DELINEATION OF SUBSURFACE STRATIGRAPHY AND STRUCTURES BY A SINGLE CHANNEL, CONTINUOUS SEISMIC-REFLECTION SURVEY ALONG THE CLINCH RIVER, NEAR OAK RIDGE, TENNESSEE

By Patrick Tucci, F.P. Haeni, and Zelda Chapman Bailey

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4023

Prepared in cooperation with the

U.S. DEPARTMENT OF ENERGY

Hartford, Connecticut

1991

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
feet per second (ft/s)	0.3048	meters per second
mile per hour (mi/hr)	1.609	kilometer per hour

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The feasibility of using a single channel, continuous seismic-reflection survey to detect subsurface stratigraphic contacts; internal structures, such as bedding; and major structural features, such as thrust faults and fracture zones in bedrock, was tested along 35 miles of the Clinch River near the Oak Ridge Reservation. These features could not be delineated on all 35 miles of the seismic record, and prior knowledge of the target features from surface mapping was usually necessary to distinguish them; however, all of these targets were successfully delineated in some sections of the record. Water-column-multiple reflections and other artifacts commonly obscured the record, but structural features as deep as 225 feet were interpreted in some areas. The continuous seismic-reflection method was most successful where the water was deepest, and water-column-multiple reflections were widely spaced and therefore, not a major problem.

INTRODUCTION

Shallow-land burial of low-level radioactive and other wastes is commonly practiced on the Oak Ridge Reservation (fig. 1). The Reservation is also the site of a former deep-well injection plant for the disposal of liquid radioactive wastes (Stow and Haase, 1986). Many of these wastes have been transported from their original disposal sites by ground water along flow paths that are, in part, controlled by rock type and geologic structure (Webster and Bradley, 1988). The geology of the Reservation is complex and, with the exception of several site-specific studies, has been mapped in only a very generalized manner (McMaster, 1963). A detailed understanding of the subsurface stratigraphy and structure is important in the evaluation of potential contaminant pathways. The geology along the Clinch River (fig. 1) is of particular interest, because the river is believed to be a discharge point for ground water from the Reservation, and because the river forms most of the southern and southeastern boundaries of the Reservation.

Several site-specific, surface-geophysical investigations have been conducted on the Reservation, including seismic refraction (Rothschild and others, 1984; 1985; Davis and others, 1984; Staub and Hopkins, 1984; Dreier and others, 1987), direct-current resistivity, (Tucci, 1987; Rothschild and others, 1984 and 1985; Davis and others 1984), and electromagnetic surveys (Tucci, 1987; Rothschild and others, 1984; 1985; Ketelle and Pin, 1983; Pin and Ketelle, 1983) in an effort to describe the geology of the Reservation, but no geophysical work has been previously conducted on the Clinch River.

The study was conducted by the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, as part of their on-going investigations of the hydrogeology of low-level radioactive-waste disposal sites.

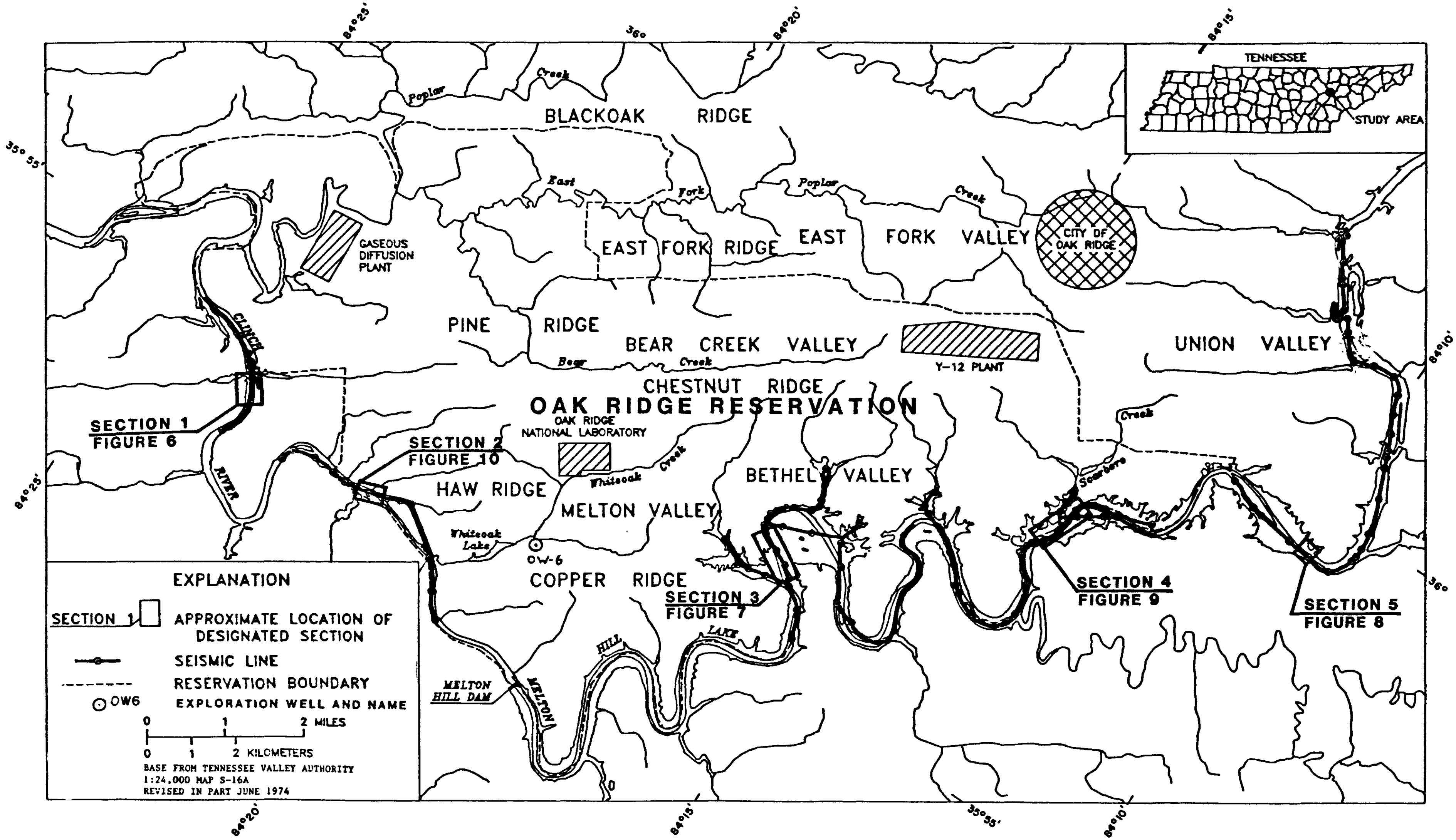


Figure 1.--Location of the Oak Ridge Reservation and seismic lines and sections along the Clinch River.

Purpose and Scope

This report documents the results of a single channel, continuous seismic-reflection survey along the Clinch River conducted during April 1986. The survey was conducted to test the feasibility of using this seismic method to delineate specific targets in the consolidated bedrock underlying the river. These targets were (1) subsurface stratigraphic contacts; (2) internal structures, such as bedding; and (3) major structural features, such as thrust faults and fracture zones. Continuous seismic-reflection data were obtained along approximately 35 mi (miles) of the Clinch River on the northeastern, southeastern, and southwestern sides of the Reservation (fig. 1). These data were analyzed and compared to existing geologic maps. Because of the large amount of data produced during this study, only a few selected examples of the seismic record and interpretations are discussed in this report.

Location, Physical Features, and Drainage

The Oak Ridge Reservation includes about 58,000 acres in eastern Tennessee (fig. 1). The Reservation is bordered on the northeast, southeast, and southwest by the Clinch River and associated lakes, and on the northwest by Blackoak Ridge and the City of Oak Ridge. Oak Ridge National Laboratory (ORNL), the Y-12 Plant, and the Gaseous Diffusion Plant (ORGDP) are the three main research and production facilities on the Reservation (fig. 1).

The Oak Ridge Reservation is located in the Ridge and Valley physiographic province (Fenneman, 1938), which is characterized by northeast-trending valleys separated by ridges that are locally 200 to 500 ft (feet) above the valley floor. The sequence of ridges and valleys in the Reservation area, from northwest to southeast, is Blackoak Ridge, East Fork Valley, East Fork Ridge and Pine Ridge, Bear Creek Valley and Union Valley, Chestnut Ridge, Bethel Valley, Haw Ridge, Melton Valley, and Copper Ridge.

The Clinch River is the main drainage in the study area (fig. 1). Tributary streams that drain the Reservation include Poplar Creek, East Fork Poplar Creek, Bear Creek, Scarboro Creek, and Whiteoak Creek. The Clinch River is confined by Melton Hill Dam, which forms Melton Hill Lake along the southeastern boundary of the Reservation (fig. 1). Depth of the Clinch River ranges from about 6 ft downstream from Melton Hill Dam to about 60 ft upstream from the dam.

SINGLE CHANNEL, CONTINUOUS SEISMIC-REFLECTION SURVEYS

General Theory

The seismic-reflection exploration method (Telford and others, 1976) was used in this investigation because of its suitability for distinguishing detailed subsurface layers and structure. In this method, energy is received after it has been reflected from a subsurface layer. Reflection data can be collected on land and water; however, the continuous seismic-reflection method can only be used on water. Because data are collected continuously over great distances, this method can be used to interpret the geology and hydrology of a large area in a short period of time.

The continuous seismic-reflection method was adapted to marine use by Ewing and Tirey (1961) and Hersey (1963) and has been used for many years in deep ocean and marine geology studies. Multichannel data aquisition seismic systems and subsequent digital processing of the field data are common operations for geothermal, oil and gas exploration, and other deep- water geologic studies. The development of high-frequency sound sources and the continuing modification of this deep-water technology has made single channel seismic systems applicable for shallow-water engineering studies, where the top several hundred feet of earth materials are of interest.

The application of this method to engineering problems is well documented in the literature, and examples of direct hydrologic uses of the technique are available (Moody and Van Reenan, 1967; Haeni, 1971; Haeni and Sanders, 1974; Missimer and Gardner, 1976; Freeman-Lynde and others, 1982; Wolansky and others, 1983; Haeni and Melvin, 1984; Morrissey and others, 1985; Haeni, 1986; Hansen, 1986; Haeni, 1989; Reynolds and Williams, 1989). In most of these studies the purpose of using the continuous seismic-reflection method was to map the stratigraphy of the shallow unconsolidated earth materials. None of these engineering-oriented studies have used the technique to map the structural features of consolidated rock units.

An explanation of the continuous seismic-reflection method is given below. More detailed treatment of this subject is available in Leenhardt (1969), Haeni (1971), EG and G Environmental Equipment (1977), Sylwester (1983), and Trabant (1984).

The operating principle of the seismic-reflection method is that an acoustic signal transmitted from a sound source is reflected at air-water, water-sediment, sediment-sediment, or rock interfaces due to changes in the acoustic impedance at these interfaces. The acoustic impedance is the product of the seismic velocity and the bulk density of the geologic units. The reflectivity of each interface is a function of the acoustic impedance and the angle of incidence of the impinging seismic-wave train. With a large contrast in acoustic impedance, such as at the air-water interface, a large part of the normally incident energy is reflected. The reflected energy from an interface decreases as the acoustic impedances on either side of the interface become nearly equal, and, if they are equal, energy will be transmitted through the interface without generating a reflected wave.

The detection of horizontal stratigraphic boundaries is possible if there is a contrast in acoustic impedance at the boundary such that the reflected signal generated is large enough to measure. As the angle of dip of the subsurface units increases, the seismic section begins to deviate from the geologic section due to the aquisition geometry (migration) and the dip on the seismic section becomes an apparent dip and not the true dip. The dip on the seismic section will be less than the actual dip of the interface and must be corrected, or "migrated" to its real position. At the extreme, a true reflector dip of 90° will appear as a 45° dip on the raw seismic section. The relation, sine (true dip) = tan (apparent dip) applies for a homogeneous subsurface.

The detection of faults on a seismic record is usually indirect. Offsets in bedding planes are commonly indicative of faulting. Occasionally, the fault plane itself can be detected if it separates two different rock types or generates diffraction patterns on the seismic record. In addition, the continuity of reflections beneath a fault plane is deteriorated or the reflections are completely missing (Telford and others, 1976).

The continuous seismic-reflection method requires a boat to tow an energy source that emits acoustic impulses or pressure waves at regular intervals (fig. 2). The reflected acoustic waves are received by a line of hydrophones that convert them to electrical signals and transmit them to an amplifier and band-pass filter and to a tape recorder, before being displayed on a variable-density analog recorder. The recorder display is a permanent paper record of the reflected signals that shows a time section of the bottom and subbottom in cross-sectional view.

The main advantage of the continuous seismic-reflection method is that recording the reflected signals is almost continuous because of emission of acoustical impulses at regular, short intervals (two to four impulses per second). The display is, therefore, a continuous delineation of subsurface acoustic property changes, greatly aiding the interpretation of geological formations, structure, and contacts between geologic units. Another advantage of this geophysical method is that the data can be collected very rapidly and economically, and if high seismic frequencies are used, a very detailed record of the subsurface is obtained.

Three types of sound sources are typically used in continuous seismic-reflection profiling. The choice of sound source depends on the target of the investigation and the characteristics of the sound source (table 1).

Table 1.--General characteristics of continuous seismic-reflection profiling sound sources

[Modified from Sylwester, 1983, p. 97; kHz, kilohertz; ms, millisecond; ft, feet; <, less than; in^3, cubic inches]

Instrument	Frequency spectrum (kHz)	Input energy	Pulse length (ms)	Typical resolution (ft)	Typical penetration (ft)
High-resolution boomer	0.4 - 14	100-500 (joules)	0.6 - 3	1 - 3	< 400
Sparker	.2 - 1	1,000 (joules)	3 - 7	2 - 30	<1,000
Air gun	.05 - .5	40 (in^3)	10 - 15	30 - 50	<2,000

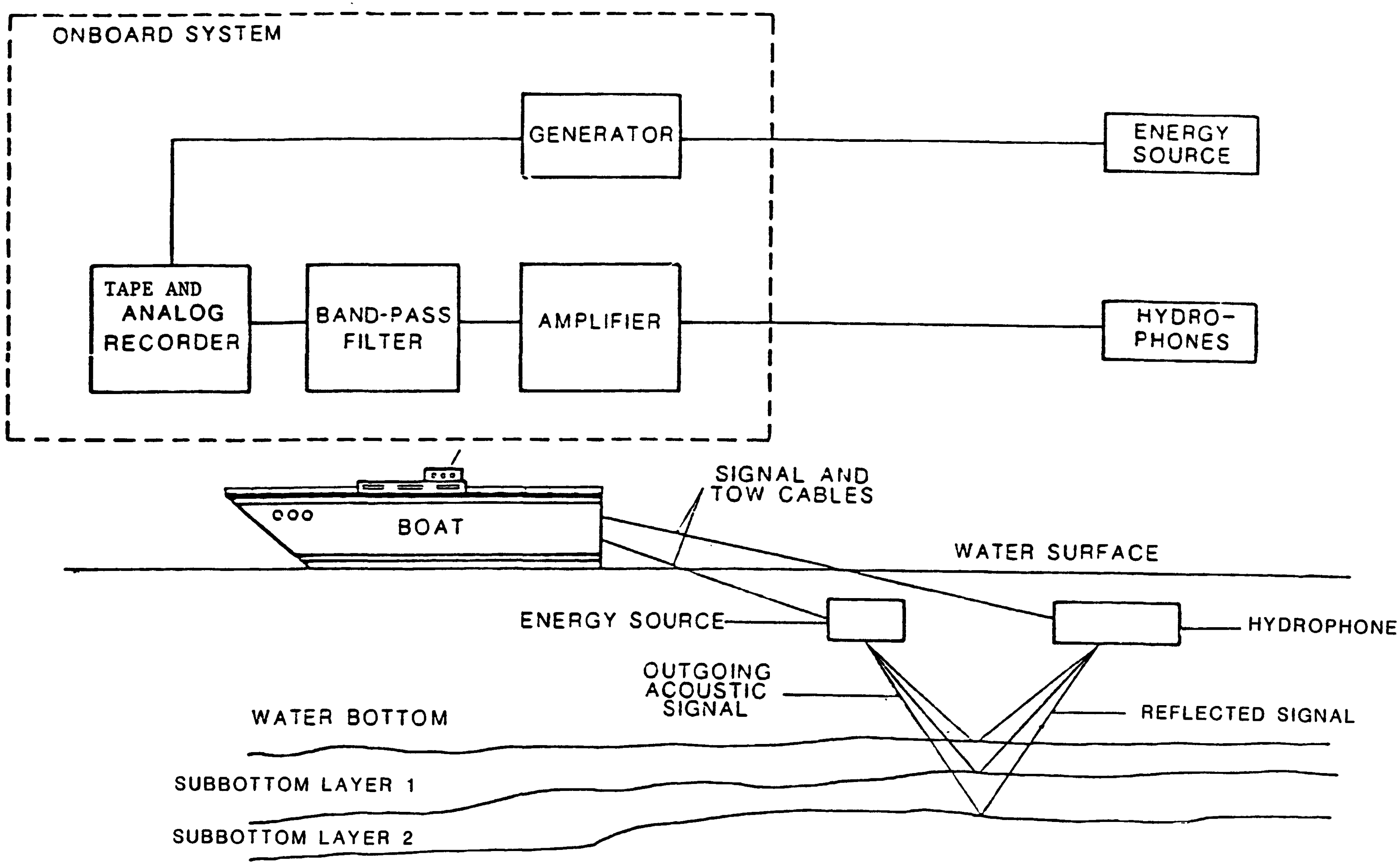


Figure 2.--Continuous seismic-reflection-profiling system. (Modified from Wolansky and others, 1983).

Methodology

A 22-ft workboat was used to conduct the profiling operations in the very shallow water and narrow channels of the Clinch River. The boat was powered by an outboard motor that required a minimum water depth of 2 ft, which consequently allowed access to all but the shallowest areas of the river. A shelter on the forward half of the boat protected the operating personnel and the electronic equipment from rain and spray. A 4.5-kilowatt gasoline-powered generator provided 110 volts of alternating current for the sound-source power supply and the electronic equipment.

The sound source and the hydrophone array were towed 100 ft behind the boat--one on each side (fig. 2). The horizontal separation of the source and receiver was about 10 ft. The single channel hydrophone array was made up of 24 evenly spaced elements (6 in. (inches) apart) connected in parallel with each other. The elements were enclosed in a plastic tube filled with mineral oil, so that the entire unit was almost neutrally buoyant. The hydrophone array was towed as close to the water surface as possible, without actually breaking the surface. The array was positioned away from the wake of the boat by an outrigger.

Because this investigation addressed the hydrogeology of shallow rock units that generally occur at depths of less than 400 ft below the water surface, a Ferranti-ORE Geopulse [1/] (high-resolution boomer) system was selected as the sound source for this study. The Geopulse produces a seismic wave capable of penetrating to a depth of 400 ft or less with a resolution of 1 to 3 ft. The Geopulse consists of an electrical coil and a plate. When energy contained in electrical storage capacitors is discharged into the coil, the result is a sudden movement of the plate, causing a sharp pressure pulse to be transmitted into the water.

The sound source used for this study was mounted on a catamaran and towed behind the boat with the top of the source just below the water surface. The power level of the sound source ranged from 105 J (joules) in shallow water to 175 J in deep water. The lowest possible power setting was used to minimize the number of water-column-multiple reflections and to obtain the best resolution.

The signals received from the hydrophones were passed through a preamplifier and filter unit and simultaneously recorded on tape and passed to a recorder. Most of the records shown in this report were produced in the field with the band-pass filter set for 600 to 2,000 Hz (hertz). The record shown in figure 8 was processed with the band-pass filter set for 1,000 to 2,500 Hz. Additional computer processing of the raw, single-channel seismic data was beyond the scope of this study.

[1/] The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

The recorder used in the study utilized 9-in.-wide dry paper. It was set on a display scale of 0.1 seconds full scale and it fired the sound source at 0.5-second intervals. The paper advance was set at 150 lines per inch.

Profiling was conducted by maintaining a constant boat speed, usually about 2 to 4 mi/hr (miles per hour) between plotted navigational aids and prominent landmarks. Although the exact speed for each survey line was not known, the starting and ending points of each line were known and were used to scale the records horizontally.

GEOLOGIC SETTING

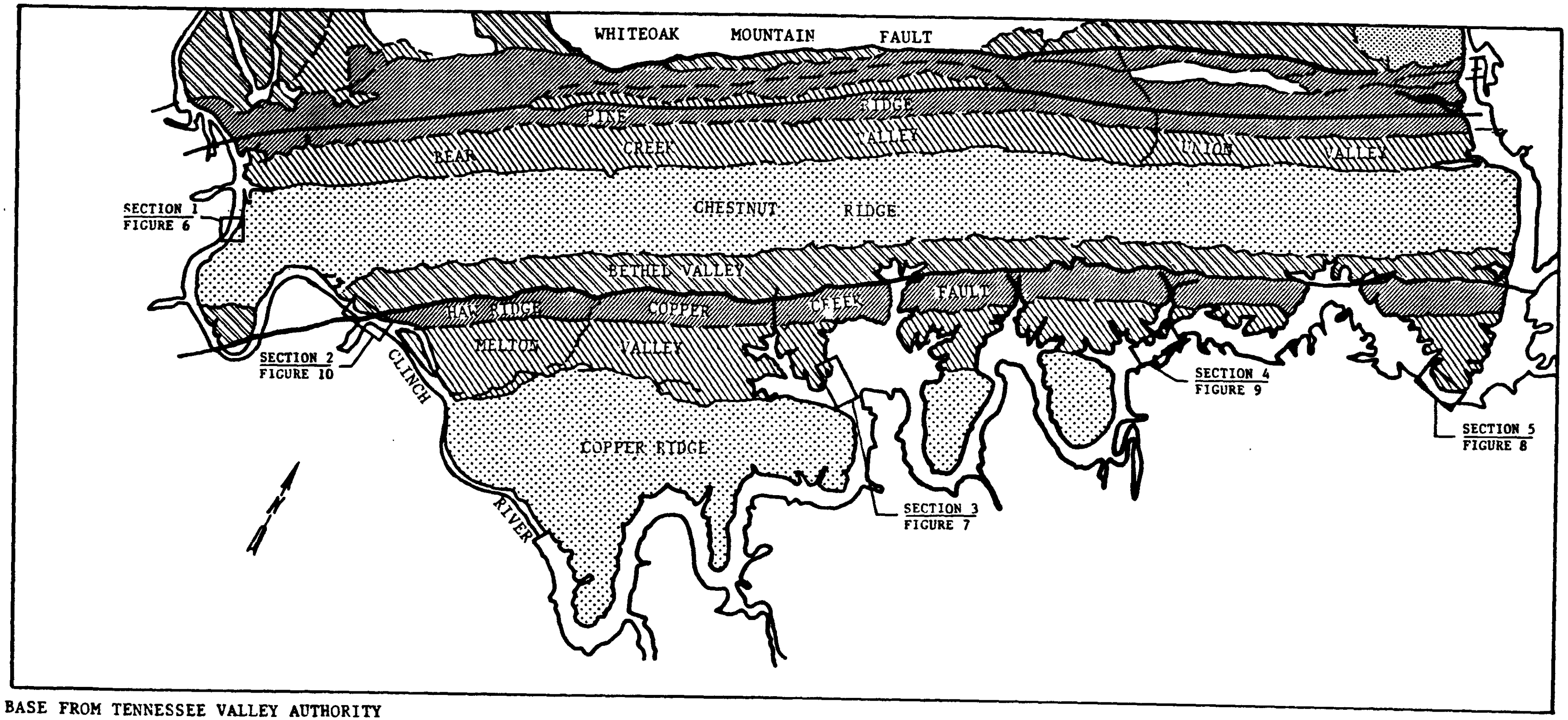
The Reservation is located in eastern Tennessee near the southwestern edge of the Ridge and Valley physiographic province, which is underlain by southeastward-dipping sedimentary rocks that range in age from Cambrian through Mississippian. Carbonate rocks (limestone and dolomite) are somewhat more abundant than clastic rocks (sandstone, siltstone, and shale). Most of the Reservation is underlain by Cambrian and Ordovician rocks including, from oldest to youngest, the Rome Formation, the Conasauga and Knox Groups, and the Chickamauga Group (table 2; fig. 3). The topography of the area is controlled by lithology and structure. The valleys are underlain by the weakly resistant Chickamauga Group (Bethel Valley) and the Conasauga Group (Bear Creek Valley including Union Valley, and Melton Valley). The ridges are underlain by the weather-resistant Rome Formation (Pine and Haw Ridges) and the Knox Group (Chestnut and Copper Ridges).

Table 2.--Stratigraphy of bedrock formations on the Oak Ridge Reservation

[Modified from Haase and others, 1985; Hoos and Bailey, 1986; Ketelle and Huff, 1984; and McMaster, 1963]

System	Group	Formation	Estimated thickness (in feet) for formations in: Chestnut Ridge, Bear Creek Valley, Pine Ridge	Copper Ridge, Melton Valley, Haw Ridge	Bethel Valley
Ordovician	Chickamauga 1/				1,750
Ordovician	Knox	Newala equivalent 2/	900		
Ordovician	Knox	Longview equivalent 3/	50		
Ordovician	Knox	Chepultepec Dolomite	700		
Cambrian	Knox	Copper Ridge Dolomite	1,000-1,300	495 (minimum)	
Cambrian	Conasauga	Maynardville Limestone	250	324	
Cambrian	Conasauga	Nolichucky Shale	600	551	
Cambrian	Conasauga	Maryville Limestone	440	463	
Cambrian	Conasauga	Rogersville Shale	100	130	
Cambrian	Conasauga	Rutledge Limestone	100	101	
Cambrian	Conasauga	Pumpkin Valley Shale	310	309	
Cambrian	Rome Formation	Upper part	800-1,000	617	
Cambrian	Rome Formation	Lower part	undetermined		

1/ Usage of the Tennessee Division of Geology.
2/ Equivalent to upper part of the Kingsport Dolomite and overlying Mascot Dolomite.
3/ Equivalent to lower part of the Kingsport Dolomite.



BASE FROM TENNESSEE VALLEY AUTHORITY
1:24,000 MAP S-16A
REVISED IN PART JUNE 1974

0 1 2 MILES
0 1 2 KILOMETERS

Modified from Ketelle and Huff, 1984

EXPLANATION

GEOLOGIC UNITS

- Undifferentiated Lower Silurian and Upper Ordovician rocks
- Chickamauga Group (usage of Tennessee Division of Geology)
- Knox Group
- Conasauga Group
- Rome Formation
- APPROXIMATE LOCATION OF SEISMIC SECTIONS--Number is figure number in text
- GEOLOGIC CONTACT --dashed where approximate
- FAULT

Figure 3.--Bedrock geology of the Oak Ridge Reservation.

Description of Stratigraphic Units

Rome Formation

The Rome Formation of Cambrian age, which underlies Pine and Haw Ridges, is a mixture of sandstone, siltstone, shale, dolomite, and limestone. The upper part of the Rome is primarily massive to medium-bedded sandstone with some interlayered shale, and the lower part of the Rome is medium-bedded sandstone and siltstone interbedded with thinly-bedded mudstone and shale (Haase and others, 1985, p. 48). The upper and lower parts of the Rome Formation are divided on Pine Ridge by a thrust fault that is parallel to strike, and the formation is bounded by the Whiteoak Mountain fault on the northwestern face of this ridge (McMaster, 1963) (fig. 3). Similarly, the Rome Formation is bounded by the Copper Creek fault on the northwestern face of Haw Ridge.

The various lithologies of the Rome Formation weather differentially. Regolith developed on the Rome Formation is generally less than 15 ft thick (McMaster, 1963, p. 8), but may be as thick as 60 ft in some locations (J.K. Carmichael, U.S. Geological Survey, oral commun., 1989).

Conasauga Group

The Conasauga Group of Cambrian age is primarily a calcareous shale interlayered with limestone and siltstone (McMaster, 1963, p. 9). Formations within the group (table 2), from oldest to youngest, are the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone (Rodgers, 1953, p. 47). Despite the lithology implied by the names, lithology is commonly mixed within each of these formations, and contacts between the formations are gradational. All the formations underlie both Bear Creek and Melton Valleys. A row of low knobs on the valley floors are erosional features formed on the Maryville Limestone.

Thickness of the clay-rich regolith developed on the Conasauga Group is 0 to 60 ft. Regolith is thickest beneath the ridges and thinnest or absent in creek bottoms.

Knox Group

The Knox Group of Cambrian and Ordovician age, which underlies Chestnut and Copper Ridges, is composed primarily of massive, siliceous dolomite (McMaster, 1963, p. 10). The group can be divided into four formations (table 2): Copper Ridge Dolomite, Chepultepec Dolomite, and the Longview and Newala equivalents (Ketelle and Huff, 1984, p. 16). The Longview is a bedded chert zone, and the remaining formations are composed of cherty dolomite. Sinkholes are common on Chestnut and Copper Ridges. As much as 100 ft of cherty regolith has developed on ridges underlain by the Knox Group.

Chickamauga Group [1]

The Chickamauga Group of Ordovician age underlies Bethel Valley, however, at least 500 ft of the Chickamauga Group have been removed by faulting by the Copper Creek fault (McMaster, 1963, Lee and Ketelle, 1988). The stratigraphic sequence of the Chickamauga in the valley was divided into eight units designated A through H by Stockdale (1951). Three redbeds, near the base, middle, and top of the Chickamauga, are interbedded with gray, shaly limestone. Beds of blocky chert cause the development of low hills on the northwestern side of the valley floor. The limestone beds have some minor sinkhole development. Regolith is generally thin but may be as much as 40 ft thick.

Geologic Structure

The geologic structure is characterized by a series of subparallel thrust faults that trend to the northeast and dip to the southeast. Stratigraphic sequences are repeated in two thrust sheets that span the Reservation. These thrust sheets are bounded by the Whiteoak Mountain and Copper Creek faults (fig. 3). As a result of these faults, the Rome Formation (Cambrian) has been overthrust onto the younger (Ordovician) Chickamauga Group (fig. 4). The thrust faults are complex, and imbricate splays of the Copper Creek fault are common (R.B. Dreier, Martin Marietta Energy Systems, Inc., written commun., 1987). The rocks in the study area generally strike about N. 56° E., and dip southeastward at angles that range from 0° to 90° but commonly are 20° to 50°. The rocks usually dip steeply near the outcrop of the thrust faults; the dip decreases away from the fault and with depth (fig. 4). The dip of the thrust fault also decreases with depth. The rocks in Bear Creek Valley dip 30° to 70° SE., and the average dip is about 45°. The rocks in Melton Valley have a shallower dip, averaging about 20° SE. Local, small-scale secondary structural features, such as fractures, folds, and faults, are present throughout the Reservation.

[1] The Chickamauga (Limestone) raised to Group status by Swingle (1964), represents the usage of the Tennessee Division of Geology.

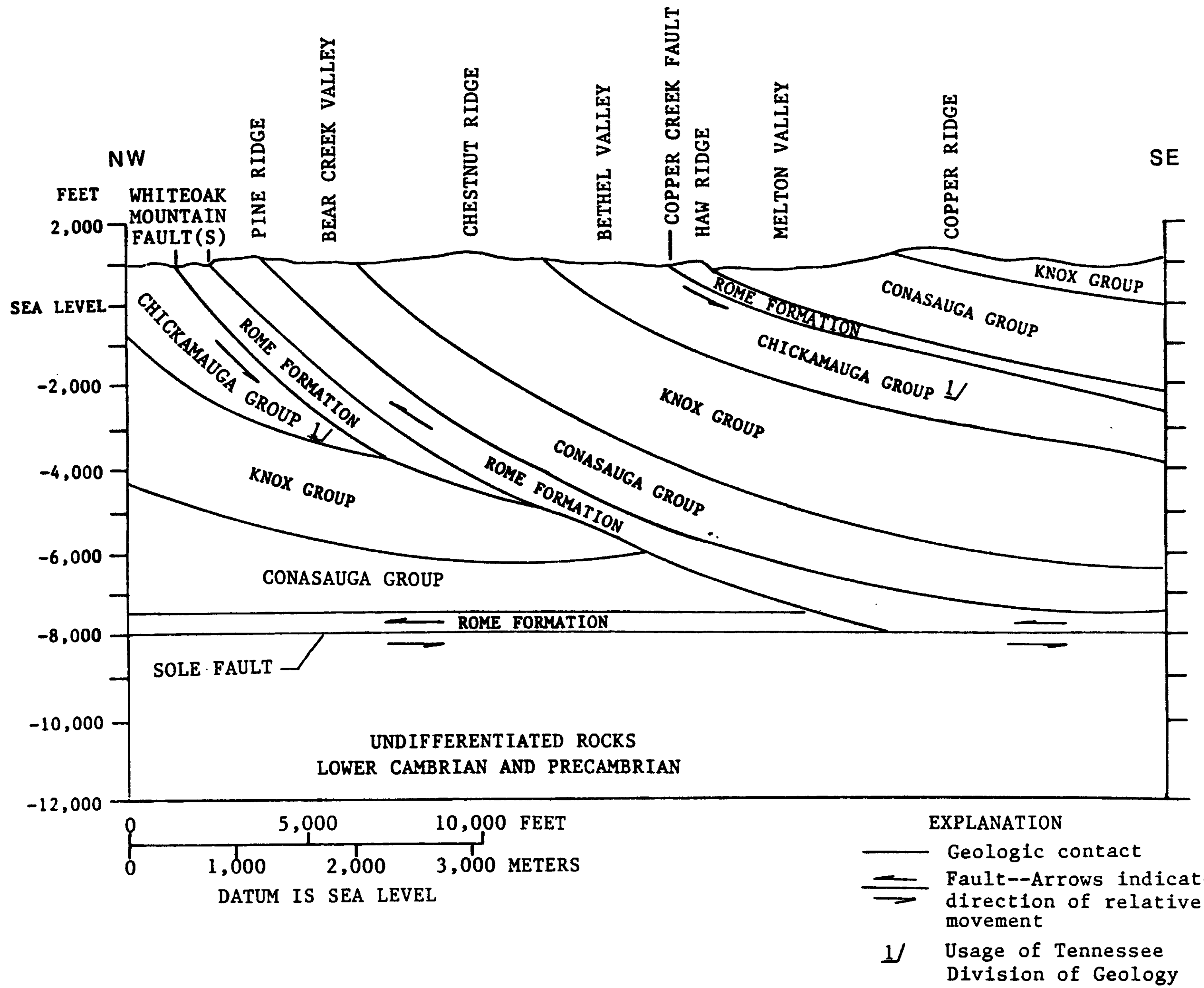


Figure 4.--Generalized geologic section through the Oak Ridge Reservation. (Modified from Ketelle and Huff, 1984).

SEISMIC VELOCITIES

In order to determine depths to reflectors, such as the river bottom or a thrust fault, the average seismic velocity of the medium through which the sound waves travel must be known. The seismic record has a vertical scale of two-way travel time (the time required for a seismic wave to reach a reflector and return). The depth to a reflector is calculated using the following formula:

Depth to reflector = Average velocity × (Two-way travel time ÷ 2)

Haeni (1988, p. 41) reports the velocity of sound in water as 4,800 ft/s (feet per second), and the velocity in saturated alluvium as 4,000 to 6,000 ft/s. In this study, an average seismic velocity of 5,000 ft/s was assumed for alluvium and the water column. Seismic velocities for rock units within the study area range from 10,000 to 20,000 ft/s (table 3). These velocities were determined from geophysical surveys conducted by other investigators and from an acoustic velocity log of well OW-6 (fig. 5) in Melton Valley. The velocities reported for individual formations vary, in part, because the other surveys were conducted over a wide range of depths. The slowest velocities (10,000 ft/s) are commonly associated with shallow, weathered rocks, and faster velocities (greater than 16,000 ft/s) are commonly associated with deeply buried, unweathered rocks. An average seismic velocity of 13,000 ft/s was used to estimate depths of features below the top of bedrock.

Table 3.--Seismic velocities of geologic units

[---, no data available]

Geologic unit	Seismic velocity (feet per second)	Data source
Chickamauga Group	16,000-16,625	Rothschild and others, 1985
Knox Group	12,000-20,000	Staub and Hopkins, 1984
Conasauga Group		
Maynardville Limestone	---	---
Nolichucky Shale	10,000-12,200	Rothschild and others, 1984; OW-6; Dreier, 1987
Maryville Limestone	12,400-15,000	Dreier, 1987; OW-6
Rogersville Shale	10,200-13,000	Rothschild and others, 1984; OW-6
Rutledge Limestone	13,800	OW-6
Pumpkin Valley Shale	11,200-15,500	Rothschild and others, 1984; OW-6
Rome Formation	16,250	Tegland, 1978

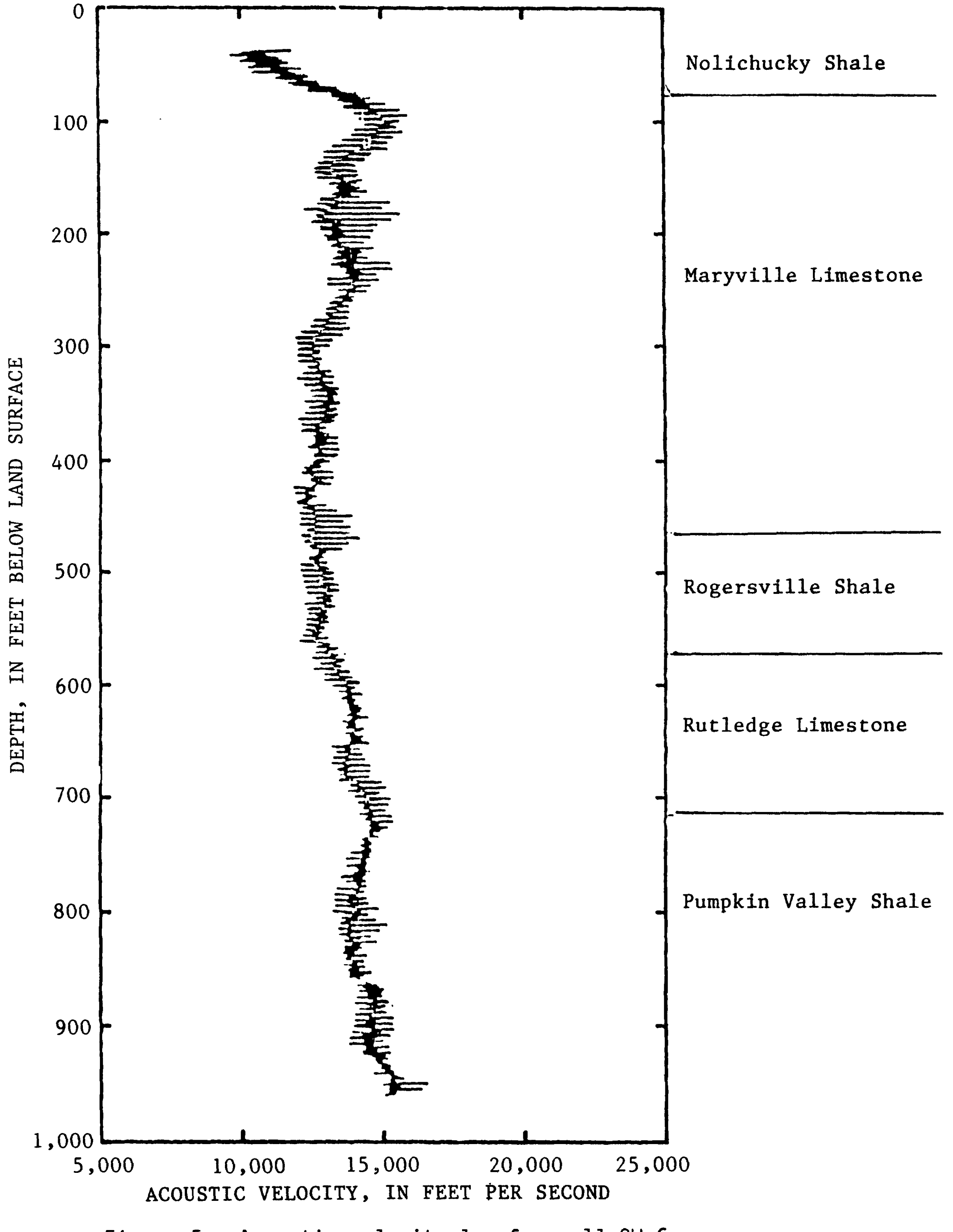


Figure 5.--Acoustic velocity log for well OW-6.

DELINEATION OF SUBSURFACE STRATIGRAPHY AND STRUCTURES

The targets for the study were subsurface stratigraphic contacts; internal structures, such as bedding; and major structural features, such as thrust faults and fracture zones. The success of the single channel, continuous seismic-reflection survey in delineating the chosen targets was mixed. The targets could be delineated in some parts of the record, but not in others. In most instances, the target could be delineated only because some prior knowledge was available on the location of the target.

The examples discussed in the following seismic sections represent only a small part of the data obtained in the study. The examples were chosen to show the success or failure of the method in delineation of the target. The records shown and discussed are single-channel-reflection records that have been filtered and have had time-varying gain applied, but are essentially unprocessed. The seismic sections are shown in two parts in each figure. The upper part is the filtered seismic record and the lower part is the interpreted seismic section. The approximate location of each section is shown on figure 1.

Most seismic sections collected in deep water provided useful information for two-way travel times of 0.05 seconds or less. Water-column-multiple reflections obscured subsurface data in records collected in shallow water. The greatest depth of penetration of the seismic signal was about 225 ft from the water surface, and occurred where the water depth was greatest. Further computer processing of this data may aid in the interpretation of the seismic record, by reducing the interference effects of the water-column-multiple reflections. Processing of single-channel seismic-reflection records is not commonly done in shallow engineering studies.

Subsurface Stratigraphic Contacts

Subsurface stratigraphic contacts in the study area are commonly gradational. Changes in the physical properties of the rocks, such as density and seismic velocity, are also commonly gradational. For example, there is very little difference in acoustic velocity between the Maryville Limestone and the Rogersville Shale (fig. 5). The increase in acoustic velocity from the Nolichucky Shale to the Maryville Limestone (fig. 5) is probably more the result of weathering of the Nolichucky Shale near land surface rather than a change in the physical properties of the unweathered rocks.

Previously mapped stratigraphic contacts appear to correlate with changes in the character of the reflection record in the shallow water segments of the survey. In figure 6, no obvious reflector appears at the location of the geologic contacts, but the character of the record appears to change as these contacts are crossed, possibly because of fortuitous changes in river bottom sediments or, more likely, by a change in the physical properties of some of the rock units. The Maynardville Limestone and the upper part of the Copper Ridge Dolomite generate substantially more water-column-multiple reflections than do the Nolichucky Shale and the Chepultepec Dolomite. If the river-bottom sediments have not changed, the Maynardville Limestone and the Copper Ridge Dolomite would be less weathered and more compact; they would therefore, reflect more of the incident energy, causing the increase in the number of water-column-multiple reflections.

The four changes in reflective character of the seismic record shown in figure 6 coincides almost perfectly with the mapped stratigraphic changes. These changes were not apparent throughout the study area, however. Unconsolidated sediments were either absent or too thin to be distinguished at this site. Water depth at this site is 18 ft, and the depth to the first water-column-multiple reflection is 60 ft.

Delineation of known stratigraphic contacts on the seismic record was often unsuccessful. In figure 7, the contact between the Maryville Limestone and the Nolichucky Shale, based on geologic mapping, should be at about station 35; it should dip about 20° SE. and strike NE.-SW. The contact between the Nolichucky and the Maynardville should be between station 33 and 34 and dip at about 10 to 15° SE. The orientation of the seismic line in this section of the river is SE.-NW.--almost perpendicular to the strike of the contact. Reflections from these dipping stratigraphic contacts or changes in the character of the seismic record at this deep water site are not apparent on the seismic record. The contact between flat-lying, unconsolidated sediments that overlie the dipping bedrock (station 34 to 35) can be interpreted from this seismic record. The maximum thickness of these sediments is about 7 ft. Water depth in this example is 60 ft, and the first water-column-multiple reflection appears on the record at 0.05 seconds, which represents a depth of about 225 ft below the water surface.

Bedding

Except for some of the more massive rock units, such as the Copper Ridge Dolomite, the apparent attitude of the bedding planes, which is a good indicator of subsurface structure, was readily observable on most of the seismic records collected in deep water (figs. 7, 8, 9). The dip of the beds on the seismic record is not the true dip of the geologic units. The measured dip on the seismic record must be corrected for vertical exaggeration, acquisition geometry (migration), and the angle of the boat's track to the strike of the unit. The true dip of the bedding planes is much gentler than the dip shown on the seismic record.

The bedding planes on the seismic section shown in figure 7 have a measured dip of about 60°. To correct for vertical exaggeration, the following formula is used:

$$\tan(\text{true dip angle}) = \frac{\tan(\text{apparent dip angle})}{\text{vertical exaggeration}}.$$

When the 60° dip angle measured on figure 7 is corrected for the vertical exaggeration of 4, it becomes 23°. Because this survey line is perpendicular to the strike of the valley, the seismic dip need only be migrated to obtain the true dip. To calculate the effect of migration on dip, the following formula is used:

$$\text{sine}(\text{true dip angle}) = \tan(\text{apparent dip angle})$$
$$\text{sine}(\text{true dip angle}) = \tan 23^\circ$$
$$\text{true dip} = 25^\circ.$$

The calculated dip from the seismic section is, therefore, about 25°--a value that agrees reasonably well with the measured field values. The field-measured dip of the bedding planes in Melton Valley is about 20° SE.

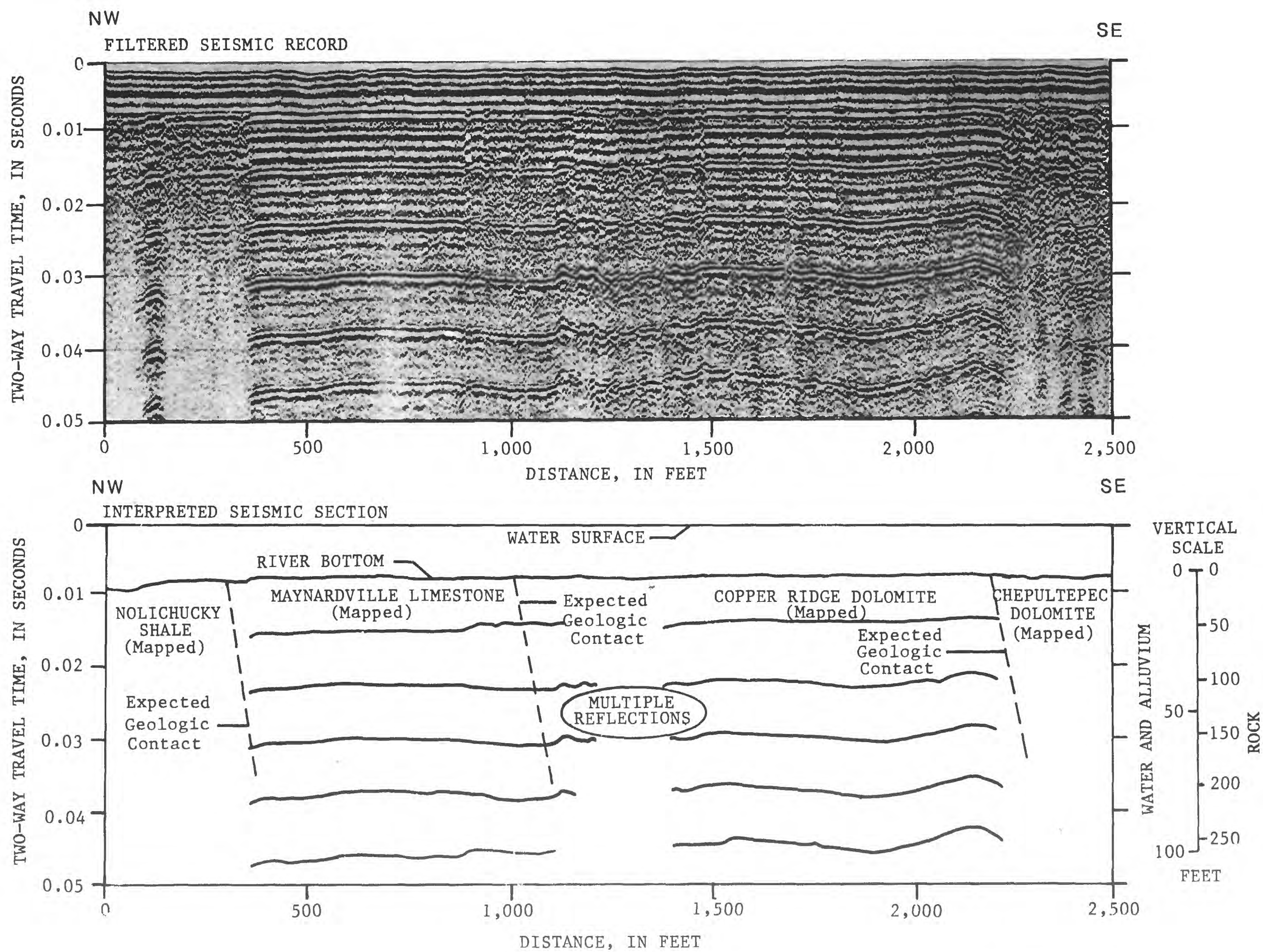


Figure 6.--Seismic-reflection section #1, showing an example of successful delineation of stratigraphic contacts.

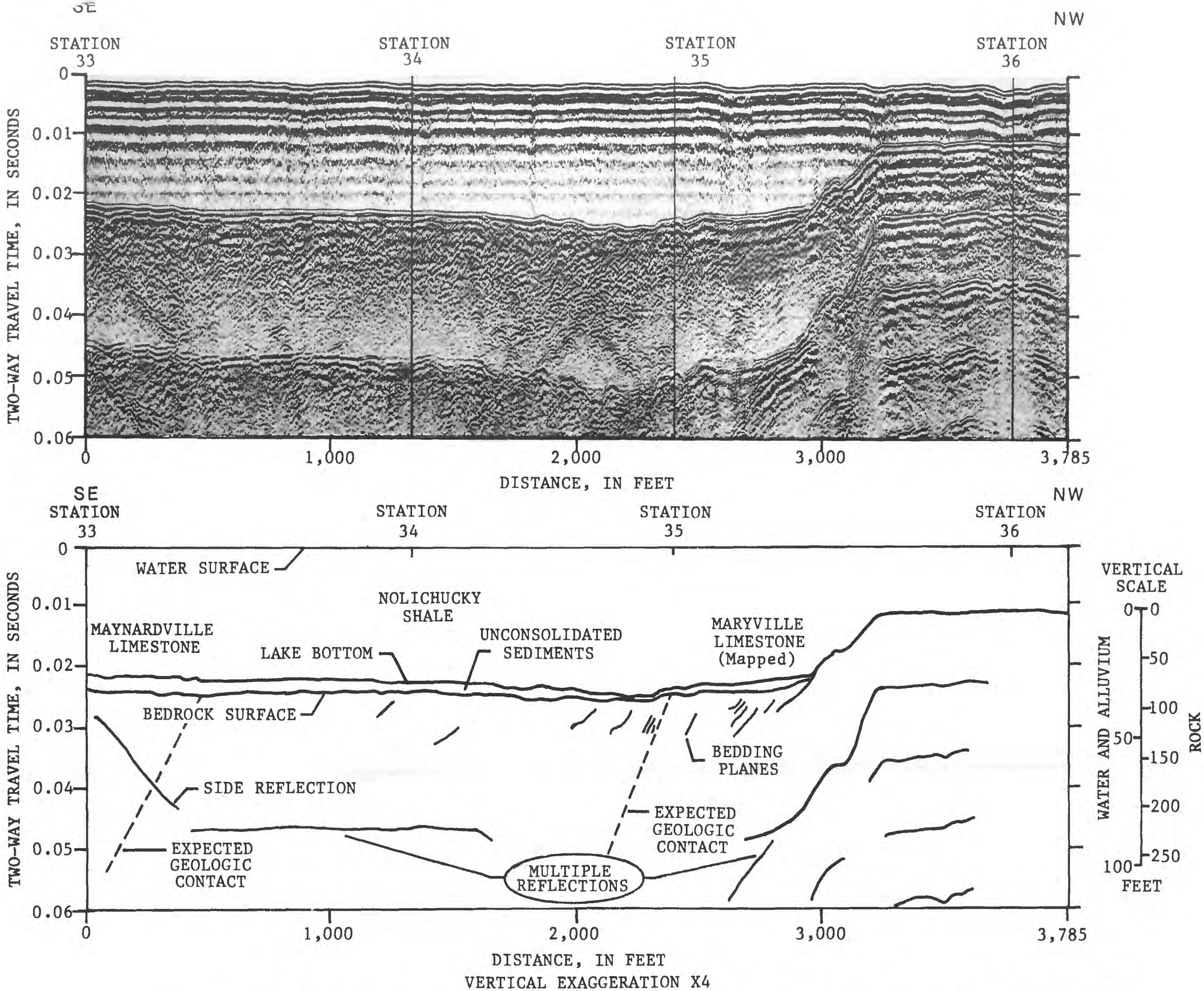


Figure 7.--Seismic-reflection section #3, showing an example of unsuccessful delineation of stratigraphic contacts.

A seismic section that was replayed from the original field data with an expanded vertical scale (0.06 seconds, two-way travel time, full scale) and filtered at a higher frequency (1.0 to 2.5 kHz) is shown in figure 8. The record was replayed to better distinguish bedding planes that are clearly shown on this enhanced section. The bedding planes on the seismic section shown in figure 8 have measured dips between 20° and 40°. When these angles are corrected for a vertical exaggeration of three, they range from 7° to 16°. There is very little change when these angles are corrected for migration, because the dips are low. An additional correction must be made to account for the angle of the boat's track to the strike of the geologic unit (45° in this example), by means of the following formula (Billings, 1954, p. 443):

$$\tan(\rho) = (\tan\delta)(\sin\alpha),$$

where ρ is the apparent dip angle
δ is the true dip angle,
α is the angle between the boat's track and strike of the geologic unit.

The calculated dip from this seismic section, with all corrections applied ranges from 10° to 22°. This section is in the northwestern part of the study area (fig. 1) and transverses the Nolichucky Shale, which has an average dip of about 20° SE. in this area.

Bedding was successfully delineated on other segments of the record, especially when the water depth was greater than 30 ft. The bedding planes dip to the left in the example in figure 9, but the angle of dip must be corrected for the vertical exaggeration of 4. The dip of the beds appears to steepen in a northeastern direction from station 6. The increase in dip angle is caused by a change in orientation of the boat's track to the strike of the unit. The calculated dip from this seismic section, after corrections for vertical exaggeration, migration, and angle of the boat's track to the strike of the geologic unit, is about 16°. This agrees with the measured dips in this area, which are 10° to 20°. Note that not all of the bedding planes visible in the seismic record are shown on the interpreted section. Approximately 5 ft of flat-lying unconsolidated sediments, deposited since construction of Melton Hill Dam, overlie the bedded rock units of the Conasauga Group in this example (fig. 9). Water depth in this example is 60 ft, and the depth to the first water-column-multiple reflection is 175 ft.

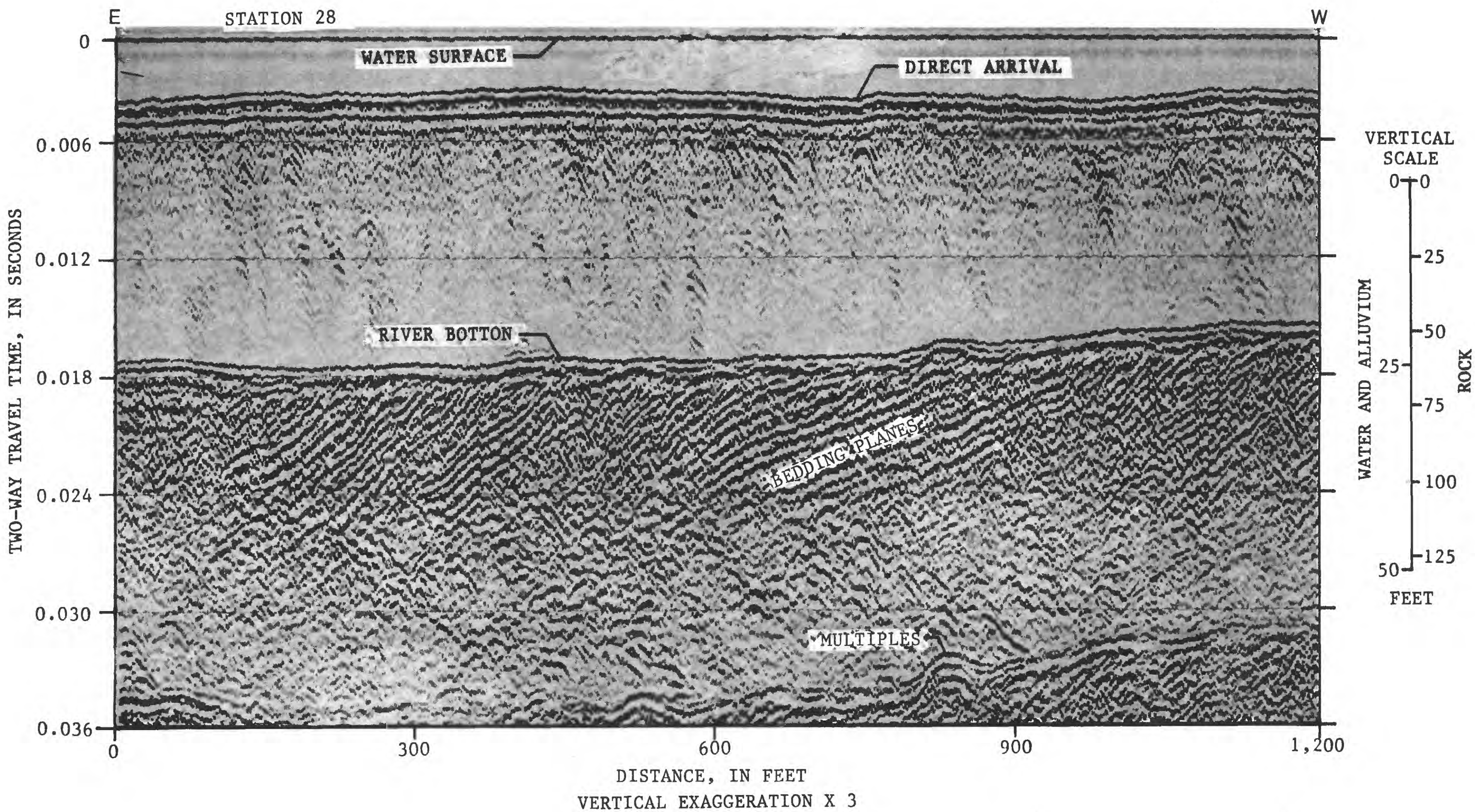


Figure 8.--Seismic-reflection section #5, enhanced to clearly show bedding.

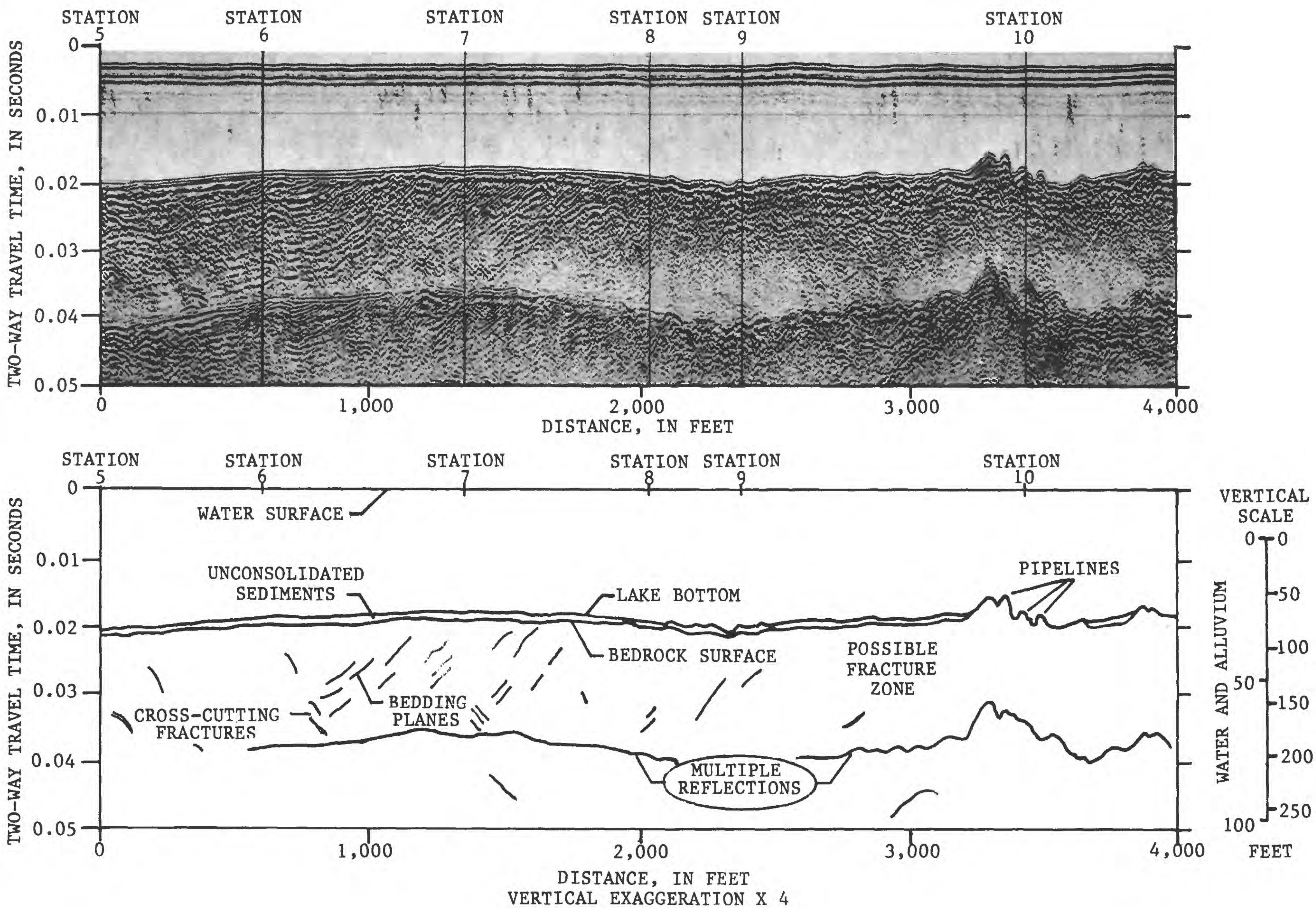


Figure 9.--Seismic-reflection section #4, showing an example of delineation of bedding, small-scale faults, and possible location of fracture zone associated with a photolinear feature.

Structural Features

Both large-and small-scale structural features were targets in this study. Small-scale faults, shown by displacement of bedding, are apparent between stations 5 and 7 (fig. 9) and at station 28 (fig. 8). These types of structural features are common in the Oak Ridge area, and are commonly seen in road cuts or disposal-trench excavations.

The delineation of the Copper Creek and other major thrust faults were targets of this study. These faults are apparent on deep seismic-reflection lines delineated in other areas of eastern Tennessee (Tegland, 1978); however, these faults were not obvious in the single channel, continuous seismic-reflection records from this study. The Copper Creek fault is complex; several small faults branch from it, and folding and gouging of the rocks in the fault zone are associated with it. The dip of the fault plane generally is shallow, 10° to 15° SE., but locally is 45° or greater (R.B. Dreier, Martin Marietta Energy Systems, written commun., 1987). The survey crossed the mapped location of the Copper Creek fault (McMaster, 1963) on the southwestern end of the study area (fig. 10). Although water-column-multiple reflections obscure most of the record, several subtle reflections in the vicinity of the mapped fault cut across the water-column-multiple reflections and may represent the fault zone. These reflections can be traced to a depth of about 225 ft below the water surface.

On the seismic section, the measured angle of these reflectors is about 55°. When this angle is corrected for vertical exaggeration and migration, it becomes 28°. Because the orientation of the boat's track is about 25° to the strike of the geologic units, the final correction is needed. The calculated dip of the fault determined from the seismic section is 49°. This angle is greater than average for the Copper Creek fault, but it is plausible given the complex nature of the fault.

Several large-scale, northwest-trending linear features, thought to be associated with fracture zones, appear on satellite and radar imagery of the Reservation area. The seismic line shown in figure 9 crossed one such feature, and the zone should be approximately between stations 9 and 10. The only indication of this feature on the record is that the bedding planes, seen to the left and right of stations 9 and 10, are absent between these stations. If the linear feature from the imagery represents a fracture zone that has disrupted the bedding, the lack of distinct reflections from the bedding planes on the record is consistent with that interpretation.

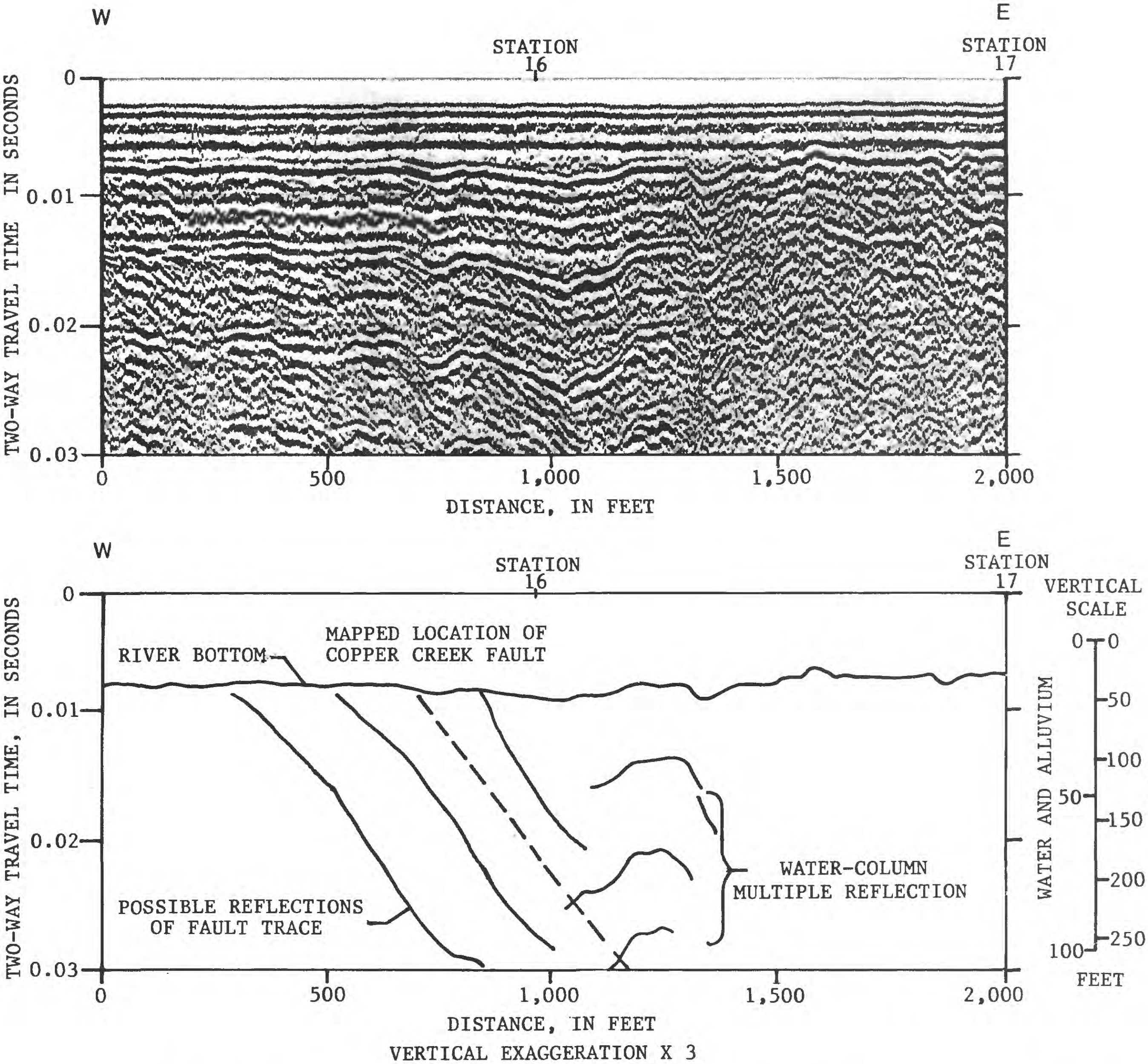


Figure 10.--Seismic-reflection section #2, through Copper Creek fault.

SUMMARY

Continuous seismic-reflection data were collected along approximately 35 mi of the Clinch River on three sides of the Oak Ridge Reservation. The data were obtained to test the feasibility of using the method to delineate subsurface stratigraphic contacts; internal structures such as bedding; and major structural features such as thrust faults and fracture zones. The seismic-reflection method was used because of its suitability for distinguishing detailed subsurface layers, and because subsurface geology and hydrology of a large area can be interpreted in a short period of time.

The degree of success of the seismic-reflection survey in delineating the chosen targets was variable. Reflections associated with stratigraphic contacts were not apparent on most of the seismic records. The location of some contacts could be inferred from the reflective character of the rock units and the number of water-column-multiple reflections that were generated on the seismic record. This change in seismic-record character could also be caused by a change in river bottom material, and not just by changes in the physical properties of the rock units.

Dipping reflectors interpreted as bedding planes were readily apparent in most of the seismic record, especially the record obtained in the deep water of Melton Hill Lake. Reflections associated with major thrust faults were not obvious but were identified in some sections of the record. Interpretation of the seismic record showed several reflections that are believed to be associated with the fault zones and indicated that the faults are complex structures. Fault traces were interpreted to depths of 225 ft on the record.

Water-column-multiple reflections commonly obscured the record at shallow water depths (20 ft). The deepest reflector interpreted from the seismic record was about 225 ft below water surface and was located in parts of the river that had deep water. Further computer processing of the data to remove these water-column-multiple reflections may aid in the interpretation of the seismic record.

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