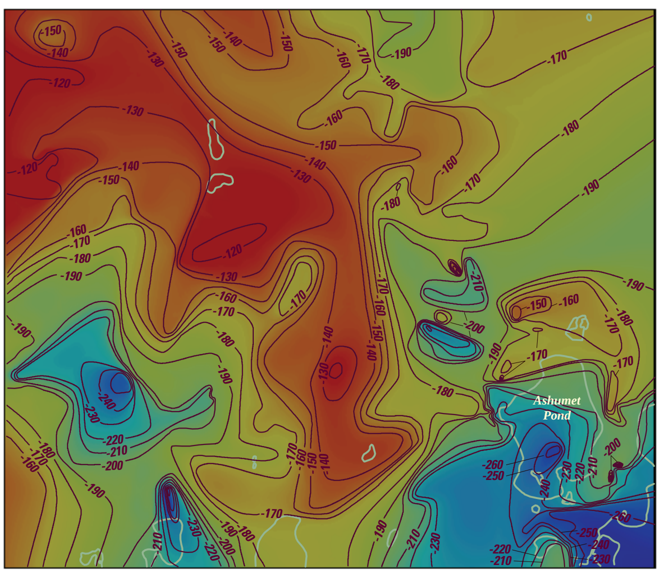
Toxic Substances Hydrology Program

Bedrock Topography of Western Cape Cod, Massachusetts, Based on Bedrock Altitudes from Geologic Borings and Analysis of Ambient Seismic Noise by the Horizontal-to-Vertical Spectral-Ratio Method

By Gillian M. Fairchild, John W. Lane, Jr., Emily B. Voytek, and Denis R. LeBlanc



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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83).

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

List of Abbreviations

AFCEE	Air Force Center for Engineering and the Environment (April 2007–present) Air Force Center for Environmental Excellence (prior to April 2007)
ARNG	Army National Guard
GPS	global positioning system
HVSR	horizontal-to-vertical spectral ratio
MMR	Massachusetts Military Reservation
USGS	U.S. Geological Survey

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Introduction

The bedrock surface of western Cape Cod defines the lower boundary of groundwater models that are used to predict the transport of groundwater contaminants originating on the Massachusetts Military Reservation (MMR). The bedrock surface is represented by a no-flow boundary in the models, and the topography of the surface plays an important role in determining the patterns of groundwater flow. The bedrock surface has been characterized in the past by using the results of seismic refraction surveys and geologic borings drilled to bedrock (Oldale, 1969; Air Force Center for Environmental Excellence (AFCEE), 2006). The horizontal-to-vertical spectral-ratio (HVSR) method, which is a passive seismic technique that uses an analysis of the horizontal and vertical components of ambient seismic noise (microtremors), has been introduced as a method to collect data on the depth to bedrock in a manner that is noninvasive and less expensive than drilling (Lane and others, 2008). These advantages are beneficial in an area such as western Cape Cod, where the land is occupied by residential and commercial properties, and depths to bedrock commonly exceed 200 feet (ft). The Toxic Substances Hydrology Program of the U.S. Geological Survey (USGS), working cooperatively with the Army National Guard (ARNG) and the Air Force Center for Engineering and the Environment (AFCEE), used the HVSR method during 2008–10 to estimate bedrock depth in areas for which there was little information from drilling and to prepare a map of the altitude of the bedrock surface for western Cape Cod.

The purpose of this report is to present an updated topographic map of the bedrock surface beneath western Cape Cod, Massachusetts, for use in groundwater-flow models of the Sagamore lens of the Cape Cod aquifer. The bedrock surface was first mapped by Oldale in 1969, and the map was updated in 2006 by using bedrock altitudes estimated during the drilling by AFCEE and ARNG to identify the boundaries and sources of the contaminant plumes originating on the MMR (AFCEE, 2006). The borings are concentrated on the MMR and in the immediately surrounding area. This report updates the bedrock-surface map with new data points collected by using the HVSR method as well as data from additional borings drilled to bedrock since the 2006 map was prepared.

The area of the map presented in this report is on western Cape Cod (fig. 1) and includes the towns of Bourne (as far west as the Cape Cod Canal), Mashpee, Falmouth, and Sandwich, and the western portion of the town of Barnstable. The MMR covers the northwestern part of this area (fig. 1). The study area overlies unconsolidated glacial drift deposits that consist of medium-to-coarse-grained glaciofluvial sand and gravel outwash overlying fine-to-medium-grained glaciolacustrine sand and silt, with sandy moraines near the northern and western coasts. These deposits form the Sagamore lens of the Cape Cod aquifer, which underlies the entire area (Walter and Whealan, 2005). The underlying bedrock is primarily granodiorite (Oldale and Barlow, 1986; Oldale, 1992). The surficial topography of the study area is characterized by gently sloping areas on the outwash plains and hummocky terrain on the moraines.

The aquifer, which consists of the unconsolidated glacial sediments, is an unconfined system that is surrounded by saltwater. The water table in the unconfined glacial sediments reaches a maximum altitude of approximately 70 ft at the eastern boundary of the MMR (Walter and Whealan, 2005). Several contaminant plumes originate on the MMR from historical defense-related activities (Massachusetts National Guard, 2012). The direction of movement of each contaminant plume depends on the position of the source of the contamination on the groundwater mound. Groundwater modeling has been used extensively to assist in predicting the fate and transport of the various contaminants originating on the MMR (AFCEE, 2006; Masterson and others, 1996; Walter and Masterson, 2003; Walter and LeBlanc, 2008).

Figure 1. Location of study area near the Massachusetts Military Reservation, western Cape Cod, Massachusetts.

Study Design and Data Collection

This effort included the compilation of geologic boring and seismic refraction survey data and the collection and analysis of the HVSR data for areas with little or no bedrock information. The HVSR method was applied at a total of 164 sites on and near the MMR.

Boring Logs and Seismic Refraction Surveys

Geologic borings were drilled on and near the MMR in an effort to characterize the contaminant plumes originating on the MMR and obtain data on the hydrogeologic framework of the aquifer. The locations of 559 borings reported to have hit bedrock in the area are shown in figure 1–1 (appendix). These sites are concentrated near the contaminant plumes caused by chemical spills, fuel spills, leachate from landfills, and firing ranges used for artillery and small-arms practice (Massachusetts National Guard, 2012). The lithologic log and driller's report for each of these locations were checked, and an estimated altitude of the bedrock surface was calculated from the reported depth to bedrock and land-surface altitude. A set of 463 additional borings that were drilled to at least 200 feet below land surface but reportedly did not hit bedrock was also compiled (figure 1–1 in appendix). The boring logs were obtained from the environmental databases maintained by AFCEE and ARNG.

Three seismic refraction surveys were done in Falmouth in 1958 (Oldale and Tuttle, 1964). These inline refraction traverses were made with a 12-channel portable refraction amplifier and oscillograph. Each survey was 1,100 feet long. These surveys recorded signals that are characteristic of geologic settings where unconsolidated sedimentary deposits overlie crystalline bedrock. Additional seismic refraction surveys were conducted on western Cape Cod in 1968 (Oldale, 1969). Based on the data collected in each of these surveys, the average depth to bedrock was calculated over the length of the survey line.

Analysis of Ambient Seismic Noise by the Horizontal-to-Vertical Spectral-Ratio Method

The HVSR method is based on a relationship between the resonance frequency of ambient seismic noise as measured at land surface and the thickness of the unconsolidated sediments that overlie consolidated bedrock. A spectral analysis of the ambient seismic noise from the earth's surface is used to determine the fundamental resonance frequency for the measurement site. Ambient seismic noise is composed of microtremors caused by ocean waves, wind, rainfall, and anthropogenic activities such as traffic and industry (Ibs-von Seht and Wohlenberg, 1999). The HVSR method works best at locations where the subsurface can be approximated by a two-layer model consisting of a layer of generally homogeneous, unconsolidated sediments overlying a consolidated bedrock layer. The HVSR method is effective in areas where there is a strong contrast in acoustic impedance between the sediment and bedrock (Lane and others, 2008; more detailed descriptions in Nakamura (1989) and Geopsy (2011)). Cape Cod's geologic structure, with unconsolidated glacial sediments on top of granitic bedrock, produces a very distinct contrast in acoustic impedance at the sediment-bedrock interface; this structure makes Cape Cod an ideal setting in which to apply the HVSR method.

At each measurement site, a single, broadband, three-component seismometer was used to record ambient seismic noise from the earth's surface. The seismometer was placed directly on the ground or on a metal plate with spikes (fig. 2A). The spikes on the bottom of seismometer or the metal plate were firmly driven into the ground to ensure that the seismometer was coupled well with the earth. A bullseye spirit level and north arrow built into the instrument and an external compass were used to level the instrument and align it with magnetic north. The seismometer was then connected to a laptop computer, a global positioning system (used for timing only), and a battery. The seismometer was covered with a weighted 5-gallon bucket to reduce interference from wind and weather (fig. 2B). Data collection was initiated by using the program Scream! (Guralp Systems, 2011) on the laptop computer. Data were collected for no less than 30 minutes at each location. To minimize noise, the equipment was set up approximately 30 feet from traffic when possible and where pedestrians, including those collecting the data, were not walking in the immediate area around the equipment; these disturbances would have created excessive noise that later would have had to be removed from the record.

The raw seismic data were processed by using the program Geopsy version 2.7.0 (Geopsy, 2011). An example from site 00MW0584 of the graphical representation, produced by the Geopsy program, of the raw seismic data is shown in figure 3. The horizontal scale represents time, and the vertical scale represents the amplitudes of the data collected for seismic components in three perpendicular directions: vertical (Z), north-south (N), and east-west (E). The raw data were divided into time intervals 60 seconds long that overlap adjacent intervals by 30 seconds each. The small spikes in amplitude above the generally smooth traces were caused by high-amplitude noise disturbances such as the nearby passage of individual vehicles or pedestrians as data were being recorded. Data from these time intervals, which are not colored in figure 3, were removed prior to further data processing.

The fundamental resonance frequency at each site was determined by a spectral analysis of the horizontal and vertical components of the recorded ambient seismic noise. The amplitudes of the spectra of the vertical and two horizontal components of the microtremors for each of the 60-second time intervals were calculated by the Geopsy program. The average of the amplitudes of the horizontal components was divided by the vertical component, and this ratio (the

Figure 2. Closeup photographs showing *A,* a single broadband, three-component seismometer, and *B,* the seismometer and data-collection system as typically deployed in the field.

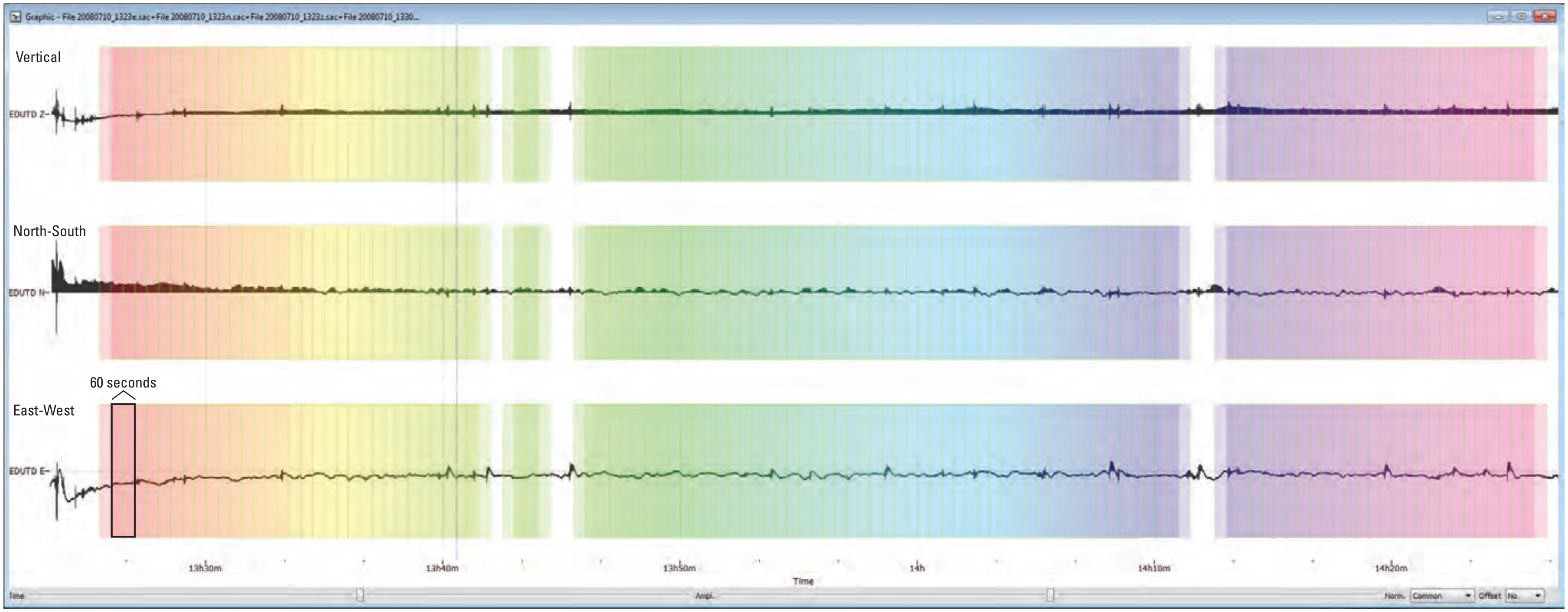


Figure 3. Example from site 00MW0584 of the graphical representation of the raw seismic data. Site location shown in figure 5.

HVSR) was plotted as a function of frequency. The graphical output from the Geopsy software is shown in figure 4 for the example from site 00MW0584. Each colored line is the result of this analysis of the data from the 60-second time interval delineated by the similarly colored vertical band in figure 3. For this study, the processing parameters, which are defined and explained in detail in Geopsy (2011), included Konno and Ohmachi (1998) smoothing with a constant bandwidth of 40, a cosine taper width of 5 percent, and a squared average for the horizontal components. An average HVSR spectral plot and spectral plots representing upper and lower limits of one standard deviation were calculated from the plots for the individual time intervals (fig. 4). The fundamental resonance frequency for the site is the frequency defined by the peak in the average HVSR plot. For the example from site 00MW0584, the peak is located at a frequency of 1.06 Hertz (fig. 4). The Geopsy program automatically selects the peak in the processed data and determines the average resonance frequency and its standard deviation (fig. 4). The user also can manually select the peak if the peak selected by the program is unsatisfactory.

The depth to bedrock (or thickness of the unconsolidated sediments composing the top layer of the two-layer model) can be estimated from the fundamental resonance frequency by using the following relationship:

$$Z = af_{r0}^{\,b}, \qquad (1)$$

where

Z is the sediment thickness in ft,

f_{r0} is the fundamental resonance frequency in Hertz (s^{-1}), and a (in ft•s) and b (dimensionless) are determined empirically from a nonlinear regression of data acquired at sites where Z is known from adjacent boreholes (Lane and others, 2008).

The constants a and b for this study (a = 297 ft•s and b = -1) were developed by Lane and others (U.S. Geological Survey, written commun., 2011) from a regression analysis of known bedrock depths from borings versus depths obtained by the HVSR method at 8 sites in this study area and 29 additional sites on the glacial deposits of eastern Cape Cod and southeastern mainland Massachusetts. The 8 sites from this study area that were used to develop the empirical equation are highlighted in bold in tables 1–1 and 1–2 (appendix). The estimated depth to bedrock for the example from site 00MW0584 is 279 ft. The altitude of the bedrock surface was obtained by subtracting the estimated depth to bedrock from the land-surface altitude. At site 00MW0584, where the land-surface altitude is 50 ft above NGVD 29, the resulting bedrock-surface altitude is 229 ft below NGVD 29.

A total of 164 sites were chosen for application of the HVSR method from areas for which little bedrock information from geologic borings and the seismic refraction surveys had been collected. These areas generally are near the coast in Bourne, Sandwich, Falmouth, Mashpee, and along the eastern edge of the map area in Barnstable. Sites with known land-surface altitudes were selected to allow the calculation of bedrock altitude from the estimated depth to bedrock. The HVSR data were collected during 2008–10 by several different seismometers. The measurements were repeated eight times at the Ashumet Pond public boat launch (site 164 on fig. 1–1, appendix) and 15 times adjacent to building 1146 (site 163 on fig. 1–1, appendix) on the MMR. Analysis of these repeated measurements was used to confirm that the instruments were collecting spatially and temporally consistent, comparable data.

Description of Data Sets

Several datasets were used to prepare the updated topographic map of the bedrock surface in this report. Data from sites where the bedrock surface was hit during drilling are given in table 1–1 (appendix). Seismic refraction data are documented in the reports by Oldale and Tuttle (1964) and Oldale (1969). Data from the HVSR method are given in table 1–2 (appendix). Finally, data on the maximum possible bedrock altitude at 463 sites where geologic borings were drilled to at least 200 ft below land surface but reportedly did not hit bedrock are given in table 1–3 (appendix). The locations of the borings and HVSR measurement sites are shown in figure 1–1 (appendix).

Bedrock Topography of Western Cape Cod, Massachusetts

A topographic map of the bedrock surface beneath western Cape Cod was prepared by using data from the geologic borings, seismic refraction surveys, and HVSR measurements. The map was prepared by manually contouring the bedrock altitudes estimated from the data-collection methods.

Interpretation of Bedrock-Surface Topography

The bedrock-surface altitudes from the HVSR survey, seismic refraction surveys, and geologic borings that reportedly hit bedrock were plotted on a map of western Cape Cod and hand-contoured with a 25-ft contour interval (fig. 5). This interval is within the range of estimated uncertainty of about 10 percent of the depth to bedrock (20–30 ft) in the bedrock-surface altitudes estimated for much of the area from the HVSR method. Bedrock-surface altitudes in two smaller areas near Snake Pond (fig. 6) and Ashumet Pond (fig. 7) with closely spaced data points were contoured with a 10-ft contour interval. The bedrock-surface altitudes in these two areas were measured mostly from borings; the altitudes from the borings were estimated to have a range of uncertainty of about 5 ft.

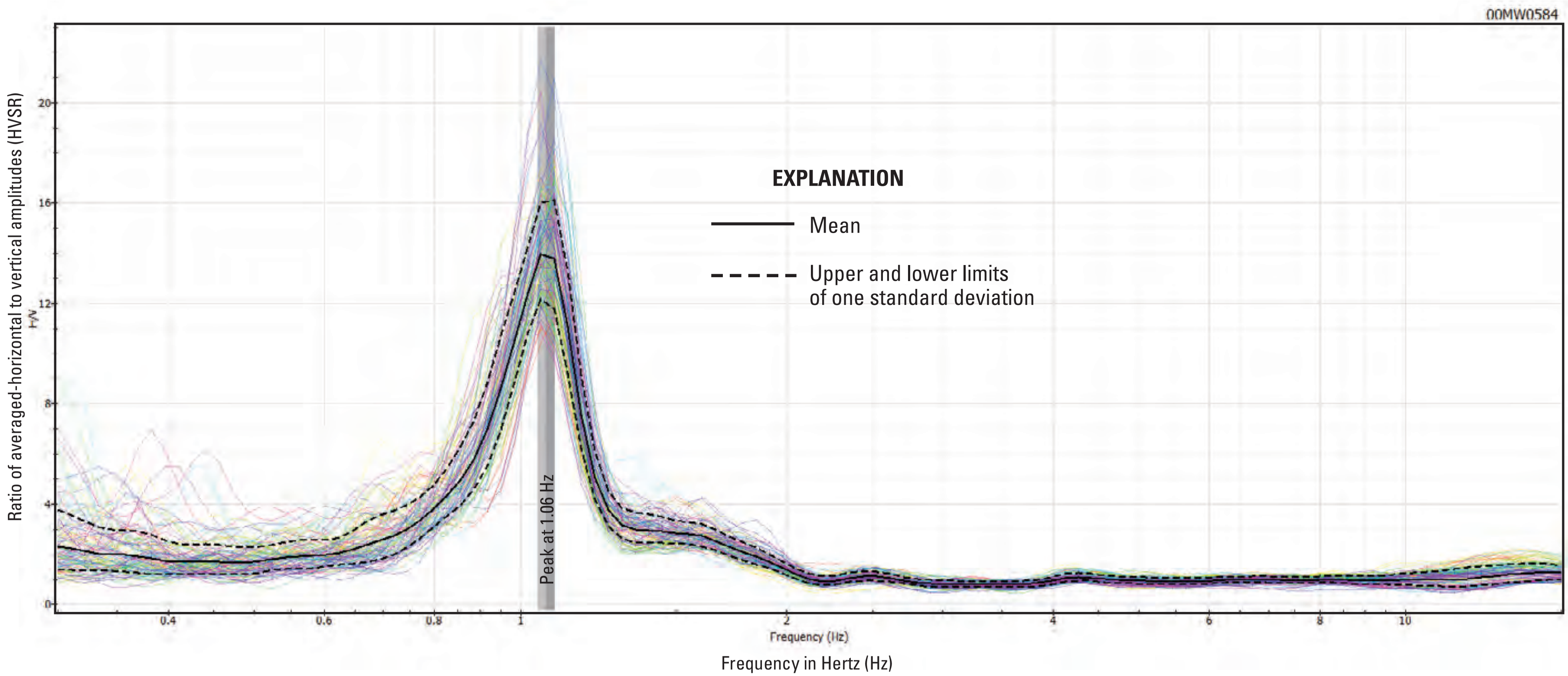
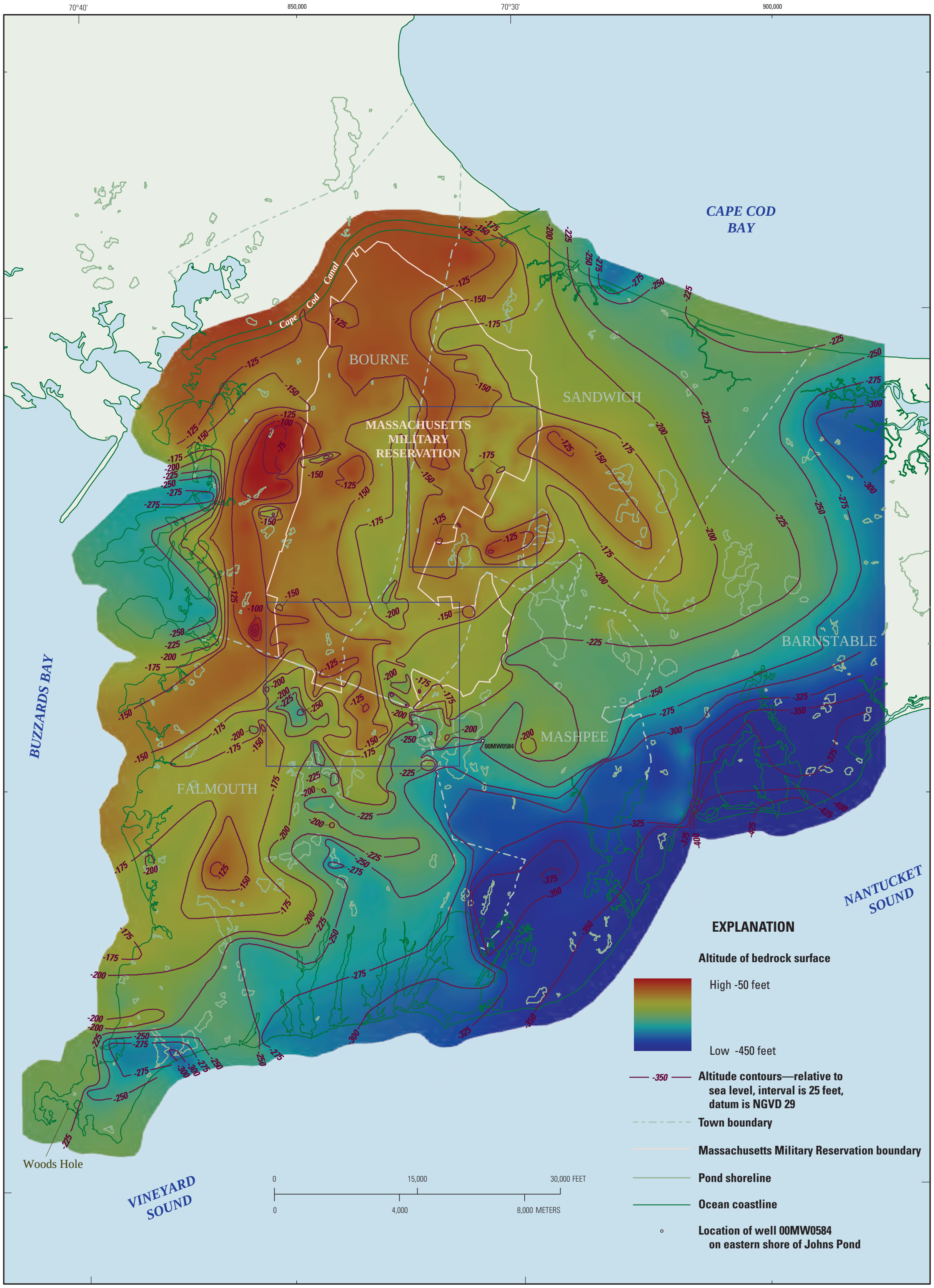


Figure 4. Example of the Geopsy output graph of the fundamental resonance frequency determined by the spectral plot of the ratio of the averaged-horizontal to vertical components of the ambient seismic noise at site 00MW0584. Site location shown in figure 5.



Base from USGS and MassGIS sources, North American Datum of 1927 (NAD 27)
Altitudes relative to the National Geodetic Vertical Datum of 1929 (NGVD 29)

Figure 5. Topographic map of the bedrock surface beneath western Cape Cod as interpreted from horizontal-to-vertical spectral-ratio measurements, seismic refraction surveys, and geologic borings, western Cape Cod, Massachusetts. Location of map shown in figure 1.

The contours were initially drawn by adhering strictly to the estimated altitudes, but were then adjusted slightly where appropriate within the range of uncertainty described above to smooth the surface near anomalous features based on single data points. Finally, the contours were checked for consistency with the maximum possible altitudes at the deep borings that did not hit bedrock; the contours required only minimal adjustments during this final check.

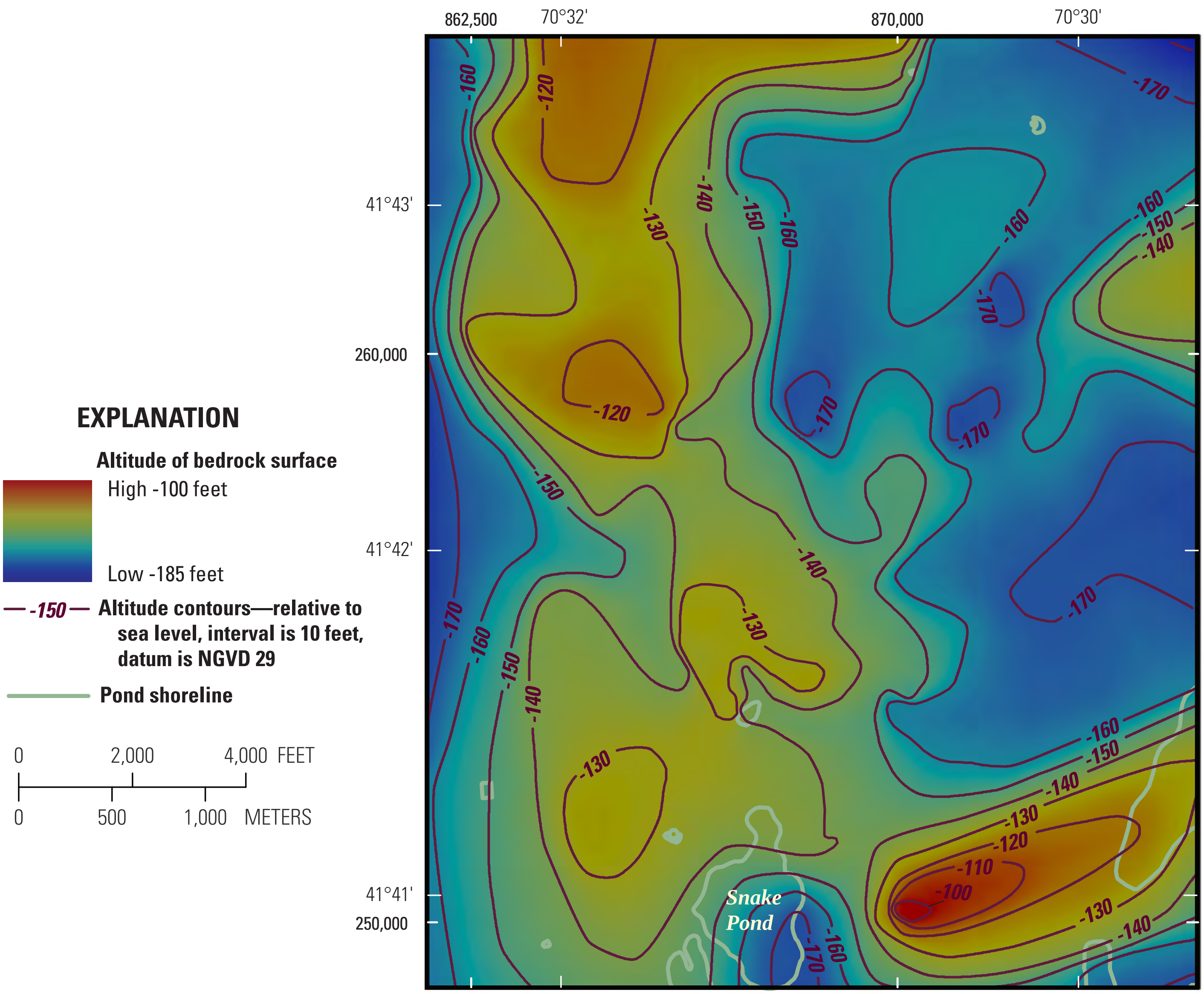


Figure 6. Topographic map of the bedrock surface beneath the area near Snake Pond as interpreted mostly from geologic borings, western Cape Cod, Massachusetts. Location of map shown in figure 5.

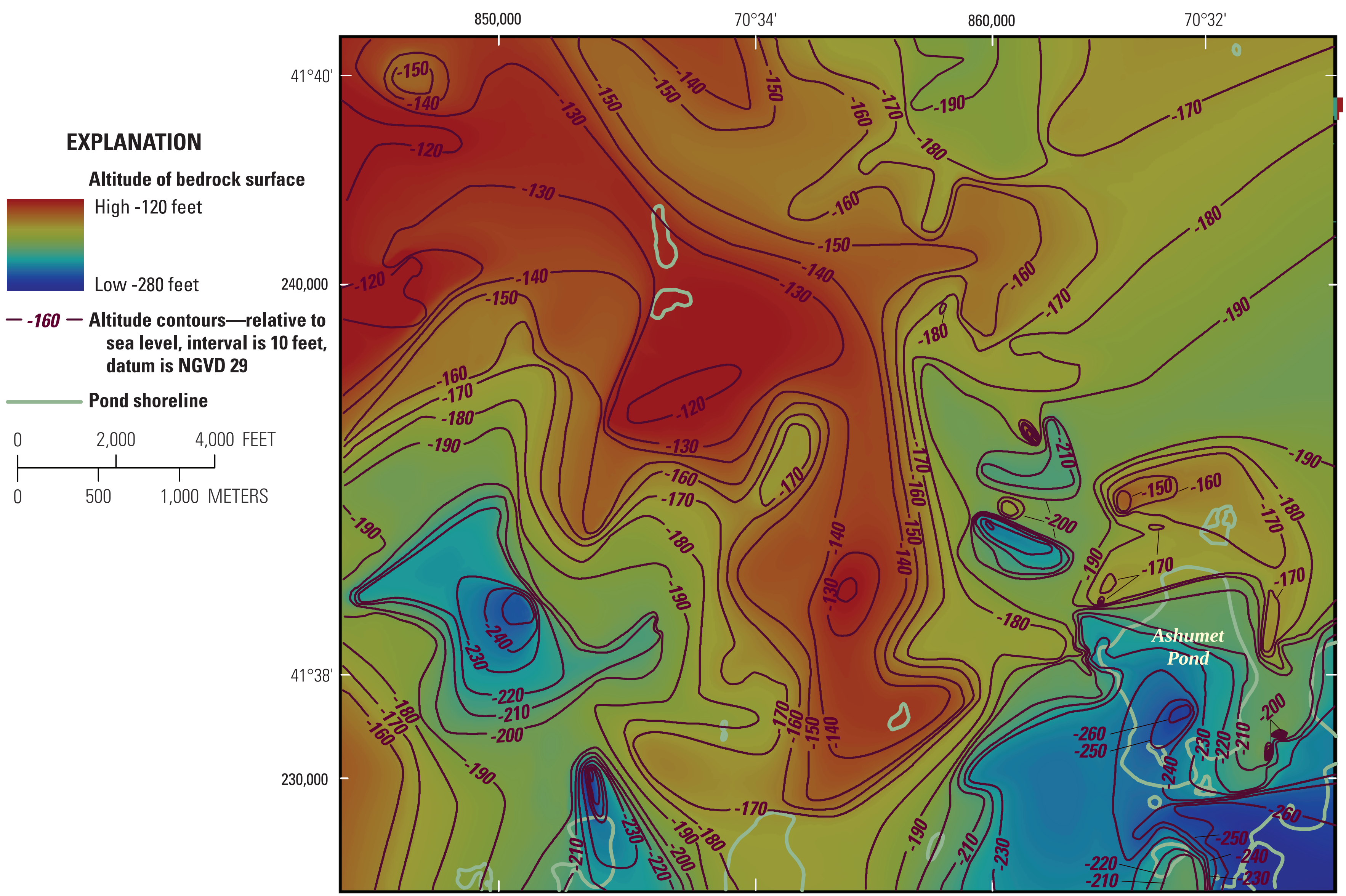


Figure 7. Topographic map of the bedrock surface beneath the area near Ashumet Pond as interpreted mostly from geologic borings, western Cape Cod, Massachusetts. Location of map shown in figure 5.

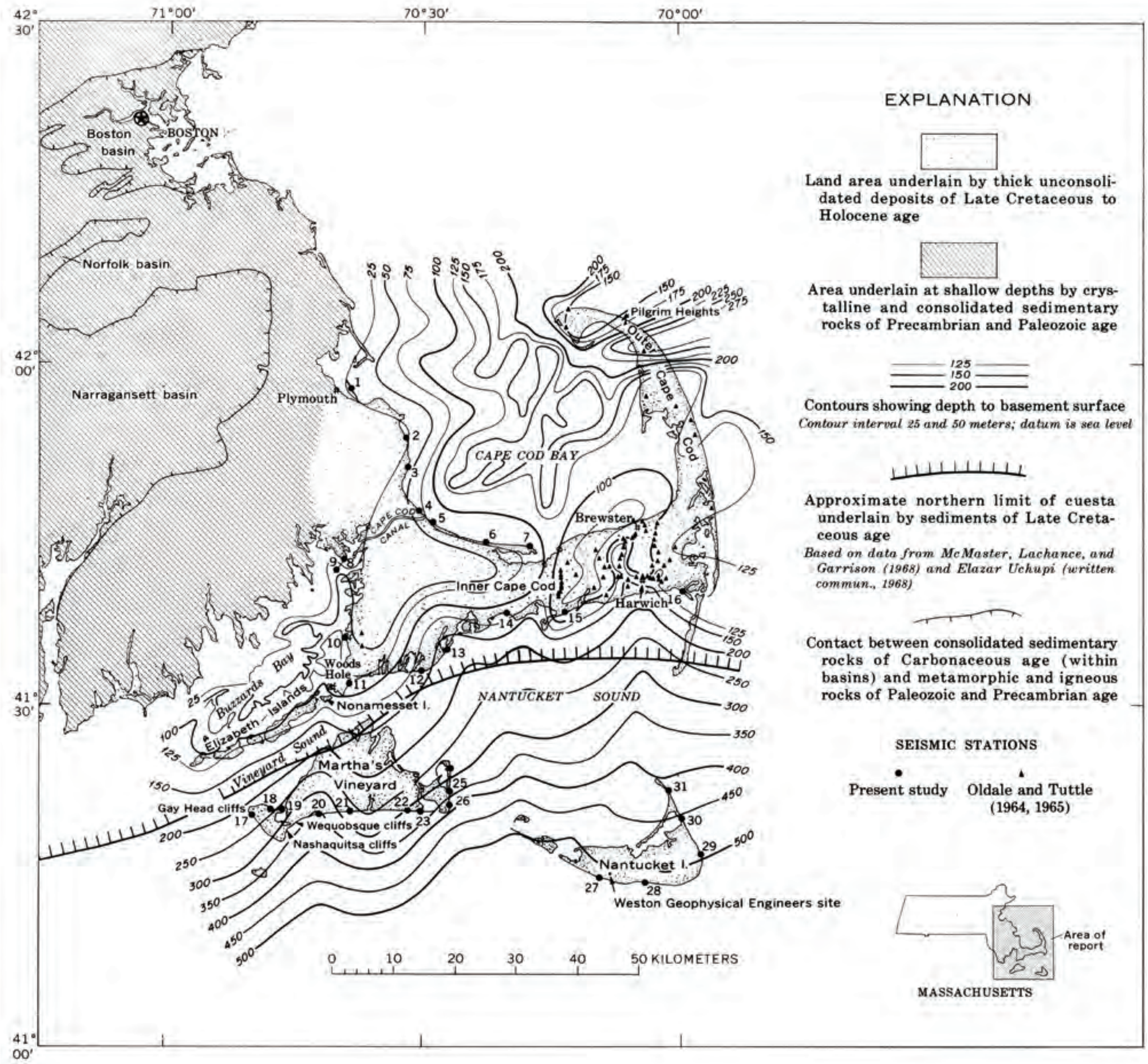


Figure 8. Topographic map of the bedrock surface beneath Cape Cod, Martha's Vineyard, and Nantucket, Massachusetts (from Oldale, 1969).

Comparison to Earlier Maps of the Bedrock Topography

The interpreted representation of the bedrock surface in figure 5 is similar in its general features to Oldale's 1969 map (fig. 8) and AFCEE's 2006 map. In all three maps, the bedrock surface generally slopes downward to the southeast from the Cape Cod Canal toward Nantucket Sound. The maps similarly show lobes of shallower bedrock extending to the east toward Barnstable and to the south toward Woods Hole. The bedrock surface is at least 47 ft below NGVD 29 (sea level) throughout the mapped area and therefore does not crop out at the land surface.

The bedrock surface presented in this report shows more topographic detail than the earlier maps owing to the increase in the quantity of data available for use in drawing the contours. The general trends in altitude shown on the small-scale map (fig. 5) may reflect preglacial drainage patterns in the bedrock surface. The large-scale maps (figs. 6 and 7), however, show a surface whose altitude varies considerably over a small area. The same variability could be characteristic of the entire study area, but more data would be needed to test this hypothesis. Small-scale variations, including closed depressions in the bedrock surface, are consistent with a glacially eroded bedrock surface (B.D. Stone, U.S. Geological Survey, oral commun., 2011).

Summary

The HVSR method was used successfully to obtain estimates of the bedrock-surface altitude for western Cape Cod, Massachusetts, in areas for which altitudes from borings drilled to bedrock or from seismic refraction surveys had not been estimated. The HVSR method was effective in determining sediment thickness on Cape Cod owing to the distinct difference in the acoustic impedance between the sediments and the underlying bedrock. The HVSR data for 164 sites were combined with data from 559 borings to bedrock to create a spatially distributed dataset for the study area that was manually contoured to prepare a topographic map of the bedrock surface. The interpreted bedrock surface generally slopes downward to the southeast as was shown on previous maps by Oldale (1969) and AFCEE (2006). The surface also has complex small-scale topography, as was also shown in the AFCEE (2006) map. The updated map reflects the data available through October 2012 from borings to bedrock and better spatial resolution from the HVSR data in areas outside the MMR for which less information on the bedrock altitudes had been collected.

References Cited

Air Force Center for Environmental Excellence (AFCEE), 2006, Massachusetts Military Reservation Plume Response Program, final Chemical Spill-23 wellfield design report: Jacobs Engineering Group, Inc., A4P–J23–35BC06VB–M23–0003, variously paged.

Geopsy, 2011, Geopsy Project: Geopsy, accessed February 24, 2011, at http://www.geopsy.org/.

Guralp Systems, 2011, Scream! Software for Windows and Linux: Guralp Systems, accessed February 24, 2011, at http://www.guralp.com/category/software.

Ibs-von Seht, Malte, and Wohlenberg, Jürgen, 1999, Microtremor measurements used to map thickness of soft sediments: Bulletin of the Seismological Society of America, v. 89, no. 1, p. 250–259.

Konno, Katsuaki, and Ohmachi, Tatsuo, 1998, Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor[s]: Bulletin of the Seismological Society of America, v. 88, no. 1, p. 228–241.

Lane, J.W., Jr., White, E.A., Steele, G.V., and Cannia, J.C., 2008, Estimation of bedrock depth using the horizontal-to-vertical (H/V) ambient-noise seismic method, *in* Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 6–10, 2008, Philadelphia, Penn., Proceedings: Denver, Colo., Environmental and Engineering Geophysical Society, 13 p.

Massachusetts National Guard, 2012, Massachusetts Military Reservation, Cape Cod, Massachusetts—Environmental overview, accessed April 30, 2012, at http://states.ng.mil/sites/MA/MMR/environ-overview.htm.

Masterson, J.P., Walter, D.A., and Savoie, Jennifer, 1996, Use of particle tracking to improve numerical model calibration and to analyze groundwater flow and contaminant migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2482, 50 p.

Nakamura, Y., 1989, A method for dynamic characteristics estimations of subsurface using microtremors on the ground surface: Quarterly Report, Railway Technical Research Institute, Japan, v. 30, p. 25–33.

Oldale, R.N., 1969, Seismic investigations on Cape Cod, Martha's Vineyard, and Nantucket, Massachusetts, and a topographic map of the basement surface from Cape Cod Bay to the Islands, *in* Geological Survey Research 1969, Chapter B, Scientific notes and summaries of investigations in geology, hydrology, and related fields: U.S. Geological Survey Professional Paper 650–B, p. B122–B127.

Oldale, R.N., and Barlow, R.A., 1986, Geologic map of Cape Cod and the Islands, Massachusetts: U.S. Geological Survey Miscellaneous Investigations Series Map I–1763, 1 sheet, scale 1:100,000.

Oldale, R.N., and Tuttle, C.R., 1964, Seismic investigations on Cape Cod, Massachusetts, article 145 *in* Geological Survey Research 1963, Short papers in geology and hydrology, Articles 122–172: U.S. Geological Survey Professional Paper 475–D, p. D118–D122.

Oldale, R.N., 1992, Cape Cod and the Islands—The geologic story: Orleans, Mass., Parnassus Imprints, 208 p.

Walter, D.A., and LeBlanc, D.R., 2008, Use of inverse-modeling methods to improve groundwater-model calibration and evaluate model-prediction uncertainty, Camp Edwards, Cape Cod, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2007–5257, 49 p.

Walter, D.A., and Masterson, J.P., 2003, Simulation of advective flow under steady-state and transient recharge conditions, Camp Edwards, Massachusetts Military Reservation, Cape Cod, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 03–4053, 51 p.

Walter, D.A., and Whealan, A.T., 2005, Simulated water sources and effects of pumping on surface and ground water, Sagamore and Monomoy flow lenses, Cape Cod, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004–5181, 85 p.

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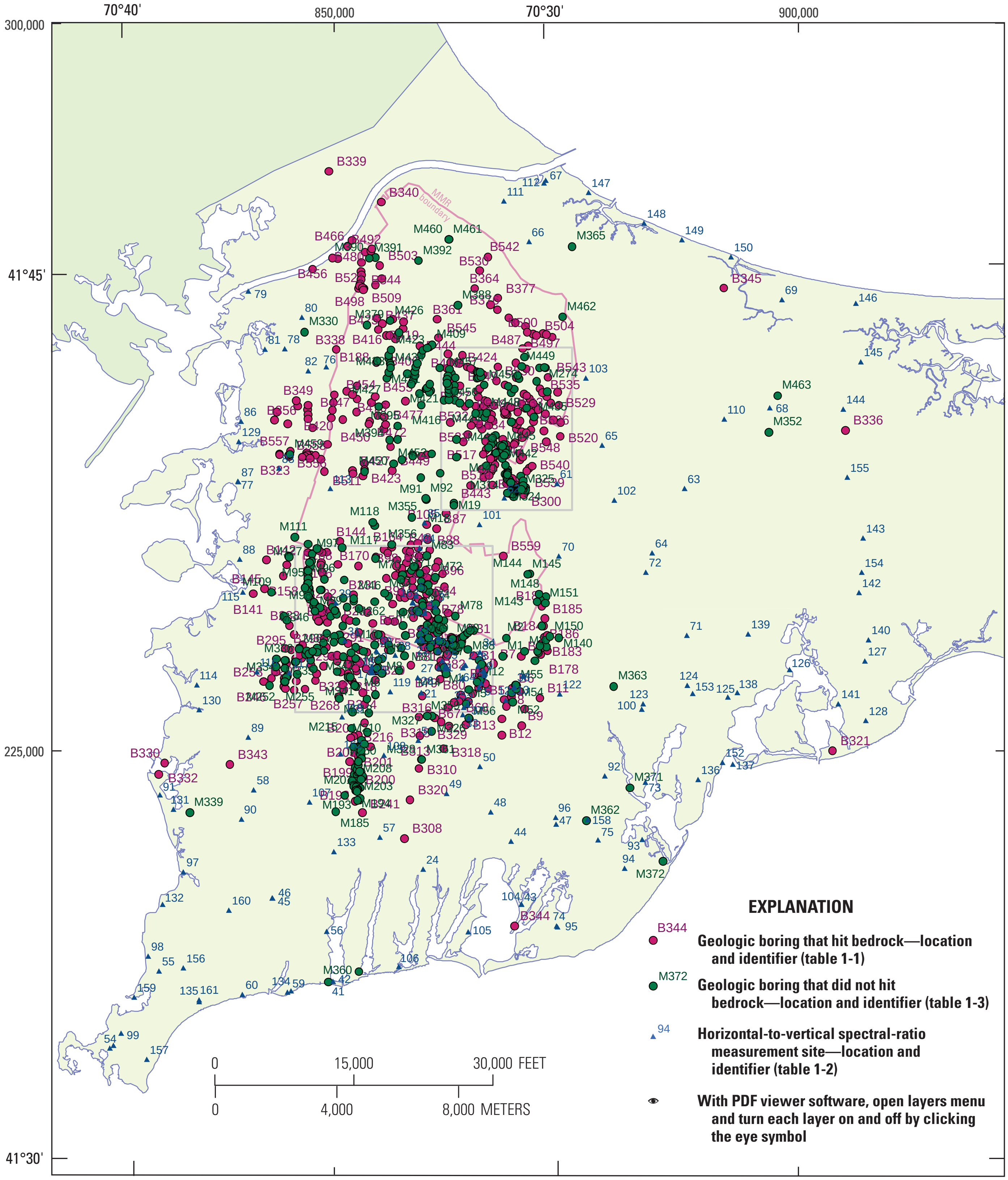
Appendix



Base from USGS and MassGIS sources, North American Datum of 1927 (NAD 27)
Northings and eastings in state plane meters, sites plotted as of October 2012

This map, as layered PDF, manufactured to allow user to turn map layers on and off

Figure 1–1. Locations of geologic borings and horizontal-to-vertical spectral-ratio measurements used to prepare the topographic map of the bedrock surface, western Cape Cod, Massachusetts. (Click here for PDF of fig. 1–1)

Table 1–1. Locations, altitudes of land and bedrock surfaces, and depths below land surface to bedrock for geologic borings where bedrock was hit during drilling, western Cape Cod, Massachusetts. (Click here)

Table 1–2. Locations, altitudes of land surface, estimated altitudes and depths below land surface of the bedrock surface, and fundamental resonance frequencies at locations of horizontal-to-vertical spectral-ratio (HVSR) measurements, western Cape Cod, Massachusetts. (Click here)

Table 1–3. Locations, altitudes of land surface, maximum altitudes of the bedrock surface, and depths below land surface for geologic borings where bedrock was not hit and drilling was extended to at least 200 feet below land surface, western Cape Cod, Massachusetts. (Click here)

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