APPLICATION OF SURFACE-GEOPHYSICAL METHODS TO INVESTIGATIONS OF SAND AND GRAVEL AQUIFERS IN THE GLACIATED NORTHEASTERN UNITED STATES

REGIONAL AQUIFER-SYSTEM ANALYSIS

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1415–A

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Application of Surface-Geophysical Methods to Investigations of Sand and Gravel Aquifers in the Glaciated Northeastern United States

By F.P. HAENI

REGIONAL AQUIFER-SYSTEM ANALYSIS—
NORTHEAST GLACIAL VALLEYS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1415-A

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

GORDON P. EATON, *Director*

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Library of Congress Cataloging in Publication Data

Haeni, F.P.
Application of surface-geophysical methods to investiations of sand and gravel aquifers in the glaciated northeastern United States / F.P. Haeni.
p. cm. — (Regional aquifer system analysis—northeast glacial valleys) (U.S. Geological Survey professional paper ; 1415–A)
Includes bibliographical references.
Supt. of Docs. no.: I19.16:1415–A
1. Aquifers—northeastern States. 2. Prospecting—Geophysical methods. I. Title. II. Series. III. Series: U.S. Geological Survey professional paper ; 1415–A.
GB1199.3.N77H34 1995
551.49′0974—dc20
93–13284
CIP

For sale by U.S. Geological Survey
Information Services, Box 25286
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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Gordon P. Eaton
Director

TABLES

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
millisiemens per meter (mS/m)	0.305	millisiemens per foot (mS/ft)
ohm-meter (ohm-m)	3.281	ohm-foot (ohm-ft)
kilometer per second (km/s)	3,281	foot per second (ft/s)

Abbreviated water-quality units used in the report: μS/cm at 25°C=microsiemens per centimeter at 25 degrees Celsius

For temperature conversions between degrees Celsius (°C) and degrees Fahrenheit (°F), the following formula may be used:

$$°F=(1.8\times °C)+32$$

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

APPLICATION OF SURFACE-GEOPHYSICAL METHODS TO INVESTIGATIONS OF SAND AND GRAVEL AQUIFERS IN THE GLACIATED NORTHEASTERN UNITED STATES

By F.P. Haeni

ABSTRACT

Reconnaissance hydrogeologic mapping and ground-water-flow modeling in the glaciated Northeastern United States require data on the hydrogeologic boundaries and grain-size characteristics of sand and gravel aquifers. The combined use of surface-geophysical methods such as seismic-refraction, direct-current-resistivity, very-low-frequency terrain-resistivity, and inductive terrain-conductivity can provide these data.

Forward-modeling studies of 10 hypothetical aquifer systems indicated that very-low-frequency terrain-resistivity and inductive terrain-conductivity methods can be used to detect horizontal and vertical changes in the electrical properties of typical sand and gravel aquifers.

Surface-geophysical surveys at eight sites in Connecticut, New York, and Maine, have shown that the combined use of four geophysical methods can define the hydrogeologic boundaries and can distinguish between fine-grained and coarse-grained stratified drift. The seismic-refraction method could be used to determine depths to the water table and to bedrock at all the field sites where it was used, but could not be used to detect lithologic changes within the aquifer. Direct-current-resistivity methods could be used to detect large-scale resistivity changes that were related to either specific conductance of ground water or major lithologic changes in the aquifers. In some hydrogeologic settings, this method could be used to identify the water table and bedrock surface. Very-low-frequency terrain-resistivity and inductive terrain-conductivity methods used in conjunction with the other surface-geophysical methods can be used to identify anomalies caused by small-scale changes in aquifer lithology or specific conductance of ground water.

Comparisons of the interpreted electrical resistivity of the aquifer with the logs of test holes and wells indicate that for a given specific conductance of ground water, the bulk electrical resistivity of the stratified drift increases with increasing grain size. This relation is useful for distinguishing fine-grained drift deposits from coarse sand and gravel deposits.

INTRODUCTION

Sand and gravel aquifers are the principal sources of ground water in the glaciated Northeastern United States. The use of surface-geophysical methods to investigate sand and gravel aquifers was evaluated as part of the U.S. Geological Survey's Northeast Glacial Valleys Regional Aquifer-System Analysis (RASA). The background and objectives of the Northeast Glacial Valleys RASA are described by Lyford (1986) and the overall objectives of the RASA program are described in the Foreword.

This report is one of several chapters in U.S. Geological Survey Professional Paper 1415 that describe various aspects of the geology, hydrology, and geochemistry of the glacial aquifers in the Northeastern United States.

Delineation of hydrogeologic boundaries and grain-size characteristics of sand and gravel aquifers is required for reconnaissance hydrogeologic mapping and ground-water flow modeling studies. Test drilling is generally used to obtain such data but commonly at only a few sites. Surface-geophysical methods can be used to rapidly obtain areal hydrogeologic data on sand and gravel aquifers. The geophysical data, although not as detailed as drill-hole data, provide broader areal coverage and therefore are well suited for most hydrogeologic studies.

All surface-geophysical methods measure some physical property of subsurface materials, or the fluids within them, from the surface of the Earth. Typical physical properties measured are electrical resistivity or conductivity, velocity of sound, and the strength of gravity and magnetic fields. Knowledge of the physical properties of the subsurface unit of interest and the properties of the surrounding units is critical for the successful application of surface-geophysical methods. Selection of the appropriate geophysical method is determined by the specific physical properties of a hydrogeologic unit or the differences in these properties between adjoining hydrogeologic units.

PURPOSE AND SCOPE

This report presents the results of a study conducted to show how a combination of seismic-refraction, direct-current-resistivity (dc-resistivity), very-low-frequency (VLF) terrain-resistivity, and inductive terrain-conductivity methods can be used to map hydrogeologic boundaries and to determine general lithologic characteristics of sand and gravel aquifers in the Northeastern United States.

The first part of this study used forward-modeling computer programs to calculate the response of VLF terrain-resistivity and inductive terrain-conductivity methods to several hypothetical aquifer settings. The results were then used to determine whether these electromagnetic methods could detect horizontal and vertical resistivity variations typical of glacial aquifers. In this modeling process, it was assumed that (1) the depths to the water table and bedrock were known from drill-hole or seismic-refraction data, (2) the gross subsurface-layer resistivities were known from dc-resistivity data, and (3) the conductivity of the ground water was constant. Variations in the resistivities of the aquifer should represent variations in the grain size of the aquifer material.

The second part of this study was an application of the surface-geophysical methods at eight field sites, representing typical sand and gravel aquifers in the glaciated Northeastern United States. It demonstrated that (1) the combined use of seismic-refraction, dc-resistivity, and electromagnetic methods could be used to detect hydrogeologic boundaries and determine the resistivity variations within the aquifer material, and (2) the resistivity variations represented differences in the grain size of the aquifer material.

PREVIOUS STUDIES

A combination of surface-geophysical methods can be used advantageously in hydrogeologic investigations. Many papers have described the use of individual and combined surface-geophysical methods in hydrogeologic studies and are important sources of information for hydrogeologists (Lennox and Carlson, 1970; Mabey, 1970; Ogilvy, 1970; Shiftan, 1970; Zohdy and others, 1974; Worthington, 1975; Collett, 1979).

The two surface-geophysical methods that have been most widely used in hydrogeologic studies are seismic-refraction and dc-resistivity methods. The references listed above all contain sections on the use of seismic-refraction method in hydrogeologic investigations. In addition, Bonini and Hickok (1958), Eaton and Watkins (1970), and Haeni (1986a, 1988) specifically discuss use of the seismic-refraction method in hydrogeologic studies. The seismic-refraction method is used primarily to determine the boundaries of aquifers in situations where seismic-velocity discontinuities between hydrogeologic units exist. This method has been used to map depth to the water table and depth to bedrock in many glacial-aquifer reconnaissance studies (Warrick and Winslow, 1960; Gill and others, 1965; Lennox and Carlson, 1967; Watkins and Spieker, 1971; Dickerman and Johnston, 1977; Sharp and others, 1977; Haeni and Anderson, 1980; Mazzaferro, 1980; Fretwell and Stewart, 1981; Grady and Handman, 1983; Tolman and others, 1983; Haeni and Melvin, 1984; Ayers, 1989; Ayotte, 1989; Moore, 1990; Melvin and Bingham, 1991) and in a few simulation studies (Birch, 1976; Haeni, 1978; Morrissey, 1983; Haeni, 1986a; Mazzaferro, 1986; Toppin, 1987; Tepper and others, 1990).

Dc-resistivity methods have been used successfully to delineate hydrogeologic boundaries that are characterized by changes in electrical properties of subsurface materials. Thick clay layers, the presence of coarse-grained beds within a fine-grained unit, and water-quality changes are examples of hydrogeologic conditions that can be detected by dc-resistivity methods.

In most hydrogeologic studies where dc-resistivity methods have been applied, high-resistivity zones are associated with coarse-grained aquifer material saturated with water, having low dissolved-solids concentrations. Low-resistivity zones have been interpreted as fine-grained materials or highly conductive water (Page, 1968; Zohdy, 1969; Flathe, 1970; Zohdy and others, 1974; Worthington, 1975; Zohdy and others, 1977; Gorhan, 1976; Rijo and others, 1977; Worthington, 1977; Martinelli, 1978; Bisdorf and Zohdy, 1979; Verma and others, 1980; South Florida Water Management District, 1982). Only a few dc-resistivity studies in glacial terrains have been reported (Kelly, 1962; Buhle and Brueckmann, 1964; Lennox and Carlson, 1967; Frohlich, 1974, 1979). Several applications of this method have been reported where the quantitative relation between aquifer resistivity and hydraulic conductivity has been investigated. These studies and the subsequent discussion of their results show that only empirical relations, over limited geographical areas, can be established (Kelly, 1977a, 1977b, 1978, 1980; Sabet, 1978; Heigold and others, 1979; Mazac and Landa, 1979; Heigold and others, 1980; Kosinski and Kelly, 1981; Urish, 1981; Kelly and Kosinski, 1982; Leonard-Mayer and Taylor, 1982; Biella and others, 1983; Mazac and others, 1985; Huntley, 1986).

Electromagnetic methods also can be used to map variations in aquifer conductivity or resistivity. These methods have been used successfully for the qualitative delineation of conductive plumes in contaminated glacial aquifers (Duran and Haeni, 1982; Greenhouse and Slaine, 1982; Greenhouse and Harris, 1983; Grady and Haeni,

TABLE 1.—*General relation of hydrogeologic units in the glaciated Northeastern United States to the velocity of sound in each unit*

Hydrogeologic unit	Velocity of sound (km/s)
Unconsolidated, stratified-drift or alluvial deposits:	
Unsaturated	0.3–0.6
Saturated	1.2–1.8
Saturated till	2.1–2.4
Saturated sedimentary rocks	3.4–4.3
Saturated crystalline rocks	4.6–6.1

1984; Barlow and Ryan, 1985; Grady, 1989; Greenhouse and others, 1989). Stewart (1982) used this method to map the saltwater interface in coastal aquifers. Grady and Haeni (1984) also showed how these methods could be used for the quantitative delineation of a conductive contaminant plume in a glacial aquifer. The use of electromagnetic methods for aquifer assessments has been limited (Wynn, 1979; Sinha, 1980; Haeni, 1986b) and no quantitative work has been reported using these methods in glacial terrains.

PRINCIPLES OF SURFACE-GEOPHYSICAL METHODS

Dc-resistivity, VLF terrain-resistivity, and inductive terrain-conductivity methods, and data from previously conducted seismic-refraction studies were used in this study. Each method provided different hydrogeologic information about the subsurface. The seismic-refraction data were used to determine the depth to water table and depth to bedrock. The dc-resistivity method was used to determine if an empirical relation between aquifer resistivity and grain size existed, and to measure the gross electrical properties of each subsurface unit. The VLF terrain-resistivity and inductive terrain-conductivity methods were used to map the horizontal and vertical resistivity variations within an aquifer or adjacent units. Each surface-geophysical method has unique operating principles, advantages, and limitations.

SEISMIC-REFRACTION METHOD

Sand and gravel aquifers in the Northeastern United States generally consist of unconsolidated sand and gravel deposits underlain by till and crystalline or sedimentary bedrock. There are substantial changes in the velocity of sound at the water table in unconsolidated material and at the till and bedrock interfaces (table 1). The velocity of sound in the various geologic units, which is called seismic velocity, generally increases with depth. The seismic velocity also increases as the density of the geologic materials increases.

In the seismic-refraction method, sound waves are produced by a variety of methods such as sledge hammer strikes on a metal plate, explosives, and weight drops, and travel through the subsurface. When the seismic velocity in the subsurface units increases with depth, some of the sound energy is refracted along the higher seismic-velocity unit. The refracted sound energy is eventually transmitted back to the surface where it is received by geophones and recorded by the seismograph. Measurement of the sound wave traveltimes from the sound source to the receiver, and the measured distance between source and receiver can be transformed into a time-distance plot (fig. 1). From this plot, seismic velocity of individual layers and depth to refracting layers can be calculated.

Explosive sound sources and a 12-channel commercial seismograph, the EG&G model 1210F, were used to collect the refraction data used in this study. Methods for the interpretation of field seismic-refraction data are well documented (Dobrin, 1976; Telford and others, 1976; Mooney, 1981; Sjogren, 1984) and many computer modeling programs are available (Scott and others, 1972; Scott, 1973, 1977a, 1977b; Ackermann and others, 1982). In this study, the method described by Scott and others (1972), Scott (1973), Haeni and others (1987), and Haeni (1988) was used and the result of the interpretation is a cross-sectional profile of the refracting layers. An example of a geohydrologic section based on interpreted results of a seismic-refraction profile conducted in Stonington, Conn. is shown in figure 2.

DIRECT-CURRENT-RESISTIVITY METHOD

The theory of dc-resistivity methods is well described by several authors (Zohdy and others, 1974; Dobrin, 1976; Telford and others, 1976; Mooney, 1980). The bulk resistance of porous earth material depends on several variables with complex interrelations, but principally depends on the electrical conductivity of the matrix material and the electrical conductivity of the fluid within the porous medium. Urish (1981) concluded from his laboratory packing tests and from the work of Kezdi (1974) that fine-grained materials tend to have higher porosities than coarse-grained materials. He also showed through theoretical calculations and field tests that, if the fluid conductivity remains constant, the resistivity of the aquifer material will generally increase with grain size. Resistivity methods, therefore, have the capability of providing a qualitative estimate of the grain size of sand and gravel aquifers over a limited geographic area.

A commercial dc-resistivity unit, the Bison model 2390, consisting of a transmitter, receiver, and switchbox, was used in this study. The resistivity of subsurface materials is measured in the field by putting a direct

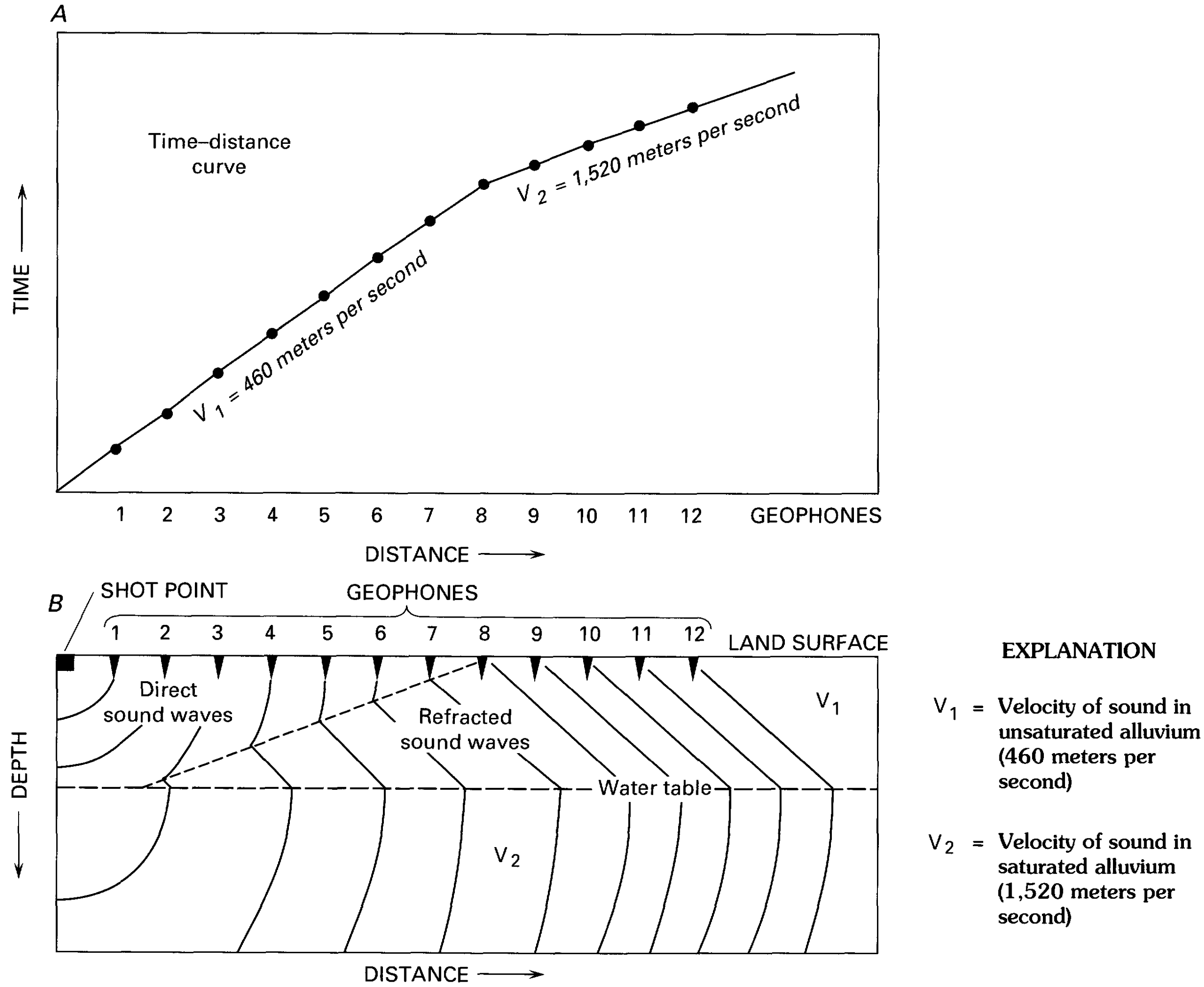


FIGURE 1.—Seismic-refraction time-distance plot and section showing direct and refracted sound waves. (Modified from Haeni, 1988, fig. 2.)

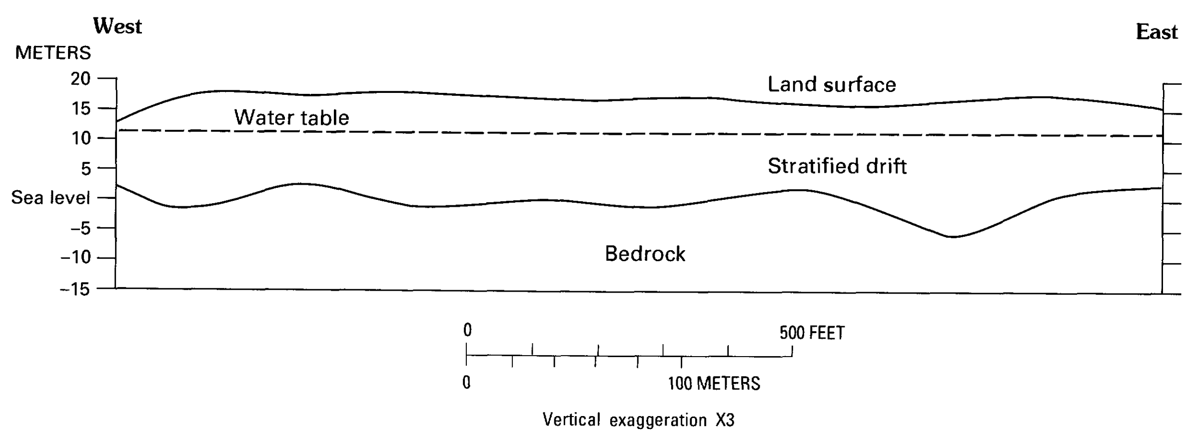


FIGURE 2.—Interpreted seismic-refraction profile in Stonington, Conn.

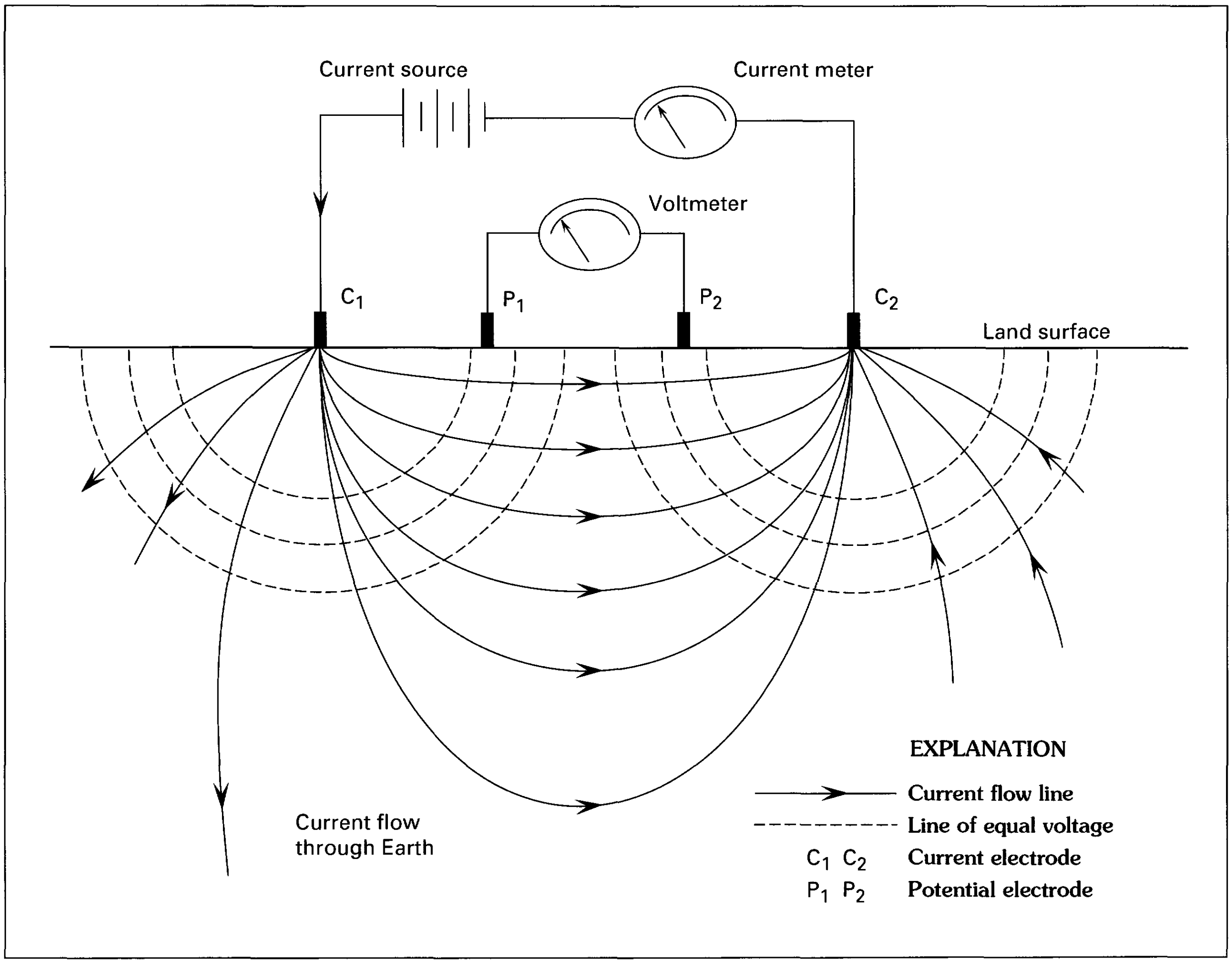


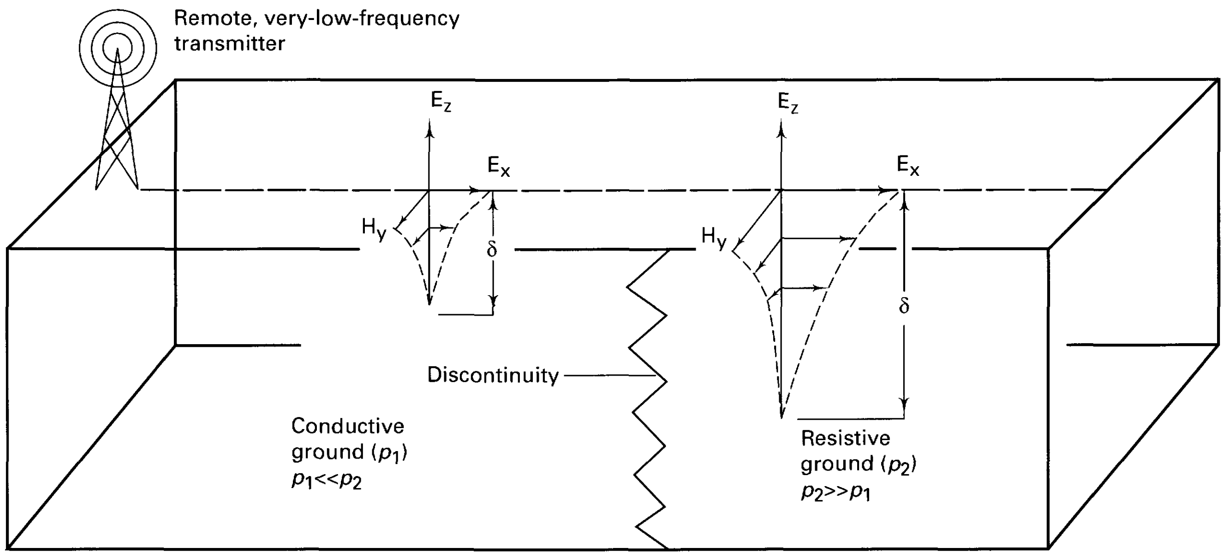
FIGURE 3.—Principles of direct-current-resistivity method.

current or a low-frequency alternating current into the ground and measuring the resultant voltage drop across a given distance (fig. 3). The apparent resistivity then can be calculated, and using one of several interpretation procedures, the resistivity of individual subsurface units can be interpreted (Zohdy, 1974; Zohdy and Bisdorf, 1975). Many geometric arrangements of the current and voltage electrodes have been developed (Zohdy and others, 1974). Schlumberger soundings were used in this study. The distance between the current electrodes was systematically increased and the distance between the potential electrodes was periodically increased to measure the effect on deeper geologic units. This method has limited horizontal resolution because the interpretation assumes that each subsurface layer is horizontal and homogeneous over the distance between the electrodes.

ELECTROMAGNETIC METHODS

VERY-LOW-FREQUENCY TERRAIN-RESISTIVITY METHOD

Very-low-frequency, 15–24 kilohertz (kHz), radio waves are transmitted from U.S. Navy communication centers located around the world. As these waves propagate over the Earth's surface, magnetic and electrical fields are induced in the ground (fig. 4). The magnitude of the horizontal component of these fields depends on the apparent resistivity of the subsurface materials at the measuring point and on the frequency of the VLF radio wave. The angle between the horizontal components of the electrical and magnetic fields (the phase angle) depends on the stratification of the subsurface. The mathematical expressions for these relations are derived



EXPLANATION

E_z = vertical electrical field

Apparent terrain resistivity $(\rho_a) = \frac{0.2}{F}\left[\frac{E_x}{H_y}\right]^2$

and, the exploration depth $(\delta) = 500\,(\rho/F)^{1/2}$

where:

$\rho_1 << \rho_2$ = relative resistivity of conductive and resistive ground

F = frequency of transmitter

E_x = horizontal radial electrical field

H_y = horizontal radial magnetic field

FIGURE 4.—Principles of very-low-frequency terrain-resistivity method. (Modified from Collett, 1979, fig. 6.)

by Wait (1982) and discussed by Keller and Frischknecht (1966). In a homogeneous Earth, the phase angle is 45° and the measured resistivity is the true resistivity of the subsurface. If the shallow subsurface material is more conductive than the deep subsurface material, the phase angle will be less than 45°. When the subsurface layering is reversed, the phase angle will be greater than 45°.

A commercial VLF unit, the Geonics model EM16R, was used in this study. Field measurements were taken by determining the direction to the transmitting station using the receiver coils in the handle of the electronic receiver, orienting the two probes and cable in the same direction as this station, and reading the apparent resistivity and phase angle.

This method is limited by the effects of cultural interference such as pipelines, fences, power lines, or other metal objects. The depth of penetration is limited by the frequency of the transmitting station and the conductivity of the subsurface units. In very conductive units (1–100 ohm-meters (ohm-m)), the penetration depth is limited to a few meters or tens of meters. In very resistive material (100–10,000 ohm-m) penetration depths can be as great as 400 meters (m). An example of how the penetration depth of the instrument varies with terrain resistivity and VLF transmitting frequencies is shown in figure 5.

INDUCTIVE TERRAIN-CONDUCTIVITY METHOD

Inductive terrain-conductivity methods induce electrical currents in the Earth by energizing a coil of wire (the transmitter coil) at the surface of the Earth with an alternating current (fig. 6). This alternating current produces a magnetic field which induces current flow in the Earth, which, in turn, produces a secondary magnetic field. The secondary field induces a voltage in the instrument, which is converted to apparent conductivity

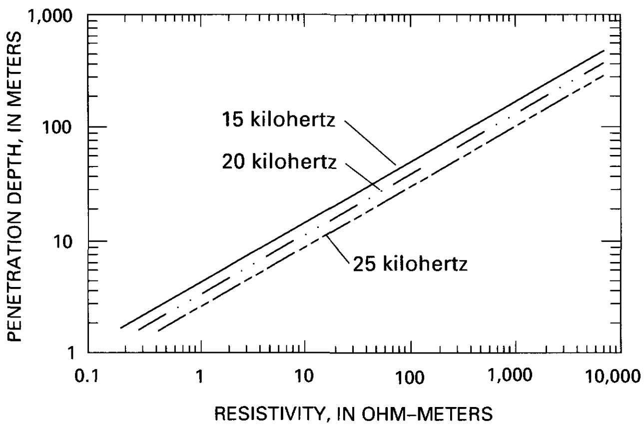
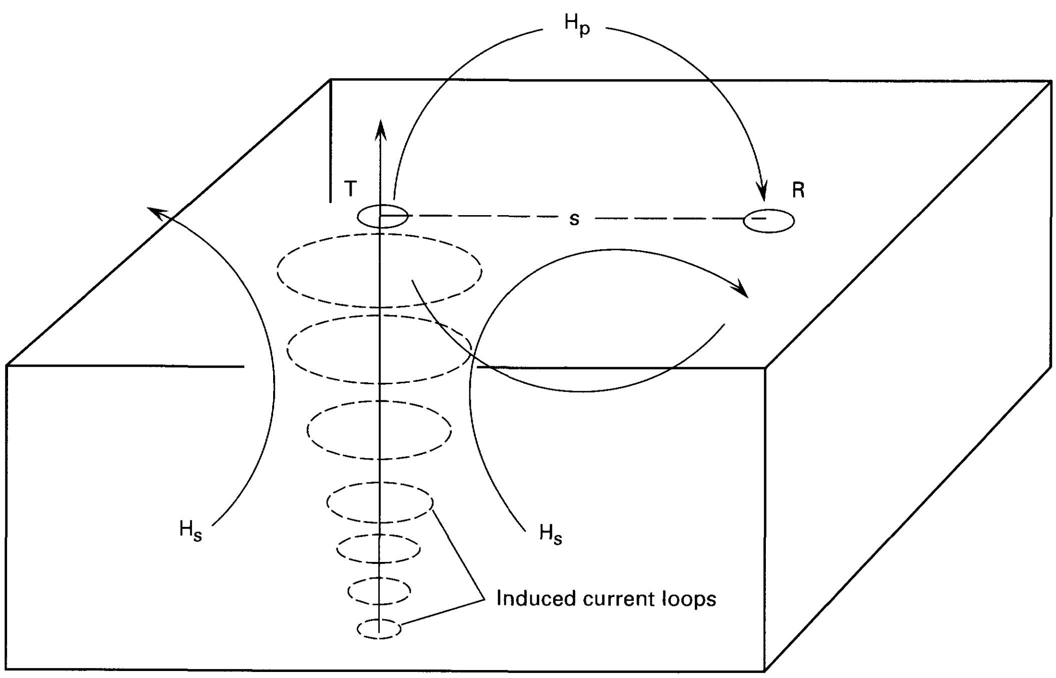


FIGURE 5.—Penetration depth of very-low-frequency terrain-resistivity method.

and displayed. Apparent conductivity would equal true conductivity only if the Earth were homogeneous. The magnitude of the secondary field is directly proportional to the conductivity of the Earth. This proportion is true only when the coil spacing is much less than the depth at which the electromagnetic wave attenuates to 0.3679 of its original amplitude (low induction number assumption). In practice, this means that the conductivity of the Earth is less than 100 millisiemens per meter (mS/m) (McNeill, 1980b). McNeill gives a clear explanation of the principle of operation of this method and the importance of the low induction number assumption.

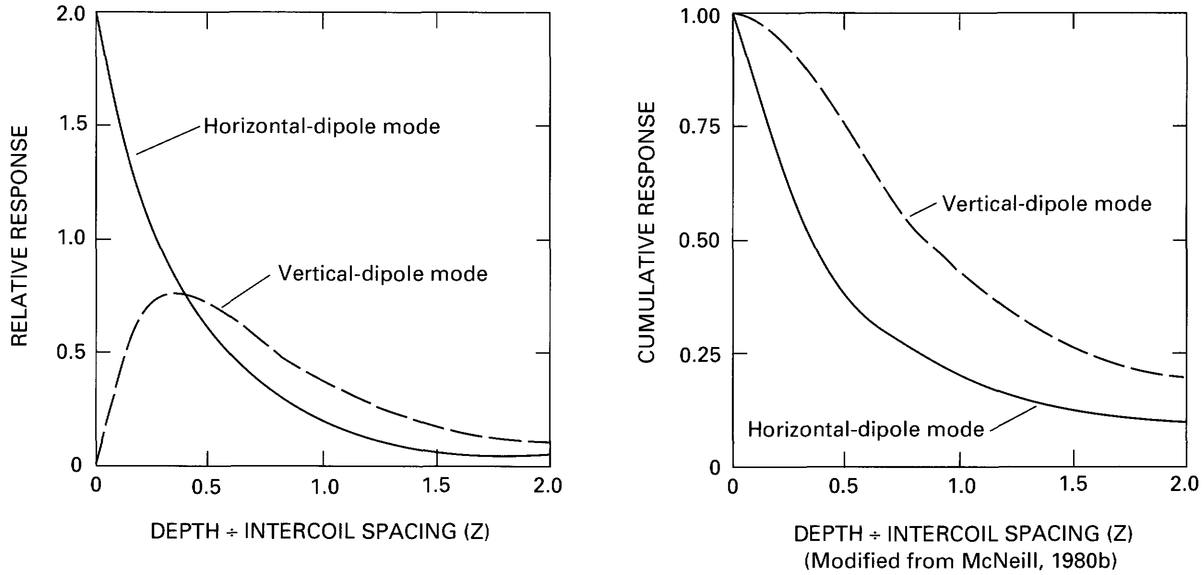
A commercial inductive terrain-conductivity meter, the Geonics model EM34-3, which measures apparent conductivity directly, was used in this study. It consists of a transmitter and a transmitting coil; a receiver and a receiving coil; and 10-, 20-, and 40-m intercoil connecting cables. The depth of penetration is dependent on the



EXPLANATION

T = Transmitter coil
R = Receiver coil
Terrain conductivity (σ) = $4/2 \pi f \mu_o s^2$ (H_s / H_p)
Where f = operating frequency
μ_o = permeability of free space
s = intercoil spacing
H_s = secondary magnetic field
H_p = primary magnetic field

FIGURE 6.—Principles of inductive terrain-conductivity method. (Modified from Geonics, 1979, fig. 1.)



Depth ÷ intercoil spacing (Z)		0	0.5	1.0	1.5	2.0
		Depth (in meters)				
Coil spacing (in meters)	10	0	5	10	15	20
	20	0	10	20	30	40
	40	0	20	40	60	80

	0	0.5	1.0	1.5	2.0
	Depth (in meters)				
10	0	5	10	15	20
20	0	10	20	30	40
40	0	20	40	60	80

FIGURE 7.—Relative and cumulative response curves for the Geonics EM34-3 inductive terrain-conductivity instrument. (Modified from McNeill, 1980b, figs. 6 and 11.)

spacing and orientation of the coils and the conductivity contrast of the target; it is relatively independent of the resistivity of the subsurface material. The influence of subsurface material at different depths (in a homogeneous Earth) on the apparent conductivity (recorded by the instrument) is shown on the left side of figure 7 for different coil (dipole) positions and intercoil spacings. When the coils are in the horizontal-dipole mode (coils held vertically and coplanar), the instrument responds mainly to earth materials located from the surface to a depth of 0.75 times the intercoil spacing and is most sensitive to near-surface materials (fig. 7). In the vertical-dipole mode (coils held horizontally and coplanar), the instrument responds to mainly earth materials between 0.1 and 1.5 times the intercoil spacing and is most sensitive to layers at a depth of about 0.4 times the intercoil spacing. Near-surface materials have little effect on the instrument in this mode.

The cumulative response curves, defined as the contribution to the secondary magnetic field from all material below a given depth, are shown in the right side of figure 7. These curves allow the computation of instrument response to any hypothetical combination of layers and are used in the forward-modeling programs. It is important to note that the measured apparent conductivity is a function of the conductivity and thickness of individual layers and the response characteristic of the instrument.

Conductivity is the reciprocal of resistivity and is defined by

$$\textit{Conductivity (in mS/m)} = \frac{1{,}000}{\textit{resistivity (in ohm-m)}}$$

The change in conductivity (ΔC) for a given change in resistivity (ΔR), in a known environment having a resistivity of R, can be approximated by

$$\Delta C = \frac{-1{,}000\Delta R}{R^2}$$

Because of the inverse square relation of resistivity and conductivity in resistive terrains (R=1,000 ohm-m), a 1-mS/m change in conductivity reflects a 1,000-ohm-m

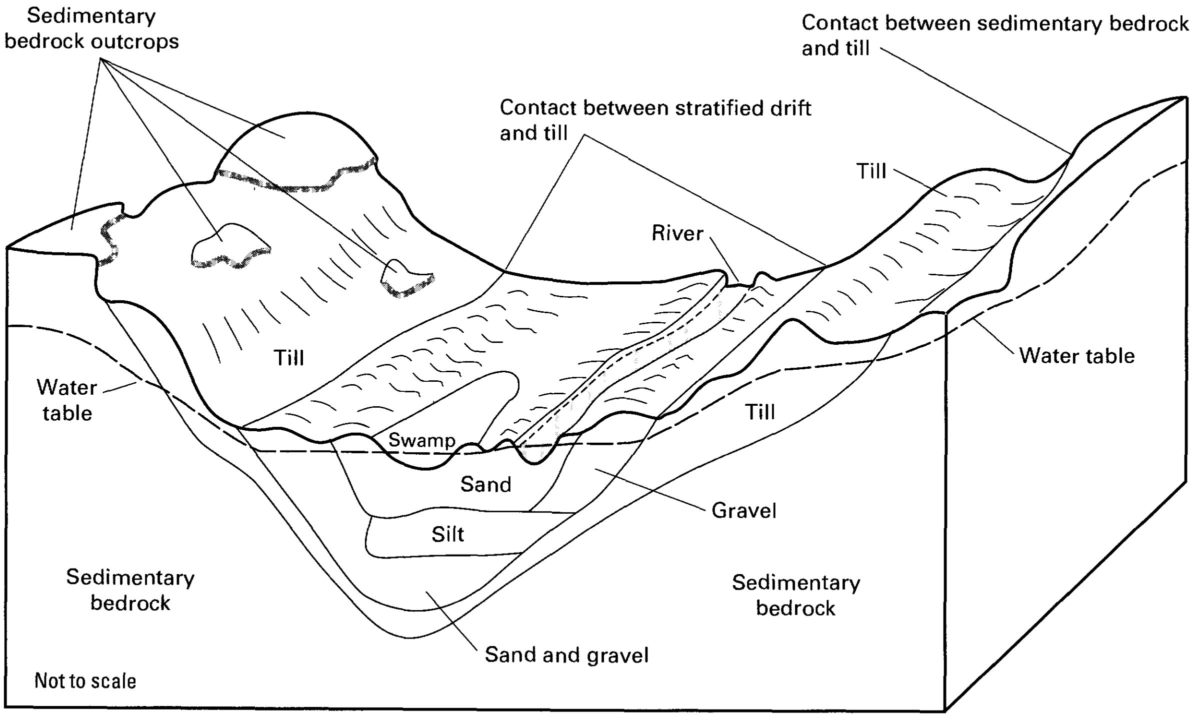


FIGURE 8.—Relations among stratified drift, till, and bedrock in a typical glacial valley.

resistivity change, whereas the same change (1 mS/m) in conductive terrain (R=42 ohm-m) reflects only a 1.8-ohm-m change in resistivity.

Six measurements that correspond to both dipole positions at each intercoil spacing can be made at each data collection station, giving the instrument a limited depth-sounding capability. Horizontal conductivity changes within the subsurface can be detected by making a series of measurements along a profile across the area of interest.

This method is limited by electrical or cultural interference caused by power lines, pipelines, and fences; the depth of penetration is limited by the strength and frequency of the transmitter and the intercoil spacing.

RESPONSE OF ELECTROMAGNETIC METHODS TO HYPOTHETICAL GEOELECTRIC EARTH MODELS

Hypothetical geoelectric Earth models were used to determine if VLF terrain-resistivity and inductive terrain-conductivity methods could be used to define horizontal and vertical lithologic changes within typical sand and gravel aquifers found in the Northeastern United States. Sand and gravel aquifers in this region consist primarily of unconsolidated deposits of varying grain sizes, often underlain by till that is thin and discontinuous. These units are underlain by either sedimentary or crystalline bedrock (fig. 8). In order to model these aquifers, the following simplifying assumptions were made:

1. Sand and gravel aquifer material can be unsaturated or saturated;
2. Till is usually thin and discontinuous, and therefore is assumed to have little effect on the model;
3. Resistivity of the aquifer units can be empirically related to the grain size of the aquifer material;
4. Quality of water in the aquifer is constant within the modeled area;
5. Unsaturated zone is homogeneous, with constant resistivity;
6. Unsaturated zone has a constant thickness;
7. Each bedrock type is homogeneous and infinitely thick, with a constant resistivity; and
8. All layers are homogeneous and of infinite horizontal extent.

Using these assumptions, 10 hypothetical geoelectric Earth models were used in this study to represent conditions typical of glacial valleys: (1) coarse-grained stratified drift overlying sedimentary or crystalline bedrock; (2) fine-grained stratified drift overlying sedimentary or crystalline bedrock; (3–6) coarse-grained stratified drift over fine-grained stratified drift overlying

TABLE 2.—*Resistivity values of various materials used in the hypothetical Earth models*

Material description	Resistivity (ohm-m)
Unsaturated, coarse-grained stratified drift	2,000
Unsaturated, fine-grained stratified drift	300
Saturated, coarse-grained stratified drift	800
Saturated, fine-grained stratified drift	50
Sedimentary bedrock	500
Crystalline bedrock	2,000

sedimentary or crystalline bedrock; and (7–10) fine-grained stratified drift over coarse-grained stratified drift overlying sedimentary or crystalline bedrock.

For each hypothetical geoelectric layer in the model, the resistivities were estimated from previous investigations or published tables (Collett, 1979; Telford and others, 1976; McNeill, 1980a; Mooney, 1980). The resistivity values used to represent the various geologic layers are given in table 2.

Two forward-modeling computer programs were used to calculate the response of VLF terrain-resistivity and inductive terrain-conductivity instruments over various hypothetical geoelectric Earth models. The VLF computer program, VLF.BAS, is based on plane-wave electromagnetic theory and is written in Basic computer language for an IBM or compatible personal computer. The computer program, documented by Grantham and others (1986), calculates the apparent resistivity and phase angle between the induced horizontal magnetic and electric fields that would be measured by a Geonics EM16R VLF terrain-resistivity instrument over a horizontally layered Earth.

The inductive terrain-conductivity computer program, EM34.FOR, calculates the electromagnetic potential generated by an oscillating magnetic dipole over a horizontally layered Earth, and from that, the apparent conductivity of the Earth is calculated. Calculations are made for the Geonics EM34–3 instrument's three intercoil spacings, three frequencies, and two dipole orientations. The program, written in Fortran for an IBM or compatible personal computer, is documented by Grantham and others (1987).

The results of the forward-modeling programs are presented in figures 9 through 18 for the 10 hypothetical geoelectric Earth models. The variation of apparent conductivity between the various intercoil spacings and dipole orientation for each model can be qualitatively understood by comparing the model characteristics (such as the thickness and conductivity of individual layers) with the relative and cumulative response curves (fig. 7). The apparent resistivity, as measured by the method, is a function of the product of the conductivity of individual layers and the response function of a particular intercoil spacing and dipole orientation.

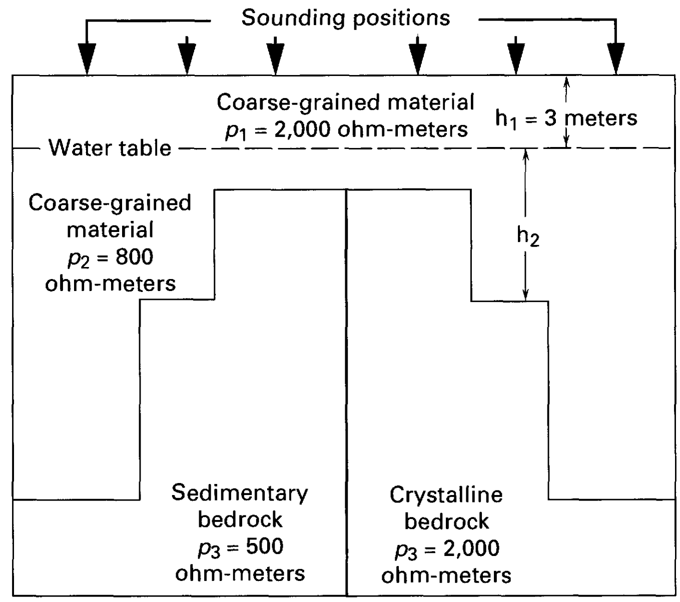
COARSE-GRAINED AQUIFER MATERIAL

The first hypothetical geoelectric Earth model is a resistive geologic setting. The model consists of a coarse-grained unconsolidated aquifer saturated with freshwater (resistivity of 800 ohm-m) and is underlain by relatively conductive sedimentary bedrock (resistivity of 500 ohm-m) or relatively resistive crystalline bedrock (resistivity of 2,000 ohm-m) (fig. 9).

In this setting, the VLF terrain-resistivity method measures a high apparent resistivity (590–1,630 ohm-m), and penetrates to a depth of about 100 m (fig. 5). A change in apparent resistivity is related to the thickness of the aquifer material over a given bedrock type. Over sedimentary (conductive) bedrock, the apparent resistivity will increase as the aquifer thickness increases. Over crystalline (resistive) bedrock, the apparent resistivity will increase as the aquifer thickness decreases. A change in the measured phase angle is related to the type of bedrock, if the bedrock is within the penetration depth of the method. For a given aquifer thickness, if the bedrock is resistive (relative to the aquifer material; for example, crystalline bedrock), the phase angle would be less than 45°; if the bedrock is conductive (relative to the aquifer material; for example, sedimentary bedrock), the phase angle would be greater than 45°. The phase angle is generally independent of the aquifer thickness.

In this same geologic setting, the inductive terrain-conductivity method measures a low apparent conductivity (0.6–1.7 mS/m, fig. 9). The readings of individual intercoil spacings and dipole modes are dependent on the conductivity of the subsurface layers and the response curves of the instrument (fig. 7). McNeill (1980b) presents a detailed discussion of the response of the method to subsurface conductors. In general, however, the response is related to the product of the layer conductivity and the instrument response for a given intercoil spacing and dipole orientation.

In resistive terrains, the response of the instrument to relatively large changes in resistivity is small because of the design of the conductivity meter and the units of measurement. A change in apparent conductivity is related to the thickness of the aquifer material over a given bedrock type. Over sedimentary (conductive) bedrock, the apparent conductivity (fig. 9) will decrease slightly (0.1–0.4 mS/m) as the aquifer thickness increases. Over crystalline (resistive) bedrock, the apparent conductivity will increase slightly (0.1–0.4 mS/m) as the aquifer thickness increases. All of the conductivity measurements are slightly higher (0.1–1.1 mS/m) over the conductive bedrock than over the resist-



EXPLANATION

$\rho_{1,2,3}$ = **Resistivity**

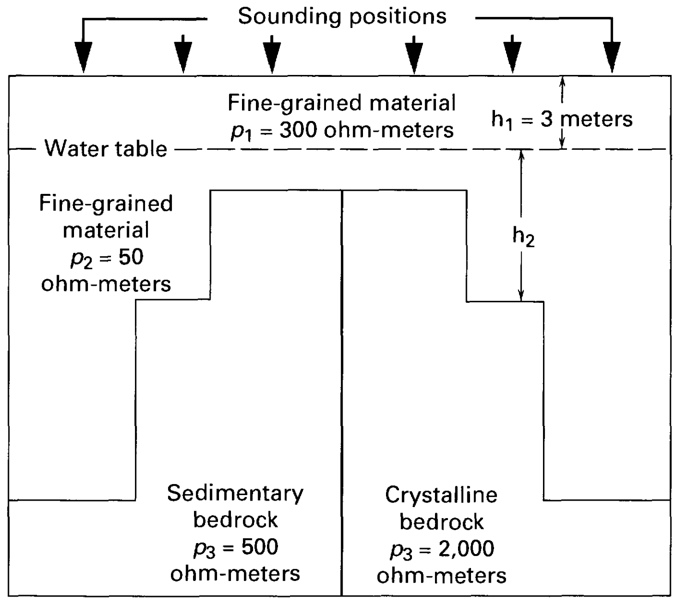
	Layer thickness, h (meters)					
Unsaturated, coarse-grained material, h_1	3	3	3	3	3	3
Saturated, coarse-grained material, h_2	62	32	12	12	32	62

VLF Terrain-resistivity method						
Apparent resistivity (ohm-meters)	790	680	590	1,630	1,210	910
Phase angle (degrees)	50	50	49	41	38	39

Terrain-conductivity method		Apparent conductivity (millisiemens per meter)					
	10 V[1,2]	1.1	1.1	1.2	0.9	1.0	1.1
	10 H	.9	.9	1.0	.8	.8	.9
	20 V	1.2	1.3	1.5	.8	1.0	1.1
	20 H	1.0	1.1	1.2	.8	.9	1.0
	40 V	1.3	1.5	1.7	.6	.8	1.0
	40 H	1.2	1.3	1.4	.8	.9	1.0

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 9.—Hypothetical geoelectric Earth model of a coarse-grained unconsolidated aquifer overlying sedimentary and crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



EXPLANATION

$\rho_{1,2,3}$ = **Resistivity**

	Layer thickness, h (meters)					
Unsaturated, fine-grained material, h_1	3	3	3	3	3	3
Saturated, fine-grained material, h_2	62	32	12	12	32	62

VLF Terrain-resistivity method						
Apparent resistivity (ohm-meters)	60	53	88	102	50	60
Phase angle (degrees)	50	47	31	23	46	50

Terrain-conductivity method	Apparent conductivity (millisiemens per meter)					
[1]10 V[2]	13.3	13.3	11.3	11.1	13.3	13.3
10 H	10.6	10.6	9.5	9.4	10.6	10.6
20 V	14.8	13.5	9.0	8.4	13.3	14.8
20 H	13.4	12.8	10.2	9.7	12.7	13.4
40 V	13.7	10.5	5.2	4.2	10.0	13.5
40 H	14.5	12.7	8.6	7.9	12.4	14.4

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 10.—Hypothetical geoelectric Earth model of fine-grained unconsolidated material overlying sedimentary and crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.

ive bedrock and are most noticeable in the 40-m vertical-dipole mode (1.1 mS/m).

FINE-GRAINED MATERIAL

The second hypothetical geoelectric Earth model is a conductive geologic setting (resistivity of 50 ohm-m), such as fine-grained unconsolidated material, an unconsolidated aquifer saturated with conductive ground water, or till, which is underlain by relatively resistive sedimentary bedrock (resistivity of 500 ohm-m) or crystalline bedrock (resistivity of 2,000 ohm-m) (fig. 10).

In this setting, the VLF terrain-resistivity method measures a low apparent resistivity (50–102 ohm-m), and penetrates to a depth of about 20 m (fig. 5). A change in apparent resistivity is related to the thickness of the fine-grained (conductive) material, as well as the type of bedrock, if the bedrock is within the penetration depth. The apparent resistivity will generally decrease as the thickness of the fine-grained material increases, over either sedimentary or crystalline bedrock (fig. 10). This happens because both types of bedrock are resistive compared to the fine-grained material. A change in the measured phase angle is related to the type of bedrock (if the bedrock is within the penetration depth) and the thickness of the fine-grained material. The phase angle measured over shallow sedimentary bedrock is higher than the phase angle measured over shallow crystalline bedrock because the crystalline bedrock is much more resistive than the sedimentary bedrock. Both phase angles are less than 45° because both types of bedrock are resistive compared to the fine-grained material. As the fine-grained material thickens, the effect of the bedrock diminishes because of the decreased penetration depth of the method, thus, the phase angle increases. The phase angle will exceed 45° if a relatively resistive (unsaturated) layer is present at the surface and the bedrock is below the penetration depth of the method. In general, VLF terrain-resistivity instrument readings are dominated by resistivity of the conductive material.

The inductive terrain-conductivity method measures a moderately high apparent conductivity (4.2–14.8 mS/m) in the geologic setting. The depth of penetration of this method is not affected by the conductivity of the subsurface layers. The apparent conductivity increases over both sedimentary and crystalline bedrock as the thickness of the fine-grained material increases. The 10-m and 20-m horizontal-dipole mode readings are generally lower than the corresponding vertical-dipole mode readings when bedrock is deep. This difference results from the position of the thick fine-grained (conductive) layers and the response curves of the instrument. The readings are affected by the bedrock when the fine-grained material is thin. In this case, the 20-m and 40-m horizontal-dipole mode readings are higher than the corresponding vertical-dipole mode readings over both bedrock types; four readings are higher for sedimentary bedrock than for crystalline bedrock.

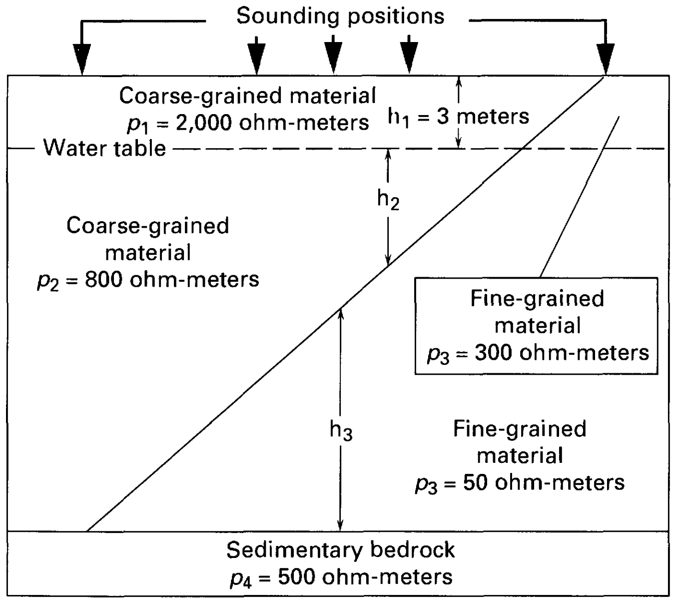
COARSE-GRAINED AQUIFER MATERIAL OVER FINE-GRAINED MATERIAL

The next four hypothetical geoelectric Earth models are examples of geologic settings that have resistive units (coarse-grained, saturated aquifer material) overlying more conductive units (fine-grained, saturated material or till). The models had different total thicknesses of coarse-grained and fine-grained materials (thin or thick) over different bedrock types (sedimentary or crystalline) (figs. 11–14).

In these settings, the VLF terrain-resistivity readings of apparent resistivity and phase angle vary with the geometry of the site. Also, as the thickness of the resistive layer (aquifer material) decreases and the thickness of the fine-grained material increases, the resistivity increases and the penetration depth of the method decreases from 100 to 20 m (fig. 5).

Where the glacial material is thin (12 m), the apparent resistivity decreases from 1,630 to 102 ohm-m (over crystalline bedrock, fig. 13) and from 590 to 88 ohm-m (over sedimentary bedrock; fig. 11) as the thickness of the conductive material increases and the thickness of the aquifer material decreases. The apparent resistivity values are always higher over resistive bedrock than over conductive bedrock. The readings are affected less by the type of bedrock as the thickness of the conductive material increases and the penetration depth of the method decreases. The phase angle also decreases from 41° to 23° (over crystalline bedrock) and from 49° to 31° (over sedimentary bedrock) as the thickness of the conductive material increases and the effect of bedrock is decreased. When bedrock is within the penetration depth of the method, the phase angle is higher over sedimentary bedrock than over crystalline bedrock because of the different resistivities of these units.

Where the glacial material is thick (62 m), the apparent resistivity decreases from 910 to 60 ohm-m (over crystalline bedrock, fig. 14) and from 790 to 60 ohm-m (over sedimentary bedrock, fig. 12) as the thickness of the conductive material increases and the thickness of the aquifer material decreases. The apparent resistivity and phase angles are relatively independent of bedrock type because the penetration depth of the method is exceeded, except when no fine-grained material is present. The phase angle does not vary much (65–69°, fig. 14) until the section is either all fine grained (50°) or all coarse grained (39°).



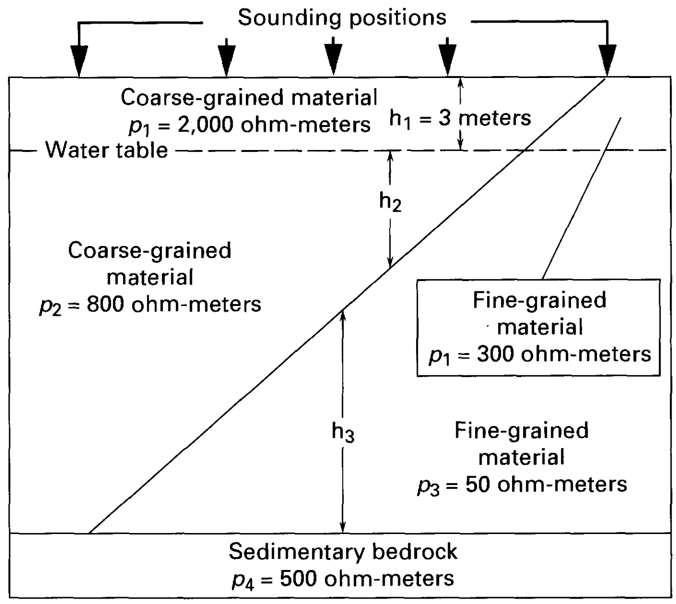
EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

		Layer thickness, h (meters)				
Unsaturated, coarse-grained material, h_1		3	3	3	3	3
Saturated, coarse-grained material, h_2		12	8	6	4	0
Saturated, fine-grained material, h_3		0	4	6	8	12
VLF Terrain-resistivity method		Apparent resistivity (ohm-meters)				
		590	266	192	143	88
		Phase angle (degrees)				
		49	41	39	37	31
Terrain-conductivity method		Apparent conductivity (millisiemens per meter)				
	[1]10 V[2]	1.2	3.0	4.3	6.0	11.3
	10 H	1.0	1.9	2.7	3.8	9.5
	20 V	1.5	3.7	5.0	6.4	9.0
	20 H	1.2	2.7	3.8	5.2	10.1
	40 V	1.7	3.1	3.8	4.4	5.2
	40 H	1.4	3.1	4.2	5.3	8.6

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 11.—Hypothetical geoelectric Earth model of a thin unconsolidated section consisting of a coarse-grained aquifer overlying fine-grained material, all of which overlies sedimentary bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



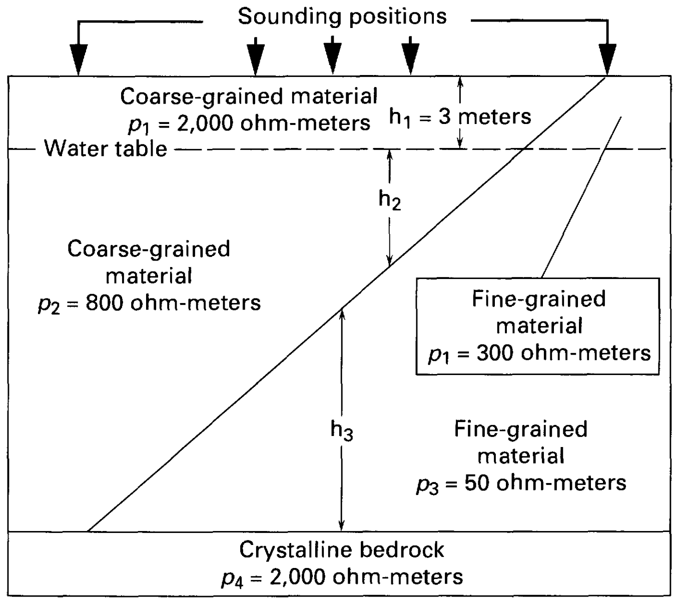
EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

		Layer thickness, h (meters)				
Unsaturated, coarse-grained material, h_1		3	3	3	3	3
Saturated, coarse-grained material, h_2		62	42	32	20	0
Saturated, fine-grained material, h_3		0	20	30	42	62
		Apparent resistivity (ohm-meters)				
VLF Terrain-resistivity method		790	376	325	186	60
		Phase angle (degrees)				
		50	66	69	67	50
		Apparent conductivity (millisiemens per meter)				
Terrain-conductivity method	[1]10 V[2]	1.1	1.4	1.7	2.5	13.3
	10 H	.9	1.0	1.2	1.6	10.6
	20 V	1.2	2.2	3.1	5.1	14.8
	20 H	1.0	1.5	2.0	3.1	13.4
	40 V	1.3	3.3	4.9	7.8	13.7
	40 H	1.2	2.3	3.2	5.2	14.5

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 12.—Hypothetical geoelectric Earth model of a thick unconsolidated section consisting of a coarse-grained aquifer overlying fine-grained material, all of which overlies sedimentary bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



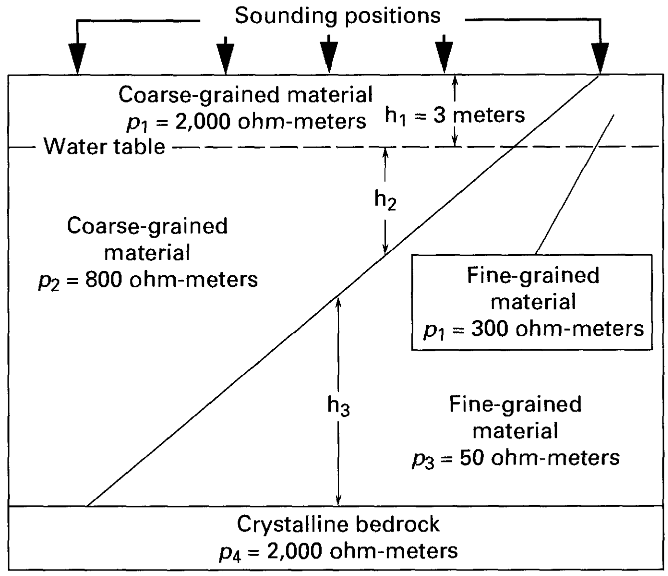
EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

		Layer thickness, h (meters)				
Unsaturated, coarse-grained material, h_1		3	3	3	3	3
Saturated, coarse-grained material, h_2		12	8	6	4	0
Saturated, fine-grained material, h_3		0	4	6	8	12
VLF Terrain-resistivity method		Apparent resistivity (ohm-meters)				
		1,630	407	258	177	102
		Phase angle (degrees)				
		41	30	29	28	23
Terrain-conductivity method		Apparent conductivity (millisiemens per meter)				
	[1]10 V[2]	0.9	2.7	4.0	5.7	11.1
	10 H	.8	1.8	2.5	3.7	9.4
	20 V	.8	3.0	4.3	5.7	8.4
	20 H	.8	2.4	3.5	4.9	9.7
	40 V	.6	2.0	2.7	3.3	4.2
	40 H	.8	2.5	3.5	4.7	7.9

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 13.—Hypothetical geoelectric Earth model of a thin unconsolidated section consisting of a coarse-grained aquifer overlying fine-grained material, all of which overlies crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



EXPLANATION

$\rho_{1,2,3,4}$ = **Resistivity**

	Layer thickness, h (meters)				
Unsaturated, coarse-grained material, h_1	3	3	3	3	3
Saturated, coarse-grained material, h_2	62	42	32	20	0
Saturated, fine-grained material, h_3	0	20	30	42	62

VLF Terrain-resistivity method					
Apparent resistivity (ohm-meters)	910	360	318	180	60
Phase angle (degrees)	39	65	69	67	50

Terrain-conductivity method	Apparent conductivity (millisiemens per meter)					
	10 V[1,2]	1.1	1.4	1.7	2.5	13.3
	10 H	.9	1.0	1.2	1.6	10.6
	20 V	1.1	2.1	3.0	5.1	14.8
	20 H	1.0	1.5	2.0	3.1	13.4
	40 V	1.0	3.0	4.7	7.5	13.5
	40 H	1.0	2.1	3.1	5.1	14.4

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 14.—Hypothetical geoelectric Earth model of a thick unconsolidated section consisting of a coarse-grained aquifer overlying fine-grained material, all of which overlies crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.

In summary, as the thickness of the conductive (fine-grained) layer increases, and the thickness of the overlying aquifer material decreases (figs. 11 to 14), the depth of penetration of the method is exceeded. Because of this, the measured apparent resistivity and phase angles are independent of bedrock type and, thus, are dependent upon the thickness and resistivity of the fine-grained conductive material and the resistive aquifer material.

For the inductive terrain-conductivity method and where the glacial material is thin (12 m, figs. 11 and 13), the apparent conductivity readings all increase as the thickness of the conductive material increases and the thickness of the aquifer material decreases. In addition, the readings over conductive bedrock are all higher (0.1–1.1 mS/m) than the equivalent readings over resistive bedrock and are most noticeable in the 40-m vertical-dipole mode, which is most responsive to deep layers (fig. 7). The vertical-dipole readings (figs. 11 and 13) are generally higher than the horizontal readings. This difference reflects the position of the resistive over conductive glacial material in the subsurface and the response characteristics of the two dipole orientations (the horizontal-dipole mode is generally affected by shallow layers and the vertical-dipole mode is affected by deeper layers). As the aquifer material thins and the fine-grained material thickens, first the 40-m horizontal-dipole and then the 20-m horizontal-dipole readings become larger than the vertical-dipole readings. This change is due to the thickening conductive material and its effect on the relative response curve of the horizontal-dipole mode (fig. 7).

Where the glacial material is thick (62 m, figs. 12 and 14), the inductive terrain-conductivity method has readings that again all increase as the thickness of conductive material increases and the thickness of the aquifer material decreases. All of the readings except for the 40-m vertical-dipole readings are independent of bedrock type. The 40-m vertical-dipole readings are slightly higher (0.2–0.3 mS/m) over the conductive bedrock than over the resistive bedrock since this dipole mode has the greatest depth of penetration. Vertical-dipole mode readings are almost all higher or equal to the horizontal-dipole readings reflecting the occurrence of resistive over conductive material. This difference is due to the presence of the conductive fine-grained material at the maximum point on the relative response curves for the vertical-dipole modes. The difference also results from the presence of the resistive unsaturated surface material or the resistive aquifer material at the maximum point on the relative response curve for the horizontal-dipole modes (fig. 7). The one exception is the 40-m reading when the section consists entirely of fine-grained material. In this case, the relatively resistive bedrock is affecting the 40-m vertical dipole, causing it to be less conductive than the horizontal dipoles which gets most of its response from the conductive fine-grained material.

FINE-GRAINED MATERIAL OVER COARSE-GRAINED AQUIFER MATERIAL

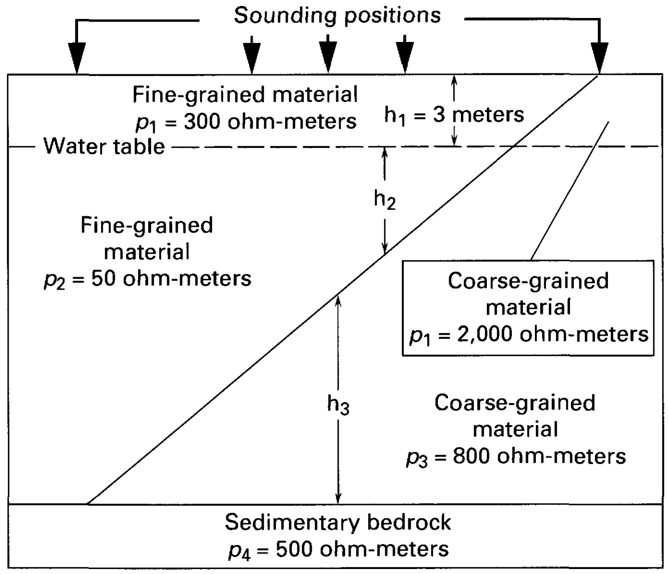
The next four hypothetical geoelectric Earth models are examples of geologic settings that have conductive units (fine-grained saturated material) overlying resistive material, such as a buried coarse-grained esker. These models specified either thick or thin layers of fine-grained and coarse-grained glacial material over different bedrock types (sedimentary or crystalline) (figs. 15–18).

In these settings, the depth of penetration of the VLF terrain-resistivity method is limited due to the high conductivity of the shallow fine-grained material. For example, the penetration depth of the method in material with a resistivity of 50 ohm-m is only 20 m (fig. 5).

Where the glacial material is thin (12 m, figs. 15 and 17), the method penetrates the entire unconsolidated section. The increasing thickness of the coarse-grained material and the decreasing thickness of the fine-grained material may be detected by increases in the measured apparent resistivity (88–590 and 102–1,630 ohm-m). The phase angle is independent of the relative thickness of the fine- and coarse-grained material, until the section becomes entirely coarse-grained. However, the phase angle is affected by the bedrock type. More resistive bedrock decreases the phase angle, and increases the apparent resistivity.

Where the glacial material is thick (62 m, figs. 16 and 18), buried coarse-grained materials and different bedrock types beneath about 26 m of fine-grained material are undetectable because of the limited penetration depth of the method. VLF terrain-resistivity readings of phase angle and apparent resistivities therefore become independent of the resistivity of deeper layers as thickness of the upper fine-grained section increases and the thickness of the coarse-grained aquifer unit decreases.

For the inductive terrain-conductivity method and where the glacial material is thin (12 m, figs. 15 and 17), the apparent conductivity readings decrease (11.3–1.0 and 11.1–0.6 mS/m) as the thickness of the conductive material decreases and the thickness of the coarse-grained aquifer increases. The 10-m spacing vertical-dipole readings are generally greater or equal to the 10-m horizontal dipole readings. This difference is due to the presence of the conductive saturated fine-grained materials underlying the relatively more resistant unsaturated fine-grained materials. In the 20-m and 40-m intercoil spacings, however, the horizontal-dipole readings are higher than the vertical-dipole readings because



EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

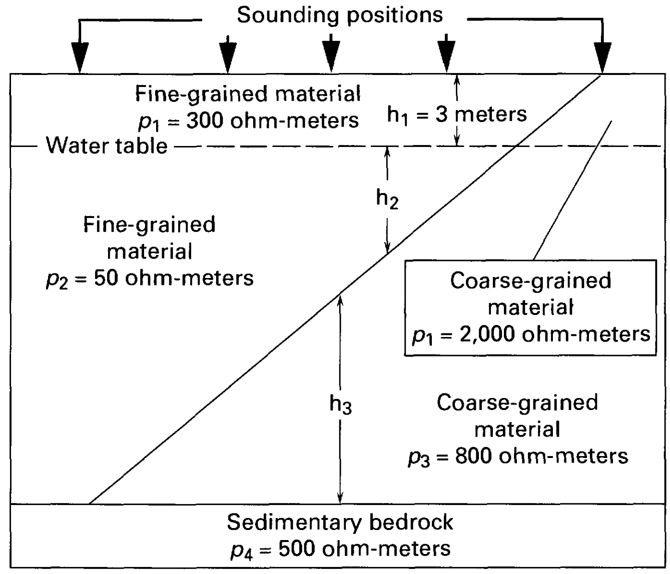
	Layer thickness, h (meters)				
Unsaturated, fine-grained material, h_1	3	3	3	3	3
Saturated, fine-grained material, h_2	12	8	6	4	0
Saturated, coarse-grained material, h_3	0	4	6	8	12

VLF Terrain-resistivity method					
Apparent resistivity (ohm-meters)	88	121	159	222	590
Phase angle (degrees)	31	30	30	32	49

Terrain-conductivity method	Apparent conductivity (millisiemens per meter)				
10 V [1,2]	11.3	9.7	8.5	6.7	1.2
10 H	9.5	8.6	7.9	6.7	1.0
20 V	9.0	6.9	5.6	4.2	1.5
20 H	10.1	8.6	7.5	6.1	1.2
40 V	5.2	3.8	3.1	2.5	1.7
40 H	8.6	6.9	5.8	4.7	1.4

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 15.—Hypothetical geoelectric Earth model of a thin unconsolidated section consisting of a fine-grained material overlying a coarse-grained aquifer, all of which overlies sedimentary bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

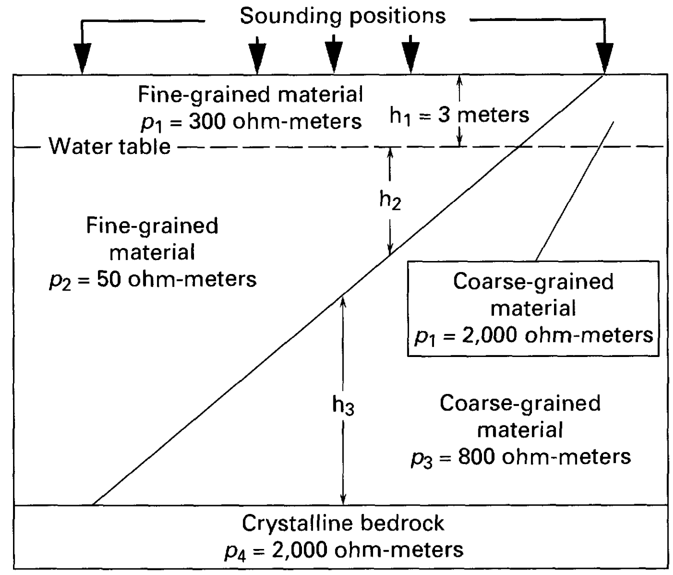
	Layer thickness, h (meters)				
Unsaturated, fine-grained material, h_1	3	3	3	3	3
Saturated, fine-grained material, h_2	62	42	32	20	0
Saturated, coarse-grained material, h_3	0	20	30	42	62

VLF Terrain-resistivity method					
Apparent resistivity (ohm-meters)	60	56	54	60	786
Phase angle (degrees)	50	50	49	37	50

Terrain-conductivity method	Apparent conductivity (millisiemens per meter)					
	[1]10 V[2]	13.3	13.4	13.3	12.7	1.1
	10 H	10.6	10.6	10.6	10.3	.9
	20 V	14.8	14.2	13.4	11.5	1.2
	20 H	13.4	13.1	12.7	11.6	1.0
	40 V	13.7	11.9	10.3	7.5	1.3
	40 H	14.5	13.5	12.6	10.6	1.2

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 16.—Hypothetical geoelectric Earth model of a thick unconsolidated section consisting of a fine-grained material overlying a coarse-grained aquifer, all of which overlies sedimentary bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



EXPLANATION

$\rho_{1,2,3,4}$ = **Resistivity**

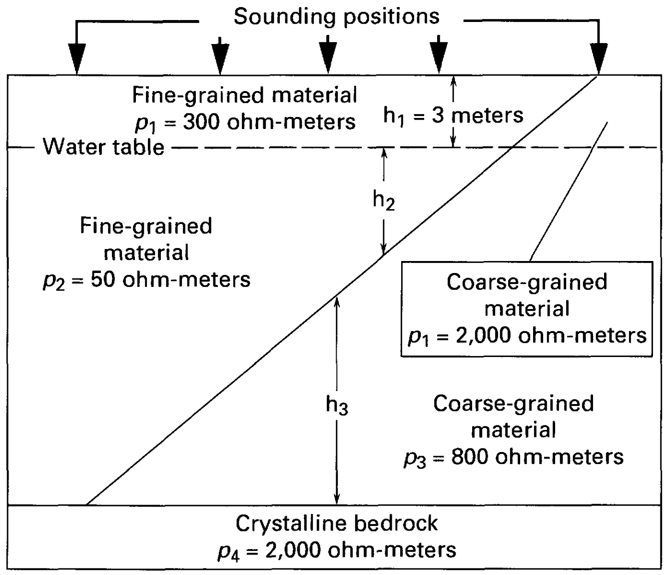
	Layer thickness, h (meters)				
Unsaturated, fine-grained material, h_1	3	3	3	3	3
Saturated, fine-grained material, h_2	12	8	6	4	0
Saturated, coarse-grained material, h_3	0	4	6	8	12

VLF Terrain-resistivity method					
Apparent resistivity (ohm-meters)	102	150	213	233	1,630
Phase angle (degrees)	23	21	21	22	41

Terrain-conductivity method	Apparent conductivity (millisiemens per meter)				
[1]10 V[2]	11.1	9.4	8.2	6.4	0.9
10 H	9.4	8.5	7.7	6.6	.8
20 V	8.4	6.2	4.9	3.5	.8
20 H	9.7	8.2	7.1	5.7	.8
40 V	4.2	2.7	2.1	1.5	.6
40 H	7.9	6.2	5.2	4.0	.8

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 17.—Hypothetical geoelectric Earth model of a thin unconsolidated section consisting of a fine-grained material overlying a coarse-grained aquifer, all of which overlies crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.



EXPLANATION

$p_{1,2,3,4}$ = **Resistivity**

		Layer thickness, h (meters)				
Unsaturated, fine-grained material, h_1		3	3	3	3	3
Saturated, fine-grained material, h_2		62	42	32	20	0
Saturated, coarse-grained material, h_3		0	20	30	42	62
VLF Terrain-resistivity method		Apparent resistivity (ohm-meters)				
		63	54	52	56	912
		Phase angle (degrees)				
		50	50	49	35	39
Terrain-conductivity method		Apparent conductivity (millisiemens per meter)				
	[1]10 V[2]	13.3	13.4	13.3	12.7	1.1
	10 H	10.6	10.6	10.6	10.3	.9
	20 V	14.8	14.2	13.4	11.4	1.1
	20 H	13.4	13.1	12.7	11.6	1.0
	40 V	13.5	11.7	10.1	7.2	1.0
	40 H	14.4	13.4	12.5	10.5	1.0

[1] Intercoil spacing, in meters.
[2] H, horizontal-dipole mode; V, vertical-dipole mode.

FIGURE 18.—Hypothetical geoelectric Earth model of a thick unconsolidated section consisting of a fine-grained material overlying a coarse-grained aquifer, all of which overlies crystalline bedrock, and the modeled response based on the very-low-frequency terrain-resistivity and inductive terrain-conductivity methods.

of conductive fine-grained material being near the maximum response portion of the horizontal-dipole response curve. Both dipole readings are also affected by the conductivity of the bedrock; all readings increase (0.1–1.1 mS/m) as the conductivity of the bedrock increases. The largest increase caused by bedrock is in the 40-m vertical-dipole mode, in which most of the response is from the bedrock (fig. 7).

Where the glacial material is thick (62 m, figs. 16 and 18), all of the apparent conductivity readings except the 40-m vertical-dipole readings become independent of bedrock type since this is about the maximum penetration depth of the method. The 40-m vertical-dipole readings are slightly higher (0.2–0.3 mS/m) over the conductive bedrock than over the resistive bedrock. As in the shallow case, almost all of the apparent conductivity measurements increase with increasing thickness of the conductive material and decreasing thickness of the aquifer material. The 10- and 20-m vertical-dipole readings are generally higher than the horizontal-dipole readings—a response that reflects the resistive, unsaturated fine-grained surface material overlying the conductive saturated material. The 40-m horizontal-dipole readings are generally higher than the vertical-dipole readings. This higher reading reflects the maximum response of the horizontal dipole located within the conductive fine-grained material and the maximum response of the vertical dipole located within the resistive coarse-grained aquifer material.

SUMMARY OF MODELING STUDIES

Results of computer models that simulate the use of VLF terrain-resistivity and inductive terrain-conductivity methods in hypothetical aquifer settings, representative of the glaciated Northeastern United States, demonstrate that both methods can detect small scale horizontal and vertical electrical changes in the subsurface. Each method works better in some geologic settings than in others because of differences in the design and operating principles of the two instruments. Forward-modeling studies of specific geologic settings provide a basis for designing and interpreting field measurements.

In general, in resistive terrains composed of entirely coarse-grained aquifer material or in coarse-grained aquifer materials over fine-grained material, the VLF terrain-resistivity method is sensitive to moderate changes in the thickness of aquifer material in the subsurface. The method has a good depth of penetration (100 m in 800 ohm-m terrains) (fig. 5) and can detect conductive layers underlying resistive aquifer layers. If bedrock is within the penetration depth of the method, it affects the phase angle.

In these settings, the inductive terrain-conductivity method measures low conductivity values that may be difficult to accurately read on the instrument. Small changes in the apparent conductivity are related to the thickness of the aquifer material and to the type of bedrock.

In conductive terrains composed of fine-grained material or fine-grained material overlying coarse-grained aquifer material, the VLF terrain-resistivity method has a limited penetration depth (25 m in 50 ohm-m terrains) (fig. 5). Consequently, this method responds only to near-surface changes in resistivity. Changes in apparent resistivity are dependent on the thickness of the fine-grained conductive material and to the type of shallow bedrock.

The penetration depth with inductive terrain-conductivity methods depends on the intercoil spacing and dipole mode, and is relatively independent of the resistivity of the ground. It is sensitive to changes in the position, thickness, and conductivity of individual layers in the subsurface. The apparent conductivity increases as the thickness of the conductive fine-grained material increases. The 40-m vertical-dipole position is affected by the conductivity of the bedrock.

FIELD APPLICATION OF SURFACE-GEOPHYSICAL METHODS

Eight field sites in the glaciated Northeastern United States were selected to (1) verify the results obtained with the hypothetical geoelectric Earth models; (2) show that the combined use of seismic-refraction, dc-resistivity, and two electromagnetic methods may be capable of determining hydrogeologic boundaries and resistivity changes within sand and gravel aquifers; and (3) establish that an empirical relation exists between formation resistivity and grain size. These sites, located in Connecticut, New York, and Maine (fig. 19), represent typical hydrogeologic settings of the region, and are similar to the settings used in the hypothetical models. The sites were selected because the following criteria were met:

1. Well or test-hole data were available;
2. Seismic-refraction data or well data that defined depths to water and bedrock were available;
3. Cultural features such as power lines, pipelines, and fences were minimal;
4. Water-quality problems were not known to exist;
5. Area was large enough to conduct Schlumberger dc-electrical soundings;
6. Land-surface topography was mostly flat;
7. Site had easy field access; and
8. Water-quality information was available.

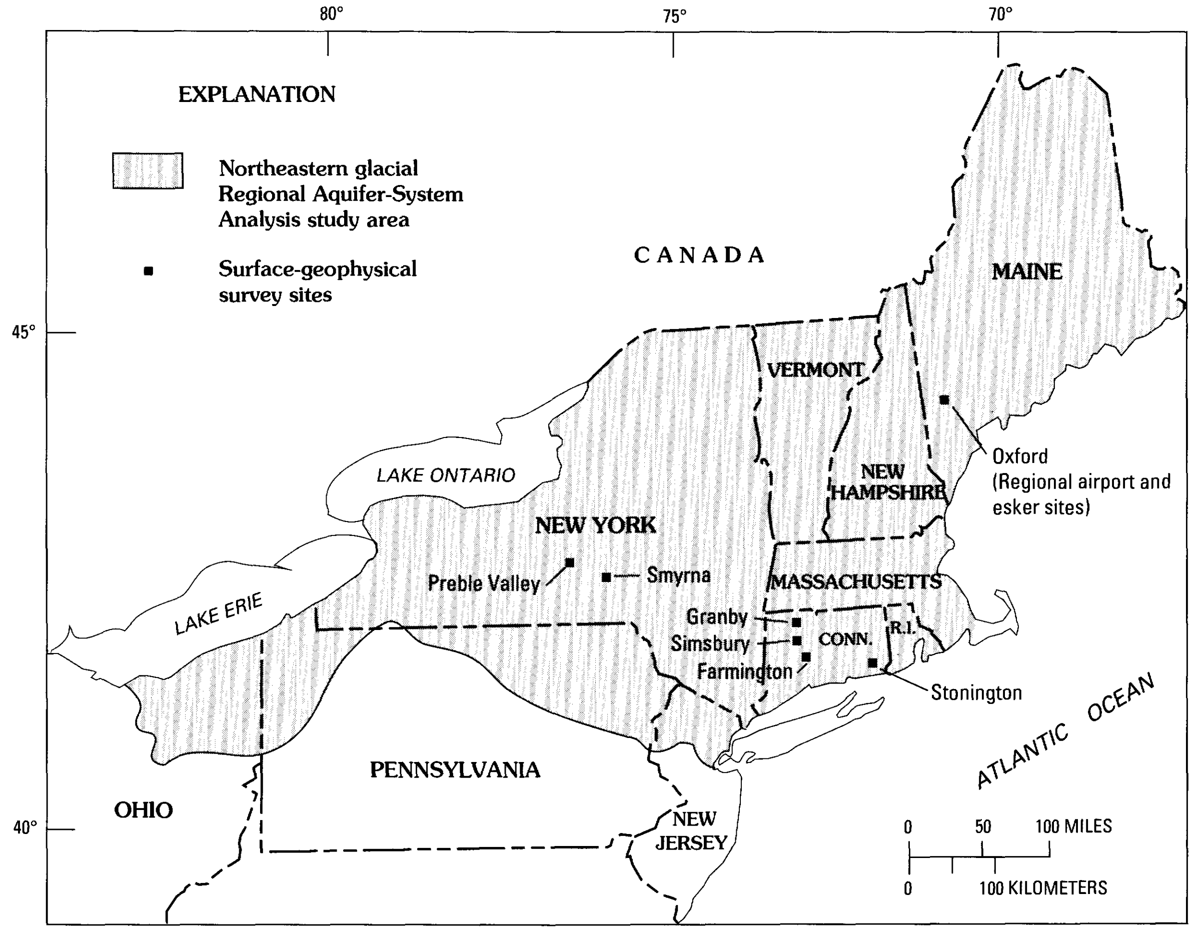


FIGURE 19.—Location of the eight field sites in the glaciated Northeastern United States for testing surface-geophysical methods. (Modified from Lyford and others, 1984.)

Existing information from seismic-refraction profiles, well and test-hole logs, water-quality data, and geologic maps of each site were evaluated prior to the commencement of field work.

A dc-resistivity sounding, a VLF terrain-resistivity survey, and an inductive terrain-conductivity survey were conducted at each site coincident with the location of a seismic-refraction profile. A dc-resistivity sounding was not conducted at one of the sites in Maine (representing an esker) because the assumption of a horizontally layered Earth was not valid.

A Bison model 2390 dc-resistivity instrument was used to conduct Schlumberger electrical soundings; the resulting plot of apparent resistivity as a function of electrode spacing was plotted in the field to ensure that a smooth curve was obtained. The electrode spacing was increased until several readings in bedrock (or the deepest layer of interest) were obtained. Since the thickness and composition of glacial materials can vary substantially across a valley, the dc-resistivity measurements are considered to represent the average lithology and thickness of the subsurface units at a particular sounding site.

Upon completion of the dc-resistivity sounding, a VLF terrain-resistivity survey using a Geonics model EM16R and an inductive terrain-conductivity survey using a Geonics model EM34-3 were run. Intercoil spacings of 10 m, 20 m, and 40 m and both horizontal- and vertical-dipole modes were used on the EM34-3 survey. At most sites, electromagnetic readings (both VLF and terrain-conductivity) were taken at 30- or 60-m intervals along the dc-sounding and seismic-refraction lines. At the esker site in Maine, the electromagnetic profiles were perpendicular to the assumed axis of the esker.

RESULTS AND INTERPRETATIONS OF FIELD STUDIES

A geologic section showing land surface, water table, and depth to bedrock was constructed from seismic-refraction and test-hole data. Next, the dc-resistivity sounding data were interpreted to obtain general resistivity values for the hydrogeologic layers at each site. The field-generated dc-resistivity sounding curves were smoothed by shifting individual segments and eliminating cusps caused by lateral inhomogeneities (Zohdy and others, 1974). Six values of apparent resistivity for each log cycle of current electrode spacing were then chosen and entered into a computer inversion program (Zohdy, 1974). The result was a geoelectric Earth model with a large number of layers based on small electrical property variations. Many of these layers were combined manually and used with the seismic-refraction and test-hole data to construct a simplified four- or five-layered geoelectric Earth model. A major limitation of this simplified geoelectric Earth model is the assumption that each subsurface layer is horizontal and homogeneous over the distance between the electrodes. Small-scale lateral variations in layer thickness or resistivity of individual layers cannot be detected using this method. The interpreted resistivity values for individual layers were used with the geologic logs of nearby wells and test holes to develop a relation between grain size and electrical resistivity.

The VLF forward-modeling computer program was used then to refine the simplified geoelectric Earth model so that it agreed with the field VLF data. Several simplifying assumptions had to be made in the VLF modeling process since a four-layer Earth model would have eight unknowns—the thickness and resistivity of each layer. Varying all of the unknowns could lead to an unreasonable subsurface model. In general, depths to the water table and to bedrock were assumed to be known from the seismic-refraction data, and were not varied during the VLF modeling process. The resistivity of the unsaturated material and the coarse-grained aquifer material was assumed to be constant. Thus, the thickness and resistivity of the fine-grained material and the resistivity of the bedrock are unknowns. To match the apparent resistivity and phase angle determined in the field by the VLF survey, some or all of these variables were changed during the modeling process. The changes depended on the specific geologic setting and results of the hypothetical modeling process. Typically, four to six modeling runs of the program were needed to match the modeled VLF data to the field data.

An interpreted geoelectric Earth model resulted from this process, but the question of whether or not it was a reasonable solution remained. Because the response of both electromagnetic methods to lateral and vertical variations in conductivity or resistivity is different, the conjunctive use of both methods would define an improved geoelectric Earth model. To accomplish this, data from the VLF model were used as input for the terrain-conductivity forward-modeling program. The output of this model then was compared with the EM34–3 terrain-conductivity field data. Points along the electromagnetic profile then were computed and compared with the measured field data. If the field data varied substantially, the points were noted as problem areas and the differences were attributed to one or more of the following: (1) errors in obtaining field measurements of electromagnetic data, (2) cultural interference with field measurements, (3) a nonreasonable VLF model, and (4) the presence of unknown water-quality problems.

COARSE-GRAINED AQUIFER MATERIAL OVERLYING CRYSTALLINE BEDROCK

A stratified-drift deposit located in Stonington, Conn., (fig. 20) represents a coarse-grained aquifer overlying crystalline bedrock. A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted in an open field parallel to and 15 m from a dirt road. Power and telephone lines along the road service a baseball field in the area. Seismic-refraction data from line *B–B′* and a geologic log, water level, and water-quality data from well SN-164 were available from a previous study of this area (Bingham, 1991). The depth to the water table determined from seismic-refraction data agrees with the water level in the well, but the depth to bedrock determined from seismic-refraction data is about 4 m deeper than the depth determined from the well and test holes.

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model are shown in figure 21. This multilayered geoelectric Earth model was simplified into a four-layer model by using the seismic-refraction data for depths to the water table and bedrock, and by combining layers with similar resistivities. Comparison of this simplified four-layer geoelectric Earth model with the geologic logs from well SN-164 and the two test holes SN-143th and SN-144th, drilled for this study (fig. 22), shows that the top two geoelectric layers (450 and 2,000 ohm-m) can be correlated with unsaturated soil and unsaturated, coarse-grained stratified drift, respectively. The third geoelectric layer (500 ohm-m) represents the saturated aquifer material that varies in grain size from very fine sand to gravel. The lowest geoelectric layer (1,600 ohm-m) represents crystalline bedrock. The specific conductance of ground water from the coarse-grained stratified drift (well

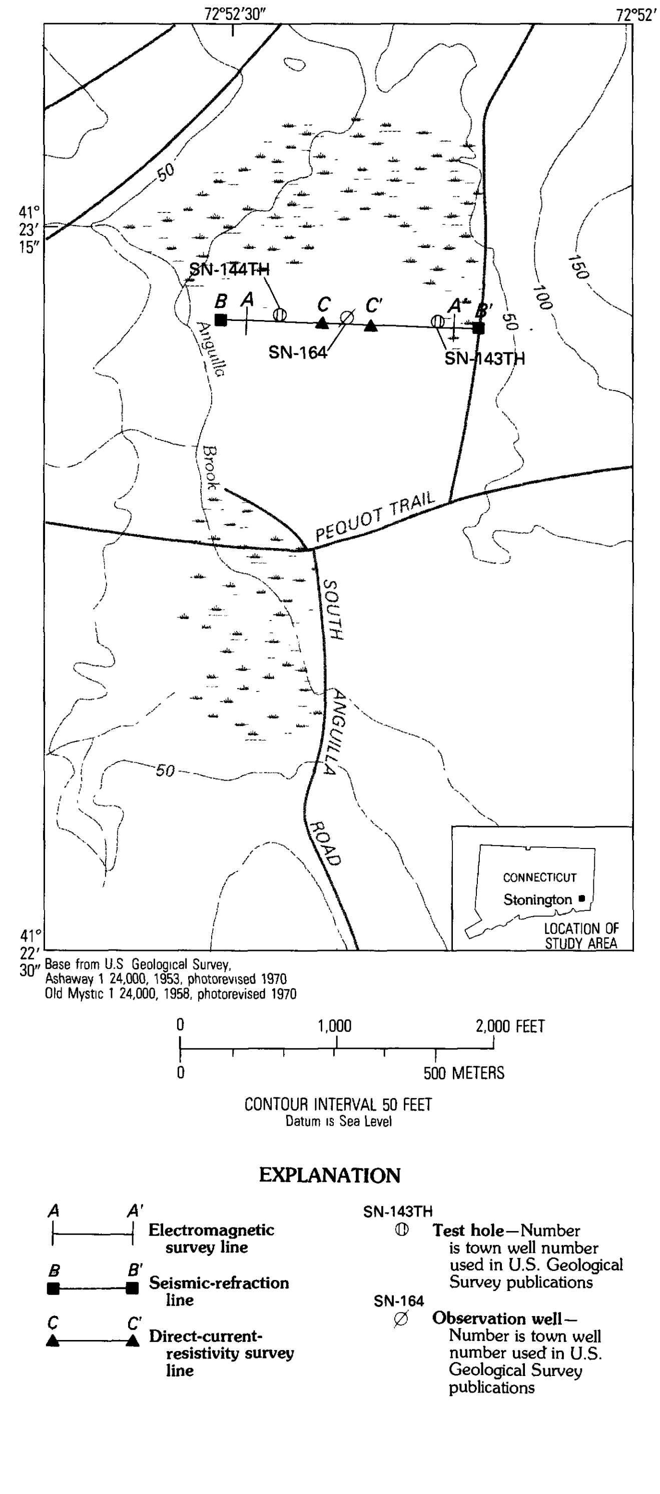


FIGURE 20.—Location of the study site in Stonington, Conn., including wells, test holes, and surface-geophysical survey lines.

SN-164) was 102 microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C) on August 17, 1982.

This field site is similar to the hypothetical model shown on the right side of figure 9. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 23. The data show generally high apparent resistivities of 1,200–1,700 ohm-m in the middle of the line and lower values, 300–700 ohm-m, at each end of the line. The phase angles are all less than 45°, which indicates relatively conductive material over resistive material (saturated, coarse-grained stratified drift over crystalline bedrock).

In the VLF forward-modeling interpretation, the electrical resistivities, the thicknesses of layers 1 and 2 (unsaturated soil and stratified drift) and the thickness of layer 3 (saturated stratified drift) were not varied. The only variables in the modeling process were the electrical resistivities of layers 3 and 4 (saturated stratified drift and bedrock).

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 23. The apparent resistivity and phase angles generated in the modeling program closely matched the field values. The interpreted electrical resistivity of layer 3 (saturated stratified drift) is highest in the middle of the section and decreases at both ends. Because the specific conductance of ground water is assumed to be constant across this section, this resistivity change may indicate that the coarsest material is in the center of the section and that the amount of fine material increases toward each end. The modeled resistivity of the bedrock also varies along the section and is largely dependent on the depth of penetration of the VLF terrain-resistivity method and the degree and depth of water-filled fractures in the bedrock. The difference in the number of fractures at depth, and hence the bulk resistivity of the bedrock, probably accounts for the resistivity change of this unit.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 23) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 24). The computed values agree with the field values with the exception of two values: the 20-m vertical-dipole readings at stations 60 and 120. Because only these two field readings are high, and because these readings differ substantially from adjacent values, they may reflect nearby electrical interference from telephone or power lines. The close agreement of the remaining data points suggests that the geoelectric Earth model (fig. 23) interpreted from the dc-resistivity, terrain-resistivity, and seismic-refraction data is a reasonable model of the subsurface. Geologic logs from the two test holes and one

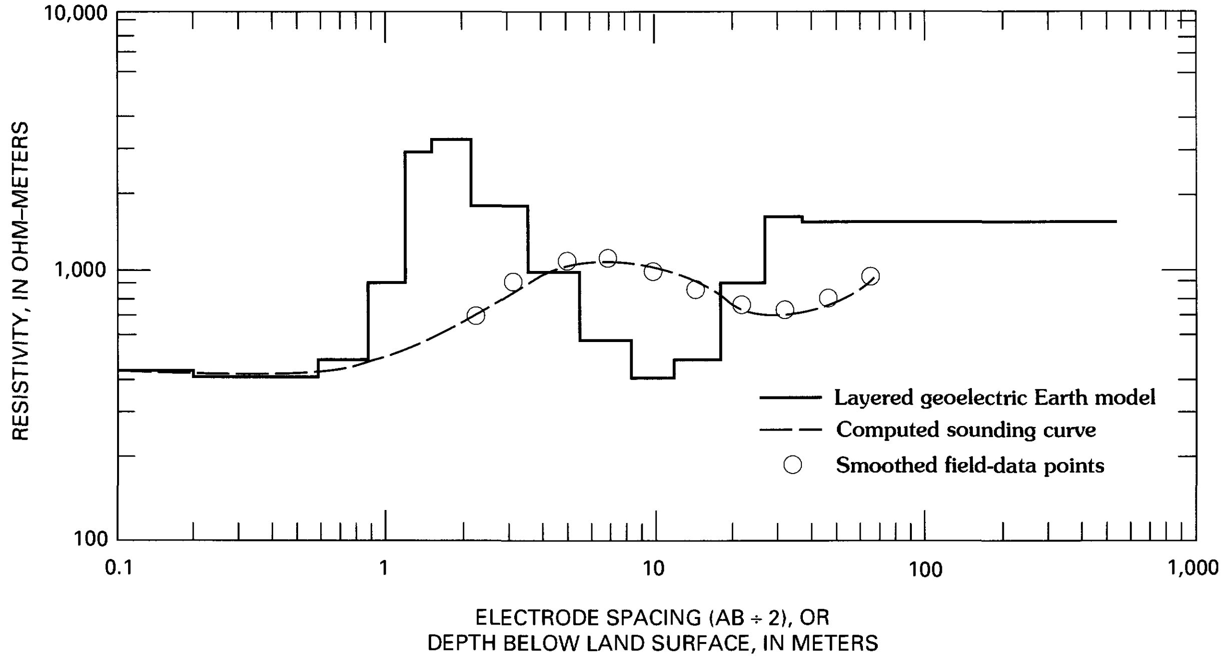


FIGURE 21.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Stonington, Conn.

well along this profile indicate that the center of the profile has slightly coarser grained material than the ends of the profile (fig. 22).

COARSE-GRAINED AQUIFER MATERIAL OVERLYING SEDIMENTARY BEDROCK

Stratified-drift deposits located in Granby, Conn., and Smyrna, N.Y., represent coarse-grained aquifers overlying sedimentary bedrock. At the Granby site (fig. 25), a dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile, were conducted parallel to the axis of the valley, 200–300 m from a paved road. Seismic-refraction data from line *B–B′* and a geologic log and water-level data from well GR-330 were available at this site. Water-quality data were collected on February 14, 1985. The depths to water table and bedrock determined from seismic-refraction data are similar to data from well GR-330, although complete seismic-refraction coverage was not available.

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting geoelectric Earth model are shown in figure 26. This multilayered geoelectric Earth model was simplified into a five-layer model by using the seismic-refraction data for depth to water table and bedrock and by combining layers having similar resistivities. Comparison of this simplified five-layer geoelectric Earth model with the geologic logs of well GR-330 and test holes GR-25th and GR-26th (fig. 27) shows that the top two geoelectric layers (425 and 7,000 ohm-m) can be correlated with unsaturated soil and unsaturated, coarse-grained stratified drift respectively. The next two layers (2,000 and 450 ohm-m) represent the saturated aquifer material, with the lower unit reflecting the combined effect of a thin layer of till beneath a layer of slightly finer-grained aquifer material. The bottom geoelectric layer was initially assumed to be all sedimentary bedrock. This sounding actually included two bedrock types on each side of a major fault. The resistivity value, therefore, is not indicative of either rock type. The specific conductance of ground water from the coarse-grained stratified drift (well GR-330) was 130 μS/cm at 25°C on February 14, 1985.

This field site is similar to the hypothetical model shown on the left side of figure 9. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 28. The data show a low apparent resistivity value of 100 ohm-m at the southern end (*A*) of line *A–A′*, and an increase to 200 ohm-m near the northern end of the line. The phase angles are all greater than 45°, which indicates resistive over conductive material (saturated, coarse-grained stratified drift over sedimentary bedrock).

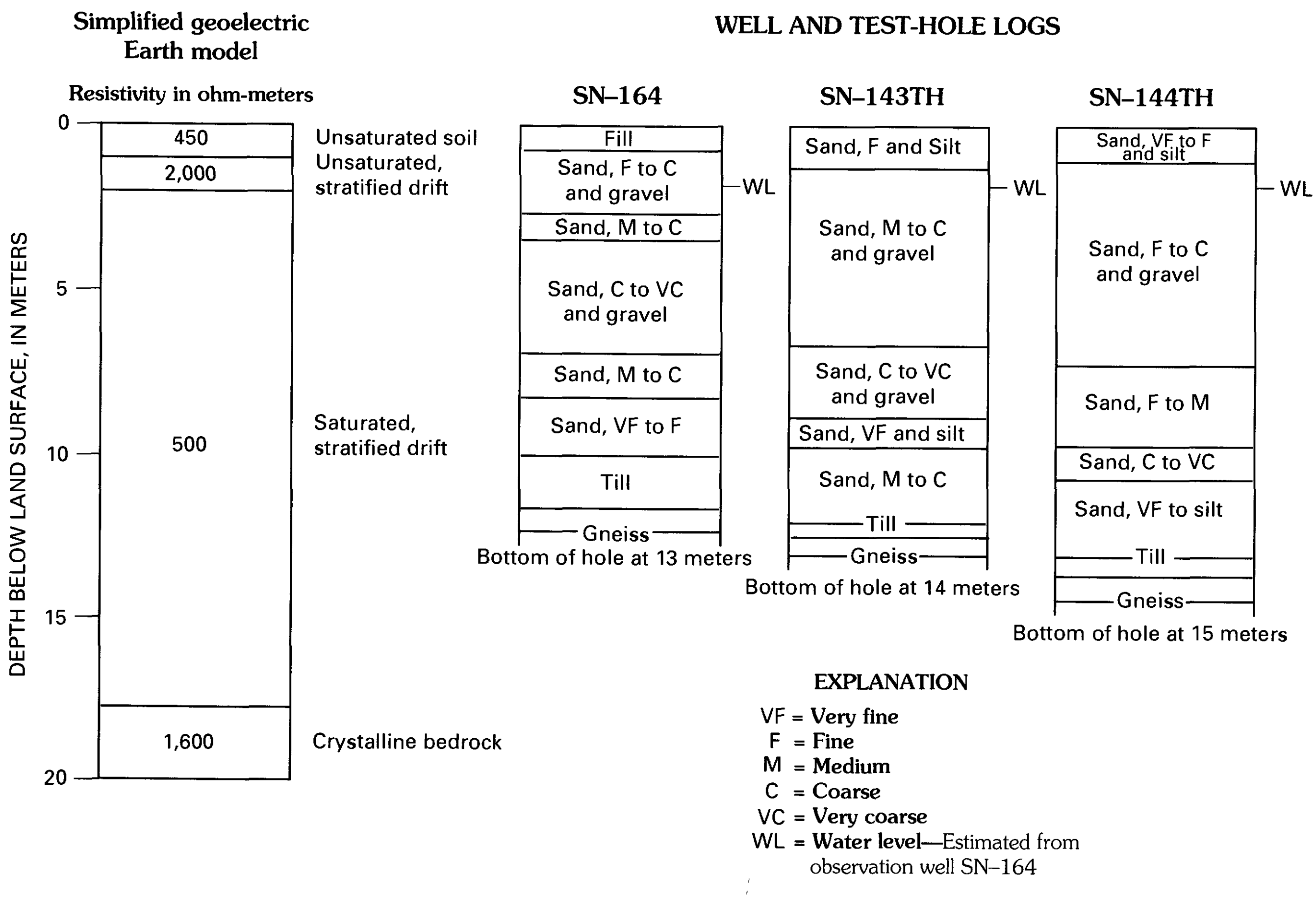
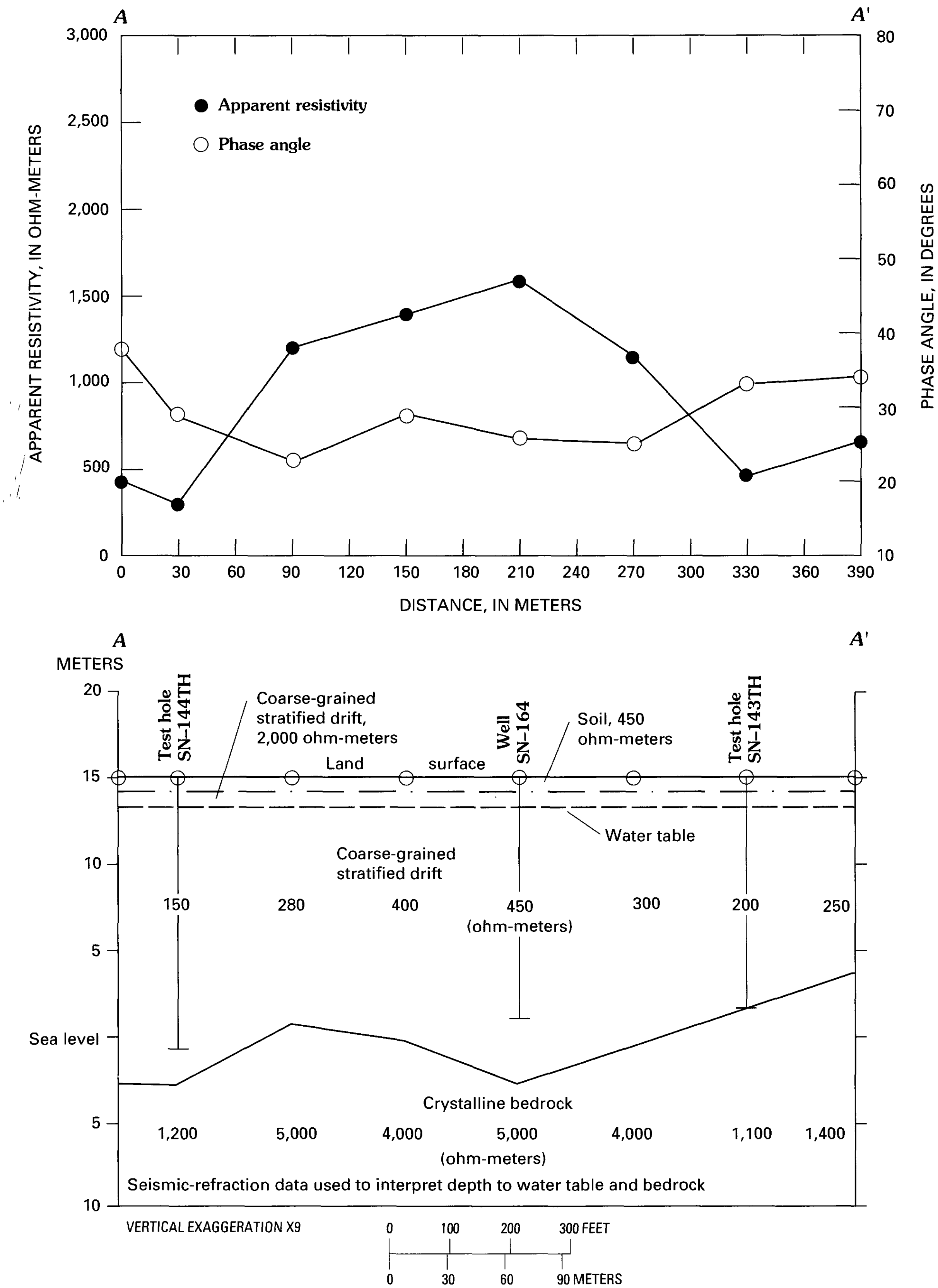


FIGURE 22.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Stonington, Conn.

In the VLF forward-modeling interpretation, electrical resistivities and thicknesses of layers 1 and 2 (unsaturated soil and stratified drift) were held constant. Layers 3 and 4 were combined into one layer, representing the saturated, coarse-grained aquifer material. The thickness of this layer was varied in the modeling process only where seismic-refraction data were not available. Therefore, the variables in the modeling process were the electrical resistivities of layers 3 and 4 (saturated stratified drift and bedrock) and, in some areas, the thickness of the saturated stratified drift.

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 28. The apparent resistivity and phase angles generated in the modeling program closely matched the field data. Depth to bedrock, determined from the modeling process where seismic-refraction data were unavailable, had mixed results. The depths were similar to those in test hole GR-25th and well GR-330. However, modeled depth was substantially in error at test hole GR-26th, near station 0. The bedrock resistivity was generally low (35–115 ohm-m), but at stations 420 and 480, it increased to 150 and 135 ohm-m, respectively. A geologic map of the Tariffville quadrangle (Schnabel and Eric, 1965) shows the location of a major Triassic boundary fault that separates sedimentary and crystalline bedrock in this area (fig. 25). The change in bedrock resistivity was, therefore, interpreted as a change in bedrock type. The change in bedrock type was later confirmed with rock samples from test holes GR-25th and GR-26th (fig. 27). The low resistivity of the crystalline bedrock (as compared to the Stonington and Oxford sites) is interpreted to be caused by a greater number of fractures in the crystalline bedrock associated with the boundary fault and the possibility of more conductive water in these fractures. Specific conductance of ground

FIGURE 23.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site in Stonington, Conn. ▶


A
A'
Apparent resistivity
Phase angle
APPARENT RESISTIVITY, IN OHM-METERS
PHASE ANGLE, IN DEGREES
DISTANCE, IN METERS
METERS
Test hole SN-144TH
Coarse-grained stratified drift, 2,000 ohm-meters
Land surface
Well SN-164
Soil, 450 ohm-meters
Test hole SN-143TH
Water table
Coarse-grained stratified drift
150
280
400
450 (ohm-meters)
300
200
250
Sea level
Crystalline bedrock
1,200
5,000
4,000
5,000
4,000
1,100
1,400
(ohm-meters)
Seismic-refraction data used to interpret depth to water table and bedrock
VERTICAL EXAGGERATION X9
0 100 200 300 FEET
0 30 60 90 METERS

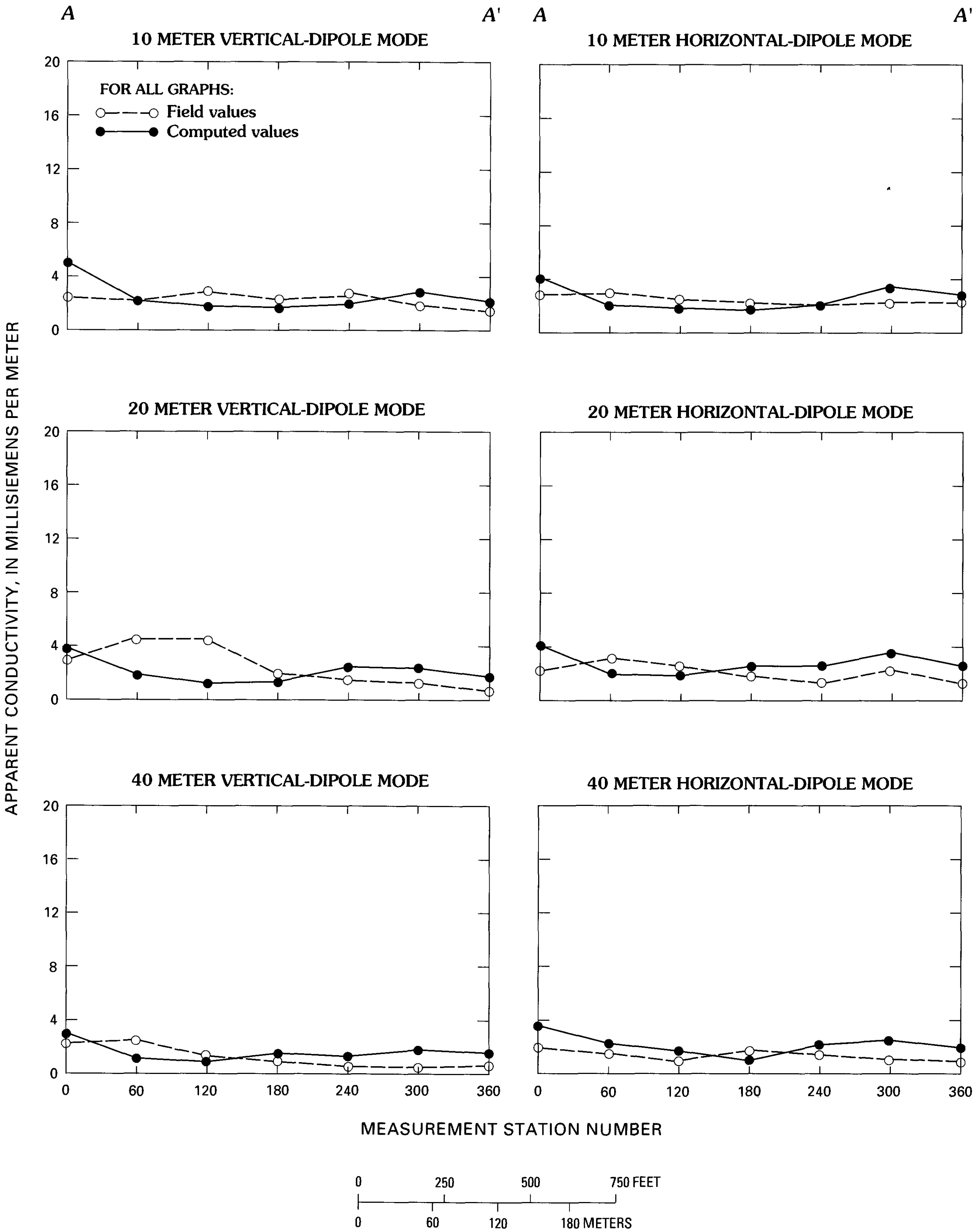


FIGURE 24.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Stonington, Conn.

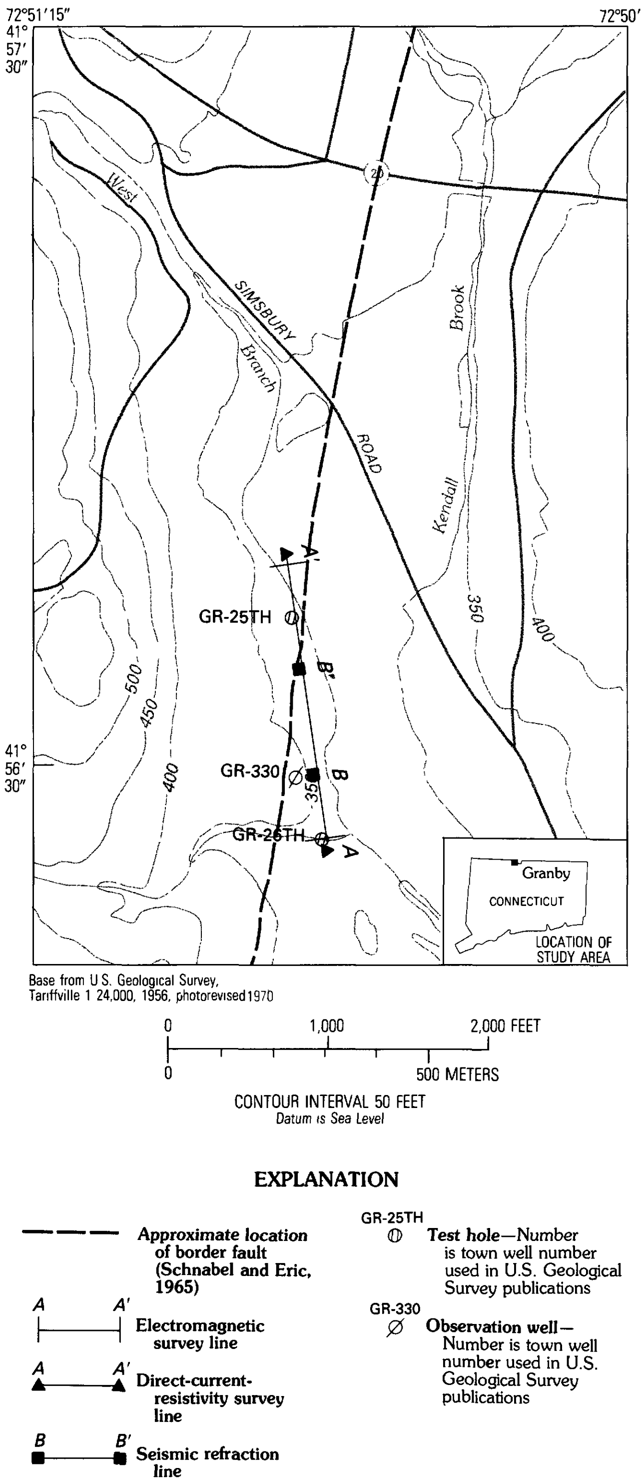


FIGURE 25.—Location of the study site in Granby, Conn., including wells, test holes, and surface-geophysical survey lines.

water from sedimentary rocks of the Upper Connecticut River basin ranges from 86 to 2,150 μS/cm at 25°C (Ryder and others, 1981, p. 59).

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 28) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 29). Data from stations 0 and 300 do not agree, possibly because field data at these points are poor or the geoelectric Earth model was interpreted incorrectly. In addition, all of the computed 40-m vertical-dipole readings are too high. The field values indicate that the bedrock is more resistive than the value obtained in the VLF modeling process. The causes for this observation are the oversimplification of the interpreted Earth model and the different penetration depths of the two electromagnetic methods. The penetration depth of the VLF terrain-resistivity method is limited in conductive material (at 90 ohm-m it penetrates 35 m of material), which at this site consists of a thin glacial till and upper fractured and saturated sedimentary and crystalline bedrock. The inductive terrain-conductivity method maintains its depth penetration in this setting (penetration depth of the vertical-dipole mode at the 40-m spacing is about 60 m) and therefore measures deeper, more resistive bedrock layers. The detailed dc-resistivity data (fig. 26) indicate that the bedrock is not uniform, but rather is layered. The top 30 m of bedrock has an interpreted resistivity value of 175 ohm-m and is underlain by a 400 ohm-m layer.

A stratified-drift deposit located in Smyrna, N.Y., (fig. 30) represents a second example of a coarse-grained aquifer overlying sedimentary bedrock. A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted perpendicular to the axis of the valley. Seismic-refraction data from line *B–B′* were available from a previous study (Reynolds and Brown, 1984), and water-quality data were collected at well 13–23 on June 11, 1985. A comparison of the depths to the water table and bedrock determined from seismic-refraction data with the log of test hole 14–21 is difficult at this site because the test hole is located 200 ft from the seismic-refraction line. Water-level measurement was not obtainable for this well. Well 13–23 did not have a log or water level because it is a domestic well and only water-quality information from the coarse-grained stratified drift was available.

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model are shown in figure 31. This multilayered geoelectric Earth model was simplified into a four-layer model by using the

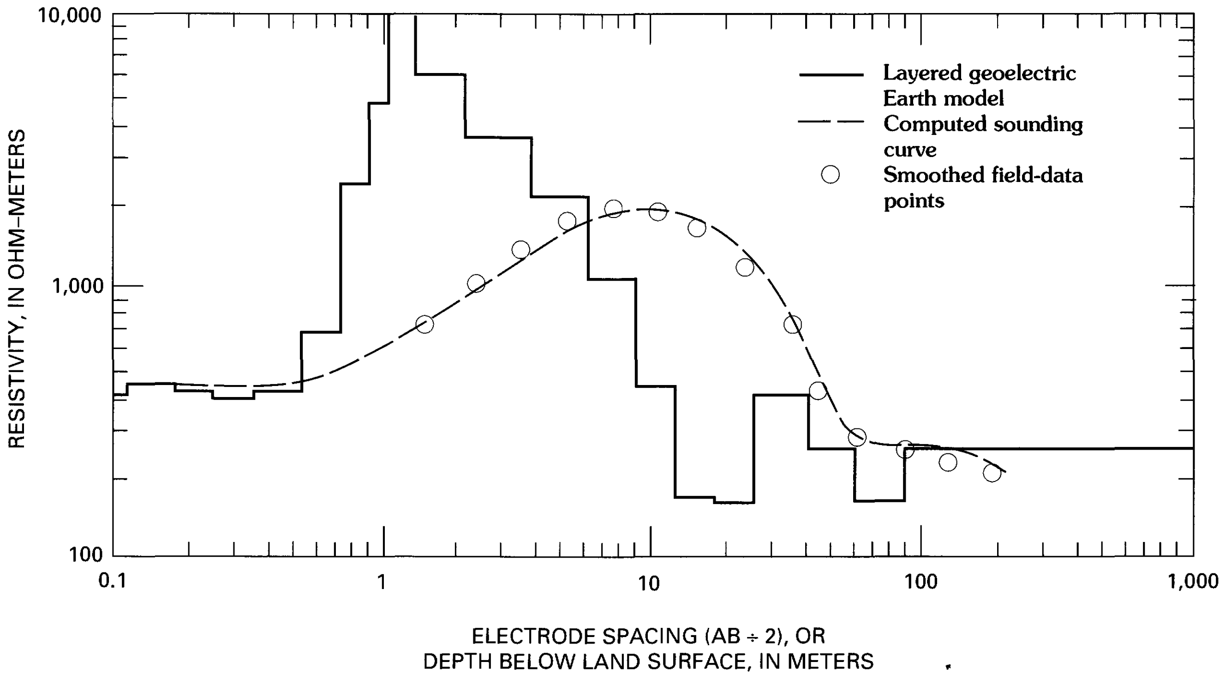


FIGURE 26.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Granby, Conn.

seismic-refraction data for depth to bedrock and by combining layers with similar resistivities. Comparison of the simplified four-layer geoelectric Earth model with the geologic log of test hole 14–21 (fig. 32) shows that the top two geoelectric layers, 700 and 2,200 ohm-m, can be correlated with unsaturated soil and coarse-grained material and that the bottom two layers, 550 and 300 ohm-m, represent saturated, coarse-grained material and sedimentary bedrock. The interpreted resistivity values of the saturated coarse-grained layer (550 ohm-m) is substantially lower than the 2,000 to 2,500 ohm-m determined for coarse-grained drift at Granby, Conn. This lower value is due primarily to the high conductivity of the ground water at the Smyrna site. The specific conductance of the ground water from the coarse-grained stratified drift (well 13–23) at Smyrna was 710 μS/cm at 25°C as compared to 130 μS/cm at 25°C for the stratified drift at Granby. The more conductive ground water substantially lowers the bulk resistivity of the coarse-grained aquifer.

This field site is similar to the hypothetical model shown on the left side of figure 9. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 33. These data show that the apparent resistivity varies from 150 to 300 ohm-m. The phase angles are all 45° or slightly higher, reflecting slightly more resistive material overlying slightly more conductive material (the unsaturated and saturated stratified drift over sedimentary bedrock).

In the VLF forward-modeling process, the electrical resistivities of layers 1 and 2 (unsaturated soil and stratified drift) and the thickness of layer 1 were held constant and the depths to water table and bedrock, determined from seismic-refraction data, were specified. Therefore, variables in the modeling process were the resistivities of layers 3 and 4 (saturated stratified drift and bedrock).

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 33. The apparent resistivities and phase angles generated in the modeling program closely matched the field data. The resistivity of both saturated stratified drift (160–300 ohm-m) and bedrock (133–330 ohm-m) did not vary greatly.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 33) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 34). All stations show a good correlation at all intercoil spacings except for station 0. At this station, the field values are substantially greater than the predicted values. Station 0

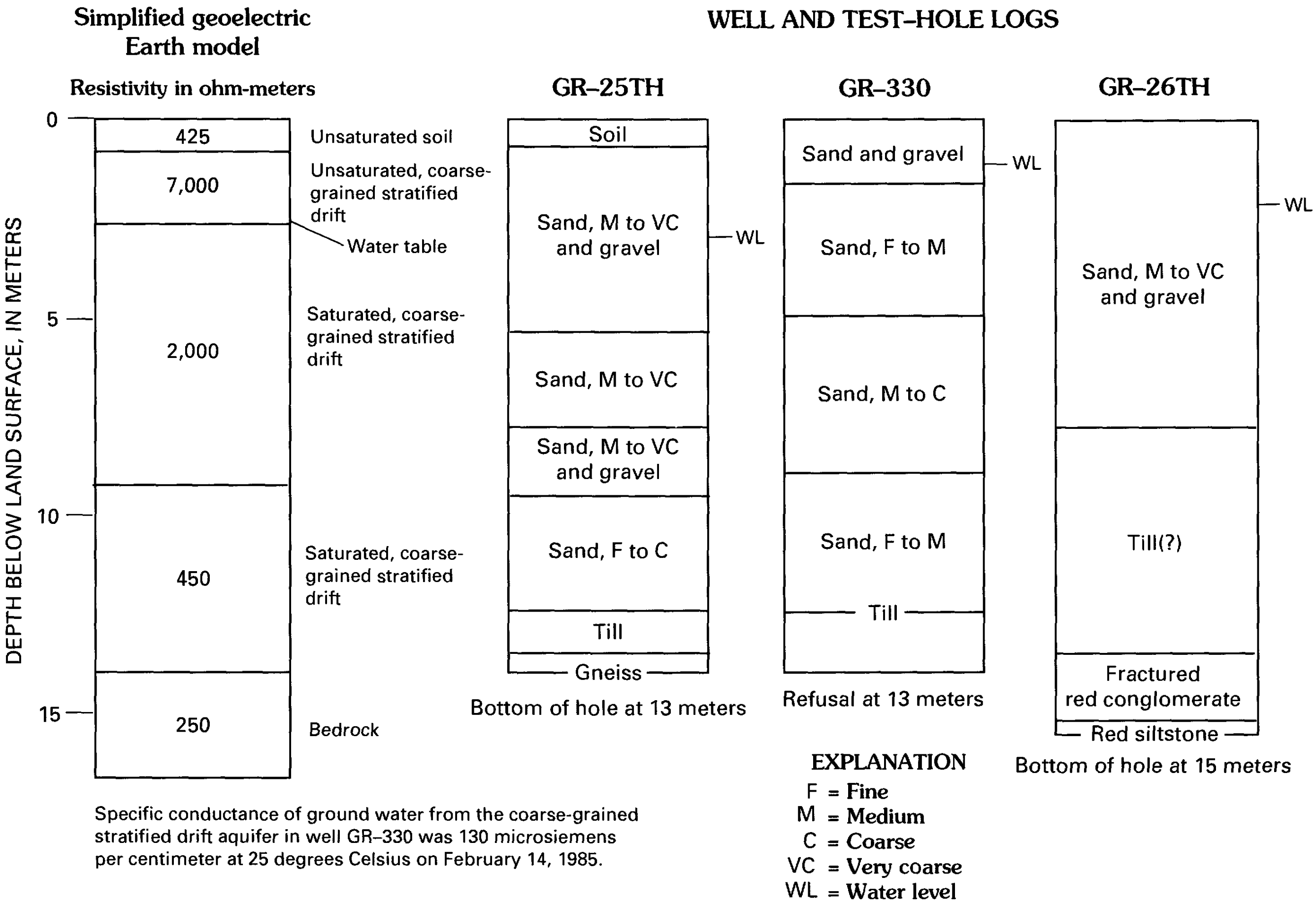


FIGURE 27.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Granby, Conn.

is located next to a state highway that receives heavy applications of deicing chemicals each winter. The large field readings of this station could be due to the interference from power lines and guard rails along the highway or the presence of deicing chemicals in the ground water.

FINE-GRAINED MATERIAL OVERLYING SEDIMENTARY BEDROCK

A stratified-drift deposit located in Simsbury, Conn., (fig. 35) represents fine-grained material overlying sedimentary bedrock. A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted along a dirt road that crosses the axis of the valley. Sources of cultural interference occurred at the west end of the profile from railroad tracks and from a construction company workshop with power and telephone lines. The remainder of the area, which is used partly for agricultural activities, was a relatively flat flood plain free from cultural interference. Seismic-refraction data from line *B–B′*, and the geologic log of well SI–363 were available from an ongoing study of this area (Melvin and Bingham, 1991). Specific conductance of ground water in the fine-grained stratified drift and depth to the water table was measured in well SI–363 on February 11, 1985. The depths to the water table and bedrock determined from seismic-refraction data agree with the limited data from well SI–363.

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model are shown in figure 36. This multilayered geoelectric Earth model was simplified into a four-layer model by using the depths to water table and bedrock determined from seismic-refraction data and by combining layers with similar resistivities. Comparison of this simplified four-layer geoelectric Earth model with the geologic log of well SI–363 (fig. 37) shows that the top layer, with a resistivity of 800 ohm-m, can be correlated with the

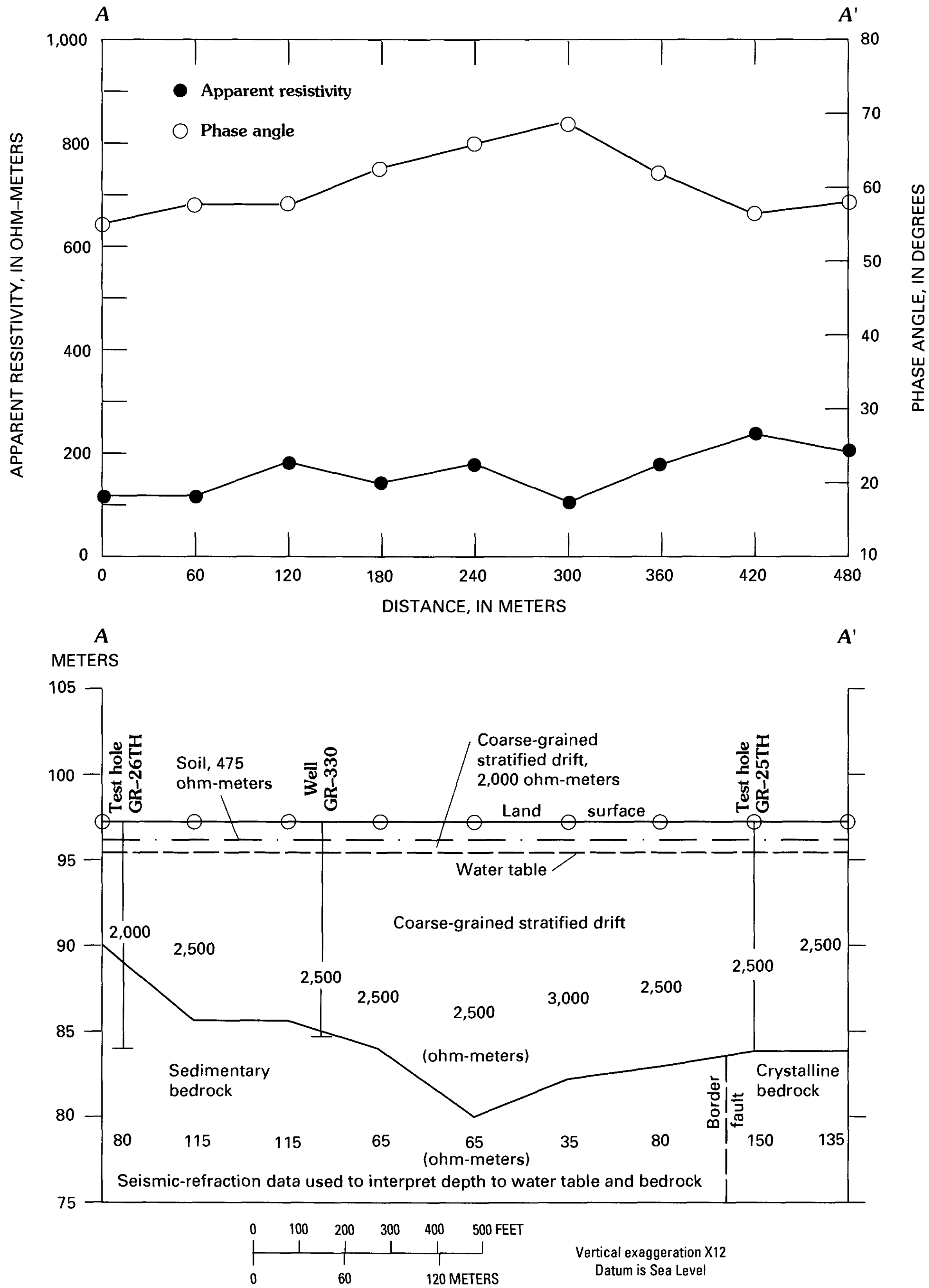


FIGURE 28.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site in Granby, Conn.

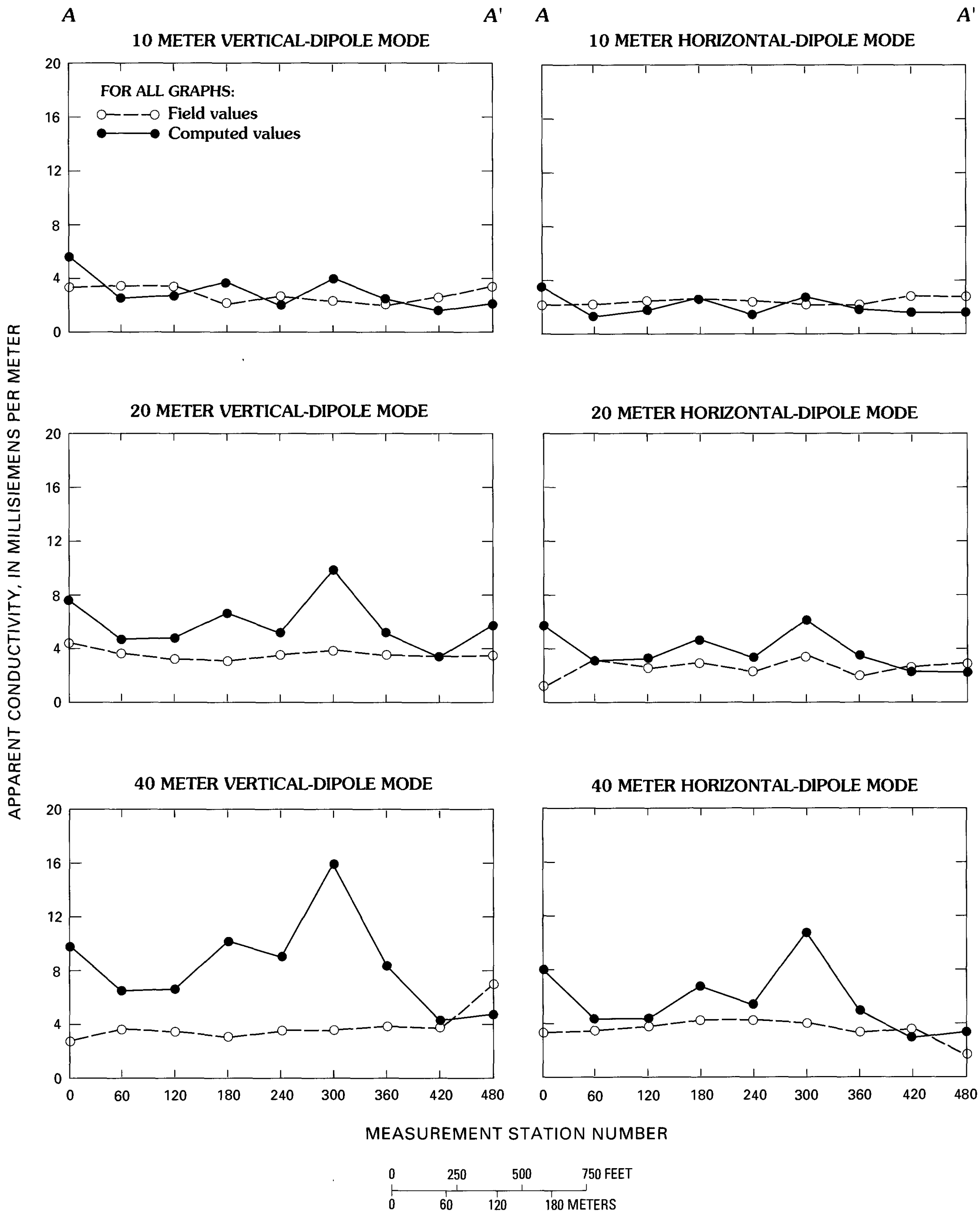


FIGURE 29.—Graphs showing field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Granby, Conn.

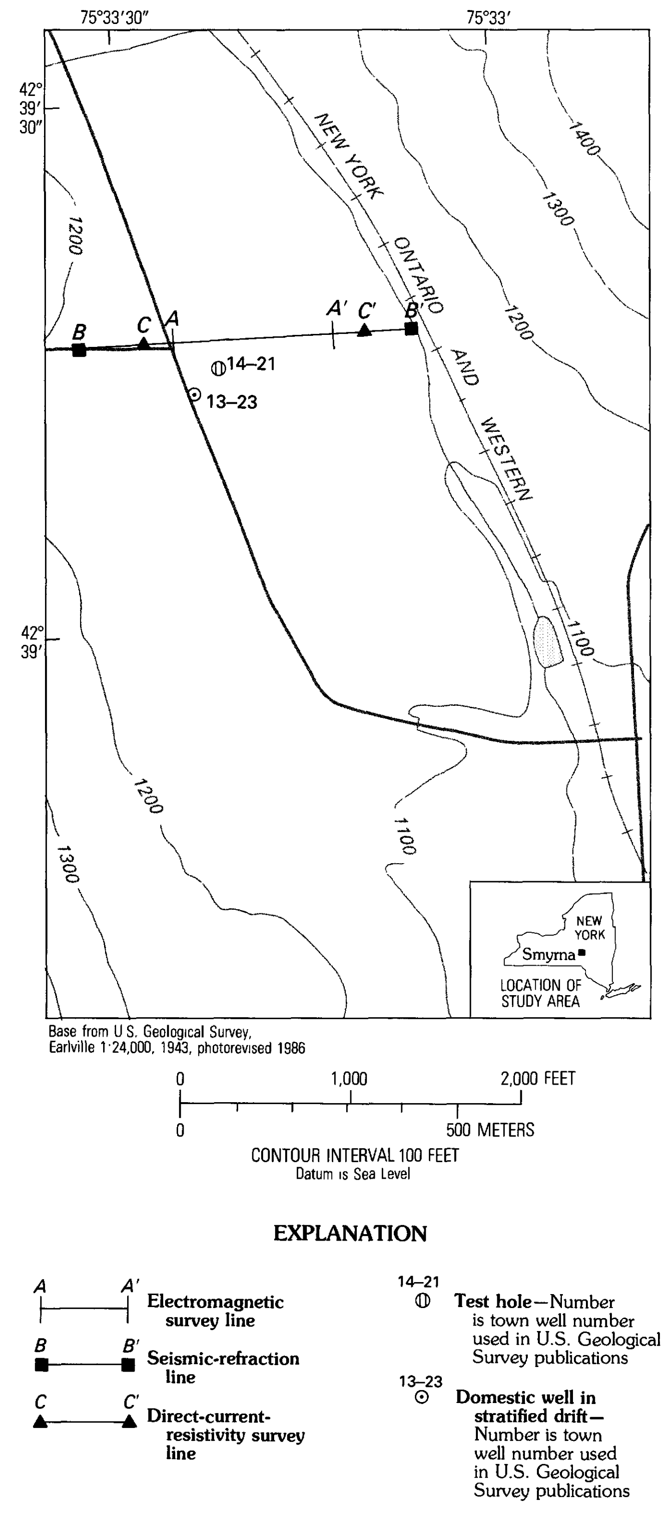


FIGURE 30.—Location of the study site in Smyrna, N.Y., including wells, test holes, and surface-geophysical survey lines.

combined unsaturated stratified drift and soil layers. The second layer, with a resistivity of 500 ohm-m, represents a thin layer of saturated coarse-grained material. The third layer, with a resistivity of 140 ohm-m, represents a very thick section of fine-grained material, and the lowest layer, with a resistivity of 200 ohm-m, represents the sedimentary bedrock. The specific conductance of the ground water in the fine-grained stratified drift in the well was 180 μS/cm at 25°C.

This field site is similar to the hypothetical model shown on the left side of figure 10, except that a shallow resistive coarse-grained unit is present. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 38. The field measurements generally have a low apparent resistivity, 30–150 ohm-m, and phase angles of 45°–60°, indicating resistive over conductive material. These readings reflect the limited penetration of the VLF method in conductive terrains (approximately 25 m of penetration in 50-ohm-m material) and the presence of thin layers of resistive unsaturated and saturated, coarse-grained material above the thick conductive fine-grained section. At this site, the VLF terrain-resistivity method cannot detect resistivity changes in the bedrock.

The electrical resistivity determined by the dc-resistivity sounding, of layer 1 (soil), layer 2 (saturated, coarse-grained stratified drift), and layer 4 (bedrock), as well as the depths to water table and bedrock, as determined from the seismic-refraction profile, were not varied in the VLF forward-modeling process. Variables in the modeling process were therefore, thickness of saturated, coarse-grained material and thickness and resistivity of fine-grained material.

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 38. A good match between field and calculated VLF apparent resistivities and phase angles was obtained. This interpretation shows a thin, discontinuous high-resistivity layer of saturated, coarse-grained material overlying a conductive (16–140 ohm-m) layer or section of saturated, fine-grained material. The resistivity of the deep sedimentary bedrock had no effect on the model calculations.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 38) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 39). Field data do not agree with the computed values obtained at the beginning of the profile (stations 0–300) but agree beyond this point. Because the values measured in the field were anomalously high, it was inferred that either an unknown water-quality problem exists at this site or

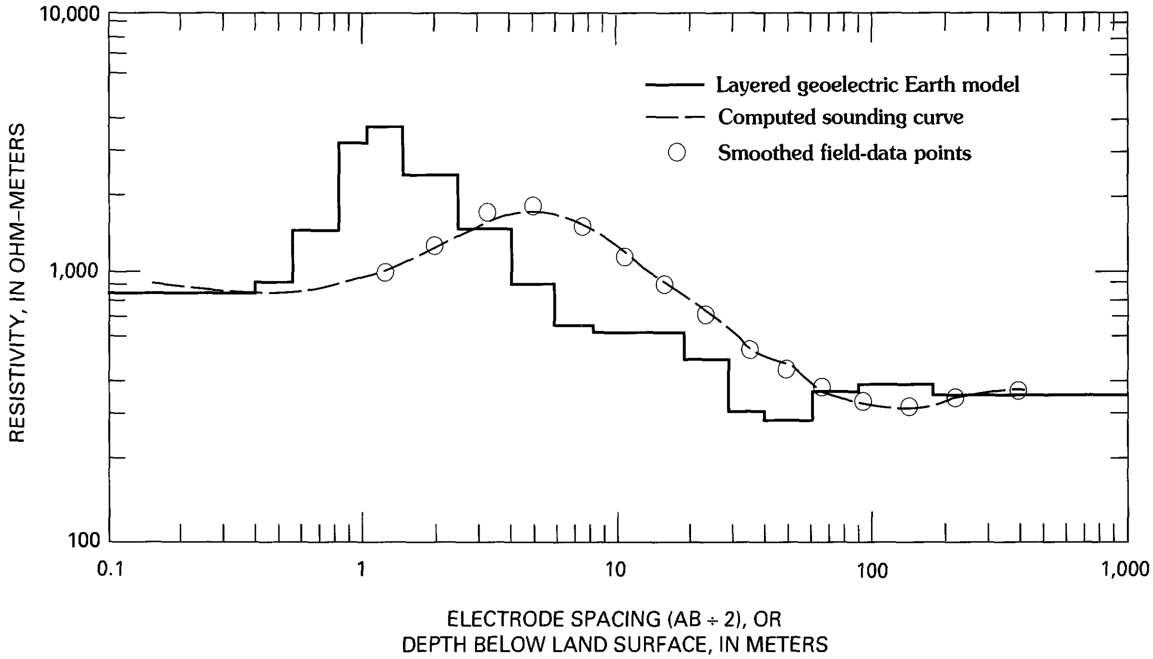


FIGURE 31.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Smyrna, N.Y.

cultural interference strongly affects the readings. Readings could not be made in this area at the 40-m intercoil spacing; therefore, the high readings are assumed to be caused by cultural interference.

COARSE-GRAINED AQUIFER MATERIAL OVER FINE-GRAINED MATERIAL OVERLYING SEDIMENTARY BEDROCK

Stratified-drift deposits located in Farmington, Conn., and Preble, N.Y., represent coarse-grained aquifer material over fine-grained material overlying sedimentary bedrock. The Farmington, Conn., site (fig. 40) is located in the bottom of a flat valley with no nearby cultural interference, and is underlain by an arkosic sandstone (Simpson, 1966). A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted in an open field perpendicular to the axis of the valley. Seismic-refraction data from line *B–B′*, the geologic log and water-level data from well F–282 and test hole F–68th, and water-quality data from well F–295 were available from a previous investigation (Mazzaferro, 1980). The depth to the water table determined from seismic-refraction data agrees with the test-hole and well data, and the depth to bedrock agrees in general with other test-hole data in the valley (Mazzaferro, 1980).

The smoothed plot of the field-data points from the dc-resistivity sounding, computed sounding curve, and resulting layered geoelectric Earth model are shown in figure 41. This multilayered geoelectric Earth model was simplified into a five-layer model by using the seismic-refraction data for depths to water table and bedrock, the geologic log from test hole F–68th, and by combining layers with similar resistivities. Comparison of this simplified five-layer geoelectric Earth model with the geologic log (fig. 42) shows that the two top layers, with resistivities respectively of 900 and 1,740 ohm-m, are unsaturated soil and coarse-grained material. It is underlain by a saturated, coarse-grained unit with a resistivity of 560 ohm-m, which, in turn, is underlain by a thick, fine-grained unit with a resistivity of 240 ohm-m. The entire section is underlain by sedimentary bedrock with a resistivity of 140 ohm-m. The specific conductance of the ground water from the coarse-grained stratified drift (well F–295) was 162 μS/cm at 25°C on May 17, 1977.

This field site is similar to the hypothetical model shown in figure 11. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 43. The field data show low apparent-resistivity values, 150–400 ohm-m, and phase angles greater than 45°, indicating resistive material (saturated, coarse-grained stratified drift) over conductive material (fine-grained stratified drift and sedimentary bedrock).

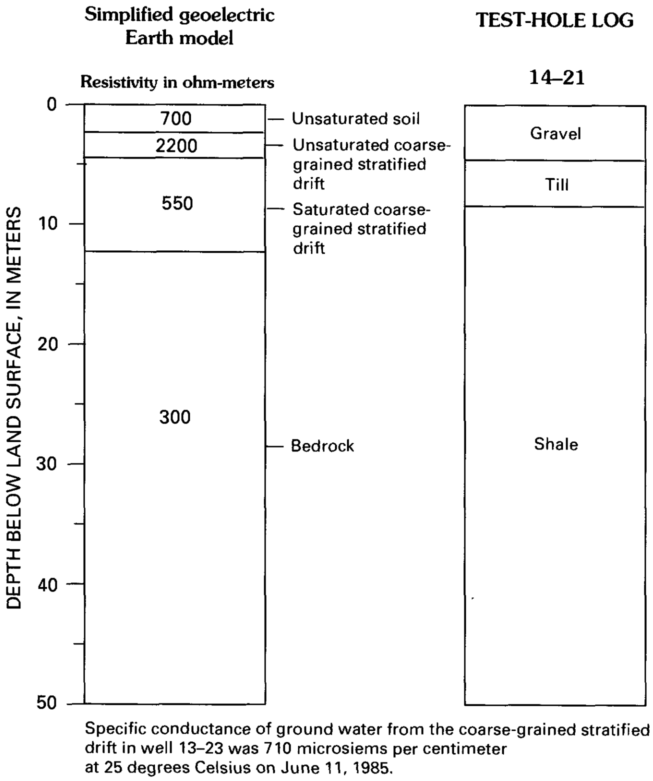


FIGURE 32.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Smyrna, N.Y.

In the VLF model, the top two layers of the simplified geoelectrical model were combined into one layer with a resistivity of 1,250 ohm-m. In the VLF forward-modeling process, the resistivity of layer 1, soil and unsaturated stratified drift, was decreased from 1,250 ohm-m to 300 ohm-m and then held constant. One reason for the different values of the upper layer between the two methods is that the low resistivity soil could have been absent from the area near the center of the dc-resistivity spread. The resistivities of layer 2, saturated, coarse-grained stratified drift; and layer 4, sedimentary bedrock, were not changed. Thickness of layer 1 and depth to bedrock were determined from seismic-refraction data and were not varied. Variables, therefore, were thickness of layer 2 (coarse-grained stratified drift) and resistivity of layer 3 (fine-grained stratified drift).

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 43. A good match between the calculated and field values for apparent resistivities and phase angles was obtained. The interpreted geoelectric Earth model shows a saturated, coarse-grained unit of varying thickness over a fine-grained unit. As in the previous site at Simsbury, Conn., the low resistivity of the fine-grained layer prevented deep penetration by the VLF method; therefore, the modeling results are independent of the bedrock resistivity.

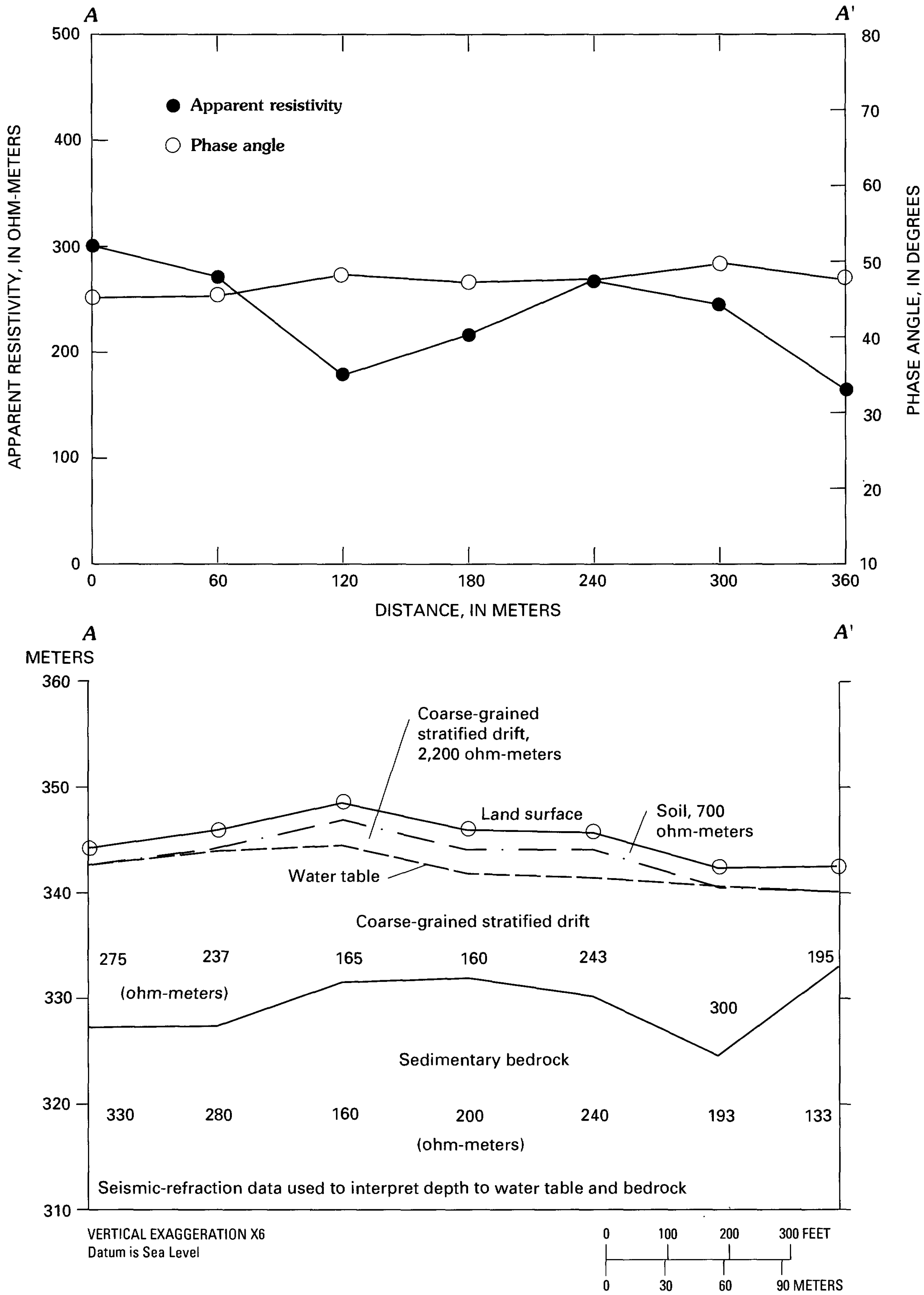
The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 43) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 44). The agreement was generally very good with the exception of the data at station 650. At this station, the interpreted geoelectric Earth model does not represent the subsurface.

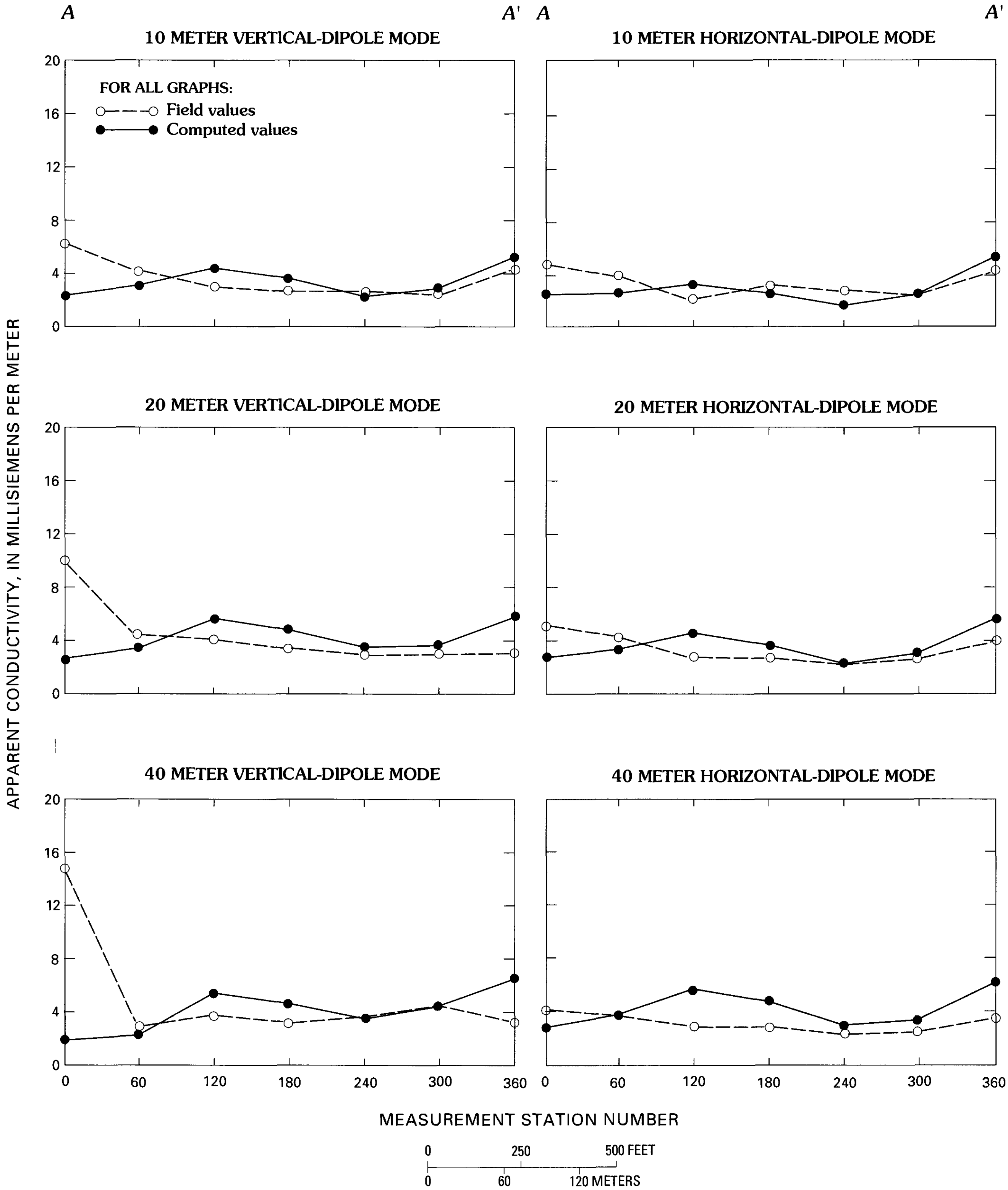
Upon completion of the geophysical surveys, six test holes were drilled along the geophysical survey line to confirm the interpreted Earth model. The logs of the drill holes are shown in figure 45 and, in general, confirm the interpreted geoelectric model. The one exception is the test hole at station 650 (F–73th) where the predicted contact between coarse- and fine-grained stratified drift is much deeper than the contact reported in the test hole. This confirms the previous conclusion that the interpreted geoelectric Earth model does not represent the subsurface at this station.

A stratified-drift deposit filling a broad valley in the town of Preble, N.Y., (fig. 46) is a second example of coarse-grained aquifer material over fine-grained material overlying sedimentary bedrock. The field site is located between two lakes and a major interstate highway, in a gently rolling glacial valley underlain by Devonian shale. The highway has power lines, guard rails, lights, and buried pipes associated with it. A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted near the shores of Green and Upper Little York Lakes, as far away from the highway as possible. Geologic logs from test holes 54–49b and 44–26b were available from a previous study (Randall, 1972). Water-quality data were available from well 05–50 (Buller, 1978, well CP38) and from well 00–01, which was sampled for this study on June 12, 1985.

Bedrock was penetrated at 102 m in a test hole, 4 kilometers (km) south of the study area (Buller, 1978) and is assumed to be at about the same depth under the study area. Because bedrock is beyond the penetration depth of electromagnetic methods, it was not considered in the interpretation process.

FIGURE 33.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site in Smyrna, N.Y. ▶


A
A'
500
400
300
200
100
0
80
70
60
50
40
30
20
10
Apparent resistivity
Phase angle
APPARENT RESISTIVITY, IN OHM-METERS
PHASE ANGLE, IN DEGREES
0
60
120
180
240
300
360
DISTANCE, IN METERS
A
A'
METERS
360
350
340
330
320
310
Coarse-grained stratified drift, 2,200 ohm-meters
Land surface
Soil, 700 ohm-meters
Water table
Coarse-grained stratified drift
275
237
165
160
243
195
(ohm-meters)
300
Sedimentary bedrock
330
280
160
200
240
193
133
(ohm-meters)
Seismic-refraction data used to interpret depth to water table and bedrock
VERTICAL EXAGGERATION X6
Datum is Sea Level
0
100
200
300 FEET
0
30
60
90 METERS


A
A'
10 METER VERTICAL-DIPOLE MODE
10 METER HORIZONTAL-DIPOLE MODE
FOR ALL GRAPHS:
Field values
Computed values
20 METER VERTICAL-DIPOLE MODE
20 METER HORIZONTAL-DIPOLE MODE
40 METER VERTICAL-DIPOLE MODE
40 METER HORIZONTAL-DIPOLE MODE
APPARENT CONDUCTIVITY, IN MILLISIEMENS PER METER
0
4
8
12
16
20
0
60
120
180
240
300
360
MEASUREMENT STATION NUMBER
0
250
500 FEET
0
60
120 METERS

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model are shown in figure 47. The multilayered geoelectric Earth model was simplified to a five-layer model by assuming that the adjacent lake levels represent the altitude of the water table and combining layers with similar resistivities. Comparison of the simplified five-layer geoelectric Earth model with test-hole logs 44–26b and 54–49b (fig. 48) shows that the two top layers, with resistivities of 325 and 1,500 ohm-m, can be correlated with soil and unsaturated coarse-grained material, respectively. These units are underlain by saturated sand and gravel with some silt having an interpreted resistivity of 250 ohm-m. This relatively low resistivity is due to the high specific conductance of the ground water in the coarse-grained stratified drift, 500 μS/cm at 25°C, as measured in wells 05–50 and 00–01. The bottom two geoelectric layers, having resistivities of 60 and 175 ohm-m, are correlated with the fine sand and silt layers that are present in sections of this valley.

This field site is similar to the hypothetical model shown in figure 12. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 49. The field data show a relatively low apparent resistivity (100–250 ohm-m), which reflects the high specific conductance of ground water in coarse and fine-grained material underlying it. Phase angles from 50° to 60° indicate resistive material over conductive material (saturated, coarse-grained stratified drift over fine-grained stratified drift).

In the VLF forward-modeling process, the electrical resistivity of the two unsaturated zones and the saturated, coarse-grained stratified drift was held constant at 325, 1,500, and 250 ohm-m respectively; depth to water table was estimated from the lake level. Bedrock was considered to be too deep to affect the VLF readings. Depth to and resistivity of the fine-grained material were the variables at this site.

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 49. A good match between the calculated and field values of apparent resistivity and phase angle was obtained at each station. The interpreted geoelectric Earth model shows 5–15 m of saturated coarse-grained material overlying a relatively uniform fine-grained section (60–105 ohm-m). Because

◀ FIGURE 34.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Smyrna, N.Y.

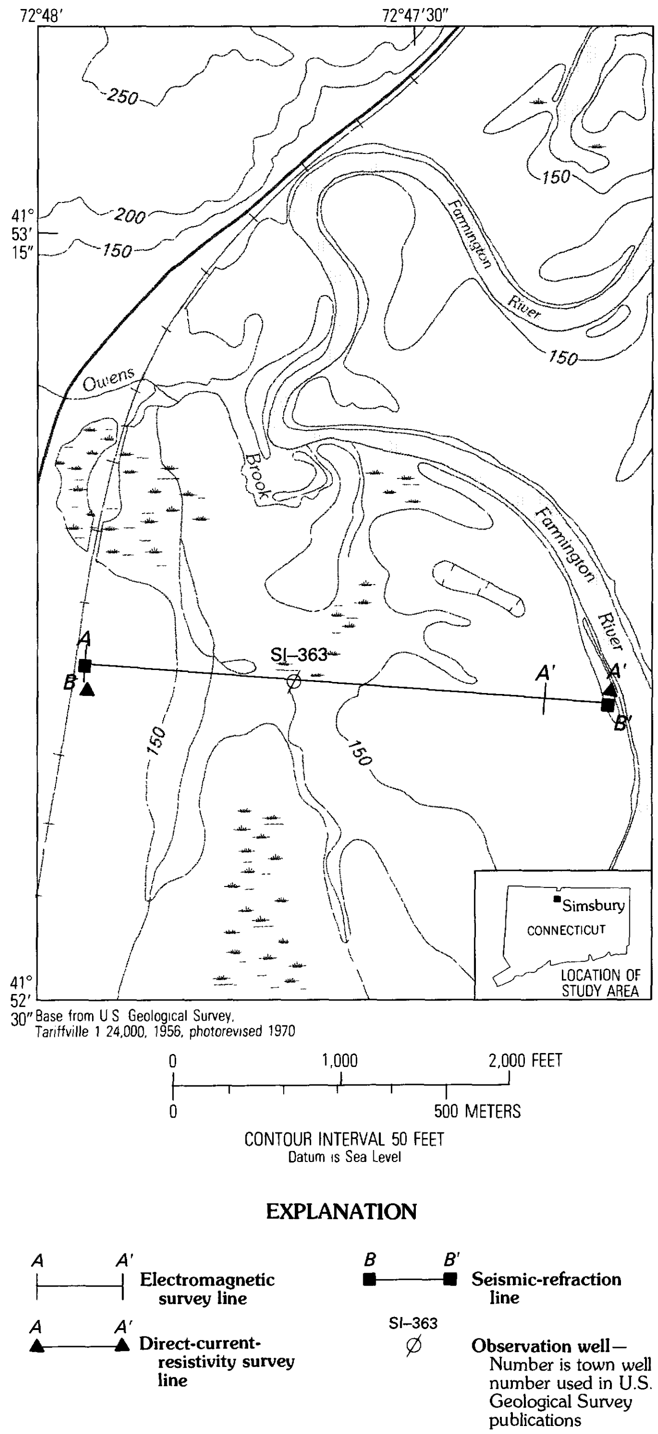


FIGURE 35.—Location of the study site in Simsbury, Conn., including wells, test holes, and surface-geophysical survey lines.

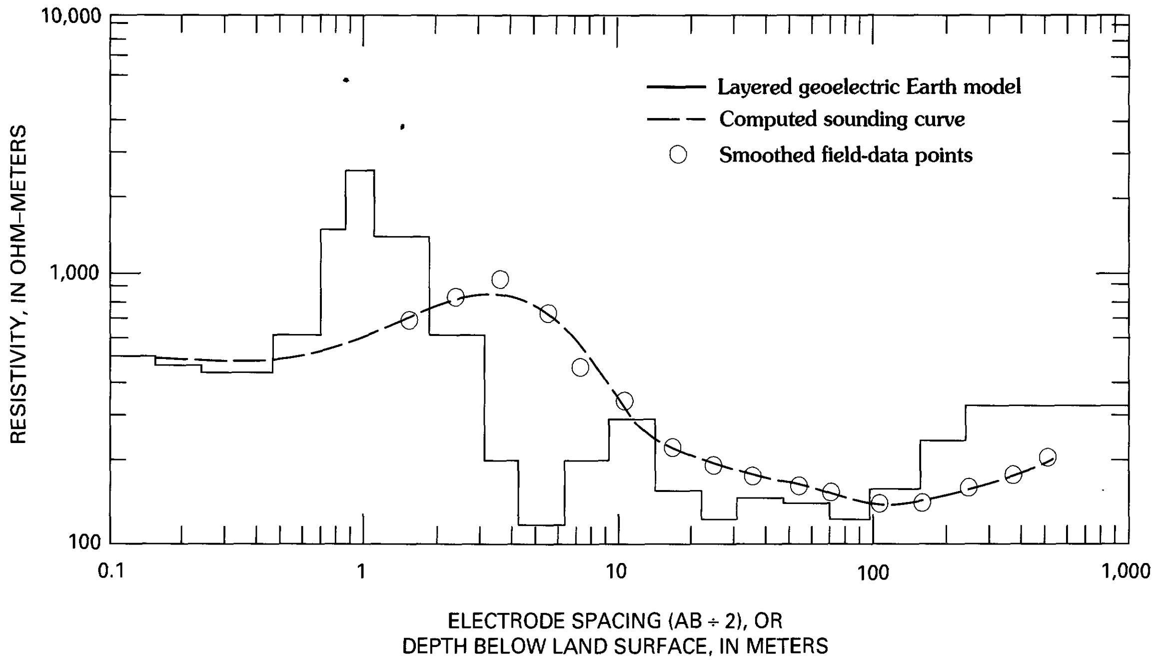


FIGURE 36.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Simsbury, Conn.

bedrock is beyond the penetration depth of the electromagnetic methods, it was not considered in the interpretation process.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 49) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 50). The field readings at the north (*A′*) end of the profile (station 480, which is nearest the highway) are very high for the 20-m horizontal-dipole mode (32 mS/m) and could not be measured for the 40-m horizontal-dipole mode or the 40-m vertical-dipole mode. It is inferred, therefore, that either the interpreted geoelectric Earth model at station 480 is not a true representation of the subsurface, or the field readings are affected by cultural interference from the highway.

COARSE-GRAINED AQUIFER MATERIAL OVER FINE-GRAINED MATERIAL OVERLYING CRYSTALLINE BEDROCK

A stratified-drift deposit in Oxford, Maine, represents coarse-grained aquifer material over fine-grained material overlying crystalline bedrock. The site is located on a flat outwash plain near the Oxford County Regional Airport (fig. 51) and could have cultural interference from the airport or the utilities along nearby roads. A dc-resistivity sounding, a VLF terrain-resistivity profile, and an inductive terrain-conductivity profile were conducted next to the airport access road. Geologic, water-level, and water-quality data were available from wells 0–1223 and 0–1367, as well as a detailed bedrock contour map from a previous study (Morrissey, 1983).

The smoothed plot of the field-data points from the dc-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model are shown in figure 52. This multilayered geoelectric Earth model was simplified into a four-layer geoelectric model by using depth to water from well 0–1223, depth to bedrock from the bedrock contour map, and by combining layers of similar resistivity. The upper layer (fig. 53) is a thin, unsaturated, coarse-grained layer, with a resistivity of 10,000 ohm-m. It is underlain by saturated, coarse-grained material, with a resistivity of 800 ohm-m, which overlies saturated, fine-grained material with a resistivity of 60 ohm-m. The lowest layer is crystalline bedrock with a resistivity of 1,700 ohm-m. The specific conductance of the ground water from the coarse-grained stratified drift (well 0–1367) was 35 μS/cm at 25°C on August 12, 1980.

This field site is similar to the hypothetical model shown in figure 14. The results of the VLF terrain-resistivity survey are shown in the upper part of figure

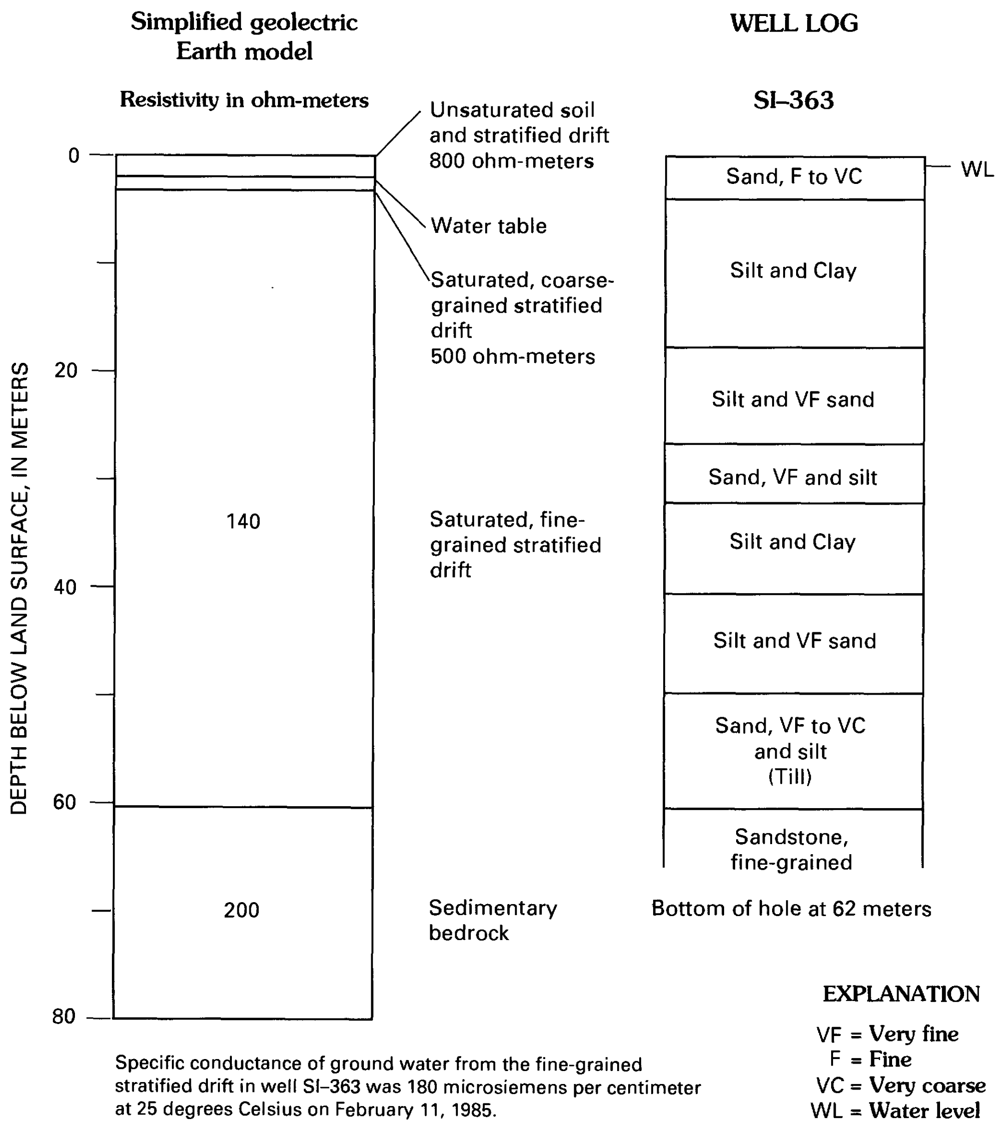


FIGURE 37.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Simsbury, Conn.

54. The low apparent resistivities of 90–200 ohm-m, reflect the presence of the buried fine-grained material. Phase angles of about 60° also indicate that resistive material overlies conductive material (saturated, coarse-grained material over the fine-grained material). The fine-grained layers prevented deep penetration by the VLF method; therefore, the VLF data were independent of the bedrock resistivity.

In the VLF forward-modeling interpretation, the resistivity and thickness of the unsaturated zone, and the resistivities of the saturated, coarse-grained material and the bedrock were held constant. The only two variables, therefore, were thickness of the coarse-grained material and resistivity of the fine-grained material.

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 54. A good match between the calculated and field apparent resistivity values and phase angles at each station was obtained. The interpreted geoelectric Earth model shows a layer of saturated, coarse-grained material, which varies in thickness from

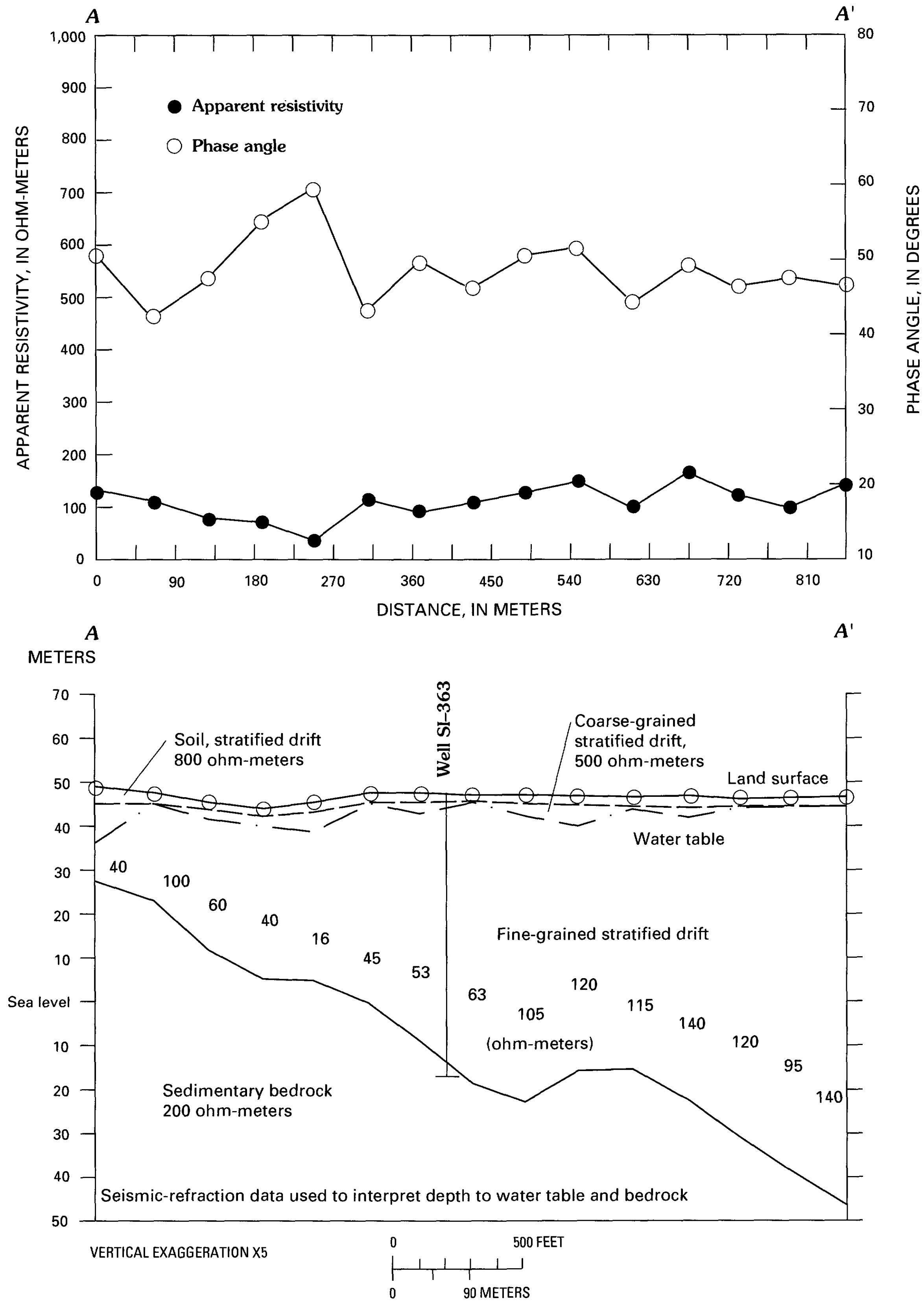


FIGURE 38.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site in Simsbury, Conn.

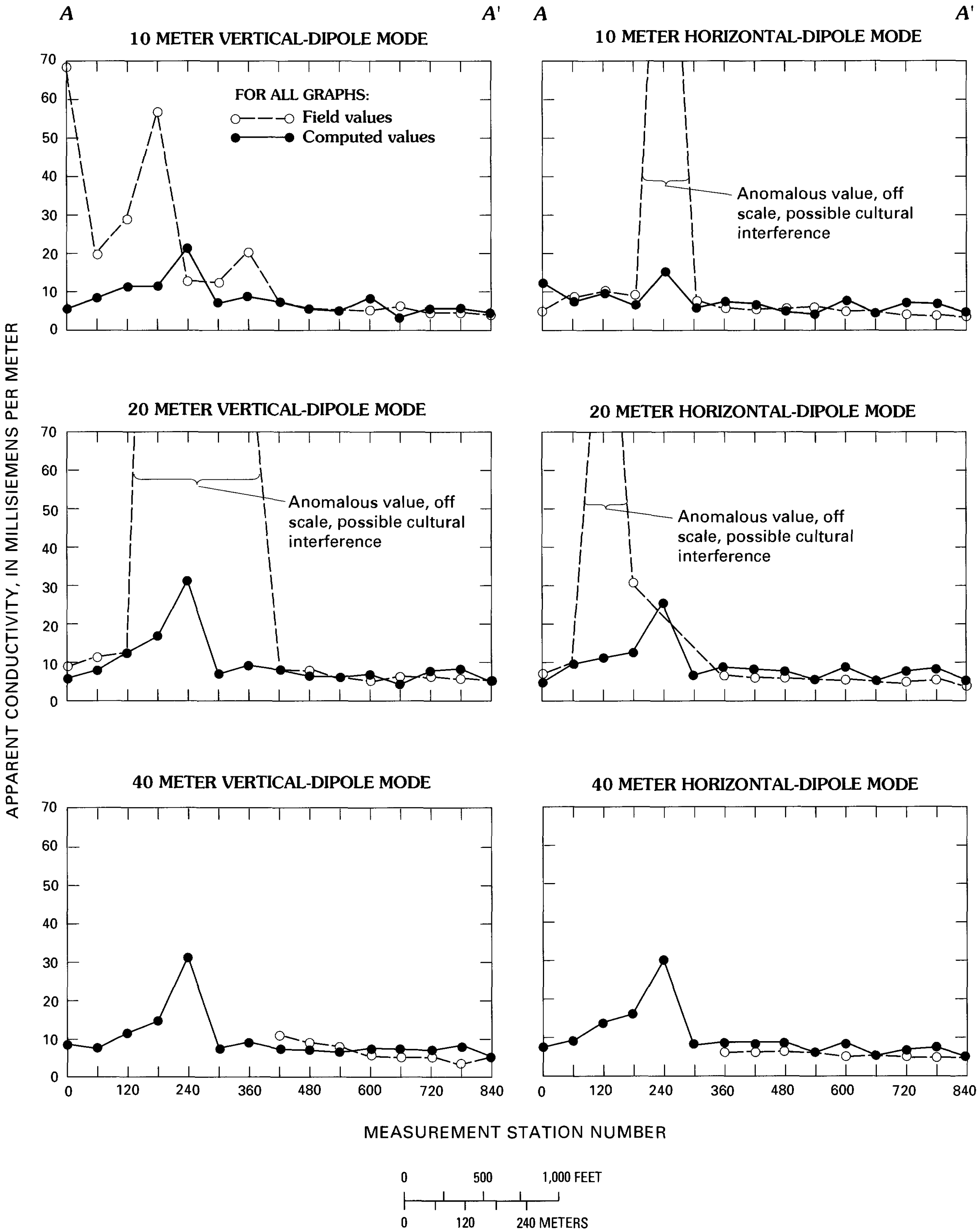


FIGURE 39.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Simsbury, Conn.

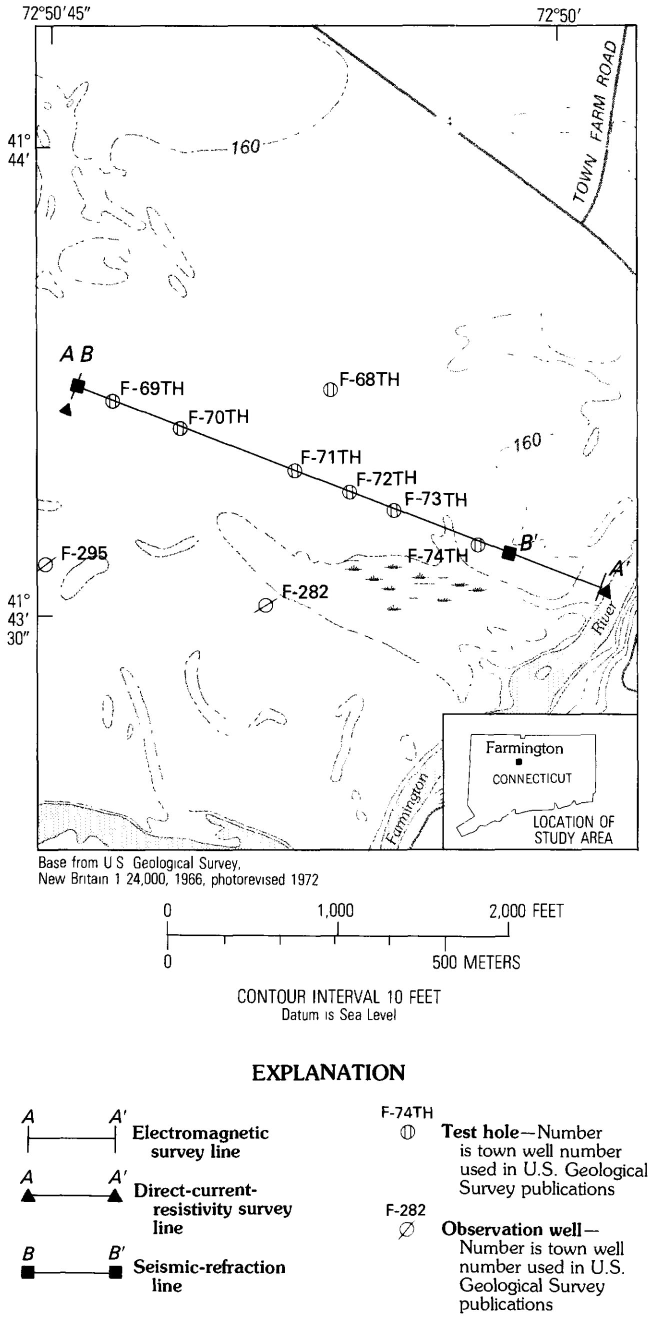


FIGURE 40.—Location of the study site in Farmington, Conn., including wells, test holes, and surface-geophysical survey lines.

8 to 13 m. This unit overlies a fine-grained layer with resistivity of 47–70 ohm-m. The model is not affected by the resistivity of the bedrock.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 54) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 55). The data at stations 180, 240, and 300 do not agree. This disagreement may indicate that the resistivity of the fine-grained layer is higher than the VLF-modeled value or that the terrain-conductivity measurements are affected by the resistivity of the bedrock.

FINE-GRAINED MATERIAL OVER COARSE-GRAINED AQUIFER MATERIAL

The final field site, also located in Oxford, Maine (fig. 56), represents fine-grained material over coarse-grained aquifer material. This deposit is an esker, a sinuous glaciofluvial deposit of coarse sand and gravel. The esker occurs in the shallow subsurface embedded within fine-grained glaciomarine sediments (Morrissey, 1983). There is no topographic evidence of the esker at the site, but a sand and gravel quarry was operated here and a prominent topographic ridge delineates the esker deposit 3 km south of the site. A VLF terrain-resistivity profile, an inductive terrain-conductivity profile, and a seismic-refraction profile were conducted between a trailer park and the Little Androscoggin River. Because the subsurface layers are not horizontal and homogeneous over a sufficiently wide distance, a dc-resistivity sounding was not conducted at this site. The specific conductance of the ground water in a nearby unused spring (U.S. Geological Survey number 1366) was 110 μS/cm at 25°C on August 24, 1980.

This field site is similar to several hypothetical models. In the center of the section, it is similar to figures 17 and 18, fine-grained material overlying coarse-grained material. At the *A* end of the profile, it is similar to figure 14, a thick section consisting of coarse-grained material overlying fine-grained material. At the *A'* end of the profile, it is similar to the right side of figure 10, fine-grained material over crystalline bedrock. The results of the VLF terrain-resistivity survey are shown in the upper part of figure 57. The data show a marked increase (from 150 to 1,500 ohm-m) in the apparent resistivity near the center of the profile, and a corresponding decrease in the phase angle. The increase in resistivity is due to the presence of the resistive coarse-grained esker material in the center of the profile. The phase angle is 30°–35° on both ends of the line, reflecting the thick conductive fine-grained material over the resistant bedrock. The phase angle decreases to 15°–25°

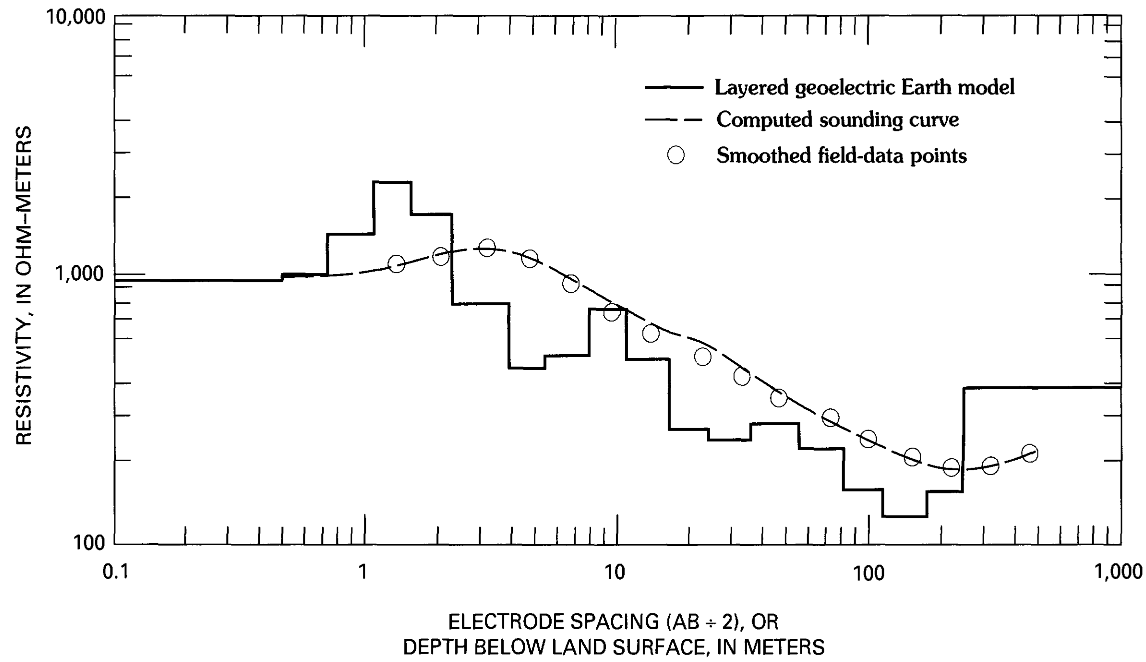


FIGURE 41.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Farmington, Conn.

in the center of the profile because to the presence of a thin layer of conductive material over very resistive, thick, coarse unconsolidated material and bedrock.

In the VLF forward-modeling interpretation, the resistivity of the unsaturated zone and the shallow, saturated, coarse-grained material was held constant. The depth to the water table and bedrock were determined from the seismic-refraction data and were not varied. Therefore, the variables in the modeling process were the thickness and resistivity of the buried coarse-grained aquifer material, the resistivity of the fine-grained material, and the resistivity of the bedrock.

The interpreted geoelectric Earth model resulting from the VLF forward-modeling process is shown in the lower part of figure 57. A good match between computed and field apparent resistivities and phase angles was obtained. The interpreted geoelectric Earth model shows a thin, saturated, coarse-grained unit near the surface underlain by fine-grained material. The esker, shown in the center of the profile, contains as much as 20 m of resistive coarse-grained material.

The interpreted layer thicknesses and resistivities calculated by the VLF modeling process (fig. 57) were used as input data to the inductive terrain-conductivity forward-modeling program. The computed results were compared with the field measurements (fig. 58). The terrain-conductivity model agrees fairly well with the field data for all terrain-conductivity intercoil spacings and dipole modes, indicating that the interpreted geoelectric Earth model closely approximates the subsurface.

After the geophysical survey was completed, two test holes (0–1719 and 0–1720) were drilled to confirm the geophysical interpretation. The geologic logs, shown in figure 59, verify the geophysical interpretation, except that they do not show the thin, fine-grained layer overlying the esker.

SUMMARY OF RESULTS OF FIELD STUDIES

Seismic-refraction, dc-resistivity, and electromagnetic surface-geophysical methods were used at eight field sites in the glaciated Northeastern United States. These sites are characterized by unconsolidated stratified-drift deposits underlain by crystalline or sedimentary bedrock.

Results of the field investigations show that no single method is capable of defining the hydrogeologic boundaries and differentiating between fine-grained and coarse-grained stratified drift. The combined use of all these methods, or the selective use of several of them, in combination with the specific conductance of ground water and geologic logs of test holes or wells, can help to define depth to the water table, depth to bedrock,

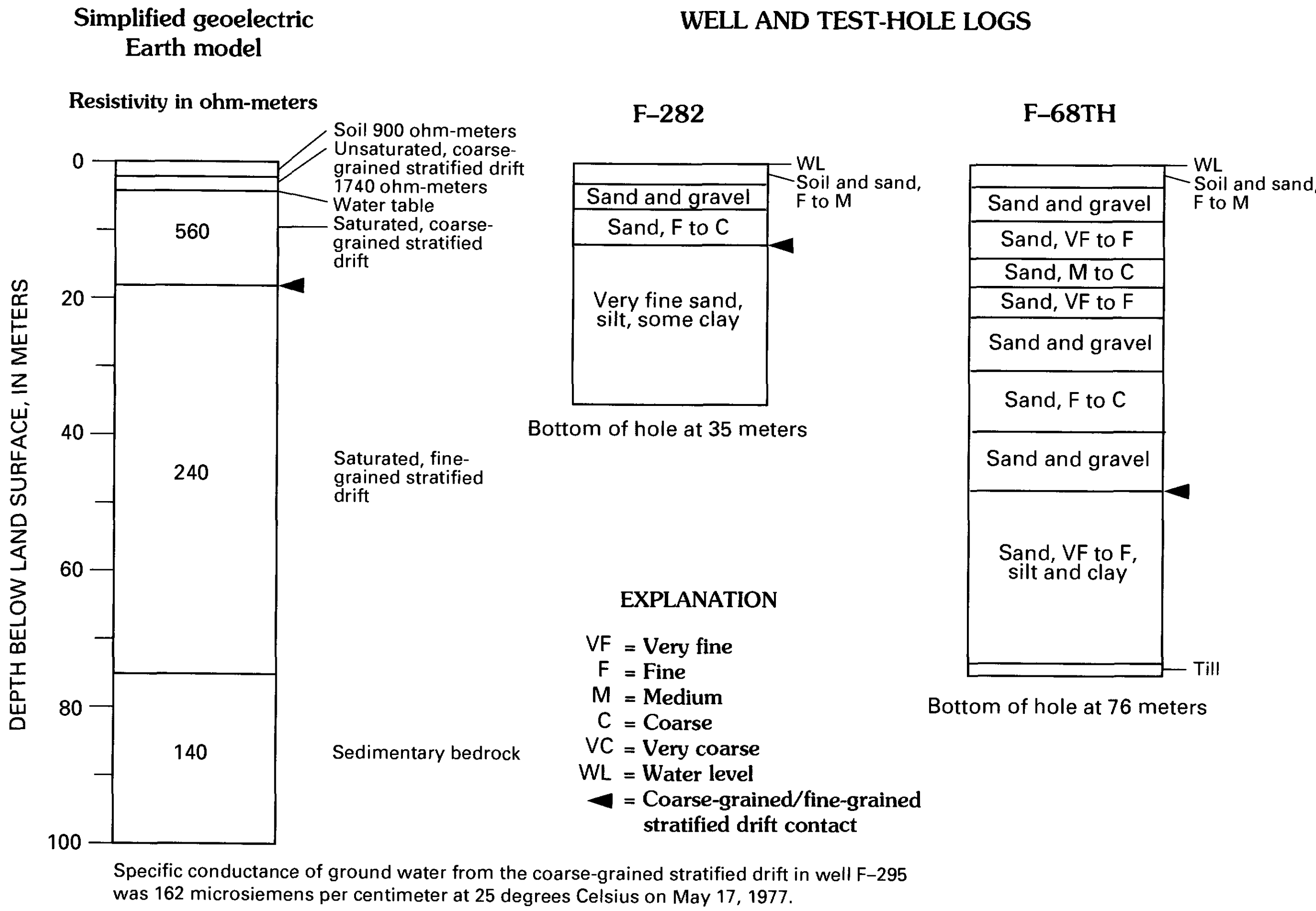


FIGURE 42.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Farmington, Conn.

general lithologic characteristics of sand and gravel aquifers, and lithologic changes within these glacial deposits.

DEPTH TO THE WATER TABLE

Seismic-refraction surveys were capable of determining the depth to the water table in unconsolidated stratified-drift deposits at all field sites. This method was successful because of the mean difference in seismic velocity between unsaturated (0.32 kilometer per second (km/s)) and saturated (1.54 km/s) stratified drift. Table 3 compares the seismic velocities for these two materials at the six field sites that have available seismic-refraction data. Similar seismic velocities have been reported by Haeni and Melvin (1984), Morrissey and others (1985), and Haeni (1988).

TABLE 3.—*Interpreted seismic velocities in stratified-drift deposits at six field sites in the glaciated Northeastern United States*

Field site	Depth of water table determined from seismic refraction data (m)	Interpreted seismic velocity in unsaturated material (km/s)	Interpreted seismic velocity in saturated material (km/s)
Stonington, Conn. .	2.44	0.34	1.59
Granby, Conn......	1.83	.30	1.56
Smyrna, N.Y......	1.22	.34	1.40
Simsbury, Conn....	1.22	.21	1.59
Farmington, Conn..	3.66	.46	1.56
Oxford, Maine (esker site)......	2.14	.27	1.53
Mean		.32	1.54

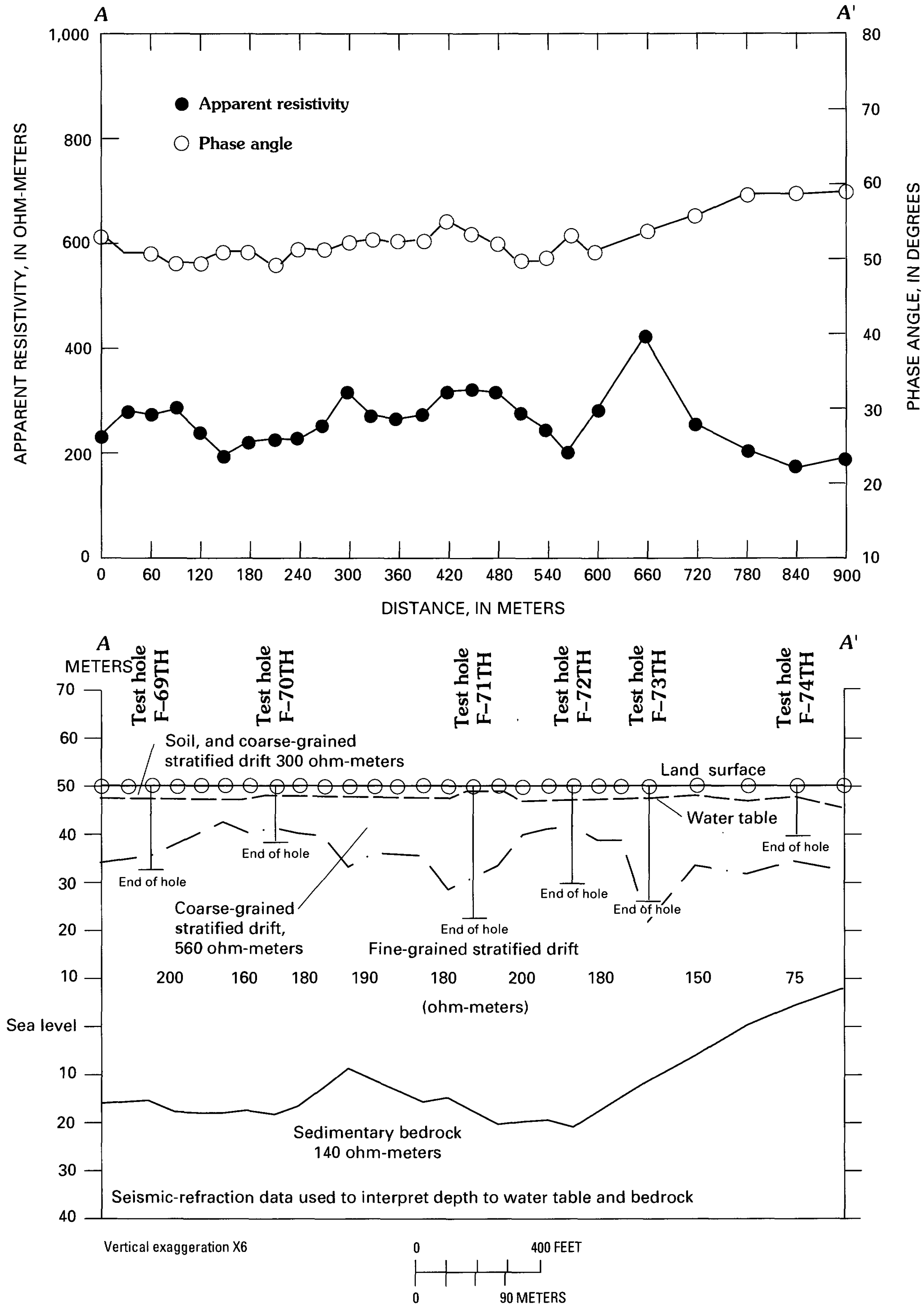


FIGURE 43.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site in Farmington, Conn.

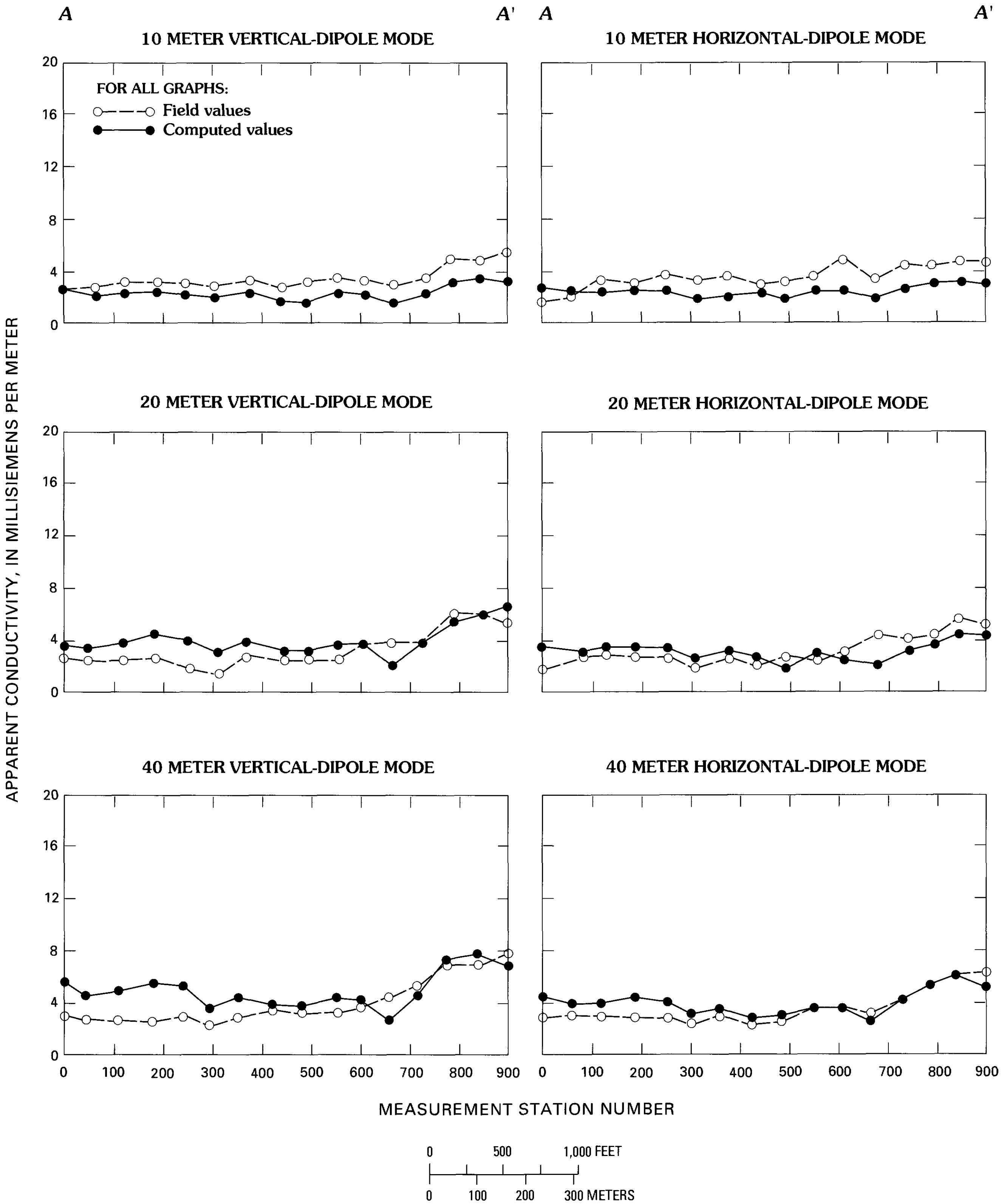


FIGURE 44.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Farmington, Conn.

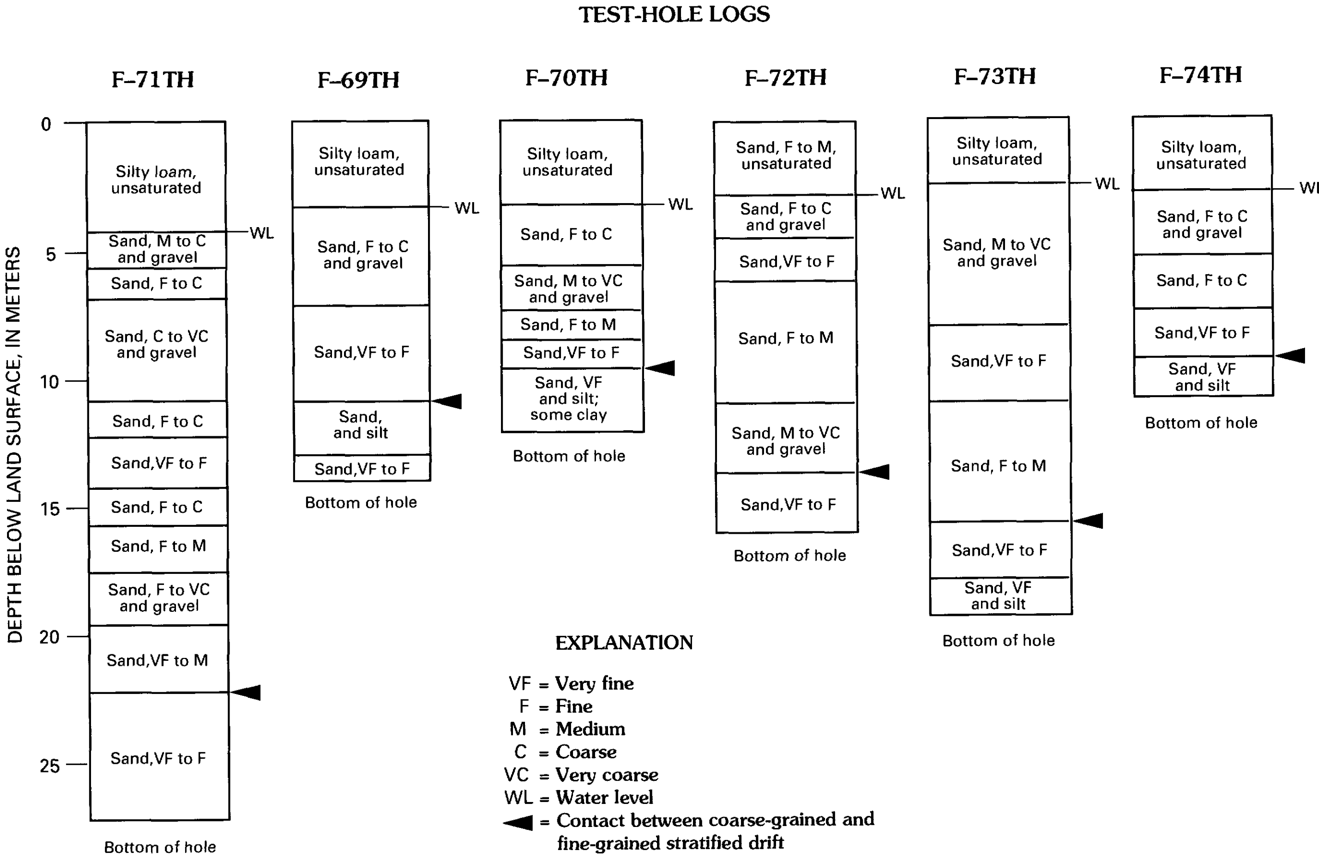


FIGURE 45.—Geologic logs from test holes in Farmington, Conn.

The dc-resistivity of unsaturated and saturated stratified-drift deposits depends on a combination of factors, including porosity, moisture content, mineralogy, and specific conductance in each unit. In combination, these variables do not always result in a resistivity contrast at the water-table surface. The dc-resistivity method was able to detect the water table at the Simsbury, Stonington, and Farmington, Conn.; the Smyrna, N.Y.; and the airport road in Oxford, Maine, field sites, but not at the Preble, N.Y., nor Granby, Conn., field sites.

The unsaturated layer resistivities presented in table 4 were determined by combining several individual geoelectric layers from the interpreted dc-resistivity data and comparing these values with the lithologic description of the layer from a well or test hole at the site. In general, two layers were defined: an upper soil layer, with resistivities ranging from 325 to 10,000 ohm-m; and a more resistive, unsaturated stratified-drift layer, with resistivities ranging from 1,500 to 10,000 ohm-m. The saturated stratified-drift layer resistivities shown in table 5 were similarly determined and varied from 60 to 2,000 ohm-m.

Electromagnetic methods depend on the resistivity contrast between layers to differentiate the boundaries between them and, therefore, are subject to the same limitations as the dc-resistivity method.

DEPTH TO BEDROCK

Depth to bedrock was consistently defined by interpreting seismic-refraction data from all of the field sites where it was used. The velocity difference between saturated, unconsolidated materials and bedrock ranged from 2.13 km/s at Granby, Conn., to 3.90 km/s at Stonington, Conn. The seismic velocity of the saturated, unconsolidated materials is listed in table 3. The seismic velocity of the bedrock at each site is listed in table 6. These velocities are similar to those reported by Haeni

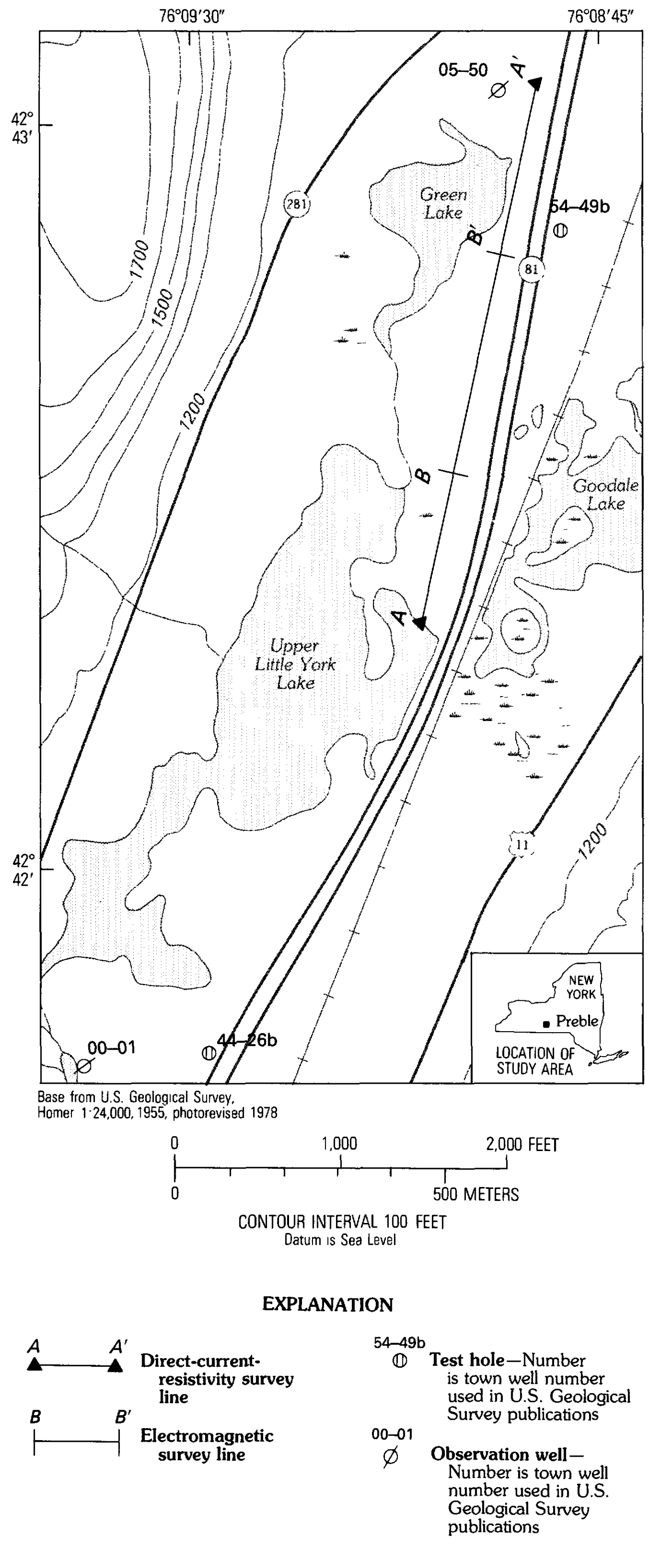


FIGURE 46.—Location of the study site in Preble, N.Y., including wells, test holes, and surface-geophysical survey lines.

TABLE 4.—*Interpreted resistivity of unsaturated, stratified-drift deposits at seven field sites in the Northeastern United States*

Field site	Generalized lithologic description from well or test-hole logs	Thickness unsatured layers (m)	Interpreted resistivity from direct current-sounding data (ohm-m)
Stonington, Conn.	Soil; sand fine; and silt	0.0–0.9	450
	Sand, fine to coarse; gravel	.9–2.0	2,000
Granby, Conn.	Soil, and silty loam	.0–.5	425
	Sand, medium to coarse; gravel	.5–3.6	7,000
Smyrna, N.Y.	Soil	.0–.6	700
	Gravel	.6–2.4	2,200
Simsbury, Conn.	Soil	.0–.5	400
	Sand, very fine to medium	.5–1.8	1,500
Farmington, Conn.	Soil and sand, fine to medium	0.0–0.8	900
	Sand and gravel	.8–2.5	1,740
Preble, N.Y.	Soil	.0–1.5	325
	Sand and gravel	1.5–5.6	1,500
Oxford, Maine (airport site)	Soil and sand, coarse to very coarse	.0–1.2	10,000

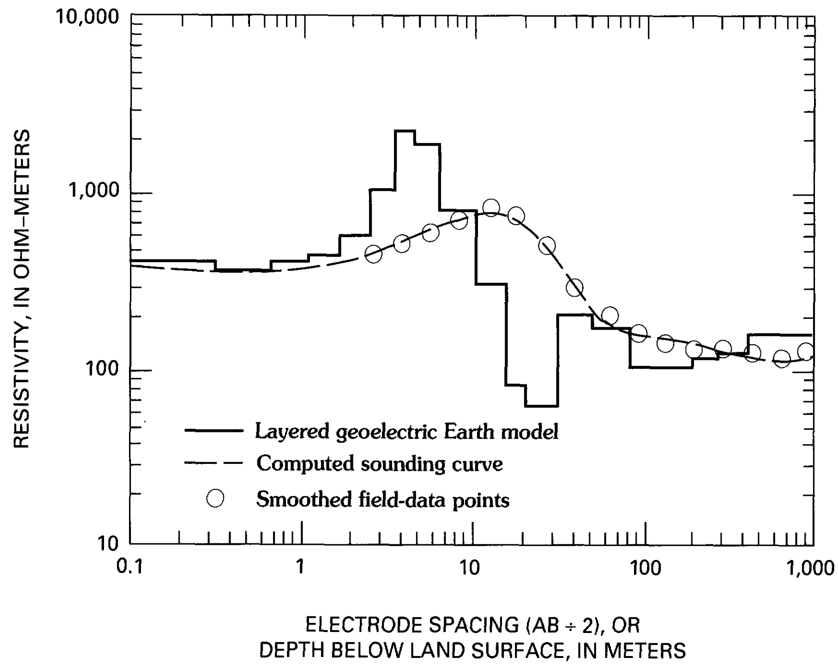


FIGURE 47.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site in Preble, N.Y.

TABLE 5.—*Interpreted resistivity of saturated, stratified-drift deposits at eight field sites in the Northeastern United States*

[—, no data available]

Field site	Generalized lithologic description from well or test-hole logs	Specific conductance of ground water (µS/cm at 25°C)	Interpreted resistivity from direct-current sounding data (ohm-m)	Interpreted resistivity from very-low-frequency modeling (ohm-m)
Stonington, Conn.	Sand, medium to very coarse, and gravel	102	500	150–450
Granby, Conn.	Sand, medium to very coarse, and gravel	130	2,000	2,000–3,000
	Sand, fine to coarse		450	held constant
Smyrna, N.Y.	Gravel, well sorted	[1]710	550	160–300
Simsbury, Conn.	Sand, fine to very coarse	180	500	held constant
	Sand, very fine, and silt and clay		140	16–140
Farmington, Conn.	Sand, fine to coarse, and some gravel	162	560	held constant
	Sand, very fine to fine, and silt and clay		240	75–200
Preble, N.Y.	Sand and gravel, some silt	550	250	held constant
	Sand, fine, and some silt		60	60–105
Oxford, Maine (airport site)	Sand and gravel	35	800	held constant
	Sand, very fine to fine, and silt and clay		60	47–70
Oxford, Maine (esker site)	Sand and gravel	110	—	800–5,000
	Sand, very fine, and silt and clay		—	110–255

[1]Possible road salt contamination in well.

TABLE 6.—*Interpreted seismic velocity and resistivity of sedimentary and crystalline bedrock at seven field sites in the Northeastern United States*

[—, no data available]

Field site	Lithologic description	Seismic velocity (km/s)	Interpreted resistivity from direct-current sounding data (ohm-m)	Interpreted resistivity from very-low-frequency modeling (ohm-m)
Stonington, Conn.	Gneiss, quartz-feldspar-biotite	5.49	1,600	1,100–5,000
Granby, Conn.	Gneiss, muscovite-biotite-quartz	—	250	135–150
	Siltstone, very fine-grained	3.69	250	35–115
Smyrna, N.Y.	Shale	4.42	300	133–330
Simsbury, Conn.	Sandstone, fine-grained	4.39	200	—
Farmington, Conn.	Sedimentary, arkose	4.09	140	held constant
Oxford, Maine (airport site)	Granite, biotite-rich	—	1,700	held constant
Oxford, Maine (esker site)	Granite, biotite-rich	5.03	—	2,000–10,000

TABLE 7.—*Comparison of depth to bedrock, determined by seismic-refraction, direct-current-resistivity, and drill-hole data*

[—, no data available]

Field site	Depth to bedrock, in meters, as determined by: Seismic refraction	Direct-current resistivity	Drill hole
Stonington, Conn.	14.0		14.0 (SN–143th)
	16.2	17.8	13.4 (SN–164)
	17.7		14.3 (SN–144th)
Granby, Conn.	12.7	14.0	12.5
Smyrna, N.Y.	17.0	12.4	—
Simsbury, Conn.	60.0	not detected	61.0
Farmington, Conn.	73.2	not detected	76.0 (refusal)
Oxford, Maine (esker site)	24.0	—	22.0 (O–1720) (refusal)
	34.0		31.0 (O–1719) (bottom of hole)

and Anderson (1980), Morrissey and others (1985), Haeni (1986a), and Haeni (1988) for similar geologic settings.

The dc-resistivity method was able to detect the bedrock surface at Stonington and Granby, Conn., and Smyrna, N.Y. This method was not able to detect the bedrock at Farmington or Simsbury, Conn., because of the lack of electrical resistivity contrast between the saturated, unconsolidated material (table 5) and bedrock (table 6). A comparison of the depth to bedrock determined by drilling with the depth interpreted from the seismic-refraction and dc-resistivity data are shown in table 7. In general, the seismic-refraction depths agree with the test-hole data for all of the field sites. The depths determined from resistivity data were not as accurate as the seismic-refraction data. At two sites, depth to bedrock could not be detected from resistivity data. Resistivity values for crystalline rock changed substantially between Granby, Stonington, and Oxford (table 6). Resistivity values at Granby were obtained near a major geologic fault separating crystalline and sedimentary rocks. In outcrops near the fault, both rock types are highly fractured. These fractures and the presence of more conductive ground water in the sedimentary rocks are probably the reasons for the abnormally low resistivities in the crystalline bedrock.

Electromagnetic methods were used to determine the depth to bedrock at the Granby site. Interpretation of these data was satisfactory when the geoelectric Earth was limited to four layers and the only variables in the modeling process were thickness of saturated material and resistivity of the bedrock. Thickness and resistivity of the overlying unsaturated units and the resistivity of the saturated units were assumed to be known and were held constant.

CHARACTERISTICS OF SAND AND GRAVEL AQUIFERS

Dc-resistivity soundings at each field site could be correlated qualitatively with the general grain-size characteristics of the aquifer material. The relations among lithology of stratified-drift deposits, specific conductance of ground water, interpreted dc-resistivity, and interpreted VLF resistivity at the eight field sites is shown in table 5. The data presented indicate that when the specific conductance of ground water remains relatively constant, the bulk resistivity of the aquifer is generally representative of the aquifer's grain-size characteristics. Specifically, coarse-grained material generally is more resistive than fine-grained material. A limitation of the dc-resistivity method is that small-scale horizontal changes of the resistivity of the subsurface units cannot be detected with this method.

Electromagnetic methods detect smaller changes of the subsurface units than dc-resistivity methods and, therefore, are capable of mapping hydrogeologic features such as eskers and variable thicknesses of coarse-grained units. However, independent data (drill-hole logs or geologic knowledge of the area) on subsurface conditions at any site must be used to confirm the results of these methods.

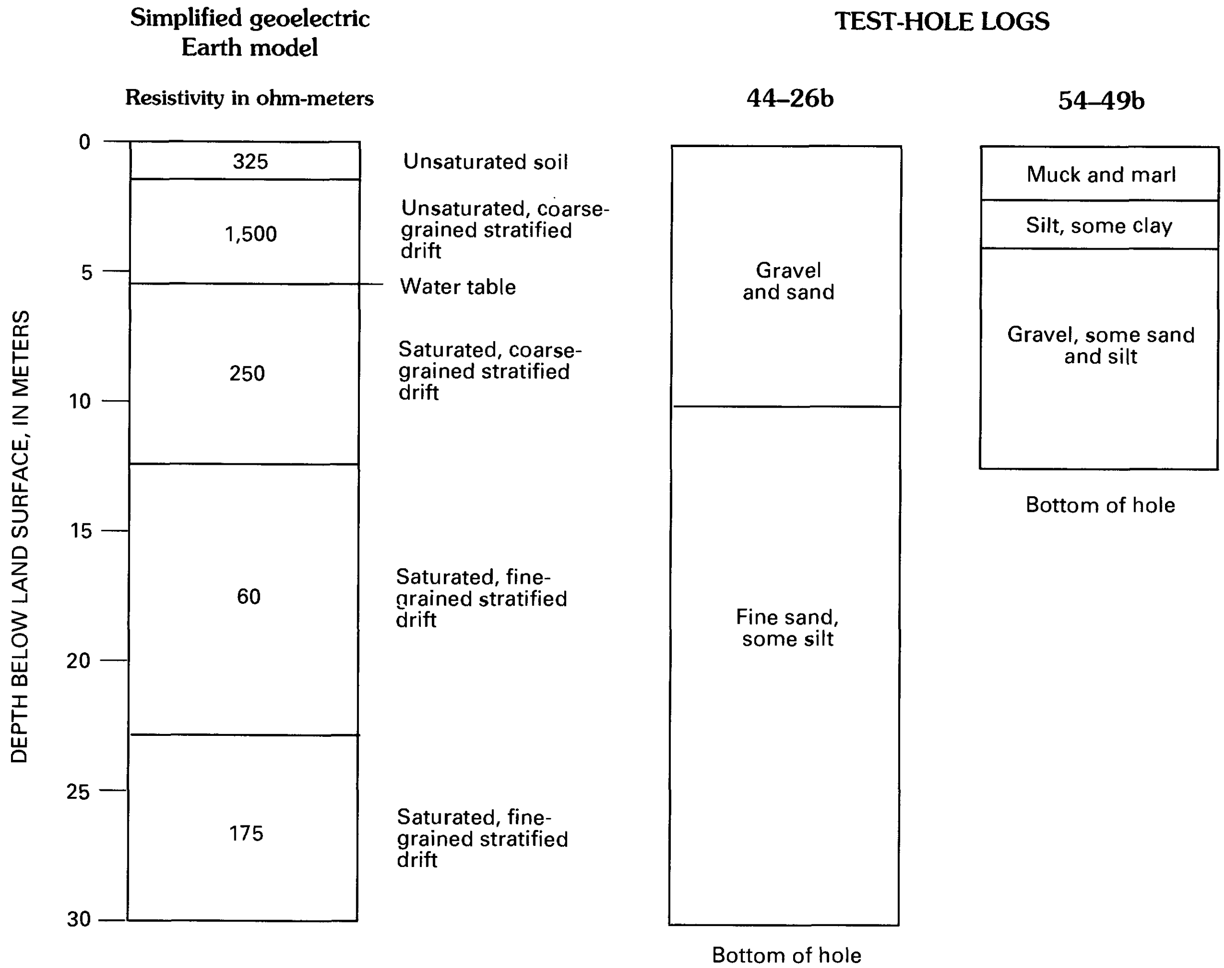
The seismic-refraction method cannot be used to detect grain-size changes in aquifer materials because seismic velocity does not vary greatly with changes in the grain size of saturated, unconsolidated materials (table 1).

CONCLUSIONS

Computer forward-modeling programs were used to calculate the response of electromagnetic methods in hydrogeologic settings typical of the glaciated Northeastern United States. Subsequent surface-geophysical field investigations were conducted at eight sites. The two parts of this study have shown that the combined use of seismic-refraction, dc-resistivity, VLF terrain-resistivity, and inductive terrain-conductivity methods can distinguish between fine-grained and coarse-grained stratified-drift aquifers and can be used to determine their hydrogeologic boundaries.

Forward-modeling studies of hypothetical systems demonstrated that both VLF terrain-resistivity and inductive terrain-conductivity methods can be used to detect horizontal and vertical changes in electrical properties of the subsurface layers or materials. Some surface-geophysical methods might work better in certain hydrogeologic settings than in others because of different operating principles of the individual methods. The forward-modeling results indicated that in resistive terrains, the VLF terrain-resistivity method (1) can be used to measure moderate horizontal and vertical changes in electrical properties of the subsurface, (2) has a penetration depth of about 100 m, and (3) can detect conductive material underlying resistive material. The inductive terrain-conductivity method (1) is insensitive to large changes in the resistivity of resistive layers, (2) maintains a constant penetration depth, and (3) can be used to detect conductive layers at depth. In conductive terrains, the VLF terrain-resistivity method is only sensitive to near-surface resistivity changes and has a limited depth of penetration. Also, the inductive terrain-conductivity method (1) is sensitive to changes in the thickness and conductivity of individual conductive layers, (2) maintains its depth of penetration, and (3) can be used to detect small changes in layer conductivities.

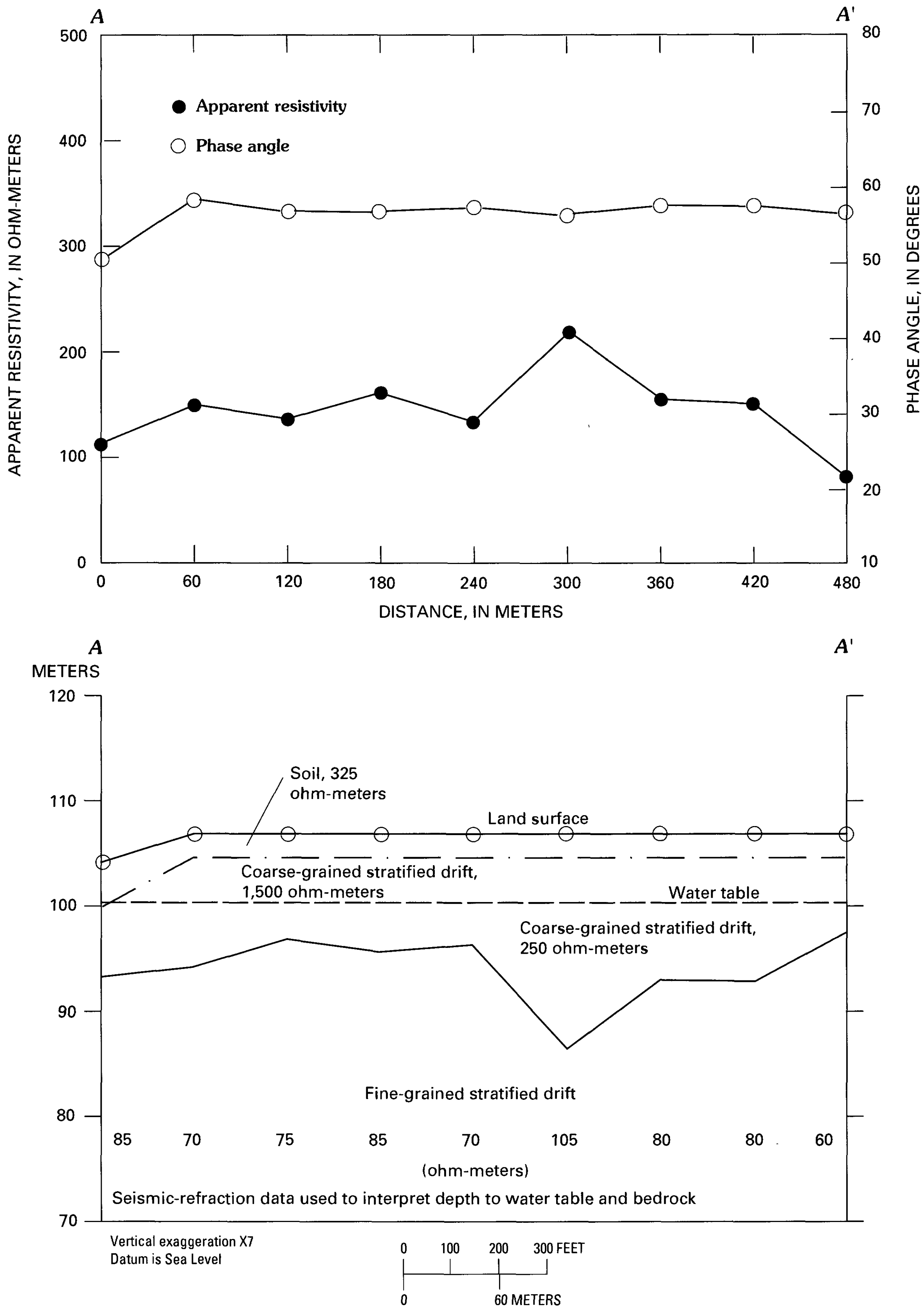
Surface-geophysical surveys—seismic-refraction, dc-resistivity, and electromagnetic methods—at eight sites in Connecticut, New York, and Maine have shown that



Specific conductance of ground water from the coarse-grained stratified drift in well 05–50 was 500 microsiemens per centimeter at 25 degrees Celsius on February 25, 1977 and from the coarse-grained stratified drift in well 00–01 was 550 microsiemens per centimeter at 25 degrees Celsius on June 12, 1985.

FIGURE 48.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site in Preble, N.Y.

FIGURE 49.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity and very-low-frequency apparent resistivity data, from the study site in Preble, N.Y. ▶


A
A'
500
400
300
200
100
0
80
70
60
50
40
30
20
10
Apparent resistivity
Phase angle
APPARENT RESISTIVITY, IN OHM-METERS
PHASE ANGLE, IN DEGREES
0
60
120
180
240
300
360
420
480
DISTANCE, IN METERS
A
A'
METERS
120
110
100
90
80
70
Soil, 325
ohm-meters
Land surface
Coarse-grained stratified drift,
1,500 ohm-meters
Water table
Coarse-grained stratified drift,
250 ohm-meters
Fine-grained stratified drift
85
70
75
85
70
105
80
80
60
(ohm-meters)
Seismic-refraction data used to interpret depth to water table and bedrock
Vertical exaggeration X7
Datum is Sea Level
0
100
200
300 FEET
0
60 METERS

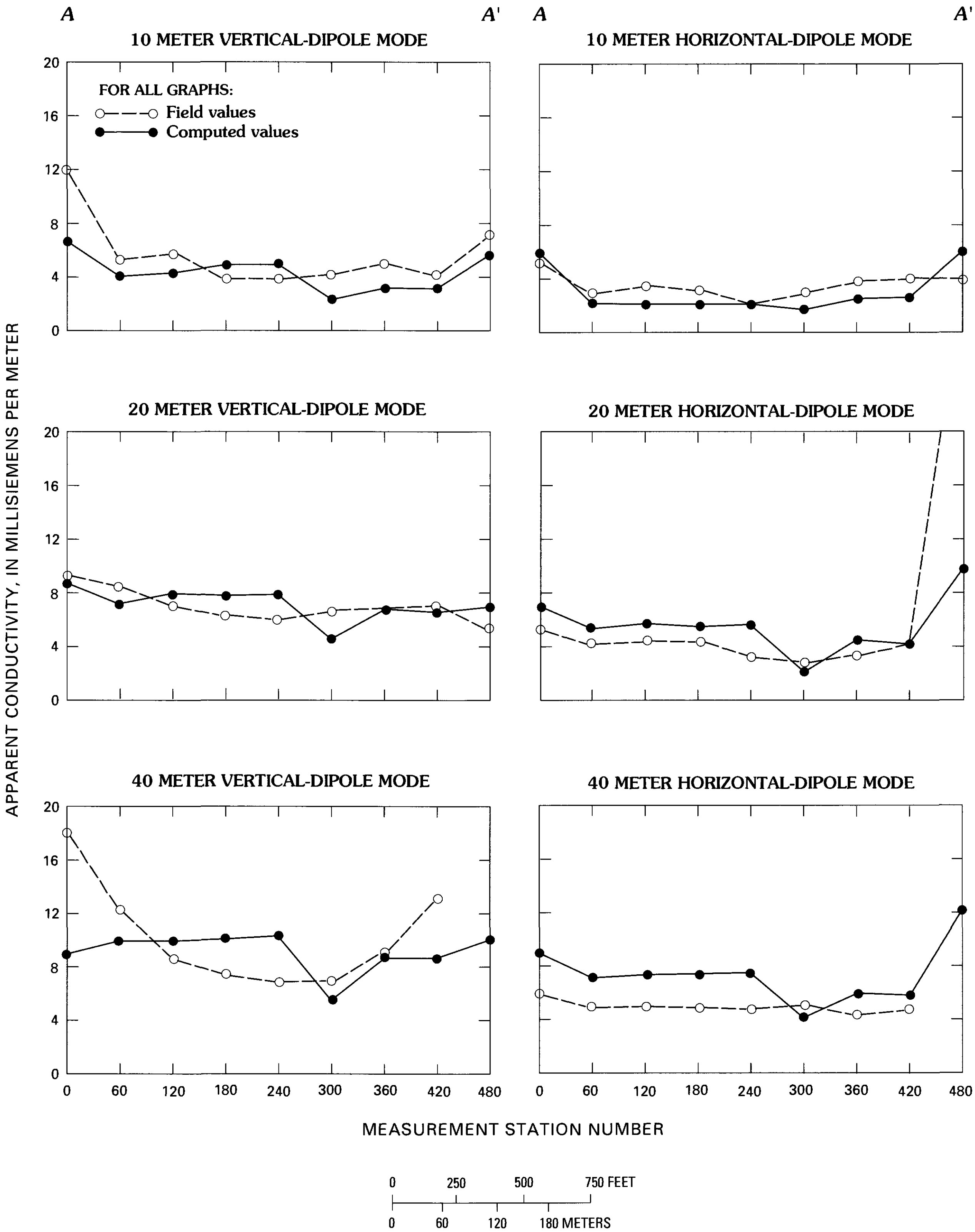


FIGURE 50.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site in Preble, N.Y.

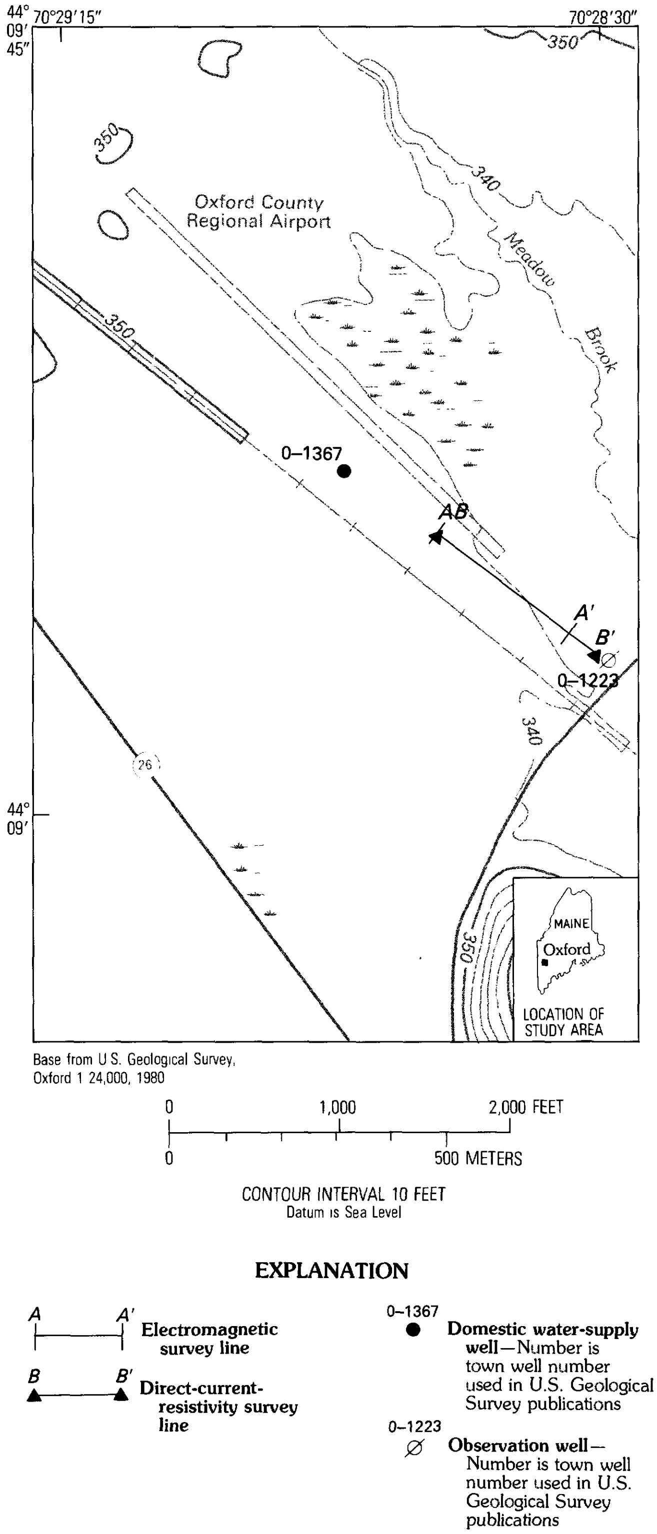


FIGURE 51.—Location of the study site at the airport in Oxford, Maine, including wells, test holes, and surface-geophysical survey lines.

no single method can be used to define the hydrogeologic boundaries and distinguish between fine-grained and coarse-grained stratified drift. The combined interpretation of the seismic-refraction and dc-resistivity data helps to delineate boundaries, distinguish between fine-grained and coarse-grained deposits, and provide information on the specific conductance of ground water within sand and gravel aquifers.

The seismic-refraction method was used to determine depths to the water table and bedrock in all hydrogeologic settings. This method cannot be used to detect lithologic changes within saturated stratified-drift aquifers.

Dc-resistivity can be used to detect resistivity changes within stratified-drift material caused by water-quality (specific conductance) or lithologic variations. At five field sites, the dc-resistivity method could be used to determine depth to water table, and at three field sites, it could be used to determine depth to bedrock.

The combined use of two electromagnetic methods, VLF terrain-resistivity and inductive terrain-conductivity, further improves characterization of the aquifer systems. These two methods can be used conjunctively to refine the interpretation of a model based on seismic-refraction and dc-resistivity data. These methods also are useful for mapping electrical anomalies that relate to small-scale vertical or lateral changes in aquifer lithology and specific conductance of ground water. The successful interpretation of the electromagnetic data, over an earth with more than two layers, requires subsurface data from seismic-refraction and dc-resistivity methods or other sources to obtain a geologically reasonable solution.

Interpreted dc-resistivities or interpreted VLF resistivities of each subsurface layer, ground-water specific conductance, and lithologic logs from nearby test holes or wells were compared at all eight field sites. The results indicate that for a given specific conductance of ground water, fine-grained stratified drift is more conductive than coarse-grained stratified drift. With increasing specific conductance of ground water, the same general relation applies, but the values of each layer's resistivity decreases. The resistivity, therefore, of sand and gravel aquifers in the Northeastern United States can be related empirically to the grain size of the aquifer material in limited geographic areas where the specific conductance of ground water is considered uniform.

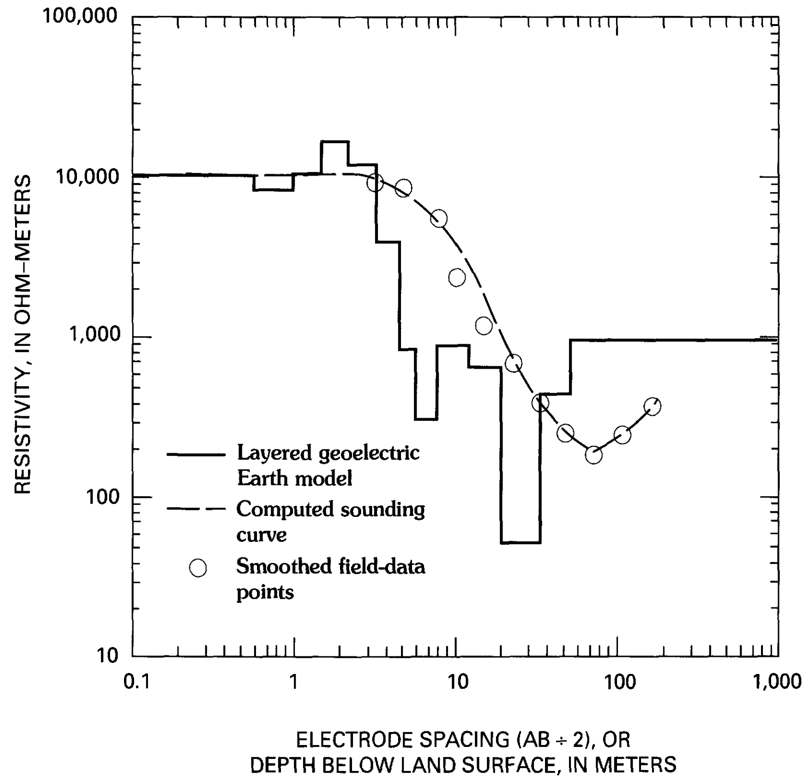


FIGURE 52.—Smoothed plot of field-data points from direct-current-resistivity sounding, the computed sounding curve, and the resulting layered geoelectric Earth model for data from the study site at the airport in Oxford, Maine.

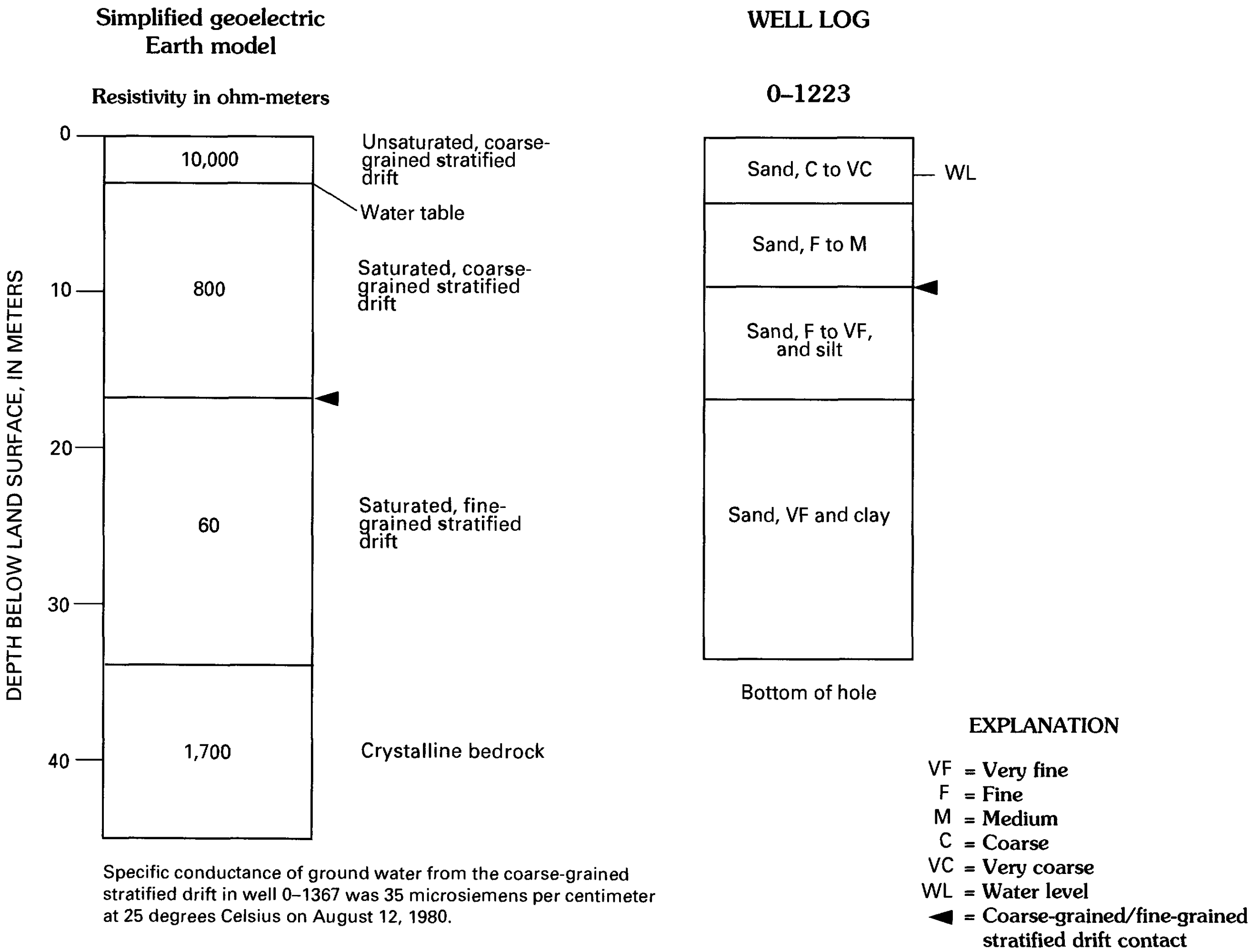


FIGURE 53.—Simplified geoelectric Earth model from direct-current-resistivity data, and well and test-hole logs from the study site at the airport in Oxford, Maine.

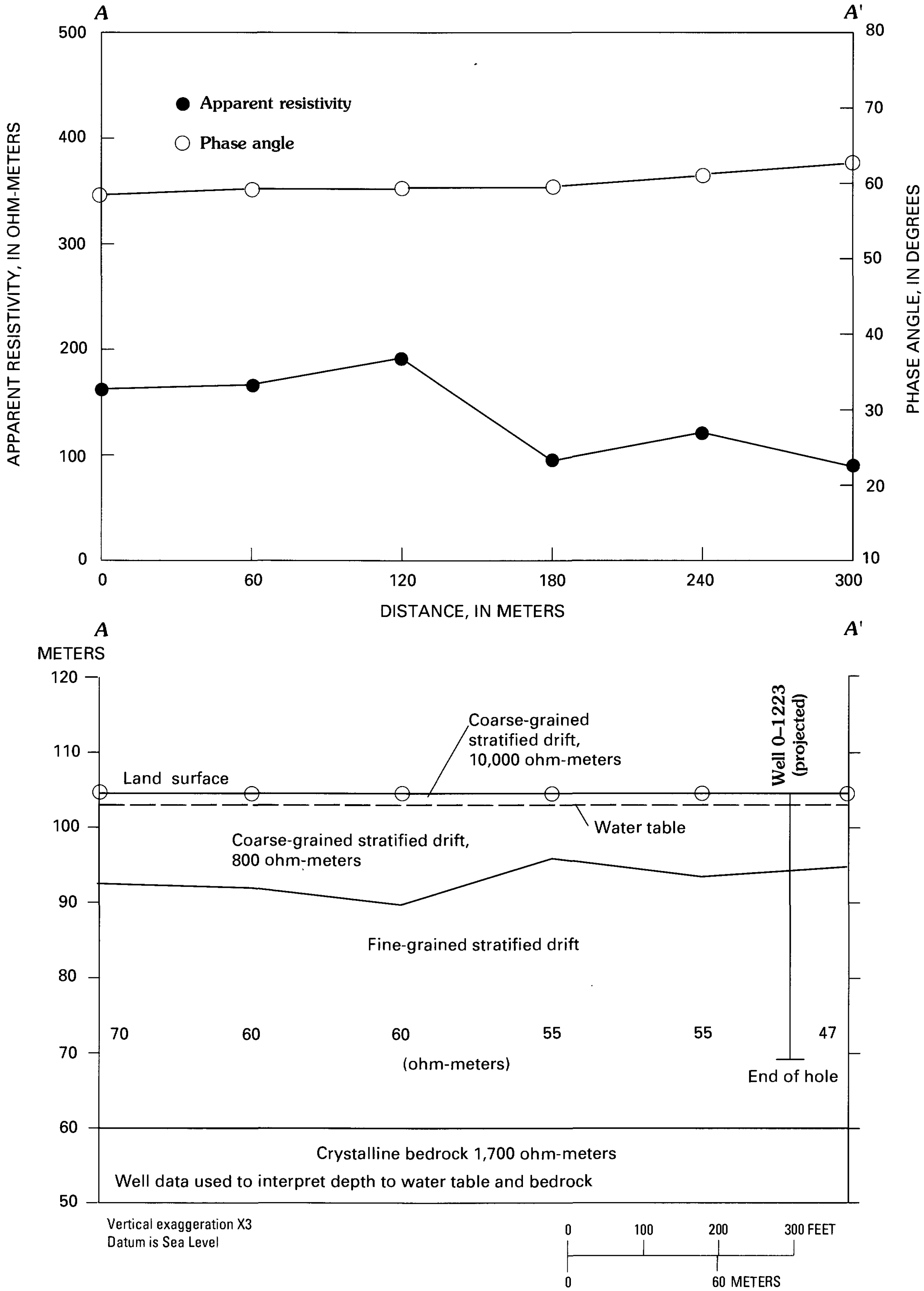


FIGURE 54.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the study site at the airport in Oxford, Maine.

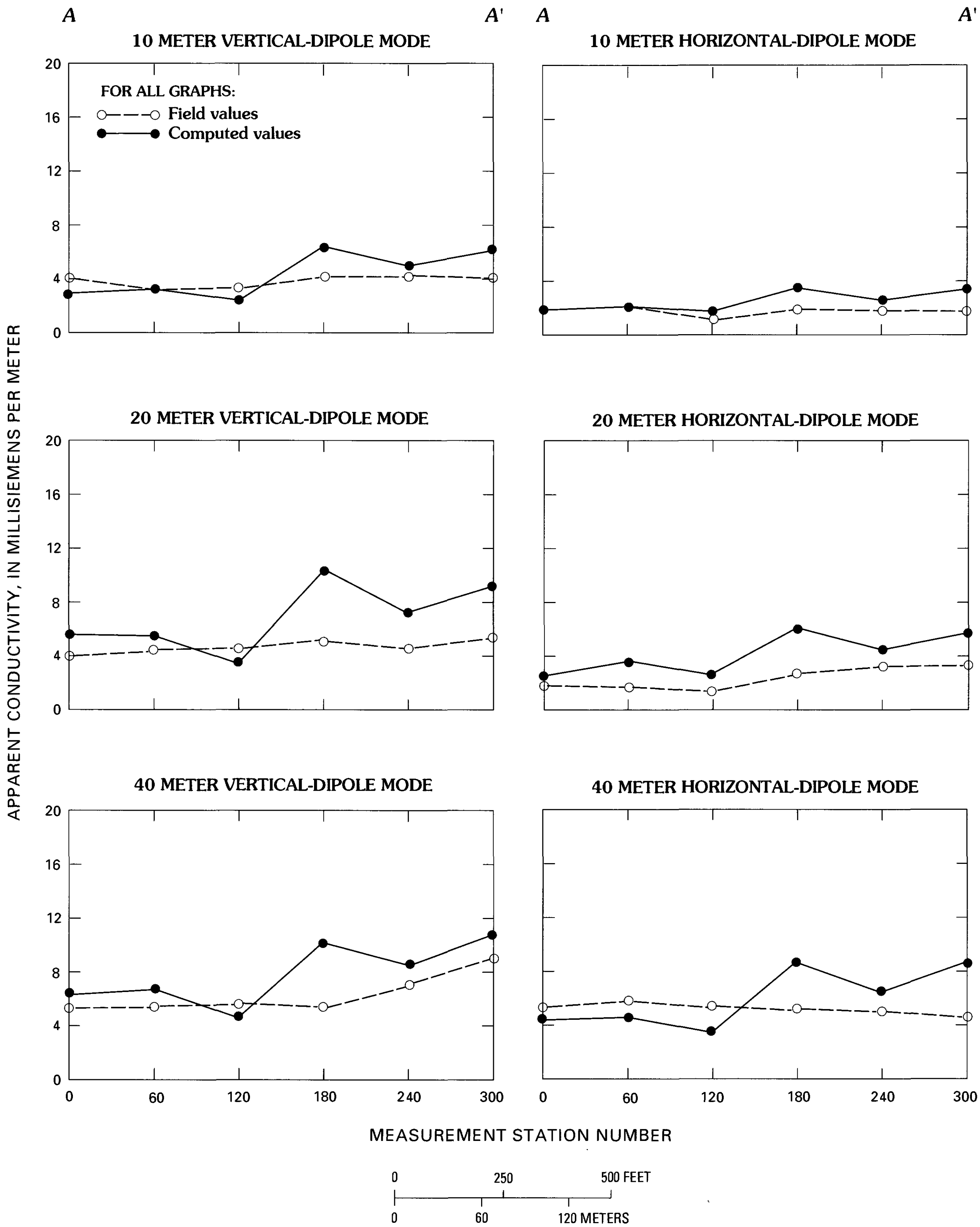
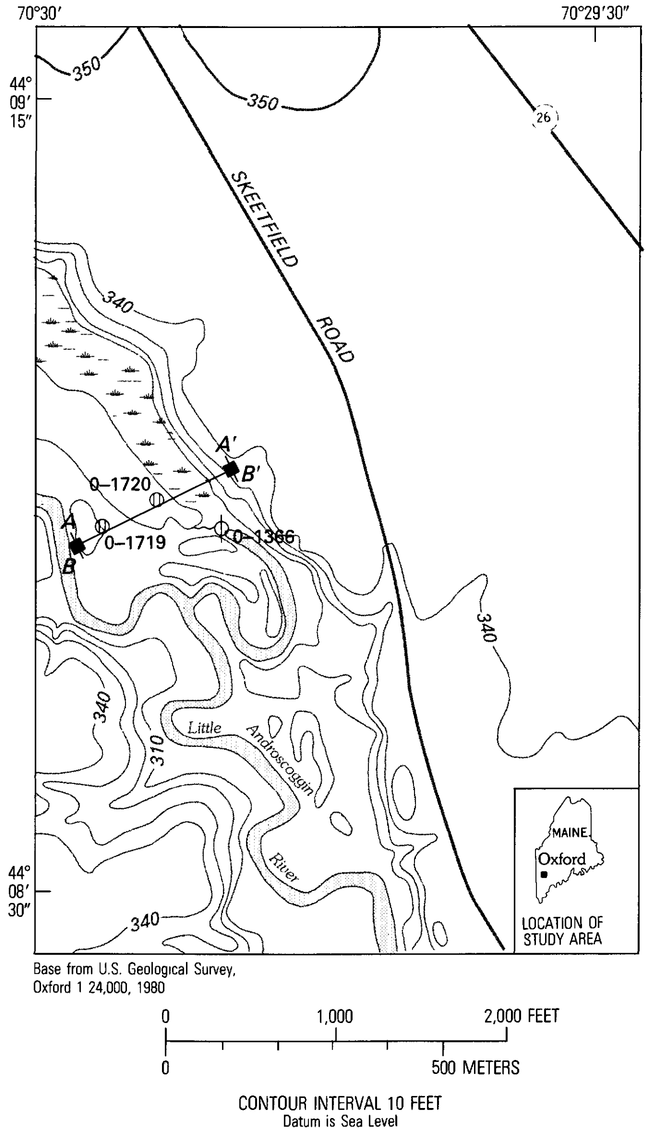


FIGURE 55.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the study site at the airport in Oxford, Maine.



EXPLANATION

A —— A′ **Electromagnetic survey line**

B —— B′ **Seismic-refraction line**

0–1720 **Test hole**—Number is town well number used in U.S. Geological Survey publications

0–1366 **Unused spring**—Number is county number used in U.S. Geological Survey publications

FIGURE 56.—Location of the esker site in Oxford, Maine, including test holes, spring, and surface-geophysical survey lines.

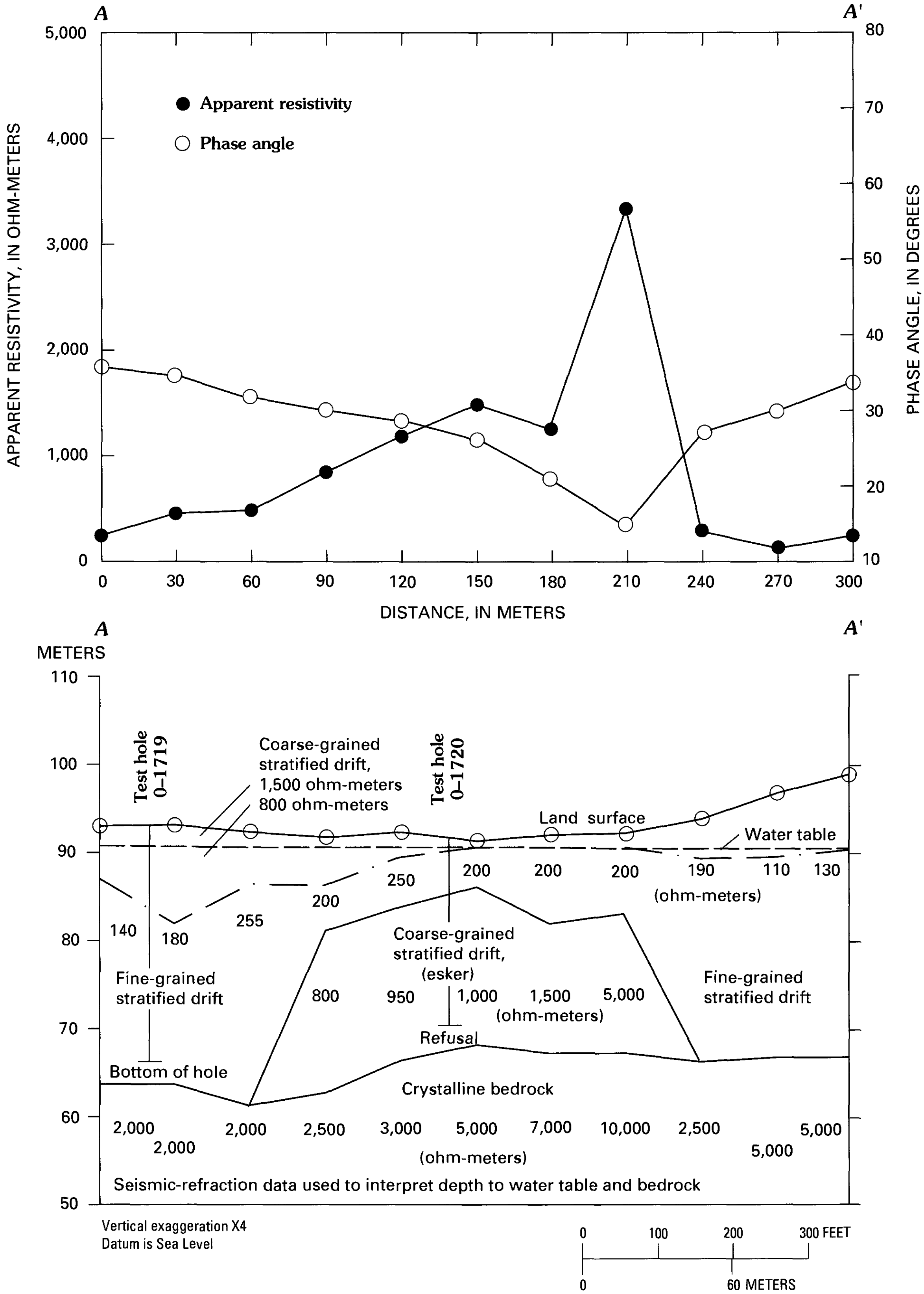


FIGURE 57.—Very-low-frequency apparent resistivity and phase-angle field data, and the interpreted geoelectric Earth model from direct-current-resistivity, seismic refraction, and very-low-frequency apparent resistivity data, from the esker site in Oxford, Maine.

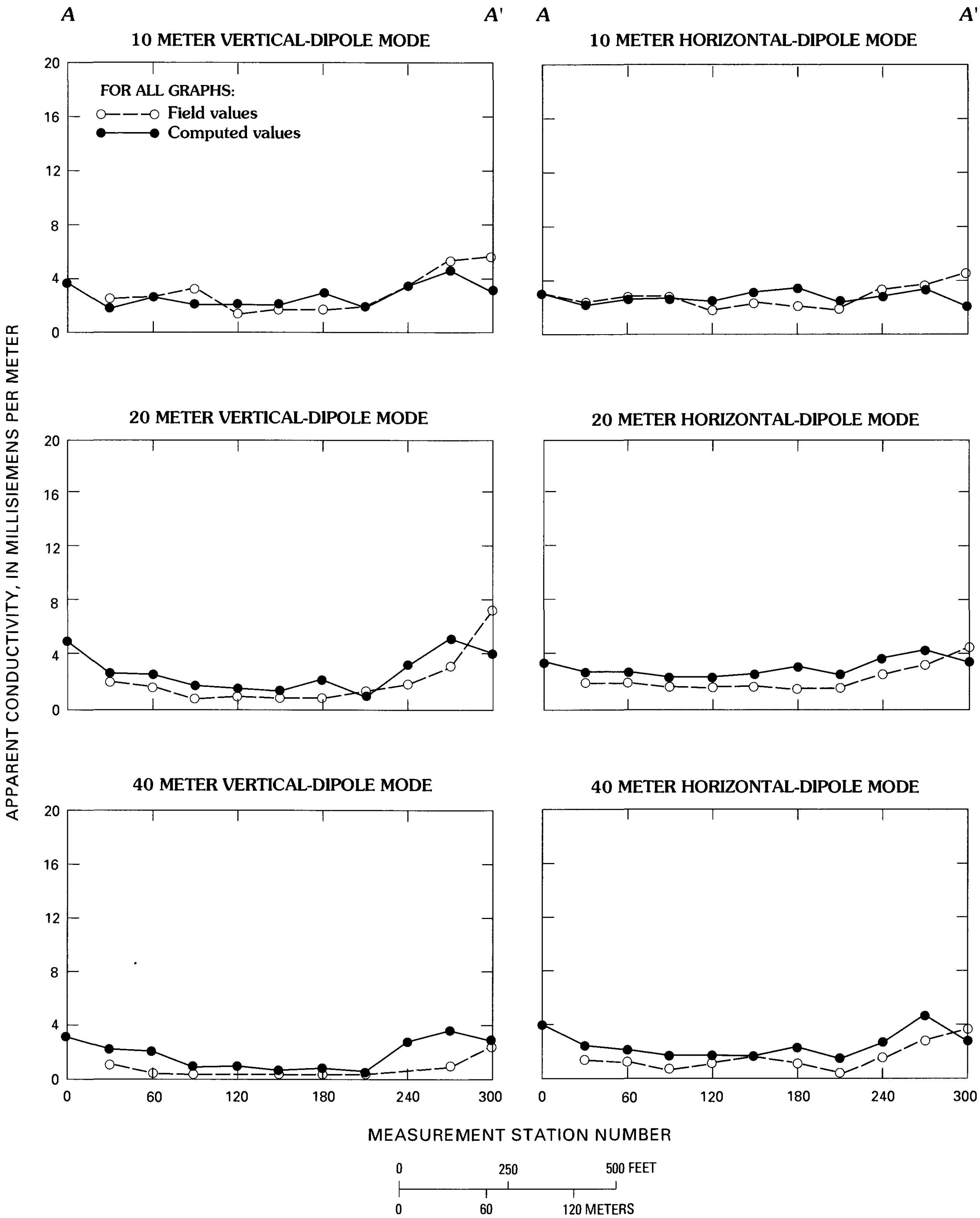


FIGURE 58.—Field and computed inductive terrain-conductivity values for the 10-, 20-, and 40-meter-intercoil spacings at the esker site in Oxford, Maine.

TEST-HOLE LOGS

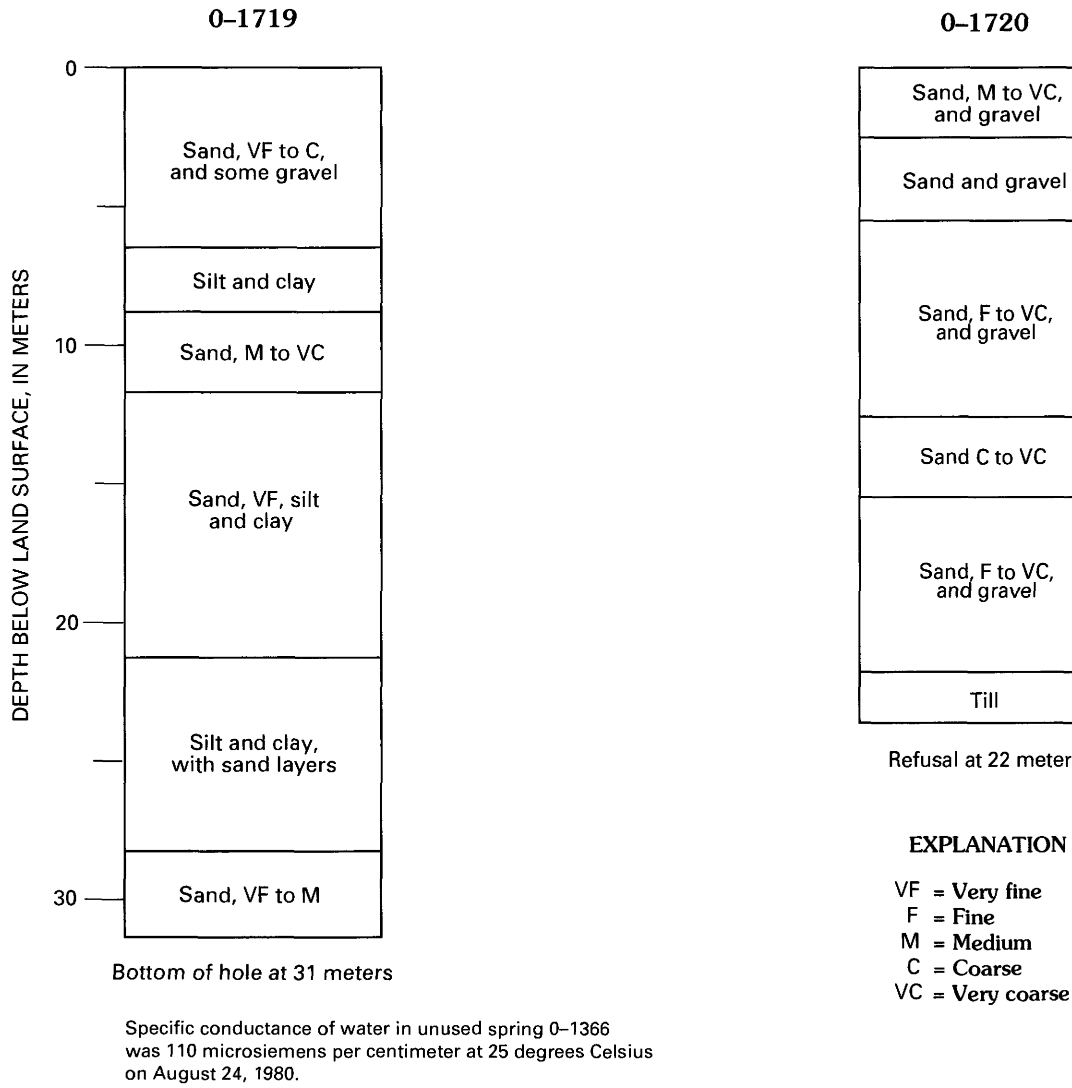


FIGURE 59.—Geologic logs from test holes at the esker site in Oxford, Maine.

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