FEASIBILITY OF OBTAINING REFLECTIONS FROM GEOLOGIC INTERFACES SHALLOWER THAN 30 M AT THE PITTMAN LATERAL, HENDERSON, NEVADA

by

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INTRODUCTION

The Pittman transect in Henderson, Nevada is a site where polluted waters from an unknown source location are moving laterally toward intake facilities for the Las Vegas water supply. Several geophysical and geological exploration techniques have been employed at the site over the past several years by Lockheed Engineering Management Services Company (LEMSCO) and its subcontractors under contractual funding from the Las Vegas office of the Environmental Protection Agency (EPA). This is a report on a seismic-reflection survey at the Pittman Transect by the Kansas Geological Survey under contractual funding from LEMSCO.

Detailed knowledge of the bedrock surface is often crucial in the planning of well locations for ground-water-quality monitoring. Changes in ground-water quality often first appear in monitor wells located in topographic lows in the bedrock surface. Data possessing necessary detail for conclusive mapping of bedrock surfaces have generally come from extensive drilling programs which are time consuming, expensive, and environmentally undesirable. High-resolution seismic-reflection profiling has been used to image surfaces as shallow as 3 meters (m) and resolve beds as thin as 1 m in a variety of near-surface geologic settings (Schepers, 1975; Doornenbal and Helbig, 1983; Birkelo et al., 1987; Myers et al., 1987; Branham and Steeples, 1988). The seismic-reflection technique has the potential in suitable geologic conditions to image a shallow (4-20-m deep) bedrock surface with sufficient detail to pinpoint optimum locations for monitor wells (Miller et al., 1989).

Mapping a bedrock/overburden contact at depths greater than 20 m has commonly been done using reflection seismology (Hunter et al., 1984). Using conventional reflection techniques, bedrock reflectors shallower than 20 m are difficult to separate from other energy arriving in the early portions of seismograms

(Steeples and Miller, 1986). The amplitudes of these shallow-reflected waves at commonly recorded frequencies are smaller than the amplitudes of unwanted waves, particularly ground roll, refractions, direct waves, and air-coupled waves.

Typical energy sources for shallow engineering studies have included sledge hammer (Hunter et al., 1981; Meidav, 1969), weight drop (Doornenbal and Helbig, 1983), projectiles (Steeples and Knapp, 1982), and small explosive charges (Pakiser and Warrick, 1956). Under ideal conditions (water table within 1 m of ground surface, solid geophone and source-ground couple, etc.), the dominant frequency generated by any shallow seismic source could exceed 100 Hz at depths of 100 m or more (Miller et al., 1986). Certain seismic sources will generate comparatively higher frequencies in areas where surface and very near subsurface conditions are less conducive to the propagation of seismic energy and amplitude seismic energy (Pullan and MacAuley, 1987). Previous experience in similar geologic settings (dry, sandy near-surface material and water table in excess of 3 m deep) has shown surface projectile sources to be a cost-effective, consistent, high-frequency source (Treadway et al., 1988; Miller et al., 1989; Miller et al., in press; Birkelo et al., 1987).

Detection of shallow seismic reflections requires closely spaced source-receiver stations, severe analog low-cut filtering, suitable high-frequency seismic source and receivers, and a seismograph with a large instantaneous dynamic range (Knapp and Steeples, 1986). These criteria allow less unwanted energy to be recorded which sometimes allows identification of subtle shallow reflections that are obscured using more common seismic-reflection procedures.

RESOLUTION

Increasing the dominant frequency and broadening the frequency spectrum (bandwidth) of recorded reflection energy improves resolution of shallower, smaller, and thinner beds (Knapp and Steeples, 1986; Widess, 1973). Increasing the dominant frequency of recorded energy can often be accomplished by severe low-cut filtering, using proper field equipment for conditions, and carefully employing consistent field procedures. Severe low-cut filtering effectively attenuates the lower frequency information (generally ground roll) allowing balancing of the spectrum toward higher frequencies. Attenuation of much of the high-amplitude, low-frequency information, allows increased analog gaining (fixed or floating point) improving the signal-to-noise ratio (S/N) of the recorded data. Firm geophone plants made in conjunction with a consistent seismic source are paramount to optimizing bed resolution of seismic-reflection surveys. Resolution (both vertical and horizontal) of any additional data recorded at this site could be improved by decreasing variability of the near-surface material which inhibited consistent solid geophone plants and good source-to-ground coupling.

GEOLOGIC SETTING AND FIELD PROCEDURES

A 12-fold CDP line, 260 m long, was acquired parallel to a series of wells approximately 60 m apart (Figure 1). Conductivity and gamma geophysical logs and geologist's stratigraphic logs, previously acquired at each well, were used to assist in planning the seismic field work and interpreting the resulting data.

The water table at this site is at a depth of roughly 5 m and is overlain by alluvial material composed predominantly of poorly sorted sands and clays. Drill data suggest these sands and clays terminate against a semi-consolidated clay bedrock at a depth of 12-30 m. The preliminary bedrock-profile map, compiled from drill data and geophysical logs, shows a bedrock low on the west end of the line (Figure 2). The borehole data suggest the acoustical impedance contrast across this stratigraphic bedrock boundary is marginal for production of seismic reflections. The seismic survey was intended to determine the feasibility of mapping the boundary between the alluvial materials and the underlying clay bedrock.

The data were collected using a .30-06 hunting rifle as the seismic source. The rifle was modified with a blast-containment device to reduce the amplitude of the air-coupled wave as well as to contain any stray bullet or rock fragments . The .30-06 rifle possesses source characteristics conducive to the generation of high-quality seismic signal in dry, unconsolidated near-surface environments (Miller and Steeples, 1986; Birkelo et al., 1987; Miller et al., 1989; Miller et al., in press; Treadway et al., 1988).

The receivers, single 100-Hz Mark Products geophones with 14 cm spikes, characteristically attenuate energy below 100 Hz (6 dB/octave) while maintaining a flat response to energy at frequencies up to 1000 Hz. High-resolution compressional-wave surveys have generally had success with high natural-frequency geophones (Steeples and Knapp, 1982; Hunter et al., 1984; Myers et al., 1987; Miller et al., 1989; Gochioco and Cotten, 1989).

An end-on source/receiver configuration with a source-to-closest-receiver distance of 3.7 m was used to collect the data. The 0.6 m shot and receiver station interval resulted in an effective spread length of 14.5 m. This spread geometry allowed the optimum recording window (Hunter et al., 1984) to be maintained while minimizing the horizontal subsurface sampling interval and therefore maximizing horizontal resolution across the entire line. Close attention to source and receiver ground coupling improved frequency response and reduced unwanted noise.

A 24-channel Input/Output DHR 2400 seismograph recorded the data on half-inch magnetic tape in modified SEG-Y format. The record length was 125 ms with a sampling interval of 0.25 ms. Analog-to-digital (A/D) conversion was 11 bits plus sign. The amplifiers have a factory noise specification of 120 nanovolts

RMS, providing a fixed-gain dynamic range of 72 dB. Pre-A/D low-cut filters with a -3 dB point of 220 Hz and a 24 dB/octave roll-off were used to maximize potential resolution and reduce ground roll effects.

DATA PROCESSING

Data processing was done on an Intel 80386-based microcomputer using a proprietary set of algorithms (Eavesdropper) developed by the Kansas Geological Survey (Somanas et al., 1988). The processing flow was similar to those used in petroleum exploration. The main distinctions relate to conservative use and application of correlation statics, precision of the near-surface velocity analysis, extra care during muting operations, and lack of deconvolution.

The shallowest reflection wavelets on the more distant source-to-receiver offset traces are slightly distorted and possess inconsistent trace-to-trace amplitude and frequency characteristics. These wavelet inconsistencies are at least partially related to interference between the reflection identified at 40 ms and refraction arrivals (Figure 3). A first-arrival mute was applied to eliminate as much of the refraction and direct-wave energy as possible (Figure 4). The trace-to-trace variability in the shallow reflection wavelet would have made separation of reflection from refraction energy impossible on stacked data without a properly applied first-arrival mute.

Digital frequency filtering improved the signal-to-noise ratio and therefore the overall clarity of reflections previously identified on raw field data (Figure 5). Other potential reflection energy hidden by noise was not obviously enhanced by the filtering operation. Ground roll and seismic noise on these data have dominant frequencies in the 125 to 150 Hz range.

Variability in near-surface material at this site inhibited determination of a unique velocity function using standard constant-velocity stack analysis techniques. Compensation for static anomalies from velocity and/or structural variability in the near surface is routinely accomplished with correlation statics routines. Conventional correlation statics routines require data be corrected for non-vertical incidence (i.e., application of appropriate NMO velocity function) prior to trace-by-trace correlation. The circular nature of the problem becomes obvious when correlation statics routines cannot properly remove static effects without an appropriate velocity function; but an appropriate velocity function cannot be determined without first properly removing static effects.

Determination of an initial velocity function required analysis of a series of test sections, each simultaneously adjusted for a variety of possible velocity and static values. To allow a first-guess approximation of velocity, the entire CDP sorted data set was iteratively corrected at a series of potential velocities. The resulting group of constant velocity gathers were individually corrected (no single trace was time-shifted more than 15 percent of the dominant reflection period, i.e., 1 ms) for apparent static variability, using a correlation routine, and then CDP stacked. The series of constant velocity stacks resulting from this iterative velocity/statics technique were analyzed and preliminary time/velocity pairs were determined for use in the primary processing flow. We emphasize that this procedure was only used to establish a velocity model and was not used for the final processed sections.

Correcting for NMO has the effect of stretching seismic traces between the time of onset of the shallowest reflection and the time of disappearance of the deepest reflection. This lowers the apparent frequency of the processed data. To minimize this effect, data that are stretched too much are thrown away by muting them to zero amplitude.

Application of the appropriate NMO stretch mute is critical to an accurate interpretation of shallow-reflection data (Figure 6). An incorrect NMO stretch mute can result in a misleading drop in the dominant frequency and an incorrect determination of the NMO stacking velocity for shallow reflection events. The NMO stretch mute relates the amount of allowable stretch between two successive samples in comparison to the original sample interval. This dynamic shift or stretch between successive samples is necessary to compensate reflection arrivals for a non-vertical source-to-receiver travel path. On shallow low-velocity data sets, variation on the order of a couple percent can decrease the apparent dominant frequency and the coherency of stacked reflection energy. Careful analysis of the effects of various stretch-mute criteria proved beneficial in generating CDP stacked sections in this alluvial environment.

Reflection information on the CDP stacked section lacks consistency in trace-to-trace wavelet characteristics over distances as small as several meters (Figure 7). This inconsistency is probably related to the variable near-surface materials. Generating a seismic section representative of true acoustical-earth response requires removing the source signature by a deconvolution routine. The signal-to-noise ratio of this data set is sufficiently low that attempts to suppress source wavelets by deconvolution resulted in a drastic reduction in overall quality, so the deconvolved data are not shown.

RESULTS

Unequivocal identification of reflection information on field files is crucial for discriminating reflection energy from noise on a CDP stacked seismic section. A strong reflection event can be identified on some of the raw field files at about 40 ms (Figure 3). The average calculated normal moveout (NMO) velocity of the event at 40 ms is around 525 m/s. This velocity and two-way time suggests a reflector depth of approximately 10 m. Deeper reflection energy present around 60 ms on the unprocessed file possesses an average NMO velocity of approximately

615 m/s representing a reflector depth of about 20 m. The coherency and consistency of the two events on unprocessed field files, in conjunction with high correlation of the calculated moveout velocities to appropriate hyperbolae, allows high confidence in classifying them as reflections.

The reflection energy, as identified on field files, possesses a dominant frequency of around 180 Hz. Vertical bed resolution on the order of 1 m can be expected, assuming the 1/4 wavelength bed discrimination criterion (Widess, 1973). A significant amount of coherent energy, with dominant frequencies around 240 Hz, can be identified prior to the arrival of seismic signal on unprocessed field files. This energy is probably related to a higher mode of 60 Hz energy from high voltage power lines approximately 60 m from and parallel to the seismic line (Figure 1). The dynamic range of the seismic data and the potential to detect subtle high-frequency reflections was reduced as a result of noise from the power lines.

Common Offset Section Discussion

The high-frequency spectral characteristics of reflection information on shallow seismic data sets are generally negatively affected by the CDP stacking process in comparison to common offset displays. Common offset gathers were generated from processed CDP gathers to ascertain the maximum capability of the optimum window technique (Hunter et al., 1984) in this area. Three optimum offsets were chosen after analysis of processed field files. The offset distances were 6.7, 9.7, and 12.7 m (Figure 8). Data grouped into each of the three common offset gather sections have been processed identical to the CDP stacked section (Figure 7) except the CDP stack was replaced by a trace sort according to source-to-receiver offset as the final process.

The CDP processing optimizes the common offset data in a way not available to standard common offset surveys. CDP processing allows each common offset trace to benefit from pre-stack enhancement techniques normally available exclusively to multi-fold data sets. In other words, the processing used here presents the common-offset data in a way that makes the data look better than they would look when processed by common offset techniques alone.

The low signal-to-noise ratio makes identification and correlation of reflection events from trace-to-trace difficult on the common offset gathers. Potential for misinterpretation is high on the common offset gathers. The 30 ms event is most easily interpreted on the 6.7 m and 9.7 m offset gathers. Mutually exclusive portions of the 60 ms reflection event can be identified on either the 9.7 m or 12.7 m gather. Sporadic, subtle indications of the 60-ms reflection event can be interpreted on the 9.7 m gather between CDPs 650 and 900. The intermediate event interpreted on the CDP stacked section is interpretable on the 9.7 m gather between CDPs 300 and 350 as well as CDPs 500 to 650 and on the 12.7 m gather between CDPs 700 and 800 as well as CDPs 500 to 600. The 12.7 m offset gather possesses interpretable signal predominantly at times of 60 ms and greater, especially between CDPs 300 and 550. Some reflection energy can be identified on each of the three gathers. A group of unique times and offset distances can be selected for each reflection which accentuates coherency and maximizes dominant frequencies.

Without the CDP stacked section to use as a guide for interpretation, the common offset gathers would be very difficult if not impossible to interpret. The variability in optimum offset distances for particular reflection events suggests spatially varying offsets would need to be selected for each reflection using the common offset optimum window method along this line. The purpose of the common offset analysis was to ensure that no information pertinent to this study was overlooked, distorted, or removed during CDP processing.

CDP Stacked Section Discussion

Several reflection events can be interpreted on both final stacked sections in Figure 7. Two of the three reflection events interpreted on the CDP stacked sections can be identified on the filtered field files (Figure 5). The shallowest reflection (30 ms) equates to a reflector depth of approximately 10-12 m across most of the line. The deepest interpretable reflection event varies across the line from 50 ms (15 m) to 70 ms (21 m) and is interpreted as an unknown layer below the clay bedrock noted in drill cuttings. A subtle intermediate reflecting event is identified at times ranging from 40 to 60 ms (12 to 18 m) and is interpreted as the top of the clay bedrock. The 20 ms of variation in two-way traveltime of the intermediate reflection represents approximately 6 m of vertical change in the reflector along the line. Stratigraphic interpretations of the reflection data are speculative at this time without detailed drill information from at least two additional drill holes.

Slight variations in stacking velocities between CDPs 600 and 700 change the seismic characteristics of the intermediate reflection event (Figure 7). Two final stacked sections with slightly different NMO velocities provide potentially different interpretations. One extra layer velocity was added to stacked section 7a between the shallow reflection (30 ms) and the deeper bedrock reflection (65 ms). The change in NMO velocity between Figures 7a and 7b for that time window was less than 100 m/s. The velocity function used in stack 7b is not conducive to the enhancement of this intermediate feature identifiable at approximately 45 ms between CDPs 600 and 700 on stack 7a. Such variations in seismic characteristics (i.e , velocity) resulting in alternative final CDP stacked sections and interpretations, were not present along any other part of the line. The choice of preferred final stacked section (7a or 7b) can only be confidently determined after confirmation drilling.

Interpretation

The reflectors imaged by this seismic survey range in depth from approximately 10 to 25 m. No attempt was made to record reflections from times greater than 70 ms. The intermediate reflection interpreted on the seismic section is probably the unit defined by drilling and geophysical logs as the bedrock surface. The interpreted surface of this reflector agrees quite well with the drill and log information. This unit may or may not be completely eroded away in the valleys near CDP 600 and 210. Some subtle interference phenomena along the edges of the buried valleys suggest that the unit may be very thin (i.e., less than 2 m) or absent in the valleys. Seismic data suggest that a deeper reflector is present that is relatively flat at a depth of 20 to 25 m.

The horizontal resolution of drilling at this site was not sufficient to detect the buried valley interpretable on the seismic-reflection data. The low between CDPs 500 and 700 is on the order of 30 to 50 m across depending on which interpretation (7a or 7b) is correct. Regardless of which interpretation is correct, the relative low in the layer was invisible to previous drilling. The horizontal sample spacing of the seismic data is on the order of 1/3 m, while the horizontal spacing of the drilling was 60 m. The same number of drill holes could have detected all the relative highs and lows in the intermediate reflector across the expanse of the seismic line if the seismic survey had preceded the drilling.

The interpretation derived from both drill data (cuttings) and borehole logging data provided by LEMSCO is displayed (Figure 10 a & 10b) at the same horizontal scale as the geologic interpretation (Figure 10c) of the seismic reflection data (Figure 9b). The LEMSCO interpretation is not sufficiently compelling evidence to justify refuting the seismic interpretation. Examination of drill cuttings from the four boreholes would be necessary to become sufficiently familiar with the lithologic units present to confidently judge the validity of the seismic or log interpretation.

The seismic data do suggest the presence of acoustical interfaces as interpreted (Figure 10c). These acoustical interfaces can represent either velocity or density contrasts that can sometimes be caused by age discontinuities that are difficult or impossible to interpret from drill cuttings. For that reason, any verification holes should be core-drilled.

Borehole information suggests a bedrock low at the west end of the line centered on approximately CDP 210 (Figure 2). The bedrock/alluvial contact, inferred from drill data east of CDP 300, shallows to less than 8 m around CDP 600. The interpretation of the drill data suggests the most significant decrease in depth-to-bedrock occurs between CDPs 300 and 500. Locations of wells with respect to the actual location of the seismic survey are only approximate on the site map (Figure 1). Correlation between the seismic line and well locations is from seismic observer notes taken during the acquisition portion of the survey. Actual well locations could be off by as much as 10 m.

Positive correlation of the interpreted reflection events to borehole information is not possible without an uphole seismic-velocity survey. One-way traveltime measured from an uphole velocity survey would allow an accurate time-to-depth conversion. This report uses NMO velocities estimated from a curve fitting routine and then multiplied by 1/2 the reflection time to calculate approximate reflector depths (Figure 10).

CONCLUSIONS

I. The seismic-reflections technique can be used to map at least three reflectors shallower than 25 m at the Pittman Lateral in Henderson, Nevada.

2. Correlation of the reflection times to geologic unit depths will require a seismic uphole survey.

3. Reflection energy was recorded from as deep as 70 ms two-way travel time. The deepest recorded reflection is relatively flat but fluctuates between about 60 and 70 ms in two-way traveltime which is probably about 20 m deep.

4. Higher-frequency seismic energy would eliminate, or at least greatly reduce, the interference observed between the refractions and the 30-40 ms reflector.

5. The "bedrock"/alluvium interface does not possess a strong enough acoustic impedance contrast to generate high-quality reflections on unprocessed data. However, substantial effort during velocity analysis and careful application of minimal static corrections resulted in the enhancement of an intermediate reflection. This reflection is probably what has been called "bedrock" on the basis of drill cuttings and geophysical logs. A previously unknown 20-25 m deep valley is interpreted on the stacked section between CDPs 500 and 700.

RECOMMENDATIONS

1. Boreholes should be drilled to a depth of at least 35 m at CDPs 400 and 600 to confirm or refute the seismic-reflection results. We strongly recommend continuous coring, high-quality geophysical logging, and uphole velocity surveys for these holes.

2. If the seismic results are confirmed, a hole at CDP 675 will allow discrimination of the correct seismic interpretation (i.e., Figure 9a or 9b).

3. Slight modifications to the acquisition parameters and techniques could improve the quality of the reflection data. More high-frequency energy as well as consistent and better geophone plants (by water saturating a grader ditch) would clean up the distorted reflection at 40 ms and decrease the observed static effects. The use of a new-generation engineering seismograph with improved dynamic range and floating-point amplifiers could improve amplitude and coherency of reflections from deeper than 50 ms. Also, a grader or bulldozer run along the line to scrape off the upper few inches of loose unconsolidated near-surface material would reduce the statics problems. If the resulting flat surface were to be water-saturated for a day or two prior to a subsequent reflection survey, dominant frequencies as much as 30-40 Hz higher could be produced to improve resolution.

4. Offsetting any subsequent seismic survey line 200 m plus from the power lines would allow more effective use of the dynamic range of the seismograph.

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FIGURE CAPTIONS

FIG. 1 Base map showing the 260 m of CDP seismic line with respect to the well clusters, power lines, and other significant obstacles and landmarks. The line is offset approximately 20 m from the well placements at the west end of the line and less than 4 m on the east end. The power lines are approximately 60 m from the seismic line and roughly parallel to it.

FIG. 2 Geophysical logs and original interpretation provided by LEMSCO. No attempt was made to modify or re-interpret the log information provided to the Kansas Geological Survey in an analog, interpreted form.

FIG. 3 Reflection information is difficult to interpret on the unprocessed files. The most prominent reflection event is at a time of approximately 40 ms. The curvature and coherency of the event make a high-confidence identification possible. Deeper reflection energy is more difficult to identify on the unprocessed file; however, subtle indications of a reflection are present around 65 ms. The inconsistent trace amplitudes within this file are indicative of the variability in the near surface material at this site.

FIG. 4 Digital bandpass filtering and automatic gain control (AGC) improved the coherency and the spectral characteristics of both the clearly identifiable reflection around 40 ms on the unprocessed file as well as the reflection suspected at approximately 65 ms. Subtle indications of a reflection event as deep as 85 ms can be interpreted on this processed version of the field file. Static effects can be observed on both the 40 and 65 ms reflection events. The wide-angle effects on the 40 ms reflection can be observed at source-to-receiver offsets greater than about 10 m.

FIG. 5 A severe surgical mute was applied to the filtered and scaled data to minimize the possibility of misinterpreting refraction or direct-wave energy as reflections. The refractions and direct wave can be easily identified on the filtered and scaled field file in Figure 4.

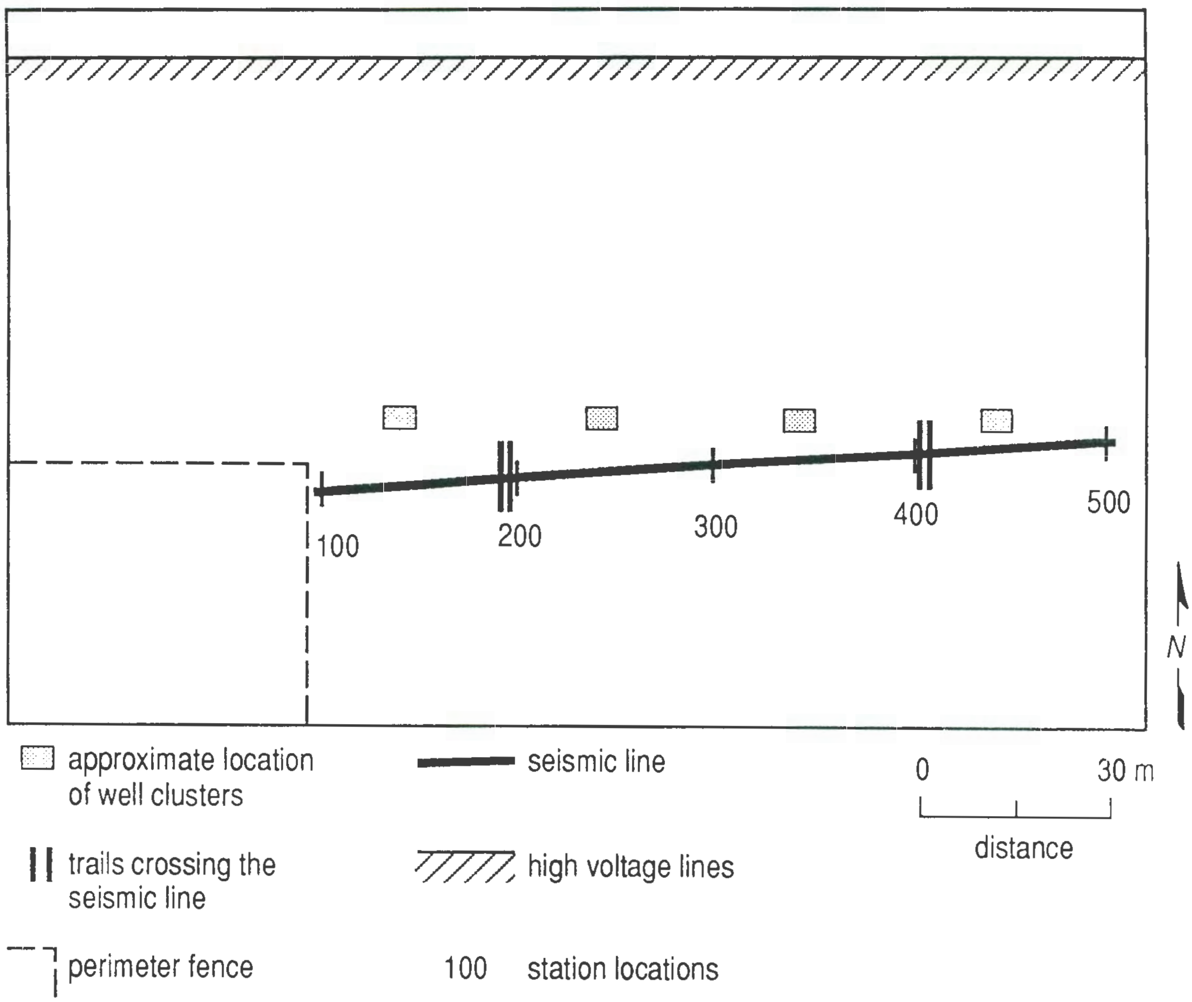
FIG. 6 Incorrect NMO stretch mute values can greatly reduce the amplitude, frequency, and coherency as well as introduce artifacts into CDP stacked seismic sections. These effects are the result of the dynamic intra-trace sample interval stretching necessary to correct for non-vertical incidence. Three different allowable stretch ratios were used to exemplify the variability in both the moved-out common-shot gather as well as the CDP stacked section. The three maximum allowed stretch percentages were (a) 25%, (b) 17%, and (c) 15%. The common-shot gathers have been processed through the same flow as the stacked section with the exception of the stack itself. The effect of the incorrect stretch mute is not only evident with respect to the wavelet characteristics, but it also drastically affects the effectiveness of the correlation statics routine.

FIG. 7 The nominal 12-fold CDP stacked section represents two potential finished sections with the only difference being the NMO velocity applied between CDPs 600 and 700 within the time window between 35 and 55 ms. Nowhere else on the remainder of the section was such variability observed with subtle changes in velocity. The change in velocity is on the order of 100 m/s.

FIG. 8 These three common offset gathers were generated and displayed to ensure that no information was overlooked or distorted during the CDP stacking process which could be significant to feasibility of the technique at this site. The three offset distances, chosen from common shot gathers, were within the optimum offset for each of the three reflections interpreted on the CDP stacked sections. Indications of the reflections interpreted on the CDP stacked sections can be interpreted at various places on each common offset gather. Offsets are (a) 6.7 m; (b) 9.7 m; (c) 12.7 m.

FIG. 9 The two CDP stacked sections, identical with the exception of the slight variation in velocity between CDPs 600 and 700 as displayed in Figure 7, are interpreted. The three most prominent reflection events are interpreted with the shallowest event at a depth of approximately 8-10 m, the second within a depth range between 10 and 17 m, while the third is 17-20 m deep across most of the seismic line.

FIG. 10 Natural gamma ray and formation conductivity logs for the four holes significant to this seismic survey, with a generalized geologic interpretation (a and b) and a generalized geologic interpretation (c) of the seismic data (figure 9b) are displayed with consistent horizontal scales. Interpretations of the geophysical logs and the seismic data are not totally consistent. The three different shades on the seismic interpretation represent acoustically different materials.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approximate location of well clusters
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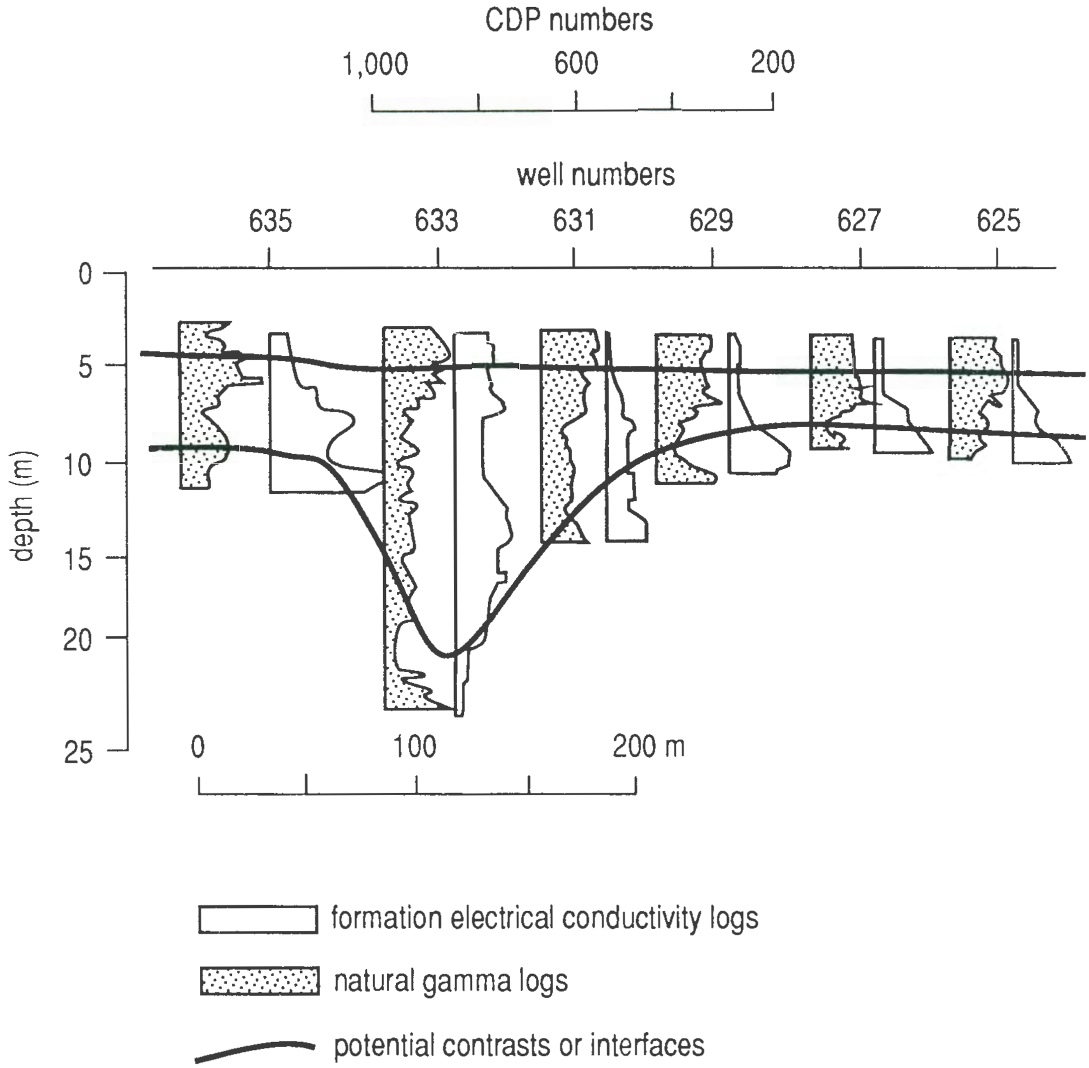
Figure 1


CDP numbers
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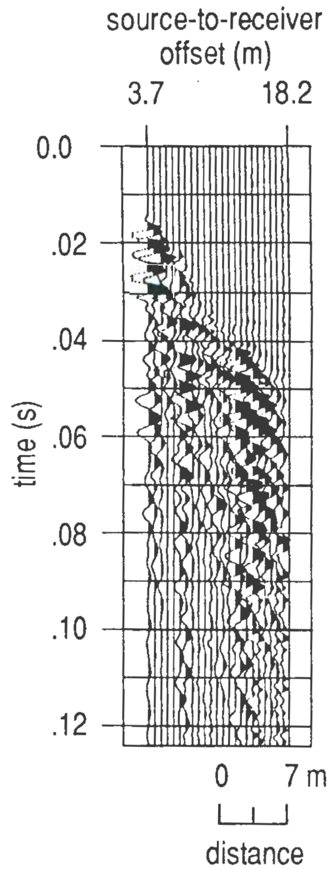
potential contrasts or interfaces

Figure 2


source-to-receiver
offset (m)
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time (s)
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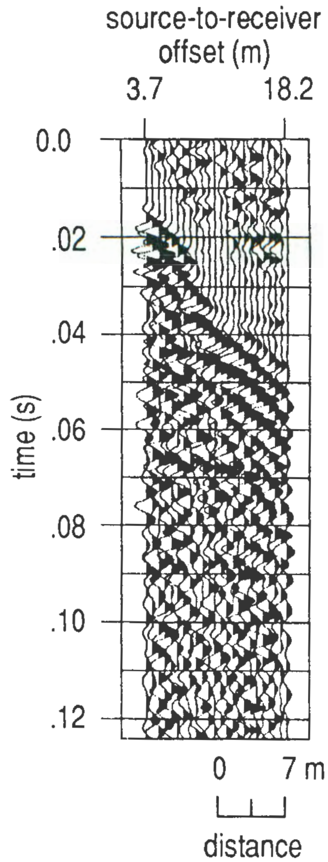
Figure 3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offset (m)
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.10
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time (s)
0
7 m
distance

Figure 4

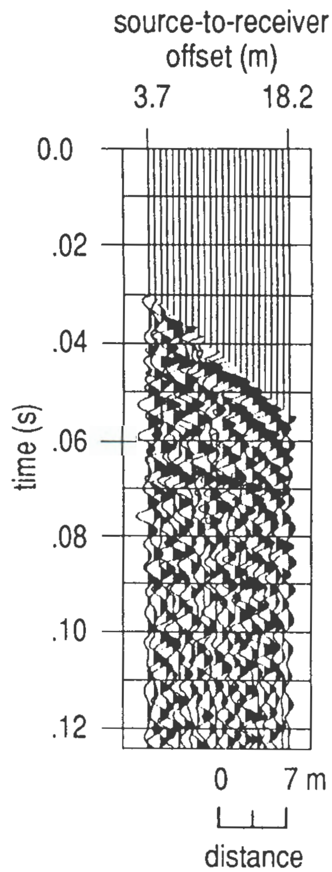
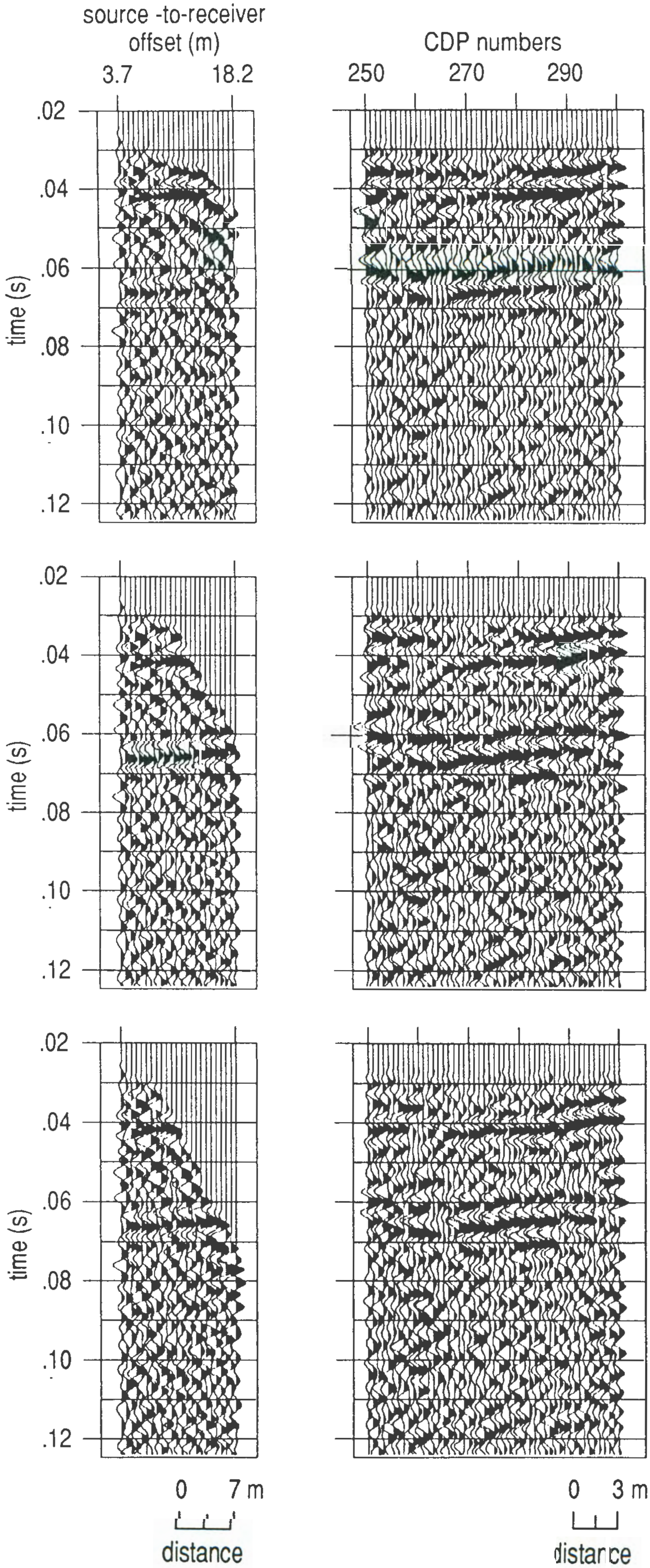
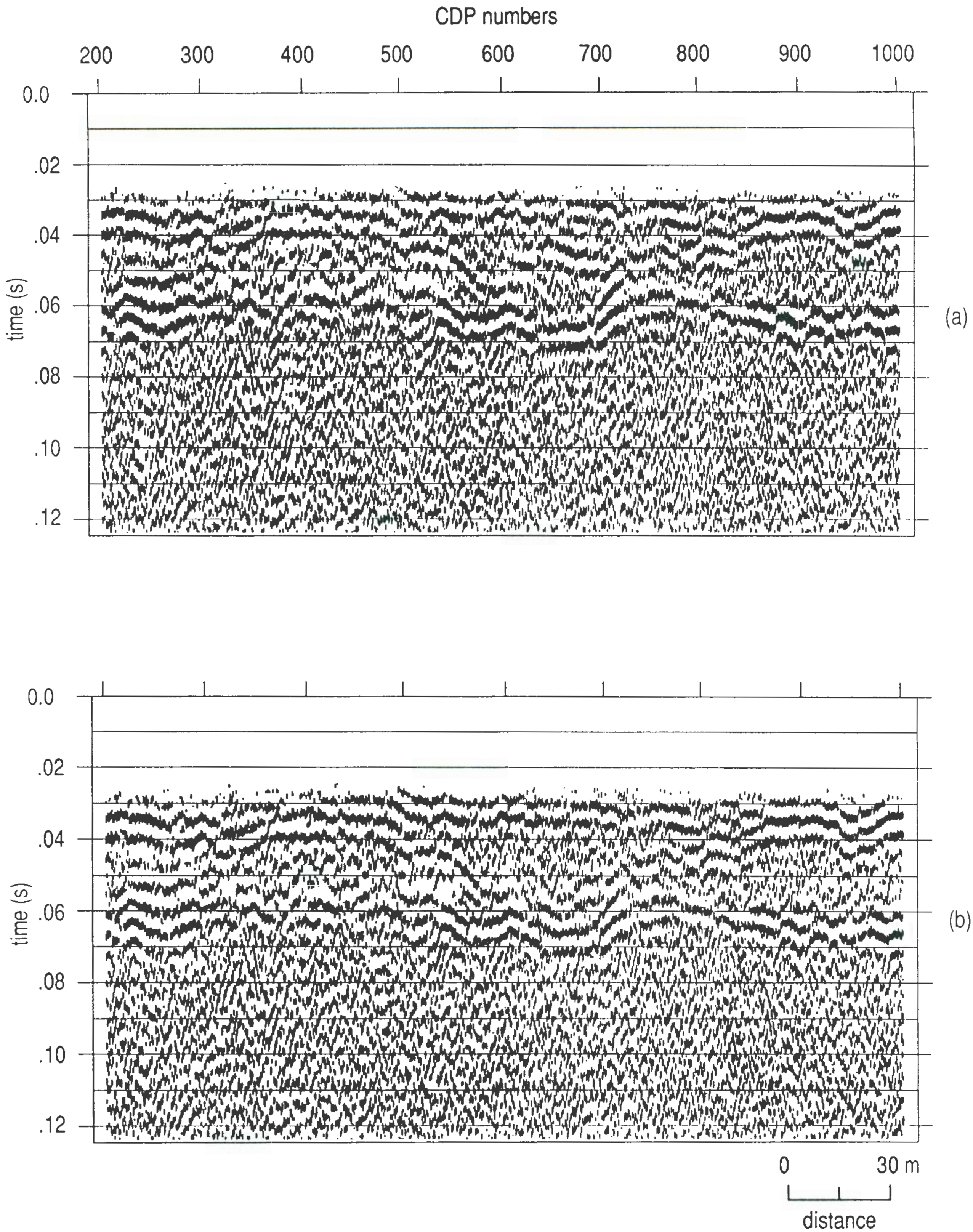

source-to-receiver
offset (m)
3.7
18.2
0.0
.02
.04
.06
.08
.10
.12
time (s)
0
7 m
distance

Figure 5



source -to-receiver
offset (m)
3.7
18.2
CDP numbers
250
270
290
time (s)
.02
.04
.06
.08
.10
.12
0
7 m
distance
0
3 m
distance

Figure 6



CDP numbers
200
300
400
500
600
700
800
900
1000
0.0
.02
.04
.06
.08
.10
.12
time (s)
(a)
(b)
0
30 m
distance

Figure 7

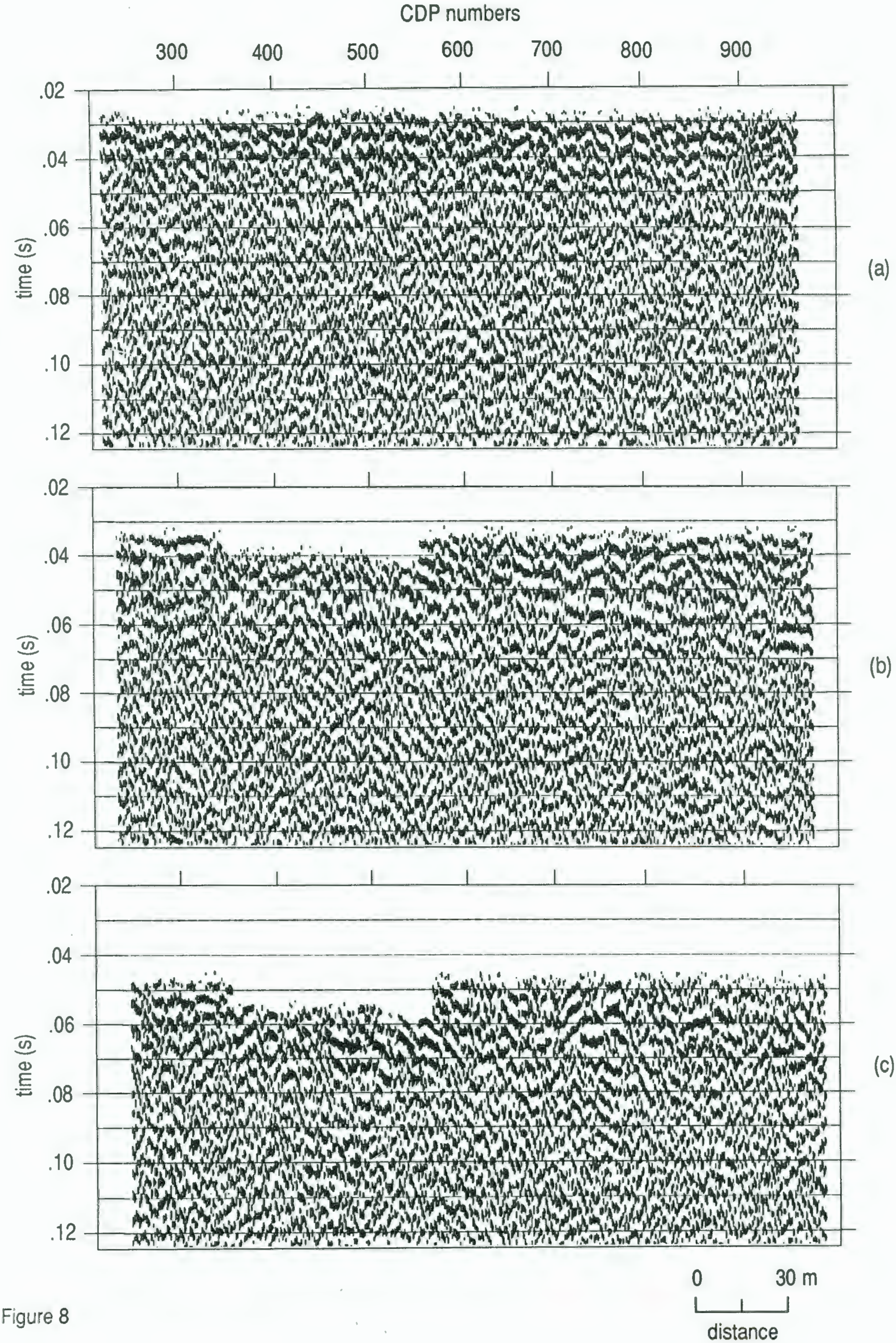

CDP numbers
300
400
500
600
700
800
900
.02
.04
.06
.08
.10
.12
time (s)
(a)
(b)
(c)
0
30 m
distance

Figure 8

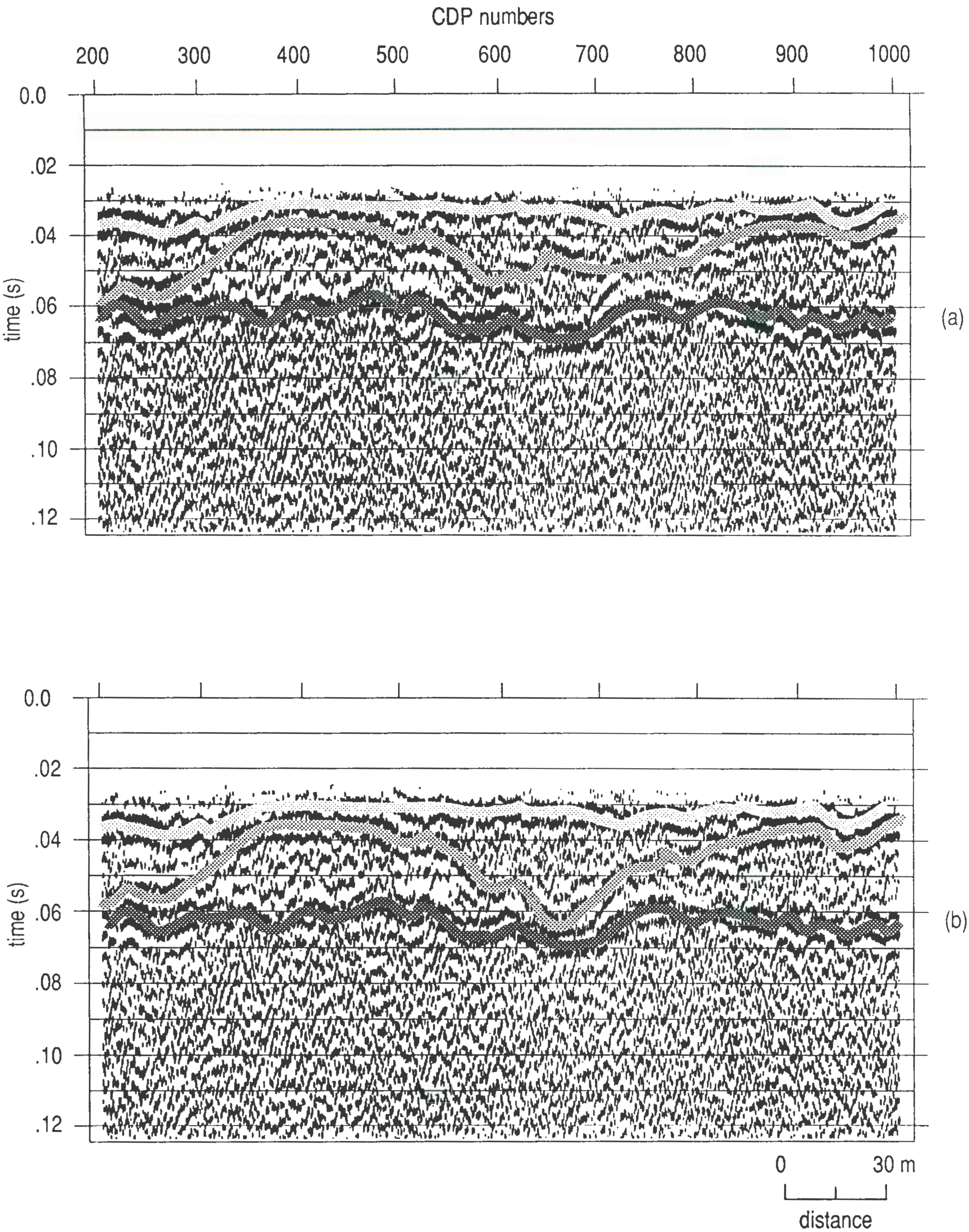
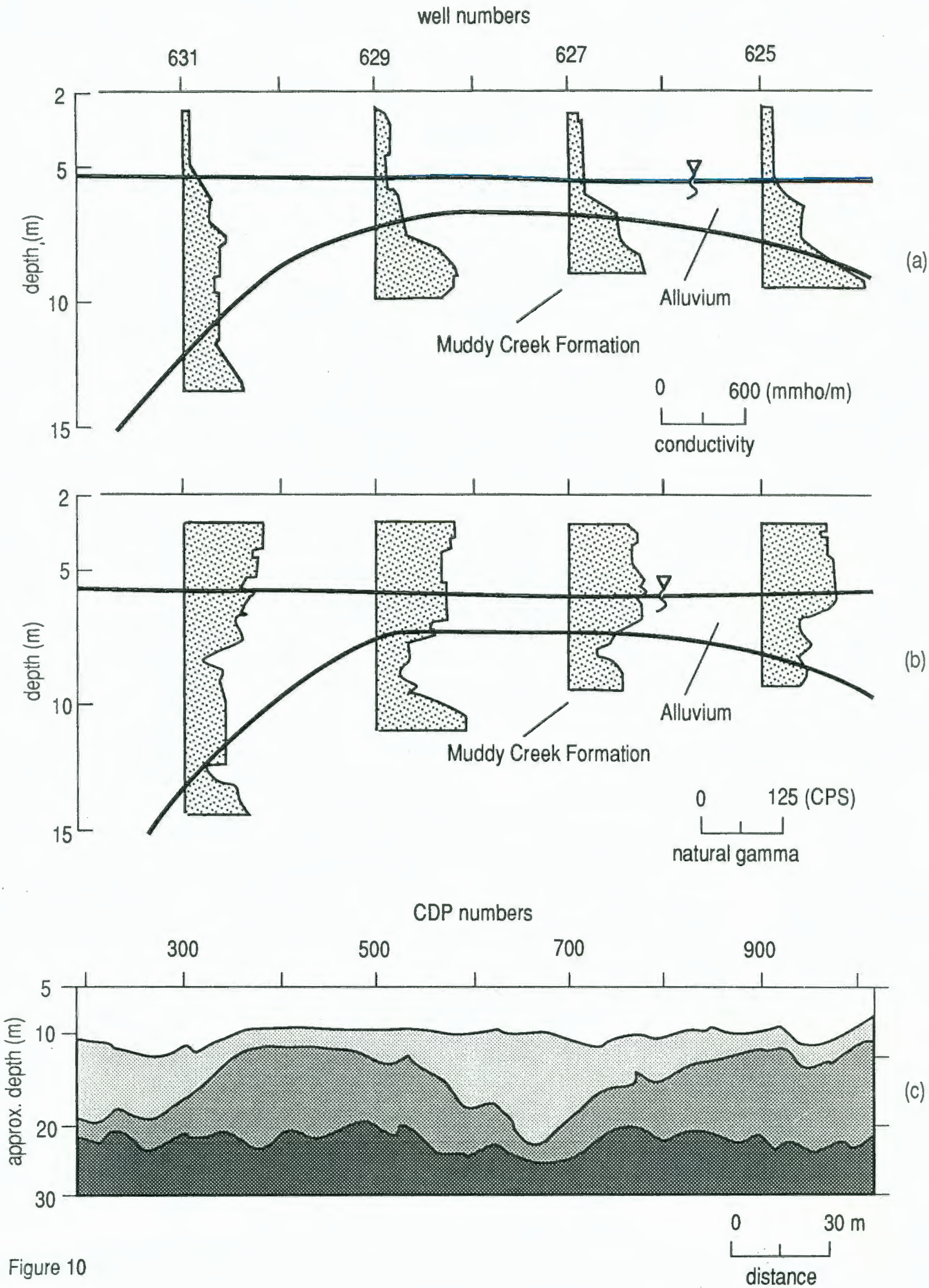

CDP numbers
200
300
400
500
600
700
800
900
1000
0.0
.02
.04
.06
.08
.10
.12
time (s)
(a)
(b)
0
30 m
distance

Figure 9



well numbers
631
629
627
625
2
5
10
15
depth (m)
Alluvium
Muddy Creek Formation
0
600 (mmho/m)
conductivity
(a)
2
5
10
15
depth (m)
Alluvium
Muddy Creek Formation
0
125 (CPS)
natural gamma
(b)
CDP numbers
300
500
700
900
5
10
20
30
approx. depth (m)
0
30 m
distance
(c)

Figure 10