USE OF A MULTI-OFFSET BOREHOLE-RADAR REFLECTION METHOD IN FRACTURED CRYSTALLINE BEDROCK AT MIRROR LAKE, GRAFTON COUNTY, NEW HAMPSHIRE

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ABSTRACT

Multi-offset, single-hole, borehole-radar reflection surveys were conducted at the U.S. Geological Survey Fractured Rock Research Site at Mirror Lake, in Grafton County, New Hampshire. The study was conducted to evaluate the benefits of applying multi-offset seismic processing techniques to borehole-radar reflection surveys in fractured rock.

The multi-offset reflection surveys were conducted in conjunction with a saline tracer-injection experiment. During injection, a sodium chloride (NaCl) solution was continuously pumped into a hydraulically conductive zone that was isolated by specially constructed, reusable, PVC straddle packers suspended from PVC casing. Eight common-offset borehole reflection profiles were collected within the PVC-sleeved portion of the borehole before and during the tracer injection. The offset between the transmitter and receiver antennas ranged from 6.4 to 9.9 m (meters). The common offset data were filtered, sorted into common distance-point (CDP) gathers, normal move-out (NMO) corrected, and stacked to produce a zero-offset borehole CDP profile.

Comparison of the common-offset and CDP profiles indicates that multi-offset data acquisition and CDP processing; (1) increases the resolution of reflectors near the borehole, (2) decreases the effects of direct wave coupling, antenna ringing, and system noise, and (3) improves the clarity of difference images used to identify the effects of saline tracer on reflections from transmissive fractures.

INTRODUCTION

Single-hole, borehole-radar reflection surveys typically are conducted using common-offset methods (fixed distance between the transmitter and receiver) (fig. 1) (Olsson and others, 1992; Haeni and others, 1993; Gaylor and others, 1994; Lane and others, 1994; Hansen and Lane, 1995; Lane and others, 1996). Although single-hole borehole-radar reflection surveys can provide information about the location, extent, and orientation of fractures and fracture zones that are within the radar range, the relatively large minimum transmitter-receiver offset makes it difficult to image near-borehole structures. In addition, reflections from structures close to the borehole are frequently obscured by the direct wave that propagates between the transmitter and receiver and by antenna ringing phenomena. Use of multi-offset data acquisition and processing methods can provide a means to (1) suppress direct arrival and instrument noise in order to enhance the imaging of structures near the borehole, and (2) estimate radar propagation velocity near the borehole. Accurate radar propagation velocities are needed to determine the dip of planar reflectors and the radial distance to point reflectors (fig. 1). Because radar velocity decreases as water content increases, knowledge of the radar velocity structure that surrounds a borehole can aid interpretation of the near-hole hydrogeology and provide useful constraints for the inversion of cross-hole tomography data. Multi-offset data could also be used to investigate the presence of possible amplitude versus offset (AVO) effects related to fracture aperture and/or fracture contents.

FIELD EXPERIMENT

The field experiment to test multi-offset data acquisition and CDP processing methods for single-hole, borehole-radar reflection surveys was conducted in July 1997 at the U.S. Geological Survey Fractured Rock Research site in the U.S. Forest Service Hubbard Brook Experimental Forest in the Mirror Lake area near West Thornton, Grafton County, New Hampshire. The experiment, which was conducted at the FSE 1-4 cluster within the FSE well field (fig. 2), is part of an ongoing series of experiments begun in 1995 using borehole-radar methods and saline tracers to characterize fractured rock systems.

The arrangement of the FSE 1-4 boreholes approximates a 9 m square (fig. 3). Borehole-geophysical logging and hydraulic- and tracer-testing have identified two transmissive fracture zones that provide hydraulic connections between the four boreholes (F.L. Paillet, U.S. Geological Survey, written commun., 1994; P.A. Hsieh, U.S. Geological Survey, written commun., 1994; A.M. Shapiro, U.S. Geological Survey, written commun., 1994).

For this experiment, the transmissive zone at a depth of about 40 m was isolated in three of the boreholes (FSE 1-3; fig. 3) using specially constructed, reusable PVC packers. These packers allow radar and other borehole logs to be collected through the 10.1 cm (centimeter) PVC core pipe that suspends the packers. The transmissive zone in FSE-4 was isolated using a standard straddle packer and pump assembly. The isolated interval in FSE-4 was pumped at about 9 L/min (liter per minute), while a NaCl solution at a concentration of 28 g/L (grams per liter) was injected into the isolated interval in FSE-1 at about 7 L/min (fig. 3).

Single-hole, common-offset reflection surveys were conducted in FSE-1 before tracer injection to establish background conditions, and during injection to measure changes in radar reflectivity that result from the transport of the tracer away from the injection interval along transmissive fractures. The radar data were collected using a RAMAC [1] borehole-radar system with a 60-MHz (megahertz) electric-dipole transmitting antenna and a 60-MHz magnetic-dipole directional receiving antenna. Eight common-offset reflection profiles were collected before and during the tracer injection for a total of sixteen profiles. The offset of the transmitter and receiver ranged from 6.4 to 9.9 m, with a 0.5-m increase in offset between surveys. The common-offset surveys were conducted within the PVC-sleeved portion of FSE-1. Reflection measurements were made every 0.25 m, beginning at a depth of 24.2 m. The profiled length along the borehole ranged from 38 to 42 m.

[1] The use of trade names in this report is for identification purposes only and does not constitute an endorsement by the U.S. Geological Survey.

DATA PROCESSING

To simplify the application of multi-offset processing methods for this paper, considerations of antenna directionality were eliminated by processing the electric-dipole (omni-directional) component extracted from the directional data (Falk, 1992). The phase of the extracted data is nearly identical to that measured by a standard electric-dipole antenna, but the amplitudes are lower due to the design of the directional antenna.

The electric-dipole component data were converted to SEG-Y format and processed using the freeware package Seismic Unix [1] (Colorado School of Mines) and the commercial seismic processing package Promax [1]. The common-offset data were processed prior to sorting using the following radar data processing flow: (1) Removal of linear direct arrival time shift due to transmitter firing time drift; (2) standardization of direct arrival samples such that transmitter firing occurs at the first sample in the record; (3) bandpass filtering using a zero-phase, sine-squared filter with corner frequencies of 20, 30, 80, and 100 MHz. An example of unprocessed and processed data is shown in figure 4. The most noticeable effects of the processing are the shift in the arrival time of the direct wave and a reduction of high-frequency noise. After processing, the data were sorted into CDP gathers, and data beyond 350 nanoseconds (ns) was muted. The minimum transmitter-receiver offset was 6.4 m, due to the design of the radar antennas and batteries. The maximum offset was limited by the necessity to remain within the PVC-sleeved portion of the borehole. The limited range of offsets reduces the total move-out curve available for velocity analysis, and limits the range of illumination angles for the observation of possible AVO effects (fig. 5). Figure 5 indicates that minimization of the transmitter-receiver offset would significantly increase the range of illumination angles. The limited angular coverage reduced the resolution of radar velocities and prompted the decision to analyze and stack the data using NMO instead of DMO (dip move-out) methods.

After CDP sorting, an NMO-based velocity analysis was performed on every 10th CDP gather. The velocities that produce the highest semblance are near 120 m/μs (meters per microseconds) (fig. 6), which is in general agreement with velocities observed in other cross-hole radar experiments (Haeni and others, 1993). After velocity analysis, the data were NMO corrected and stacked to produce zero-offset CDP profiles.

DATA INTERPRETATION

The CDP profiles before and during tracer injection are shown in figure 7 juxtaposed to common offset profiles (6.4 m offset) before and during tracer injection. More reflectors are identifiable in the CDP profiles than in the common-offset profiles. In the CDP profiles, the amplitude and continuity of reflectors near the boreholes is increased, the direct arrival is suppressed, and the antenna ringing and system noise is reduced. The frequency of the data in the stacked profile is lower than that in the common offset profile due to poor resolution of stacking velocities and because the NMO correction reduces the frequency of the far offset traces due to NMO stretching.

Some effects of saline tracer are observed in the CDP profiles. For example, changes in reflectivity can be identified near the borehole between 45-50 m (the injection interval) during tracer injection (fig. 7). To interpret the effects of saline injection, subtle differences in reflectivity need to be identified. One way to image changes in reflectivity is through data differencing. The goal of differencing is to isolate those reflectors that have been significantly affected by the transport of the saline tracer within transmissive fracture zones. Although simple subtraction of radar waveforms to extract amplitude changes is problematic because small-phase differences between waveforms can produce significant apparent amplitude differences, simple subtraction was used in this study to compare difference images of common-offset profiles and CDP profiles (fig. 8).

Qualitatively, the CDP difference image provides a clearer indication of the effects of the salt injection than the common offset difference image: the reflectors are more continuous, and the image contains less noise. For example, the down-dipping reflection and diffraction events between 45-50m in depth, which are clearly seen in the CDP difference image, are only faintly observed in the common-offset difference. These reflectors correlate with fractures that cross the borehole at depths of about 44.5 and 47.5 m, identified in acoustic televiewer logs and in conventional and oriented video logs (F.L. Paillet, written commun. 1994; C.D. Johnson, written commun. 1994). These results illustrate the advantage to using differencing methods on CDP profiles to interpret the effects of saline tracer injection.

The reflection behavior of a 60 MHz Ricker wavelet was modeled using GPRMODV2 (Powers and Olhoeft, 1995). The modeling results indicate that increasing the specific conductance of water in thin (~1mm) fractures from 'background' levels of about 300 μS/cm to saline tracer levels of about 30,000 μS/cm should result in a three-fold increase in reflection amplitude. Direct comparison of background and tracer reflection amplitudes is difficult because the presence of tracer in the borehole annulus and in fractures within the near field of the antennas can be expected to change the operating characteristics of the antennas. Loading of the antenna by the electrically conductive fluids would reduce the antenna frequency and alter the antenna radiation pattern. Quantitative determination of changes in reflectivity and comparative analysis of possible AVO effects will require the implementation of data equalization procedures to compensate for the effects of saline tracer within and near the borehole.

CONCLUSIONS

Multi-offset data acquisition and CDP processing methods were applied to single-hole borehole-radar reflection surveys conducted at the U.S. Geological Survey Fractured Rock Research Site at Mirror Lake, Grafton County, New Hampshire. Comparison of common-offset and CDP profiles indicates that there are benefits to using multi-offset acquisition and CDP processing methods. These benefits include; (1) an increase the resolution of reflectors near the borehole, (2) a decrease the effects of direct-wave coupling, antenna ringing and system noise, and (3) clearer difference images to identify the effects of saline tracer on reflections from transmissive fractures.

ACKNOWLEDGEMENTS

The authors would like to thank Allen Shapiro and Carole Johnson for their technical advice and assistance, as well as Jared Abraham, Marc Buursink, Peter Joesten and Rick Perkins for their efforts during the field experiment. We wish to specially thank Wayne Martin of the U.S. Forest Service for permitting the experiment to be conducted at the Hubbard Brook Experimental Forest, Grafton County, New Hampshire. Roelof Versteeg acknowledges the support of the Schlumberger Foundation.

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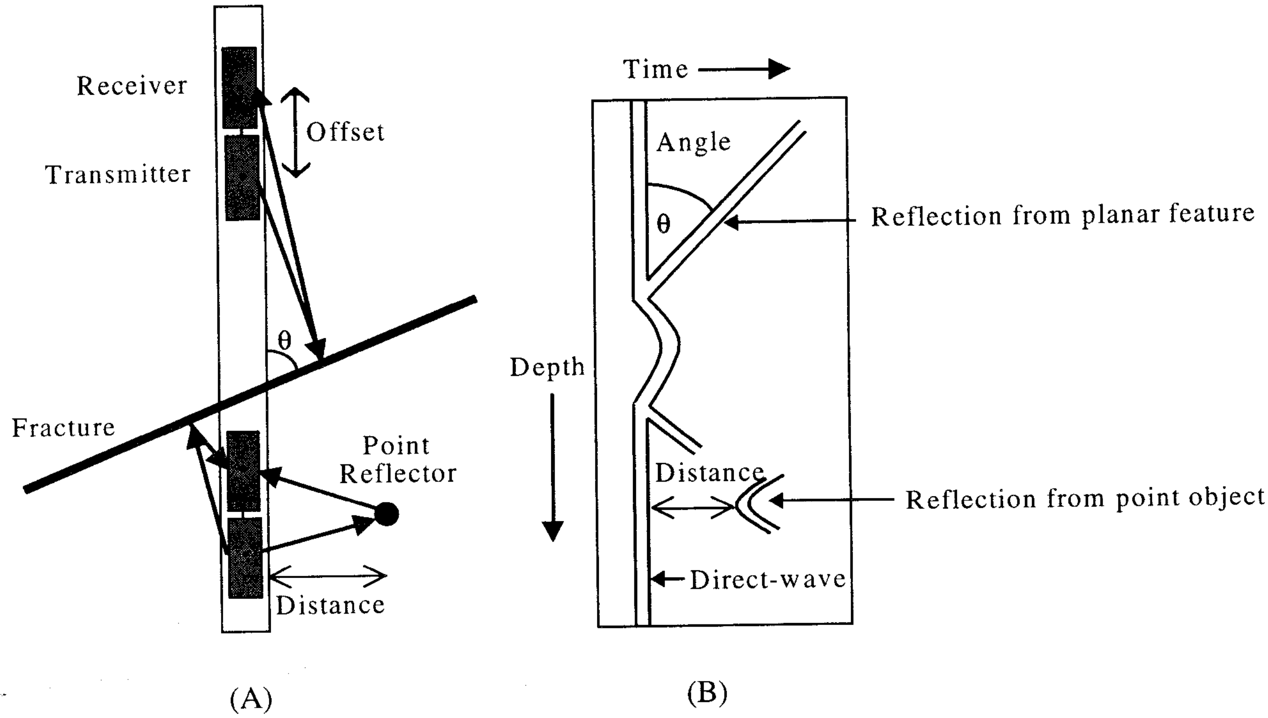


Figure 1. Diagram showing (A) antenna arrangement and (B) typical reflection patterns observed in single-hole borehole-radar reflection records.

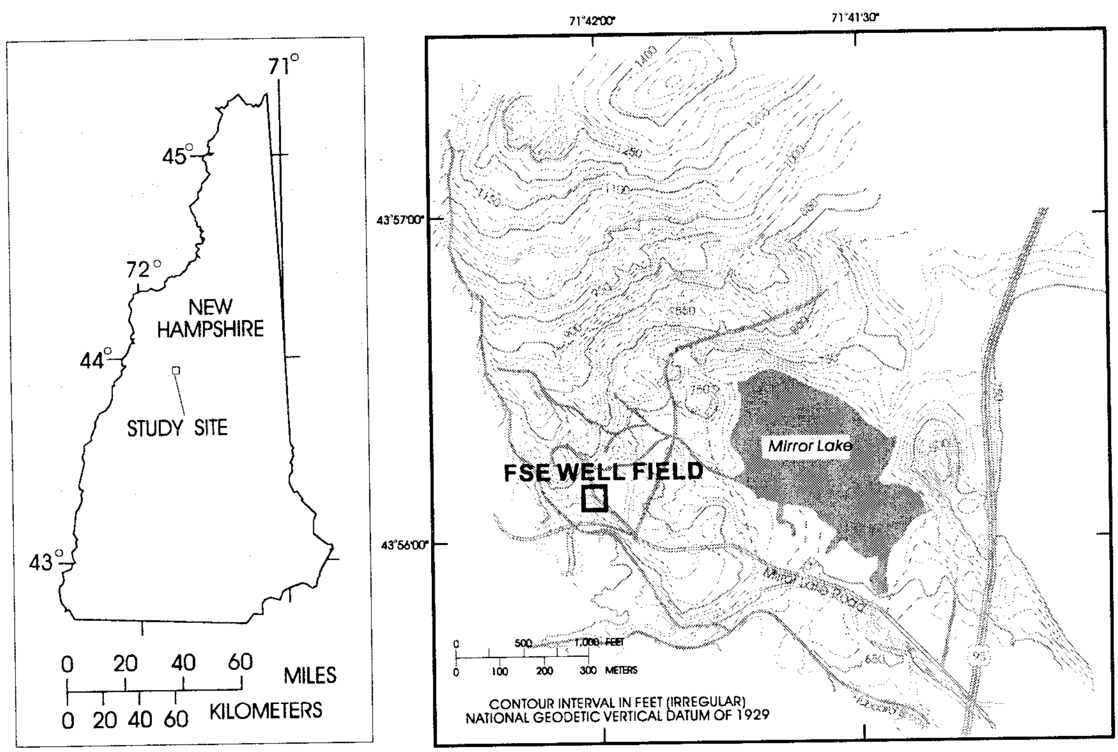


Figure 2. Location of study area and the FSE well field at the U.S. Geological Survey Fractured Rock Research site, Mirror Lake, Grafton County, New Hampshire

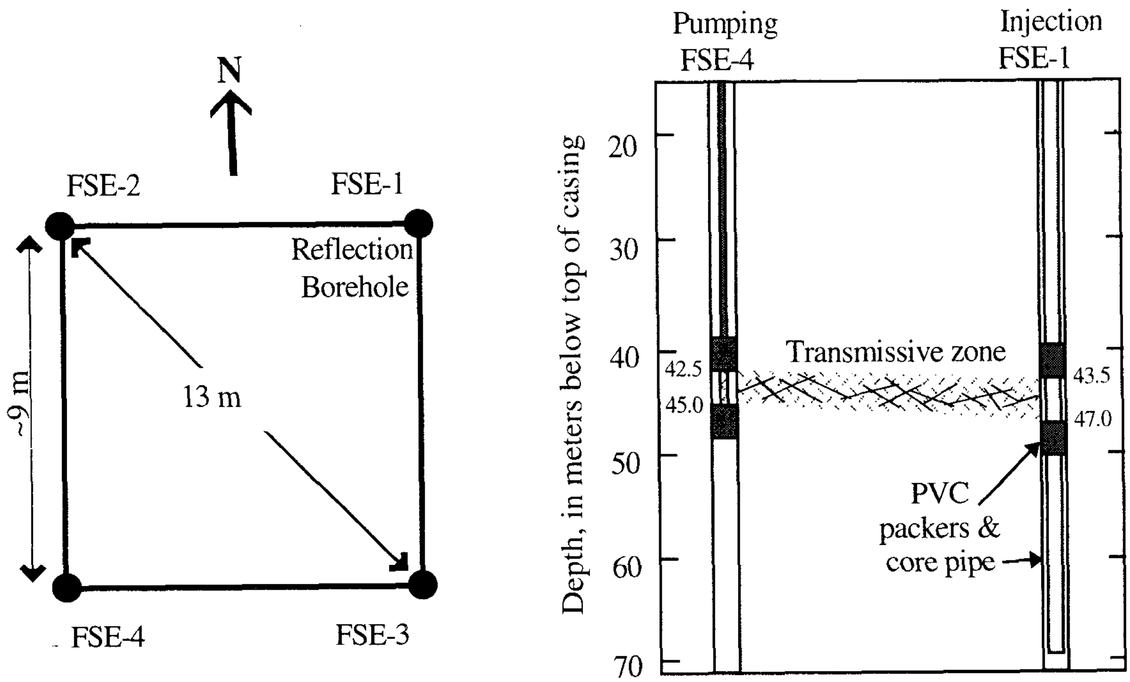


Figure 3. Layout of FSE 1 to 4 boreholes and diagram showing the experiment design.

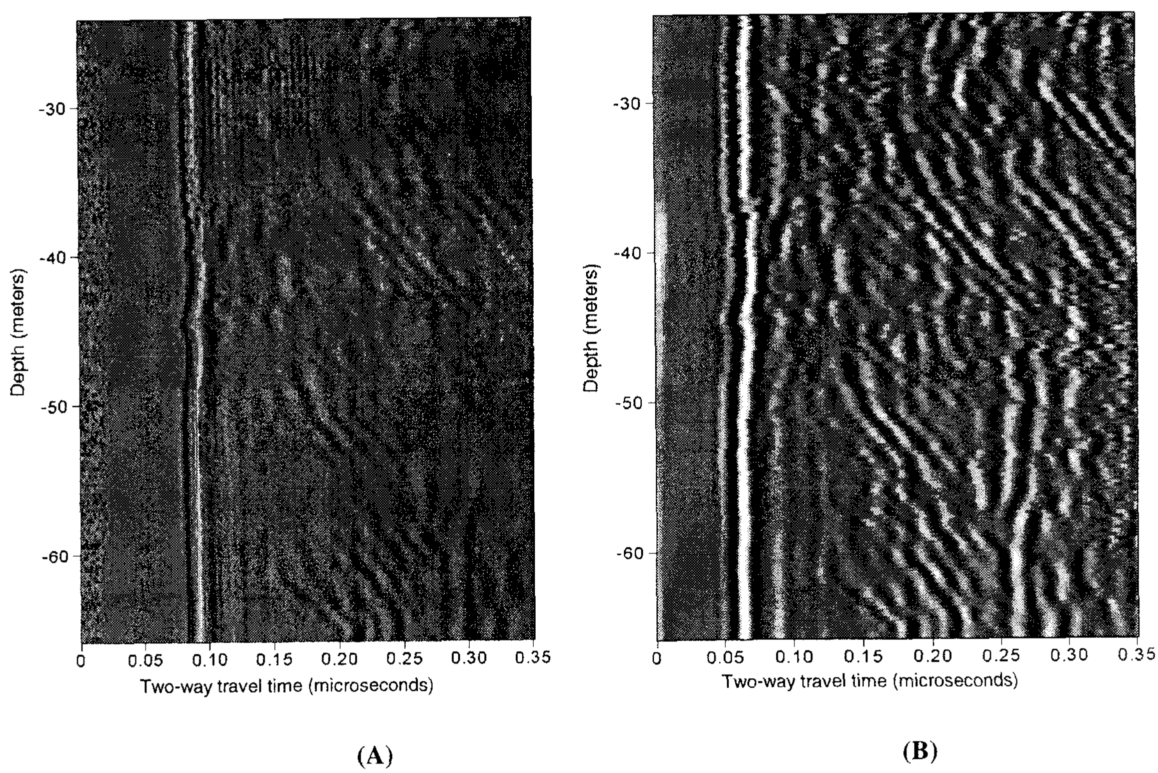


Figure 4. Single-hole, common-offset reflection records from FSE-1 (A) before and (B) after processing to remove noise and correctly position the onset of the direct-wave.

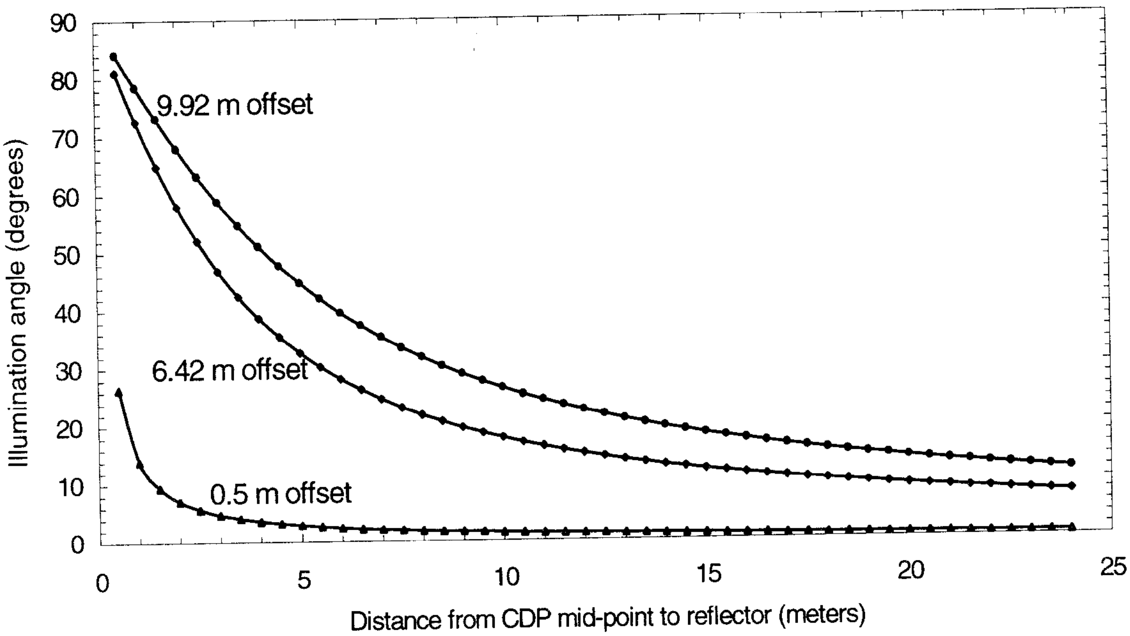


Figure 5. Graph of CDP reflection illumination angle plotted against the distance to a reflector. The graph shows the limits of reflection angular coverage for the range of offsets used in this study (6.42-9.92 m) and the increase in coverage if the minimum offset were reduced to 0.5 m.

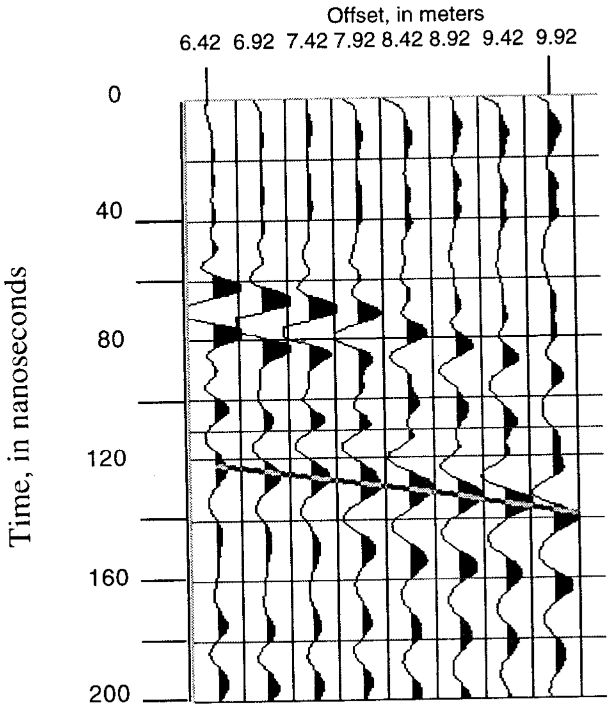


Figure 6. CDP gather at 41.25m showing the normal moveout curve for a velocity of 120 m/μs overlain on a reflector about 7.2m from the borehole.

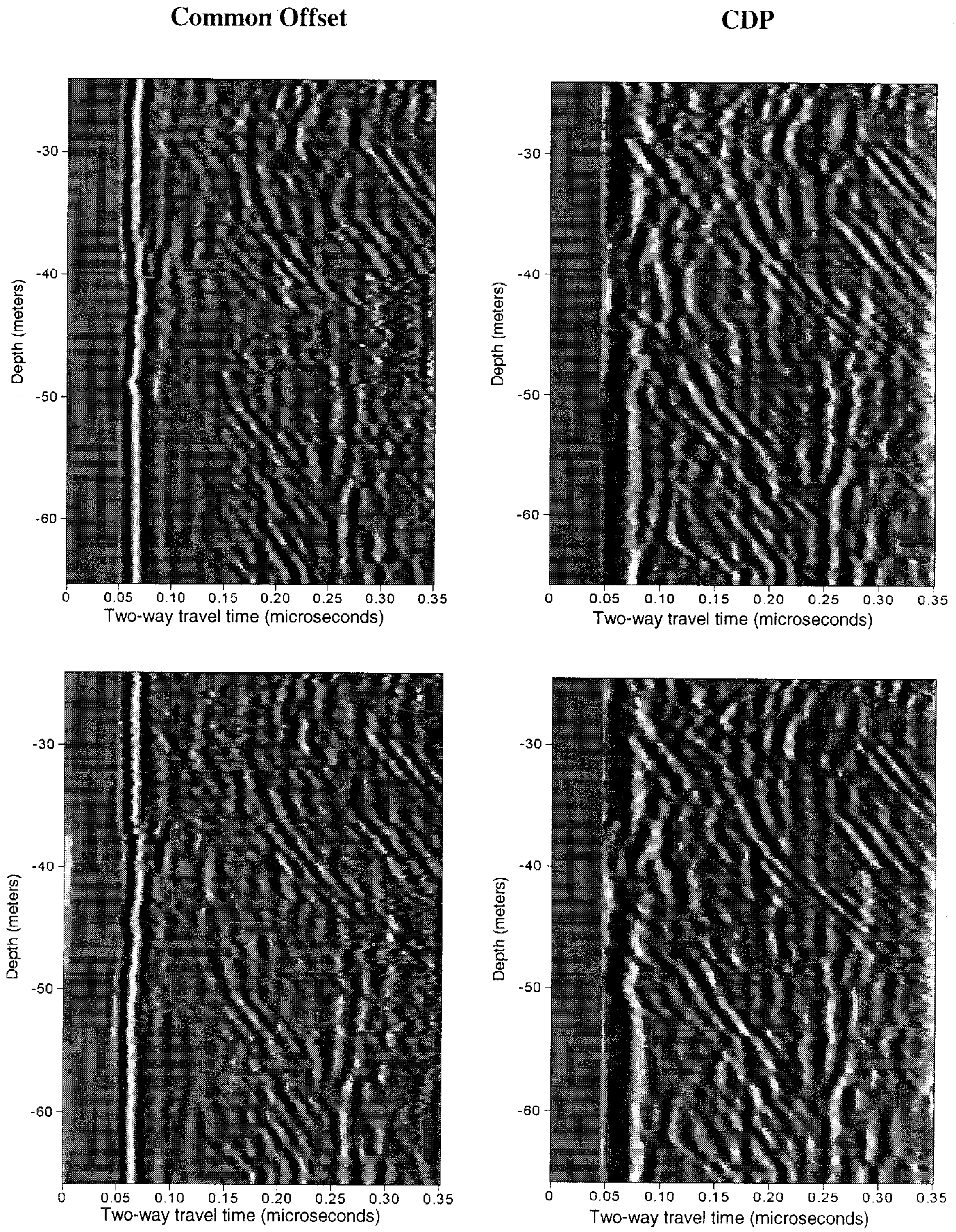
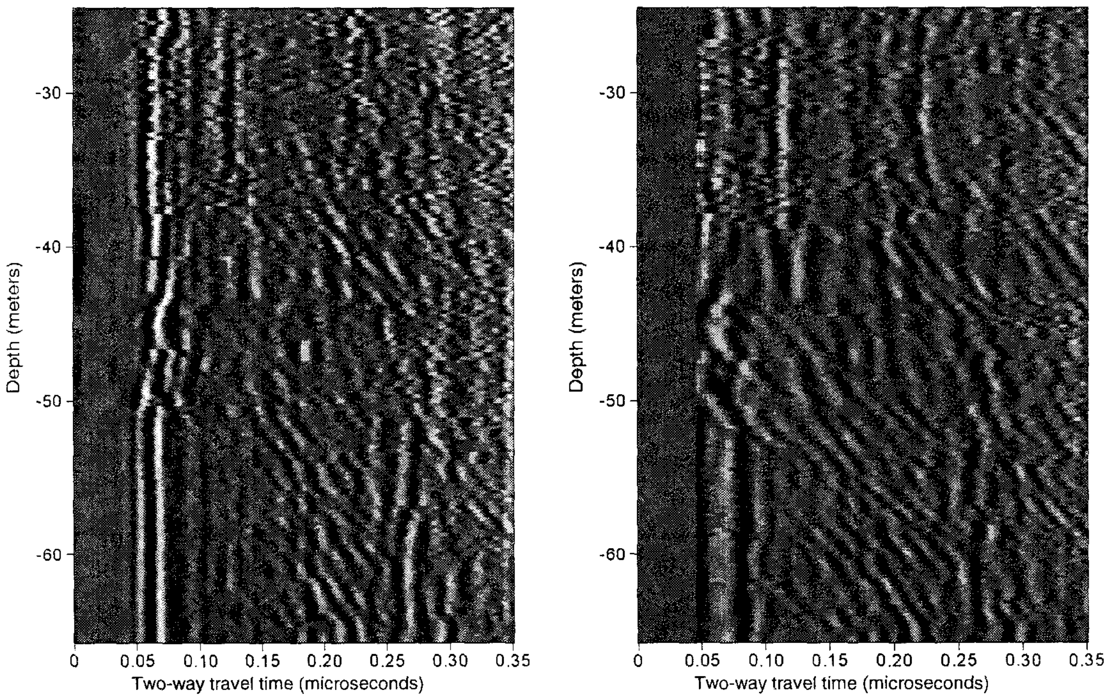


Figure 7. Common-offset (6.4m) and CDP stacked profiles before (top) and during (bottom) tracer injection.



(A) (B)

Figure 8. Difference images for (A) 6.4m common-offset profile and (B) CDP processed profile showing the results of subtracting background reflection data from tracer reflection data.