GEOPHYSICS, VOL. 55, NO. 6 (JUNE 1990); P. 761–768, 11 FIGS., 1 TABLE

A shallow seismic reflection survey in basalts of the Snake River Plain, Idaho

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ABSTRACT

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 variations in quality, seismic character, and reflector geometries observed on seismograms give the appearance of varying geologic settings and are 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.

INTRODUCTION

Detailed knowledge of shallow subsurface layers is often necessary to evaluate hydrologic flow at environmentally sensitive sites to assist in developing effective monitoring and mitigation procedures. This paper demonstrates the feasibility of using shallow high-resolution seismic reflection surveys to characterize structure and stratigraphy near the actively used, over 30 year old radioactive-materials storage site at the Idaho National Engineering Laboratory (INEL). The technique was used here to determine the feasibility of seismically identifying structural and stratigraphic changes in an interlayered basalt-sand sequence to depths as shallow as 10 m.

Data possessing the detail necessary to map shallow structures have generally come from extensive drilling programs. High-resolution seismic-reflection profiling, using the CDP technique under ideal conditions, has imaged surfaces as shallow as 3 m and resolved beds as thin as 1 m in a variety of near-surface geologic settings (Birkelo et al., 1987; Jongerius and Helbig, 1988; Branham and Steeples, 1988; Miller et al., 1989). The seismic reflection method cannot replace drilling, but it can decrease necessary drilling by an order of magnitude. This paper presents data that will help select drilling sites at INEL.

GEOLOGIC SETTING

The study area is located within the central-eastern Snake River Plain (SRP) between Arco and Idaho Falls, Idaho (Figure 1). 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 that 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 (Figure 2). 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

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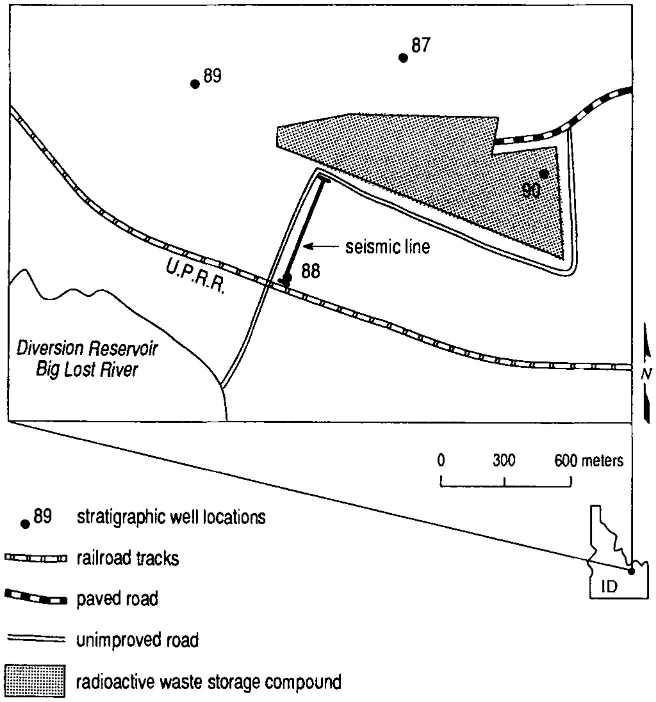


FIG. 1. Site map indicating the approximate location and orientation of 500 m seismic reflection line. The location of well 88 is also indicated on the map. Base map was provided by EG&G.

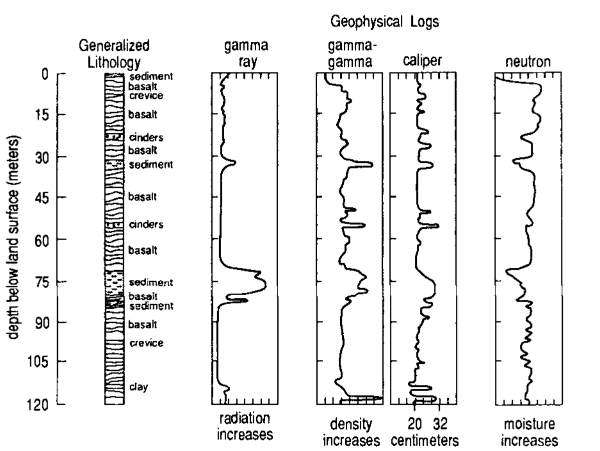


FIG. 2. Graph of generalized geology and geophysical logs for well 88. Provided by EG&G.

conditions and/or with equipment possessing greater dynamic range and double the recording channels.

FIELD PROCEDURES

The producing and recording of high-frequency and high signal-to-noise (S/N) shallow reflection data require careful attention to detail and proper choice of parameters. If a consistent high-frequency source pulse with a broad bandwidth is not produced and recorded, it is difficult to digitally enhance reflection energy during later data processing sequences. [Broad-band recording does not necessarily result in broad-band data; conversely, narrow-band recording does not necessarily result in narrow-band data (Knapp and Steeples, 1986a).]

The seismic data were collected along one 500-m-long line intersecting well 88 at CDP 258 (Figure 1). 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. Close attention was given to source-and-receiver coupling during acquisition to improve the frequency response and reduce unwanted noise.

The source was a silenced .50 caliber rifle fired vertically into the ground through a silencer held firmly to the earth's surface (Steeples et al., 1987). The .50 caliber rifle was chosen bacause of its characteristic high-frequency seismic pulse, low ratio of ground-roll to body waves, and total energy output. The silencer acts not only as a damper for 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 using 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, 1986b). The array attenuates (to a lesser degree) source-generated linear coherent energy with frequencies other than the dominant one. 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 S/N 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.

The data were recorded on an Input/Output DHR 2400 seismograph. All the fixed-gain data were converted from analog to a digital 11 bits-plus-sign representation 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 rolloff) helped reduce the amount of recorded ground roll, boosting the S/N ratio (Figure 3).

The production of high-resolution CDP seismic reflection profiles is highly dependent upon an awareness of the geologic situation, emphasis on uniformity during acquisition, and attention to details. Without proper understanding of the geologic situation and target, it is not possible to optimize the recording parameters and field procedures. Producing and recording seismic energy in excesss of 150 Hz for eventual generation of CDP stacks requires consistency in field procedures, the most important of which include the time-break system, energy-source characteristics, geophone plants, and source coupling to the ground. The need for attention to detail is obvious when a 0.5 m error in surface elevation equates to a 2 ms shift which, for 150 Hz data, is almost one-third of a wavelength.

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 (Figure 4). The common-shot gather at CDP 183 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 a depth of about 30 m on geophysical logs from well 88 (Figure 2). 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.

The data were processed on the Kansas Geological Survey's 32-bit Data General MV-20000 computer using a proprietary set of algorithms that has been in standard use on TIMAP seismic systems marketed by Texas Instruments. The processing flow was nonstandard to accommodate extreme inconsistency in reflector depths and NMO velocity probably related to variable thickness of the low-velocity near-surface layer (Table 1). 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 1/8 wavelength maximum allowable shift (1 ms). Extraordinary emphasis was placed on point-by-point velocity analysis and surface-consistent statics operations.

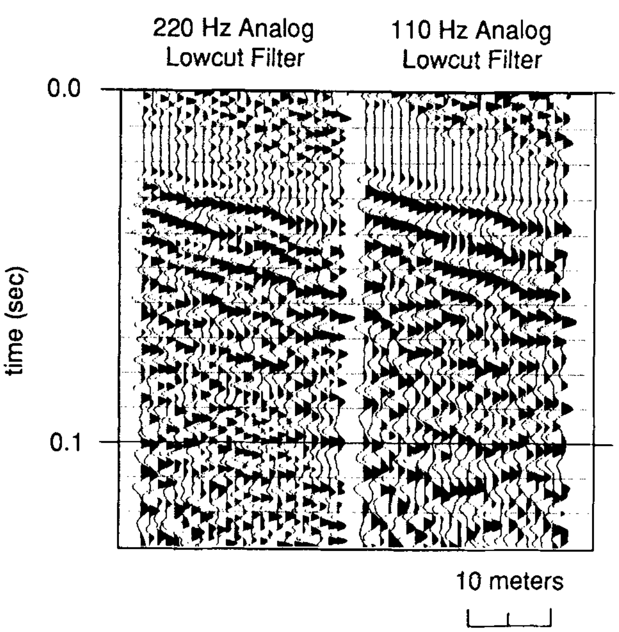


FIG. 3. 220 Hz low-cut filters were selected after an extensive series of filter tests during the walkaway-noise analysis. The dominant recorded frequency of the 220 Hz data is clearly 50 Hz higher than the 100 Hz data. Many subtle features not observable on the 110 Hz file are interpretable on the 220 Hz file. A high-frequency event, clearly identifiable at about 42 ms on the 220 Hz low-cut filtered seismogram, is not evident on the 110 Hz low-cut filtered seismogram.

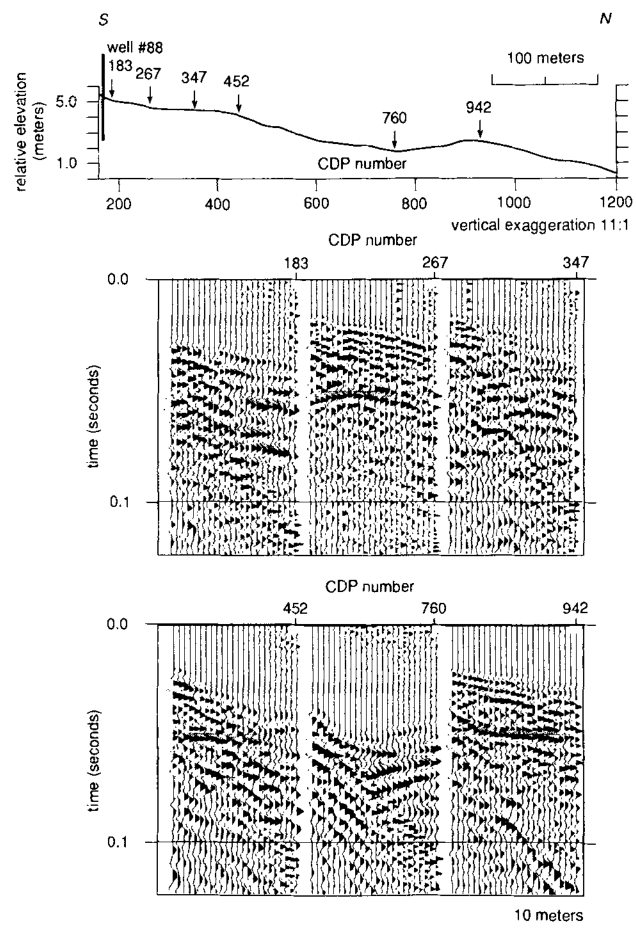
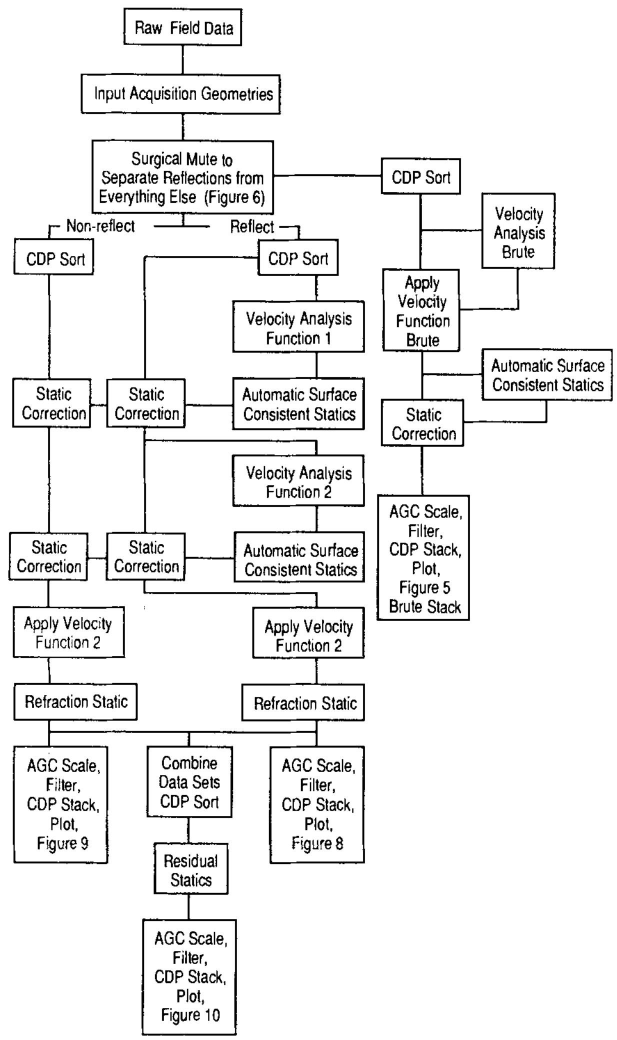


FIG. 4. Raw field files from various places along the seismic line. The surface topography cross-section on the top of the figure has approximate surface locations of the shots fired for the included field files as well as the approximate location of well 88. Significant seismic events are highlighted 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.

Table 1



The velocity structure is complicated by flow irregularities, nonuniform 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 (Figure 5). No coherent reflection information can be identified confidently on the brute stack.

In an effort to enhance the high-quality reflections seen on the raw field files but not 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 contain only reflection energy 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 (Figure 6). The velocity analysis and surface-consistent statics computations were done on the reflection-only information to avoid the influence of coherent noise or other nonreflection 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. The stacking velocities ultimately assigned to each CDP gather identify hyperbolas 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. The lack of dip compensation may slightly distort both the frequency characteristics and apparent spatial location of reflection wavelets on a stacked section.

The reversed refraction survey was used to remove the effects

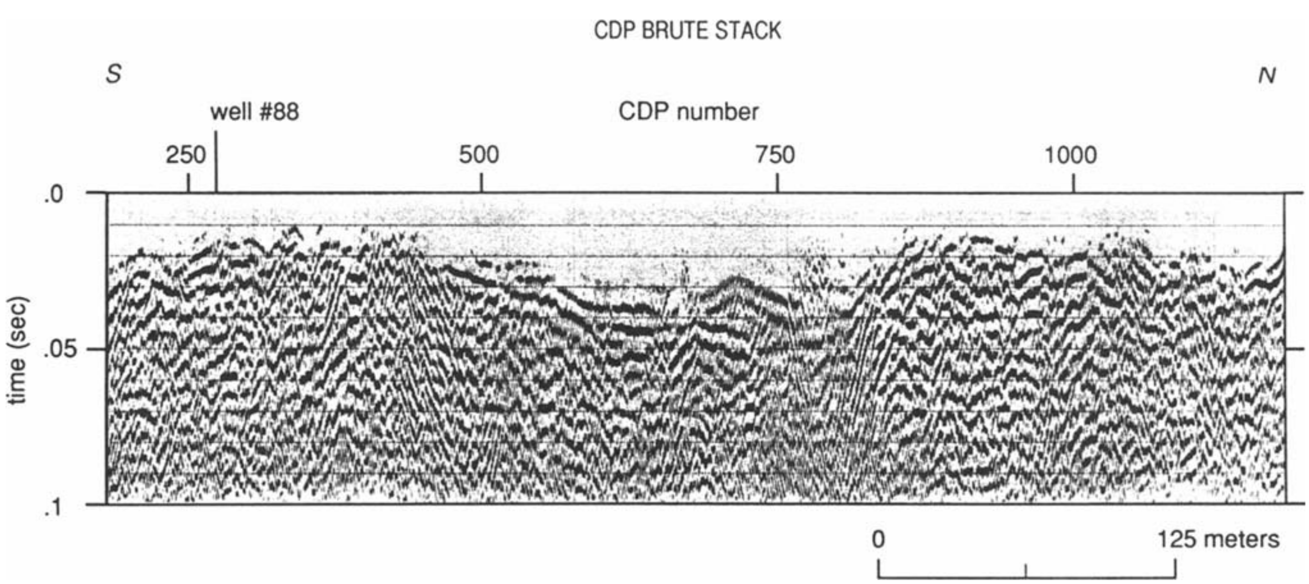


FIG. 5. Brute-stack section processed using preliminary conventional velocity, statics, and spectral analysis (see Table 1).

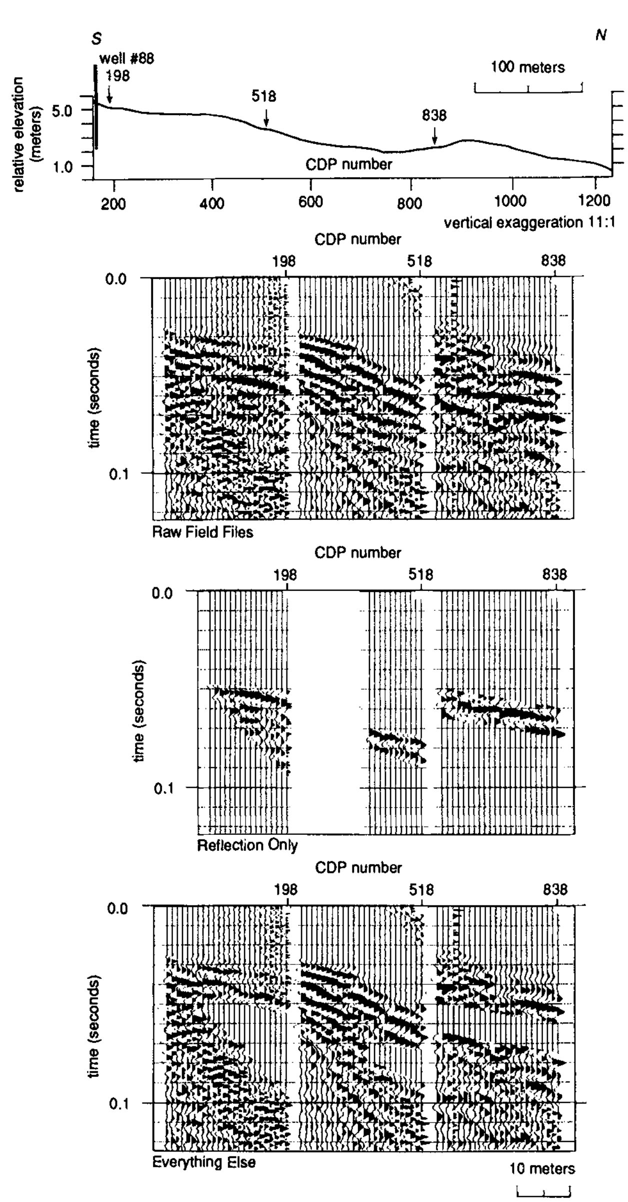


FIG. 6. Analyses of data with reflections only should result in the most accurate velocity and static corrections. (a) Cross-section of the surface topography with respect to locations of the example files, (b) the original field files, (c) the reflection-only remnants of the surgical-muting process, and (d) everything else. Several questionable reflection events were placed in the everything else data set. Only high-confidence reflections were retained after muting to minimize the potential for error.

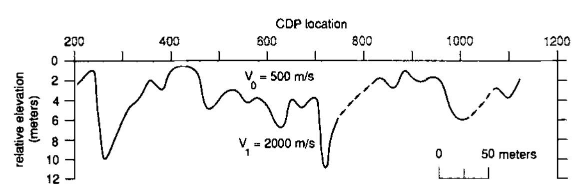


FIG. 7. This interpreted cross-section was derived from the reversed refraction data set. A dipping two-layer model was used to formulate the cross-section. The actual values used to remove the static effects of the near surface were a 30 m running average of the actual values. The dashed lines indicate poor data areas not allowing confident determination of the refraction horizon.

of inconsistent thickness and average velocity of the near-surface layer (Figure 7). The very-short wavelength undulations (less than approximately 30 m) in the interpreted basalt upper surface were smoothed manually 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 indicate 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.

RESULTS

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 radius of the first Fresnel zone at this site is approximately 8 m at 30 m of depth. 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 appears to be reversed (reflected energy arriving earlier in time at receiver locations farther from the source). Arrivals at approximately 50 ms on record numbers 267 and 198, in particular, have a slightly distorted hyperbolic curvature with the apex near the middle of the spread (Figures 4 and 6). The right sides of the curves possess wavelet characteristics and arrival patterns consistent with other reflections from this part of the line and are interpreted as primary reflections. The left sides however, may be diffraction arrivals because they have a slightly higher frequency and possess reduced amplitude. The diffraction arrival (left side of the curves) may have emanated from the termination point of the acoustic interface responsible for the 50 ms reflection arrival (right sides of the curves).

The data contain evidence that static corrections by some conventional methods may sometimes produce incorrect results in basaltic areas. Some static shifts observed in first-break arrivals (usually assumed to be indicative of inhomogeneous near-surface layers) are inconsistent with static shifts observed in later reflection arrivals (Figure 8). The static delay of first arrivals identified on seismogram 942 beginning with trace 18 and extending to trace 22 differs by 3 ms from the static anomaly observed in the 50 ms reflection event. The presence of velocity anomalies a few meters across within a few meters of the earth's surface (possible lava tube?) is implied by these intratrace static differences. Generally, first-arrival correlation routines assume first-arrival static shifts are valid for a whole trace. If such a routine were used on this data set, the 50 ms reflection event on file 942 could be incorrectly shifted by as much as a third of a wavelength.

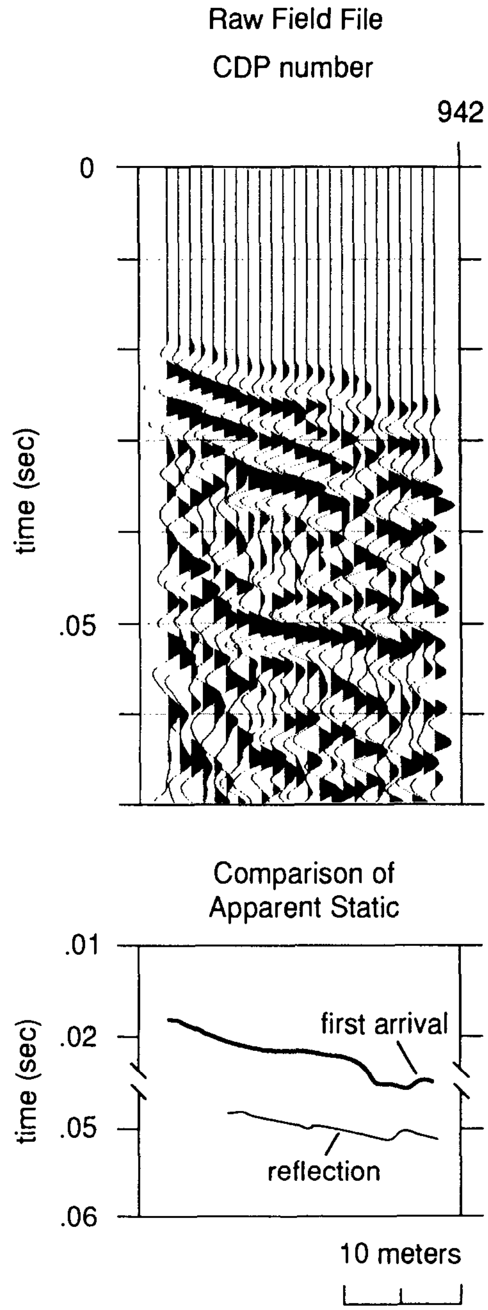


FIG. 8. The apparent static shift observable in the first-break energy is not consistent with the observed static shift in the reflection at 50 ms on seismogram 942. Static corrections based on first-break information would incorrectly compensate the traces in this field file.

The data on Figure 11 have a ringy appearance. Analog 220 Hz low-cut filters probably contributed to the ringiness; however, obvious reflections on field files (Figures 4 and 6) tend not to be ringy, reinforcing the selection of these low-cut filters. Also, traces 5 to 13 on Figure 3 show a reflection at 42 to 45 ms on the 220 Hz low-cut data that is not visible on the 110 Hz low-cut data. The ringiness of the reflection wavelet on the stacked data is probably an effect of both the digital low-cut filter designed to attenuate ground roll and digital high-cut filter designed to attenuate air-wave noise. The digital filtering narrowed the bandwidth of the reflection information while significantly attenuating coherent noise. The choice of field and processing parameters was based on a tradeoff between the need for high resolution with decreased ground roll and air-coupled wave versus some reflection ringiness on the processed section.

The reflections-only data (Figure 9) were a critical guide not only during data processing but also in maintaining a consistent interpretation on the combined stacked section (Figure 11). The rejoining process (reflections only of Figure 9 and everything else of Figure 10) was necessary to preserve many subtleties not observable on the reflection-only stacks.

The stacked reflection section (Figure 11) 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 reflections identified on field files at about 50 ms. (This reflection occurs at about 40 ms on the stacked sections after dynamic and static corrections.)

The reflection wavelet appears to be mixed phase, with the majority of the energy arriving within the first two complete cycles. The two-way reflection time is taken at the first identifiable break of the wavelet. Slight variations in the phase of the reflection wavelet across the 500 m long line cause the apparent occasional lack of consistency in the reflection first break. The prominent reflections identified on the stacked section are restricted to a relatively narrow time window between about 30 and 70 ms. This narrow time-window appearance of the data is a result of the very precise and focused (specific target) acquisition and processing parameters as well as the limited dynamic range and number of acquisition channels of the DHR-2400 seismograph.

The apparent major long-wavelength synclinal structure and the multiple localized structural lows observable in the 40 ms deep sedimentary layer (Figure 11) are related to real geologic features and/or physical-property 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. Structures interpretable on the stacked section that mimic the refraction-derived bedrock map and/or the stacked-refraction arrivals on the everything-else section (Figure 10) (such as the synclinal feature centered on CDP 760) may be related to changes in physical properties not completely compensated for during processing.

Reflections interpretable on the south end of the final stacked section (between CDPs 200 and 500 on Figure 11) dip north while the stacked refractions across the same portion of the everything-else section (Figure 10) have an apparent south dip. This apparent divergence of reflections from refractions supports the identification of the events around 50 ms on the stacked section (Figure 11) as true reflection energy unrelated to and undisturbed by refracted arrivals. Similar divergence of coherent reflection (Figure 9) and refraction (Figure 10) energy can be observed at the north end of the stacked sections between CDPs 800 and 1200.

Frequency and phase anomalies evident at several places on the seismogram make it difficult to correlate the sedimentary reflector along the line with confidence (Figure 11). Some of these anomalies could possibly be reduced with a band-limited deconvolution. Slight horizontal variations in the frequency of the reflection wavelet are noticeable at some places along the

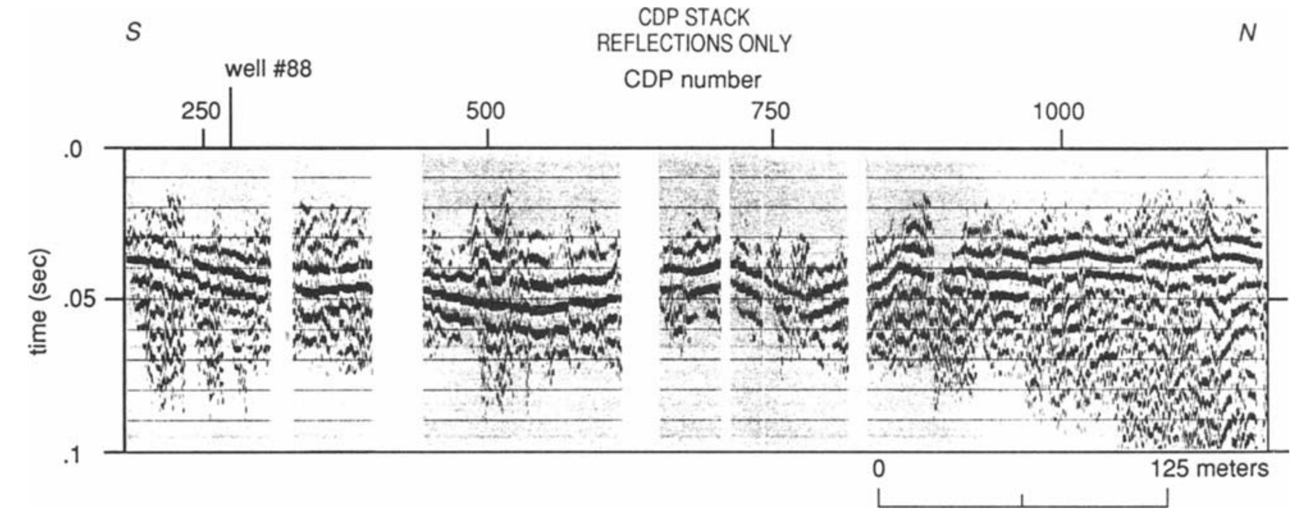


FIG. 9. The 12-fold CDP stacked data displayed here are the result of severe surgical muting necessary to extract only high-confidence reflection information. The surface-consistent statics corrections as well as the velocity function were formulated using this data set (Table 1).

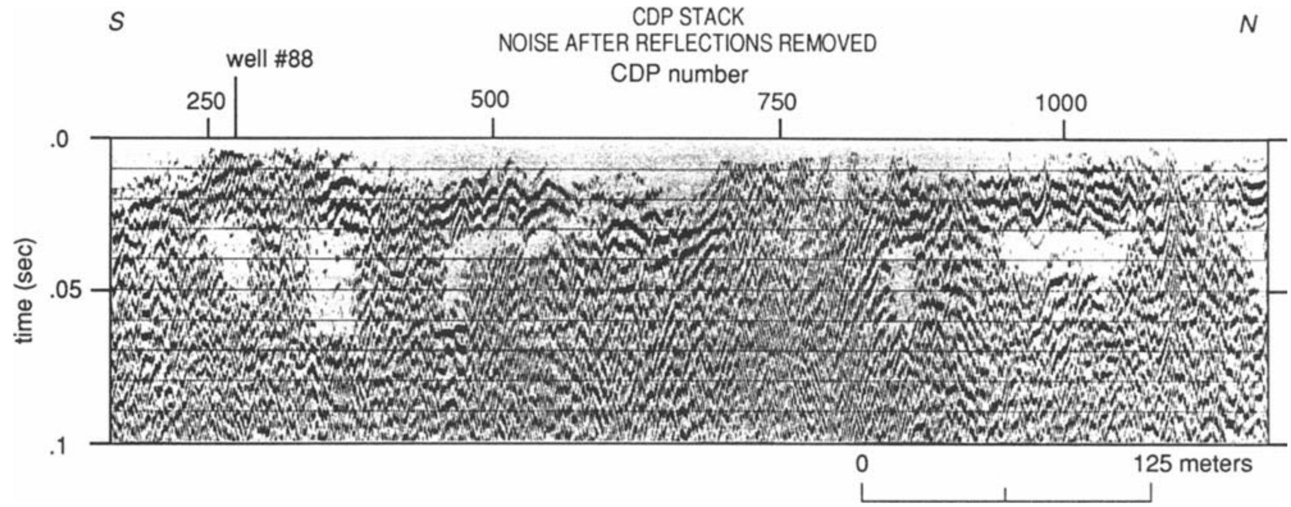


FIG. 10. These 12-fold CDP stacked seismic data (everything else) are what remained after the reflection data were extracted. The processing flow used on these data was identical to that used on the data in Fig. 9 (Table 1).

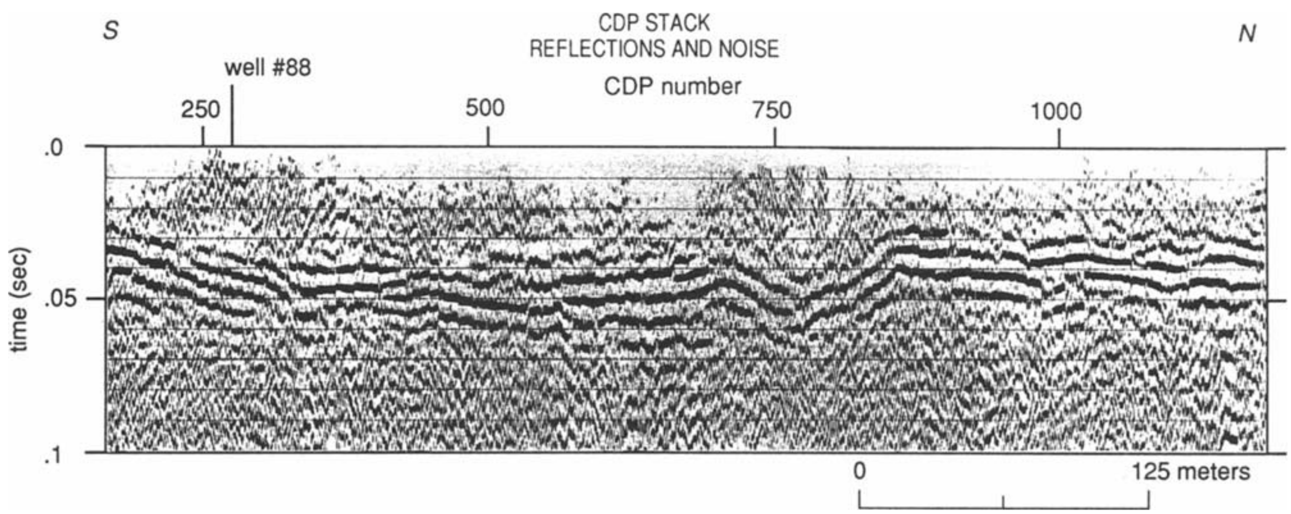


FIG. 11. This CDP stack is the result of combining the two data sets — reflections-only and everything-else — after they were processed individually. This 12-fold stack contains information that was corrected (static and dynamic) with reflection-derived values. After recombining the two parts of this data set, a residual statics operation, automatic gain control scale (trace amplitude balancing), and spectral shaping (filter) process were applied to the data before stack.

line. For example, between CDPs 350 and 400 and between CDPs 625 and 700, the reflection frequency varies as much as 25 percent. These variations probably relate to inconsistent source-and-receiver ground coupling and abrupt changes in the near-surface material. 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 is possible.

Some of the slightly disjointed appearance of the reflections 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.

DISCUSSION

The primary reflection event at 50 ms on field files and approximately 40 ms on stacked sections correlates to a borehole-confirmed 3 to 4 m thick sedimentary layer at 30 m of depth within a thick basalt-layer/sand-layer sequence. Some reflections on the field files are of exceptional quality. The extreme variability in quality and seismic character of field files along the 500 m long seismic line is uncommon for such short distances. Associated with and possibly related to the variability is the variation in thickness of 0 to 8 m of the near-surface unconsolidated layer.

The dominant frequency of the seismic data was higher than expected for this area. Substantial reflection energy is present in the 150 to 200 Hz range. Much of the spectral variability evident on the seismic data can be attributed to the complicated composite depositional structure of the different lobes of the basalt flows. The data are of sufficient quality, however, to guide and minimize a test-drilling program for monitoring wells.

This seismic survey was designed specifically to map the sedimentary reflector at a depth of about 30 m. On some of the intermediate processed sections (not shown) a deeper reflection at about 65 ms can be identified, which probably corresponds to the sedimentary layer detected at 70 m depth in well 88. It would probably be feasible to map that reflection with a seismic reflection survey designed for that depth window.

The results described here may be of significance to much deeper seismic reflection surveys in basalt-covered areas. The extreme variability observed on seismograms from this shallow survey could be diagnostic of near-surface problems on conventional data from depths of thousands of meters. For example, intra-array static corrections could be a major problem for a conventional survey performed at this site. These statics problems could be at least partially overcome by acquiring data on several hundred recording channels connected to either single geophones or small (1 or 2 m) geophone arrays.

A near-surface velocity-depth model derived from shallow reflections in areas of highly variable near-surface material would improve static corrections on deeper conventional data.

CONCLUSIONS

(1) The seismic reflection method was shown to be useful in selecting sites for test drilling for water-quality monitoring in the vicinity of radioactive waste storage facilities at INEL.

(2) Data processing was difficult, but the use of selective and severe muting early in the processing flow allowed concentration of the processing routines on seismic reflections. After static correction values and velocity functions had been determined, data muted early in the processing flow were rejoined with the reflection data. The recombined data sets were then processed into a CDP stack.

(3) Dominant reflection frequencies of 150 to 200 Hz were obtained. The data were highly variable in frequency content, amplitude, and observed velocity along a line only 500 m long.

(4) Reflections shown in this paper are primarily from the 30 m depth range. Hints of deeper reflections suggest that a reflection survey properly designed to detect reflections in the 50 to 100 m depth range would be successful.

(5) The data shown here suggest that deeper conventional seismic reflection surveys in basalt-covered areas could benefit from detailed knowledge of the near surface.

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