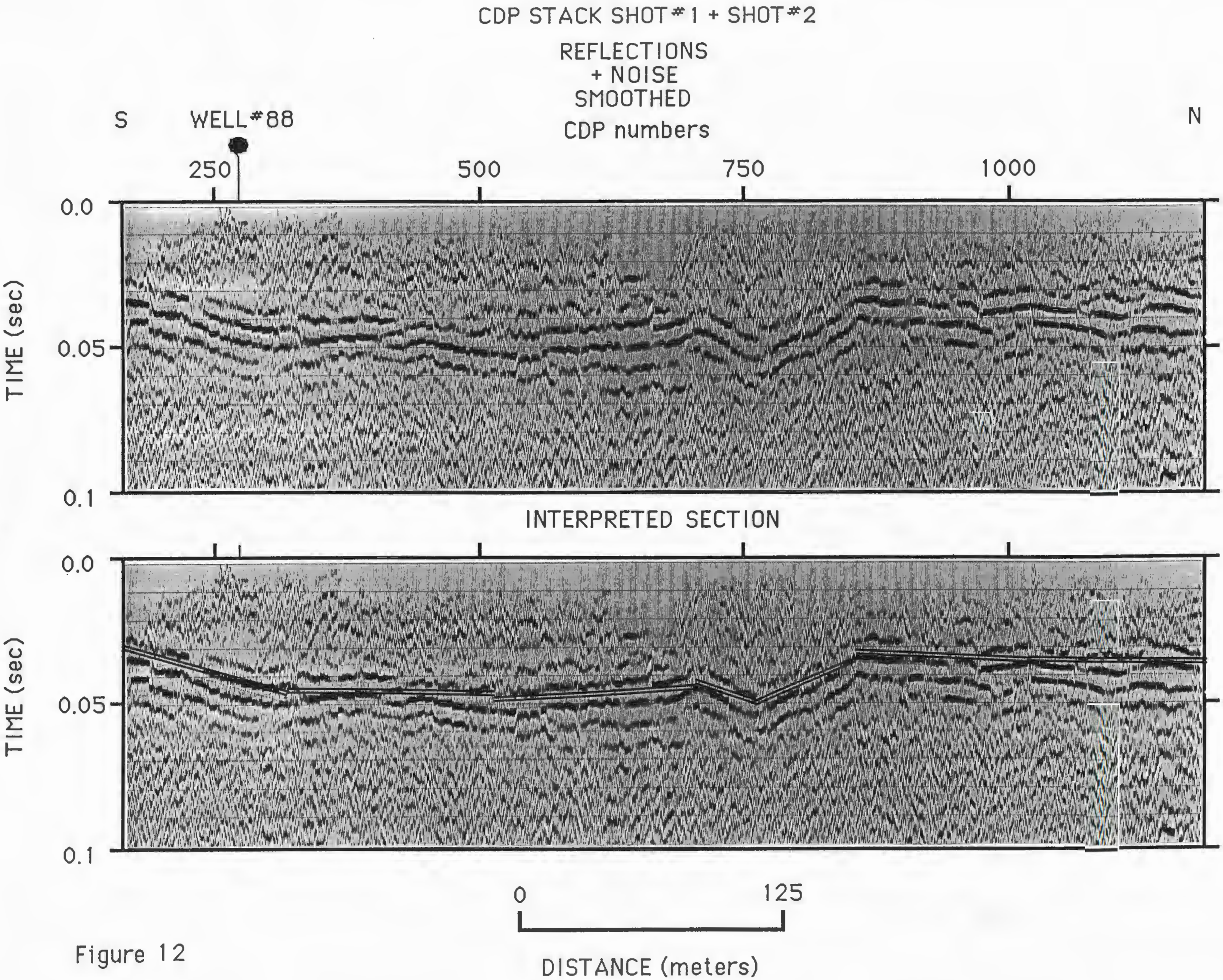

CDP STACK SHOT#1 + SHOT#2
REFLECTIONS
+ NOISE
SMOOTHED
S
WELL#88
CDP numbers
N
250
500
750
1000
TIME (sec)
0.0
0.05
0.1
INTERPRETED SECTION
TIME (sec)
0.0
0.05
0.1
0
125
DISTANCE (meters)

Figure 12

APPENDIX A

CONCEPTS OF SEISMIC REFLECTION PROSPECTING

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.

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.

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..

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.

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.

The simplest case of seismic reflection is shown in Figure 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.

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.

In the real world, there are commonly several layers beneath the earth's surface that are within reach of the seismic-reflection technique. Figure 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.

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 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.

In Figure 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.

The seismic-reflection method is used to determine the spatial configuration of underground geological formations. Figure 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.

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.

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.

APPENDIX A FIGURE CAPTIONS

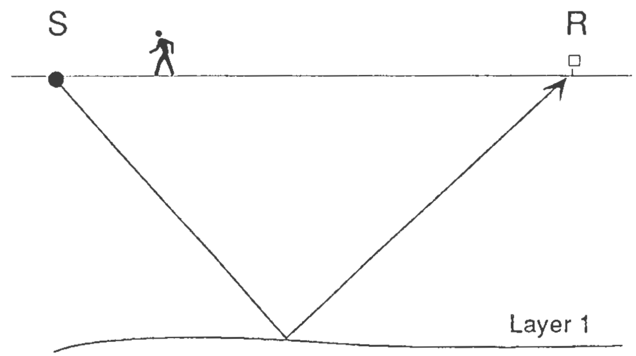
Figure 1 Reflection from one layer.

Figure 2 Reflection from three layers.

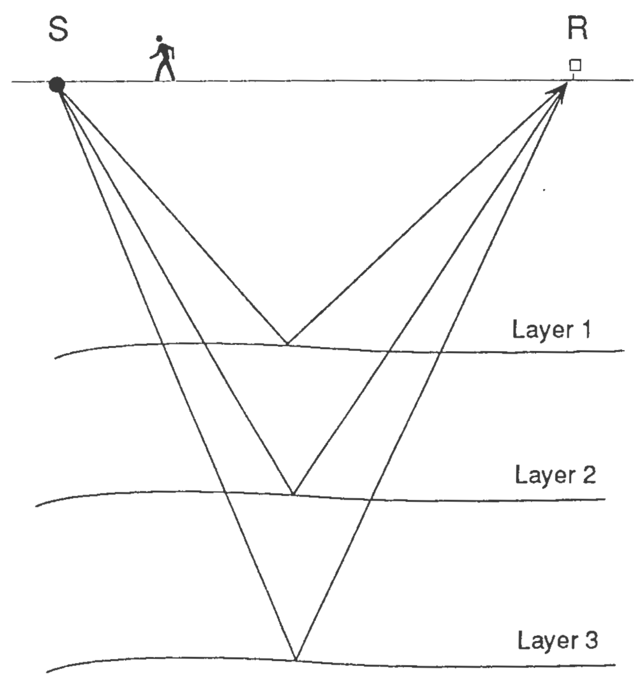
Figure 3 Schematic drawing of seismic ray paths for a single shot with a six-channel reflection seismograph.

Figure 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.

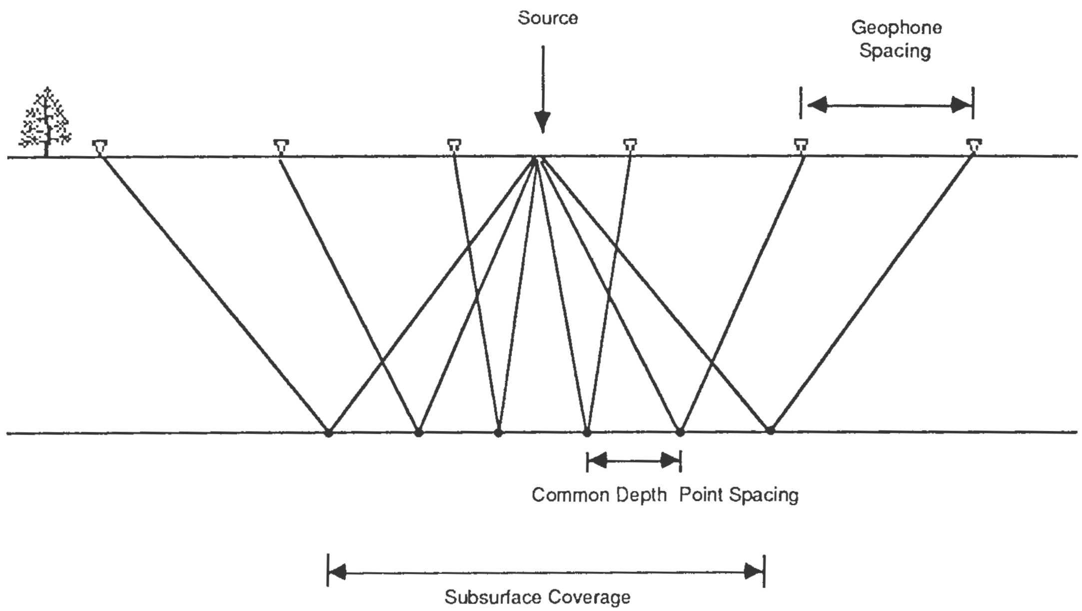
Figure 5. Schematic showing a seismic section relating to real-world geology.


S
R
Layer 1

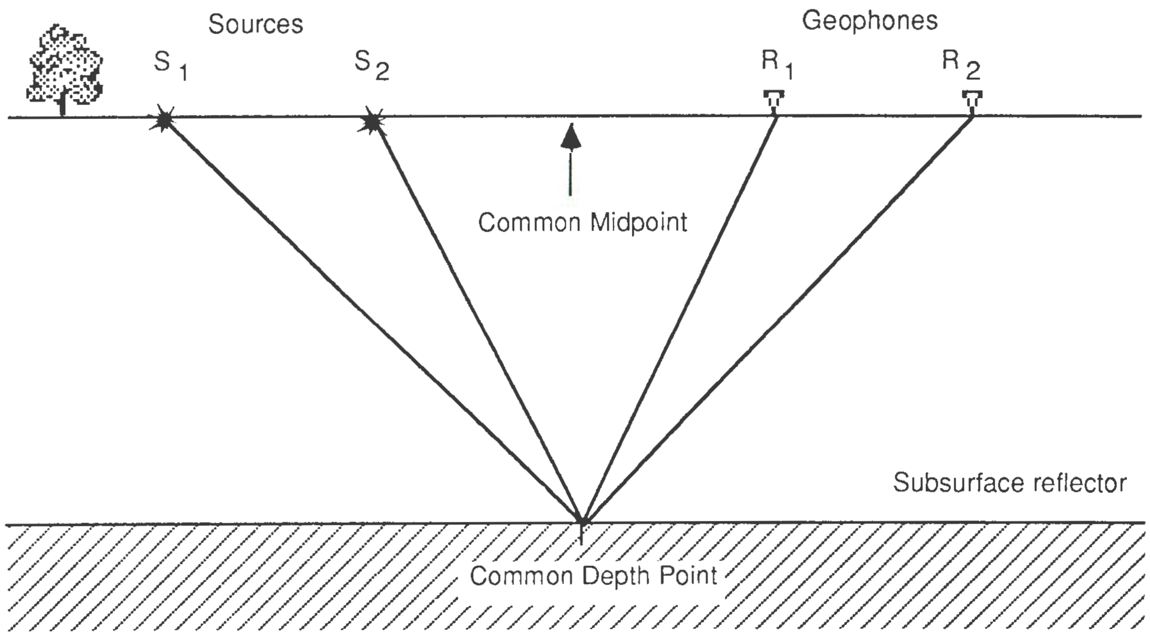
Reflections from Three Layers

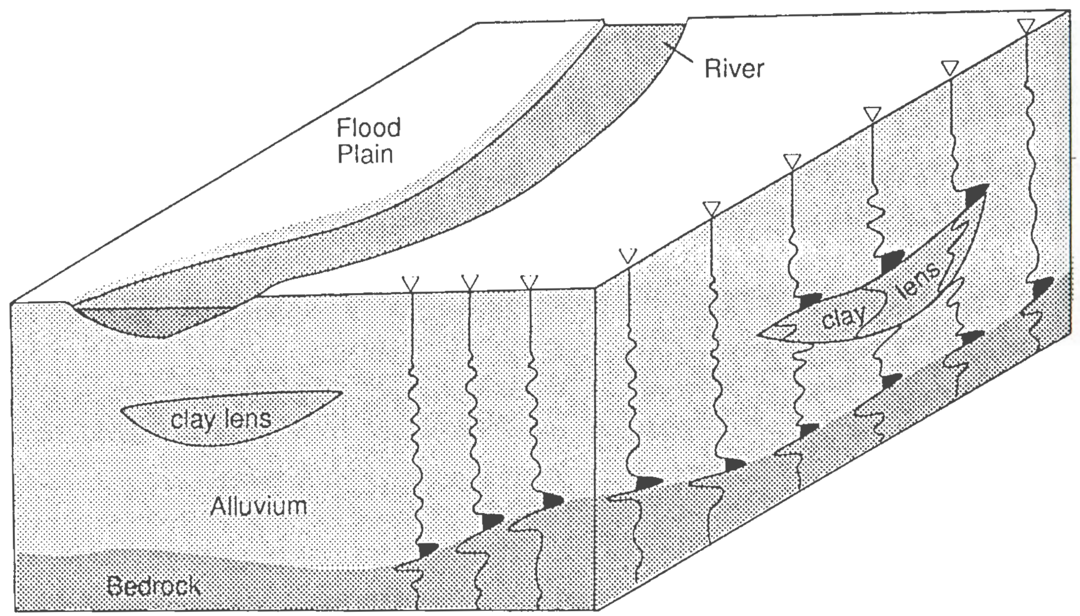


Simple Reflection Ray Paths



CDP Concept


Sources
Geophones
S 1
S 2
R 1
R 2
Common Midpoint
Subsurface reflector
Common Depth Point


Flood
Plain
River
clay lens
Alluvium
Bedrock
clay
lens

APPENDIX B

FIELD PROCEDURES

The producing and recording of high-frequency and high signal-to-noise (S/N) reflection data requires careful attention to detail and proper choice of parameters. If a high-frequency source pulse with a broad bandwidth is not produced and recorded, it cannot be digitally enhanced later.

Typical energy sources for shallow engineering studies include sledge hammer, weight drop, small explosive charge, and projectiles (Miller et al. 1986), all of which, in ideal conditions, can produce energy in excess of 100 Hz at a depth of 100 m. Each type of source under specific near-surface geologic conditions can produce a broader spectrum and high dominant-frequency pulse in association with a higher body-wave-to-surface-wave ratio than other types of sources under similar conditions (Pullan and MacAulay, 1985).

Receiver type, number, and layout is significant to recording the optimum high-frequency reflection record necessary to resolve some geologic structures. Multi-geophone arrays larger than 1 m in many situations can attenuate high-frequency reflection information (Knapp and Steeples, 1986b). However, a properly designed 2-to-3-geophone array less than 1-m long can improve S/N and also attenuate high-frequency linear-arriving energy such as source-generated air waves or gusting wind incident to the seismic line (Myers et al., 1987). Previous experience has shown surface-projectile sources and three or fewer high natural-frequency geophones are a cost-effective way to produce high-frequency reflection sections targeting layers shallower than 40 m in areas with a deep water table, rough rocky terrain, and extreme variability in the near surface (Treadway et al., 1988; Miller and Steeples, 1986; Miller et al., in review).

The seismic reflection data were recorded using a standard CDP acquisition method (Mayne, 1962). An end-on source-receiver geometry was used with a source-to-closest-receiver distance of 12 m and a source-to-farthest-receiver distance of 35 m. The 1-m shot and receiver group interval resulted in 1/2 m subsurface horizontal sampling interval. The source was a silenced .50-caliber sport rifle fired into the ground. The .50 caliber was chosen because of its characteristic high-frequency seismic pulse, low ratio of ground-roll-to-body waves, and total energy output. The silencer acts not only to damp the air wave, but it also acts as a containment vessel for any fragments generated as a result of firing into a hard surface. The receivers were three undamped 40-Hz geophones connected in series on 14-cm spikes. The three geophones were in-line and equally spaced over the 1-m interval in an attempt to reduce the amount of recorded air-coupled waves and wind noise. Close attention was given to source-and-receiver coupling during acquisition in order to improve the frequency response and reduce unwanted noise. In order to optimize the available equipment and the exact procedure used during acquisition, selection of field geometries, the source, receivers, and recording parameters was made in the field after extensive testing.

The data were recorded on an I/O DHR 2400 seismograph. All the fixed-gain data were converted analog-to-digital (A/D) to an 11-bits-plus-sign value and then stored on magnetic tape in a modified SEG-Y format. A record length of 125 msec and a sampling interval of 1/4 msec were used because the primary depth of interest was less than 100 m and the dominant reflection frequencies observed during testing did not exceed 250 Hz. The system amplifiers possess 72 dB of dynamic range with a 120 nanovolts RMS noise level. The anti-alias filters used have a 60 dB per octave roll-off with a -60 dB point of 2000 Hz. The selected low-cut filters have a -3 dB point of 220 Hz with 24 dB/octave roll-off. Low-cut filters were essential to the quality and success of this survey.

The extensive series of tests preceding the acquisition of the CDP data along line 1 allowed selection of an adequate set of field parameters for the conditions at the site. Prior to arriving on site, our preferred field parameters and equipment included a downhole .50-caliber rifle (requiring augered holes), two 100-Hz geophones connected in series, 110-Hz low-cut filters, 1-m station intervals, end-on source-receiver geometry, and a source-to-nearest-geophone distance of about 6 m. This preconceived set of parameters and equipment (excluding the site logistic problems with the augering of holes) may have allowed us to record sufficient reflection information to compile a geologic interpretation of a CDP stacked section. However, without the improvement of these parameters and equipment made possible by the preacquisition testing, many of the subtleties presently interpretable on the seismic section may not have been recorded.

The key changes to the planned parameters and equipment were the use of three 40-Hz geophones, the 220-Hz low-cut filters, the 12-m source-to-nearest-receiver spacing, and the use of the surface .50 caliber rifle. The use of three 40-Hz geophones helped to attenuate much of the wind that was parallel to the line as well as respond better to some of the reflection information between 75 and 100 Hz. The 220-Hz low-cut filters helped reduce the amount of recorded ground roll and wind noise, therefore boosting the signal-to-noise ratio. The increasing of the source-to-receiver offsets was necessary because the near-surface velocity was slower than expected, making the optimum offset window for recording reflections from around 30 m of depth farther than planned from the source. The augering of holes for downhole placement of the .50-caliber rifle barrel was not possible across the entire 500 m of line due to the occasional near-surface/outcropping basalt. The surface rifle imparts about 3 to 6 dB less recordable seismic energy into the ground than the downhole rifle at most sites. In order to increase the total recorded seismic energy of the surface rifle, two shots were fired at each station. The second shot possessed approximately 3 dB more recordable seismic energy than the first. The preliminary testing was instrumental in the overall quality of the CDP stacked section.

A reversed refraction profile was performed to determine a near-surface velocity and depth model for the weathered layer. The information derived from the refraction model was necessary to compensate for the varying thickness of sand that overlies the higher velocity basalts. The refraction survey was carried out coincident with the reflection profile using the same geophone plants, a sledge hammer for a source, and a maximum source-to-receiver offset of 18-1/2 m. Two shots were taken every 12 stations, each with a split/spread source-receiver geometry—one shot with a source-to-nearest-receiver of 1/2 m and the other with a source-to-nearest-receiver of 6-1/2 m. This resulted in 1-m surface coverage, 1/2 m to 18-1/2 m out from the source in both directions parallel to the line. The resulting refraction-derived geologic cross-section was used to compute the elevation and varying bedrock thickness correction necessary to accurately correct for static inconsistencies from station to station.

The production of quality usable high-resolution CDP seismic reflection profiles is highly dependent on an awareness of the geologic situation, emphasis on uniformity during acquisition, and attention to details such as good field notes and high-quality geophone plants. Without proper understanding of the geologic situation and target, it is not possible to optimize the recording parameters and field procedures. Producing and recording seismic energy in excess of 150 Hz for eventual generation of CDP stacks require uniformity in everything, the most important of which includes the time break system, energy-source signature, geophone plants, and source-and-receiver coupling to the ground. The need for detail is obvious when a 0.5-m error in surface elevation results in a 2-msec shift which, for 150-Hz data, is almost one-third of a wavelength.

DATA PROCESSING

Data processing was done on a 32-bit Data General MV-20000 computer at the Kansas Geological Survey. The software used was a proprietary set of algorithms that has been in standard use on TIMAP seismic systems marketed by Texas Instruments. The processing flow was non-standard as a result of the extreme inconsistency in reflector depths and normal moveout velocity as well as thickness of the low-velocity near-surface layer (Table 1). Extraordinary emphasis was placed on point-by-point velocity analysis and surface-consistent statics operations.

The velocity structure at this site is complicated by flow irregularities, non-uniform sedimentary deposition, and a variable thickness of near-surface material characteristic of volcanic environments. Ideally, seismic analysis of only reflections results in the most accurate final CDP stacked data set. In this environment, the most critical operations were the normal moveout velocity and surface-consistent static corrections. In order to confidently determine these corrections, the dominant reflection information was isolated and then extracted from the background seismic signals by a severe surgical mute. The velocity analysis and surface-consistent statics computation were then done on the reflection information only so as to avoid being influenced by coherent noise or other non-reflection signal present on the seismogram. The corrections derived from this computation were then applied to both the previously extracted exclusive reflections and the non-reflection seismic signal. After the corrections were applied to the two data sets independently, they were merged, CDP sorted, and stacked.

Information derived from the refraction profile and analysis was used to compensate for the irregular bedrock surface beneath the low-velocity surface sand. A static correction was applied to the data using the average interval velocities determined by the reversed refraction profile. This correction effectively removed the dependence of depth determinations on the laterally varying near-surface thickness. The resulting CDP stacked section can be used to directly calculate depths to acoustic interfaces.

Deconvolution processes were unsuccessful in suppressing the "ringiness" of the seismic-reflection data. The application of a deconvolution operator resulted in a drastic decrease in the signal-to-noise ratio of the data as well as a reduction in the coherency of the reflection information that remained. The high-frequency noise that was injected during the deconvolution process degraded the overall data quality sufficiently to justify not using a deconvolution routine on this line.

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SEISMIC DATA PROCESSING FLOW CHART

TABLE 1