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Seismic Reflection Methods

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COMPARISON OF COMMON OFFSET AND COMMON DEPTH POINT SHALLOW SEISMIC REFLECTION METHODS

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ABSTRACT

The seismic-reflection method has been increasingly used since 1980 in applications shallower than 30 m, using both the petroleum industry standard common depth point (CDP) method and the common offset (CO) method that was developed specifically as a low-cost technique for shallow surveys. At three sites where we have conducted shallow CDP surveys, we have "de-processed" the data into CO sections to compare the two methods. With both methods it is important to carefully follow known seismic reflections throughout the data-processing phase to avoid misinterpretation of things that look like reflections but aren't. The CDP method has advantages in signal to noise ratio in many cases, but the CO method has potential for higher resolution in those localities where it works. The CO method has advantages in cost of data processing, but has only a small advantage in field efficiency. The selection of seismic recording equipment, energy source, and data-acquisition parameters are often critical to the success of a shallow-reflection project with either method.

INTRODUCTION

It is the purpose of this paper to compare features and quality of shallow seismic reflection data using the common depth point (CDP) method (Mayne, 1962) and the common offset (CO) method (Hunter et al, 1984) as applied in some recent groundwater and environmental projects. A set of high-quality shallow seismic reflection data is used to introduce both the fundamentals of seismic reflection and a short discussion of CDP seismic data processing. This and two other CDP data sets were "deprocessed" into CO sections at several offsets to illustrate the differences between the two methods.

The seismic reflection method is a powerful technique for underground exploration that has been in use for over 60 years (see Waters, 1987; Dobrin, 1976). The use of seismic reflection surveys for targets shallower than 30 m has not been widespread until the 1980's, however. The work of Jim Hunter and Susan Pullan and their colleagues at the Geological Survey of Canada (Hunter et al., 1984; Pullan and Hunter, 1985) and Klaus Helbig (Doornenbal and Helbig, 1983; Jongerius and Helbig, 1988) and his students at the University of Utrecht in The Netherlands has been instrumental in developing shallow seismic reflection procedures. The CO method is now widely and routinely used in engineering and ground-water applications. Our own research has focused on probing the limits of the resolution and the applications of shallow seismic reflection using CDP techniques and extensive routine digital processing. Both approaches to shallow seismic reflection profiling have potential for misuse by individuals without substantial training and experience.

Shallow CDP and CO seismic reflection profiling are becoming less costly, and therefore increasingly used because CDP processing can now be done efficiently on a PC/AT compatible microcomputer (Somanas et al., 1987) and CO processing can be done on an Apple II (Hunter et

al, 1984). The revolution in microelectronics has resulted in construction of engineering seismographs and microcomputers for data collection and processing that now permit the cost-effective use of seismic reflection in a wide variety of applications. While the CDP method has signal to noise ratio advantages in some areas, the computer processing needed to use the method is substantial. The CO method has advantages of decreased processing costs, cheaper capital equipment costs, and sometimes higher resolution.

SHALLOW SEISMIC REFLECTION FUNDAMENTALS

Seismic reflection techniques depend on the presence of acoustical contrasts in the subsurface. In many cases the acoustical contrasts occur at boundaries between geologic layers, although man-made boundaries such as tunnels and mines also represent contrasts. Acoustical contrasts occur as variations in either mass density or seismic velocity or both. 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 the case of P-waves, which are compressional waves, the principles of sound waves apply and, indeed, P-wave reflections can be thought of as sound wave echoes from underground. P-waves propagating through the earth behave similar to sound waves propagating in air. When a P-wave comes in contact with an acoustical contrast in the air or underground, echoes (reflections) are generated. In the underground environment, however, the situation is more complex because some of the energy that is incident on a solid acoustical interface can also be easily transmitted across the interface or converted into refractions and/or shear waves. In addition to P and S-waves, there are two types of surface waves (Rayleigh and Love waves) that are present on seismograms. Most common on P-wave surveys are Rayleigh waves, commonly called "ground roll" because of the relatively low-frequency rolling motion that they cause.

The seismic reflection technique involves no a priori 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. The classic use of seismic reflections involves layered geologic units.

The simplest case of seismic reflection, a single layer over an infinitely thick medium, 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 particular ray path originating at the source will pass energy to the subsurface layer and return an echo to the geophone at the surface first, following Fermat's principle of least time. 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 mid-way 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.

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, but the reader should note that the ray paths are in general not straight lines, but are deflected at velocity discontinuities according to Snell's law. The fact that several layers often contribute to seismograms tends to make the seismic data more complex, since reflections from greater depths arrive at later times than shallow reflections. Complexity is often also increased by the presence of seismic energy that has bounced one or more times between layers in the subsurface (multiple reflections). In most cases, refracted waves and P-waves that have been converted into S-waves at subsurface interfaces will be present.

In the case of a multichannel seismograph, several points in the subsurface return reflected seismic waves to geophones. Figure 3 shows a seismic-reflection record with a prominent reflection from bedrock at 53 msec which corresponds to a bedrock depth of approximately 15 m. Note in Figure 4 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 a two-meter interval at the earth's surface, the subsurface reflections will come from locations on the reflector that are centered one meter apart.

In Figure 5a 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) (Mayne, 1962) 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, 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 (discussed in the next section of this paper). The degree of multiplicity of data from a particular location is known as "CDP fold." A 24-channel seismograph, for example, is commonly used to gather 12-fold CDP data. From a theoretical standpoint, signal-to-noise ratio of reflections improves proportionally to the square root of the CDP fold.

Figure 5b shows source and receiver locations for a CO survey. Note that for each shotpoint, only one receiver is used to detect the energy. That is where the "common offset" terminology originates. All shot-to-receiver distances are identical. The field procedure involves moving the shotpoint and geophone along the line by a fixed distance increment between successive shots.

The purpose of both seismic-reflection methods is to determine the spatial configuration of underground geological units. Figure 6 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. We also note here that it is impossible to look at a properly processed seismic section and know for certain whether it is a CDP section or a CO section. In the following sections, we provide a comparison between CDP and CO methods at three sites.

CDP PROCESSING OF SHALLOW REFLECTION DATA

The purpose of processing CDP seismic reflection data is to enhance the reflections at the expense of everything else. There are a wide variety of filtering, display, and static correction techniques that can be employed to improve the quality of the reflections. We will discuss only those techniques that are necessary to understand the fundamental CDP processing flow. There are many places in the scientific literature to obtain details (see Waters, 1987; Yilmaz, 1987).

The raw seismic data are in a field file format with each seismic trace for a particular shot stored according to field file number or shot point number and seismograph trace number. Several steps are necessary prior to the gathering or sorting the data into a CDP format.

The first processing step is removes dead or unacceptably noisy traces by editing. The next step is to make certain that each digital seismic trace has a horizontal and vertical location and distance from geophone to shotpoint explicitly associated with it in a header. This will allow for elevation corrections and for properly sorting the data. The data can then be sorted into CDP

gathers such as those shown in Figure 7. A CDP gather is a collection of all seismic traces that, from a simplistic point of view, have a common reflection point in the subsurface. Note on these gathers in Figure 7 that there is a strong reflection visible at about 40 msec. True reflectors on a CDP gather plotted with traces in order of increasing or decreasing distance from the shotpoint, have a hyperbolic curvature to them as can be seen on Figure 7. The degree of curvature of the hyperbola is determined by the average seismic velocity above the reflector, depth to the reflector, and distance from the shotpoints to the geophones. It is also dependent on dip of the reflector and topographic slope at the earth's surface.

A trace by trace depth and distance dependent time shift must be made to each trace to correct for non-vertical incident rays prior to the stacking of the CDP gathers, which requires that we determine the seismic velocity within the materials penetrated by the reflected seismic waves. The simplest procedure with good seismic-reflection data is to fit a hyperbola to the data using a least-squares approach, which can be done with a pocket calculator (Steeple and Miller, 1990). Note in Figure 6 that the data have been displayed as though the distance between shot and geophone were zero. This is known as zero-offset (vertical incidence) and the data are processed to approximate the zero-offset (or ideal) case.

Another approach is to have the seismic processing computer apply a series of constant velocities to the field records or the CDP gathers. The velocity that flattens the reflector the best represents the best NMO velocity for that CDP (see Figure 8) at that particular two-way reflection travel time. An extension of this technique is done by stacking several of the constant-velocity gathers for a group of CDP's into a constant-velocity CDP stack (Yilmaz, 1987).

After the velocity has been determined, the NMO correction is applied to all of the data. For shallow surveys, it is common to have a velocity model composed of only one low-velocity layer over a large thickness of high-velocity bedrock. For deeper surveys, it is common to have several layers in the velocity model.

At this point in the processing flow, we have sorted the data into CDP gathers and corrected for difference in source-to-geophone distance. We are now ready to sum all of the traces together within each CDP gather. Figure 9 shows five traces of CDP stacked data in which each stacked trace is composed of the post-NMO sum of twelve traces from CDP gathers like those shown in Figure 7.

Figure 10 shows the same five traces of CDP stacked data processed at three different test velocities. Note that the correct velocity gives the highest frequency and the best coherency on the stacked data. It is also important to realize that the correct velocity is the only velocity that puts the reflector at its correct depth. In other words, stacking CDP data with the wrong velocity hurts the resolution of the data, decreases the signal-to-noise ratio, and results in the wrong time-location on the final stacked sections.

PROCESSING COMMON OFFSET SHALLOW REFLECTION DATA

Once CDP seismic data have been collected, they can be processed either as CDP sections or as CO sections, but CO data cannot be processed into CDP sections. Displaying CO data from a CDP data set can be as simple as plotting all the data from a particular numbered channel on a multi-channel seismograph. Whether the data come from a CDP data set or not, the processing involves sorting data into geographically ordered batches of traces that have a common fixed horizontal distance between the seismic source and the geophone.

Once the data are sorted into CO gathers, they can be immediately displayed. In some simple cases, that may be all that is needed. One can often see faults and bedrock lows or highs without any processing of the data. If the objective of the survey can be accomplished without processing the data, then there is little reason other than aesthetics to continue manipulating the data. More commonly, however, static corrections are needed to compensate for variations in elevation along the shot and receiver line. Digital filtering is often useful in attenuating both high-frequency and low-frequency noise. It is also necessary to perform velocity analyses to move the reflection to its proper vertical position on the CO section and to be able to estimate absolute depth to the reflector since the velocity must be multiplied by 1/2 the reflection time to calculate depth. It is also possible to use more advanced processing techniques such as deconvolution and migration to improve resolution and spatial accuracy of CO data.

In order that refractions do not stay on the CO section for possible later interpretation as reflections, they should be muted from the records prior to plotting in section format. Likewise, groundroll should be either lo-cut filtered or removed by muting.

Once the data have been processed to the analysts satisfaction, there are several display options that can be used. One of the most common displays is the variable area display such as that shown in Figure 10. Another option is to show only the wiggly traces without darkened peaks, or to show only the darkened peaks but not the troughs. The advent of relatively cheap color plotting devices also allows new display options involving amplitude, frequency, and phase or combinations thereof.

SOME PITFALLS OF SHALLOW SEISMIC REFLECTION

Some of the major pitfalls of shallow seismic reflection are briefly discussed in this section. We have seen several examples during the past few years where seismic reflection interpretations have been ascribed to seismic data composed of refractions, ground roll, air-coupled waves, and/or just plain noise. While to our knowledge none of these occurrences has been published in the refereed scientific literature, some have been in geotechnical advertisements and in consulting reports and unrefereed conference proceedings. We believe that one of the biggest obstacles to wide-spread use of seismic reflection in the next decade is the potential misuse by those who fail to appreciate and understand the pitfalls of the techniques.

It has been our experience that occasional field records will display unusually good reflections. These field seismograms can be used to correlate to either CDP or CO sections. In all of our reports and published papers, we include at least one field seismogram to show that the reflections are real. When reviewing similar works prepared by others, we always like to see a field seismogram to verify that the "reflectors" were not manufactured during processing.

The CO method in particular is subject to pitfalls of interpretation by unskilled practitioners. Unless the data are properly muted (to get rid of refractions and air blast) or filtered (to get rid of ground roll) both refractions and ground roll can appear as coherent arrivals on the CO sections. There is absolutely no way to know for sure what path the wavelet energy took to get from the source to the geophone unless some multi-channel or at least multi-offset records are available. This cannot be overstressed!

Refracted arrivals should be muted during the early stages of the processing of both CDP and CO data to remove any chance of them stacking in on the CDP section or showing up as coherent arrivals on a CO section. Unequivocally separating shallow reflections from shallow refractions is clearly one of the major limitations of the shallow seismic method at the present time.

While groundroll is sometimes a problem on CDP sections, it tends to be relatively attenuated by the CDP stacking process. It also has a tendency to have a lower frequency than reflection energy. On CO sections, however, frequency observations and time window of arrivals are often the only discriminators available to identify ground roll.

FIELD PROCEDURES FOR SHALLOW REFLECTION

Field testing should always be done prior to conducting a production reflection survey. The testing is necessary to optimize data quality and cost-effectiveness. For CO surveys, it is necessary to have some multi-offset records to identify reflections. The recommended procedure is to conduct a walkaway-noise test by setting out closely-spaced geophones very near a test shotpoint. After the first test shot, the geophones are moved progressively farther from the test shotpoint and another test shot is fired. This process is repeated until the investigator is satisfied that all possible shotpoint-geophone offset distances of interest have been tested. For target depths of less than 30 meters, we commonly use a 0.25 meter geophone interval for a walkaway noise test. A useful rule-of-thumb is to divide the primary depth of interest by 100 and use that value for the walkaway test geophone interval. If the nearest geophone is placed less than a meter from the shotpoint, this has the effect of giving the investigator 100 traces of seismic data to look at with offsets less than the depth of interest.

Geologic target considerations will dictate how long (in time) the seismograms will be. For many shallow applications a time length of 100 msec is plenty, giving records to depths of 30 m or more in most localities. On seismographs that record data into random access memory (RAM), there is often a trade-off between record length and sample interval, since the total amount of RAM may be fixed by hardware or read-only memory (ROM). Once the sample interval is selected, an anti-alias high-cut filter must be selected to avoid aliasing of high frequencies to low frequencies. We have already noted how aliasing can make buggy wheels appear to turn backward in Western movies. It is possible to use rather gentle (24 dB/octave or less) analog high-cut filters for anti-aliasing purposes, but the industry standard seems to be a high-cut filter that is down 60 dB at the alias frequency. This is not so critical when using sample intervals of 1/4 msec or less since there is very little seismic energy present above the alias frequency of 2,000 Hz. This would be critical if the seismograph or any part of the seismic system had significant noise levels at frequencies above the alias frequency.

The selection of high-cut filters is not usually critical in shallow seismic surveys once any potential aliasing problem is solved. We usually record with high-cut filters out unless there is some strong source of unwanted high frequency noise. Provided the high frequency noise is not saturating the A/D converters, it can always be filtered out later with a digital filter that allows the processor to be selective in terms of pass band.

The selection of low-cut filters, on the other hand is one of the most critical decisions for a shallow reflection project. The earlier discussion of geologic requirements will dictate to some degree what frequency must be attained to meet the survey objective. In some cases, field testing will show that it is not possible to meet that objective. We usually test three or more low-cut filter settings during the early stages of the walk-away noise test. We select the filter setting that gives the best quality data in terms of allowing us to meet the survey objective. Sometimes a 340 Hz low-cut will make the data in the upper 50 msec look great, but will not allow the imaging of reflectors below perhaps 70 or 80 msec. In that case, if our objective is below 70 msec, we back the low-cuts out to 220 Hz, or whatever value is required to see reflections below

Energy required for reflection surveys is variable, depending upon near-surface geology and depth to water table; age, lithology, and attenuation in the rock section; CDP fold; number and sensitivity of geophones per group; quality of the geophone plants; dynamic range of the seismograph; gain and filter settings; local seismic noise; depth of objective layers; and frequency necessary to obtain desired resolution.

If signal enhancement is done in the field by vertically stacking records from multiple inputs of the same energy source at the same shotpoint, it is important that the energy input to the ground be from a highly repetitive source. In other words, the signal enhancement stacking technique depends upon each impact or shot being in-phase with, and similar in spectral character to, the other impacts or shots at all locations. Repeatability is also important in cases where determination of true amplitude is one of the survey objectives.

Discussion of seismic energy sources is not complete without mention of safety. Because we are trying to impart energy to the ground very rapidly with all of these sources, there exists an element of danger with each source. The investigator must be aware of and adhere to accepted safety procedures associated with any energy source used, and should become familiar with regulations involving any explosives, ammunition, or equipment used. Even a sledge hammer is capable of smashing fingers and toes and propelling steel fragments into unprotected eyes.

FIELD EFFICIENCY OF SHALLOW CO AND CDP REFLECTION SURVEYS

We have conducted extensive experiments in shallow seismic reflection since 1978. By 1982 we had obtained reflections at dominant frequencies of about 200 Hz from depths as shallow as 5 m (Steeple and Knapp, 1982). Most recently we have worked on increasing the field efficiency of shallow CDP seismic surveys to make them a cost-effective means of engineering exploration. We can now shoot 500 to 800 meters of line per day with 12-fold CDP coverage and shotpoint intervals of 1 m.

During the past eight years, shallow CDP seismic surveys at the Kansas Geological Survey have occupied more than 25,000 shotpoints (SP's). Our most productive day resulted in 12-fold data collection at 733 shotpoints on lines in two locations in less than 10 hours with a 24-channel DHR 2400 seismograph in 1984. It is possible now to sustain a data-collection rate of 100 SP's per hour for long periods of time if a single long line is being surveyed and field conditions are favorable.

A typical CDP crew consists of the following: (1) An observer who operates the seismograph in the recording truck and keeps detailed notes including shotpoint location, roll-switch position, geophone locations, and digital tape file number for individual seismograms. (2) A shooter who moves the energy source to each shotpoint and fires on command from the observer. (3) A jug hustler who stays at least 15 SP's ahead of the live geophones while emplacing the geophones in the ground. (4) A linesman who moves seismic cable from the back of the seismic line to the front, staying ahead of the jug hustler. The job of picking up geophones is shared jointly by the jug hustler and the linesman, depending upon who is least busy. It would be possible to increase data-collection rates to some degree by adding two or three people to the crew along with extra cables and geophones. The present limitation in productivity is mostly limited by the time required to write data to digital tape after each shot.

The above quoted data-collection rates are based on a shotpoint, cable takeout, and geophone group interval of between one m and five m each. The field efficiency is dependent upon both the takeout interval and the time required to move, set up, and fire the energy source. If the cable

takeout interval is the same as the group interval, then maximum efficiency can be obtained by the linesman and jug hustler.

While the CO method would seem at first thought to be much faster in the field, that is not the case. Consider that for a comparable survey, the same number of shotpoints must be occupied and almost the same total number of geophone plants must be made. In other words, the total field work to be performed is only slightly more for the CDP method than for CO surveys. The CDP cables are commonly heavier which may require more time in handling, it takes more time to dump the CDP data to tape or disk, and more time is required for initial setup and final takedown of the line. Other than these relatively minor items, the field effort required is the same. Although we don't have extensive data available to us, we estimate field cost for a 12 fold CDP surveyed to be less than 10% more expensive than a CO survey.

CASE STUDIES COMPARING CDP TO CO

The case studies shown here all involved original CDP surveys that were deprocessed into CO sections after CDP processing had already been done. In fact, the data shown here are presented in a way that casts the CO method into the most favorable circumstances. The deprocessed CO stacks have had all of the advantages of CDP statics and velocity analysis applied to them. In other words, if one were to conduct a CO survey at any of the three case-history sites, it would not be possible obtain either static corrections or velocity analysis of this high quality using the CO data alone.

For all of the case histories described here, data were recorded on an Input/Output 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. The record length is 125 ms with a sampling interval of 1/4 ms. The dominant-reflection frequencies observed during testing did not exceed 250 Hz. The analog low-cut filters (-3 dB point of 220 Hz with 24 dB/octave roll-off) helped reduce the amount of recorded ground roll.

Case 1: Mapping Bedrock in the Texas Panhandle

Shallow seismic-reflection techniques were used to image the bedrock-alluvial interface, near a chemical evaporation pond in the Texas Panhandle, allowing optimum placement of water-quality monitor wells (Miller et al, 1989). The seismic data showed bedrock valleys as shallow as 4 m and accurate to within 1 m horizontally and vertically. The normal moveout velocity within the near-surface alluvium varies from 225 m/s to 400 m/s. All monitor-well borings near the evaporation pond penetrated unsaturated alluvial material. On most of the data the wavelet reflected from the bedrock-alluvium interface has a dominant frequency of around 170 Hz. Low-cut filtering at 24 dB/octave below 220 Hz prior to analog-to-digital conversion enhanced the amplitude of the desired bedrock reflection relative to the amplitude of the unwanted ground roll. The final bedrock contour map derived from drilling and seismic-reflection data possesses improved resolution and a bedrock valley not interpretable from drill data alone.

Geologic Setting and Field Procedures

Drill data from around the evaporation pond in Hutchinson County, Texas, prior to the seismic survey, showed a 3 to 15-m-thick layer of dry alluvium overlying a Permian-aged red-bed sequence composed of limestones, shales, and dolomites. The variations in bedrock elevation, as evidenced on the drill data, are primarily caused by an erosional surface of the Permian-aged red beds beneath the alluvium. The ground-surface topography is a generally subdued version of the major bedrock topography.

The data were collected using a modified 30-06 hunting rifle and single undamped 100-Hz Mark Products geophones. The rifle was modified with a blast-containment device that reduced the amplitude of the air-coupled wave as well as contained any stray bullet or rock fragments. The source was centered between two sets of 12 live geophones with a source-to-closest-receiver distance of 3.7 m.

Data Processing

Data processing was done on a 32-bit Data General 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 very similar to that used on seismic data for petroleum exploration (Table 1). The main distinctions were the emphasis and detail placed on near-surface velocity analysis and the extra care exercised in muting refracted arrivals.

The dry alluvium that overlies the bedrock showed extreme lateral variations in stacking velocity over very short horizontal distances. In certain areas, alluvial P-wave velocities fluctuated by 150 m/s (40%) in less than 50 m on the ground surface. With velocity changes this large, a detailed velocity function was required to optimize the normal-moveout corrections producing sharp, clean reflecting events on the stacked sections. The suite of trial velocities applied to each CDP during velocity analysis included 25 different velocities incremented by 8 m/s between about 220 m/s and 420 m/s. Slight variation in the normal-moveout velocity in this area can significantly affect the frequency, character, and apparent two-way travel time of the resulting stacked wavelet (Figure 10).

The coherency of the stacked data was improved by a surface-consistent statics routine with a 1-ms (equivalent to about 1/6 of a wavelength) maximum allowable static shift. The statics operation enhanced the subtleties previously suspected on preliminary stacked sections. No processing procedure after the detailed velocity analysis altered the general interpretation of the data.

Discussion of CO and CDP Data

The CO data at this site could be used to interpret the bedrock lows (Figure 12). Note on Figure 11, however, that the bedrock depth varies by about a factor of three along this line. This means that the optimum offset for the CO data also varies by a factor of three. Hence, it is impossible to choose one single CO that works for this whole survey. This may be the greatest limitation of the CO method at sites where the data quality is excellent, but where the target depth fluctuates with great amplitude. The bedrock reflector varies in two-way travel time between about 15 ms and 70 ms, which equates to a bedrock depth from about 4 m to 14 m.

Shallow reflections recorded from the bedrock surface at this Hutchinson County, Texas, site possessed sufficient resolution to confidently identify the major paleo-drainage and bedrock lows near an evaporation pond using the CDP method. The dominant recorded frequency of the data was about 170 Hz. The seismic data improved the overall accuracy and precision of the bedrock-structure map by more than an order of magnitude. CDP-by-CDP velocity analysis was necessary to properly correct for the normal moveout alignment of the bedrock reflector. Without the detailed lateral-velocity analysis, extreme velocity variations over short segments of the line could have resulted in decreased frequency and coherency of the stacked data and erroneous calculations of depth-to-bedrock. The detailed velocity analysis would not have been possible using the CO method by itself.

Case 2: Basalts of the Snake River Plain, Idaho

The objective of this feasibility study was to determine if the seismic-reflection method could help to optimize placement of water-quality monitoring wells near a radioactive storage facility. Seismic reflections from depths less than 30 m were recorded along a 500-m-long line over a basalt, rhyolite, and sedimentary sequence in the Snake River Plain. Some shallow reflections at 40 to 50 ms on the field files are of exceptional quality with frequency exceeding 150 Hz. Reflections and refractions from selected seismograms along the line possess vastly different normal-moveout (NMO) and apparent velocities as well as wavelet characteristics. Extreme variation in quality, seismic character, and reflector geometries observed on seismograms gives the appearance of varying geologic settings, and is uncommon for such short distances. Severe surgical muting was necessary for accurate velocity and statics analyses. The seismic-reflection data show apparent structural lows in a sedimentary layer sandwiched between basalt flows. Interpreted structural lows must be verified by drilling before a monitoring plan can be fully developed. Similar shallow-reflection surveys could also be used to improve deeper conventional seismic data in this and other basaltic terrain.

Geologic Setting

The study area is located within the central/eastern Snake River Plain (SRP) between Arco and Idaho Falls, Idaho. The SRP is a depression filled with several km of basalt, rhyolite, and sediments of Cenozoic age. In some areas within the SRP, up to 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 SRP are mostly compound pahoehoe flows, 3-to-5-m thick, interbedded with numerous, usually thin, sedimentary layers which are mostly clay and sand with occasional gravel and loess deposits. High resolution seismic-reflection techniques have previously been successful in mapping basalt/sand sequences in the SRP in the 75- to 450-m depth range (Miller et al., 1988).

This seismic-reflection profile was collected along a well-manicured road bed composed of sands and clays no more than 1-m thick overlying classic SRP surface topographic features. A single borehole with significant geologic and geophysical information (no velocity or sonic information) was present along the line. The general geology of the borehole was consistent with other boreholes from within the SRP. The horizontal consistency and continuity of the identified geologic units is unknown. The primary target of this reflection profile was the sedimentary unit shown at approximately 30 m on geophysical and geologist's logs. This unit, if continuous, could serve as a conduit for fluids flowing away from the radioactive storage facility. Of secondary interest is the thicker sedimentary unit at approximately 80 m. The 30-m and 80-m deep units could both be recorded with a single survey under more ideal surface conditions and/or with equipment possessing greater dynamic range and double the recording channels.

Field Procedures

The seismic data were collected along one 500-m-long line intersecting well 88 at CDP 258. The surface material along the line varied from fine sand to basalt with a modest stand of sagebrush. Problems of maintaining consistent source-and-receiver coupling to the sandy ground were compounded by the multiple basalt outcrops along the line. Due to the rough and variable surface terrain, the geophones were planted in the base of the road ditch. The source was fired on the road shoulder nearest the geophones maintaining consistent source-and-receiver ground

coupling from station to station while minimizing site logistic problems associated with outcropping basalt.

Seismic-reflection data were recorded using a standard CDP acquisition method (Mayne, 1962). To optimize the use of available equipment and acquisition procedures, selection of field geometry, source, receivers, and recording parameters were made in the field after extensive testing. The data were acquired using an end-on source-receiver geometry and a 1-m shot-and-receiver group interval. The optimum offset window method (Hunter et al., 1984) was used to select near and far offsets of 12 and 35 m, respectively.

The source was a silenced .50-caliber rifle fired vertically into the ground through a silencer held firmly to the earth's surface (Steeple et al., 1987). 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 also as a containment vessel for any rock or bullet fragments generated as a result of firing into a hard surface.

The receivers were three 40-Hz geophones on 14-cm spikes, damped to 0.65 of critical, and connected in series. The three geophones were in-line and equally spaced over 1-m to reduce the amount of recorded air-coupled waves and wind noise. The primary component of the air-coupled wave recorded with the 220 Hz low-cut filters had a wavelength of approximately 1.5 m. The 1-m array effectively attenuated much of the dominant 200-Hz energy of the air-coupled wave without affecting the high-frequency near vertically incident reflection energy (Knapp and Steeples, 1986a). The array will attenuate (to a lesser degree) source-generated linear coherent energy with frequencies other than the dominant. The preferential orientation of this 1-m in-line array was also effective in reducing recorded wind noise with primary direction of propagation nearly parallel to the array. The array improved the signal-to-noise ratio by reducing the amount of recorded random environmental noise. The use of small arrays is not intended to (nor can it) totally cancel wind noise or source-generated air-coupled waves, but it increases the signal-to-noise ratio of the recorded data.

Over 35 reversed-refraction profiles were shot to determine a near-surface layer velocity and depth model. The refraction data were acquired coincident with the reflection profile using the same geophone plants, a sledge-hammer source, and minimum and maximum source-to-receiver offsets of 0.5 and 18.5 m, respectively. The velocity and depth information derived from the refraction model was used to compensate the reflection data for the varying thickness of surface sand that overlies the basalts.

Data Processing

The key to identifying true geologic structures or stratigraphy on CDP stacked shallow seismic sections is clear identification of reflection energy on raw, unprocessed field files (common shot gathers). Hyperbolic time-distance moveout of reflection energy can be identified on most field files across the survey line (Fig. 13). Field file 33 from near well 88 has several relatively strong reflection arrivals. The event at approximately 55 ms has an NMO velocity of approximately 1100 m/s and a calculated depth of 30 m correlating to the 3-4-m-thick sedimentary layer at about 30 m of depth on geophysical logs of well 88. Due to the extreme variability of the near-surface geology along the line, correlating that reflection event from field file to field file is impossible over horizontal distances of more than about 30 m. The velocity, apparent structure, and general reflection character of the seismic data on the raw field files vary

greatly from one near-surface basalt-flow lobe to another. The general variability in the raw data emphasizes the need for care during 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 extreme inconsistency in reflector depths and normal-moveout velocity probably related to variable thickness of the low-velocity near-surface layer (Table 2). The surface -consistent statics operation was limited to a maximum allowable shift of less than 2 ms (1/4 wavelength). The residual statics operation was limited to less than a 1-ms maximum allowable shift (1/8 wavelength). Extraordinary emphasis was placed on point-by-point velocity analysis and surface-consistent statics operations.

The velocity structure is complicated by flow irregularities, non-uniform sedimentary deposition, and a variable thickness of near-surface material characteristic of basaltic environments. Brute-stack section processing includes preliminary velocity and spectral analysis as well as surface-consistent statics. No coherent reflection information could be confidently identified on the brute stack.

In an effort to enhance high-quality reflections present on raw field files but not obvious on the CDP brute stack, a special processing flow, involving computations on reflection energy only, was used. Processing and analysis (velocity and statics) of data that contains only reflection energy will result in the most accurate CDP stacked data set. The data were surgically separated into two data sets: (1) seismic reflections that could be identified on field files, and (2) everything-else. The velocity analysis and surface-consistent statics computations were done on the reflection-only information to avoid the influence of coherent noise or other non-reflection energy present on the raw seismograms.

The static and dynamic corrections derived from reflection-energy-only analysis were uniformly applied to both the reflection-only data and to the everything-else data. After the corrections were applied to the two data sets (reflection-only and everything-else) independently, they were merged, CDP sorted, and stacked. Refractions were muted from the everything-else data set before the two data sets were merged.

Stacking velocities were calculated from CDP gathers without dip moveout (DMO) correction (partial pre-stack migration). (Appropriate software for dip compensation was not available to us.) The stacking velocities ultimately assigned to each CDP gather identify hyperbolae that best flatten reflection events. The assigned stacking velocities may not be consistent with the true average velocities; therefore, on portions of the line with significant apparent dip, the stacking velocities were not and should not be used to estimate reflector depth. DMO correction would be necessary on this data set if migration were part of future processing. The lack of dip compensation may slightly distort both the frequency characteristics and apparent spatial location of reflection wavelets on a stacked section.

A layer over-half space model, derived from the reversed refraction survey, was used to remove the effects of inconsistent thickness/average velocity of the near-surface layer. The very short wavelength undulations (less than approximately 30 m) in the interpreted basalt upper surface were manually smoothed to concentrate the refraction static operation on long wavelength static inconsistencies. The average interval velocity of the weathered layer was calculated at approximately 500 m/s overlying an approximately 2000 m/s basalt layer. The refraction data indicated a maximum slope on the basalt surface on the order of 11 degrees. This correction reduced the effects of the laterally varying near-surface thickness on depth determinations.

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 remaining reflection information. The high-frequency noise that was injected during the deconvolution process degraded the overall data quality.

Results from Idaho data

The primary objective of the reflection survey was delineation of the unsaturated sand layer at a depth of about 30 m. The dominant frequency of much of the raw data is in excess of 150 Hz. Using a one-fourth wavelength minimum vertical resolution criterion (Widess, 1973) and assuming an interval velocity of 1000 m/s for the sand layer, the vertical bed resolution limit is approximately 1.7 m. The horizontal sampling interval was 0.5 m in the upper 30 m, providing over 15 samples within the first Fresnel zone. Minor distortion in interpreted geologic structure can occur in some situations as a result of oversampling the first Fresnel zone (Myers et al., 1987). This geologic setting, in association with the characteristics of the seismic data, suggests some smoothing of apparent structure has occurred as a result of oversampling. Oversampling of Fresnel zones was necessary, however, to maintain coherency of the reflections in this highly heterogeneous environment.

Coherent reflections on several seismograms possess uncharacteristic curvature (moveout). On a few of these seismograms the curvature of the coherent reflections appear to be reversed (reflected energy arriving earlier in time at receiver locations farther from the source). Arrivals at approximately 50 ms on record number 267, in particular, have a slightly distorted hyperbolic curvature with the apex near the middle of the spread (Fig 13). The right side of the curve possesses wavelet characteristics and arrival patterns consistent with other reflections from this part of the line and is interpreted as a primary reflection. The left side however, may be diffraction arrivals since it has a slightly higher frequency and possesses reduced amplitude. The diffraction arrival (left side of the curve) may have emanated from the termination point of the acoustic interface responsible for the 50-ms reflection arrival (right side of the curve).

The stacked reflection section (Fig. 14) possesses sufficient quality and velocity control to correlate the reflection at approximately 40 ms to the 30-m deep sedimentary layer identified on the logs of well 88. The acquisition and processing of this entire data set were focused on recording and enhancing the sedimentary reflector identified on field files at about 50 ms. (This reflection occurs at about 40 ms on the stacked section after dynamic and static corrections.)

The apparent major long-wavelength synclinal structure and the multiple localized structural lows observable in the 40-ms-deep sedimentary layer (Fig. 14) are related to real geologic features and/or physical properties changes. The long-wavelength synclinal structure located between CDPs 250 and 860 has a maximum relief of about 15 m. The multiple apparent localized structural lows, generally no more than 30 m across, have a maximum relief of no more than 10 m.

Frequency and phase anomalies evident at several places on the seismogram make it difficult to confidently correlate the sedimentary reflector along the line (Fig. 14). For example, between CDPs 350 and 400 and between CDPs 625 and 700, the reflection frequency varies as much as 25 percent. Abrupt horizontal variations in phase angle of as much as 120 degrees are observable at CDPs 200, 525, 770, and 975. Near-surface variations, changes in the geology at or near the depth of the reflector, or phase distortion in the seismograph amplifiers are responsible for these phenomena. Without additional drill information and a check-shot velocity survey, neither

confident correlation of the geology across these areas nor determination of the source of the phase and frequency distortion are possible.

Some of the slightly disjointed appearance of the reflector could be a result of extreme fluctuation in stacking velocity from point to point and is probably not related to faulting. The overall coherency and consistent appearance of the event on the processed sections support the general geologic interpretation.

The CO sections for the Idaho site are included as Figure 15. The rapid variability of the subsurface geology at this site makes it difficult to follow any wave-form for more than a few traces, except for near the center of the line where low-frequency refractions are apparent between times of 30 and 60 msec. At this site, the CO method does not have the signal to noise ratio that is needed to interpret the data. The CDP method also provides data that are probably marginal in terms of interpretability, but the interpretation is not yet tested with the drill. The CO method would likely have some danger for interpretation of refractions as reflections near the center of the line where coherent events are present.

Case 3: Pittman Lateral, Henderson, Nevada

The Pittman transect in Henderson, Nevada is a site where polluted waters from an unknown source are moving laterally toward intake facilities for the Las Vegas water supply. Several geophysical and geological exploration techniques have been employed at the site in 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. These data are from a report on a seismic-reflection survey at the Pittman Transect by the Kansas Geological Survey under contractual funding from LEMSCO.

Geologic Setting, Field Procedures, and Data Processing

The water table at the site is roughly 15 feet below the surface which is composed of poorly sorted dry alluvial sands and clays. The sands and clays terminate against a poorly-consolidated clay bedrock at a depth of 40 to 90 feet. The purpose of the seismic survey was to try to map the boundary between the alluvial materials and the underlying clay bedrock. The acoustical contrast across this stratigraphic boundary was suspected to be marginal to produce seismic reflections, and that was found to be the case during the seismic-reflection survey and subsequent processing.

The seismic survey included one 12-fold CDP line, 800 ft in length, traversing an area with good well control. The preliminary bedrock-profile map compiled from drill data and geophysical logs shows a bedrock low on the west end of the line.

The data were collected using a modified 30-06 hunting rifle and single undamped 100-Hz Mark Products geophones. The rifle was modified with a blast-containment device that reduced the amplitude of the air-coupled wave as well as contained any stray bullet or rock fragments. The source was located off-end from 24 live geophones with a source-to-closest-receiver distance of 3.7 m.

Data processing was done on a 32-bit Data General 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 very similar to that used on seismic data for petroleum exploration (Table 1). The main distinctions were the emphasis and detail placed on near-surface velocity analysis and the extra care exercised in muting refracted arrivals.

Results from Henderson, Nevada data.

Unequivocal identification of reflection information on field files is crucial for discriminating reflection energy from noise on a seismic section. A strong reflection event can be identified on most of the raw field files at about 40 ms (Figure 16). The average calculated normal move out (NMO) velocity of the event at 40 ms is 1700 ft/s. This indicates the reflector is approximately 34 ft deep. Deeper reflection energy is present on several field files around 60 ms with an average NMO velocity of 2000 ft/s. The 60 ms reflector is at a depth of approximately 60 ft.

The reflection energy identified on field files possesses a dominant frequency of around 180 Hz. This should allow bed resolution on the order of 3 ft assuming the 1/4 wavelength criterion for bed discrimination. A significant amount of coherent high frequency energy can be identified prior to the first arrival of seismic energy on raw field files. This energy is caused by the high voltage power lines approximately 200 ft from the seismic line and parallel to it. This recorded high-frequency noise decreases the dynamic range of the seismic data and our ability to detect subtle high-frequency reflections. Digital frequency filtering improved the overall clarity of reflections previously identified on raw field data but failed to greatly enhance their relative amplitude or to enhance other reflection energy hidden by noise. Ground roll and other seismic energy, where present, has a dominant frequency around 125 to 150 Hz.

The seismic line ran parallel to a series of monitor well placements 200 feet apart. The conductivity and gamma geophysical logs in conjunction with the geologists logs were compiled onto a single figure that was provided to us to help plan the seismic field work and interpret the seismic reflection data. Visual cross-correlation of the geophysical logs suggests another geologic unit above the "bedrock" could be present at approximately 25 to 30 ft on the western portion of the seismic line. This could be the interface that resulted in the pronounced reflection arrival at approximately 40 ms on the raw field files.

Interference between the reflector identified at 40 ms and refraction arrivals can be observed on most field files across the line (Figure 16). The observed effect of this interference on the reflector is a slightly distorted wavelet and drastically inconsistent trace-to-trace amplitude and frequency characteristics. This variability in the shallow reflector made separation of true reflection energy from refraction energy very difficult and in some cases impossible at various points along the line. In order to ensure accurate correlation of this reflector between raw field data and a finished CDP stack, a first-arrival mute was applied to eliminate refraction and direct-wave energy. Identification of reflected energy at each step in the processing flow was possible when using the first-arrival muted data.

Common offset gathers were produced to ascertain the feasibility of the optimum window technique (Hunter et al., 1984) in this area. The gathers are grouped into 24 different source-to-receiver categories with channel 24 farthest from the source. The common offset information was analyzed with a first-arrival mute (Figure 18). Apparent coherent signal interpretable below about 50 ms on the gathers in most cases can be correlated back to the raw field data and identified as ground roll. Some suggestion of coherent reflection energy at approximately 70 ms can be interpreted on the west portion of the line at the farther offsets. The low frequency and low signal-to-noise ratio makes identification and correlation of reflection events difficult on the common offset gathers.

The CDP stacked data have several interpretable events (Figure 17). The reflector at approximately 40 ms is the most pronounced from both an amplitude and coherency point of view. The reflection information from below 50 ms is subdued and in some places along the line lacks consistency in trace-to-trace wavelet characteristics. Some reflection information can be interpreted at about 70 ms near the west end of the line. The 70-ms reflector possesses some structure and apparently merges with the 40-ms reflector at about CDP 560. Several low amplitude coherent events can be interpreted between the 70 ms reflector and the 40 ms reflector on the west end and between 50 ms and 70 ms on the east end.

The observed interference between the shallow reflector and the refractions is responsible for the apparent drastic and occasionally abrupt changes in frequency and coherency of the 40 ms reflection. From field-file refraction analysis, the apparent refraction velocity changes from 1200 to 1700 ft/sec and apparent depth changes by at least a factor of two across the line. The degree to which the refraction interferes with the reflection varies as the refracting interface varies. The effect of this interference on the reflector cannot be effectively removed without drastically degrading quality of the reflecting event by severely digitally filtering with a narrow pass band. The interference phenomena can be observed more clearly on the post-first-arrival muted data. The reflector near the mute zone has a full octave of variability in frequency and as much as 360 degrees variability in phase. If the dominant frequency of the reflection energy could have been boosted by another 50 to 100 Hz, the observed inference phenomena would have been minimal. The shallow reflector, as it is interpreted on Figure 9, lacks good trace-to-trace coherency, but does represent the true structure of the reflecting interface.

Accurate depth correlation of this event to borehole derived information is not possible without an uphole seismic-velocity survey. However, after careful examination of the geophysical logs, there is some indication from seismic data and borehole data of a discontinuity at a depth of approximately 30 ft. This event appears to be relatively flat across the entire traverse, possibly related to some age discontinuity that may not have been noticeable in the drill cuttings. Correlation of the one-way travelttime measured from an uphole velocity survey would allow a time-to-depth conversion. Depth values obtained from such a survey would come from direct measurement as opposed to the technique used in this report which involves estimating a NMO velocity using a curve fitting routine and then calculating depth.

RESULTS AND CONCLUSIONS

(1) Near-surface alluvial materials are highly heterogeneous and sometimes anisotropic. Detailed velocity analyses are often necessary to extract reflections within alluvium and from shallow bedrock when using the CDP method. At all three localities used for this report, detailed velocity analysis was necessary. Velocities at the Texas site varied by as much as 40% over horizontal distances of as little as 20 meters. The CDP survey at the Idaho site required more than 50 velocity functions over a line length of 500 meters. Obtaining accurate velocity information at these two sites would be impossible with the CO method alone.

(2) The static corrections can be done by powerful statistical methods involving multiple combinations of source and receiver locations when the CDP method is used. The CO method is very limited in the way that static corrections can be applied.

(3) Sometimes the reflections cannot be seen at all with CO methods, but can be seen with CDP methods. This is noted at the Texas site where none of the CO sections shows the reflection continuously along the line. The CDP line has continuous reflection information from one end of the line to the other.

(4) One of the keys to detection of reflections is establishing coherency of wavelets across several traces on the field seismograms. For initial field testing at some localities, geophone group interval (i.e., the distance between single geophones) must be decreased to as little as 1/2 or 1/4 m. Note that we commonly use a group interval of 1 m during CDP production surveys. The CO method involves traces that have different source and receiver for each trace. The CDP method is much more likely to allow coherency of identifiable wavelets because of the capability to examine common shot gathers.

(5) Interpreted reflections on CDP stacked data or CO sections need to be supported by field records. The magical appearance of reflections on stacked data can be the result of various types of enhancement processing techniques or lack of muting refractions, air blast and ground roll. Any wave that is similar from shot-to-shot can look like a reflection on a CO section.

(6) Despite its difficulties, the CO method has the potential to provide better resolution in good data localities. The CDP method tends to smear data because of the imperfections in velocity and statics analysis and because of spectral variations in data caused by variable source signature and geophone plants. As a result, we commonly lose as much as 20% of the upper edge of our bandwidth. Birkelo et al (1987) showed dominant frequencies of about 325 Hz on the unprocessed field data, but dominant frequencies of only about 265 Hz from the same data after CDP processing.

(7) The CO method has some advantage in cost, particularly in terms of computational requirements of processing the data. As computer time becomes cheaper and cheaper, this will become less of a concern. The CO method also enjoys perhaps a 10% advantage in terms of cheaper field data collection.

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FIGURE CAPTIONS

- FIG. 1. The simplest case of seismic reflection. S represents the source and R represents the receiver. Layer 1 represents an acoustical discontinuity.
- FIG. 2. Reflected rays from three layers. In general the ray paths are deflected from straight lines at boundaries between layers according to Snell's law, so this figure is oversimplified.
- FIG. 3. Field seismogram (unprocessed) showing bedrock reflection at about 53 msec. The hyperbolic shape of the shaded zone is characteristic of simple reflections. The earlier arriving energy is from air blast and from direct arrivals passing through near-surface alluvium. Geophone offsets are 3 m for the inside two traces, increasing to 16 meters for the most distant traces.
- FIG. 4. Schematic view of reflection ray paths in a single layer case for a six-channel seismograph. Note that the common depth point spacing is exactly half the geophone spacing.
- FIG. 5a. Illustration of the common depth point (CDP) concept. In the case of a 24-channel seismograph with shotpoints occurring at all geophone locations, the subsurface reflection points will be sampled 12 times, resulting in 12-fold CDP data after processing.
- FIG. 5b. Shows the concept of common offset (CO). The shot point and the geophone location are progressively moved across the ground, keeping the distance between them constant.
- FIG. 6. Combining the 3-dimensional geology with a conceptual seismic section. The geology is interpreted from coherent blackened peaks on the seismic section. Seismic data are processed to emulate what they would look like if the shotpoints and geophones were located at the same point on the earth's surface.
- FIG. 7. Common depth point gather at points 988 and 989 on a particular shallow seismic survey. The most prominent seismic wavelet at times between 50 and 70 msec is a bedrock reflection from about 9 m below the surface. The geophone offsets were 3.7 m for the nearest traces and 17 m for the farthest trace with 1.22 m between geophones.
- FIG. 8. Velocity analysis on CDP gather at point 988 from Figure 7. Note that 1075 ft/sec is too slow and the moveout is too great on the far traces. A velocity of 1225 ft/sec nicely flattens the reflection signals in preparation for adding the traces in the computer. A velocity of 1375 ft/sec is too fast and does not provide enough moveout on the far traces to flatten the reflection signals.
- FIG. 9. Five traces of 12-fold CDP stacked data showing bedrock reflection at about 50 msec. Each trace has had 12 field traces added together after they were individually adjusted by applying velocity-distance normal-moveout (NMO) based on the velocity analysis of Figure 8.

FIG. 10 This figure shows the five -12-fold CDP traces of Figure 9 processed with three different velocities. Note that when the velocity is too low, the frequency of the reflection wavelet is lowered and that it is depicted too shallow on the seismic section. When the velocity is too high the frequency decreases and the reflection wavelet is depicted too low on the seismic section. The correct velocity gives the correct position for the wavelet and preserves the high frequencies which allows best resolution of small features and thin beds.

FIG. 11 This 12-fold CDP seismic-reflection section is from the Texas site.

FIG. 12 Common Offset line from Texas site.

FIG. 13 Raw field files from various places along the seismic line. The surface topography cross-section on the top of the figure has approximate surface locations of the shots fired for the included field files as well as the approximate location of well 88. Significant seismic events are high-lighted with stippling. From a seismic characteristic perspective, the field records appear to have been recorded at six geologically unrelated sites. These seismograms clearly indicate the magnitude of variability in the near-surface.

FIG. 14 This CDP stack is the result of combining the two data sets—reflections-only and everything-else after being processed individually. This 12-fold stack contains information that was corrected (static and dynamic) with reflection-derived values. After recombining the two parts of this data set, a residual statics operation, AGC scale (trace amplitude balancing), and spectral shaping (filter) process were applied to the data before stack.

FIG.15 Common offset sections from the Snake River Plain, Idaho.

FIG. 16 Unprocessed field files showing coherent reflection event at about 40 msec from the west end of the line.

FIG. 17 CDP stacked section (12-fold) at Henderson, Nevada. CDP trace spacing is one foot and time scale is in seconds.

FIG. 18 Common offset gathers of raw data without editing or muting. Near offset on channel 1 is 12 feet and far offset on channel 24 is 58 feet.

TABLE 1.

**SEISMIC DATA-PROCESSING FLOW CHART FOR
TEXAS LINE AND HENDERSON, NEVADA LINE**

- 1) Bad trace edit
- 2) Elevation statics
- 3) First-arrival mute
- 4) Spectral analysis
- 5) 2nd zero crossing auto-predictive deconvolution
- 6) Common Depth Point (CDP) sort
- 7) Velocity analysis
- 8) Surface-consistent statics
- 9) Bandpass filter
- 10) Automatic Gain Control (AGC) scale
- 11) Common Depth Point (CDP) stack

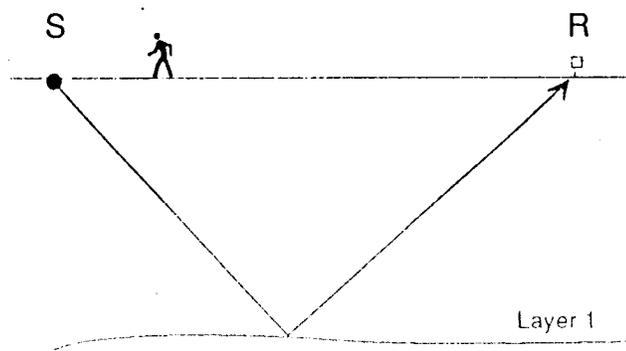


FIG. 1 The simplest case of seismic reflection. S represents the source and R represents the receiver. Layer 1 represents an acoustical discontinuity.

Reflections from Three Layers

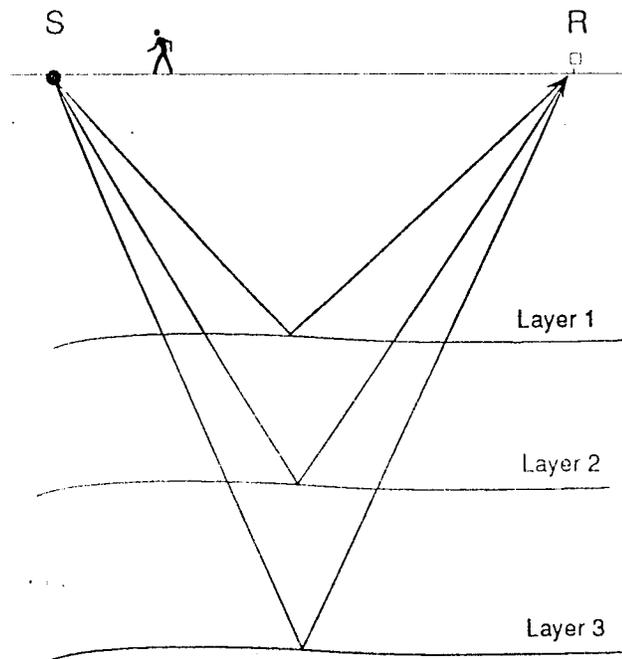


FIG. 2 Reflected rays from three layers. In general the ray paths are deflected from straight lines at boundaries between layers according to Snell's law, so this figure is over-simplified.

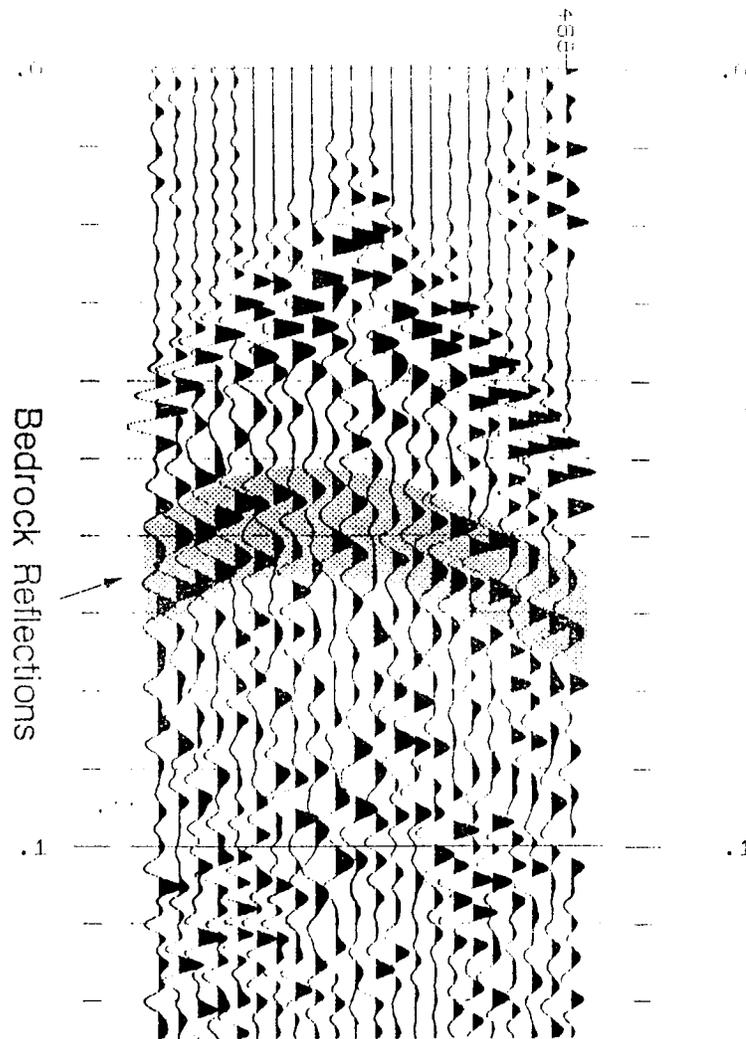


FIG. 3 Field seismogram (unprocessed) showing bedrock reflection at about 53 msec. The hyperbolic shape of the shaded zone is characteristic of simple reflections. The earlier arriving energy is from air blast and from direct arrivals passing through near-surface alluvium. Geophone offsets are 3 m for the inside two traces, increasing to 16 meters for the most distant traces.

Simple Reflection Ray Paths

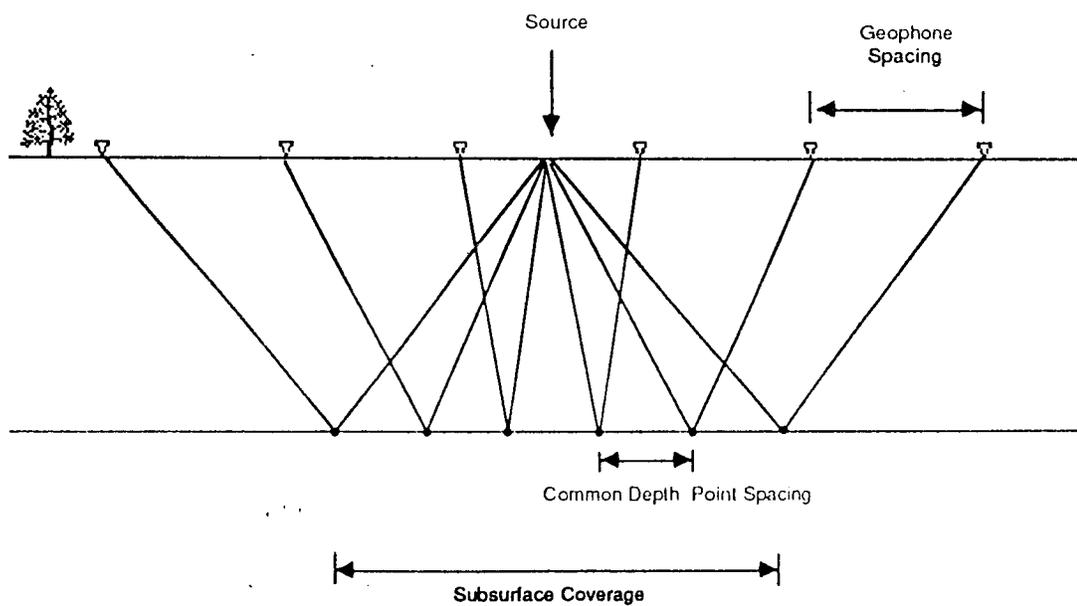


FIG. 4 Schematic view of reflection ray paths in a single layer case for a six-channel seismograph. Note that the common depth point spacing is exactly half the geophone spacing.

CDP Concept

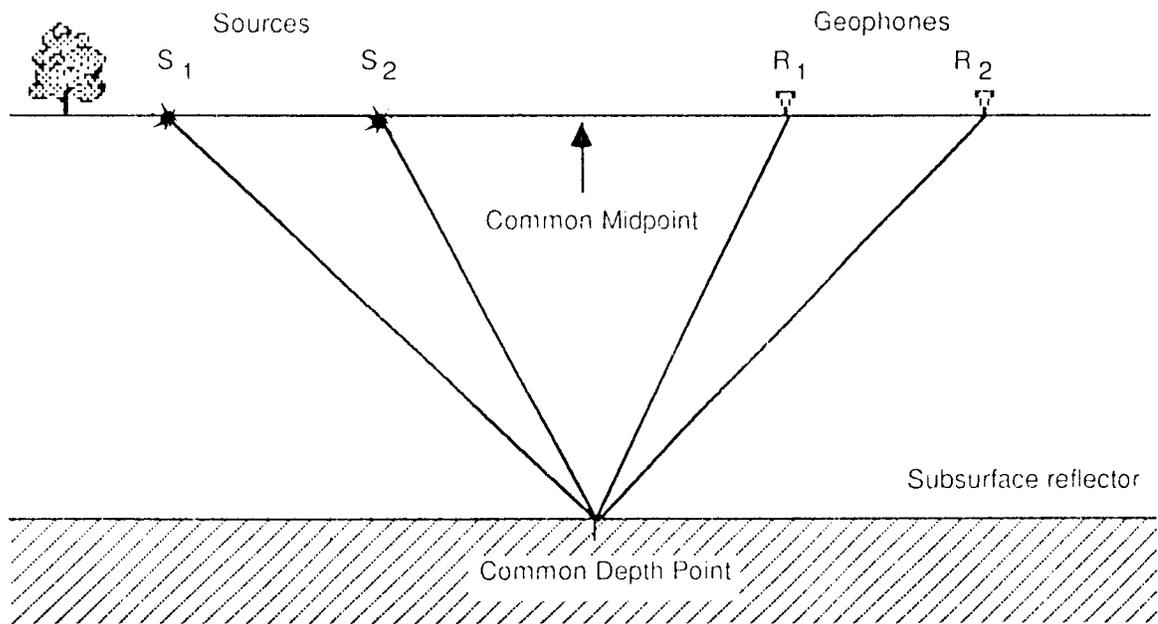


FIG. 5a Illustration of the common depth point (CDP) concept. In the case of a 24-channel seismograph with shotpoints occurring at all geophone locations, the subsurface reflection points will be sampled 12 times, resulting in 12-fold CDP data after processing.

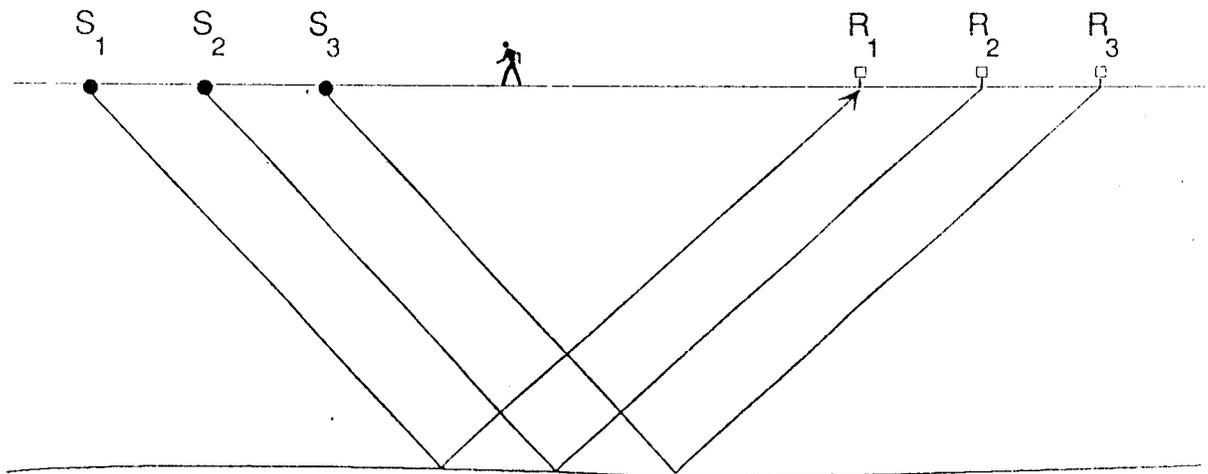


FIG. 5b Illustration of the common offset concept. Note that the offset distance from S_1 to R_1 is the same as the offset from S_2 to R_2 and S_3 to R_3 , respectively.

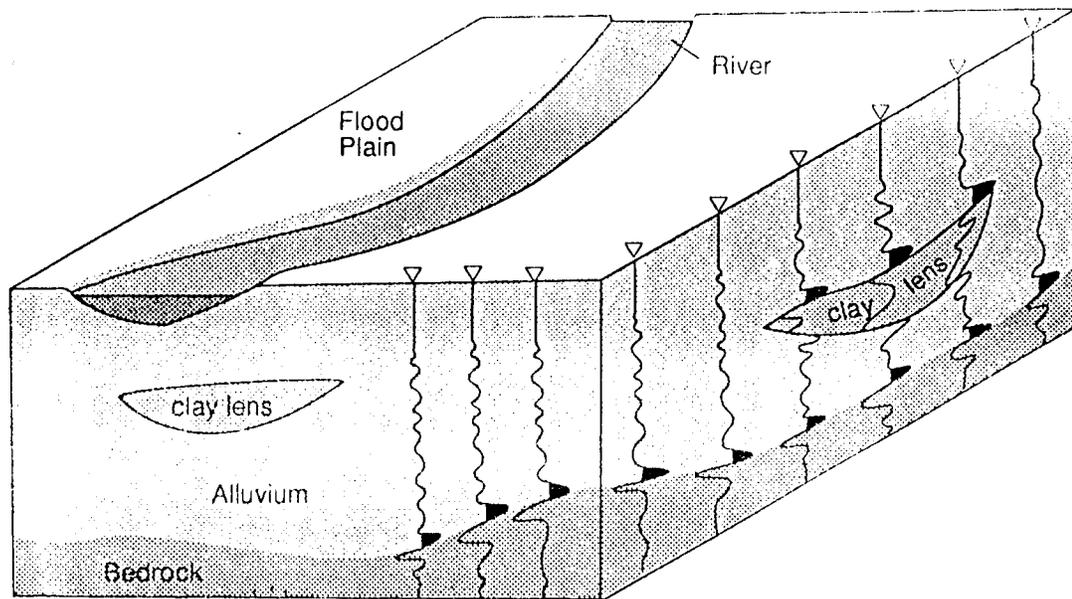


FIG. 6 Combining the 3-dimensional geology with a conceptual seismic section. The geology is interpreted from coherent blackened peaks on the seismic section. Seismic data are processed to emulate what they would look like if the shotpoints and geophones were located at the same point on the earth's surface.

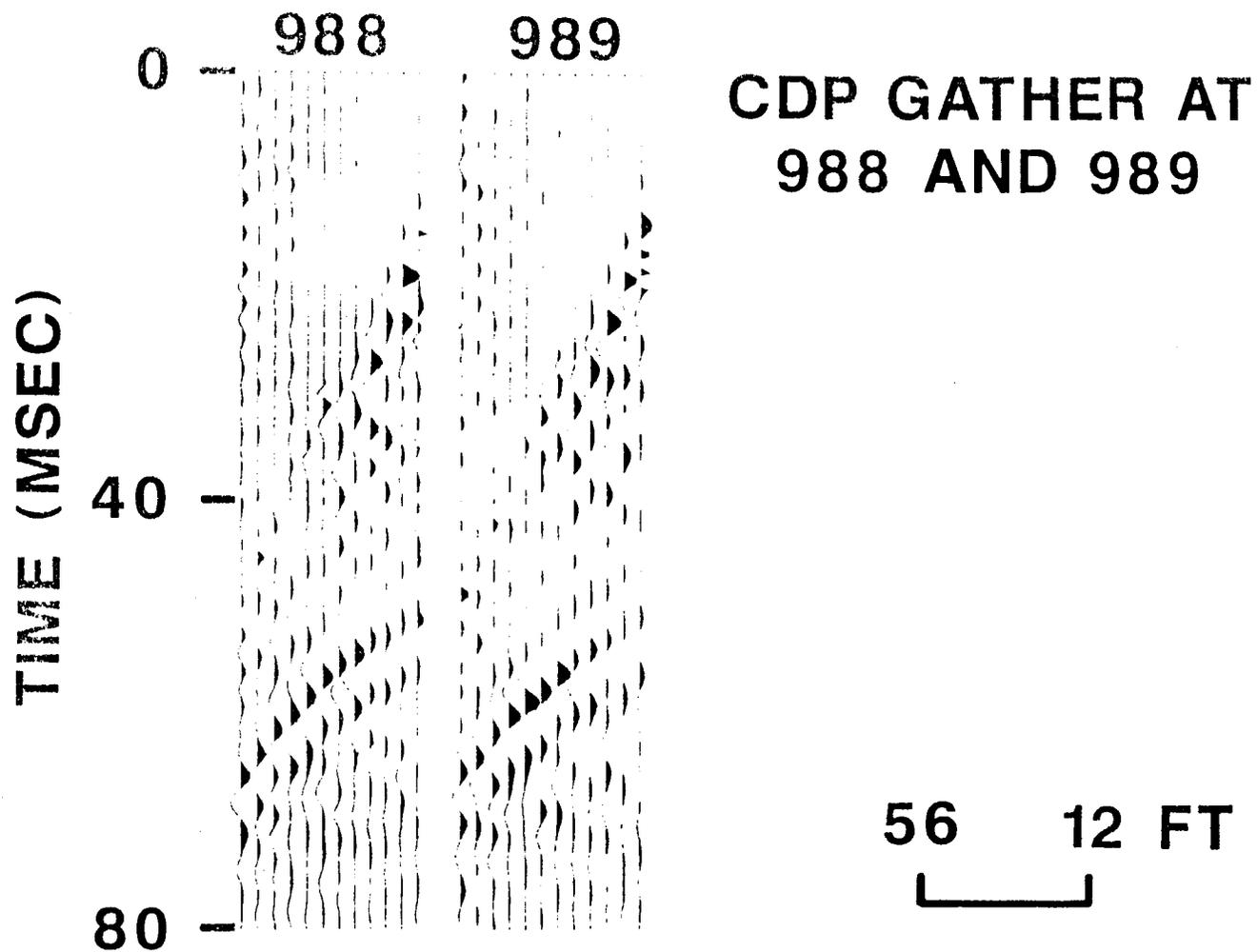
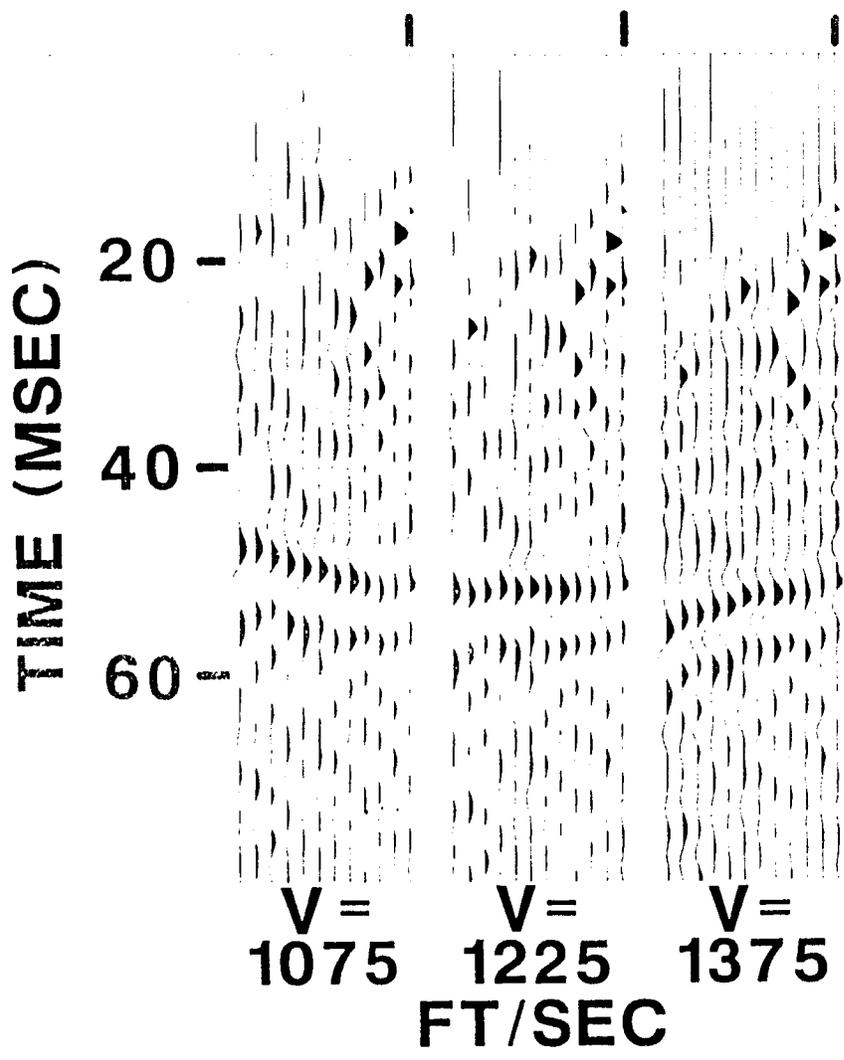


FIG. 7 Common depth point gather at points 988 and 989 on a particular shallow seismic survey. The most prominent seismic wavelet at times between 50 and 70 msec is a bedrock reflection from about 9 m below the surface. The geophone offsets were 3.7 m for the nearest traces and 17 m for the farthest trace with 1.22 m between geophones.



**VELOCITY
ANALYSIS
OF CDP
GATHER
AT 988**

FIG. 8 Velocity analysis on CDP gather at point 988 from Figure 7. Note that 1075 ft/sec is too slow and the moveout is too great on the far traces. A velocity of 1225 ft/sec nicely flattens the reflection signals in preparation for adding the traces in the computer. A velocity of 1375 ft/sec is too fast and does not provide enough moveout on the far traces to flatten the reflection signals.

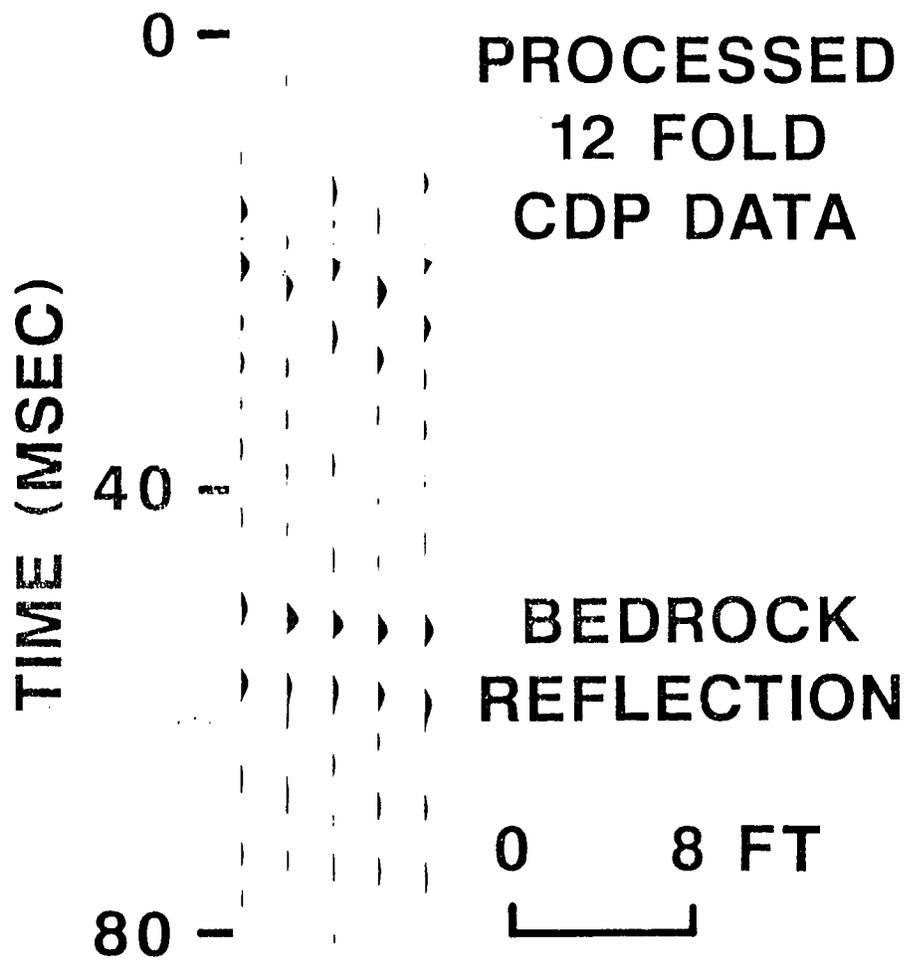
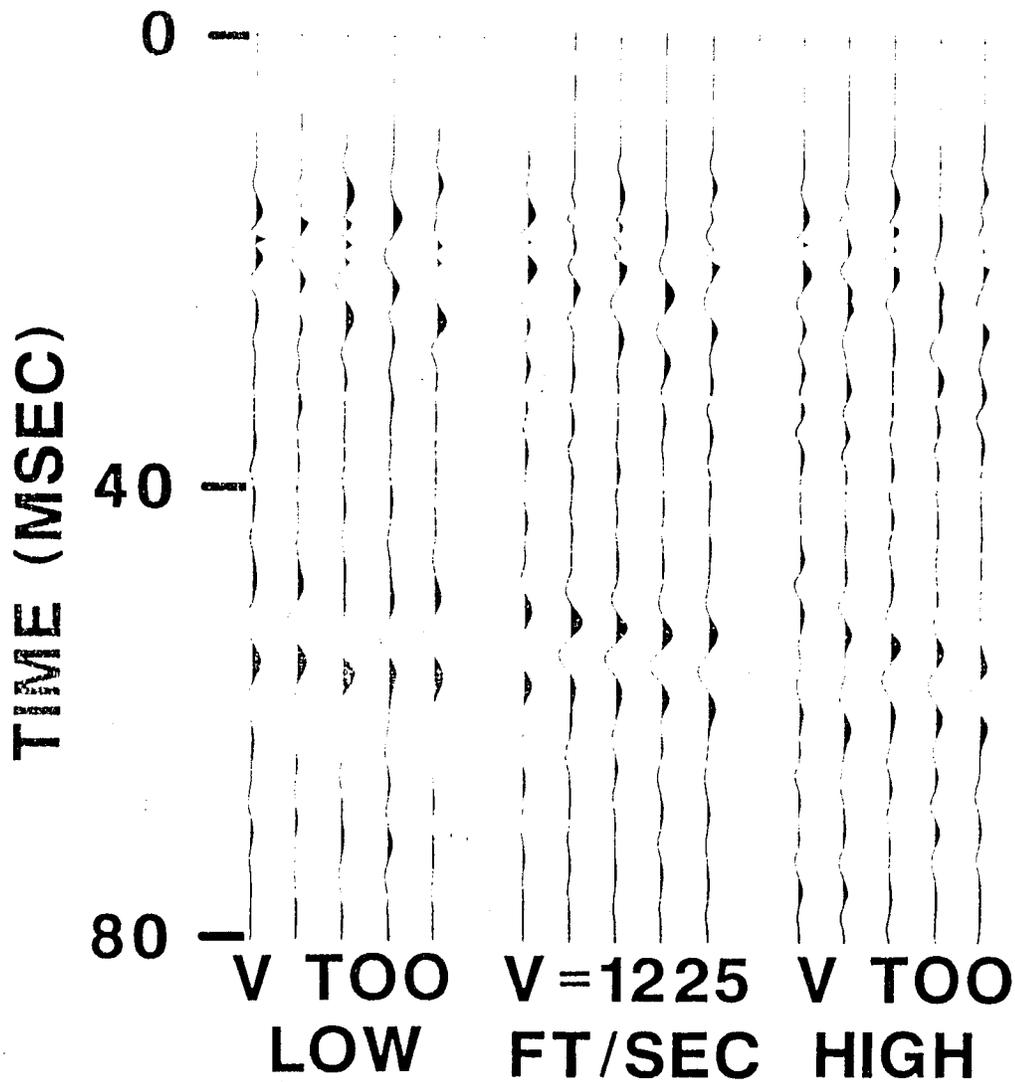
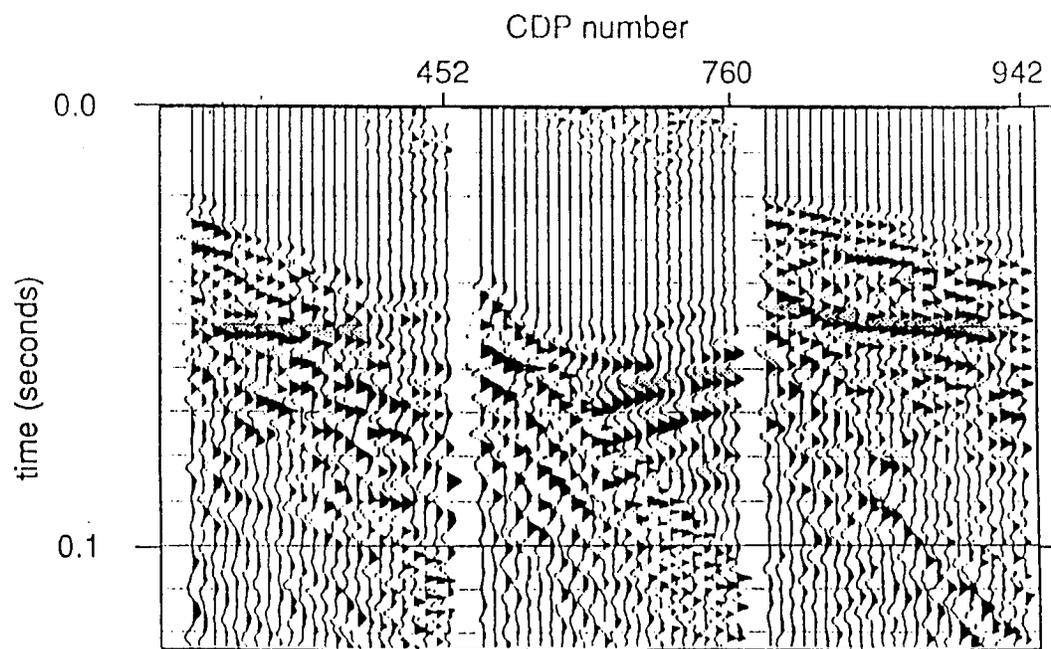
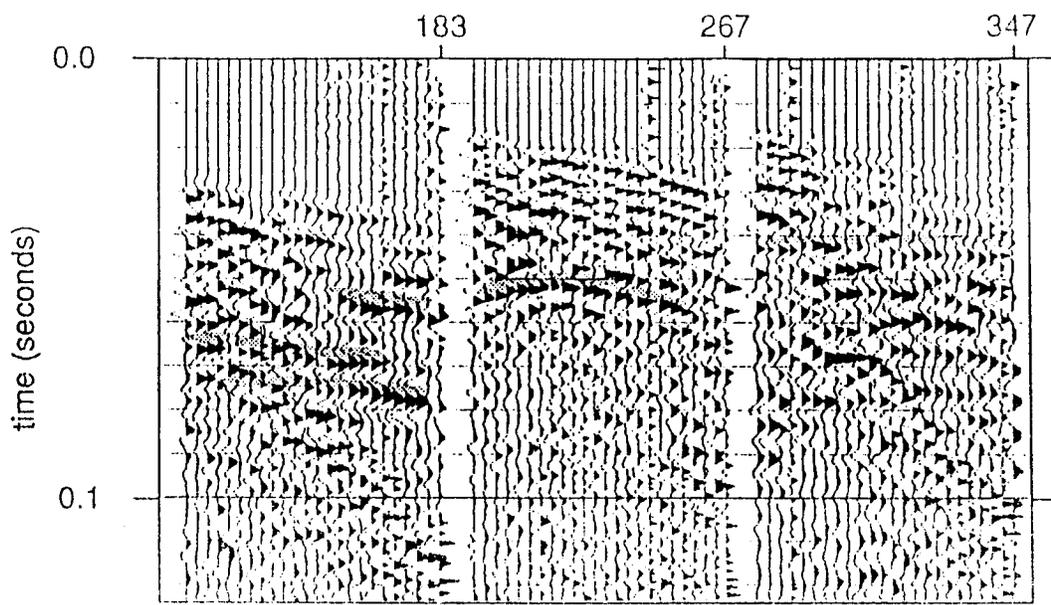
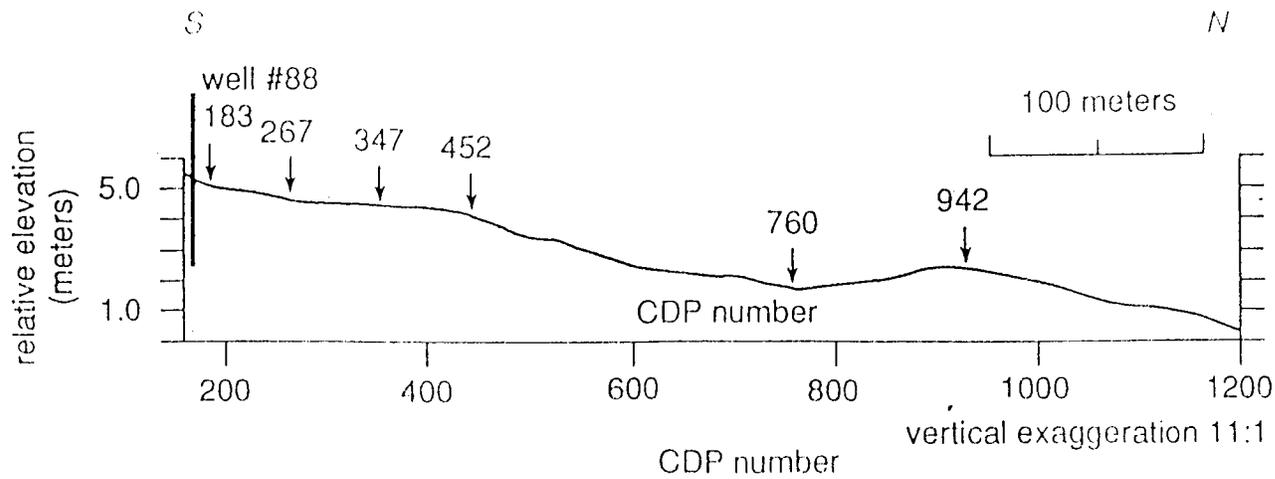


FIG. 9 Five traces of 12-fold CDP stacked data showing bedrock reflection at about 50 msec. Each trace has had 12 field traces added together after they were individually adjusted by applying velocity-distance normal-moveout (NMO) based on the velocity analysis of Figure 8.



**EFFECT OF
INCORRECT
VELOCITY
ON
CDP STACK**

FIG. 10 This figure shows the five -12-fold CDP traces of Figure 9 processed with three different velocities. Note that when the velocity is too low, the frequency of the reflection wavelet is lowered and that it is depicted too shallow on the seismic section. When the velocity is too high the frequency decreases and the reflection wavelet is depicted too low on the seismic section. The correct velocity gives the correct position for the wavelet and preserves the high frequencies which allows best resolution of small features and thin beds.



10 meters

FIG. 13

CDP STACK
REFLECTIONS AND NOISE

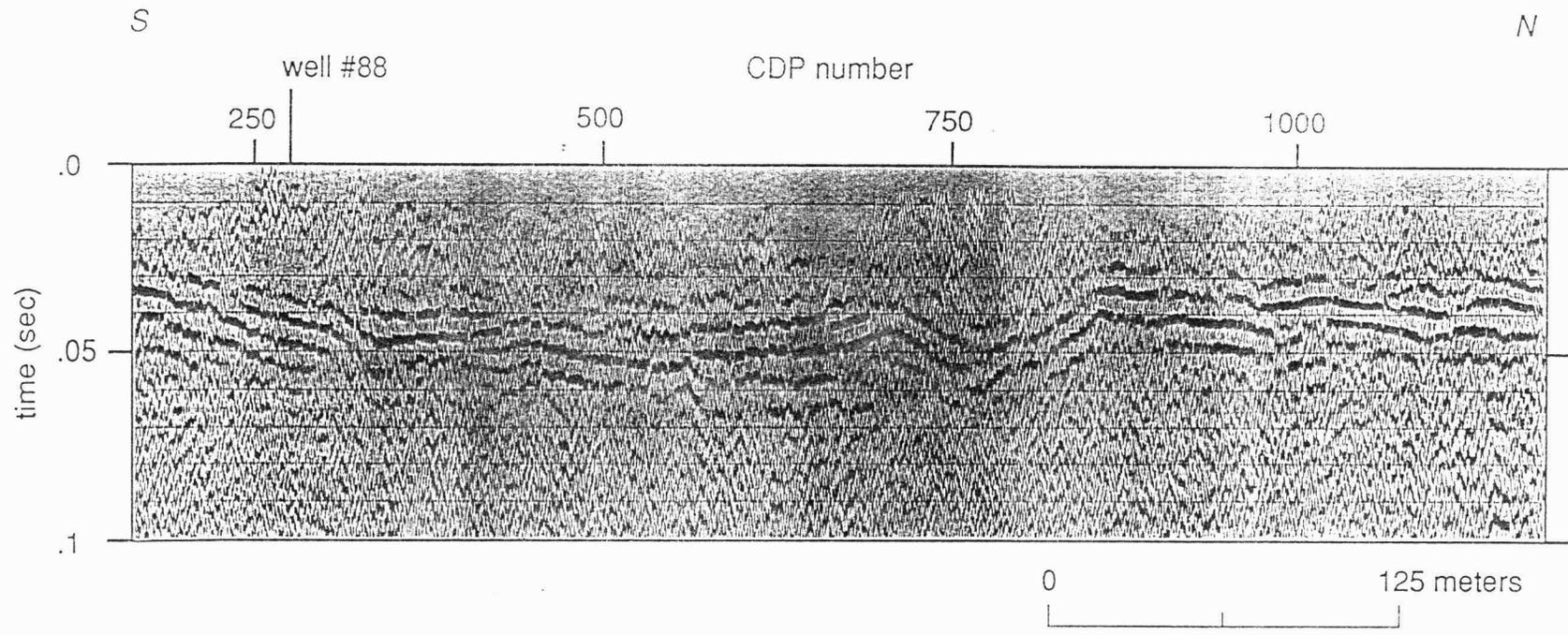


FIG. 14