USGS
science for a changing world

MARYLAND
DEPARTMENT OF
NATURAL RESOURCES

Prepared in cooperation with the
Maryland Department of Natural Resources

Collection, Processing, and Interpretation of Ground-Penetrating Radar Data to Determine Sediment Thickness at Selected Locations in Deep Creek Lake, Garrett County, Maryland, 2007

Scientific Investigations Report 2011–5223

U.S. Department of the Interior
U.S. Geological Survey

Cover. Aerial photograph of Deep Creek Lake, Garrett County, Maryland, from the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP).

Collection, Processing, and Interpretation of Ground-Penetrating Radar Data to Determine Sediment Thickness at Selected Locations in Deep Creek Lake, Garrett County, Maryland, 2007

By William S.L. Banks and Carole D. Johnson

Prepared in cooperation with the
Maryland Department of Natural Resources

Scientific Investigations Report 2011–5223

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Banks, W.S.L., and Johnson, C.D., 2011, Collection, processing, and interpretation of ground-penetrating radar data to determine sediment thickness at selected locations in Deep Creek Lake, Garrett County, Maryland, 2007: U.S. Geological Survey Scientific Investigations Report 2011–5223, 36 p.

Contents

Abstract 1
Introduction 1
    Description of Study Area 3
Methods 4
    Ground-Penetrating Radar (GPR) 5
    Continuous Seismic-Reflection Profiling 7
Processing Geophysical Data 9
Interpretation of Ground-Penetrating Radar (GPR) Profiles for Sediment Thickness 12
Summary and Conclusions 15
References Cited 15
Appendix A 17

Figures

1. Map showing location of Deep Creek Lake watershed, Garrett County, Maryland 2
2. Photograph of work boat outfitted with ground-penetrating radar, continuous seismic-reflection profiling, bathymetric, and global positioning equipment, Deep Creek Lake, Garrett County, Maryland 4
3. Map showing location and extent of ground-penetrating radar data collected at Deep Creek Lake, Garrett County, Maryland 6
4. Diagram showing ground-penetrating radar signal displayed as a “wiggle trace” along with other features on a typical radargram 7

5–6. Maps showing—
    5. Location and extent of continuous seismic-reflection profile data collected at Deep Creek Lake, Garrett County, Maryland 8
    6. Location of processed ground-penetrating radar data lines and Core 5, Deep Creek Lake, Garrett County, Maryland 10

7–8. Diagrams showing—
    7. Example of a ground-penetrating radar cross section with interpretations showing water depth and sediment thickness on two different scales 11
    8. Location and relative depths for *(A)* a processed continuous seismic-reflection profile, *(B)* a ground-penetrating radar (GPR) line, and *(C)* bathymetric data and location of Core 5 in Arrowhead Cove–south, cross section number 8, Deep Creek Lake, Garrett County, Maryland 13

Tables

1. Description of geophysical study methods 3
2. Location, descriptions, and interpreted depth of sediment of ground-penetrating radar lines in Deep Creek Lake, Garrett County, Maryland 11
3. Summary of sediment grain-size distribution in Core 5 in Deep Creek Lake, Garrett County, Maryland, 2008 14

Appendix A

A1. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Marsh Run Cove, cross section 5, Deep Creek Lake, Garrett County, Maryland, 2007 18
A2. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Marsh Run Cove, cross section 6, Deep Creek Lake, Garrett County, Maryland, 2007 19
A3. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 3, Deep Creek Lake, Garrett County, Maryland, 2007 20
A4. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 7, Deep Creek Lake, Garrett County, Maryland, 2007 21
A5. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 11, Deep Creek Lake, Garrett County, Maryland, 2007 22
A6. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 14, Deep Creek Lake, Garrett County, Maryland, 2007 23
A7. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–west, cross section 14, Deep Creek Lake, Garrett County, Maryland, 2007 24
A8. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–west, cross section 18, Deep Creek Lake, Garrett County, Maryland, 2007 25
A9. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–east, cross section 6, Deep Creek Lake, Garrett County, Maryland, 2007 26
A10. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Green Glade Cove, cross section 4, Deep Creek Lake, Garrett County, Maryland, 2007. 27
A11. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Deep Creek Cove, cross section 12, Deep Creek Lake, Garrett County, Maryland, 2007 28
A12. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 33, Deep Creek Lake, Garrett County, Maryland, 2007 29
A13. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 34, Deep Creek Lake, Garrett County, Maryland, 2007 30
A14. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 36, Deep Creek Lake, Garrett County, Maryland, 2007 31
A15. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 39, Deep Creek Lake, Garrett County, Maryland, 2007 32
A16. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Hoop Pole Cove, cross section 8, Deep Creek Lake, Garrett County, Maryland, 2007 33
A17. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–north, cross section 1, Deep Creek Lake, Garrett County, Maryland, 2007 34
A18. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–south, cross section 7, Deep Creek Lake, Garrett County, Maryland, 2007 35
A19. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–south, cross section 8, Deep Creek Lake, Garrett County, Maryland, 2007 36

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Collection, Processing, and Interpretation of Ground-Penetrating Radar Data to Determine Sediment Thickness at Selected Locations in Deep Creek Lake, Garrett County, Maryland, 2007

By William S.L. Banks and Carole D. Johnson

Abstract

The U.S. Geological Survey collected geophysical data in Deep Creek Lake in Garrett County, Maryland, between September 17 through October 4, 2007 to assist the Maryland Department of Natural Resources to better manage resources of the Lake. The objectives of the geophysical surveys were to provide estimates of sediment thickness in shallow areas around the Lake and to test the usefulness of three geophysical methods in this setting. Ground-penetrating radar (GPR), continuous seismic-reflection profiling (CSP), and continuous resistivity profiling (CRP) were attempted. Nearly 90 miles of GPR radar data and over 70 miles of CSP data were collected throughout the study area. During field deployment and testing, CRP was determined not to be practical and was not used on a large scale. Sediment accumulation generally could be observed in the radar profiles in the shallow coves. In some seismic profiles, a thin layer of sediment could be observed at the water bottom. The radar profiles appeared to be better than the seismic profiles for the determination of sediment thickness. Although only selected data profiles were processed, all data were archived for future interpretation.

This investigation focused on selected regions of the study area, particularly in the coves where sediment accumulations were presumed to be thickest. GPR was the most useful tool for interpreting sediment thickness, especially in these shallow coves. The radar profiles were interpreted for two surfaces of interest—the water bottom, which was defined as the "2007 horizon," and the interface between Lake sediments and the original Lake bottom, which was defined as the "1925 horizon"—corresponding to the year the Lake was impounded. The ground-penetrating radar data were interpreted on the basis of characteristics of the reflectors. The sediments that had accumulated in the impounded Lake were characterized by laminated, parallel reflections, whereas the subsurface below the original Lake bottom was characterized by more discontinuous and chaotic reflections, often with diffractions indicating cobbles or boulders. The reflectors were picked manually along the water bottom and along the interface between the Lake sediments and the pre-Lake sediments. A simple graphic approach was used to convert traveltimes to depth through water and depth through saturated sediments using velocities of the soundwaves through the water and the saturated sediments. Nineteen cross sections were processed and interpreted in 9 coves around Deep Creek Lake, and the difference between the 2007 horizon and the 1925 horizon was examined. In most areas, GPR data indicate a layer of sediment between 1 and 7 feet thick. When multiple cross sections from a single cove were compared, the cross sections indicated that sediment thickness decreased toward the center of the Lake.

Introduction

Geophysical data were collected in Deep Creek Lake in Garrett County, Maryland between September 17 and October 4, 2007 (fig. 1). The overall purpose was for the U.S. Geological Survey (USGS) to assist the Maryland Department of Natural Resources (MDDNR) in their effort to better manage the resources of Deep Creek Lake by determining the thickness of sediment infilling. The objective of the geophysical surveys was to provide estimates of sediment thickness and help characterize the sediment accumulation at selected locations. Not all geophysical data were processed; a subset of the data representing areas of specific interest (shallow areas of the Lake) was further interpreted to evaluate sediment thickness. However, all raw data were archived for possible future interpretation and use. The purpose of this report is to describe the methods of data collection, processing, and interpretation of these geophysical surveys.

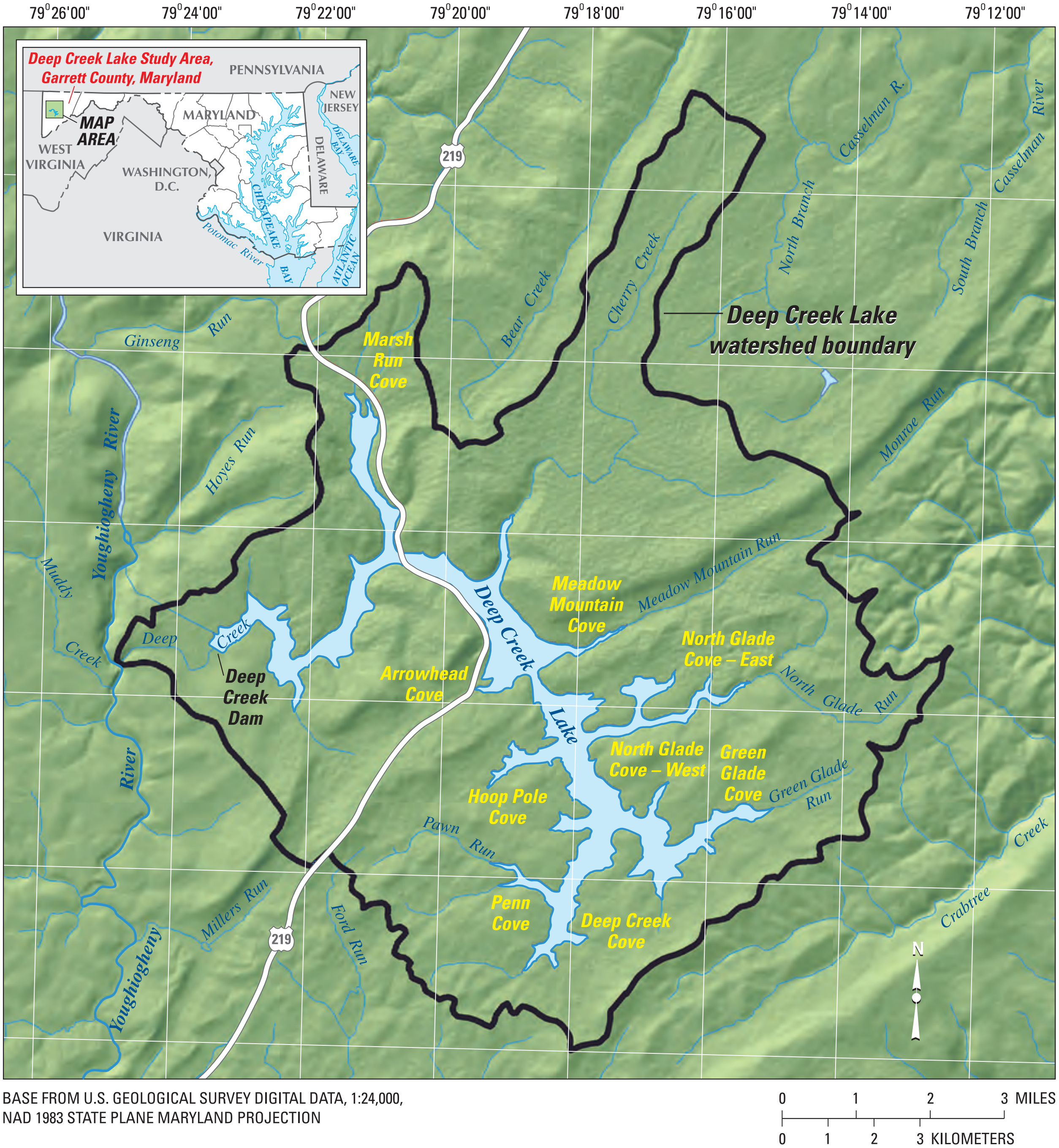


Figure 1. Location of Deep Creek Lake watershed, Garrett County, Maryland.

Three geophysical methods were proposed for testing, including continuous seismic-reflection profiling (CSP), continuous resistivity profiling (CRP), and ground-penetrating radar (GPR) (table 1). The intent was to make use of the strengths of each method while testing each instrument's effectiveness in the Deep Creek Lake setting. For example, GPR is limited in the total depth of investigation because of the depth of water in Deep Creek Lake, but can provide excellent data on presence and thickness of organic-rich deposits in shallower parts of the Lake, whereas CSP can sometimes be limited by the presence of methane gas (Powers and others, 1999). Over the depths in Deep Creek Lake, CSP methods are less limited by the depth of the water and therefore CSP was expected to provide better information in the deepest parts of the Lake.

The CSP surveys did provide some information on the thickness of sediments in the deeper part of the Lake, however, the resolution of the data was not sufficient for this study. The CRP method required a 300-ft (foot) long towed cable and was not used because of the inability to maneuver and have straight-line arrays along the circuitous shoreline near the study areas of interest. Even if the CRP method had been practical, initial GPR results indicated a thin (less than 7 ft) layer of sediments, which forward modeling indicates is too thin for the CRP method to accurately measure, so the CRP method was not used. As a result, this report only discusses the interpreted results of the GPR surveys in selected shallow parts of the Lake

Description of Study Area

Deep Creek Lake is located in Garrett County, Maryland (fig. 1) and is the largest inland body of water in the State. Average rainfall in Garrett County is 47.6 inches per year. Temperatures vary around an annual mean of about 48°F (degrees Fahrenheit). Monthly high temperatures range from 36 to 79°F, whereas monthly lows range from 17 to 57°F (National Oceanic and Atmospheric Administration, 2006). Garrett County is the westernmost county in Maryland, and has an area of approximately 662 square miles, with a population of 29,555 residents in 2009 (U.S. Census Bureau, 2009). The Lake was constructed by damming Deep Creek in 1925. Deep Creek is a tributary to the Youghiogheny River, which in turn drains to the Ohio River. Creation of the dam and subsequent Lake was the result of a Pennsylvania Electric Company project to create low-cost hydroelectric power. The Lake filled with water in 1929, and at a full-pool elevation of 2,462 ft above vertical datum, has an area of 4,500 acres, contains an estimated 34.6 billion gallons of water, has approximately 65 miles of shoreline, and a maximum depth of 75 ft (Maryland Department of Natural Resources, Fisheries Service, 2010).

In 1980, the MDDNR took over management of Lake access and the recreational facilities. The dam, intake tunnel, and powerplant remain owned and operated by Brookfield Power. Lake management regulations are promulgated through a public process that began in 1981 and were updated in 1986,

Table 1. Description of geophysical study methods.

Method	Principle	Physical property dependence	Parameters determined	Limitations
Continuous Seismic-Reflection Profiling (CSP)	Seismic waves are sent through the subsurface; reflections occur when there are changes in density and transmission velocity of materials (acoustic impedance) at interfaces and heterogeneities.	Compressional seismic velocities; and elastic moduli.	Interface depths, layer thickness and geometry; materials description based on characteristics of reflections.	Depth of investigation is limited by frequency and water-bottom materials. Hard or gas-filled sediments do not permit signal penetration.
Ground-Penetrating Radar (GPR)	High-frequency electromagnetic waves (in the range of megahertz) are transmitted through the subsurface; reflections occur at heterogeneities; reflected energy is measured at the receiver.	Dielectric permittivity and electrical resistivity.	Interface depths, layer thickness and geometry; materials description based on characteristics of reflections.	Depth of investigation is limited by frequency and by electrically conductive materials and fluids.
Continuous Resistivity Profiling (CRP)	Current is injected between a pair of electrodes and potential is measured between another pair of electrodes. Different depths are measured by varying electrode spacing.	Electrical resistivity of sediments and fluids. Dependent on porosity and pore fluid compositions.	Depth and thickness of contrasting electrical layers, electrical resistivity, inferred fluid chemistry.	Layer resolution and depth of penetration limited by electrode spacing.

1988, 1989, and 2000 (Maryland Department of Natural Resources, 2008). These regulations continue to provide the basis for the MDDNR's Lake management operations and stipulate that the Lake is to be managed primarily for recreational uses. Thus, in accordance with this mandate and as a direct result of many Lake-shore residents and MDDNR staff having noted infilling in shallow parts of the Lake, a baseline assessment report was written in 2011 noting a need for further study to determine the effects of sedimentation in both Lake headwater areas and areas where restrictions to boat docks may occur because of increased sedimentation (Kelsey and Powell, 2011). The current geophysical investigation further characterizes the sedimentation in shallow headwater coves of Deep Creek Lake. Sedimentation in coves and lowering of lake levels can complicate recreational access for fishing, boating, and swimming by Lake-shore residents.

Methods

Geophysical data were collected using a 24-ft, aluminum-hull boat piloted by Maryland Park Service personnel (fig. 2). Data-collection activities took place between dawn and 3:00 PM EST, Monday through Friday, between September 17th and October 4th, 2007. By restricting data collection to these times, the field crew was able to significantly reduce exposure to choppy water generated by recreational boaters that use the Lake during evenings and weekends. In addition to facilitating the maneuverability of the boat, the smoother water reduced potential noise in the geophysical data. Water temperature recorded periodically at the surface of the Lake was a constant 72°F during data acquisition and air temperature ranged from 60 to 75°F. Latitude and longitude for the GPR data were collected using a Lowrance LMS480 global positioning system (GPS), enhanced with a wide-area augmentation system (WAAS) referenced to the World Geodetic System of 1984 (WGS-84) map datum. Latitude and longitude data were passed directly to the GPR acquisition software at a rate of one data point per second. Location information for the seismic data was collected using a Trimble AgGPS-114, which also used WAAS and was referenced to WGS-84.

Data-collection path lines were designed to maximize Lake-surface coverage, and a zigzag pattern with straight-line segments was used in most areas. In areas where Lake width permitted, supplemental data lines were run near shore and near the center-of-channel. The average boat speed was approximately 2.0 knots or about 2.3 miles per hour. The GPR and CSP were collected concurrently for much of the survey. The following sections briefly describe the GPR and CSP methods, including the basis for the measurements, some limitations of the methods, and the actual method of data collection used in this study.

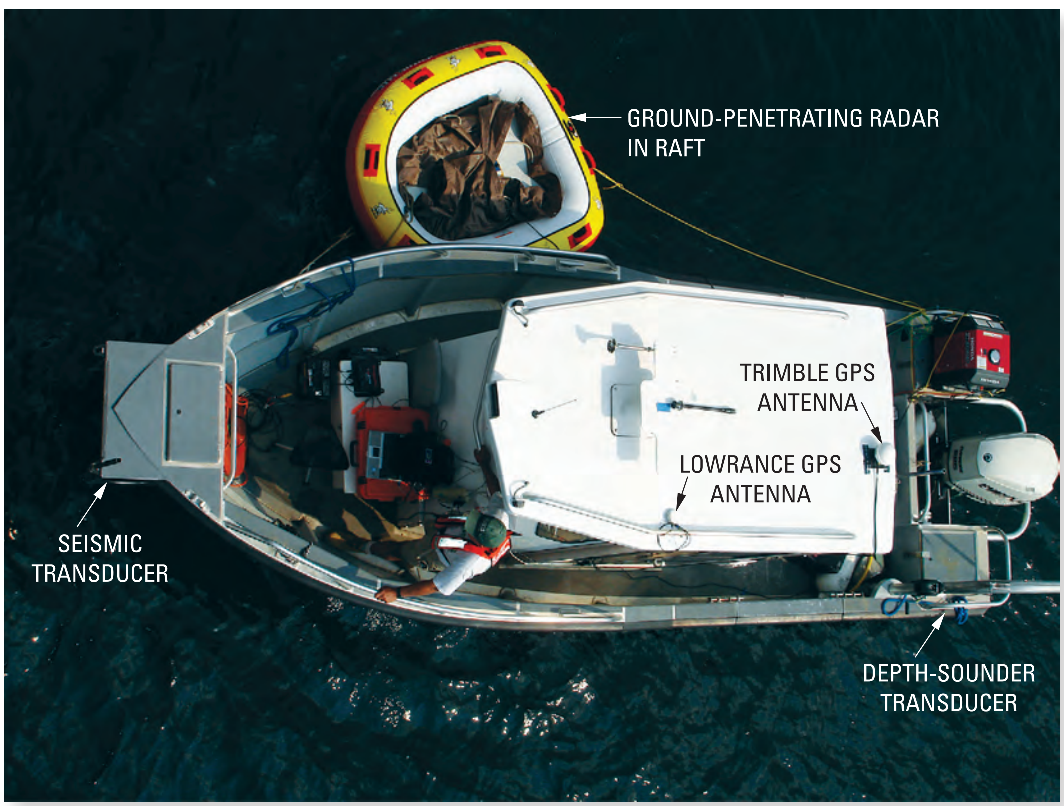


Figure 2. Photograph of work boat outfitted with ground-penetrating radar, continuous seismic-reflection profiling, bathymetric, and global positioning equipment, Deep Creek Lake, Garrett County, Maryland. [Photograph by USGS.]

Ground-Penetrating Radar (GPR)

Nearly 90 miles of raw GPR data were collected in the study area (fig. 3). GPR works by using an antenna to transmit electromagnetic (EM) waves in the microwave band of the radio spectrum [10 to 1,000 MHz (megahertz)] into the subsurface. In general, higher frequency EM waves provide better resolution than lower frequency waves, but higher frequency waves have less depth of penetration compared to lower frequency waves. The depth of penetration varies according to the transmission frequency of the antenna used and the attenuation in the earth material that the pulse is directed toward. However, if the subsurface is electrically conductive, the EM signal can be attenuated regardless of frequency. Generally, electrically conductive media, such as clay or conductive (or brackish) water, attenuates the EM waves and the subsurface cannot be imaged with this method. In addition, the EM signal is sometimes severely attenuated through the scattering of the signal on point and strong planar reflectors. Point reflectors in Deep Creek Lake sediments include cobbles and boulders, debris or other large objects in the infilled sediment. In the near-shore environment, the EM signal can be reflected off the shoreline, obscuring features of interest. The propagation of EM waves is affected by contrasts in the EM properties including the dielectric permittivity, electrical conductivity, and magnetic susceptibility of the media. Consequently, the best penetration is achieved in media that has relatively low electrical conductivity and that is free of cobble- to boulder-sized material that tends to scatter the signal.

The EM wave is directed downward from the GPR transmitting antenna into the water; the antenna is shielded on the top to prevent transmission of the EM wave upward. The wave spreads out until it encounters boundaries such as the water bottom, and then any other boundary (such as the boundary between lacustrine sediments, pre-inundation sediment, and bedrock below the sediments). When the EM waves encounter a different boundary or object that has a different dielectric than its surroundings, some of the transmitted energy is reflected back to the antenna, some energy is scattered, and some energy continues into deeper material. The energy that is reflected back is captured by a receiving antenna and is recorded digitally as a function of two-way traveltime—the time it takes energy to travel from the transmitter to a reflective surface and back to the antenna. A common method of viewing GPR data is by use of a single “wiggle” trace. A wiggle trace shows the signal amplitude as a function of two-way traveltime. A single wiggle trace (in blue) with a reflection, commonly called “an event,” at 155 ns (nanoseconds) is shown in figure 4. This event or reflection wavelet shows a wiggle around the centerline at the interface of the contrasting materials. The amplitude (departure away from the centerline) is a measure of the strength of the reflection. In addition, multiple wiggle traces can be viewed side by side in the form of a radargram in a two-dimensional subsurface profile (fig. 4). The reflection wavelets in a radargram are shown in a black-white-black pattern, which coincides with the right-left-right (positive-negative-positive) on the wiggle trace. The top 40 ns of the radar record shows the wiggle trace and the banding from a second arrival or water-bottom multiple. These multiples are caused when a signal from the transducer is repeatedly reflected between the surface and the bottom of the water column. After the initial 40 ns, closely spaced black-white-black bands represent high-frequency reflections and wider bands represent low-frequency reflections. Thin and laminated layers of sediments would be expected to produce high-frequency reflections (thin bands that are fairly parallel), and solid rock would be expected to produce low-frequency reflections (more widely spaced bands). The widely spaced bands are not as evident in the radargram (fig. 4), however, the example shows a water-bottom multiple that represents an EM wave that reverberates between the water bottom and the water surface, and produces an apparently deeper reflection with a slope that doubles with each multiple. These multiple reflections can greatly obscure other features below the water bottom. These types of GPR reflection configurations and the methods of Beres and Haeni (1991) were applied to interpret the stratigraphy of the subsurface. The depth (d) to a particular interface can be calculated using the relation between velocity of the EM wave through the media (Vm), dielectric constant (or permittivity, Er), the speed of light (c): Vm=c/sqrt(Er), and the two-way traveltime (t): d=Vm*t/2. The depth to a reflector is the sum of distances through each media. In this study, permittivity of water and sediment was assumed to be 81 and 21, respectively. Radar-wave velocity (Vm) was 109.36 ft/µs (feet per microsecond) for water, and 214.78 ft/µs for sediments.

The GPR used in this study was manufactured by MALÅ Geosciences, Malå, Sweden. The equipment consisted of an X3M control module, a 100-MHz shielded antenna with an approximate useful bandwidth of 50 to 200 MHz and peak frequency of 100 MHz, and a data acquisition computer. GPR was used in areas where water depths were less than about 30 ft (for example, the coves around Deep Creek Lake; fig. 3). The transmitting and receiving antennas were kept at a constant 1.64-ft separation and were contained in the same housing. In addition, the control unit was connected directly to the antenna housing, which was placed in a small inflatable raft so that the antenna housing was in direct contact with the raft floor (fig. 2). There were no air pockets below the antenna because a small amount of water filled the bottom of the raft floor. This provided excellent coupling of the outgoing signal with the Lake and therefore the antenna was at the water surface, thus eliminating the need for a depth correction. The raft was secured to the starboard side of the boat (fig. 2). The control unit was connected to a data acquisition computer (running Windows®[1] XP) by the computer’s parallel port. The data acquisition software used was RAMAC GroundVision (version 1.4.5), also manufactured by MALÅ Geosciences. This software synchronized the navigation data with the radar data. GPR traces were acquired at a constant rate of 10 traces per second. At a nominal boat speed of 2.0 knots, this data-collection resolution equates to 3 traces per linear foot.

---

[1] “Windows” is a registered trademark of Microsoft Corporation in the United States and other countries.

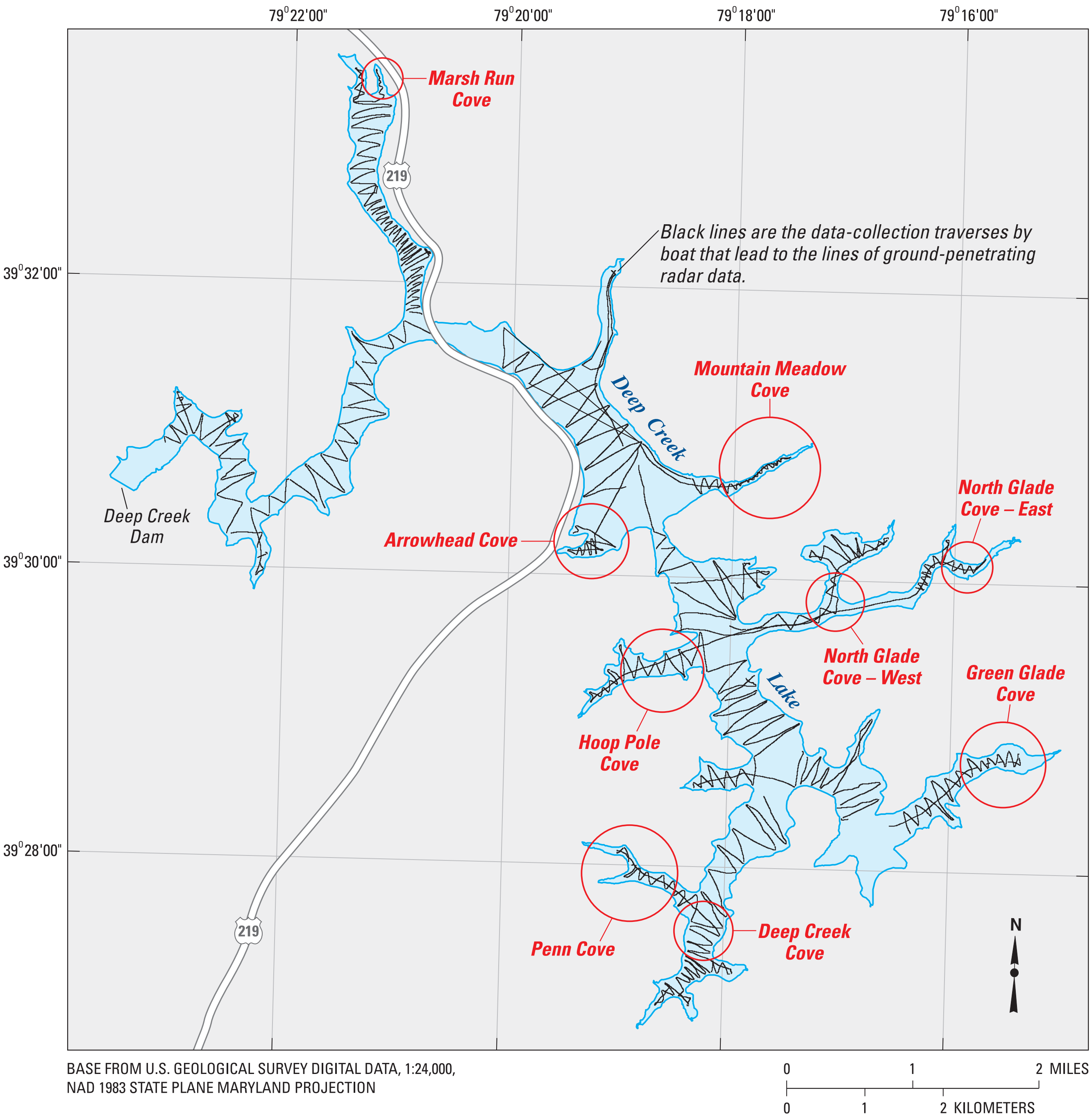


Figure 3. Location and extent of ground-penetrating radar data collected at Deep Creek Lake, Garrett County, Maryland.

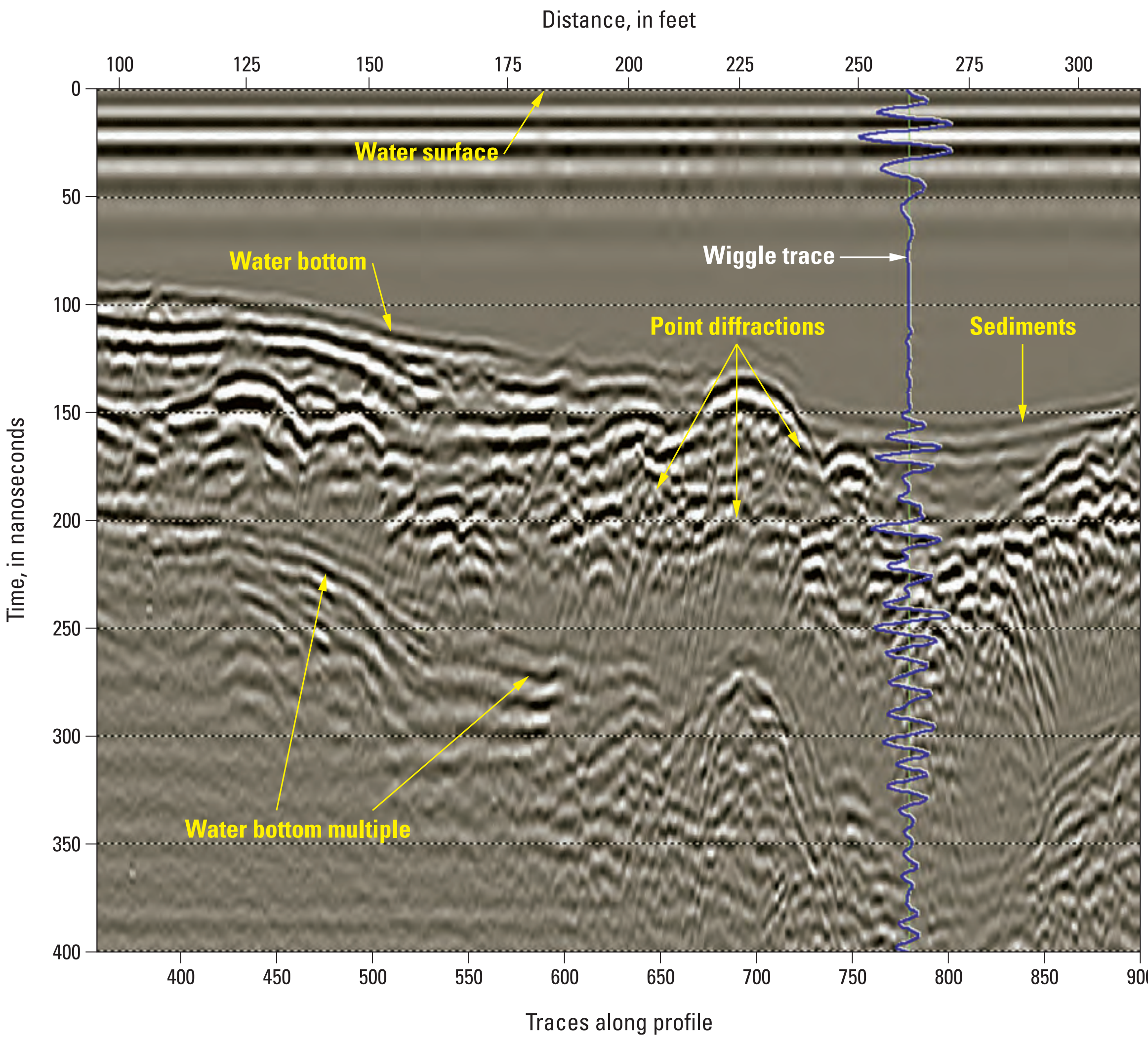


Figure 4. Ground-penetrating radar signal displayed as a "wiggle trace" along with other features on a typical radargram.

Continuous Seismic-Reflection Profiling

Over 70 miles of CSP data were collected in the study area (fig. 5). The continuous seismic profiler used in this study was a StrataBox Marine Geophysical System manufactured by SyQwest, Inc. of Warwick, Rhode Island. The system consists of a transducer assembly (seismic source and receiver, positioned about 1 ft below the water surface), a control unit that provides all of the electronics and signal processing, and a personal computer running the proprietary software StrataBox by SyQwest to record the data. In addition to the seismic data, the computer also collects contemporaneous positional data from a GPS. A 300-watt, 10-kilohertz seismic pulse was transmitted at 10 times per second. At a nominal boat speed of 2 knots (2.3 miles per hour), this equates to 3 traces per foot. The acquisition software merged the seismic data with the GPS data and stored the combined data stream in a proprietary format. As a result of this proprietary formatting, seismic data could not be post-processed, and therefore interpretations of the subbottom materials were limited.

CSP works by directing a pulse of seismic energy through the water column from a source and recording the reflected energy collected by a receiver. Seismic (or acoustic) energy is reflected from interfaces between materials with different acoustic properties. For continuous seismic-reflection profiling, the important contrasting property is acoustic impedance (table 1). This property depends on an earth material's density, the compressibility of the material, and the velocity with which sound passes through the material (Trabant, 1984). The higher the contrast in these properties between different materials, the stronger the strength of reflection. Like GPR, some seismic input energy is reflected back toward a receiver, and some is transmitted into the subsurface potentially reflecting off deeper contrasting interfaces. The amplitude of reflected arrival events is recorded as a function of the two-way traveltime; that is the time that seismic energy takes to travel the

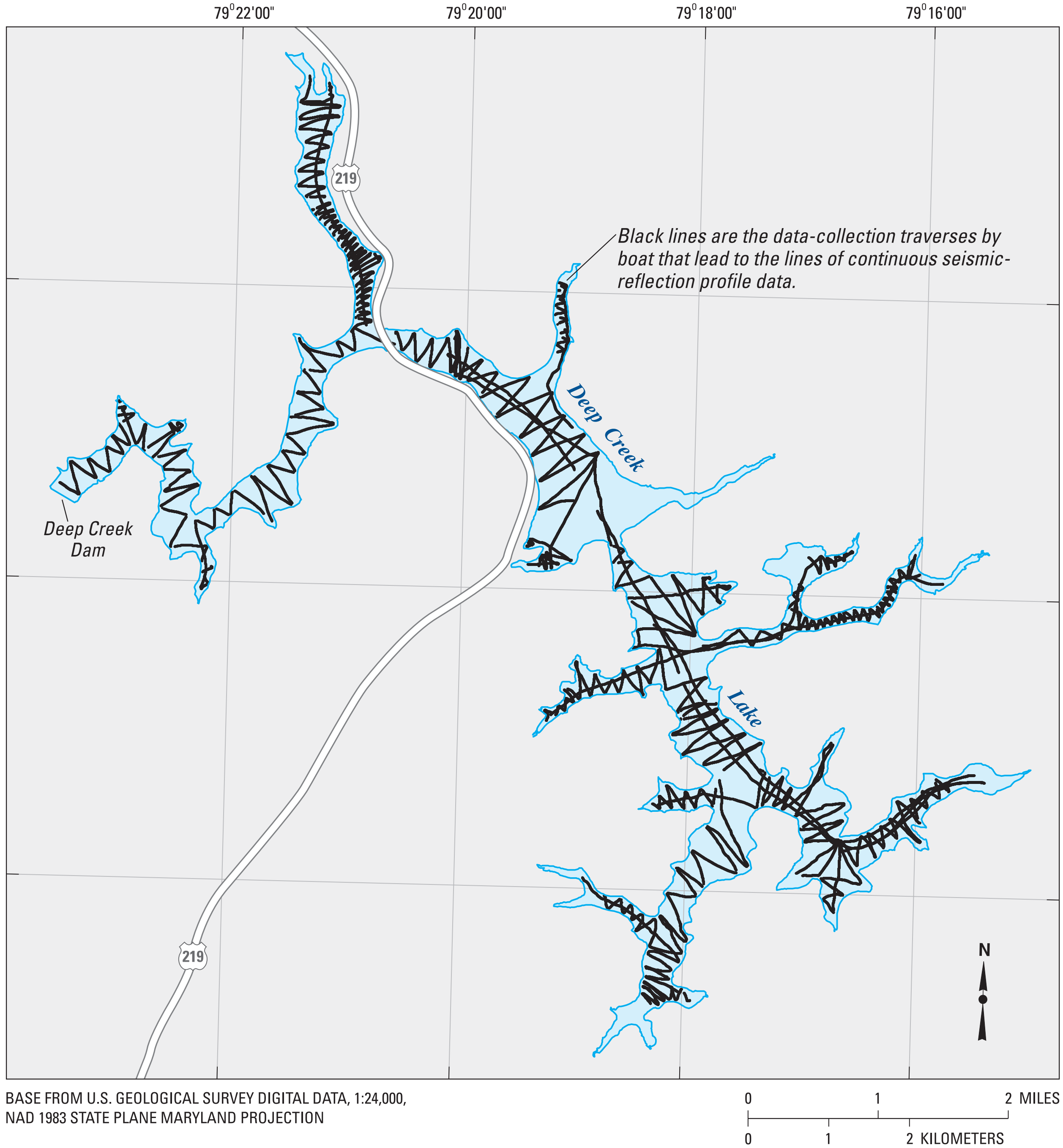


Figure 5. Location and extent of continuous seismic-reflection profile data collected at Deep Creek Lake, Garrett County, Maryland.

distance from the antenna to the reflective surface and back to the receiver. This time is divided by 2 and multiplied by the velocity of the media the energy is traveling through in milliseconds (ms) to determine depth. Seismic waves travel slower than the EM waves (for GPR), and are typically measured in milliseconds. The velocity of a sound wave (V) is proportional to elastic properties [acoustic impedance (Z)] and inversely proportional to the density (p) of the medium through which it travels (V=Z/p; Trabant, 1984). The seismic data consist of a series of traces showing the amplitude of the reflections as a function of traveltime. Plotted side by side, the trace data appear as a cross section of the subbottom under the survey line. Within the seismic cross section, diffractions and reflections can be traced, characterized, and correlated to geologic cross sections. The resolution of the seismic method is a function of both the velocity of the sound wave through the material and the frequency of the wave. In order to resolve geological layers, a reflection of seismic energy must occur at the interface of the two layers with sufficient difference in acoustic impedance—a product of the density and propagation velocity of each material. This means that there must be (1) transmission of energy into the subsurface, (2) appropriate frequency to resolve the layer, and (3) sufficient contrast in velocity through, and density of, the material above and below the layer to cause a reflection at the interface. Consequently, if a feature offers a very strong reflection, then much or the entire signal is reflected and little or no signal propagates further into the subbottom.

The lower the contrast in the acoustic impedance, the more likely the seismic signal is transmitted through the layer interface without reflections. Lower frequencies can provide an increased depth of penetration, but they have a lower resolution than higher frequency signals. At higher frequencies, there is greater resolution or increased ability to resolve smaller features, but at the expense of the depth of penetration. For reference, the velocity of sound in water is approximately 5,000 ft/s (feet per second). The velocity of sound in uncompacted Lake-bottom sediments can be slightly greater than the velocity of sound in water, but without an independent determination, the velocity of sound in these sediments was assumed to be 5,000 ft/s.

A distinct drawback to the CSP method is the inability to resolve subbottom features when there is methane gas present. Methane gas is often formed naturally in Lake-bottom sediments when organic material decomposes under anoxic conditions. The presence of methane gas can cause the entire transmitted signal to be reflected back to the water surface with none of the energy penetrating the subbottom. In areas where methane gas has accumulated, GPR may provide better records if the conditions (mainly water depth and electrical conductivity) are favorable. Since the current study is focused on shallow (less than 30 ft) areas of the lake and since shallow areas of the Lake are prone to methane gas accumulation, CSP data were not examined.

Processing Geophysical Data

Over 7 miles (of the original 90 miles collected) of GPR data were processed to determine the thickness of lacustrine sediment accumulated in selected coves and shallow areas of Deep Creek Lake since its impoundment in 1925. In order to create individual cross sections, the data stream was interrupted during data collection, labeled, and a new path (or line) begun each time the data-collection platform changed course (fig. 6).

To process the GPR data, 19 GPR data files (lines) were loaded into RadExplorer and a uniform set of processing routines were performed on each line to amplify the signal and optimize the quality of the profile. Processing included direct current (DC) removal to remove constant shifts (negative and positive) from the signal. Next, a zero-offset correction was set between 29 and 30 ns to account for the forward travel of the transmitter between the time of the energy pulse and its reflection and receipt. Band-pass filtering using a low pass of 27 MHz, low cut of 53 MHz, and a high pass of 156 MHz and high cut of 312 MHz were consistently used to reduce noise and enhance flat or slightly dipping reflectors (low pass, low cut filter), while also enhancing steeply dipping reflections and suppressing flat-lying reflectors (high pass, high cut filter). Amplitude corrections using automatic gain control (AGC) were used to help display detail in the subbottom materials and increase signal strength at depth. Processed files were saved in the proprietary format used by RadExplorer. The processed files, a subset of the data presented in figure 3, were then interpreted and presented in cross section to display the thickness of accumulated sediment in selected areas on the Lake bottom. The location, identification, direction, number of traces, length, and maximum and minimum sediment depth of the cross sections are listed in table 2 and shown in figures A1 through A19 in Appendix A.

In the processed cross sections in Appendix A, the uppermost parts of the GPR record are free of reflections as EM waves move through the water. At the bottom of the water column, a strong reflection occurs at the top of the sediments (called the “2007 horizon”). The depth of this reflection matches the depth to the bottom of the water determined with the Lowrance transducer (Banks and others, 2010). Below the water bottom and sediment interface the GPR record shows simple, parallel to wavy, continuous reflections that are consistent with laminated thin-bedded silts, fine sand, and sand (Beres and Haeni, 1991). Assuming GPR methods can resolve vertical features that are one-quarter wavelength in thickness, the 100-MHz antenna used in the current study should resolve features that are greater than 0.5 ft thick in saturated sediments.

In figure 7, the first reflector at trace 50 (A), is interpreted as the bottom of the water column and top of Lake sediment, at a depth of 3.4 ft. The depth to this reflector can be read off

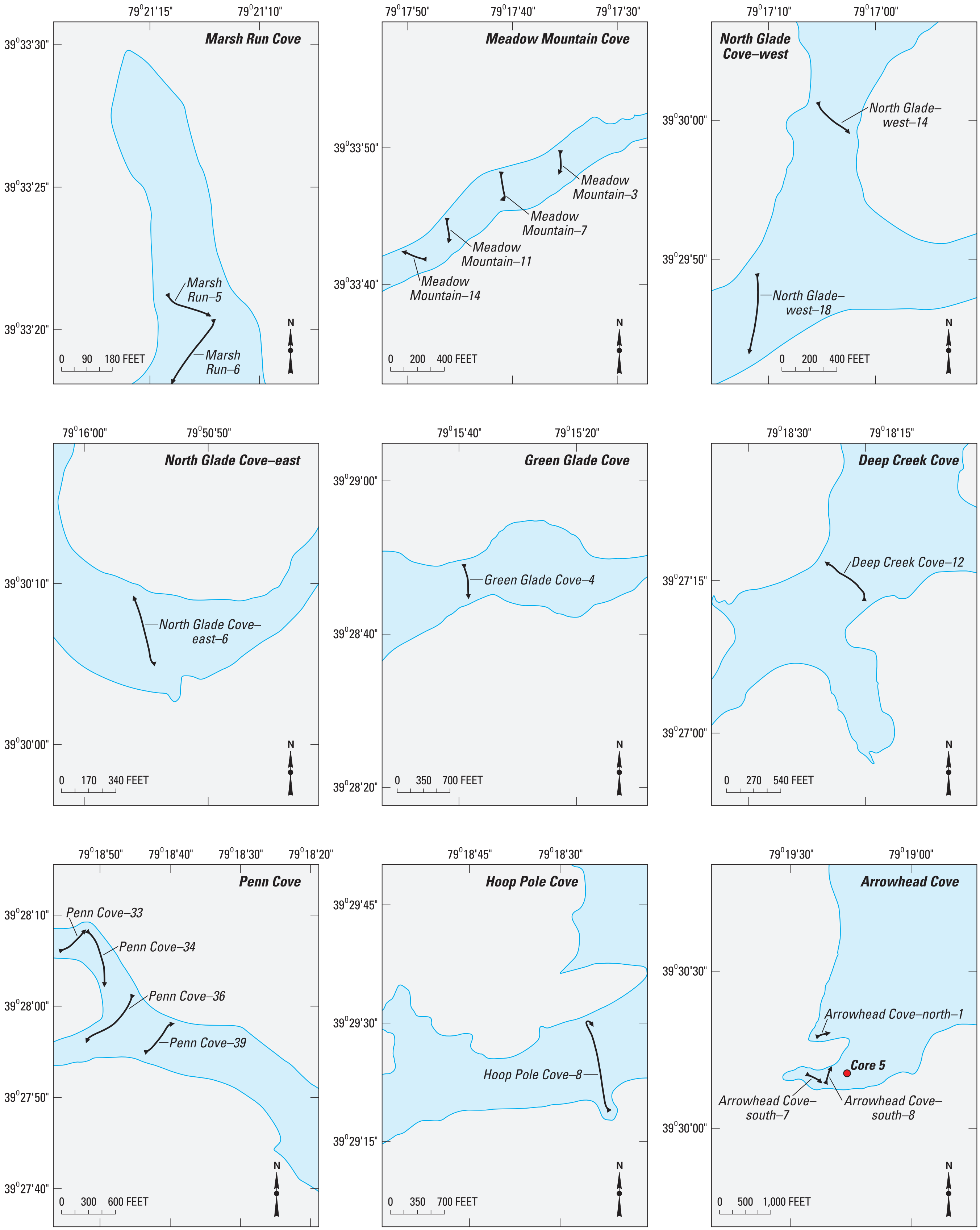


Figure 6. Location of processed ground-penetrating radar data lines and Core 5, Deep Creek Lake, Garrett County, Maryland. (Refer to figure 3 for Cove locations.)

Table 2. Location, descriptions, and interpreted depth of sediment of ground-penetrating radar lines in Deep Creek Lake, Garrett County, Maryland.

[ft, feet]

Cove identification	Cross section number	Appendix number	Data-collection platform orientation			Profile orientation			Traces	Length (ft)	Depth of sediment	
			Start		End	Left		Right	Interpreted/ Collected		Minimum (ft)	Maximum (ft)
Marsh Run	5	A1	NW	to	SE	NW	to	SE	545/600	236	1.5	5
Marsh Run	6	A2	NE	to	SW	SW	to	NE	993/1,000	328	1.5	4
Meadow Mountain	3	A3	N	to	S	N	to	S	394/400	164	3	7
Meadow Mountain	7	A4	N	to	S	N	to	S	500	258	1.5 to 3	7
Meadow Mountain	11	A5	N	to	S	N	to	S	314/400	197	2	5 or 6
Meadow Mountain	14	A6	SE	to	NW	SE	to	NW	349/400	154	1.5	3 to 4.5
North Glade west	14	A7	NW	to	SE	NW	to	SE	623/700	351	1.5	3
North Glade west	18	A8	N	to	S	N	to	S	1,050/1,100	584	1.5	2
North Glade east	6	A9	SE	to	NW	NW	to	SE	1,325/1,400	515	1.5	5.5
Green Glade	4	A10	NW	to	SE	NW	to	SE	1,358/1,400	585	1.5	4
Deep Creek	12	A11	SE	to	NW	SE	to	NW	2,366/2,400	775	1	4
Penn	33	A12	SW	to	NE	SW	to	NE	2,010/2,400	804	2	4 to 5.5
Penn	34	A13	N	to	S	S	to	N	1,128/1,200	387	2	5
Penn	36	A14	NE	to	SW	NE	to	SW	657/700	646	2	4
Penn	39	A15	SW	to	NE	SW	to	NE	1,195/1,200	492	1.5	5.5 to 7
Hoop Pole	8	A16	S	to	N	S	to	N	2,332/2,400	840	1	5
Arrowhead north	1	A17	SW	to	NE	SW	to	NE	779/800	328	1	2
Arrowhead south	7	A18	W	to	E	W	to	E	1,082/1,100	490	2	5.5
Arrowhead south	8	A19	SW	to	NE	SW	to	NE	1,187/1,200	413	1.5	3

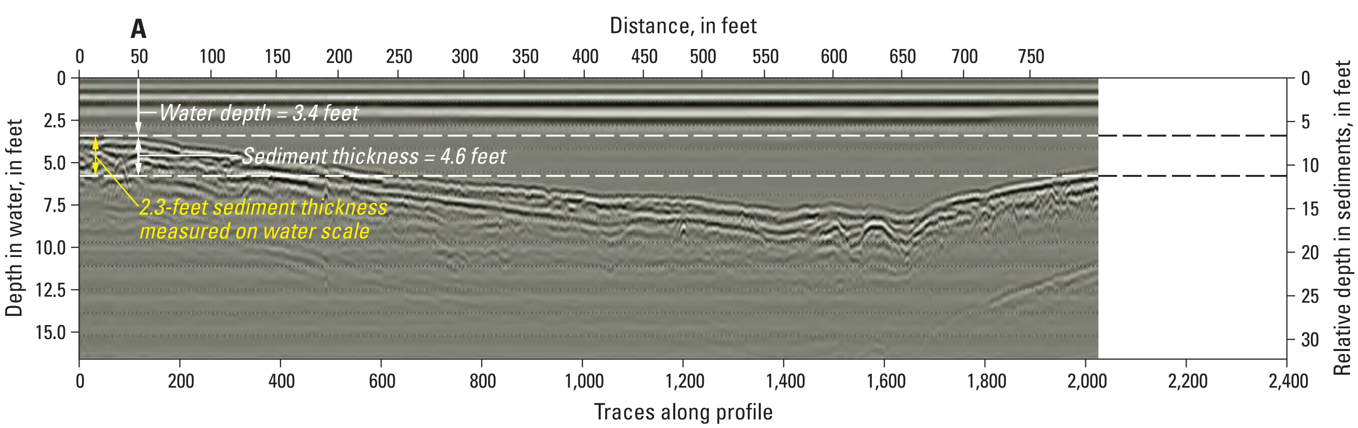


Figure 7. Example of a ground-penetrating radar cross section with interpretations showing water depth and sediment thickness on two different scales.

the left scale, which represents depth using the velocity of EM waves in water. The relative depth of the sediments is read off of the right scale. This scale represents depth using the velocity of EM waves in saturated sediment. The thickness of the laminated sediments at (A) is approximately 4.6 ft. However, if total sediment thickness were read off of the left scale (equivalent to assuming a uniform EM velocity in water and sediments), then the total sediment thickness would be underestimated by about 2 ft. In this example, the thickness would be estimated as 2.3 ft rather than 4.6 ft, as determined when a faster sediment velocity is specified.

As a proof of concept, a GPR profile was compared to other data including seismic profiles, high-frequency bathymetric data, and a sediment core (Banks and others, 2010). The location of a west-to-east trending CSP line that traces the axis of Arrowhead Cove, cross section number 8 in Arrowhead Cove-south (figure 6), and core 5 collected in 2008 (fig. A19) are shown in figure 8. Although multiple cores were collected, core 5 was the only core that penetrated through lacustrine sediment and was nearly coincidental with both GPR and CSP data lines. Bathymetric data collected near core 5 indicate a water depth between 20 and 25 ft. The CSP line presented in figure 8 is nearly coincidental with core 5, and shows that the depth to the water bottom is 18.4 ft below the transducer (the transducer is 1.25 ft below the water surface) or about 19.7 ft. The GPR line “Arrowhead Cove-south, cross section 8” (fig. A19) is 360 ft west of core 5, where according to the bathymetric data, water depth is between 10 and 15 ft. Water depth as interpreted on the GPR line is 11 ft.

Core 5 was collected as described by Banks and others (2010), and the thickness, median grain-size diameter, percent fines by weight, and sediment description of the core material are listed in table 3. The thickness of the core recovered was not corrected for any compaction that may have occurred during the coring process, and determination of the exact amount of compaction is beyond the scope of this investigation. The actual total thickness of sediments at the location of core 5 is at least as much, if not greater than, the length of core recovery (2.3 ft) reported in table 3. GPR line 8 in Arrowhead Cove-south, the line closest to core 5, has an interpreted sediment thickness of about 3 ft. Because of the inability to resolve the 1925 horizon in the CSP line in figure 8, the thickness of the lacustrine sediment as interpreted from the CSP line could be as little as 1.3 ft or as much as 5.5 ft. There was less certainty in the resolution of the 1925 interface using the CSP data. When both GPR and CSP methods are compared, only GPR compares favorably to core 5. The lack of resolution between the 2007 horizon and 1925 horizon as shown in the CSP line indicates that GPR provided better resolution and more reliable interpretation of the 1925 horizon than the CSP data.

Interpretation of Ground-Penetrating Radar (GPR) Profiles for Sediment Thickness

Nineteen radargrams were processed using the proprietary software RadExplorer (Appendix A, figures A1 through A19). The selected radargrams show both the processed radargram (labeled “*A*”) and the interpreted radargram (labeled “*B*”) in each figure. In the processed radargrams (*A*), the trace count is annotated along the x-axis, and two-way traveltime is annotated along the y-axis. Using the GPS data, the x-axis was converted to distance along the profile in feet for the radargram. To determine a y-axis for the interpreted radargrams (*B*), the two-way traveltime was converted to depth below the water surface in feet on the left axis and relative thickness of sediment in feet on the right axis.

The theoretical distance to a reflector is computed as the two-way traveltime divided by 2 and multiplied by the propagation speed of the EM wave through the media. In the simplest approximation, the propagation velocity could be considered uniform for all layers and equal to the velocity in water, which is computed as the speed of light in a vacuum divided by the square root of the dielectric permittivity for water. A more robust interpretation to a subbottom reflector computes the total distance as the sum of the distances through each medium, with the distance through each medium computed as the speed of light in a vacuum divided by the square root of the dielectric permittivity for that medium. If the simple approximation were used, then the greater the thickness of the sediment relative to the water depth, the greater the possible percent error, and the thickness of the sediment layer would be underestimated. Consequently, the velocities of both layers—the water and a layer of sediment—were considered for this investigation.

In each interpreted profile, two reflectors were picked manually. The first interface, the Lake bottom, was characterized by multiple parallel reflectors. This water-to-sediment interface (the “2007 horizon”) was readily identified in the GPR records. The second interface was defined as the bottom of the lacustrine sediments and the pre-reservoir valley floor (the “1925 horizon”). This second reflector was characterized by multiple chaotic, non-parallel reflectors. In some cases a second, deeper subbottom reflector was observed. This second subbottom reflector may represent structure or layering within the pre-reservoir sediments or the bottom of lacustrine sediment and the top of terrestrial soil (pre-reservoir). The velocity of the EM wave in water was computed using a dielectric permittivity of 81, and was equal to 109.4 ft/µs. The velocity of the lacustrine sediments was computed with a dielectric permittivity of 21, and was equal to 214.8 ft/µs. This value falls between typical values of saturated sand (180 ft/µs) and

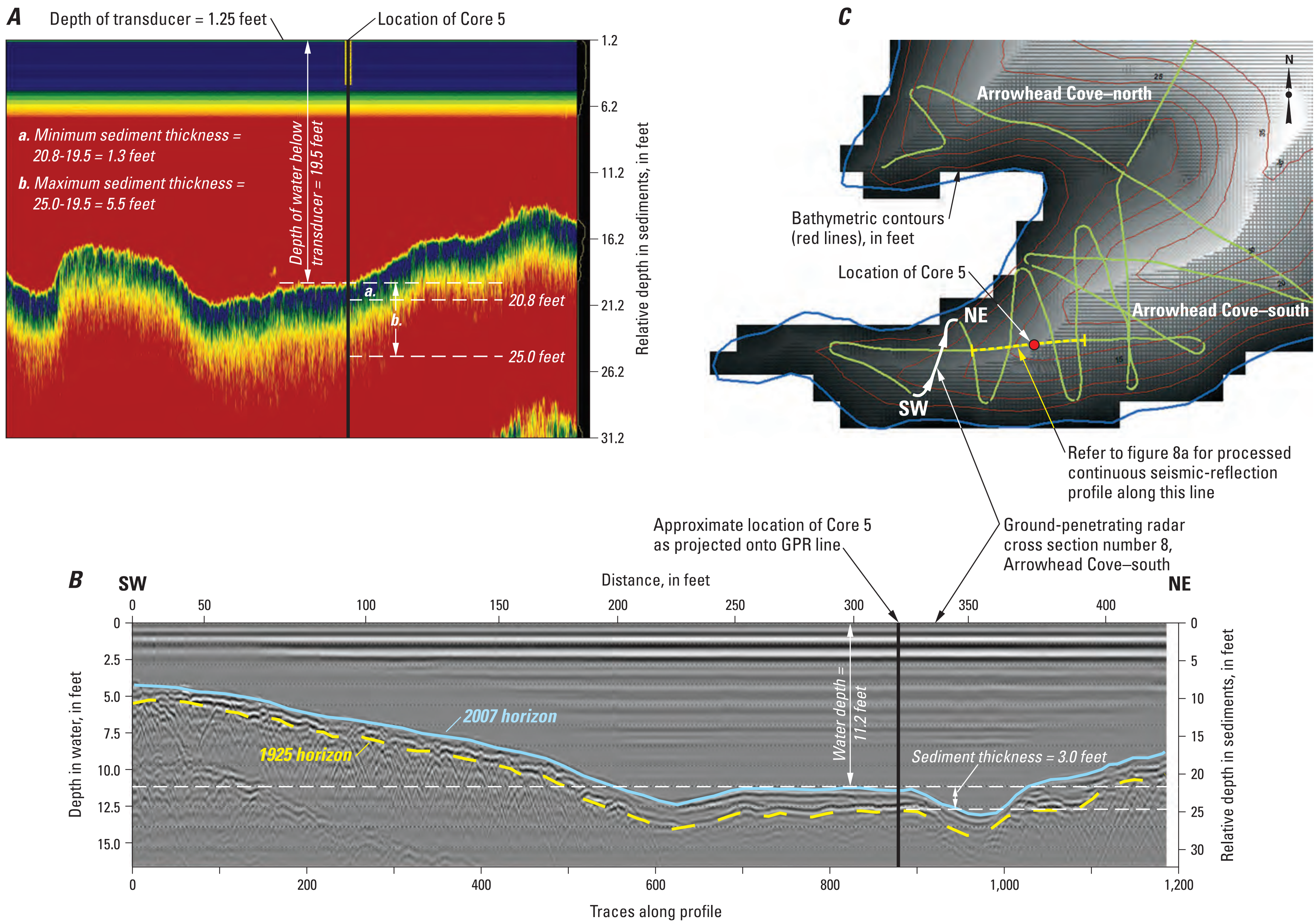


Figure 8. Location and relative depths for *(A)* a processed continuous seismic-reflection profile, *(B)* a ground-penetrating radar (GPR) line, and *(C)* bathymetric data and location of Core 5 in Arrowhead Cove–south, cross section number 8, Deep Creek Lake, Garrett County, Maryland.

Table 3. Summary of sediment grain-size distribution in Core 5 in Deep Creek Lake, Garrett County, Maryland, 2008[1].

[cm, centimeter; in., inch; ft, feet; µm, micrometer; mm, millimeter; **bold** type indicates material greater than 2.0 millimeters in botttom of core]

Core number	Interval (cm)	Interval (in.)	Interval (ft)	Median grain-size diameter (µm)	Percent of total sample weight less than 0.063 mm	Sediment-size description[2]
5	0–15	0–5.9	0.0–0.5	228.50	21.2	Coarse, silty coarse sand
5	15–30	5.9–11.8	0.5–1.0	171.10	36.3	Very coarse silty, medium sand
5	30–45	11.8–17.7	1.0–1.5	180.20	13.9	Coarse, silty medium sand
5	45–60	17.7–23.6	1.5–2.0	183.00	21.9	Coarse, silty medium sand
5	**60–70**	23.6–**27.6**	2.0–2.3	**192.40**	**14.2**	**Very coarse silty, medium sand**

[1] Modified from Banks and others, 2010.

[2] Material described from coarse to fine by mass.

saturated silt (310 ft/µs). Although this value accurately represents coarser sediment, it may underestimate fine sands, silts, and clay. Interpreted radargrams (*B*) are shown with depth in water on the left y-axis and relative depth of sediment on the right y-axis.

Processed data cross sections were prepared for 9 coves around Deep Creek Lake (fig. 6). Each interpreted cross section is described in table 2 and is ordered by cove and cross section number from the most upstream to the most downstream cross section.

Marsh Run Cove is located in the northernmost part of the Lake and is represented by two cross sections. The interpreted sections show no definitive channel or thalweg and the GPR data indicate sediment thickness ranges from 1.5 to 5 ft. Sediment depths are slightly thicker in upstream cross section 5, (fig. A1), but the reflector representing the 1925 horizon was discontinuous and difficult to trace near the middle of cross section 6 (fig. A2).

Meadow Mountain Cove is near the north-center of the Lake. The most upstream cross section, section 3 (fig. A3) indicates 3 to 7 ft of sediment accumulation and no clear channel features. Further downstream cross section 7 (fig. A4) shows a slight channel feature on the south side of the cross section, but also shows at least two possible locations for the 1925 horizon. Conservatively, minimum accumulations in this section could range from 1.5 to 3 ft of sediment, whereas a clear reflection on the north side of the section indicates as much as 7 ft of accumulated sediment. Section 11 (fig. A5) displays a somewhat defined thalweg near the center of the section with a minimum sediment thickness of about 2 ft. Maximum sediment accumulation ranges between 5 and 6 ft as a result of multiple possible selections for the 1925 horizon on the north side of the section. Section 14 (fig. A6) has a clearly defined thalweg at approximately 100 ft from the beginning of this southeast-northwest oriented section, and a minimum of 1.5 ft of sediment along the south side of this feature. Two clear reflectors were identified in the subbottom. Both have characteristics of the 1925 horizon, but it is uncertain which one is actually the original Lake bottom. Depending on which reflector is interpreted to be the 1925 horizon, the maximum sediment thickness can range from 3 to 4.5 ft southeast of the thalweg.

The North Glade Cove is divided into west and east locations. The northernmost section in the westernmost survey (section 14, fig. A7) shows a layer of laminar sediments draped across a well-defined thalweg. The 1925 horizon cannot be traced through the central part of the section possibly because of GPR signal attenuation as water depths approach the practical maximum depth for the antenna; however, multiple, chaotic reflectors also obscure the horizon and indicate little to no sediment accumulation. Sediment thickness ranges between 1.5 and 3 ft. South of section 14, section 18 (fig. A8) also shows a poorly defined, discontinuous reflector for the 1925 horizon as a result of signal attenuation in the center of the profile. Section 18 is interpreted to have a relatively thin layer of accumulated sediment between 1.5 and 2 ft thick. Section 6 (fig. A9) was collected on the east side of North Glade Cove. No thalweg is evident in the section, but a clearly defined reflector for the 1925 horizon indicates that accumulated sediment thickness ranges from 1.5 to 5.5 ft.

One section (fig. A10) was collected near the easternmost part of Green Glade Cove. Sediment thickness ranges from 1.5 to 4 ft, with maximum accumulation on the northwest side of a well-defined thalweg. Parts of the 1925 horizon are obscure between 200 and 250 ft southeast of the start of the section, and again near the far southeast side of the section.

Section 12 (fig. A11) was collected in Deep Creek Cove near the southernmost part of the Lake. The section shows a clearly defined thalweg approximately 500 ft northwest of the beginning of the section with a minimum sediment accumulation of 1 ft in this feature. Maximum sediment accumulation occurs on the northwest side of the section and reaches an interpreted thickness of about 4 ft.

Penn Cove has four cross sections, with the three most upstream sections (33, 34, and 36; figures A12, A13, and A14, respectively) located in the northernmost part of the cove. These sections show no thalweg or a poorly developed thalweg. The 1925 horizon is interpreted across each of the profiles and is fairly continuous and well-defined. The southwest side of cross section 33 (fig. A12) shows two subbottom reflectors. It is unclear which of these reflectors is the 1925 horizon. Sediment thickness for these three sections ranges from a minimum of 2 ft to a maximum of 4 to 5.5 ft, depending on which reflector is interpreted as the 1925 horizon. Section 36 (fig. A14) also shows clear hyperbolic reflectors across the section that help delineate the 1925 horizon. Section 39 (fig. A15) crosses Penn Cove east of sections 33, 34, and 36 and shows a thalweg on the northeast side of the section. In the middle of the profile, two subbottom reflectors can be traced. Minimum sediment thickness in section 39 is about 1.5 ft at the thalweg, and maximum thicknesses range from 5.5 to 7 ft, depending on which reflector is interpreted as the 1925 horizon. Note that a water-bottom multiple is clearly visible in figure A15 *B* below the 1925 horizon. The feature, beginning at the southwest side of the section and extending for about 125 ft, is parallel to but approximately twice as steep as the water bottom (the interpreted 2007 horizon).

Hoop Pole Cove, located on the west side of the Lake (due west of North Glade Cove; fig. 6) is characterized by cross section 8 (fig. A16). Interpreted sediment thickness ranges from 1 to 5 ft. The dominant feature is a 7.5-ft high mound with a center located about 750 ft north of the start of the section. As the section is oriented south to north and data collection began in a small cove just west of the main body of Deep Creek Lake, this feature could be a delta structure or the projection of the shore as the data-collection platform turned.

Arrowhead Cove, due north of Hoop Pole Cove (fig. 6), has three interpreted cross sections. Section 1 (fig. A17) is located on the north side of a small peninsula. The section is oriented roughly parallel to the shore and indicates about 1 to 2 ft of evenly distributed sediment accumulation. Sections 7 and 8 (figs. A18 and A19) are in the cove south of the peninsula and show 2 to 5.5 ft of sediment accumulation in the upstream section, and 1.5 to 3 ft of sediment accumulation in the downstream section.

Summary and Conclusions

Nearly 90 miles of ground-penetrating radar (GPR) data were collected between September 17 and October 4, 2007 in Deep Creek Lake, Garrett County, Maryland. The overall purpose of the study was for the U.S. Geological Survey to assist the Maryland Department of Natural Resources in their effort to better manage the resources of Deep Creek Lake by determining the thickness of sediment infilling. Over 7 miles of data and 19 GPR cross sections in 9 different coves were interpreted to determine two horizons—the 2007 water bottom and the 1925, pre-reservoir land surface. The difference between these two surfaces is interpreted as the total thickness of sediment accumulation that has occurred at the location of the cross section from the time the Lake was impounded in 1925 until 2007. For most of the profiles, there were a set of reflectors at the bottom of the water column that represent a thin layer of sediments. This interpretation is consistent with the results of coring. Most of the sediments collected in the core were described as fine to very coarse sand. These sediments were identified in the radar plots as closely spaced, laminated, parallel reflectors. Below the parallel reflectors chaotic, discontinuous, diffracted waves were observed. These features were interpreted as boulders, cobbles, and rocks that make up the initial pre-reservoir land surface. In this investigation, this somewhat discontinuous reflector was traced across the interface between the parallel, laminated sediments of post-reservoir timeframe and the 1925 horizon. In some places, more than one subbottom reflector could be traced over part of the profile; however, it was not possible to identify which of the reflectors was the actual 1925 horizon. In these circumstances, the deeper reflector may represent structure within the layering of the pre-reservoir sediments. When the interpreted profiles are compared in downstream order, GPR cross sections indicate that sediment thickness decreased toward the center of the Lake. Sediment thickness ranged from about 1 to 7 feet of accumulated sediment in coves around Deep Creek Lake.

References Cited

Banks, W.S.L., Davies, W.J., Gellis, A.C., LaMotte, A.E., McPherson, W.S., and Soeder, D.J., 2010, Hydrologic data for Deep Creek Lake and selected tributaries, Garrett County, Maryland, 2007–08: U.S. Geological Survey Open-File Report 2010–1092, accessed October 18, 2011 at *http://md.water.usgs.gov/deepcreek/index.html*.

Beres, Milan, Jr., and Haeni, F.P., 1991, Application of ground-penetrating radar methods in hydrogeologic studies: Ground Water, v. 29, no. 3, p. 375–386.

Kelsey, R.H., and Powell, S.L., 2011, Deep Creek Lake baseline assessment report: EcoCheck, National Oceanic and Atmospheric Administration and the University of Maryland Center for Environmental Science, 35 p.

Maryland Department of Natural Resources, 2008, Deep Creek Lake Recreation and Land Use Plan, accessed September 29, 2011 at *http://dnr.maryland.gov/publiclands/dcreport.asp*.

Maryland Department of Natural Resources, Fisheries Service, 2010, Inland fishing, Deep Creek Lake, accessed June 25, 2011 at *http://dnr.maryland.gov/fisheries/recreational/fwhotdeepcrlk.html*.

National Oceanic and Atmospheric Administration, 2006, National Weather Service Middle Atlantic River Forecast Center, accessed June 28, 2011 at *http://www.erh.noaa.gov/marfc/Climatology/*.

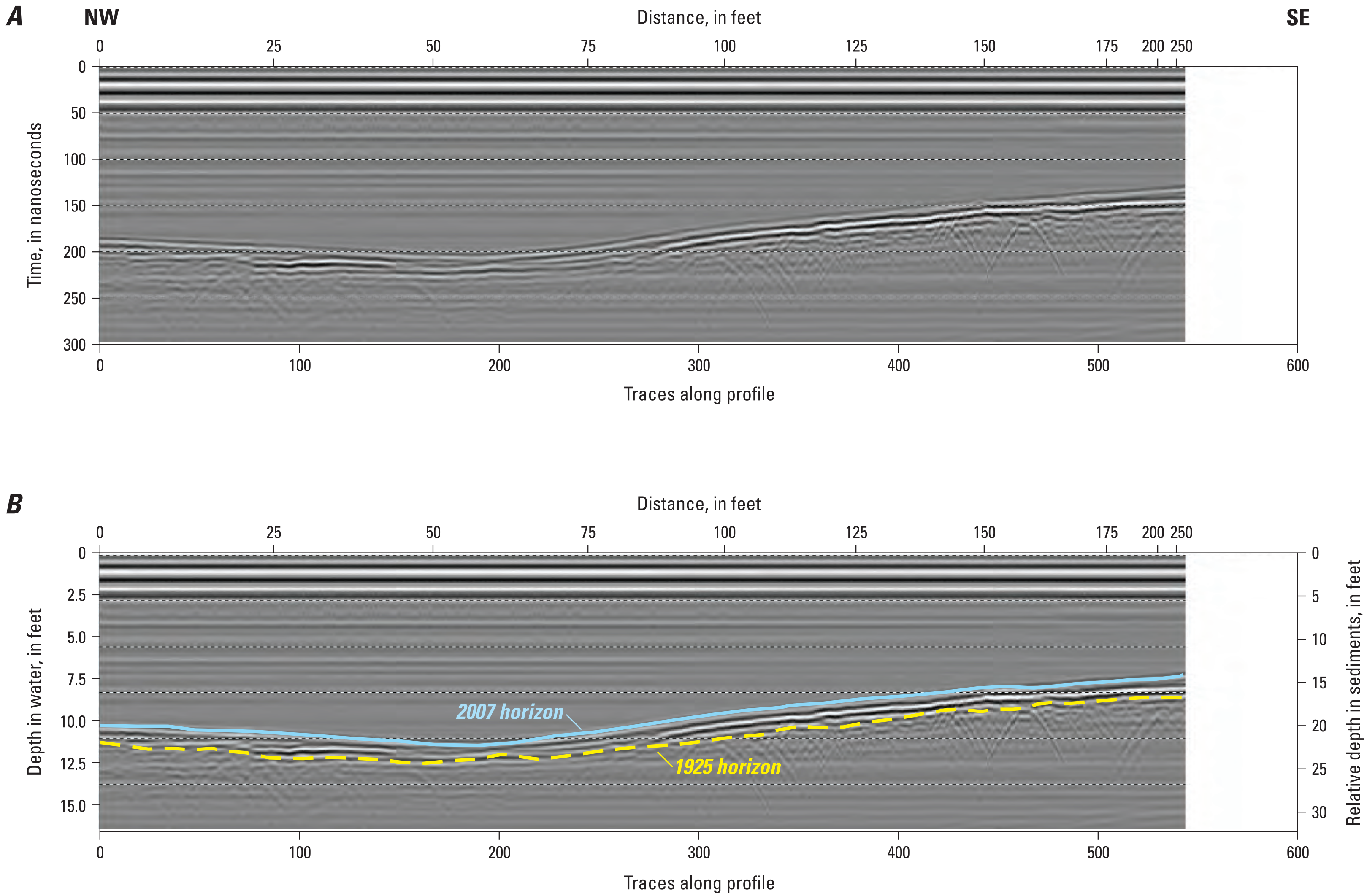
Powers, C.J., Haeni, F.P., and Smith, S., 1999, Integrated use of continuous seismic-reflection profiling and ground-penetrating radar methods at John's Pond, Cape Cod, Massachusetts *in* Powers, M.H., Cramer, Lynn, and Bell, R.S., eds., Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Oakland, California, March14–18, 1999: Wheat Ridge, Colorado, Environmental and Engineering Geophysical Society, p. 359–368.

Trabant, P.K., 1984, Applied high-resolution geophysical methods: Boston, Massachusetts, International Human Resources Development Corporation, 265 p.

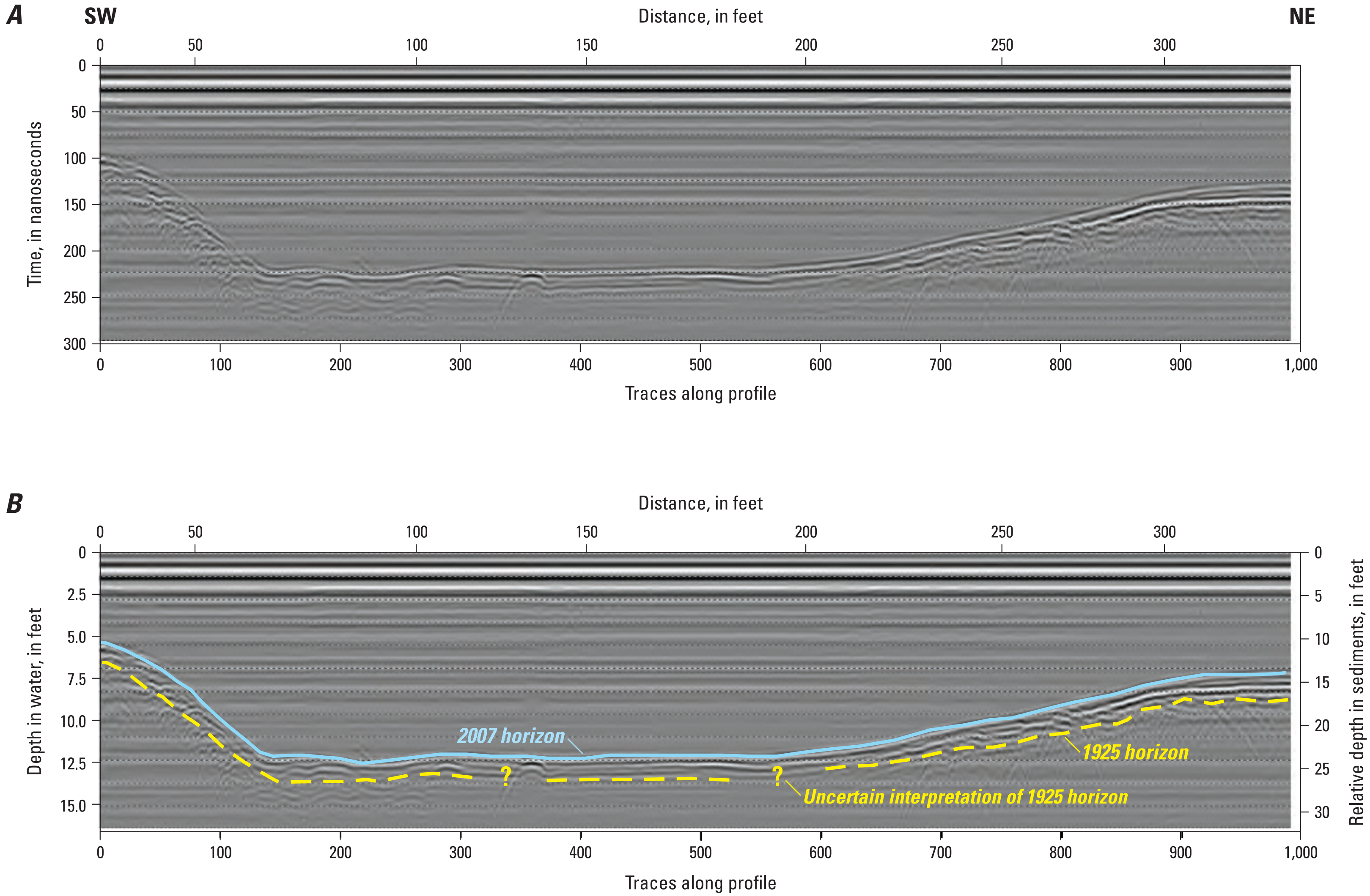
U.S. Census Bureau, 2009, American Fact Finder, accessed July 5, 2011 at *http://www.factfinder.census.gov*.

Appendix A

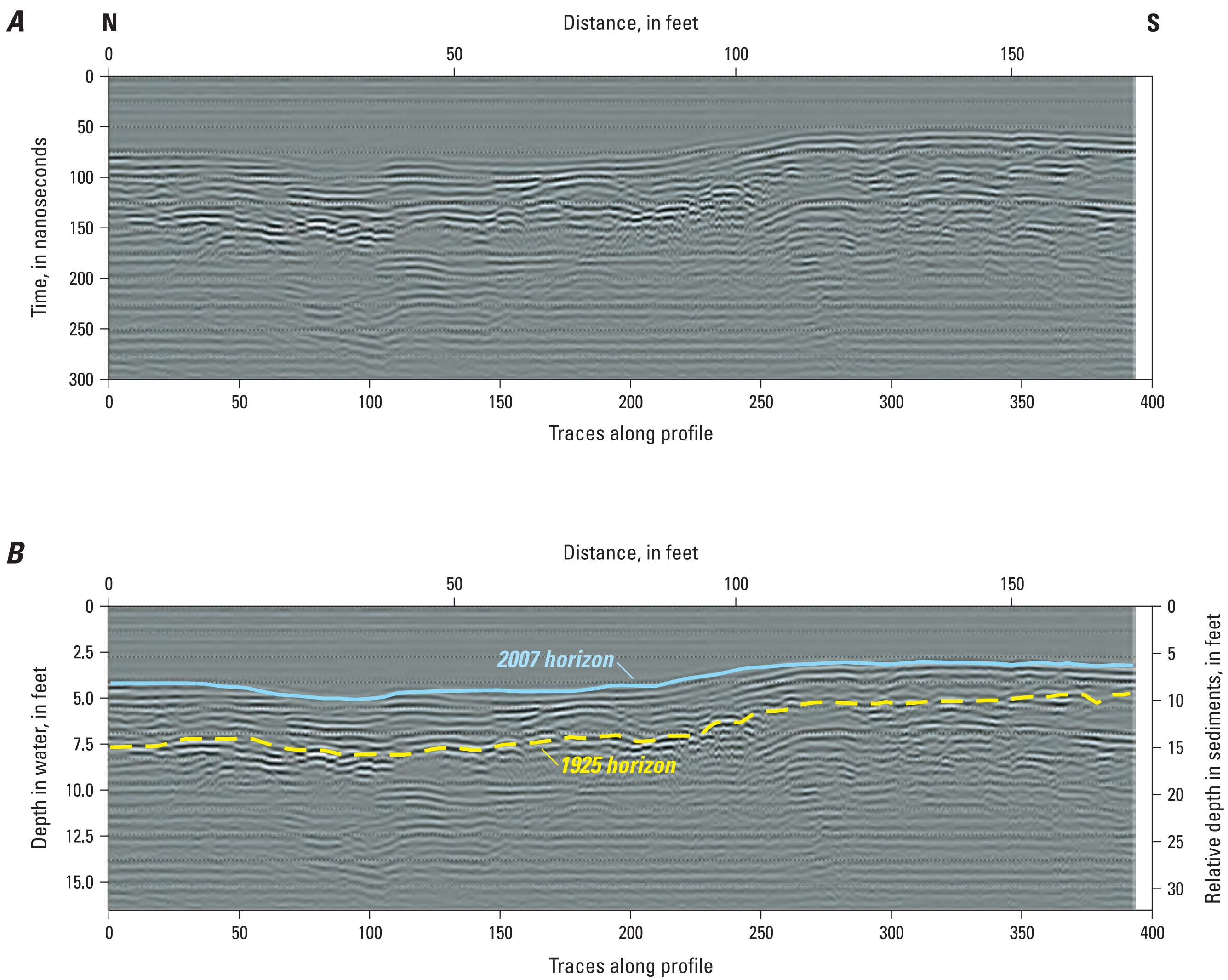
Appendix A1. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Marsh Run Cove, cross section 5, Deep Creek Lake, Garrett County, Maryland, 2007.



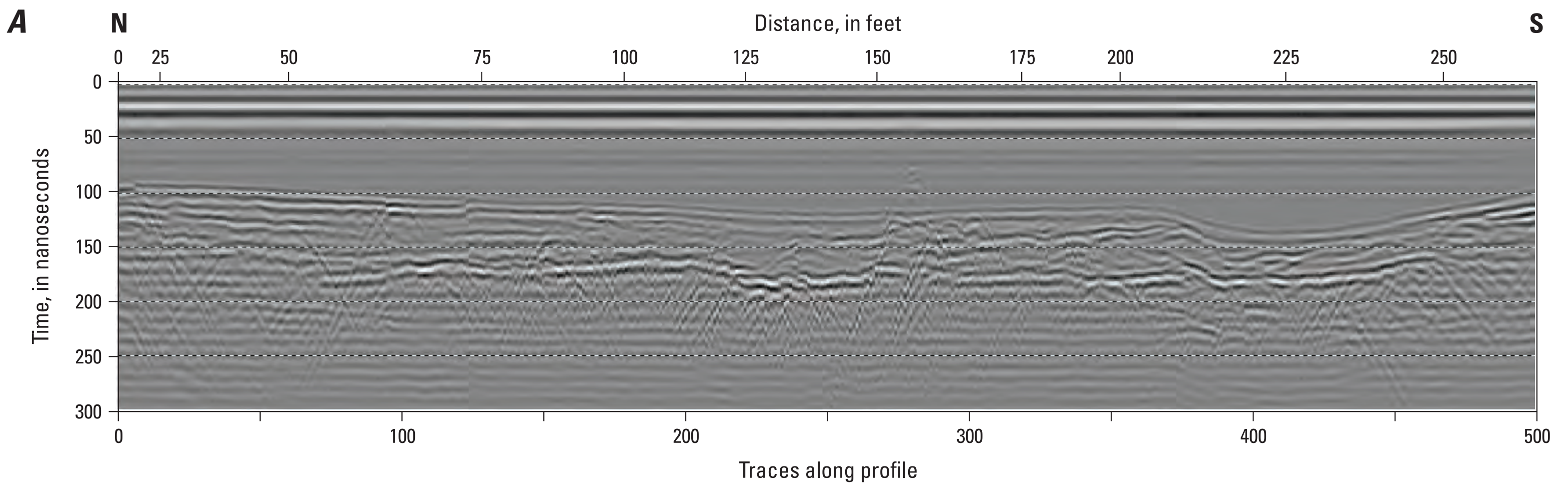
Appendix A2. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Marsh Run Cove, cross section 6, Deep Creek Lake, Garrett County, Maryland, 2007.

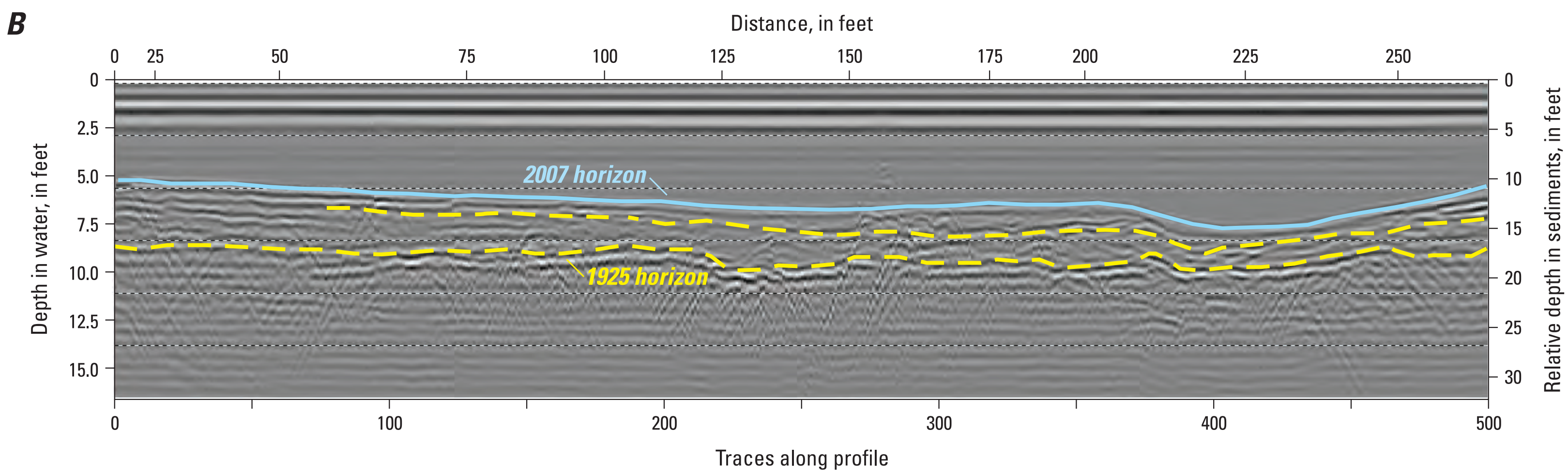


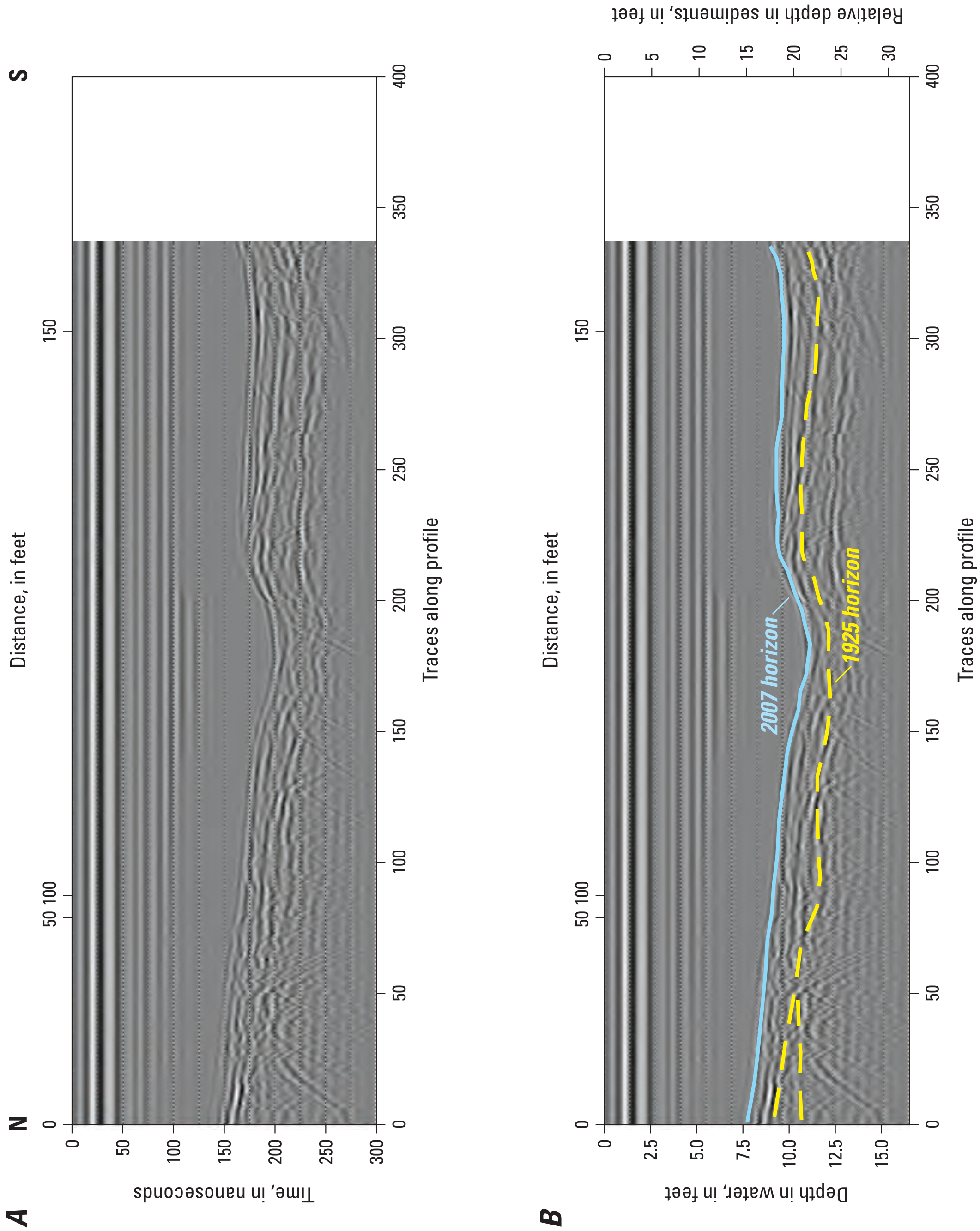
Appendix A3. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 3, Deep Creek Lake, Garrett County, Maryland, 2007.



Appendix A4. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 7, Deep Creek Lake, Garrett County, Maryland, 2007.

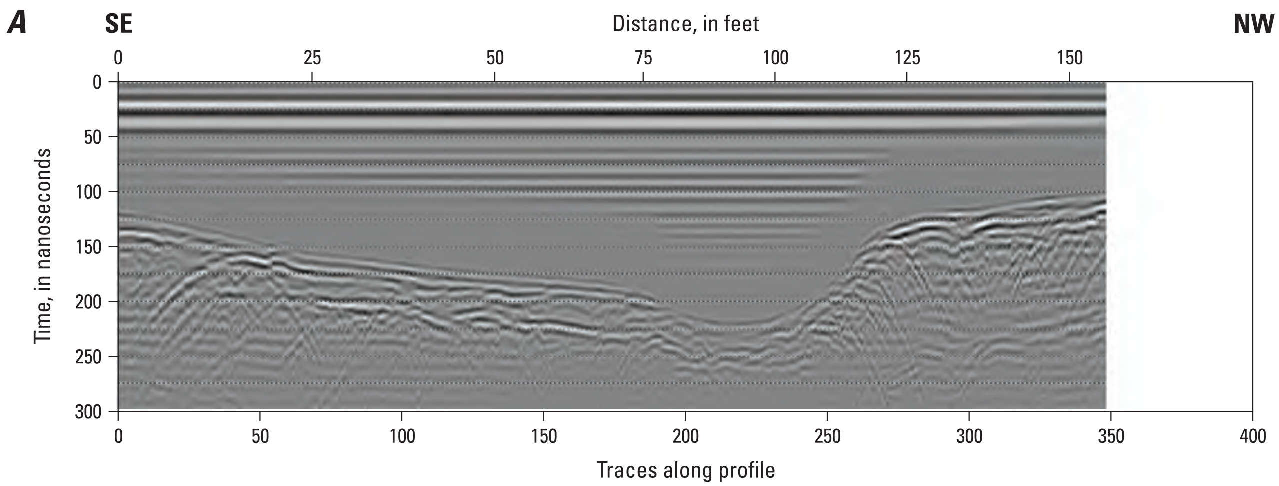


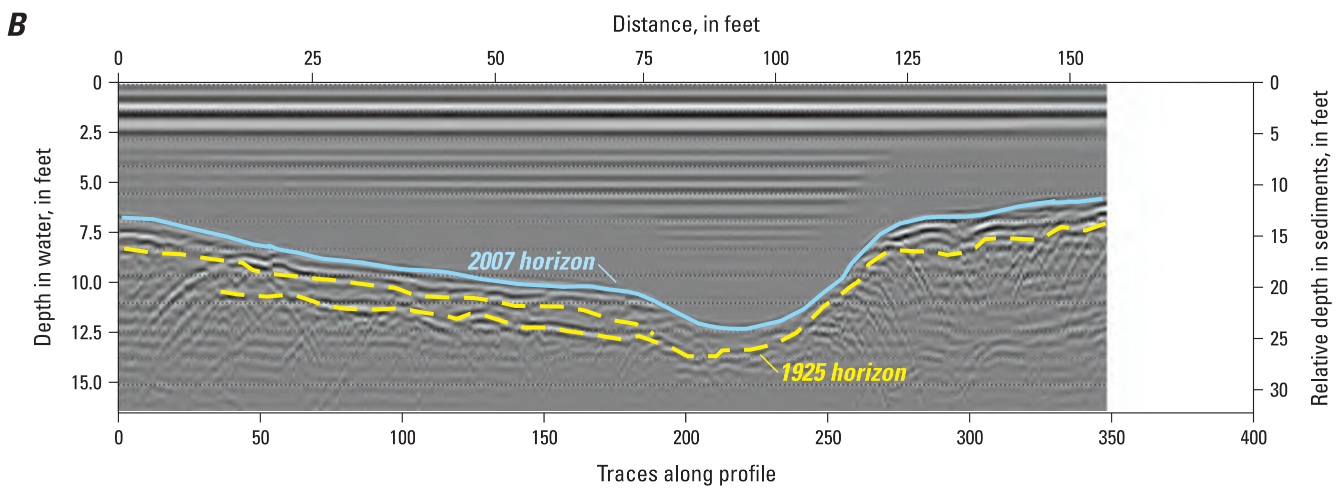




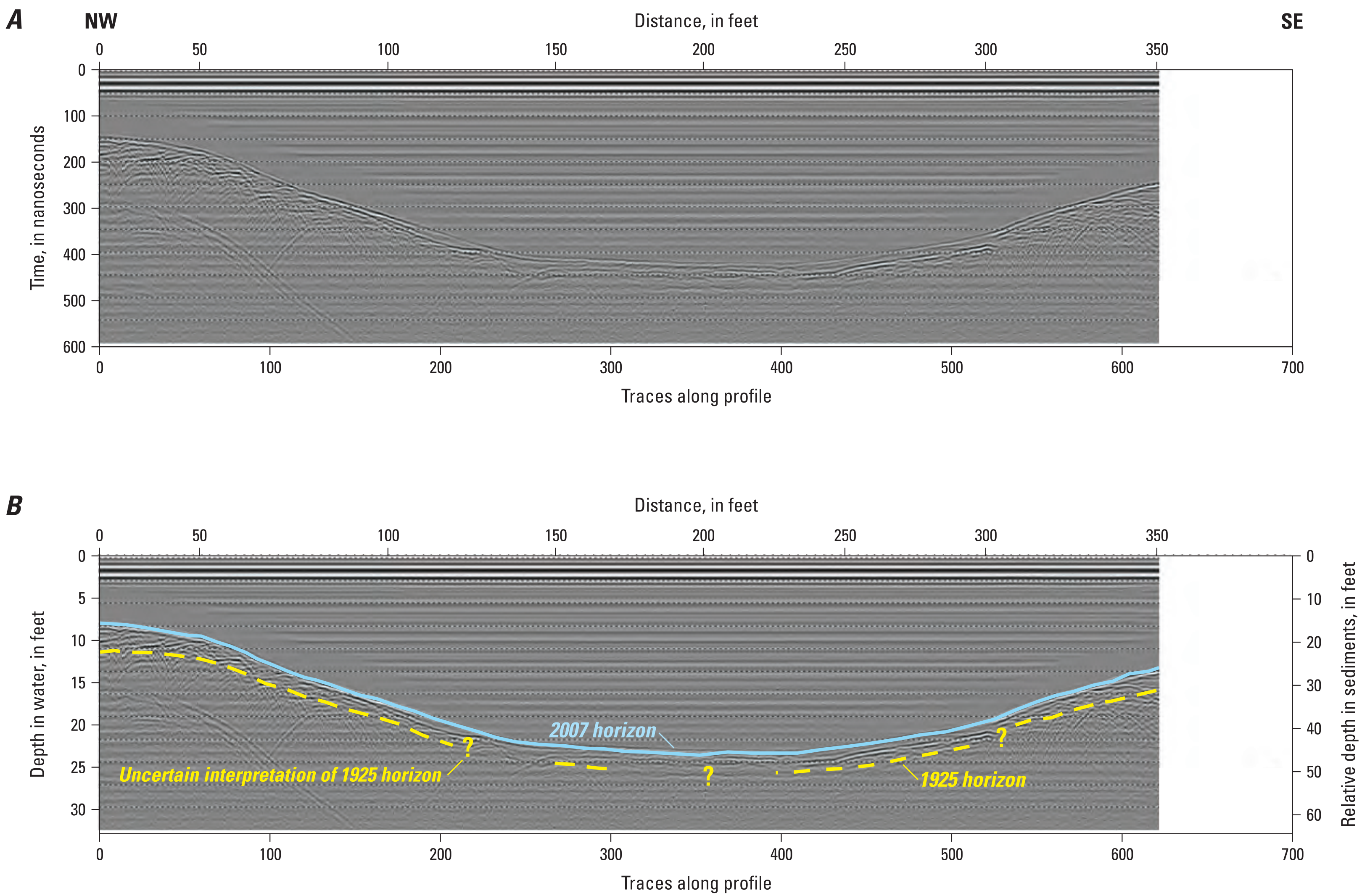
Appendix A5. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 11, Deep Creek Lake, Garrett County, Maryland, 2007.

Appendix A6. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Meadow Mountain Cove, cross section 14, Deep Creek Lake, Garrett County, Maryland, 2007.

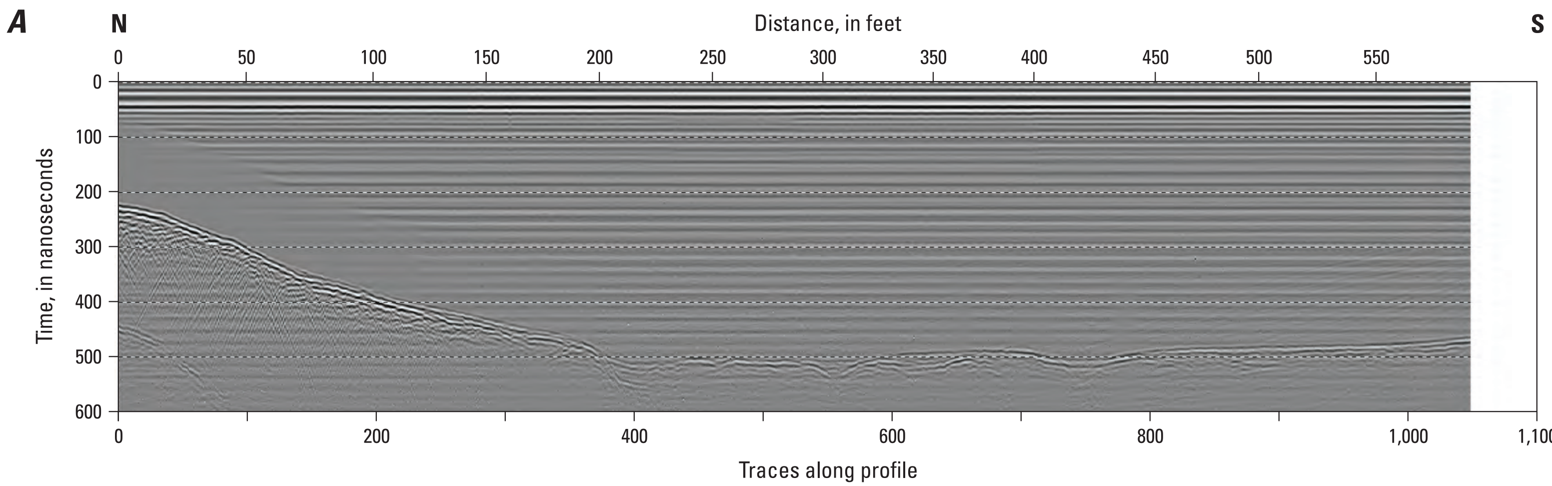


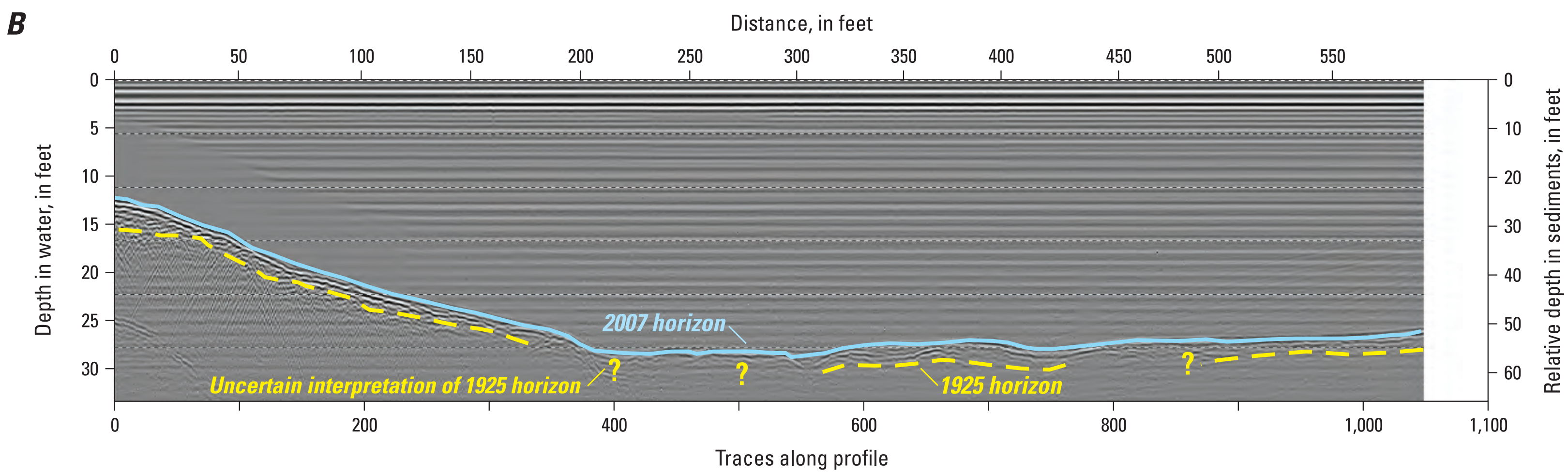


Appendix A7. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–west, cross section 14, Deep Creek Lake, Garrett County, Maryland, 2007.

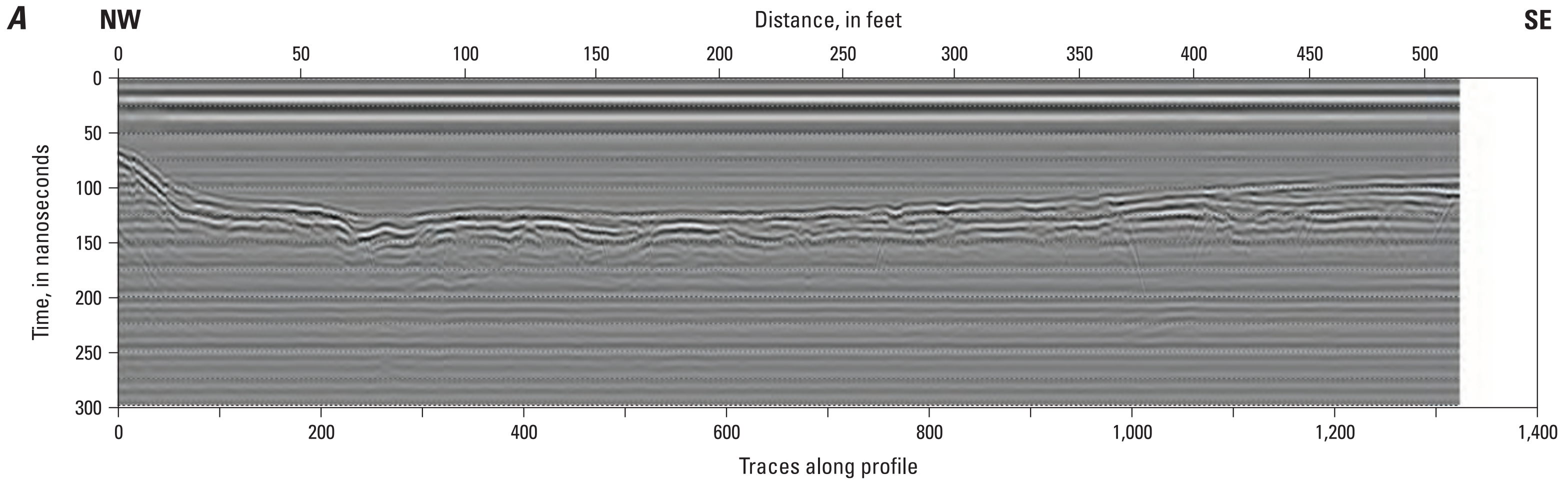


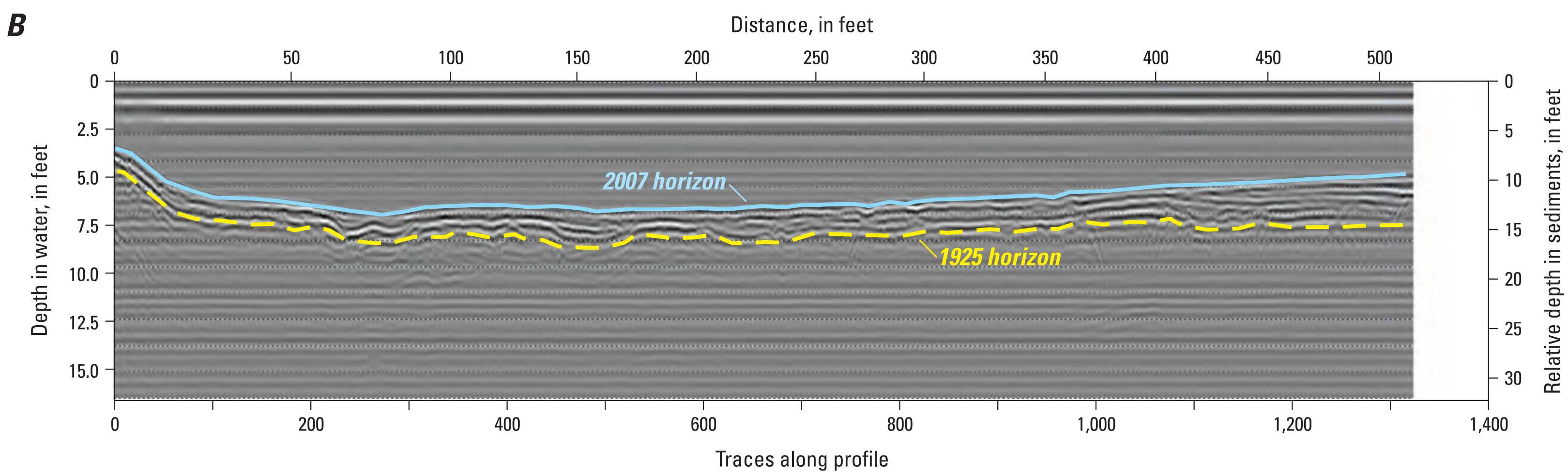
Appendix A8. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–west, cross section 18, Deep Creek Lake, Garrett County, Maryland, 2007.



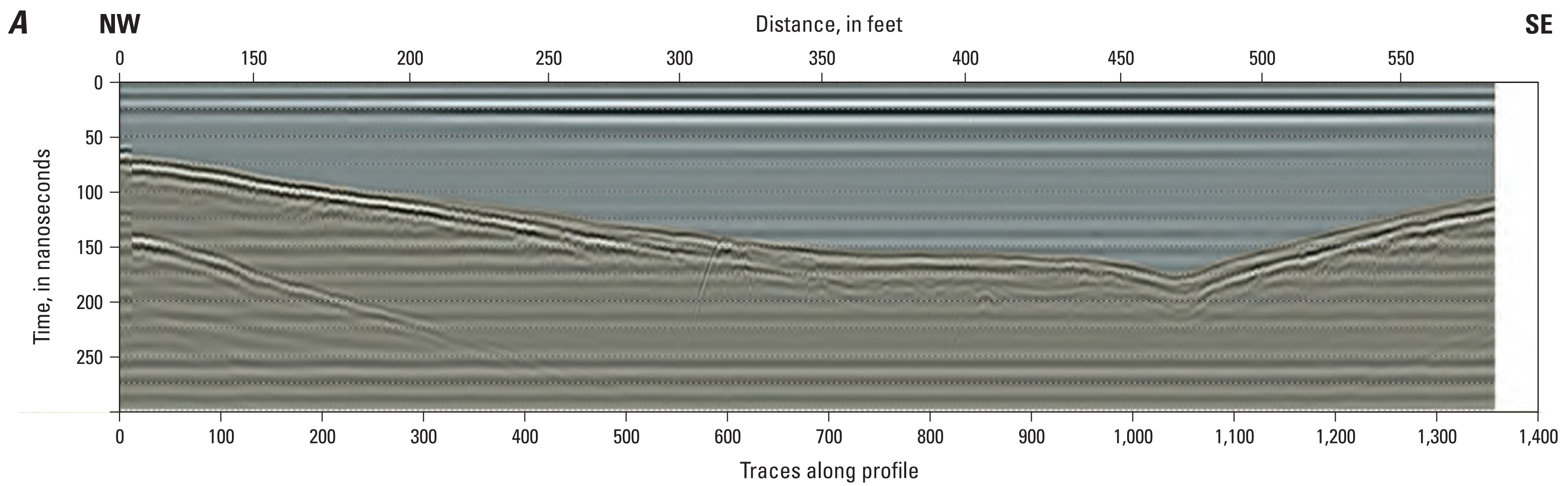


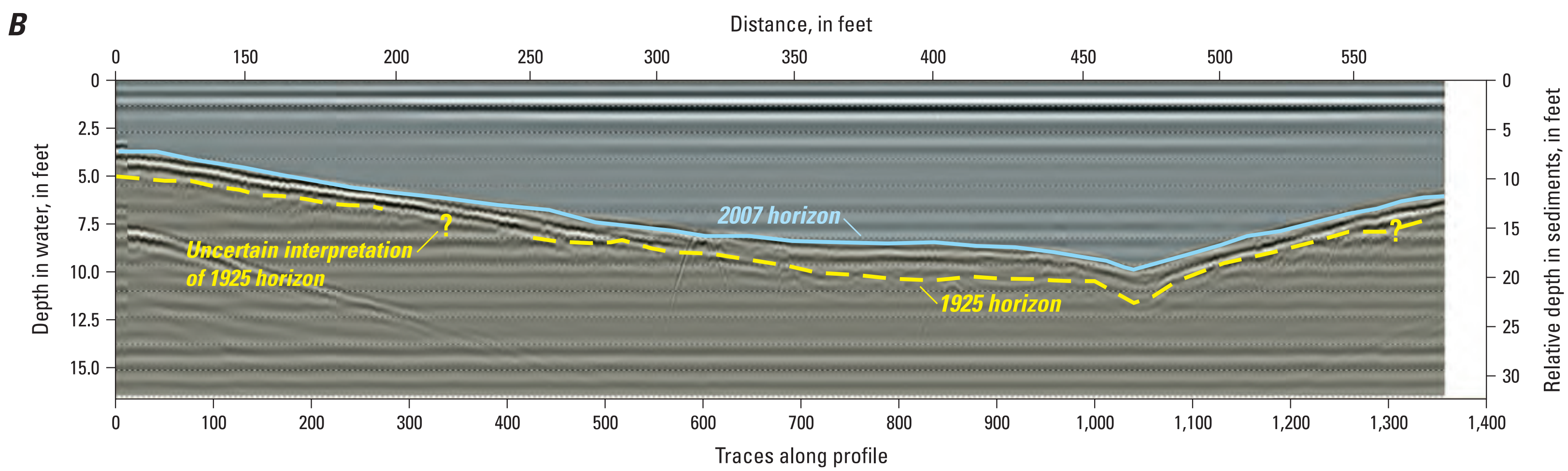
Appendix A9. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, North Glade Cove–east, cross section 6, Deep Creek Lake, Garrett County, Maryland, 2007.



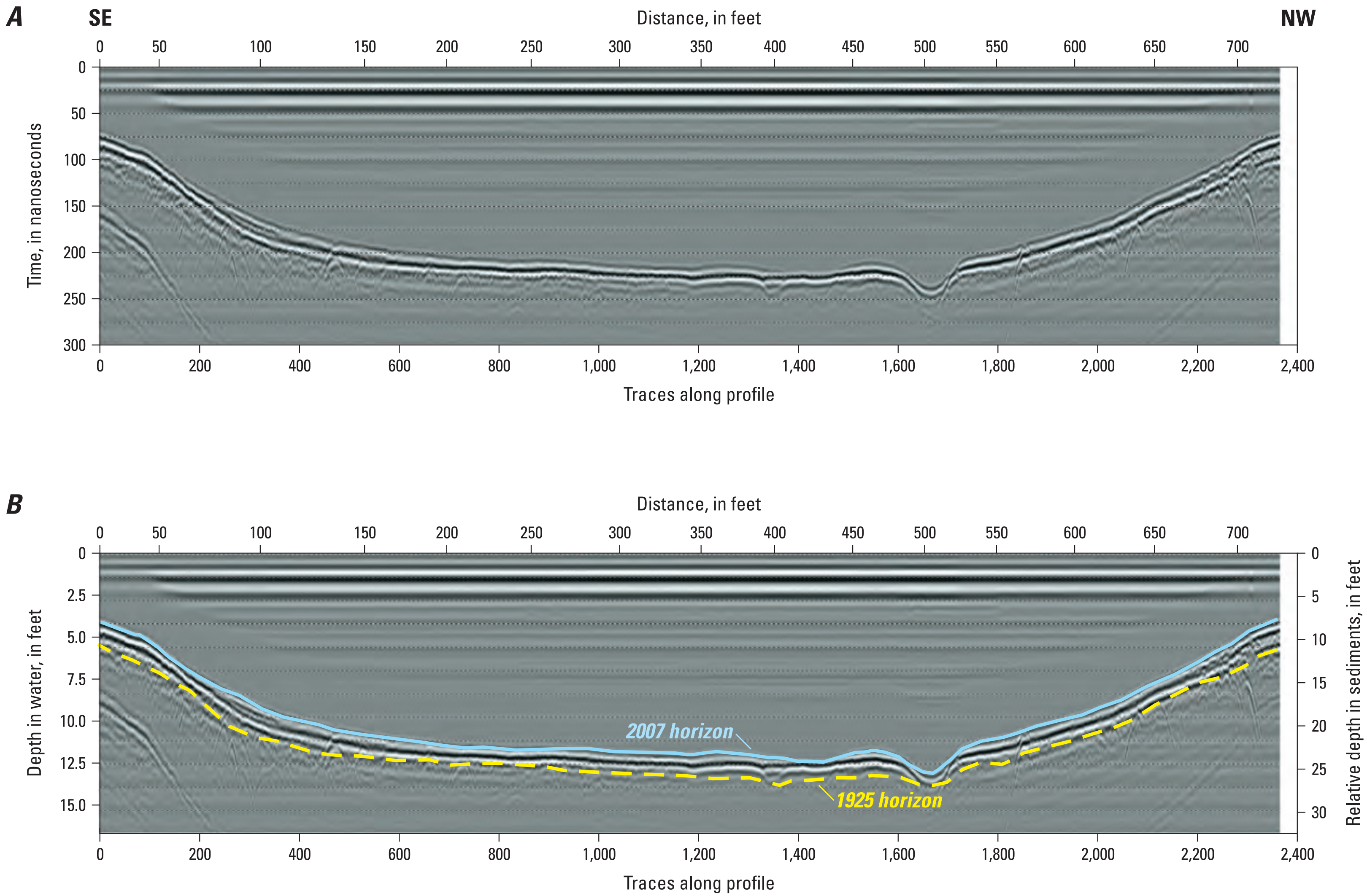


Appendix A10. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Green Glade Cove, cross section 4, Deep Creek Lake, Garrett County, Maryland, 2007.

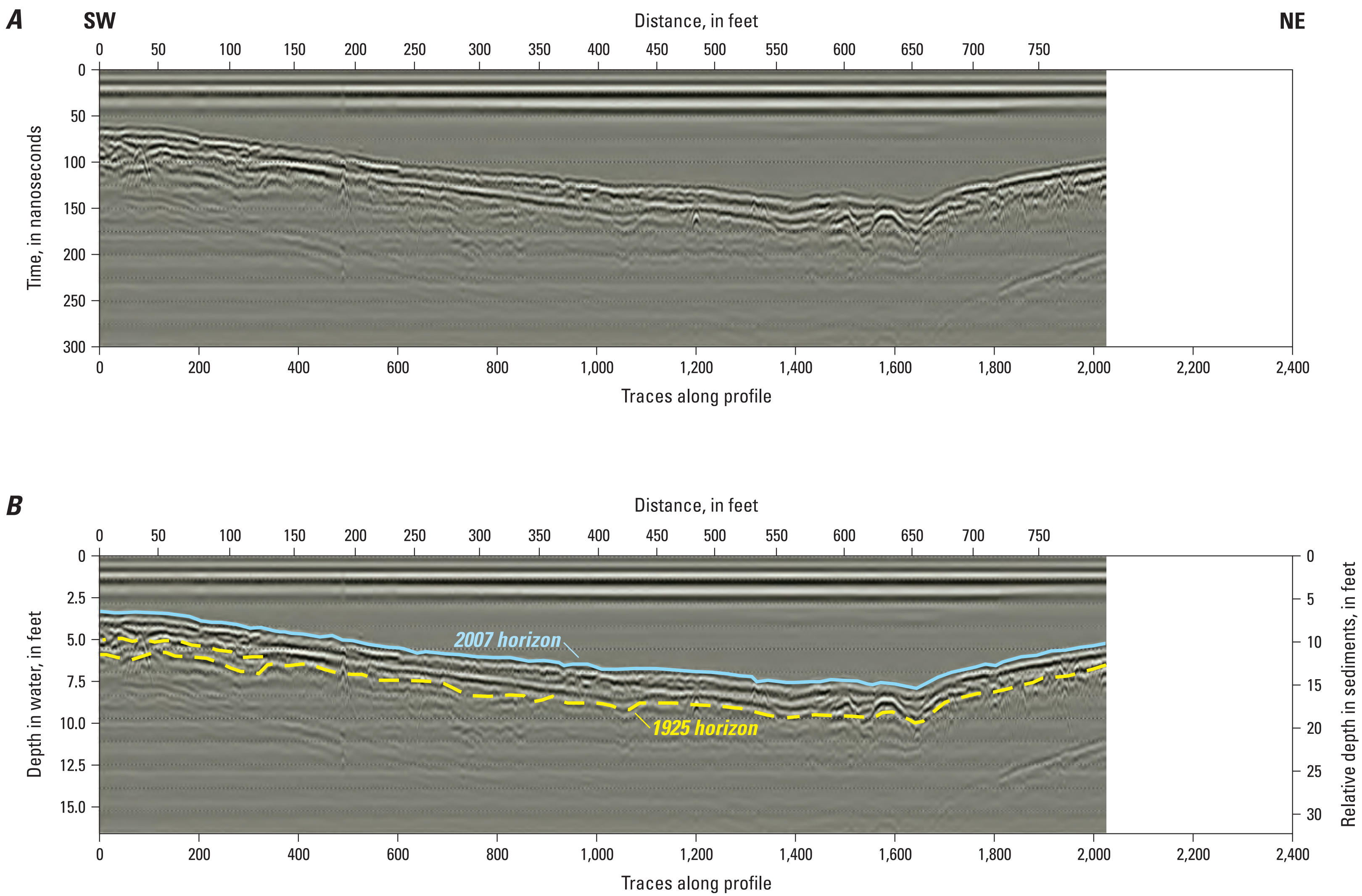




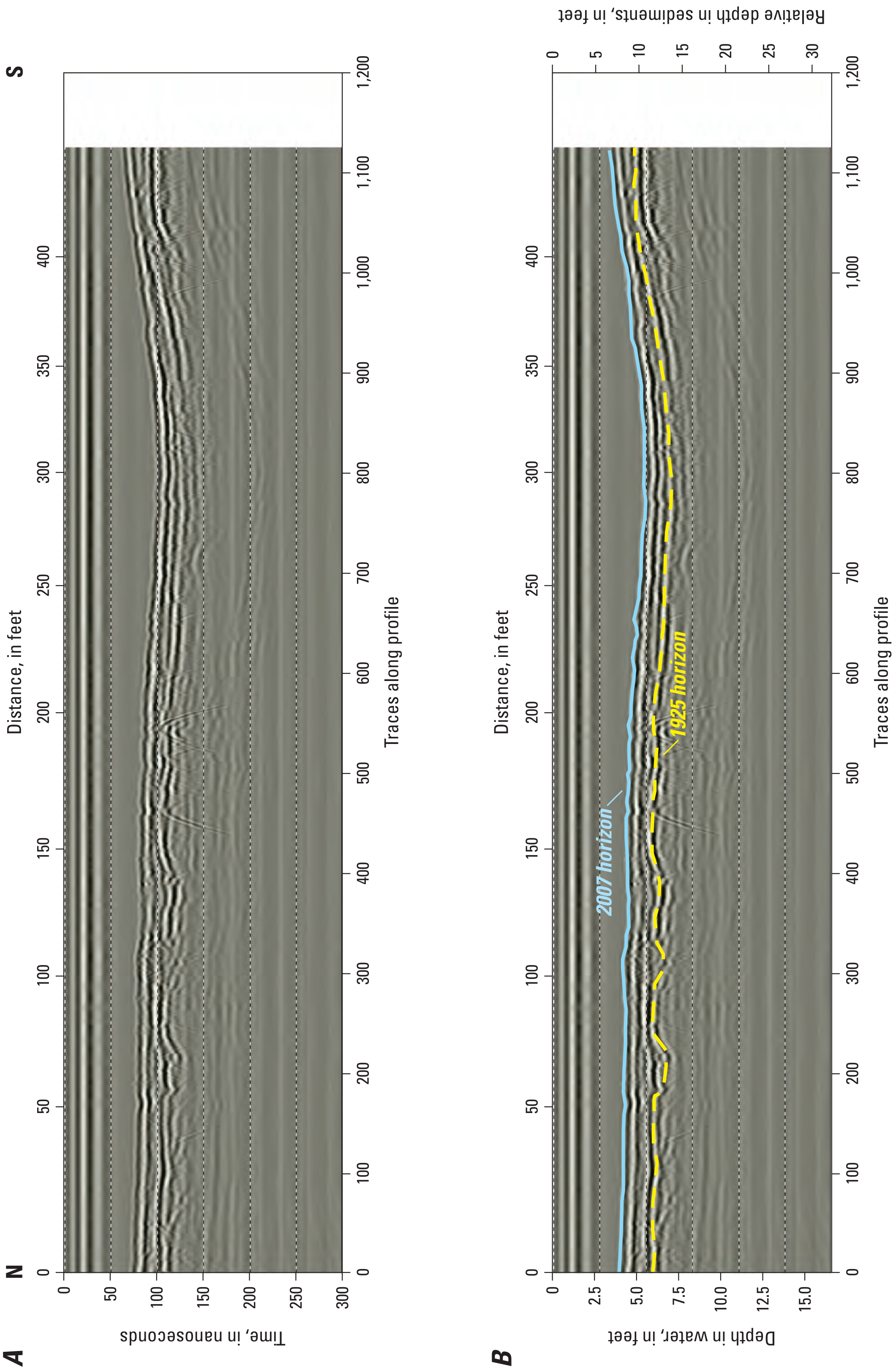
Appendix A11. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Deep Creek Cove, cross section 12, Deep Creek Lake, Garrett County, Maryland, 2007.



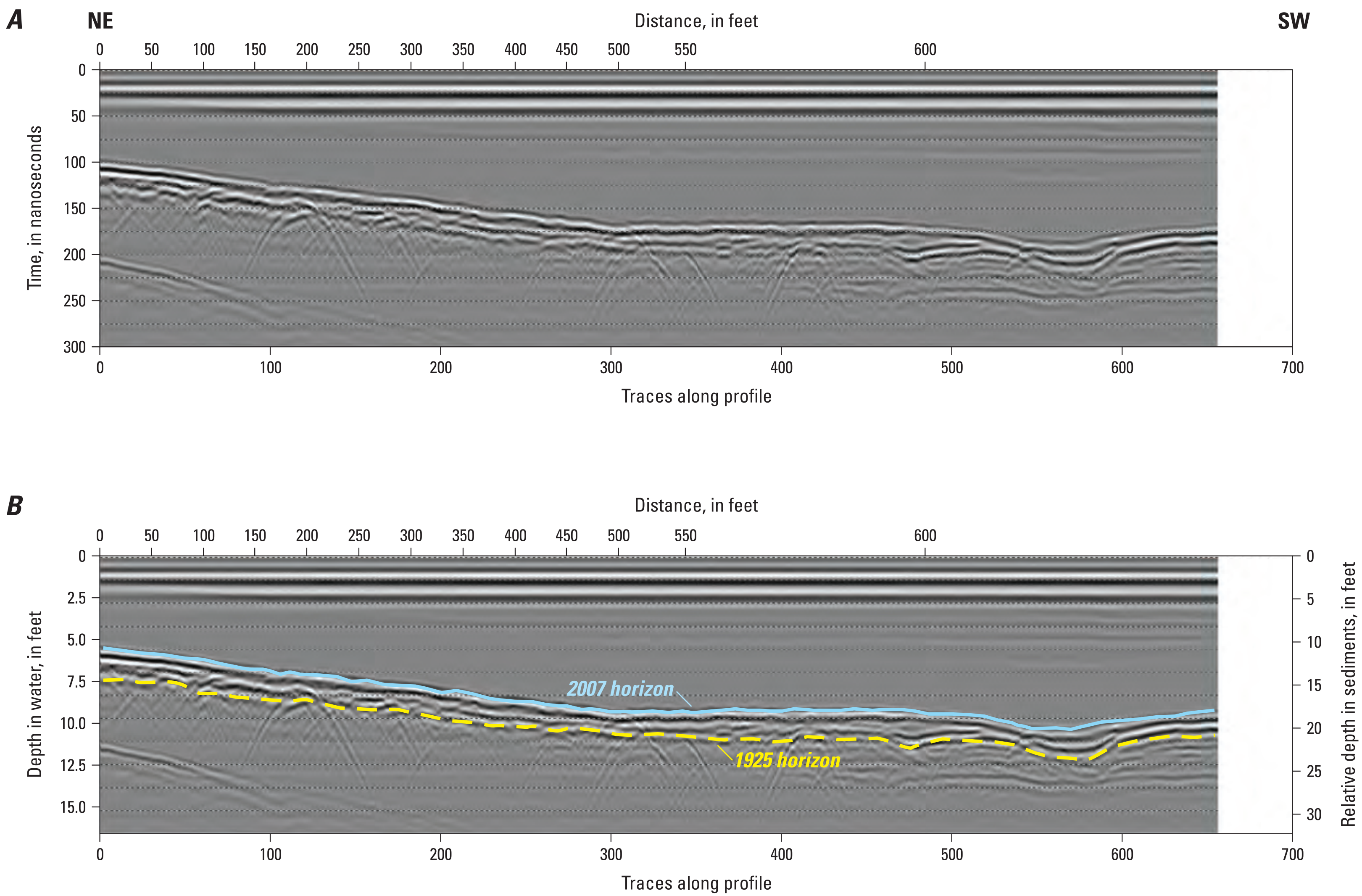
Appendix A12. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 33, Deep Creek Lake, Garrett County, Maryland, 2007.



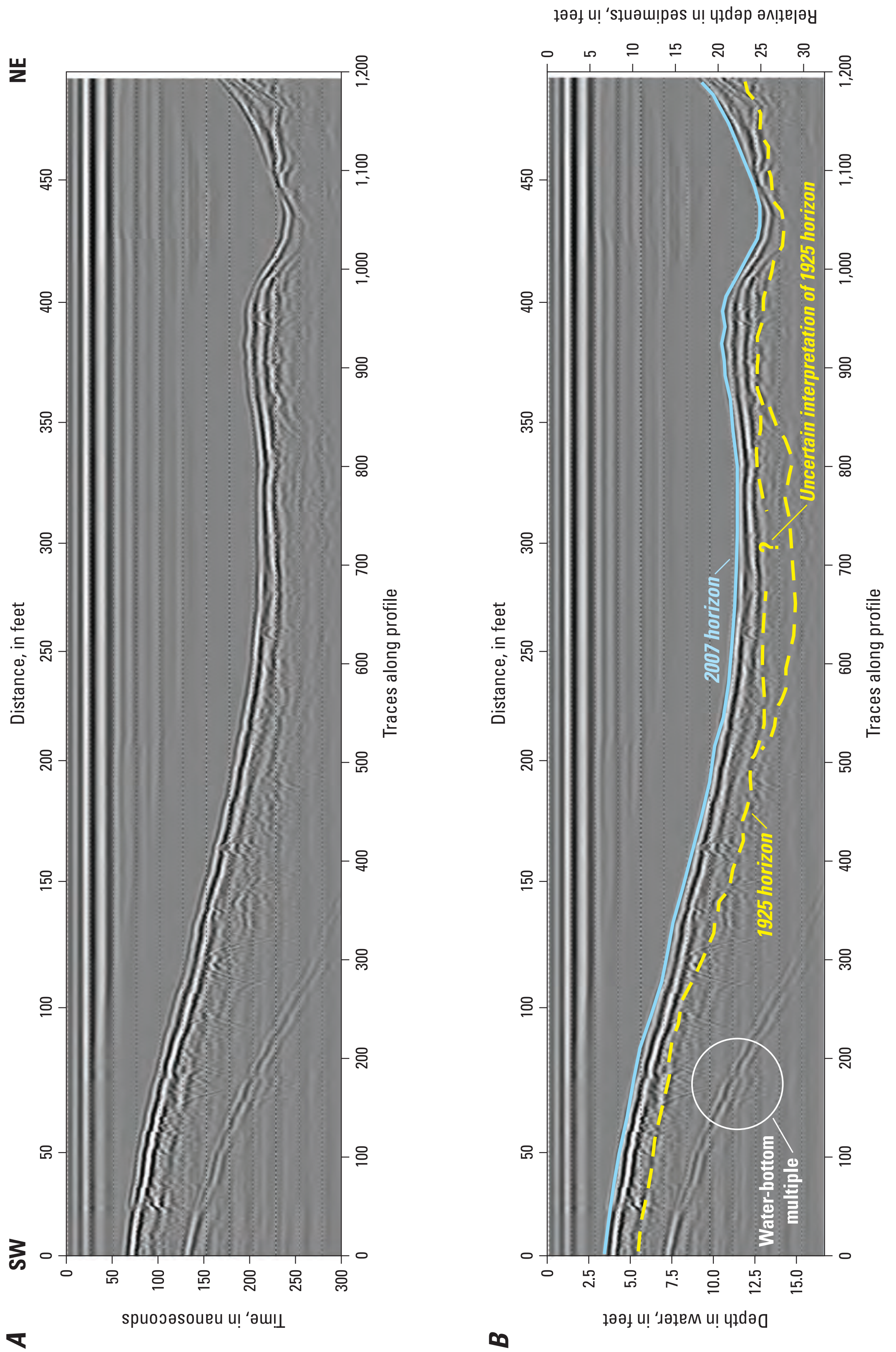
Appendix A13. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 34, Deep Creek Lake, Garrett County, Maryland, 2007.



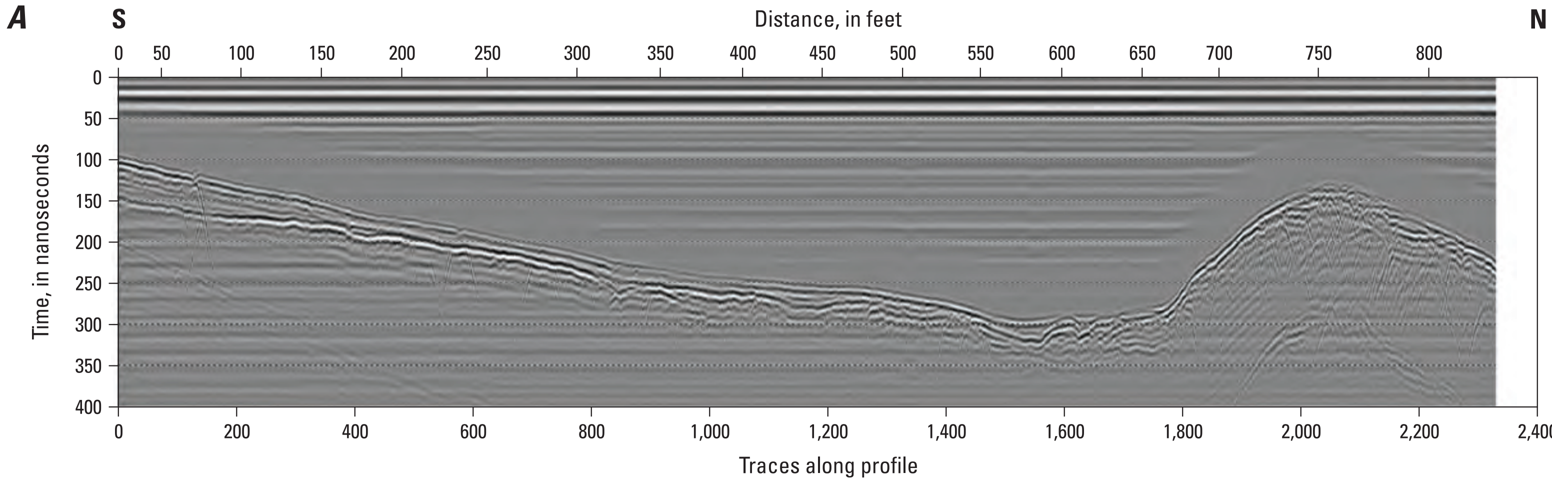
Appendix A14. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 36, Deep Creek Lake, Garrett County, Maryland, 2007.

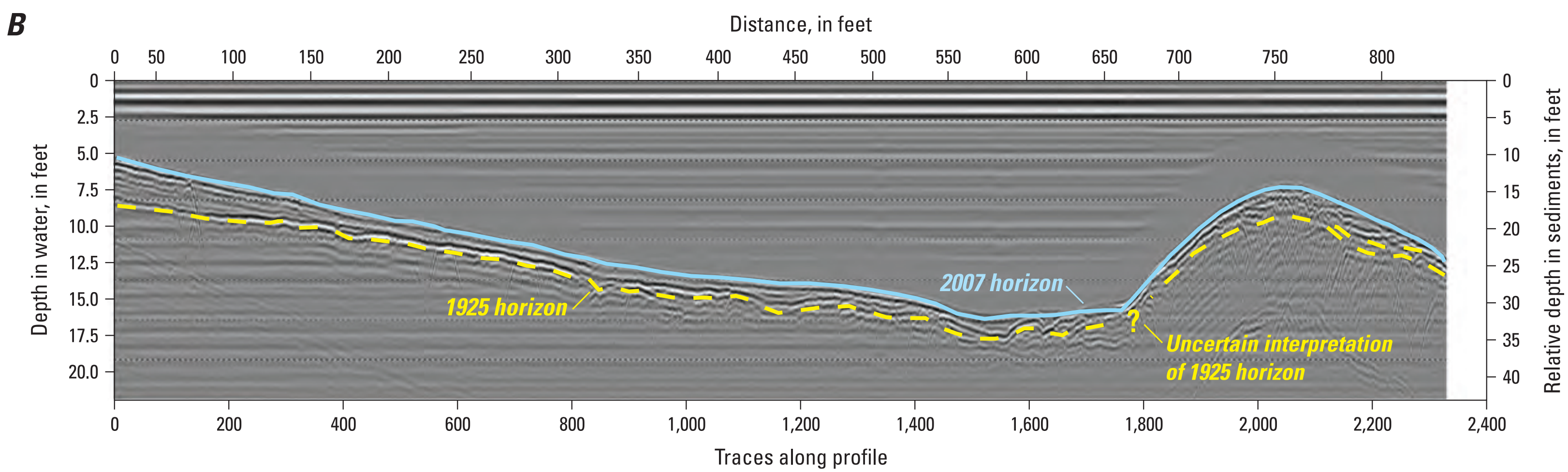


Appendix A15. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Penn Cove, cross section 39, Deep Creek Lake, Garrett County, Maryland, 2007.

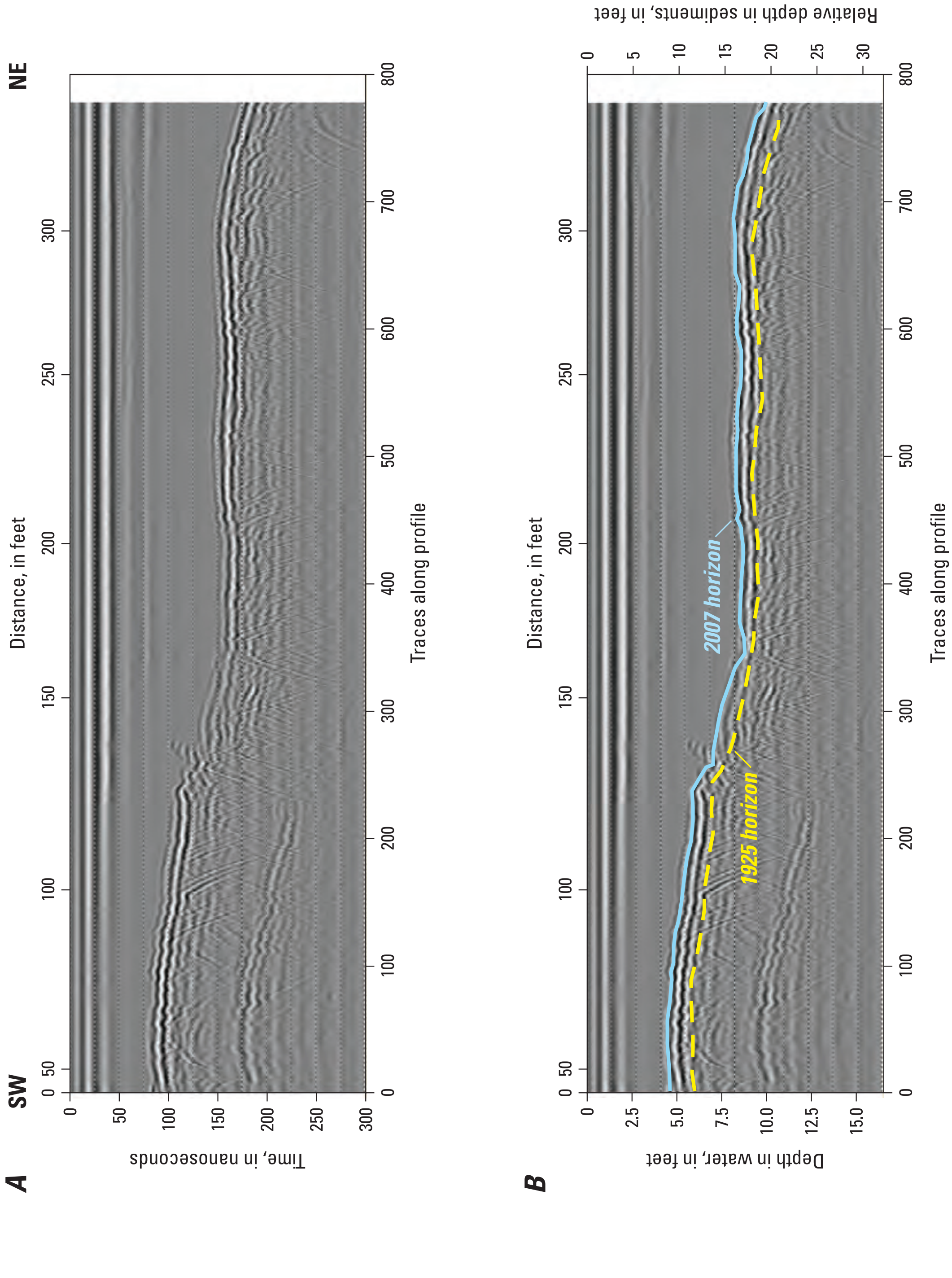


Appendix A16. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Hoop Pole Cove, cross section 8, Deep Creek Lake, Garrett County, Maryland, 2007.

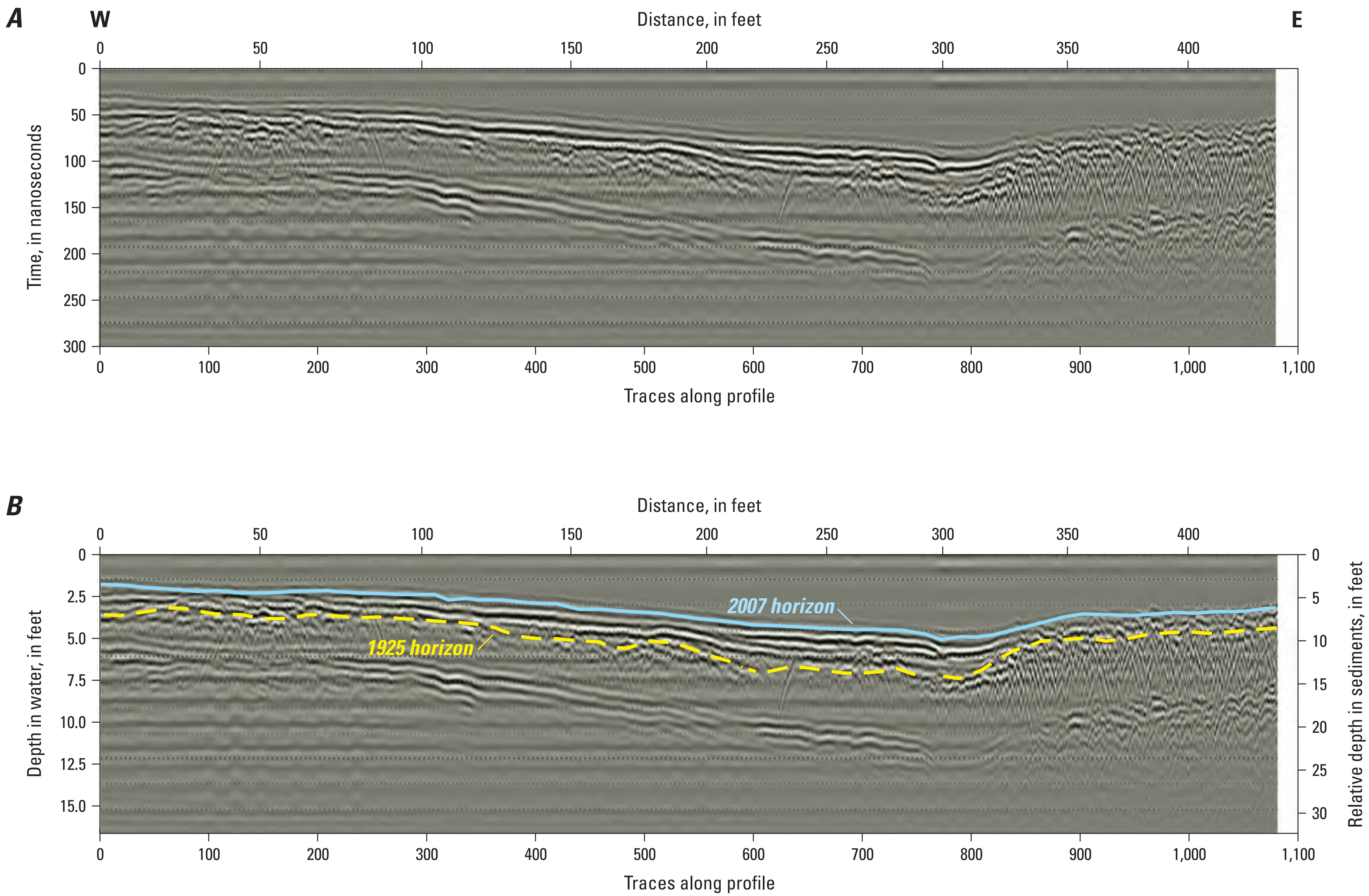




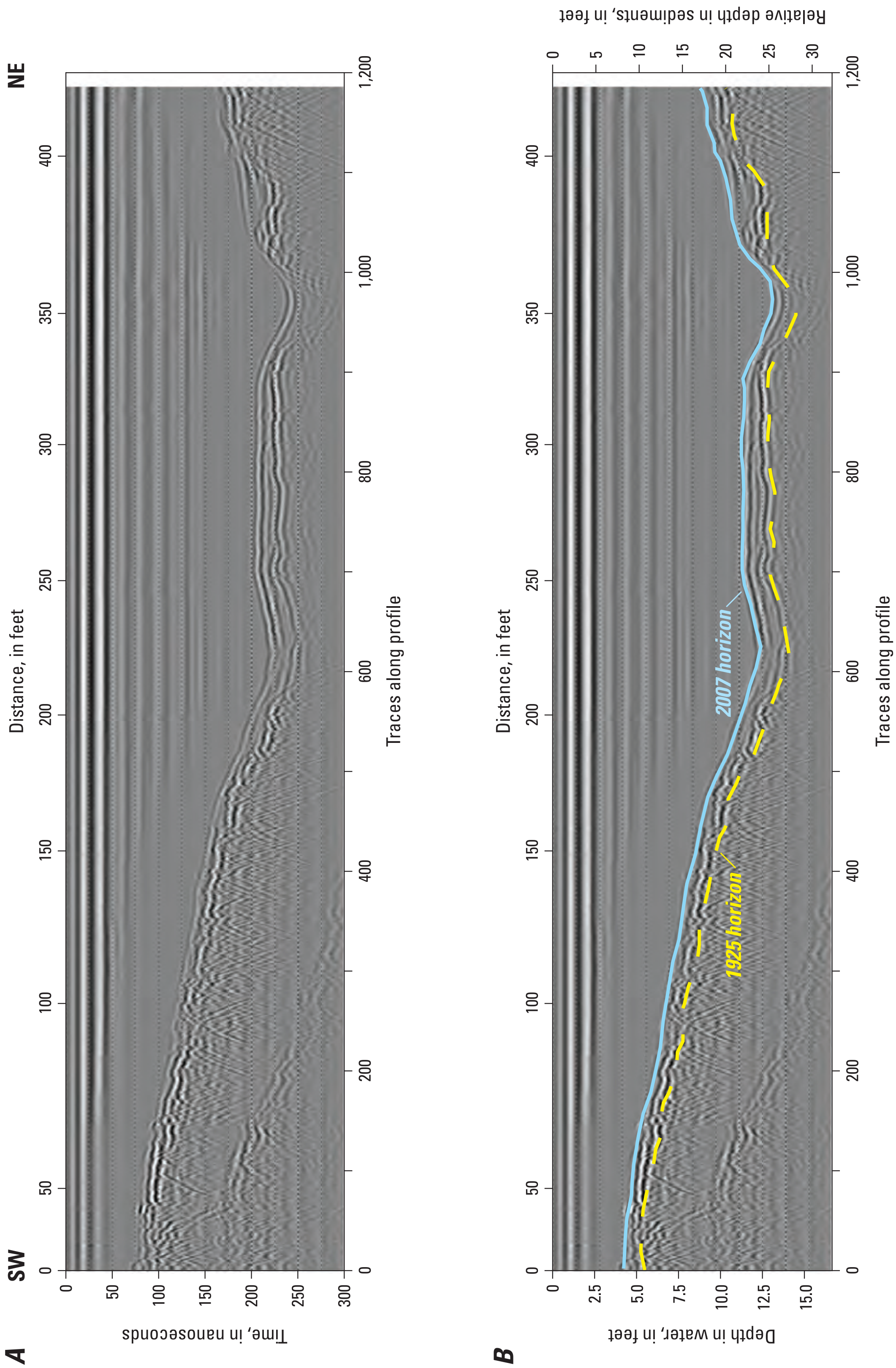
Appendix A17. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–north, cross section 1, Deep Creek Lake, Garrett County, Maryland, 2007.



Appendix A18. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–south, cross section 7, Deep Creek Lake, Garrett County, Maryland, 2007.



Appendix A19. *(A)* Ground-penetrating radar plot, and *(B)* interpretation, Arrowhead Cove–south, cross section 8, Deep Creek Lake, Garrett County, Maryland, 2007.



Prepared by USGS West Trenton Publishing Service Center.
Edited by Valerie M. Gaine.
Graphics and layout by Timothy W. Auer.

For additional information, contact:
Director, MD-DE-DC Water Science Center
U.S. Geological Survey
5522 Research Park Drive
Baltimore, MD 21228

or visit our Web site at:
http://md.water.usgs.gov

Banks, W.S.L., and Johnson, C.D.—**Collection, Processing, and Interpretation of Ground-Penetrating Radar Data in Deep Creek Lake, Garrett County, Maryland, 2007**—Scientific Investigations Report 2011–5223

Printed on recycled paper