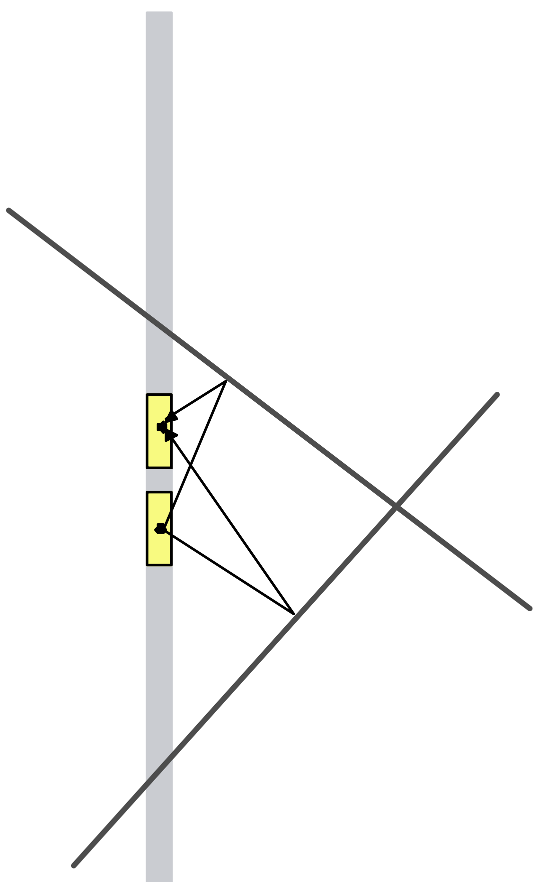
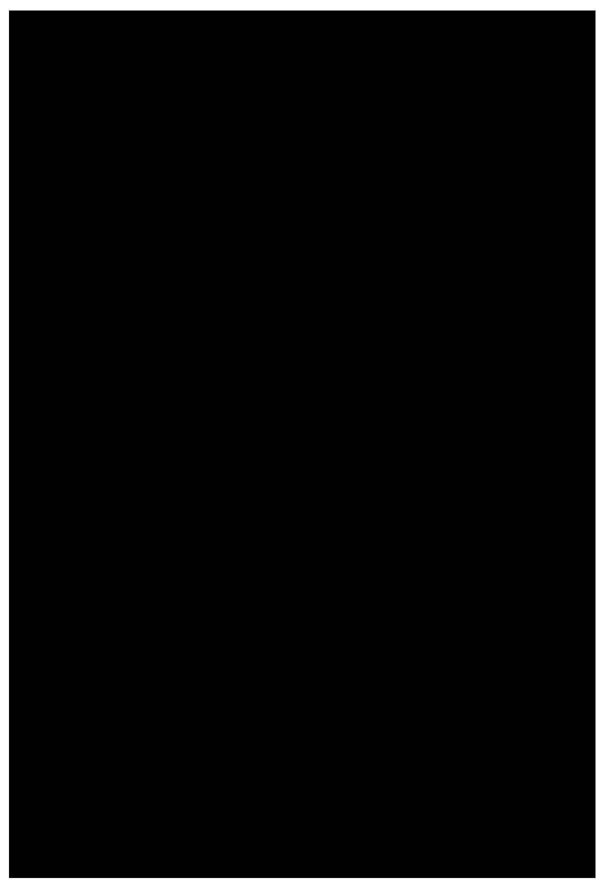
Analysis of Borehole-Radar Reflection Logs from Selected HC Boreholes at the Project Shoal Area, Churchill County, Nevada

Water-Resources Investigations Report 01-4014





Prepared in cooperation with the U.S. Department of Energy

U.S. Department of the Interior
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Front cover: Schematic diagram of the borehole-radar reflection method (left) and 60-megahertz borehole-radar reflection data from borehole HC-7, Project Shoal Area, Churchill County, Nevada (right).

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
kilometer (km)	0.6214	mile
meter (m)	3.281	foot

Other abbreviations used in this report:

°, degrees
MHz, megahertz

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ABSTRACT

Single-hole borehole-radar reflection logs were collected and interpreted in support of a study to characterize ground-water flow and transport at the Project Shoal Area (PSA) in Churchill County, Nevada. Radar logging was conducted in six boreholes using 60-MHz omni-directional electric-dipole antennas and a 60-MHz magnetic-dipole directional receiving antenna.

Radar data from five boreholes were interpreted to identify the location, orientation, estimated length, and spatial continuity of planar reflectors present in the logs. The overall quality of the radar data is marginal and ranges from very poor to good. Twenty-seven reflectors were interpreted from the directional radar reflection logs. Although the range of orientation interpreted for the reflectors is large, a significant number of reflectors strike northeast-southwest and east-west to slightly northwest-southeast. Reflectors are moderate to steeply dipping and reflector length ranged from less than 7 m to more than 133 m.

Qualitative scores were assigned to each reflector to provide a sense of the spatial continuity of the reflector and the characteristics of the field data relative to an ideal planar reflector (orientation score). The overall orientation scores are low, which reflects the general data quality, but also indicates that the properties of most reflectors depart from the ideal planar case. The low scores are consistent with reflections from fracture zones that contain numerous, closely spaced, sub-parallel fractures.

Interpretation of borehole-radar direct-wave velocity and amplitude logs identified several characteristics of the logged boreholes: (1) low-velocity zones correlate with decreased direct-wave amplitude, indicating the presence of fracture zones; (2) direct-wave amplitude increases with depth in three of the boreholes, suggesting an increase in electrical resistivity with depth resulting from changes in mineral assemblage or from a decrease in the specific conductance of ground water; and (3) an increase in primary or secondary porosity and an associated change in mineral assemblage, or decrease in ground water specific conductance, was characterized in two of the boreholes below 300 m.

The results of the radar reflection logging indicate that even where data quality is marginal, borehole-radar reflection logging can provide useful information for ground-water characterization studies in fractured rock and insights into the nature and extent of fractures and fracture zones in and near boreholes.

INTRODUCTION

In October 1963, an underground nuclear test was conducted at the Project Shoal Area (PSA) in Churchill County, about 50 km southeast of Fallon, Nevada. The nuclear test was conducted as part of a research program designed to enhance the detection of underground nuclear tests in seismically active areas (Pohll and others, 1998). Because underground nuclear tests deposit radioactive materials in the subsurface, there is a potential for radioactive materials to directly contact and contaminate ground water. At the PSA, the U.S. Department of Energy is conducting characterization studies of ground-water contamination to establish contaminant boundaries to protect human health and the environment (Pohll and others, 1998).

In support of the ground-water studies, a cooperative project was conducted by the U.S. Department of Energy and the U.S. Geological Survey under Interagency Agreement DE-A108-96NV11967. Borehole-radar reflection logging was conducted in six boreholes in the PSA to identify large fractures and fractures zones in and near the boreholes. The radar logs were analyzed and interpreted by the U.S. Geological Survey to identify planar and point reflectors near the boreholes, estimate the orientation of reflectors, determine the projection depth of the reflectors relative to the boreholes, and identify characteristics of the reflection logs that could provide information about the nature and extent of fractures and fracture zones in and near the boreholes.

Purpose and Scope

This report presents results of the analysis and interpretation of borehole-radar reflection data acquired in six boreholes at the PSA. The analysis of the radar data included determination of the location and orientation of planar and point reflectors, approximation of the length of planar reflectors, and qualitative estimation of the relative continuity and characteristics of reflectors in the field data relative to an ideal planar reflector. Results of the analysis are presented in tabular form, stereo plots, and histograms. In addition, the relative arrival time and amplitude of the direct wave traveling between the radar transmitter and receiver was analyzed. Results of the direct-wave analysis are provided in graphical form as radar velocity and amplitude logs.

Description of the Study Area

The PSA is in Churchill County, Nevada, about 50 km southeast of Fallon, Nevada (fig. 1). The regional ground-water hydrology is described by Cohen and Everett (1963) and Glancy and Katzer (1975). The University of Nevada (1965) reported results of geologic and topographic mapping, drilling operations, geophysical surveys, hydrologic testing, and geologic core analysis. Investigations have been undertaken to characterize the hydrogeology of the PSA and the effects of the nuclear test. These studies were tabulated and summarized by Pohll and others (1998).

As described in Pohll and others (1998), the PSA is in the Sand Springs Range, a north-south trending range in Nevada's Great Basin. The Sand Springs Range is bounded by near-vertical, northeast- and northwest-trending faults. Within the range, an intrusive granitic body of Cretaceous age is surrounded by metamorphosed Paleozoic and Mesozoic marine sediments. Intermittent faulting is present in the center of the Sand Springs Range as high- to moderate-angle, northeast- and northwest-trending faults. The Project Shoal test was conducted in the granite uplift of the Sand Springs Range. Near the site, ground water is present in the fractured granite about 300 m below land surface.

DATA COLLECTION AND ANALYSIS

Borehole-Radar Reflection Method

Borehole-radar reflection methods can provide information about the extent and orientation of fracture zones intersected by a borehole and fracture zones outside of the borehole that are not penetrated by drilling. This provides information about the rocks outside the borehole that would not be provided by tools that characterize only the interior of a borehole. The ability of the method to ”see” beyond the borehole can potentially provide valuable insight about the network of fractures in and near boreholes.

Borehole-radar systems and methods have been developed in the United States (Rubin and others, 1978; Wright and Watts, 1982) and in Sweden (Nilsson, 1983; Olsson and others, 1988). Single-hole radar reflection methods (using omni-directional and directional receiver antennas) have been used to detect and map fractures and fracture zones at proposed high-level nuclear waste sites (Bradley and Wright, 1987; Olsson and others, 1988, 1992a, 1992b; Sandberg and others, 1991; Holloway and others, 1992; Stevens and others, 1995) and are increasingly

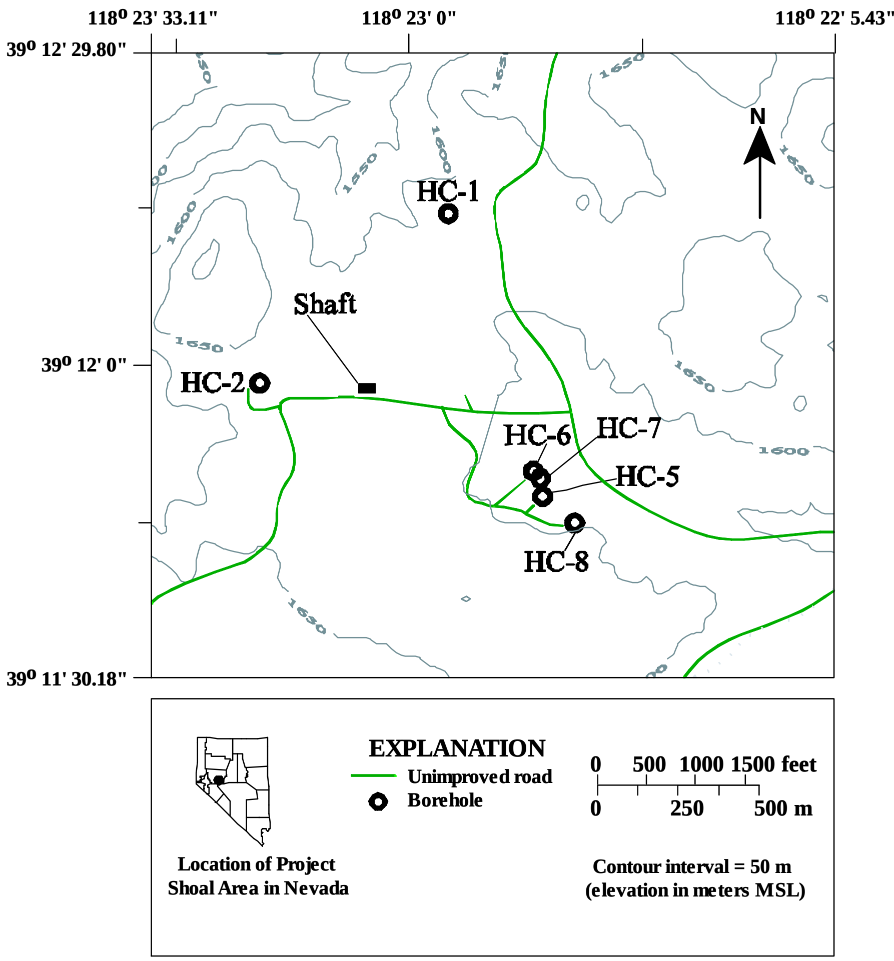

Figure 1. Location of the study area, general topography, and logged boreholes at the Project Shoal Area, Churchill County, Nevada.

utilized for ground-water investigations (Haeni and others, 1993; Gaylor and others, 1994; Lane and others, 1994; Hansen and Lane, 1995). The ABEM RAMAC borehole-radar system used for this study was developed by the Swedish Geological Survey to investigate potential high-level nuclear waste disposal sites.

Borehole-radar reflection logging is conducted by connecting a radar transmitter and receiver together as a logging tool (fig. 2). The transmitter and receiver are vertically oriented in a single borehole, and separated by a fixed distance. A high-frequency electromagnetic (EM) pulse is generated by the transmitting antenna and propagates radially into the surrounding material. Some of the energy is reflected when it encounters changes in the physical properties of the rock surrounding the borehole, such as at fractures or point-like discontinuities. Transmitted (direct-wave) and reflected energy arriving at the receiving antenna is recorded as a function of time (fig. 2).

Reflection logging can be conducted with omni-directional or directional receiving antennas. The transmitter and the receiver antennas are moved down a single hole using a computer-controlled winch, and measurements are collected at discrete, regular intervals. The transmitter-receiver antenna separation can range from 1 to 15 m depending on the radar system, selection of antenna frequency and design, and electrical resistivity of the rock. The borehole measurement interval usually ranges from about 0.1 to 1.0 m. Omni-directional (electric-dipole) antennas provide information on the dip and depth of a reflector with respect to the borehole, but do not provide information on the orientation (strike) of a reflector. Directional receiving antennas can provide

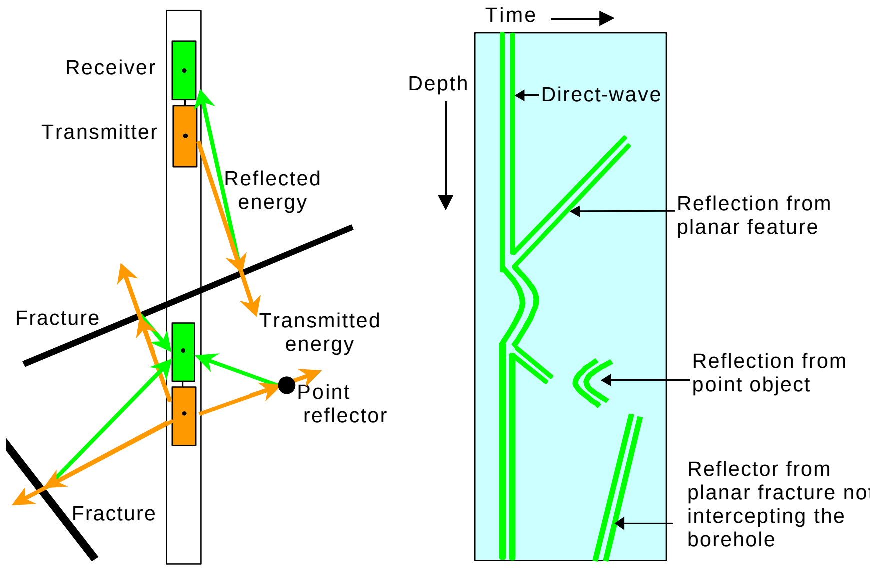

Figure 2. Transmitter and receiver antenna arrangement for borehole-radar reflection logging and the typical reflection patterns from planar and point reflectors.

information on the orientation of reflectors. The directional receiver used for this study is a magnetic-dipole type described by Falk (1992). Although the directional receiver can determine the orientation of planar reflectors and the azimuths to point reflectors, the antenna is less sensitive than the electric-dipole antenna. The radial penetration of the directional antenna used for this study is typically 50 to 70 percent that of the penetration achieved by the omni-directional antenna.

The basic principles of single-hole reflection surveying and the typical reflection patterns for planar and point reflectors, such as fractures or voids, are illustrated in figure 2. The first signal to arrive at the receiver is the direct wave, which propagates from the transmitter, through the rock, to the receiver. Due to the small diameter of most boreholes relative to the EM wavelengths used for radar reflection logging, propagation of energy along the borehole is small and limited to very high frequencies. As the transmitter and receiver antenna pair approach and pass a point scatterer, an approximately hyperbolic reflection is obtained with the apex of the hyperbola at the point closest to the borehole (fig. 2). As the transmitter and receiver antennas approach a planar reflector that intersects the borehole, the reflection travel time decreases until it merges with the direct arrival. As the transmitter and receiver pass through the intersection location of the reflector, no reflections are obtained and a delay of the arrival time of the direct wave can occur, if, for example, the reflector is a water-filled fracture or fracture zone. As the transmitter and receiver move past the reflector intersection point, the reflection travel time increases, resulting in a two-limbed or chevron-shaped reflection pattern for a reflector that intersects the borehole (fig. 2). The reflection pattern for reflectors that do not intersect the borehole is discontinuous and displays only the upper (up-dip) or lower (down-dip) limb (fig. 2).

The EM-wave propagation velocity is required to accurately interpret the dip of planar reflectors and the radial distance to point reflectors. The EM velocity for different rock types can be roughly estimated from tabulations found in the literature (Cook, 1975), by vertical radar profiling (VRP) tests, and by analysis of the shape of the reflections from point reflectors. VRP testing is performed by fixing the transmitter location while making measurements as the receiver is moved away from the transmitter in fixed increments. The slope of the best-fit line of the transmitter-receiver distance plotted against the arrival time yields the average velocity along the borehole.

Variations in the arrival time and amplitude of the direct wave provide information about the range of velocity and attenuation differences of the material surrounding the borehole. In resistive, saturated rocks, a delayed arrival of the direct wave (decreased velocity) coupled with a decreased pulse amplitude can indicate an increase in porosity due to fracturing; the high dielectric permittivity of water reduces EM-wave velocity.

Data Processing

For this study, signal processing of borehole-radar data was limited to (1) removal of the direct-current (DC) offset and (2) band-pass filtering (Yilmaz, 1987). The DC offset is caused by the analog-to-digital sampling electronics, which induce a drift in the signal level with time. The DC offset is removed by averaging the DC level of the first few samples of each trace before the onset of the direct arrival, and subtracting this average from the rest of the samples. Band-pass filtering is used to remove low- and high-frequency random and system noise and other sources of noise, such as ringing induced by the impedance mismatch of the antennas with the borehole.

Data Analysis and Interpretation

Interpretation of the strike of a planar feature or the azimuth to a point reflector is performed in a manner analogous to certain methods of radio-direction finding. Using a loop antenna, it is possible to locate the radial direction to a transmitter by rotating the loop and measuring the signal induced on the receiving antenna. The magnetic component of the electromagnetic wave induces an electric current in the loop. The electromotive force in the loop is a function of the magnetic flux through the loop. Therefore, the signal induced by a plane wave is a function of the component of the variable magnetic field passing through the antenna loop (fig. 3).

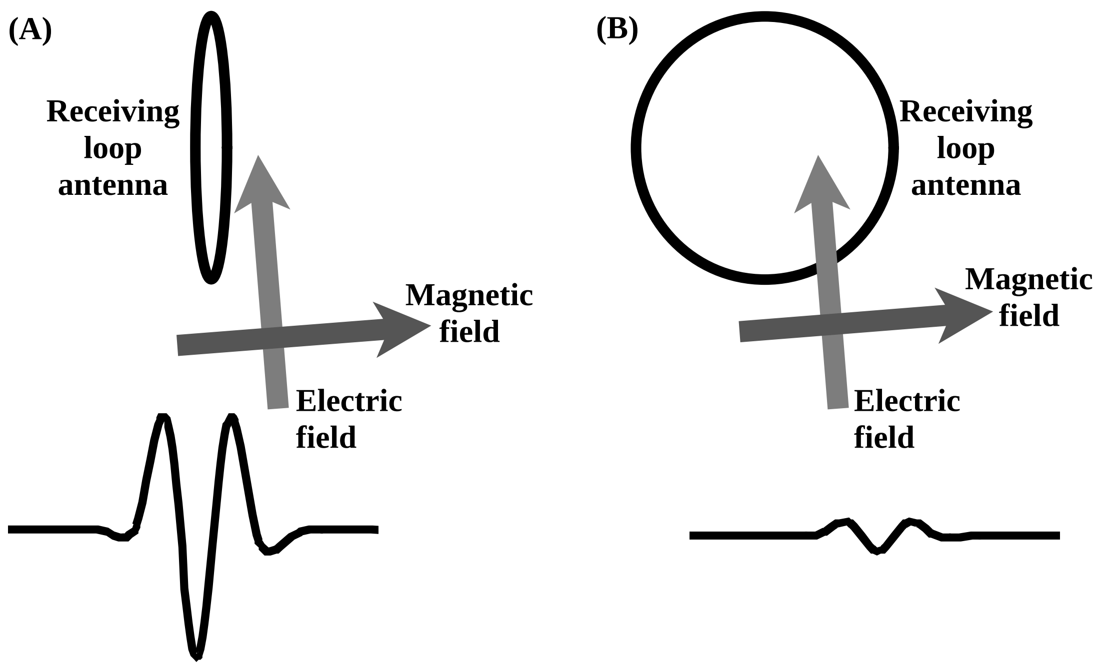

Figure 3. Effect of the orientation of a receiving loop antenna, with respect to an impinging transmitted electromagnetic wave, on the amplitude of the signal induced on the receiving antenna: (A) antenna loop parallel to incident electric field receives the maximum signal amplitude, (B) antenna loop perpendicular to incident electric field receives minimal signal amplitude.

Maximum signal is induced on the antenna when the plane of the loop is parallel to the radial direction to the transmitter. The location of the transmitter is found by determining the radial direction to the transmitter from at least two different locations.

For radar reflection logging, locating the direction to a reflection source is similar to the radio-direction finding problem of locating the direction to a transmitter. In a borehole, however, the direction of movement is limited to the borehole axis, and physical rotation of the antenna is not desirable due to the power demands of a mechanical apparatus. Therefore, specially designed directional antennas are required to determine the strike, dip, and intersection location of planar reflectors, and the azimuth, depth, and radial distance of point reflectors. The directional receiving antenna used for this study is a magnetic dipole tool containing four orthogonal, resistively-loaded, transmission line antennas, which have the same directional radiation properties described for the loop antennas, but with improved signal characteristics (Falk, 1992). The antenna contains a three-component magnetometer and a plunge sensor to determine the orientation of the receiver for each measurement. The four antennas allow the sampling of the spatial components of the reflected electromagnetic waves, without resorting to the physical rotation of the antennas.

For this study, the commercial software RADINTER was used to interpret the radar reflection logs. RADINTER is an interactive program that allows the user to interpret the projected intersection depth, dip, and strike of planar reflectors and the azimuth to point reflectors. This is done using information on the logging measurement parameters, including distance between the transmitter and receiver, measurement start location, measurement interval, sampling frequency, and average EM propagation velocity (fig. 4). A complete description of the procedures used to interpret the directional data can be found in Falk (1992). Note that the projected intersection depth is relative to the line formed by the axis of the borehole. Therefore, the projected intersection depth can be below the drilled depth of the borehole, in the cased portion of a borehole, or can be negative, which indicates the reflector projects to the borehole axis above the ground surface.

Estimation of Reflector Length

Simple geometric concepts can be used to analyze the planar reflectors observed in radar reflection logs. The simplifications ignore important details such as Fresnel zone and edge effects needed

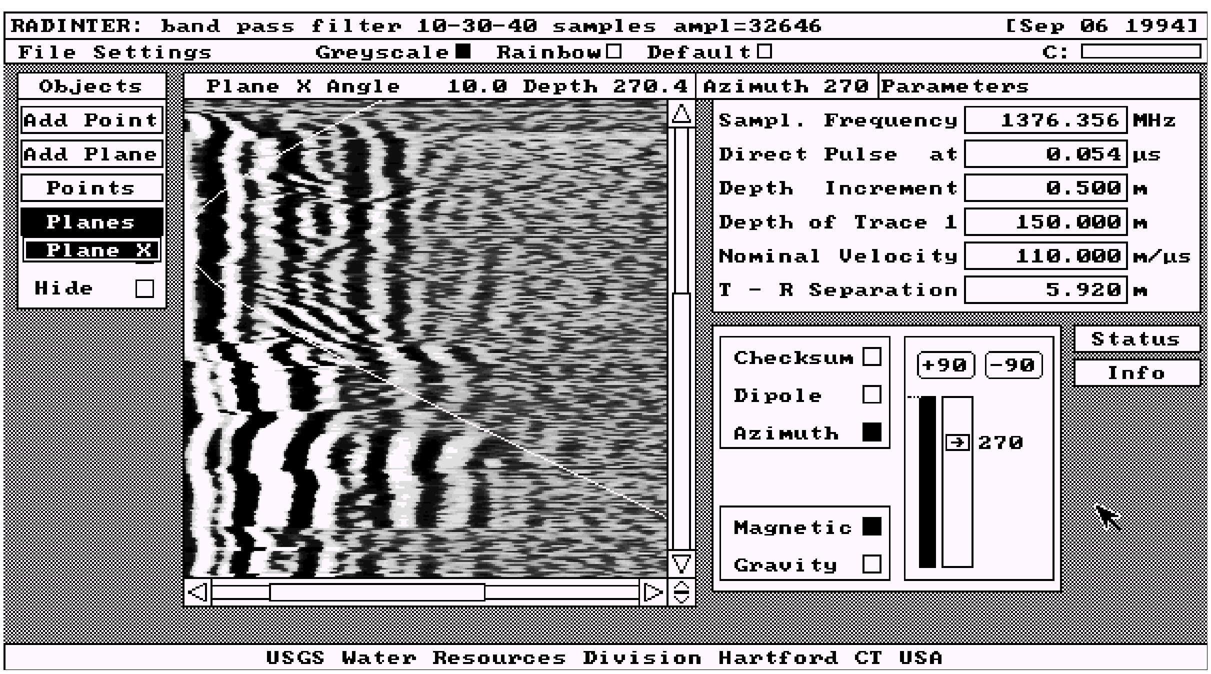

Figure 4. Screen capture showing the use of RADINTER software to interactively interpret borehole-radar reflection logs.

for a more comprehensive analysis; nonetheless, using straight-ray approximations and right-angle trigonometry, useful information about the nature and extent of planar reflectors can be extracted from radar reflection logs. For a thorough discussion of reflection physics, see Yilmaz (1987).

For planar reflectors, the part of the reflector imaged by the logging process is the component parallel to the borehole. Thus, the imaging process is biased by the orientation of the reflector relative to the borehole. For example, the effect of orientation bias on reflectors oriented parallel and perpendicular to the borehole is shown in figure 5. A reflector oriented at a large angle to the borehole reflects EM waves from nearly the same spot as the radar tool is moved along the borehole, whereas for reflectors parallel to the borehole, the imaged spot moves as the radar tool moves (fig. 5). The orientation bias also affects estimates of the location and radial distance to a reflection point; this is similar to the classic migration problem of reflection seismology (Yilmaz, 1987).

Using the geometry shown in figure 5, a reasonable approximation of the radial distance to a point on a reflector is given by

$$D_{cor} = D_{est} \cos(\alpha) \qquad (1)$$

where

D_{cor} is the corrected radial distance from the borehole,

D_{est} is the estimated distance to reflection point, accounting for fixed transmitter-receiver offset, and

α is the angle of planar reflector to the borehole.

Using this simple radial distance correction, the procedure for calculating the length of a limb of a planar reflector is to (1) use RADINTER to determine the angle of the reflector relative to the borehole; (2) estimate the maximum radial extent of the limb from the reflection record; and (3) correct this distance estimate using equation (1). An estimate of the length of the reflector parallel to the borehole, assuming that the reflector projects close to or intersects the borehole, is given by

$$L_{est} = D_{cor} \sin(\alpha) \qquad (2)$$

where L_{est} is the estimated length of imaged reflector.

Reflector Quality Scores: Reflector Continuity and Orientation Confidence

The ideal models and simple geometries used to describe theoretical reflection properties often fail to predict real earth reflection characteristics. For example, the ideal planar reflector describes a smooth surface with constant or slowly changing differences in physical properties. In contrast, fracture zones can cross lithologic boundaries; be non-planar; be locally discontinuous; and have abrupt changes in the number, length, and orientation of fractures in the zone. Also, the radar antennas used for this study couple with and are modified by the medium surrounding the antennas. Therefore, real antenna response can and does depart from ideal predicted response.

Because of the differences between ideal and real behavior, a qualitative system of scoring is used to provide a sense of the quality of the data and the confidence in a given interpretation relative to an idealized case. For this study, two scores, ranging from 1 (best) to 5 (worst) are assigned to each reflector for the following categories: (1) reflector continuity and (2) orientation confidence.

The reflector continuity score provides a sense of the spatial persistence of a reflector across the radar reflection log. A score of 1 is assigned to high-amplitude reflectors that originate at or close to the direct wave and are clearly visible with little or no amplitude variations. This type of reflector closely approximates the ideal planar reflector. A reflector continuity score of 3 is assigned to reflectors that show some discontinuity and amplitude variation but can be followed relatively easily across the radar reflection log. This type of reflector is consistent with a locally discontinuous fracture or fracture zone. A reflector continuity score of 5 is assigned to reflectors that are observed in small segments that are isolated and (or) extremely difficult to follow or trace across the radar reflection record. This type of reflector is consistent with isolated, spatially discontinuous fractures and inhomogeneities.

The orientation confidence score provides an indication of the azimuthal (directional) behavior of the reflector relative to the behavior predicted for ideal planar reflectors. The score is also a measure of the confidence of the interpretation. A score of 1 is assigned to reflectors that behave as ideal planar reflectors. A score of 3 is assigned to reflectors that

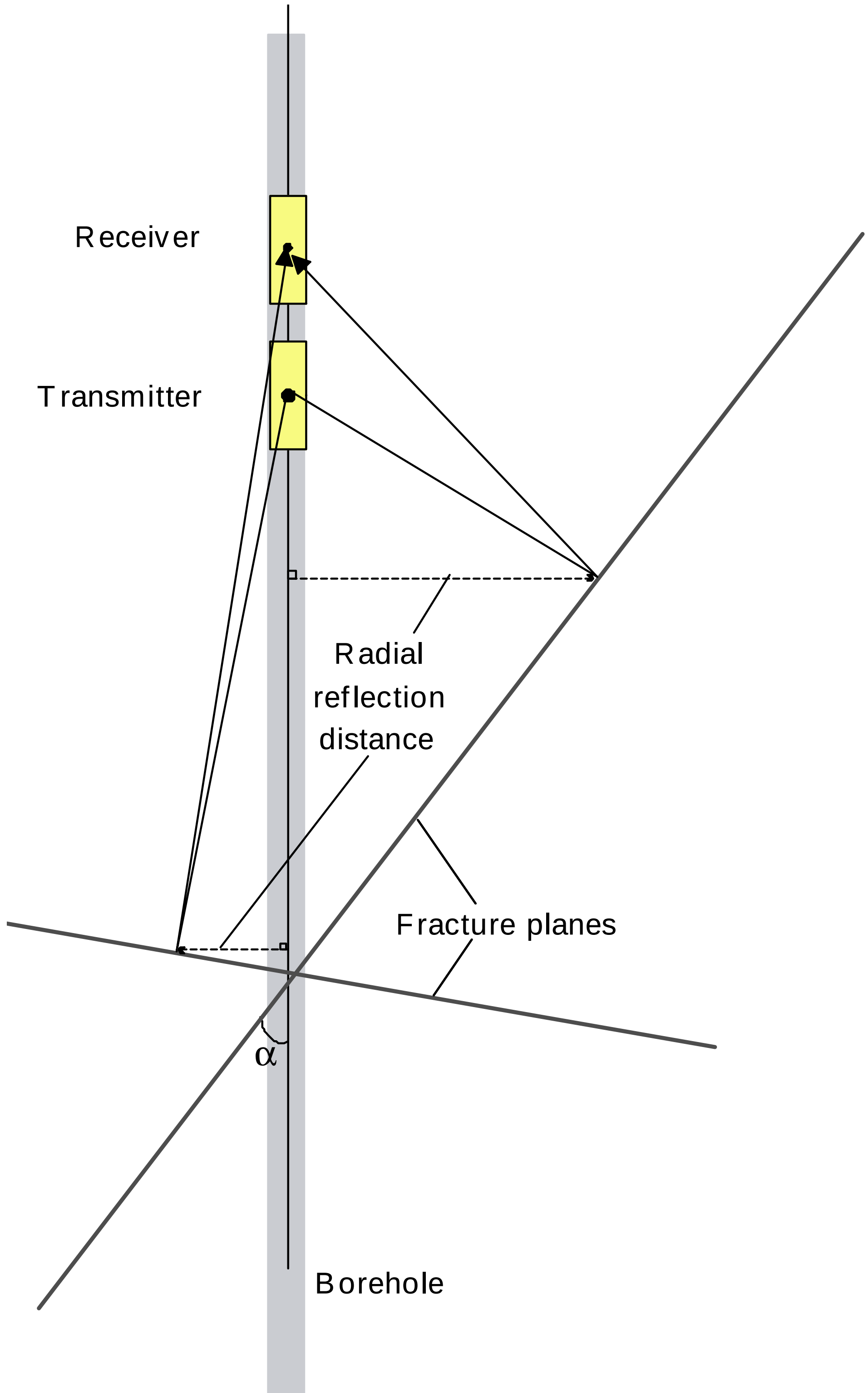

Figure 5. Effect of reflector orientation on reflection imaging.