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Distribution of Salinity in Ground Water from the Interpretation of Borehole-Geophysical Logs and Salinity Data, Calf Pasture Point, Davisville, Rhode Island

Water-Resources Investigations Report 99-4153

U.S. Department of the Interior
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1999

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectares (ha)
foot (ft)	0.3408	meter (m)
foot per day (ft/d)	0.3808	meter per day (m/d)

VERTICAL DATUM

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 the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS:

cps	count per second
ppt	parts per thousand
mS/m	millisiemens per meter

Distribution of Salinity in Ground Water from the Interpretation of Borehole-Geophysical Logs and Salinity Data, Calf Pasture Point, Davisville, Rhode Island

By Peter E. Church *and* William C. Brandon

Abstract

The distribution of salinity in ground water at Calf Pasture Point, a small coastal peninsula bounded by Narragansett Bay on the east and Allen Harbor on the west, in Davisville, Rhode Island, was interpreted from borehole-geophysical data and previously collected salinity data to help identify potential flowpaths of contaminated ground water to surface-water bodies. The surficial material at this 40-acre site, which ranges in thickness from about 30 to 85 feet, is composed of an upper sand unit, a silt unit, and a till unit overlying bedrock. Borehole-geophysical data indicate that fresh ground water is present in all surficial units in the northern and northwestern part of the site. In the central and eastern parts of the site, where most of the current land surface is composed of dredged fill placed in a small saltwater embayment, brackish and saline ground water predominate. Fresh ground water moving into this area from upgradient and recharge to this extended land surface from precipitation is diluting the saline ground water in the upper sand and till units, and to a lesser extent in the silt unit. In this area, the freshwater-flow system is slowly expanding towards Narragansett Bay and the entrance channel to Allen Harbor.

INTRODUCTION

Chlorinated hydrocarbons were released onto the land surface and into the shallow unsaturated zone intermittently between 1960 and 1974 at Calf Pasture Point, a coastal peninsula bounded by Narragansett Bay and Allen Harbor at the U.S. Naval Reservation, Construction Battalion Center, Davisville, Rhode Island (fig. 1). In the early- to mid-1990's, surface soils, soils from test and well borings, and water samples from wells in the southern 40 acres of Calf Pasture Point were analyzed to characterize the hydrogeology and distribution of the contaminants in the surficial materials and underlying bedrock (EA Engineering, Science, and Technology, 1997). These data revealed a sequence of glacial sediment, ranging in thickness from about 30 to 85 ft, overlying quartzite and phyllite bedrock, and a heterogeneous distribution of fresh, brackish, and saline waters in the coastal aquifer. These data also revealed high concentrations of contaminants in fresh ground water beneath the disposal site, and low concentrations of contaminants dispersed radially into fresh and brackish ground water. An understanding of the distribution of fresh, brackish, and saline ground water in this coastal setting can be used to determine ground-water circulation patterns and identify potential pathways of contaminants to surface-water bodies, which in turn can be used to develop an effective ground-water monitoring program.

In December 1996 and August 1997, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), collected borehole-geophysical data to provide a more detailed description of the distribution of salinity in the surficial materials at Calf Pasture Point. These borehole-geophysical data were obtained from existing wells and were interpreted in conjunction with existing hydrogeologic and salinity data. The purpose of this report is to describe the horizontal and vertical distribution of fresh, brackish, and saline water in the surficial aquifer at this site as interpreted from the existing data and the borehole geophysical data.

Description of Study Site

Calf Pasture Point, a relatively flat, low-lying peninsula that juts into Narragansett Bay, is bounded by Narragansett Bay to the east, the entrance channel to Allen Harbor to the south, and Allen Harbor to the west (fig. 1). The present land surface slopes gently from an altitude of about 20 ft at the northern part of the site to sea level at the shoreline. According to earlier maps (EA Engineering, Science, and Technology, 1997), the current shape and extent of the peninsula differs significantly from that of the early 1700's when it was a thin spit jutting to the southwest and much of the current Calf Pasture Point was a small saltwater embayment in Allen Harbor. During the next 220 years, the spit elongated in a more westerly direction to form a distinctive hook. In the early 1940's, the placement of dredged sediment from Narragansett Bay in the shallow embayment behind the spit created much of the current land surface (fig. 1). The southern tip of Calf Pasture Point has formed by coastal sedimentation since 1966.

Previous Investigations

Data collected by EA Engineering, Science, and Technology at the site include lithologic data from test holes and boreholes, and ground-water level, hydraulic conductivity, and salinity data from wells (EA Engineering, Science, and Technology, 1997). Four distinct unconsolidated lithologic units overlying bedrock were described from land surface to bedrock: an upper sand unit, a silt unit, a lower sand unit, and a till unit. The upper sand unit is composed of fine- to coarse-grained sand with varying amounts of silt, gravel, and shell fragments, and ranges in thickness from about 5 to 19 ft. This sand unit contains the dredged sediment from Narragansett Bay; however, the dredged sediment is not differentiated from the sand that surrounded the former saltwater embayment. The upper sand unit is underlain by a silt unit that ranges in thickness from 0 to about 47 ft. This silt unit is described by EA Engineering, Science, and Technology (1997) as sandy in the northern part of the site and as having a component of sand or clay, or both, in the southeastern part of the study site. In most of the area, the silt unit is underlain by a basal layer of till described by EA Engineering, Science, and Technology (1997) as a silty gravelly sand, with sandy gravelly silt in some areas, that ranges in thickness from 0 to about 36 ft. The lower sand unit is generally composed of very fine to fine sand with some silt and ranges in thickness from 0 to 28 ft. This unit is present only in the eastern part of the site and separates the silt and till units (EA Engineering, Science, and Technology, 1997). These unconsolidated surficial deposits overlie a bedrock surface that slopes to the southeast and south towards Narragansett Bay and the entrance channel to Allen Harbor. The combined thickness of the silt and till units is very uniform in a wide, northeast-southwest trending band through the central part of the site; however, the thickness of the till unit increases and the thickness of the overlying silt decreases in a southwest direction within this band.

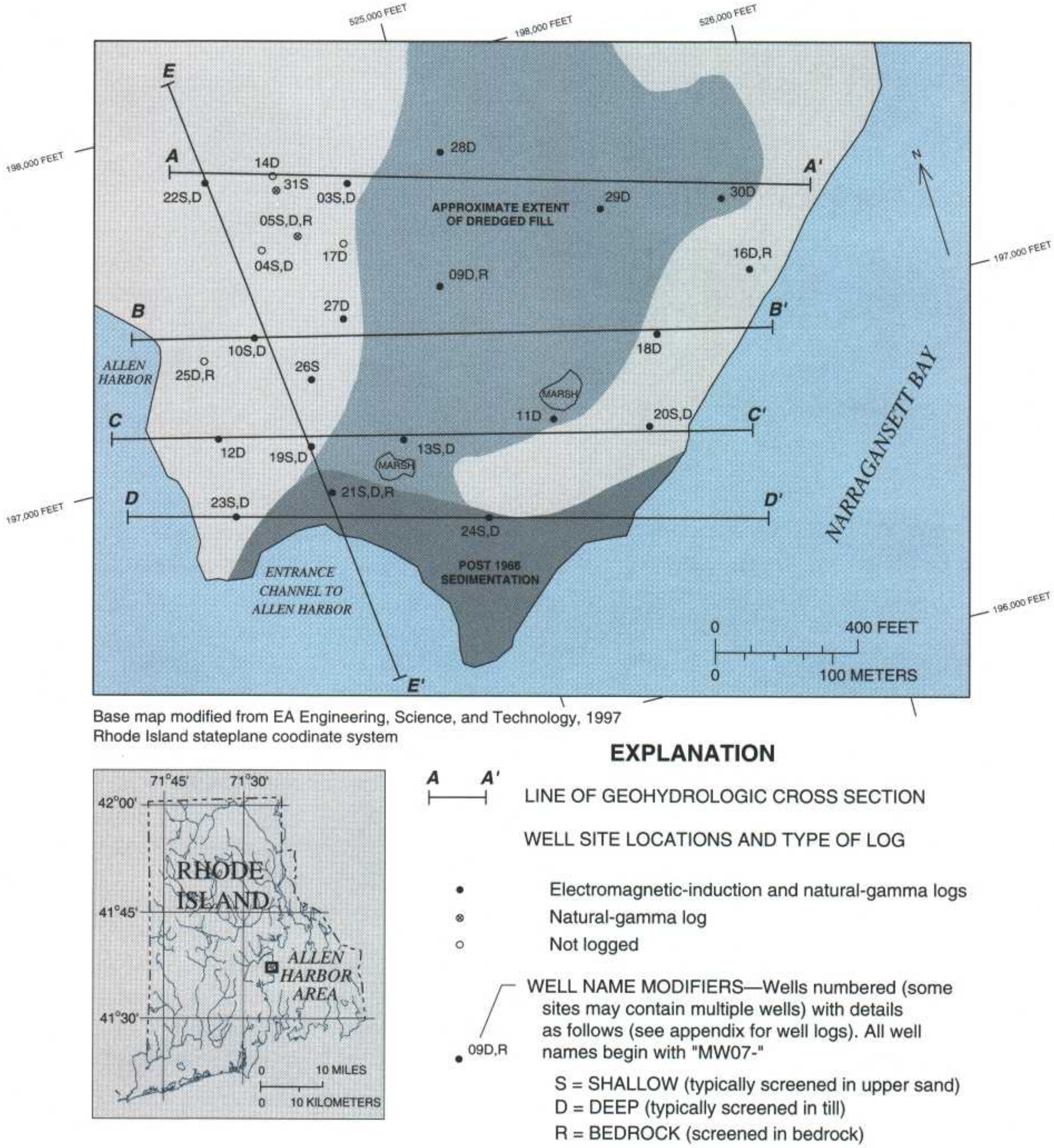
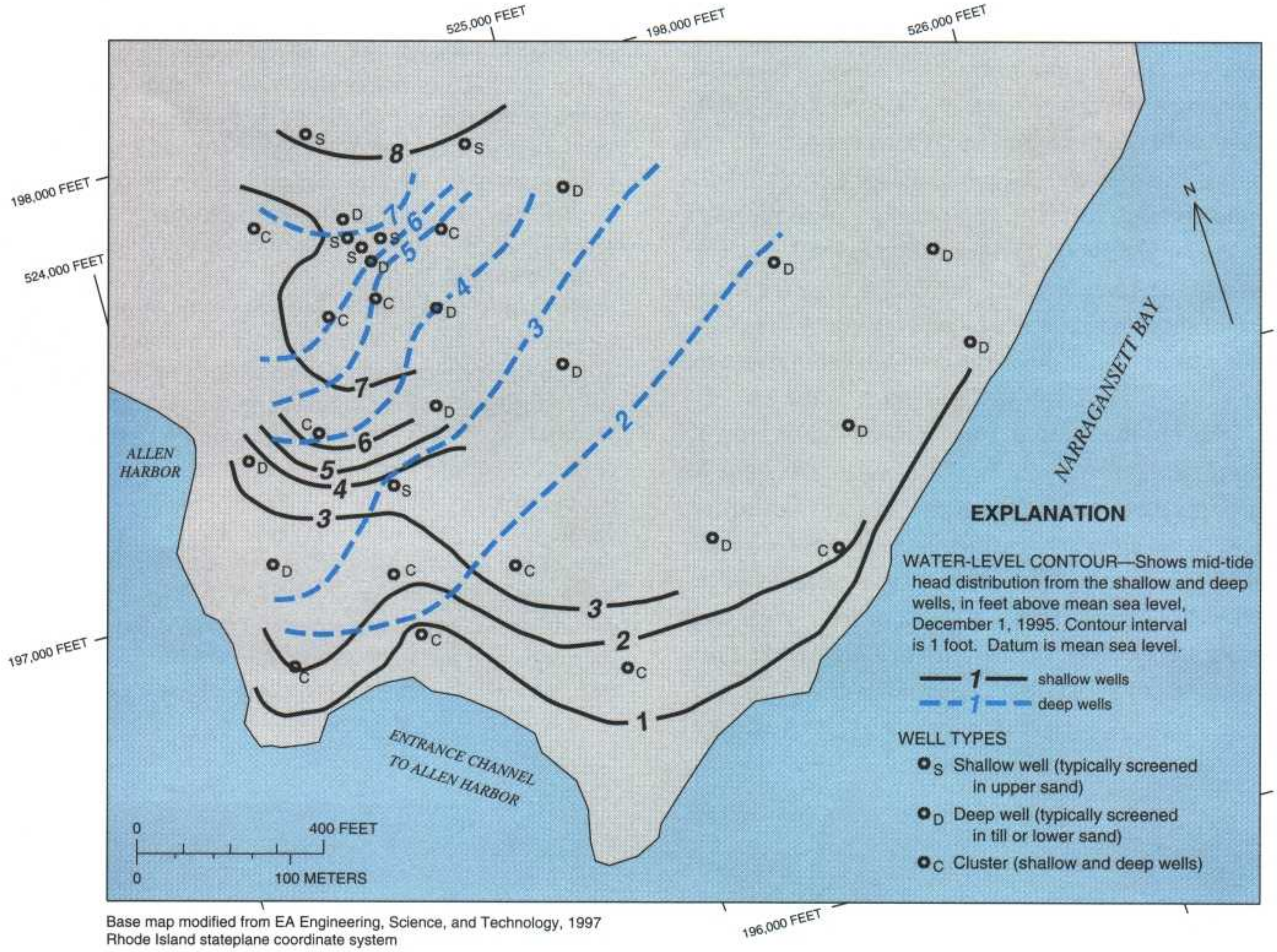


Figure 1. Calf Pasture Point study site, Davisville, Rhode Island.

Beneath a small elongated area extending from the west-central part of the site to the entrance channel to Allen Harbor (near wells MW07-26S, MW07-19S,D, and MW07-21S,D; fig. 1), the silt unit is absent and the till unit is overlain directly by the upper sand unit.

The water table, which lies within the upper sand unit, ranges in altitude from about 8 ft above mean sea level in the northern part of the site to about 2 ft above mean sea level in wells near the shoreline (fig. 2). Water-table fluctuations due to tides are about 1to 2 ft in wells near the shoreline. This tidal effect decreases landward from the shoreline; the water table is not affected by normal tides in the northern part of the site. The ground-water flow direction in this water-table aquifer is toward the shoreline of Allen Harbor, the entrance channel to Allen Harbor, and Narragansett Bay. Ground water in the till and lower sand units flows to the southeast and south towards Narragansett Bay and the entrance channel to Allen Harbor (fig. 2). Data from five wells completed in bedrock indicate a ground-water-flow direction to the southeast towards Narragansett Bay. Vertical head gradients in the surficial materials generally indicate a downward flow, or recharge, from the upper sand unit to the till unit; however, upward flow, or discharge, has been measured at wells near the shoreline. Downward flow of ground water from the till into bedrock takes place in the northwestern part of the site, and upward flow from bedrock into the till takes place in the central and southeastern part of the site. Results from slug-test analyses reported by EA Engineering, Science, and Technology (1997) indicate that hydraulic conductivities range from 8.9 to 147 ft/d in the upper sand unit, 0.1 to 19 ft/d in the silt unit, 1.2 to 21.8 ft/d in the lower



Base map modified from EA Engineering, Science, and Technology, 1997
Rhode Island stateplane coordinate system

Figure 2. Mid-tide shallow and deep well head distribution, December 1, 1995, Calf Pasture Point, Davisville, Rhode Island (data from EA Engineering, Science, and Technology, 1997).

sand unit, and 0.4 to 379 ft/d in the till unit. The highest hydraulic conductivities in the till are from the shallow wells MW07-19S (139 ft/d) and MW07-21S (379 ft/d). These wells are in the upper part of the till near the entrance channel to Allen Harbor where the silt unit is absent and the till is directly overlain by the upper sand unit. Although these hydraulic conductivities appear anomalously high compared to those in the lower part of the till, and compared to hydraulic conductivities in other till deposits in southern New England (Melvin and others, 1991), high hydraulic conductivities in this zone may be in part due the lesser amount of silt and greater amount of sand in the upper part of the till than in the lower part (EA Engineering, Science, and Technology, 1997) and the shallow depth where compaction would be small.

BOREHOLE-GEOPHYSICAL LOGGING METHODS

The borehole-geophysical methods used at the site were natural gamma and electromagnetic induction. These methods are not affected by the chlorinated hydrocarbon contaminant plume at this site. Borehole data were obtained at 0.1-ft vertical increments as probes were raised from the bottom to the top of each well. Each measurement represents a volume of the aquifer surrounding the well; its vertical dimension much greater than the 0.1-ft interval between measurements. As a result of these overlapping volumes with each subsequent measurement, distinct interfaces between lithologic units, for example, are recorded as transitional zones.

Gamma logs are a measure of the natural gamma radiation emitted from radioactive elements in rock, primarily from potassium-40 and daughter products of the uranium- and thorium-decay series (Keys and MacCary, 1971). In New England, gamma radiation results largely from potassium-40, a radioisotope in potassium feldspar (Hansen, 1993). In unconsolidated material, low levels of natural-gamma radiation generally represent materials where most of the feldspar has been removed by transport and depositional processes, such as in deposits of sand. Higher levels of natural-gamma radiation are generally emitted from fine-grained unconsolidated materials, such as silt and clay (Keys and MacCary, 1971). Silt and clay deposits generally have higher gamma radiation than sand deposits because the finer grained material contains more feldspar. About 90 percent of the natural-gamma response recorded by the probe comes from the first foot radially from the vertical axis of the well (J. H. Williams, U.S. Geological Survey, oral commun., 1998). Natural-gamma logs are generally not affected by porosity and pore fluids. Natural-gamma radiation is expressed in units of counts per second.

Electromagnetic-induction (EM) logs are a measure of the electrical conductivity of the aquifer and are a function of soil or rock type (lithology), porosity, moisture content, and the concentrations of dissolved solids in the pore fluid (Biella and others, 1983). The EM probe measures the response of the aquifer surrounding a well to an induced electromagnetic field (Hearst and Nelson, 1985). The probe measures the aquifer response in a zone from about 0.5 ft to 4 ft radially from the vertical axis of the well. Maximum response occurs at about 1 ft, and one-half of the response occurs within about 2 ft from the vertical axis of the well (McNeill, 1980). EM measurements are insensitive to organic compounds in borehole and aquifer pore fluids, nonmetallic well casing and screen material, and sand packs and grout material to borehole diameters approaching 1 ft. However, EM measurements are very sensitive to metal casing and screens and to other metallic objects within several feet of the well casing or screen, and can be affected by grout materials containing sodium, calcium, and chloride in boreholes greater than 1 ft in diameter. The presence of these materials will cause anomalously high or oscillating EM conductivities. EM conductivity is expressed in units of millimhos per meter, or millisiemens per meter as used in this report.

Borehole-geophysical logging at Calf Pasture Point was conducted in December 1996 with an EM probe attached to the bottom of a gamma probe (see table 1 for a list of wells that were logged and dates when geophysical data were collected). The measuring points for the EM and gamma probes were 3 ft and 7 ft, respectively, above the bottom of the combined probes. Because the probes could not be lowered past the bottom of the well screens, the aquifer adjacent to the bottom 3 ft of the well screens was not fully represented by the EM logs, and the bottom 7 ft was not represented by the gamma logs. Geophysical data collection in August 1997 (table 1) was performed with independent tools for gamma and EM logs. Measuring points on the gamma and the EM probes were about 0.5 ft and 2 ft, respectively, from the bottoms of the probes. As a result, geophysical data obtained in August 1997 were from a thicker portion of the aquifer adjacent to the well screens than those obtained in December 1996. Only the aquifer adjacent to the bottom 0.5 ft of the well screens was not fully represented by the gamma logs and the bottom 2 ft by the EM logs. Gamma and EM conductivity logs obtained from wells at the Calf Pasture Point study site are shown in the Appendix 1. Also included are the EM resistivity logs, which are the inverse of the EM conductivity logs.

INTERPRETATION OF BOREHOLE-GEOPHYSICAL DATA

Natural-Gamma Data

Gamma data in the surficial materials at Calf Pasture Point typically indicate subtle changes with depth that correspond to changes in lithology, and generally corroborate the lithologic and stratigraphic interpretations provided by EA Engineering, Science, and Technology (1997). The gamma radiation measured in most wells is lower in the upper and lower sand units than in silt and till units. The gamma radiation data also indicate apparent changes in grain-size distribution within lithologic units. At well MW07-19D, the gamma radiation increases significantly with depth in the bottom third of the till unit. This increase in radiation is consistent with the composition of the till changing from silty gravelly sand in the upper two-thirds of the till unit to gravelly sandy silt in the lower third. A similar increase in gamma radiation in the lower part of the till unit takes place at well MW07-21D where the till is more silty than in the till above. At well MW07-29D, the gamma radiation in the till unit increases with depth and corresponds to a change from sand and silt to gravelly sandy silt (EA Engineering, Science, and Technology, 1997). Measurements of gamma radiation in the till unit at wells MW07-23D and MW07-27D and in the lower sand unit at wells MW07-18D and MW07-30D indicate measurable variations in grain-size distribution with depth.

Electromagnetic-Induction Data

EM data collected at Calf Pasture Point indicate considerable vertical and horizontal variability in response to changes in pore fluid conductivity, porosity, and lithology. EM conductivities range from about 20 to 900 mS/m in the upper sand unit, about 20 to 1,000 mS/m in the silt unit, and about 30 to 750 mS/m in the till unit. At this site, electrical conductivity of the pore fluid is dominated by the salinity of the water. In an environment where salinity is the only variable that changes, there would be a high degree of correlation between salinity and EM conductivity. The relation between measured salinities in ground water and EM conductivities obtained adjacent to the well screens exhibits a general increase in EM conductivity with increasing salinity, but also has considerable scatter (fig. 3). This scatter can be attributed to variations in lithology, variation in porosity between and within lithologic units, and possibly other factors, such as well construction and the difference in time when salinity measurements and EM measurements were made. The relative influence of these factors on the EM conductivity is discussed below.

The effects of lithology, specifically the electrical conductivity of the sediments comprising the lithologic units, on EM logs at this site were assessed by examining data from wells in low salinity areas. EM conductivities at wells MW07-03D, MW07-10D, MW07-12D, and MW07-22D (fig. 1), where measured salinities were low or not detected, are correspondingly low, change little with depth, and appear to be unaffected by lithology. Similar EM conductivities are found in the upper sand, silt, and till units. Assuming the electrical conductivity of the sediments comprising these deposits varies little within the site, EM conductivities at these wells indicate that lithology has little effect on EM conductivities. Although the silt unit in the southeastern part of the study site, where high EM conductivities are present (wells MW07-16D, MW07-18D, and MW07-20D), is described as having a component of clay (EA Engineering, Science, and Technology, 1997), this clay is not likely to have much effect on the EM conductivities. Clays in the glacial deposits of New England are predominately composed of clay-sized particles of quartz and contribute little to the electrical conductivity of the deposits.

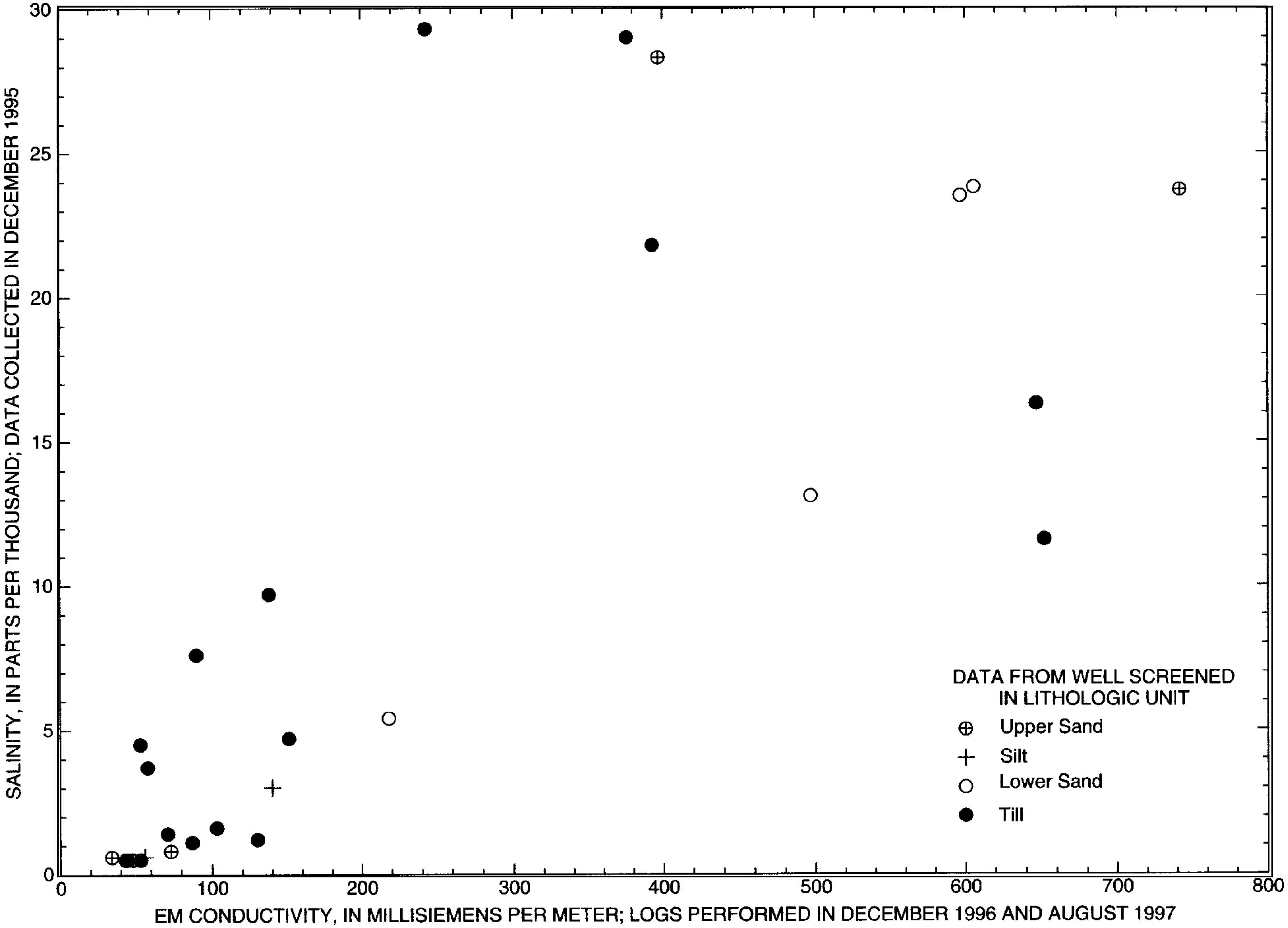


Figure 3. Relation between salinity and electromagnetic-induction conductivity by lithologic unit, Calf Pasture Point, Davisville, Rhode Island.

In other wells, particularly MW07-13D and MW07-29D (fig. 1), an apparent association of EM conductivity and lithology can be seen: EM conductivity is about 100 mS/m in the upper sand and till units, and about 300 mS/m in the silt unit at well MW07-13D; about 200 to 300 mS/m in the upper sand and till units, and about 800 to more than 900 mS/m in the silt unit at well MW07-29D. This apparent association, however, is more likely due to the different porosities in these lithologic zones or changes in pore-fluid conductivity, or both, rather than differing conductivities of the sedimentary materials. Higher porosity in the silt unit can partially explain the higher EM conductivities as the conductive pore fluid occupies a larger portion of the total volume of sediment.

The effect of porosity on EM conductivity in fully saturated sediment can be roughly estimated by use of the empirical formula developed by Archie (1942) where F, the formation resistivity factor, is equal to R_O/R_W, the electrical resistivity of the formation divided by the electrical resistivity of the of the formation fluid, and the empirical formula developed by Winsauer (1952), $F=1/\phi^m$ where ϕ is porosity and m is a cementation factor ranging from 1.3 to 2.6 (Telford and others, 1976). A specific form of this expression for granular, poorly consolidated rock, called the Humble formula, is $F=0.62\phi^{-2.15}$ (Winsauer, 1952; Keys and MacCary, 1971; Telford and others, 1976). By combining these formulae, replacing resistivity with its inverse, electrical conductivity, and rearranging, the following equation is derived:

$$C_o=(C_w\phi^{2.15})/0.62, \qquad (1)$$

where

C_o is electrical conductivity of the formation (EM conductivity); and

C_w is the electrical conductivity of the formation fluid.

To demonstrate the effect of porosity, equation 1 is applied to salinity and EM conductivity data from wells MW07-20S (shallow well) and MW07-20D (deep well). The shallow well is screened in the upper sand unit, and the deep well is screened in the till unit. The salinity in the shallow well (23.7 ppt) is about 0.8 times the salinity in the deep well (29.0 ppt). However, the EM conductivity in the shallow well (about 750 mS/m) is nearly 2 times the EM conductivity in the deep well (about 400 mS/m). By use of equation 1, the porosities of the upper sand and till are estimated to be 0.37 and 0.25, respectively. As these porosities are reasonable values for sand and till deposits (Fetter, 1980), they can account for the seemingly high contrast in salinity and EM conductivity data at these wells. Even though the salinity is lower in the shallow well, the higher porosity sand contains a larger volume of saline water than the till, producing a higher EM conductivity.

EM conductivities from other wells show large changes within and between lithologic units, such as at wells MW07-09D, MW07-11D, MW07-16D, MW07-18D, MW07-24D, MW07-28D, and MW07-30D. Assuming relatively small changes in porosities within lithologic zones, these large changes in EM conductivity are primarily the result of changes in the conductivity of the pore fluid. This is particularly evident with the high EM conductivities in the silt zone in wells near the Narragansett Bay shoreline and the shoreline along the entrance channel to Allen Harbor. Although few salinity measurements were taken from the thick and generally continuous silt zone, the EM logs are consistent with water of high salinity in the silt zone and in the upper sand in the southeastern and southern area of Calf Pasture Point.

The scatter in the relation between salinity and EM conductivity (fig. 3) also may be affected by well construction, well-screen placement, small-scale variations within lithologic units, and the different measurements times. Wells were constructed with 2-foot bentonite seals above the well screens and cement/bentonite grout along the well casings. The EM data do not appear to be affected by the bentonite seals as no consistent EM response was observed among the wells at these screen depths. Effects of the casing grout are assumed to be negligible because the borehole diameters in the surficial aquifer are less than 1 ft, the diameter beyond which the EM logger begins to respond to the induced current in the aquifer. Well-screen placement, relative to the source of the ground water sampled, could affect the EM logs. About one-third of the well screens from which the water samples were collected are screened in more than one lithologic unit. The water sample in which salinity was measured would have come preferentially from the more porous or permeable unit adjacent to the well screen. The EM log, however, represents the electrical conductivity of the aquifer material and fluid over the full length of the screen logged, regardless of the permeability of the material. As variations in grain size, shape, sorting, or packing take place within lithologic units, this preferential flow can occur even when the well screen is placed fully within one lithologic unit. Additionally, if the water sample was collected preferentially from the lower part of the well screen, the EM conductivity would be further biased because the EM logger was unable to fully measure the aquifer adjacent to the lowermost 2 ft of the well.

The EM conductivity-salinity relation appears not to have been affected by temporal variations in collection of EM and salinity data. Salinities were measured from all wells in December 1995. EM data were collected in 7 wells in December 1996, 12 months after the salinity measurements, and 14 wells in August 1997, 20 months after the salinity measurements (table 1). EM data were collected from two wells, MW07-19D and MW07-21D, in December 1996 and August 1997. Comparison of these duplicate data sets indicate that little change took place during the 8-month period, suggesting that changes in salinity over a 20-month period may be small.

Table 1. Wells with borehole-geophysical data including dates of collection, Calf Pasture Point, Davisville, Rhode Island

Well No.	Natural-gamma log, December 1996	EM conductivity log, December 1996	Natural-gamma log, August 1997	EM conductivity log, August 1977
MW07-03D			X	X
MW07-05R			X	
MW07-09D			X	X
MW07-10D	X	X		
MW07-11D			X	X
MW07-12D	X	X		
MW07-13D			X	X
MW07-16D			X	X
MW07-16R			X	
MW07-18D			X	X
MW07-19D	X	X	X	X
MW07-20D			X	X
MW07-21D	X	X	X	X
MW07-22D			X	X
MW07-23D	X	X		
MW07-24D	X	X		
MW07-26S	X	X		
MW07-27D			X	X
MW07-28D			X	X
MW07-29D			X	X
MW07-30D			X	X
MW07-31S			X	

Although a strong correlation between EM conductivity and salinity was unattainable with the existing data (fig. 3), the EM data collected provide sufficient data to delineate zones of fresh, brackish, and saline water in the surficial aquifer at Calf Pasture Point. Individual anomalies in the EM data at any given well may not be fully explainable due to the multiple factors that can affect these data, but, the salinity of the pore water is interpreted to be the primary factor affecting the EM data. Although salinities were not measured from ground-water samples in the thick silt deposit below the southeastern half of the site, EM conductivities in most of the silt unit were sufficiently high to characterize the water as saline. In the remainder of this report, references to different EM conductivities in different lithologic units imply that these differences are caused by changes in the pore water conductivity or porosity, or both, and not by changes in the composition of the sediment comprising the lithologic unit.

DISTRIBUTION OF SALINITY IN THE SURFICIAL AQUIFER

Distribution of fresh, brackish, and saline water in the surficial aquifer at Calf Pasture Point was delineated by use of previously collected salinity data (EA Engineering, Science, and Technology, 1997) and EM log data. Salinity definitions of these three categories are—fresh (<0.5 ppt), brackish (>0.5–10 ppt), and saline (>10 ppt). Salinity data indicate that the highest salinities are in the southern and southeastern parts of the site near the shoreline of Narragansett Bay and the beginning of the entrance channel to Allen Harbor. These saline waters were detected primarily in the lower sand and till units. Salinities in ground water decrease in a north-northwesterly direction. Brackish water was measured primarily in the till unit along a wide band that extends from the northeast to the southwest through the central part of the site. Freshwater was measured in the upper sand and till units in the northern part of the site; however, salinity data were not available in large areas of the upper sand unit or in most of the silt unit in this area. Salinities were further defined in the till unit and extended into the upper sand and silt units using EM data.

Vertical Distribution of Salinity

The vertical distribution of salinity is illustrated by geohydrologic cross sections, on which interpretive contours that define zones of fresh, brackish, and saline water have been drawn (figs. 4–8). Also depicted on these geohydrologic cross sections are lithology, salinity measurements, and EM logs. Five cross sections were constructed: four nearly parallel sections trend in a northwest-southeast direction across Calf Pasture Point, and one section is about 75 degrees from the other four and trends approximately north-south, as shown in figure 1. These sections are based on lithologic, salinity, and well construction data from EA Engineering, Science, and Technology (1997) and EM logs collected by the USGS. Vertical locations of well screens at well cluster sites are shown as one well. As these are straight line sections, some wells were projected short distances onto the sections. The land-surface profile that existed before the embayment was filled with dredged sediment from Narragansett Bay also is shown on the sections.

Section A-A'

This section, shown in figure 4, is in the northern part of the study site (fig. 1). The upper sand and till units change little in thickness, as compared to the silt deposit, which thickens towards the bay. A lower sand unit separates the silt unit from the till unit at wells MW07-29D and MW07-30D. Freshwater is present in the upper sand, silt, and till units in the area of wells MW07-22D and MW07-03D, consistent with the low EM conductivity, and at MW07-14D. The slight increase in EM conductivity in the central part of the silt unit at wells MW07-22D and MW07-03D could result from a small increase in porosity or a small decrease in grain size. The measured salinity in the till unit at well MW07-28D indicates the presence of brackish water at this location. Freshwater in the upper sand unit, brackish water in the upper and lower parts of the silt unit and in the till unit, and saline water in the middle of the silt unit are interpreted from the EM data. Saline water was measured in the till unit at well MW07-29D and in the lower sand unit at well MW07-30D. EM data indicate brackish water in the upper sand unit and saline water in the silt, lower sand, and till units at both wells.

Well MW07-03D is just west of the area where the dredged sediment from Narragansett Bay was placed (fig. 1). The freshwater observed at this well location is consistent with a freshwater-discharge zone near the shoreline of the former saltwater embayment. The presence of freshwater in the upper sand unit and brackish water in the till unit at well MW07-28D suggests that saline water is being diluted by upgradient fresh water moving towards the Narragansett Bay since this area was isolated from the saline embayment water by the emplacement of the fill. A similar occurrence in Florida was described by Halford (1998) where filling salt marshes and other tidally affected areas since 1942 has caused the continual expansion of the freshwater-flow system. Recharge of freshwater from precipitation onto this extended area at Calf Pasture Point also is likely to be a significant factor in reducing the salinity of ground water in the upper sand unit. The saline water in the silt unit is also being diluted by freshwater, but, at a much slower rate than in the upper sand and till units because of the lower hydraulic conductivity of the silt. Leaching of the presumed saline water in the dredged fill material may have contributed to the high salinity in the silt unit, but the former overlying saltwater is interpreted as the primary and original source of the saline water.

Section B-B'

Section B-B' (fig. 5), which is about 400 ft southwest of section A-A', extends from Allen Harbor to the northwest to Narragansett Bay to the southeast (fig.1). The lithology in this section is similar to that observed in section A-A', except for the large increase in the thickness of the till unit and a corresponding decrease in the thickness of the silt unit at well MW07-27D, and the thin till zones on both ends of this section. Freshwater was measured in the till unit and in bedrock at well MW07-25D near Allen Harbor. Although EM data were not obtained from this well, it is interpreted that freshwater also is present in the overlying silt and upper sand units. This is supported by the EM data and salinity data collected at well MW07-10D where a transition from fresh to brackish water is observed.

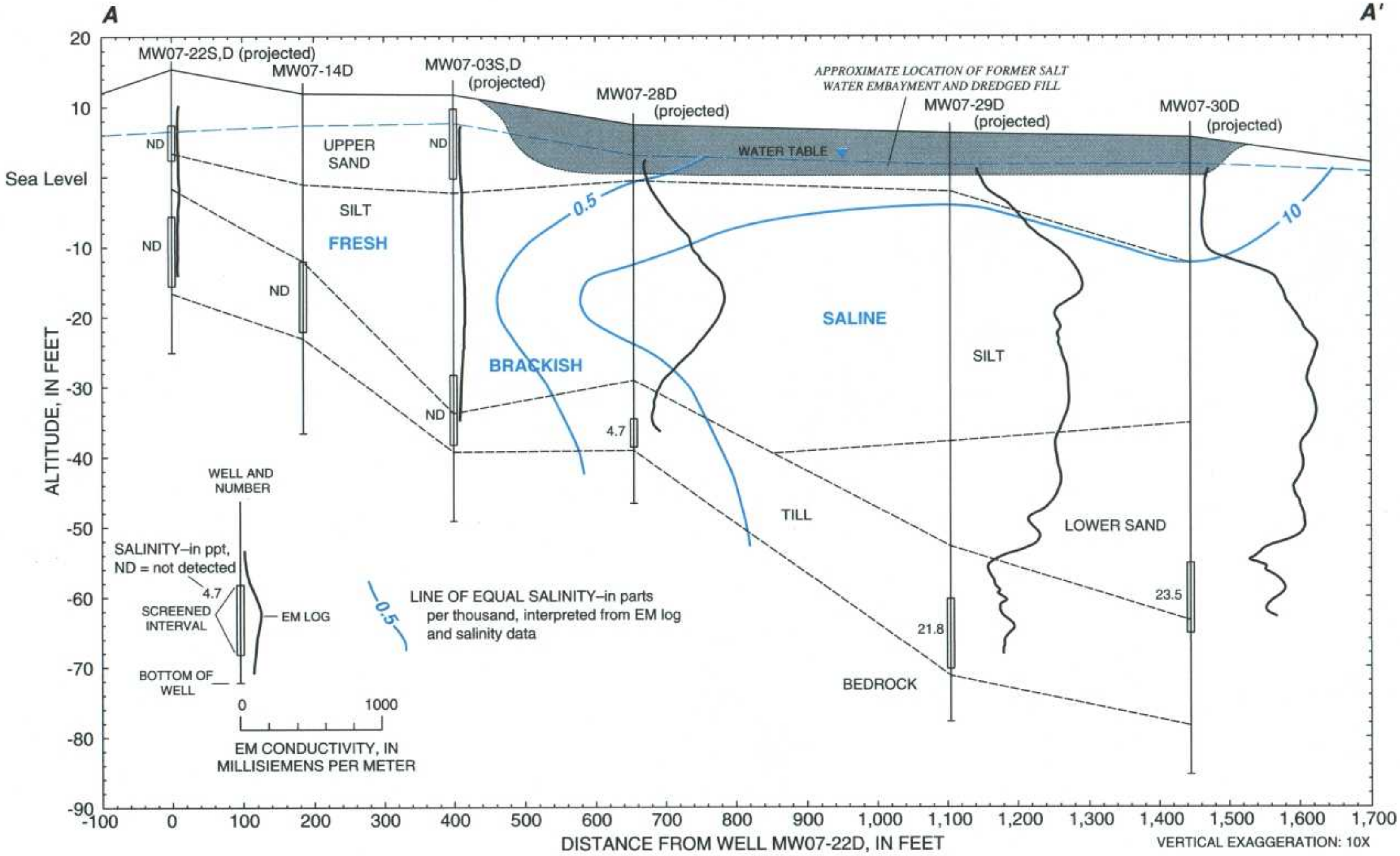


Figure 4. Geohydrologic section along line A-A', Calf Pasture Point, Davisville, Rhode Island.

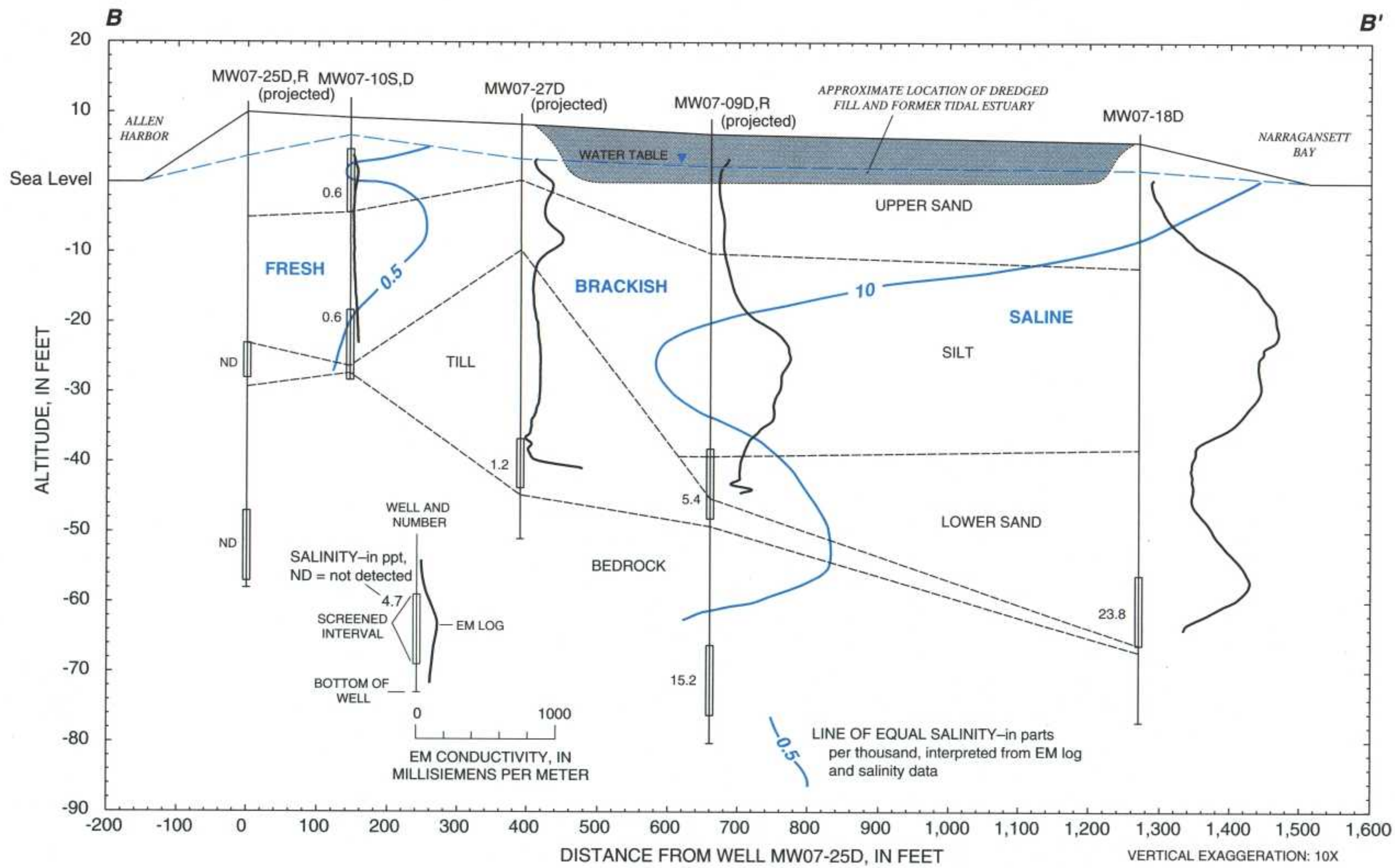


Figure 5. Geohydrologic section along line B-B', Calf Pasture Point, Davisville, Rhode Island.

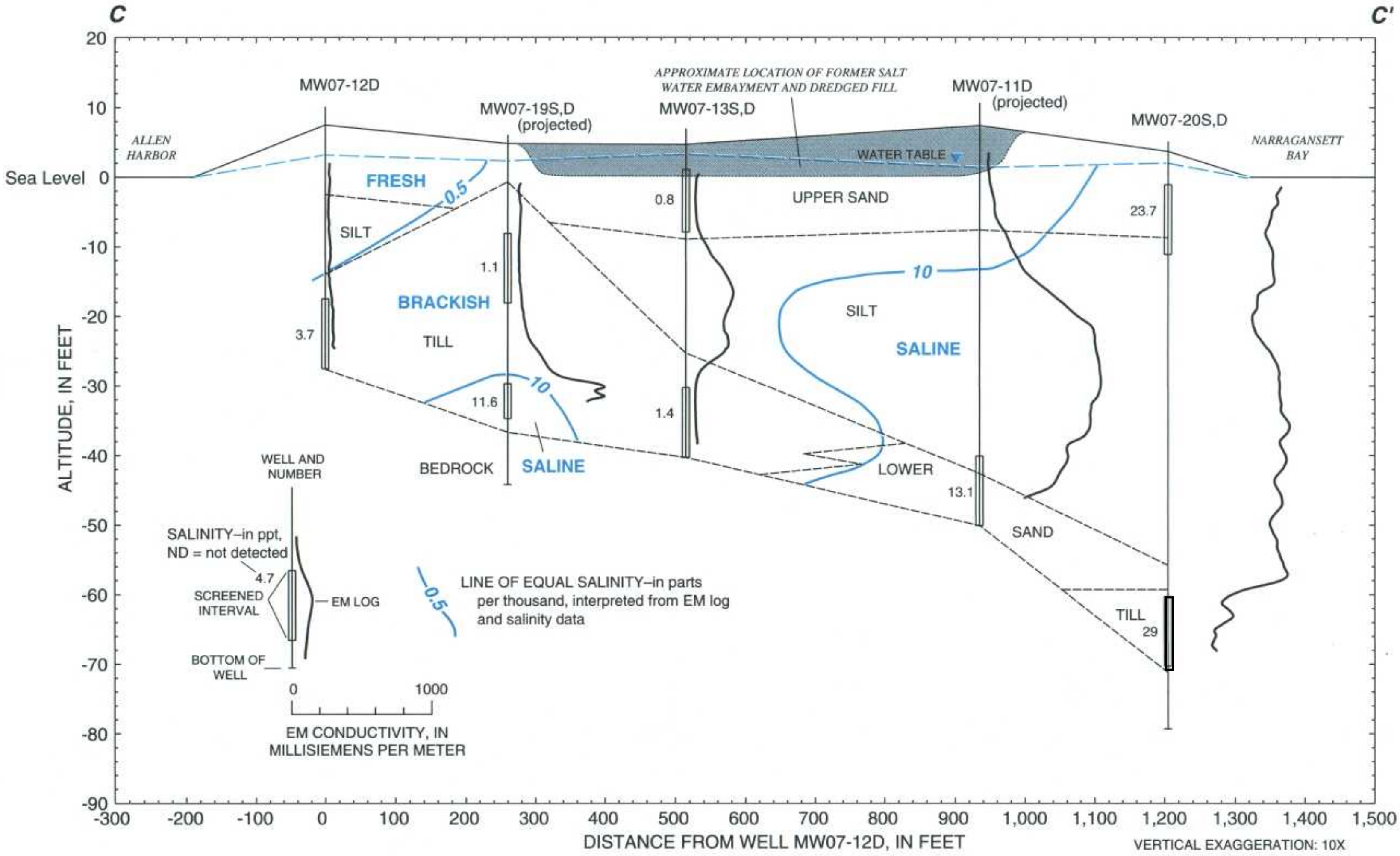


Figure 6. Geohydrologic section along line C-C', Calf Pasture Point, Davisville, Rhode Island.

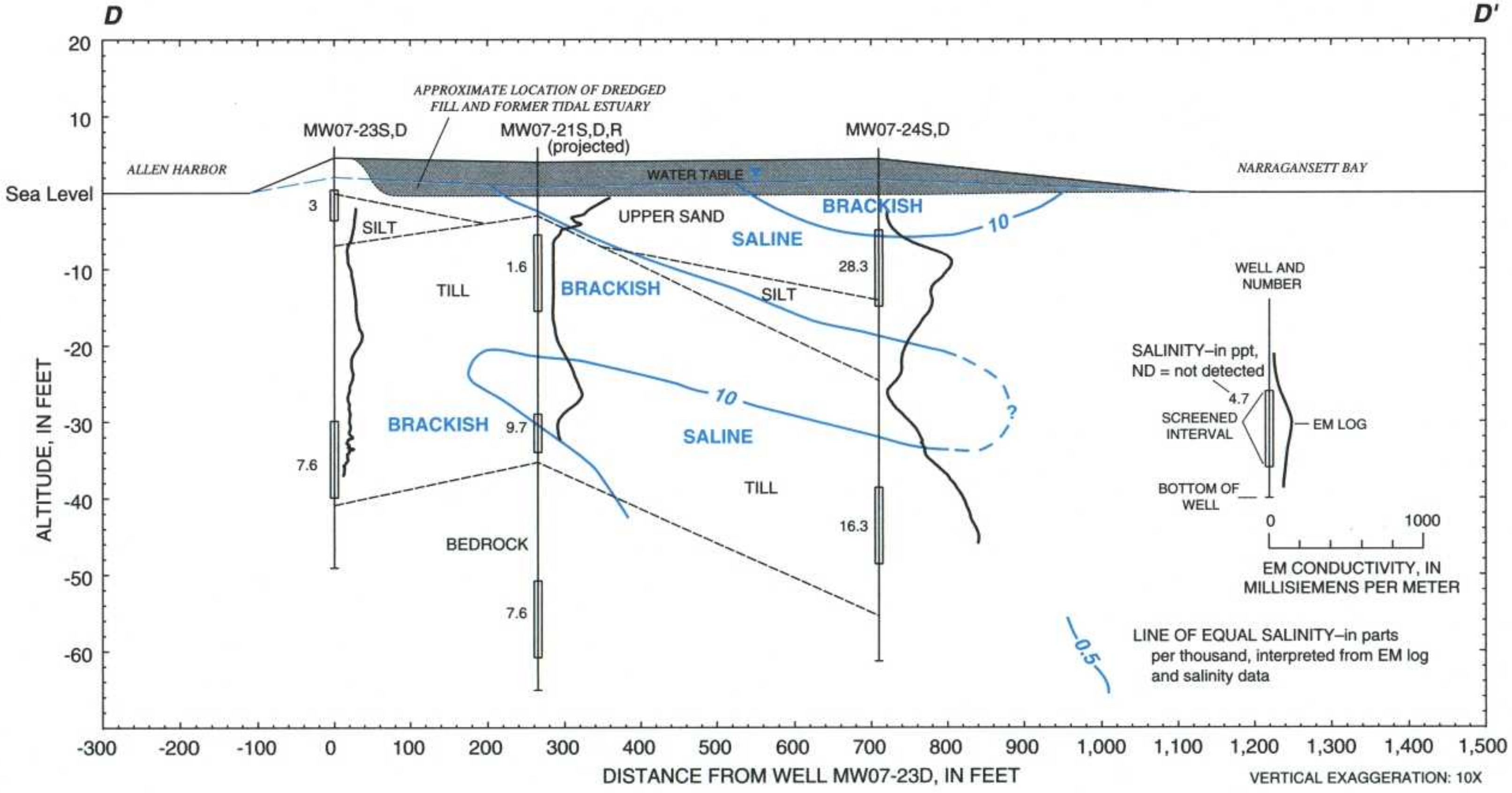


Figure 7. Geohydrologic section along line D-D', Calf Pasture Point, Davisville, Rhode Island.

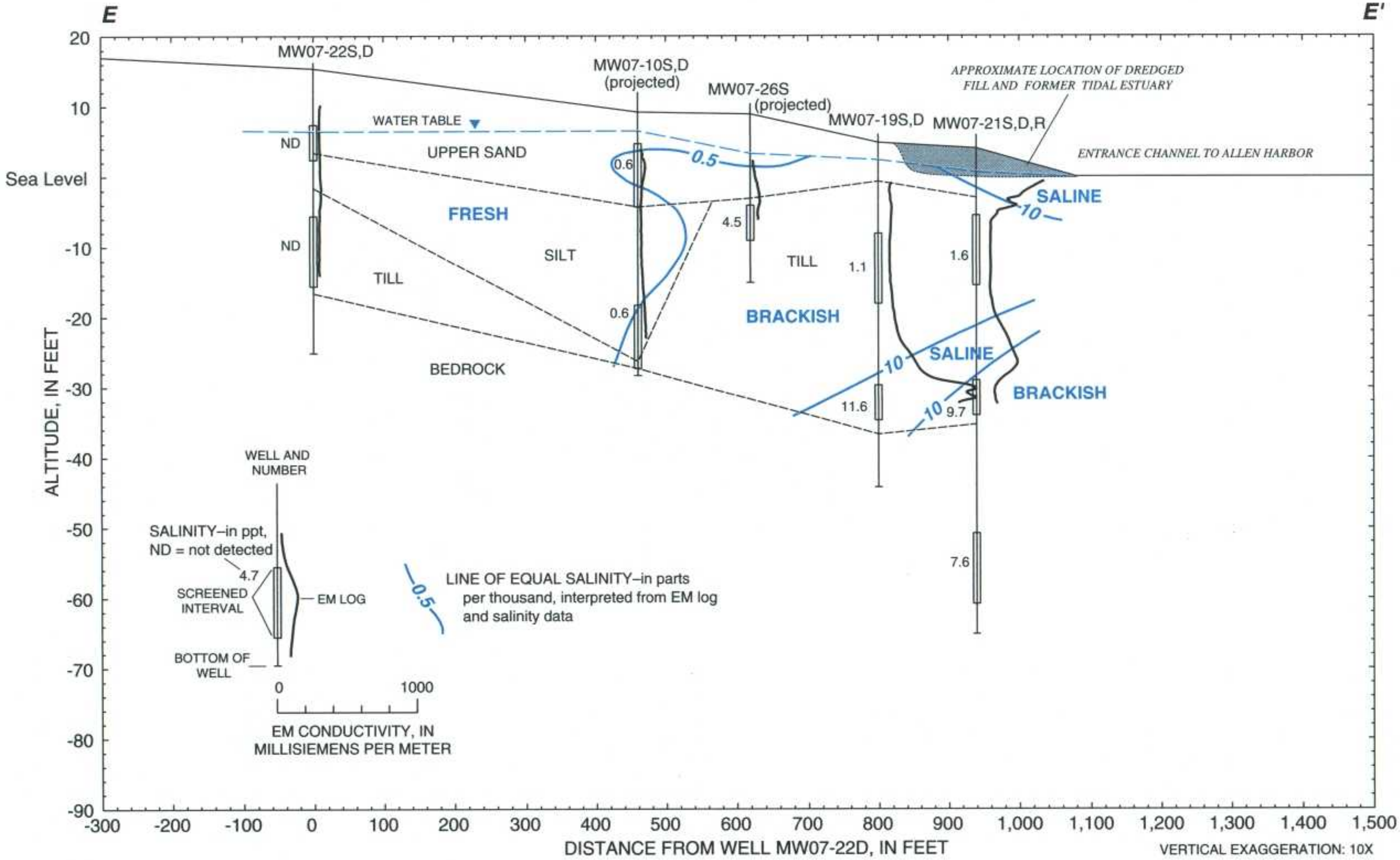


Figure 8. Geohydrologic section along line E-E', Calf Pasture Point, Davisville, Rhode Island.

Brackish water is present in the thick till unit and in the overlying silt and upper sand units at well MW07-27D. At well MW07-09D, brackish water is present in the upper sand unit, upper and lower parts of the silt unit, and the lower sand and till units. Saline water is present in the central part of the silt unit and was also measured in bedrock at this well. At well MW07-18D, which is near Narragansett Bay, brackish and saline water are present in the upper sand unit, and saline water is present in the silt, lower sand, and till units. Although EM conductivity in the upper part of the lower sand unit is considerably less than in the lower part, it is sufficiently high to characterize the water as saline.

As in section A-A', section B-B' also crosses the former saltwater embayment (fig. 1). The EM-conductivity profile at well MW07-09D is similar to that of well MW07-28D, indicating that fresh ground water from upgradient and recharge from precipitation has been diluting the saline water during the nearly 60-year period since the embayment was filled with dredged sediment from the Narragansett Bay.

Section C-C'

Section C-C' (fig. 6) is about 300 ft southwest of section B-B' (fig. 1). The lithology is dominated by the thick till unit in the northwestern part of the section and the thick silt unit in the central and southeastern part of the section. The till unit is directly overlain by the upper sand unit at well MW07-19D; the silt unit is locally absent in this area. EM conductivities at well MW07-12D are low but increase slightly in the till unit; this is consistent with the measured salinity. Freshwater is present in the upper sand and silt units at this well. The EM data from well MW07-19D displays a relatively low EM conductivity in the upper two-thirds of the till unit and a significant increase in EM conductivity in the lower one-third of this unit, consistent with the measured salinities of about 1.1 ppt in well MW07-19S and 11.6 ppt in well MW07-19D. Relatively low EM conductivities correspond with low salinity measurements in both the upper sand unit at well MW07-13S and till unit at well MW07-13D, indicating brackish water. The higher conductivities in the silt unit that separates the sand unit from the till unit can be interpreted as the presence of saline water. However, the higher conductivity also could be the result of a higher porosity and is therefore interpreted as a zone of highly brackish water. The EM-conductivity data from well MW07-11D is consistent with the measured salinity in the lower sand unit. The EM data from this well also indicate brackish water in the upper sand unit and in the upper part of the silt unit, and saline water in the remaining thick silt deposit. EM conductivities at well MW07-20D are very high in the upper sand and in the approximate 47-ft thick layer of silt because of the well's proximity to the shoreline. Thin zones of sand and till separate the silt unit from bedrock. The EM conductivity decreases rapidly from more than 800 mS/m in the silt unit to about 200 mS/m in the till unit. The salinity measured in the till was 29 ppt, equivalent to the salinity of sea water. The abrupt fall in EM conductivity from the silt unit to the till unit could be the result of a significantly lower porosity in the till unit than in the overlying silt and upper sand units.

Wells MW07-13D and MW07-11D are in the area of the former saltwater embayment. EM data from these wells show similar characteristics of high salinity in the silt unit that decreases upward and lower salinity in the upper sand and till units. This salinity pattern is the same as observed at wells MW07-09D, MW07-28D, and MW07-29D, which also are in the filled embayment. Wells MW07-12D and MW07-19D are west of the former saltwater embayment. Freshwater in the upper sand and silt units at well MW07-12D, slightly brackish water in the upper sand unit and in most of the till unit, and saline water in the lower part of the till unit at well MW07-19D are consistent with fresh and brackish water discharge zones near the shoreline of Allen Harbor and the former embayment.

Because these wells are hydraulically upgradient from the fill area, the current salinity distribution shown may also represent the pre-fill conditions.

Section D-D'

Section D-D' (fig. 7) crosses the southern tip of Calf Pasture Point very close to the entrance channel to Allen Harbor (fig. 1). It is underlain primarily by the upper sand unit and a thick till unit over bedrock. Thin zones of silt are present between the upper sand and till units at wells MW07-23D and MW07-24D. Salinity measurements at well MW07-23D indicate the presence of brackish water in the silt unit and in the lower part of the till unit. The small increase in EM conductivity in the middle of the till unit could represent a thin zone of saline water or an increase in porosity, and is therefore interpreted as a zone of highly brackish water. Salinity measurements from wells MW07-21D and MW07-21R indicate the presence of brackish water in the upper and lower parts of the till unit and in bedrock. The EM data from well MW07-21D indicate saline water in the upper sand unit and in a thin zone just above the well screen placed at the bottom of the till unit. At well MW07-24D, saline water was measured in the lower part of the upper sand unit and in the lower part of the till unit. The EM data are consistent with the presence of zones of saline water within these units and also indicate saline water in the upper part of the silt unit. Zones of brackish water were observed in the upper part of the upper sand unit, in the lower part of the silt unit, and in the upper part of the till unit.

Well MW07-23D is in an area that appears to have been stable since the early 1700's (EA Engineering, Science, and Technology, 1997). The brackish water observed in this backshore setting indicates the presence of a mixing zone where freshwater discharges into saline water. Well MW07-21D is in an area that was the mouth of the former saltwater embayment, and well MW07-24D is in a former offshore position on the eastern side of the spit that enclosed the embayment (fig. 1). The current land area in which wells MW07-21D and MW07-24D are located was formed by natural deposition of coastal sediments since 1966 (fig. 1) (EA Engineering, Science, and Technology, 1997). The saline zone in the upper sand unit at these wells is consistent with their former shoreline and offshore environments. The brackish zones in the till unit at wells MW07-23D, MW07-21D, and MW07-24D indicate movement of upgradient freshwater into zones of saline water. The thin saline zone in the till unit at well MW07-21D is considerably thicker at well MW07-24D, consistent with its former offshore position. Because this area remained offshore until at least 1966, the brackish water in the upper part of the upper sand unit at well MW07-24D indicates that saline ground water was diluted by flow of fresh ground water or infiltration of fresh surface water, or both, in the past 30 years.

Section E-E'

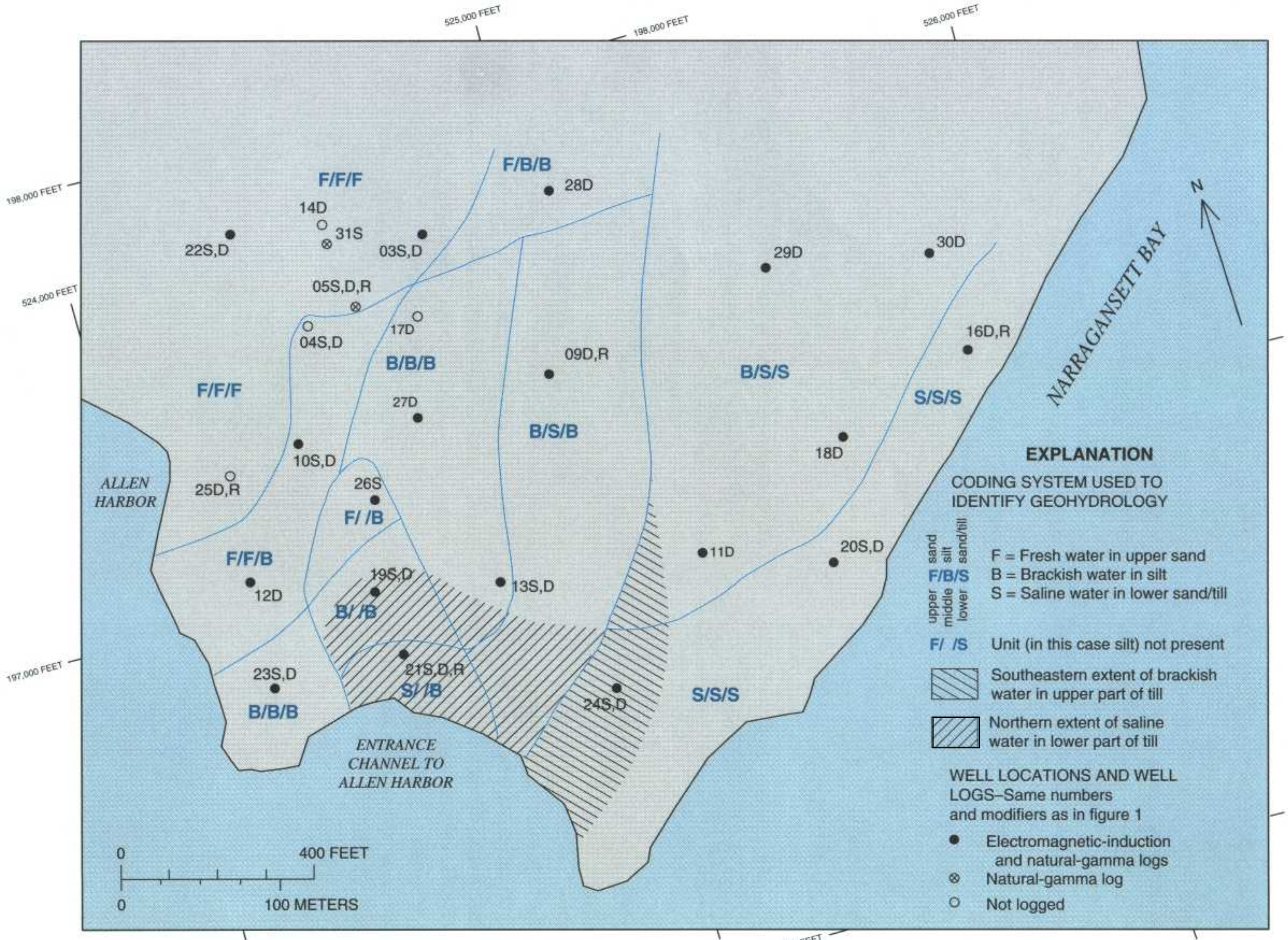
Section E-E' (fig. 8) is oriented approximately north-south and is nearly parallel to the eastern shoreline of Allen Harbor (fig. 1) and perpendicular to the ground-water-flow direction measured from the deep wells screened in the till unit (fig. 2). A thick layer of silt separates the upper sand unit from the till unit in the northern part of this section but is absent in the southern part. Salinity measurements from well MW07-22D indicate the presence of freshwater in the upper sand and till units. EM data indicate freshwater in the silt unit at this well. At well MW07-10D, salinity measurements indicate the presence of slightly brackish water in the upper sand, in the lower part of the silt, and in the till units, which correspond to small increases in EM conductivity. With the exception of these two thin zones, the EM data indicate freshwater at this well. Salinity measurements from well MW07-26S indicate the presence of brackish water in the upper part of the till unit. The EM data are consistent with the presence of brackish water in the upper part of the till unit and also indicate the presence of freshwater in the upper part of the upper sand unit and brackish water in the lower part. Salinity measurements and EM data indicate the presence of brackish water in the upper part of the till unit and saline water in the lower part at well MW07-19D. Although salinity was not measured, nor were EM data obtained from the upper sand unit at this well, the water is considered brackish because of its proximity to saline water in the upper sand unit as indicated by EM data at well MW07-21D. Salinity measurements and EM data at well MW07-21D also indicate the presence of a zone of saline water, with brackish water above and below, within the till unit and brackish water in bedrock.

Wells MW07-26D, MW07-19D are near the western shoreline and well MW07-21D is at the mouth of the former saltwater embayment. Brackish water in these wells indicates a transition from upgradient freshwater to saline water beneath the entrance channel to Allen Harbor. The saline zone in the lower part of the till unit at wells MW07-19D and MW07-21D appears to be continuous with the thicker saline zone in the till unit at well MW07-24D (section D-D', fig. 6). This saline zone also appears to extend into bedrock at wells MW07-19D and MW07-24D but is underlain by brackish water at well MW07-21D.

Horizontal Distribution of Salinity

Horizontal distribution of fresh, brackish, and saline water in the upper sand, silt, and till units (lower sand and till combined) was determined from the interpreted salinity contours shown on the geohydrologic-sections. A composite map was then made to divide the study site into areas of similar salinity and lithologic characteristics (fig. 9). Although at some wells, fresh and brackish water, or brackish and saline water, are present in the same lithologic unit, the type of water most represented in the lithologic unit was selected for this composite map. Ten distinct area types were identified, ranging from freshwater in all lithologic units to saline water in all lithologic units. Some of these area types are represented by only one well whereas others are represented by several wells.

Freshwater in the upper sand, silt, and till units was identified in the northern and northwestern parts of the site which includes wells MW07-03D, MW07-14D, MW07-22D, and MW07-25D. Two areas were characterized by brackish water in the upper sand, silt, and till units. One of these areas is in the central part of the site and includes wells MW07-13D, MW07-17D and MW07-27D. The other area is in the southwestern part of the site near Allen Harbor, represented by well MW07-23D. The southeastern area along Narragansett Bay and the beginning of the entrance channel to Allen Harbor, which includes wells MW07-16D, MW07-20D, and MW07-24D, contains saline water in all lithologic zones. Although water is primarily saline in the till unit at well MW07-24D, a thin zone of brackish water is present in the upper part of the till unit. This brackish zone appears to extend to near the entrance channel to Allen Harbor. Well MW07-09D is in a large central area where brackish water is present in the upper sand and till units, and saline water is present in the intervening silt unit. Wells MW07-11D, MW07-18D, MW07-29D, and MW07-30D are in an area characterized by brackish water in the upper sand unit and saline water in the underlying silt and till units. In the area defined by wells MW07-26S, MW07-19D, and MW07-21D, where the silt unit is absent and the till unit slopes upward towards the entrance channel to Allen Harbor, freshwater in the upper sand unit overlies brackish water in the till unit at MW07-26S, brackish water in the upper sand unit overlies predominately brackish water in the till unit at well MW07-19D, and saline water in the upper sand unit overlies predominately brackish water in the till unit at well MW07-21D. A thin zone of saline water in the lower part of the till unit appears to extend from the entrance channel to Allen Harbor to the vicinity of well MW07-19D. In the remaining areas, freshwater is present in the upper sand and silt units and brackish water in the till unit (wells MW07-04D, MW07-10D, and MW07-12D). Freshwater also is present in the upper sand unit with brackish water in the silt and till units near well MW07-28D.



Base map modified from EA Engineering, Science, and Technology, 1997
Rhode Island stateplane coordinate system

Figure 9. Spatial distribution of major salinity types in ground water by lithologic unit, Calf Pasture Point, Davisville, Rhode Island.

SUMMARY AND CONCLUSIONS

Borehole-geophysical logs of wells drilled in the surficial aquifer at Calf Pasture Point were interpreted in conjunction with previously collected salinity data to delineate zones of fresh, brackish, and saline water. These data may be used to help identify potential pathways of contaminants to surface-water bodies in this coastal aquifer and to formulate an effective ground-water-monitoring program.

This site is underlain by a sequence of glacial sediments, marine sands, and fill. The present-day land surface was formed, in part, when a saltwater embayment was filled with dredged sediments from Narragansett Bay in the early 1940's. The distribution of sediments and overlying dredged material in this coastal setting has resulted in a complex distribution of salinity in the surficial aquifer.

Interpretation of the vertical and horizontal distribution of salinity using borehole electromagnetic-induction log data indicates that the upper sand unit contains freshwater (salinities of 0.5 ppt or less) in the north and northwestern part of the site, brackish water (salinity greater than 0.5 ppt to 10 ppt) where the dredged sediments from the Narragansett Bay were deposited, and saline water (greater than 10 ppt) along the shore of the Narragansett Bay and the entrance channel to Allen Harbor. Saline water is present in the silt in the eastern half of the site, most of which can be attributed to the residual saline water since the saltwater embayment was filled with dredged sediment from the Narragansett Bay. In the western half of the site, the silt contains fresh or brackish water. Freshwater is present in till in the western part of the site near Allen Harbor and in the northwestern part of the site. Brackish water is present in the till in the central part of the site, and saline water is present in the till under about half of the site on the eastern and southeastern side. Brackish water underlies saline water in areas along a northeast-southwest band through the middle of the site. Distinct zones of brackish water are present within the till in the southwestern part of this band near the entrance channel to Allen Harbor.

When the former saltwater embayment was filled with dredged sediment from Narragansett Bay, the hydrologic-flow regime changed; this created a complex distribution of salinity in the eastern and central parts of the site. Although saline water from the dredged material may have been added to the filled area, filling the former saltwater embayment virtually eliminated the surface-water source of saline water to the underlying aquifer. By increasing the land surface area, more area was made available for infiltration of fresh water from precipitation. Fresh ground water from upgradient and local recharge appears to be diluting the saline water from the former embayment and gradually expanding the freshwater-flow system as it travels to Narragansett Bay and the entrance channel to Allen Harbor. The distribution of salinity in the western part of the site, which is dominated by freshwater, is likely to have been less affected by filling of the embayment. In the eastern and central parts of the site, however, the distribution of salinity appears to be in a dynamic state that is responding to the loss of a continuous source of saline water. Additionally, the southern and southwestern extremeties of the site, along the Allen Harbor Entrance Channel and its confluence with Naragansett Bay are also likely to continue to be effected by erosional and/or depositional processes, which have resulted in the accretion of a substantial volume of sediment to the shoreline since 1966. The ground-water flow system can be expected to continue to evolve in response to these changes.

The present-day ground-water flow regime at Calf Pasture Point, therefore, represents a complex system that results from the interaction of a number of factors and processes operating on different time scales. In the near-term, interaction of the freshwater flow system with brackish and saline waters is an important process relative to contaminant transport. However, development of an effective long-term monitoring program for ground-water quality must also consider those processes which are evolving on other time scales.

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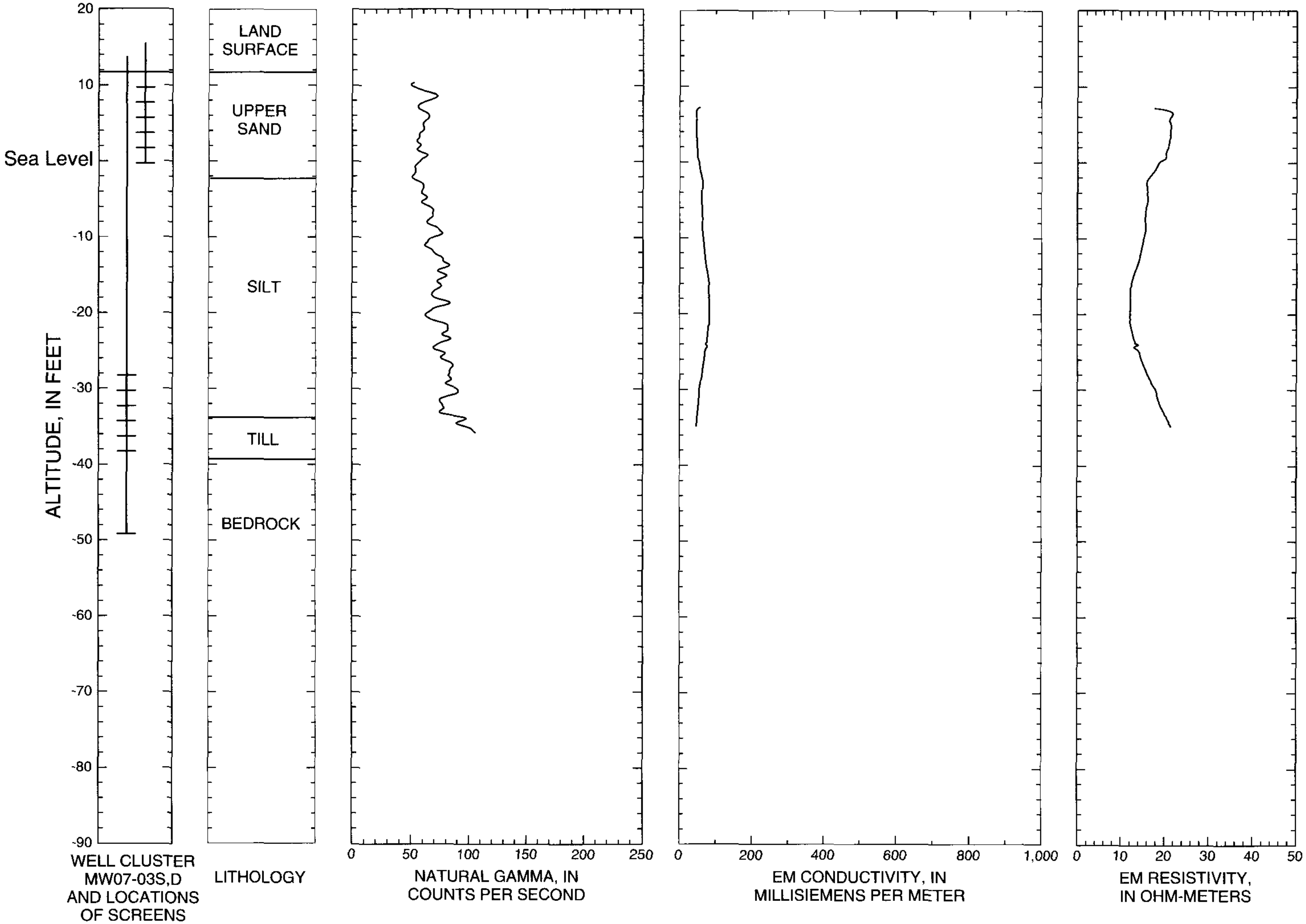
APPENDIX

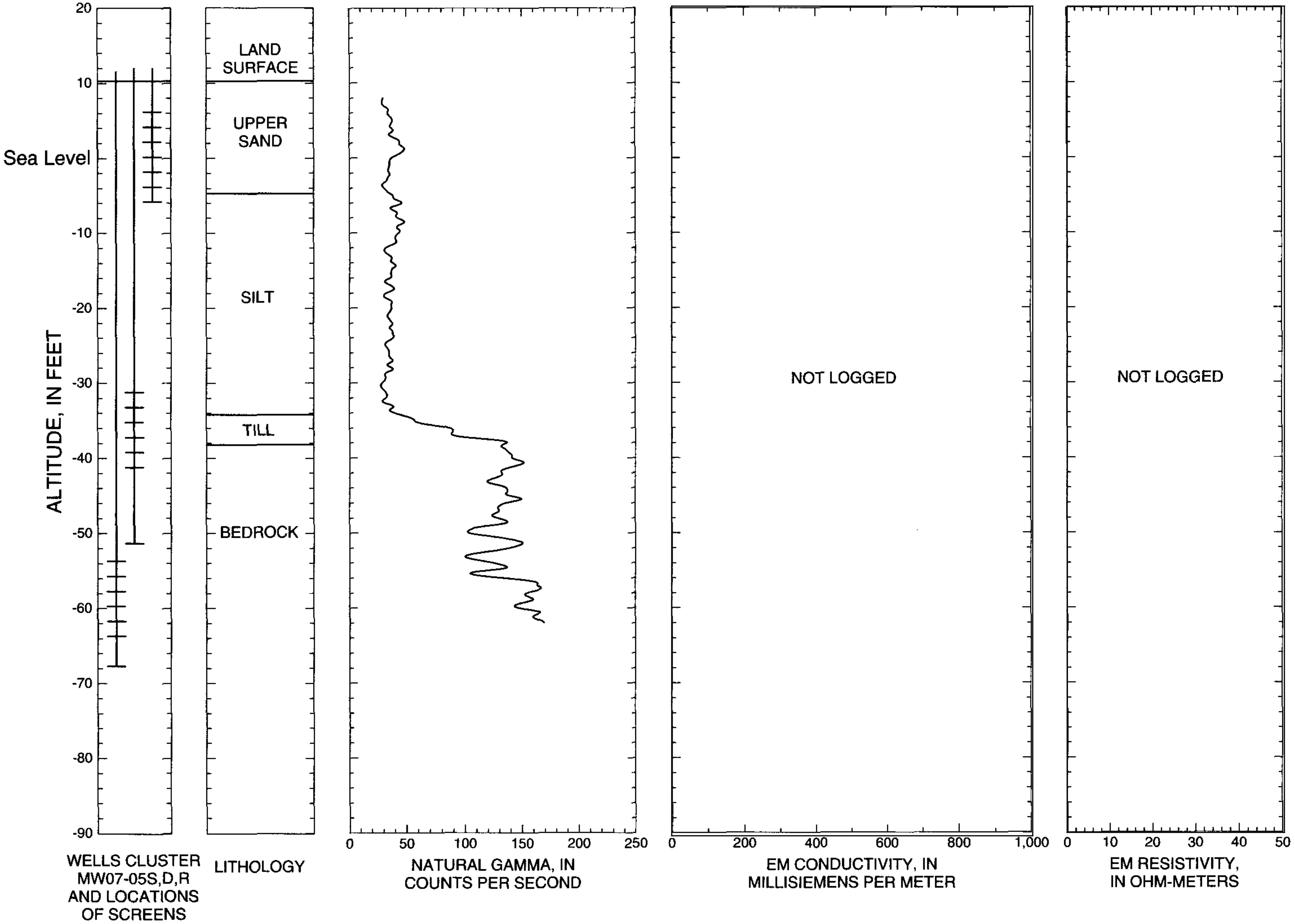
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island.

A. WELL CLUSTER MW07-03S,D

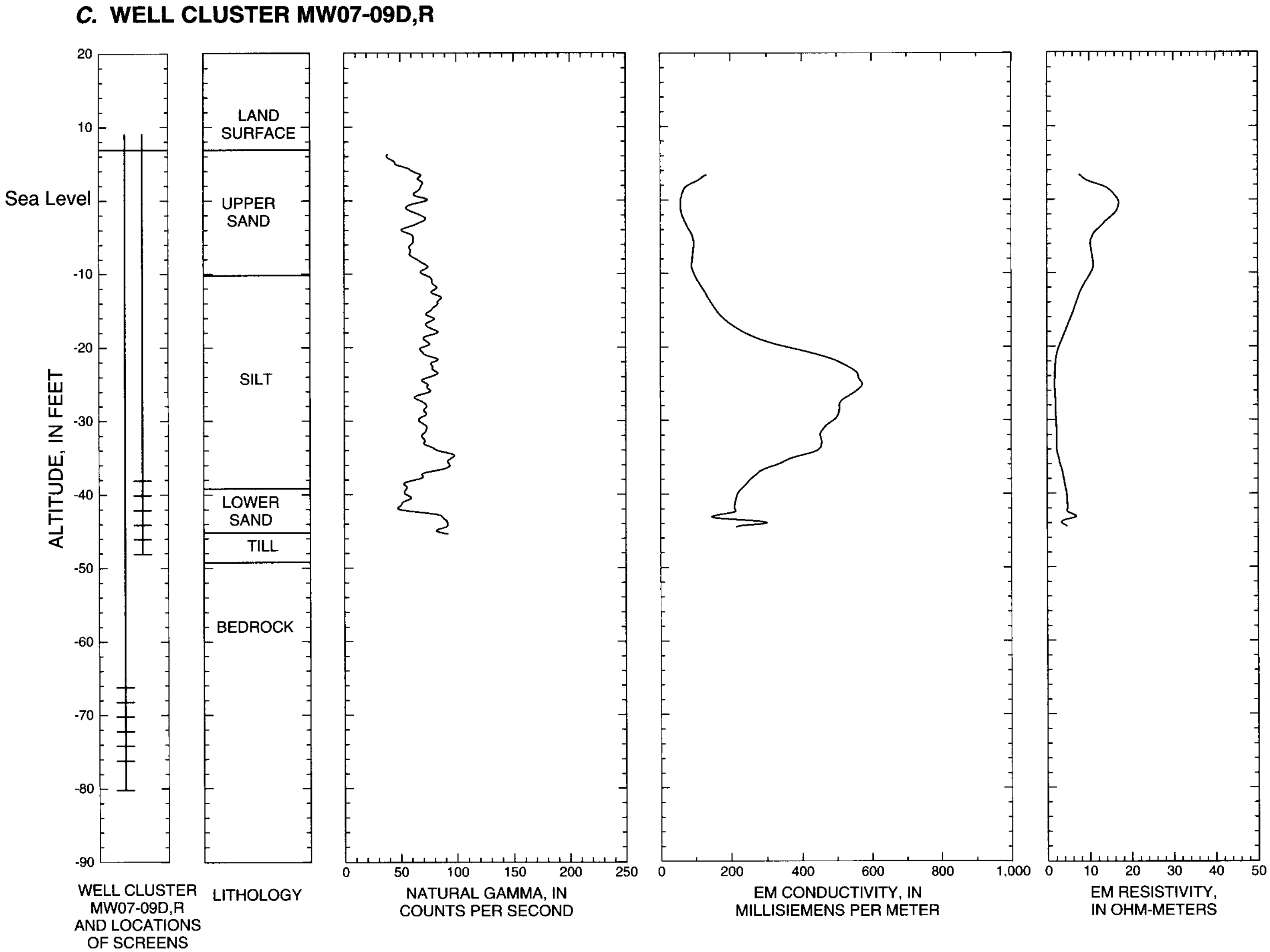


Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island.

_B._ WELL CLUSTER MW07-05S,D,R

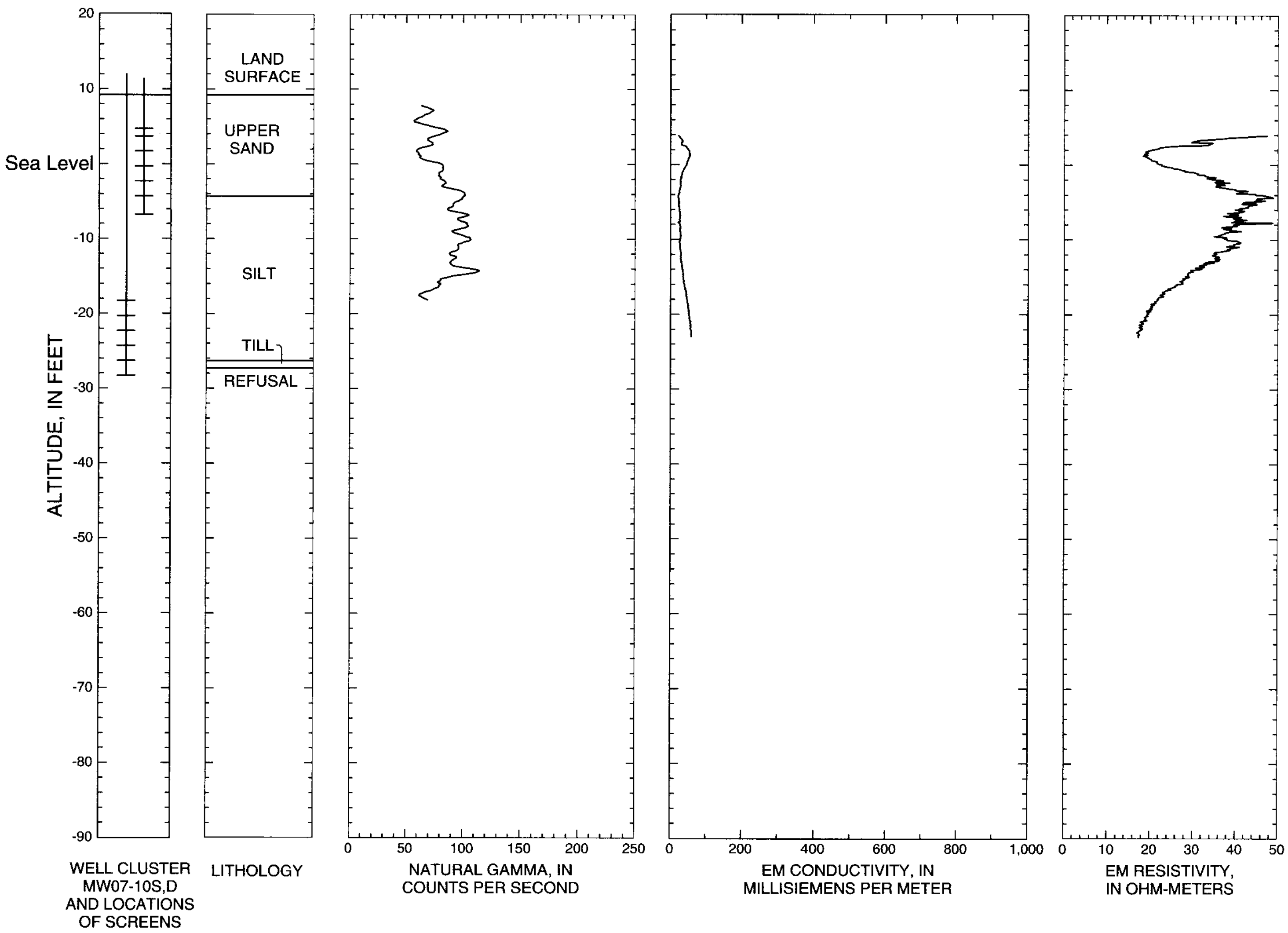


Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

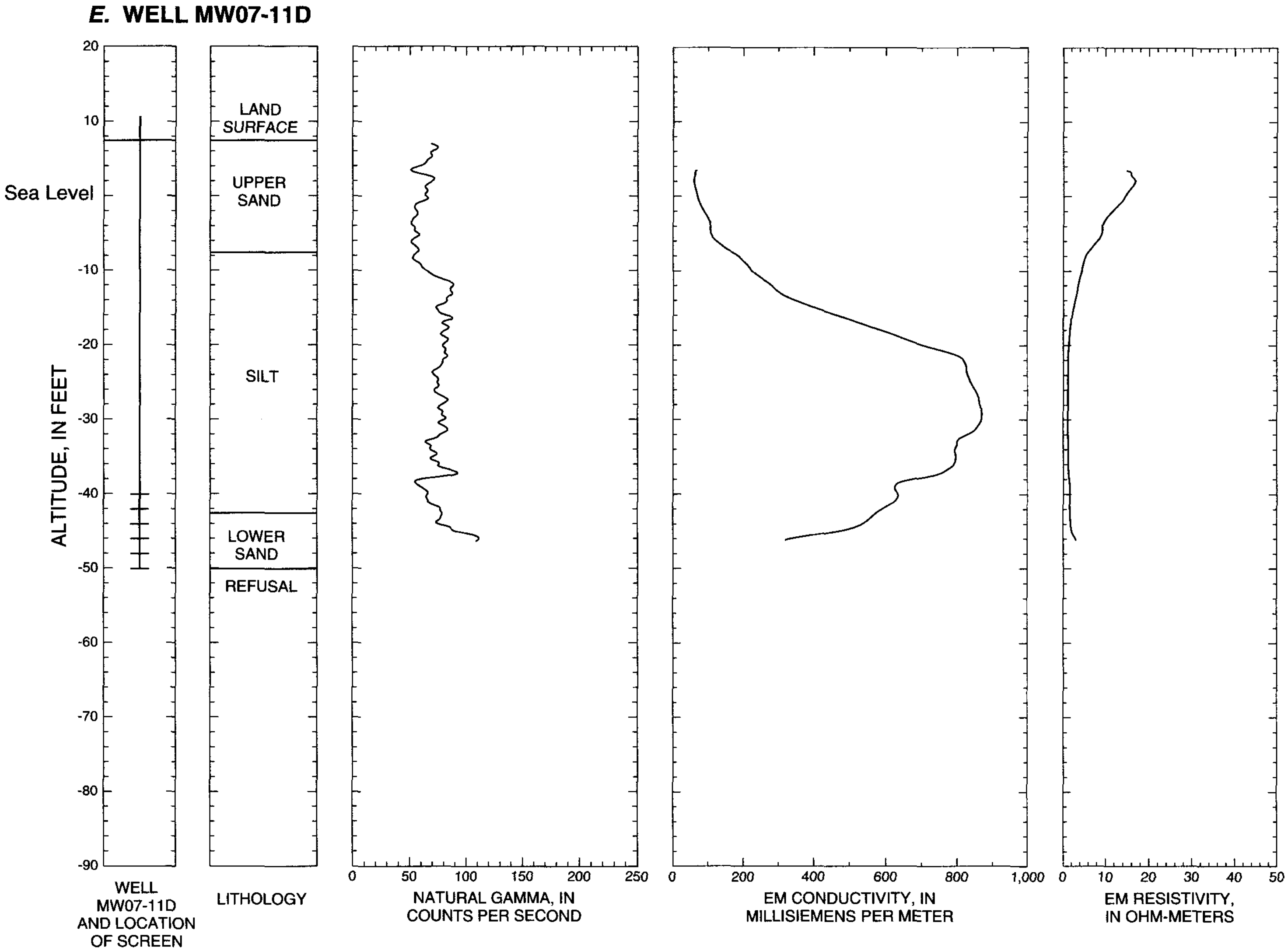


Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

D. **WELL CLUSTER MW07-10S,D**

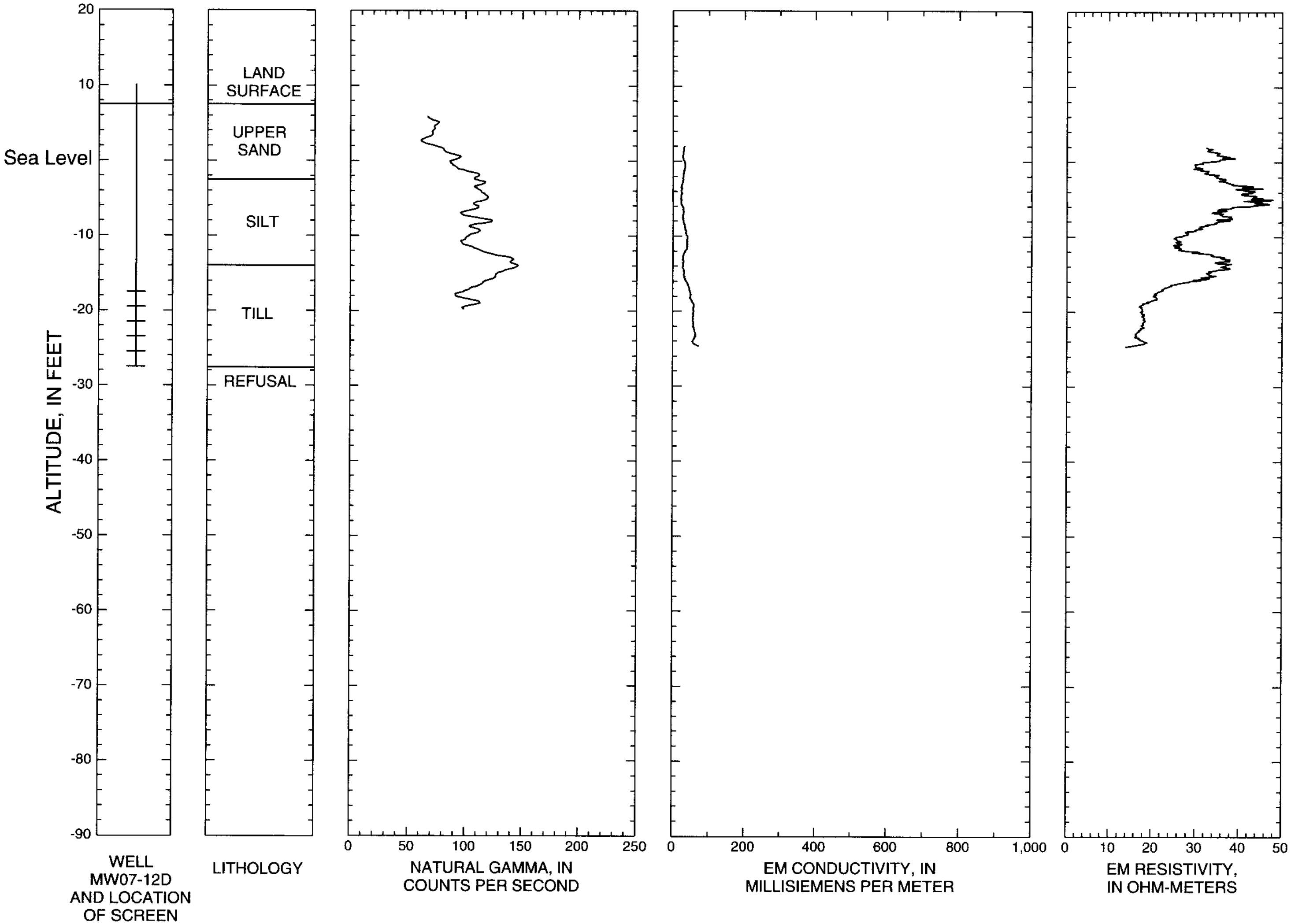


Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*



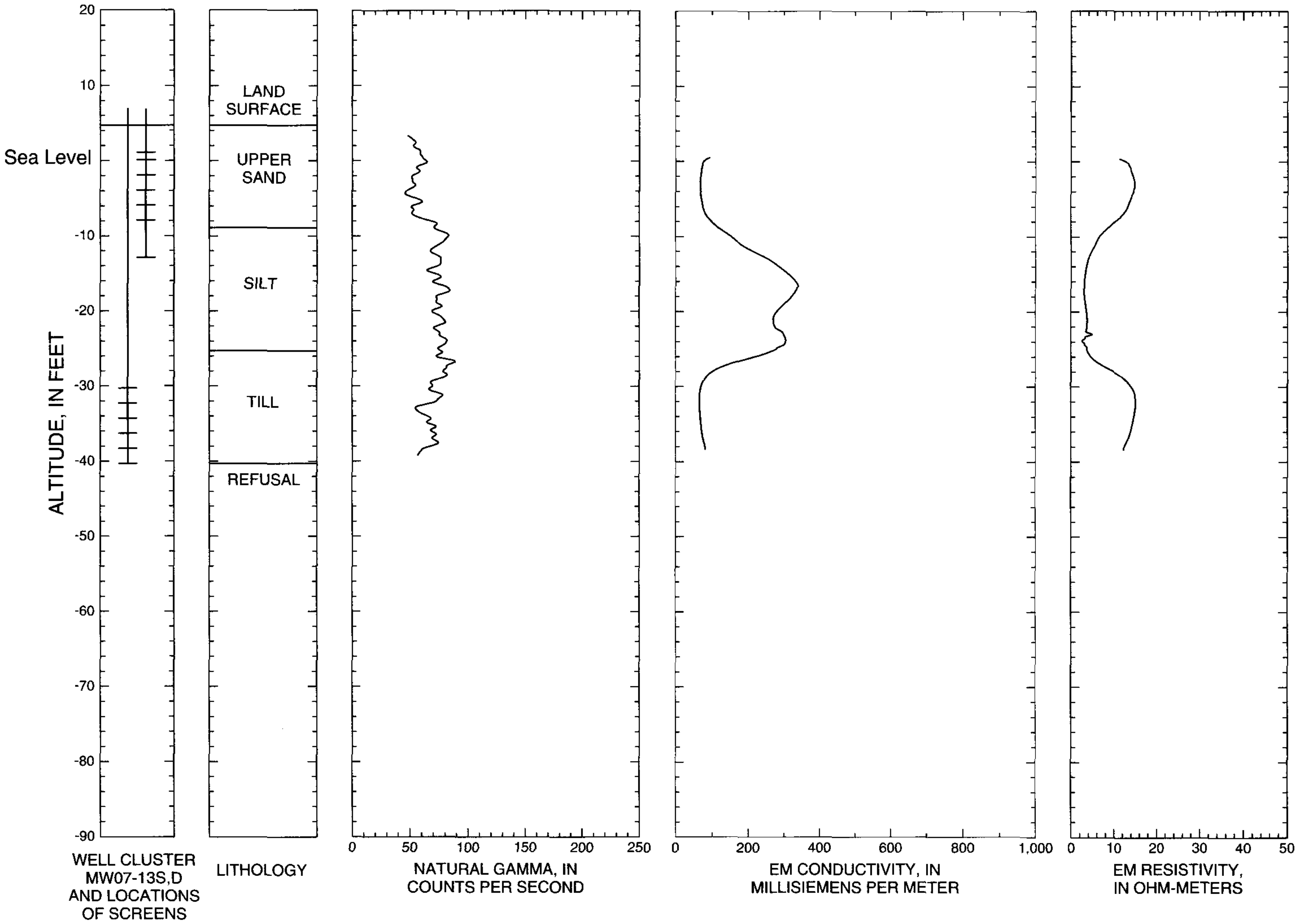
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

F. **WELL MW07-12D**



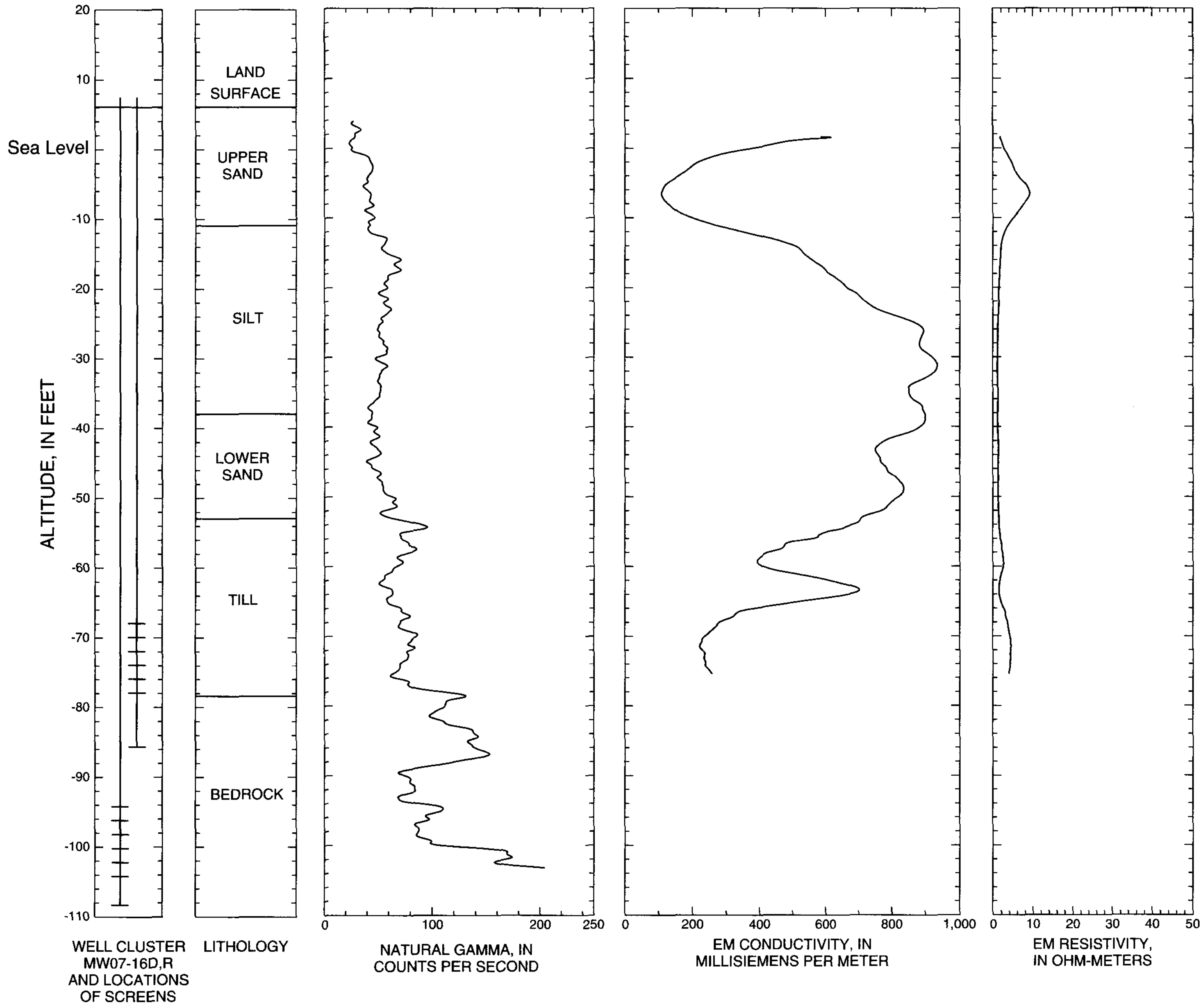
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

G. **WELL CLUSTER MW07-13S,D**



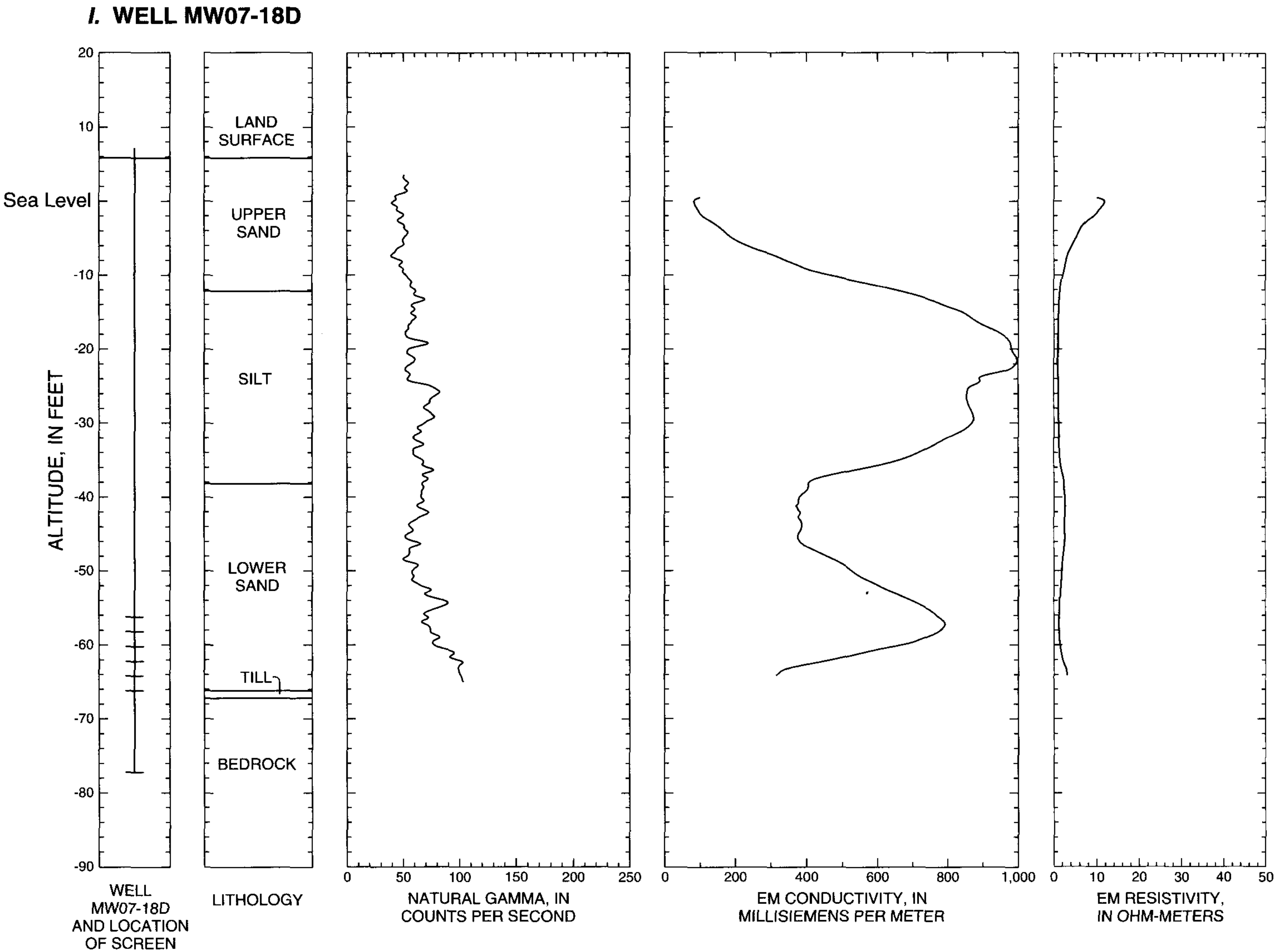
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

H. **WELL CLUSTER MW07-16D,R**



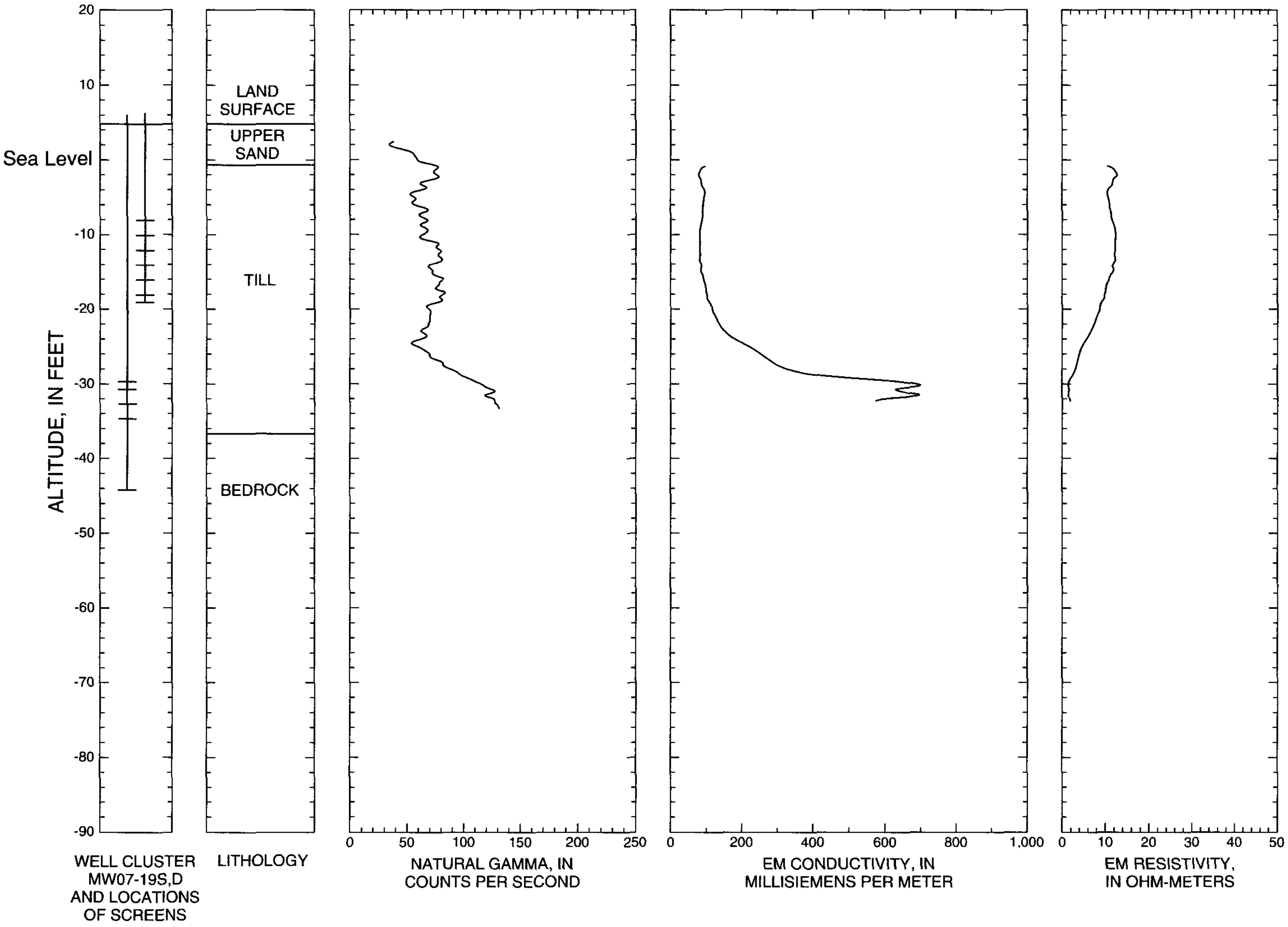
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

I. WELL MW07-18D



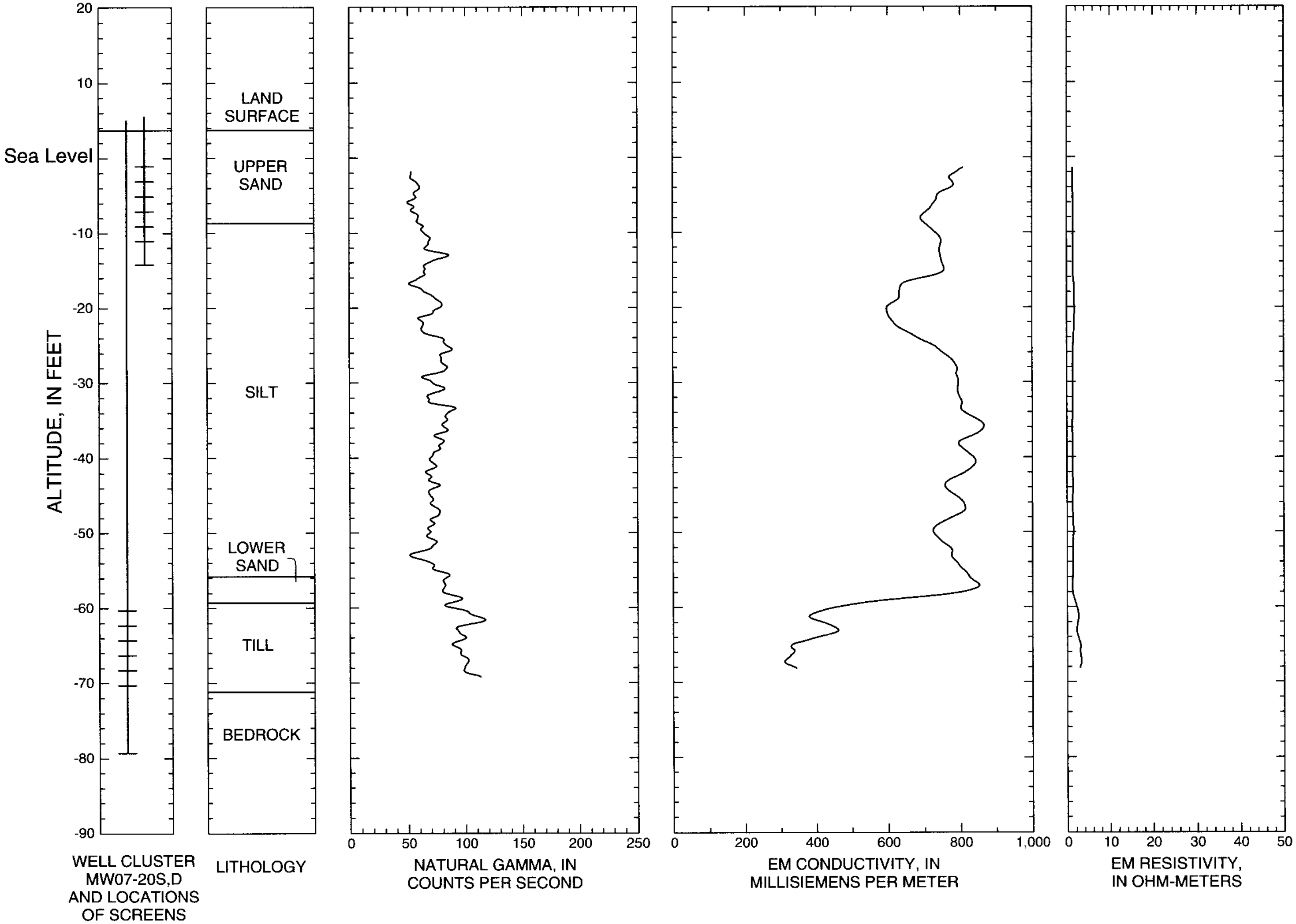
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

J. WELL CLUSTER MW07-19S,D



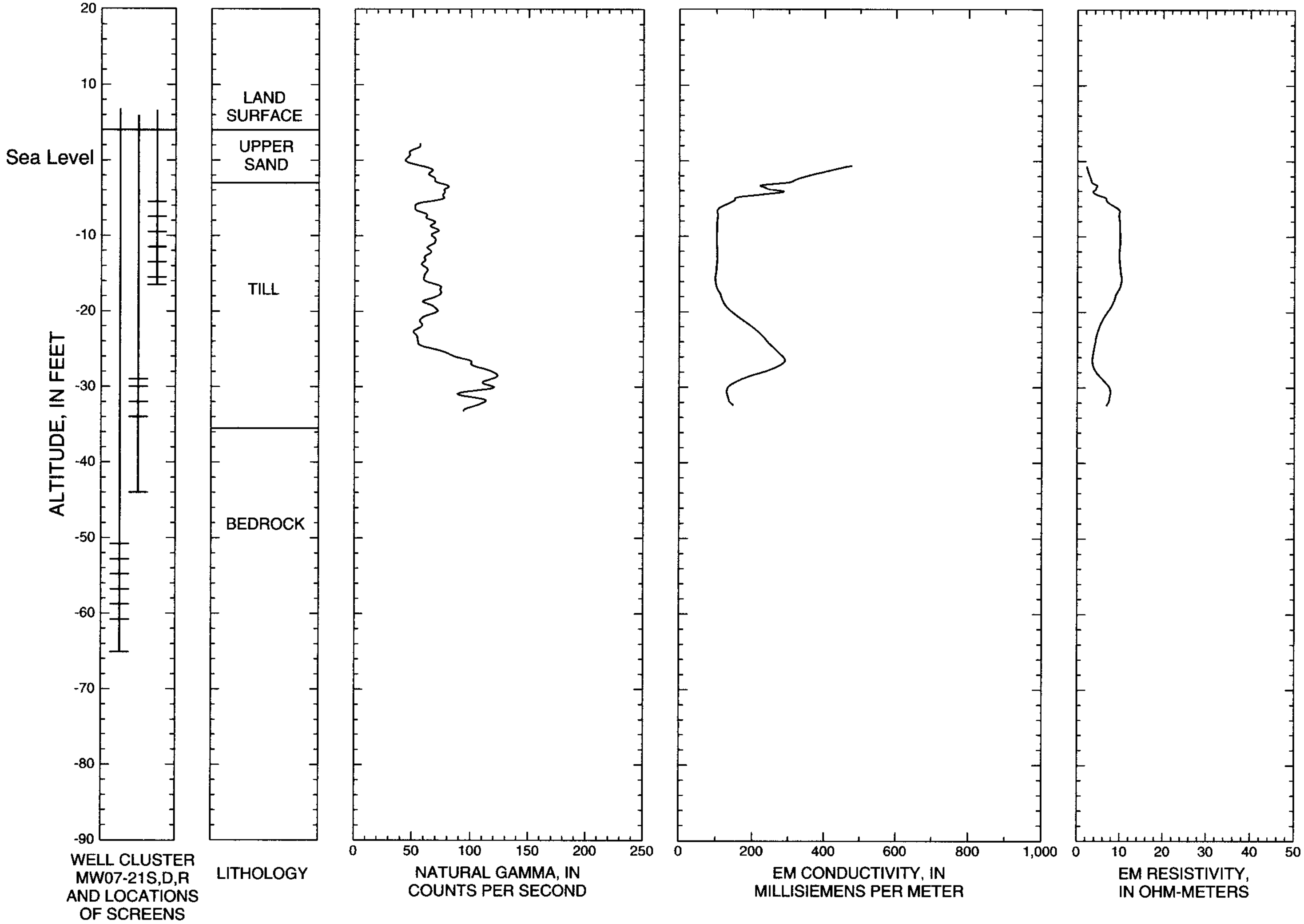
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

K. WELL CLUSTER MW07-20S,D



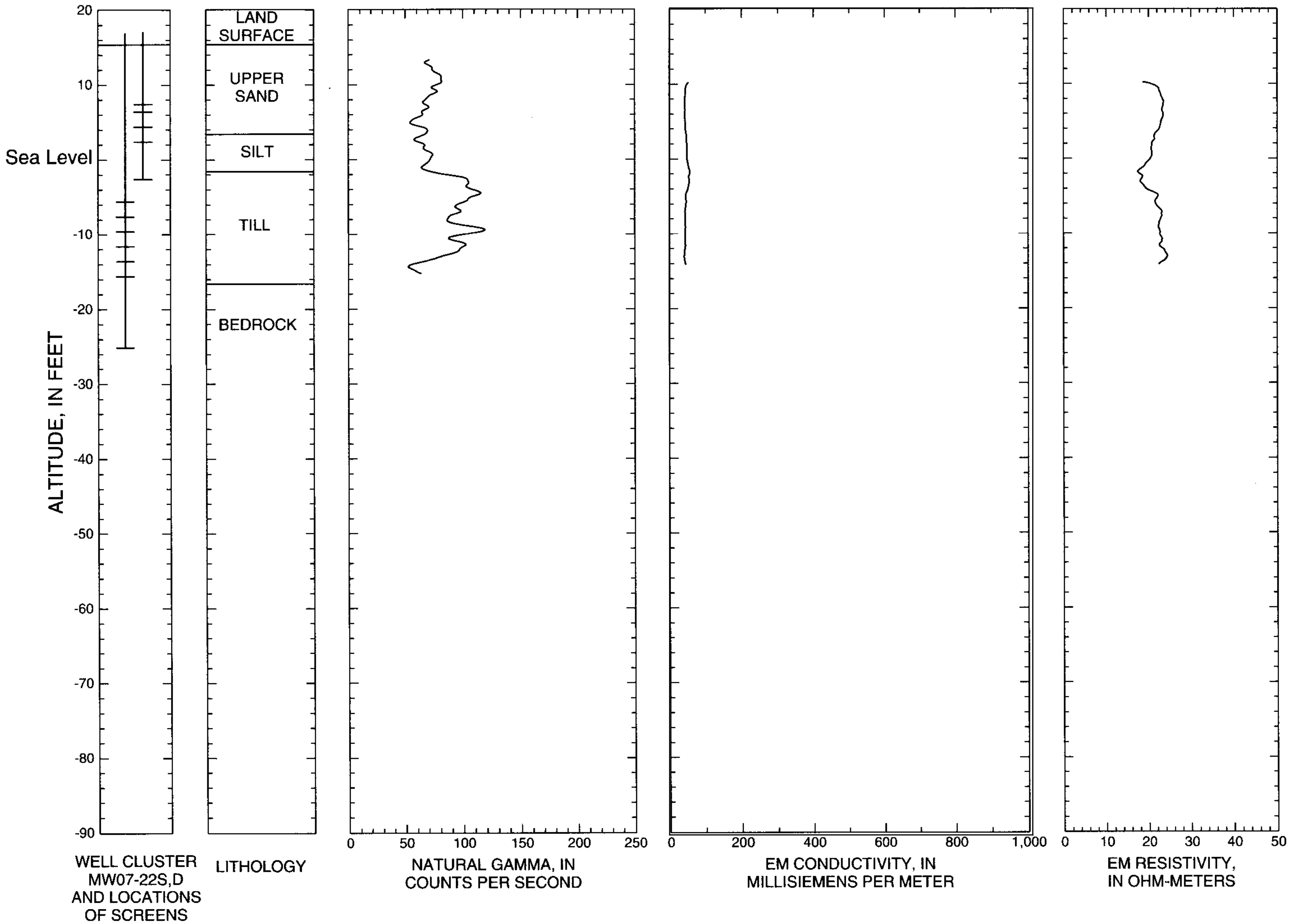
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

L. **MW07-21S,D,R**



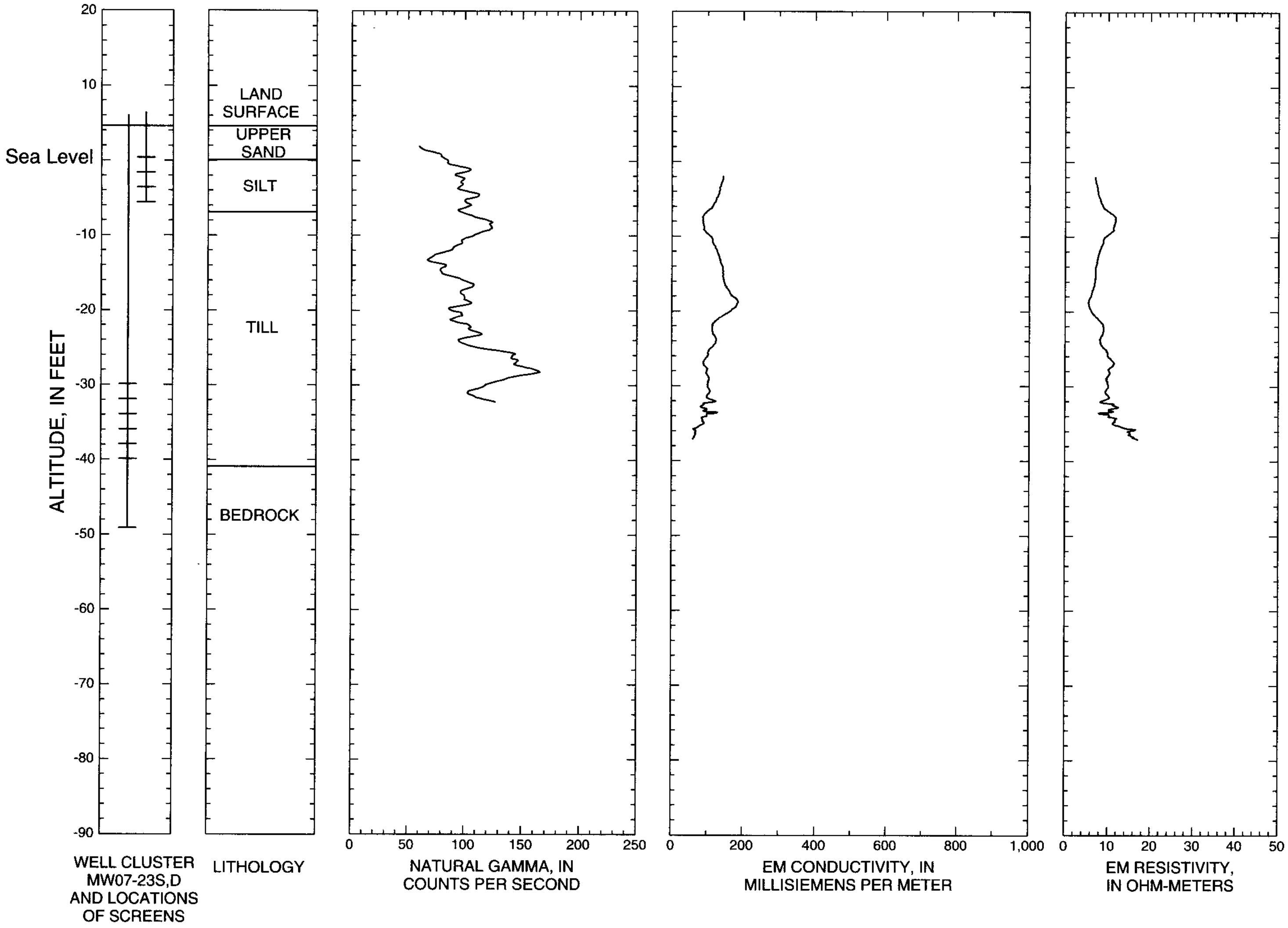
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

M. WELL CLUSTER MW07-22S,D



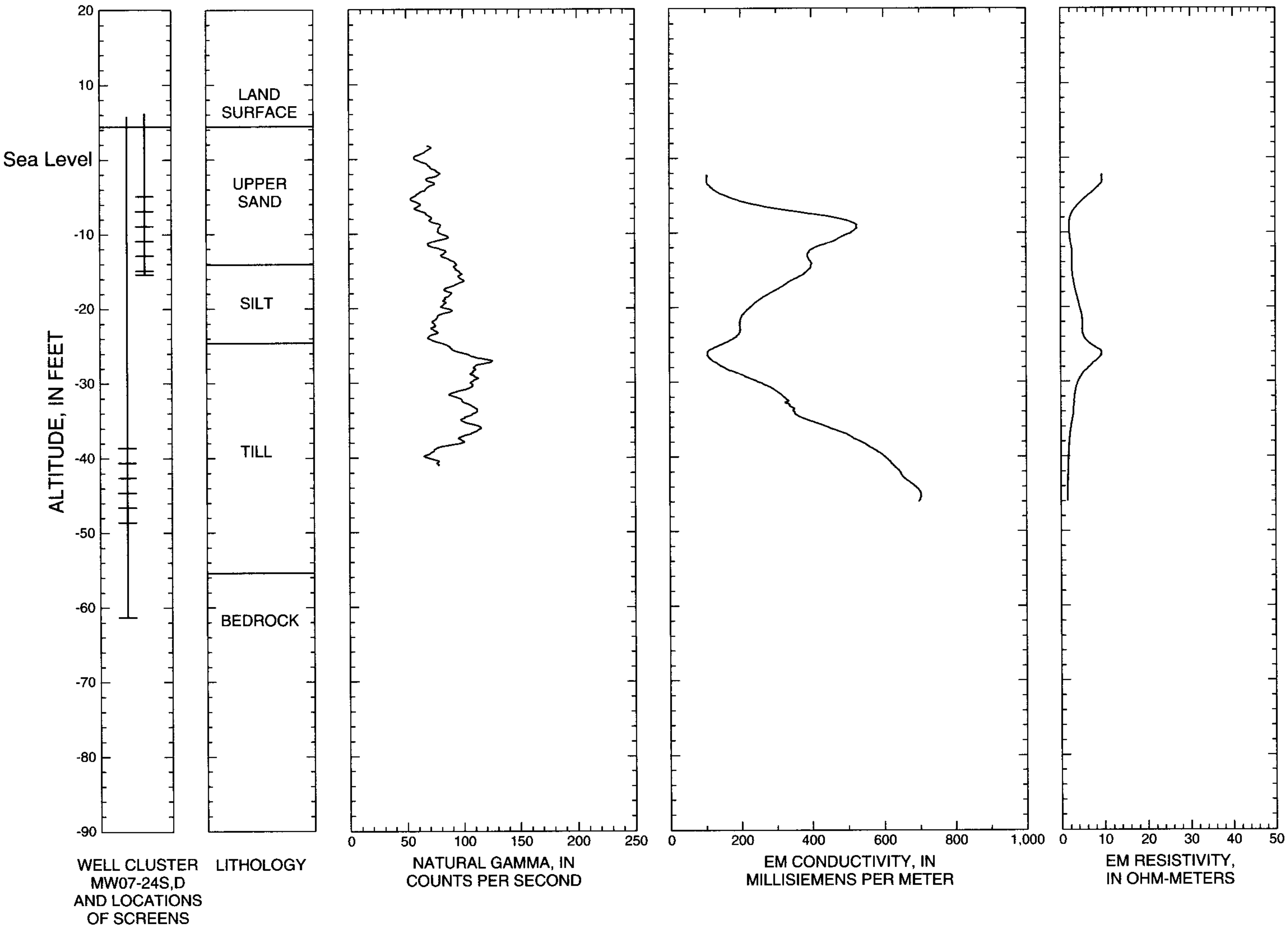
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

N. WELL CLUSTER MW07-23S,D



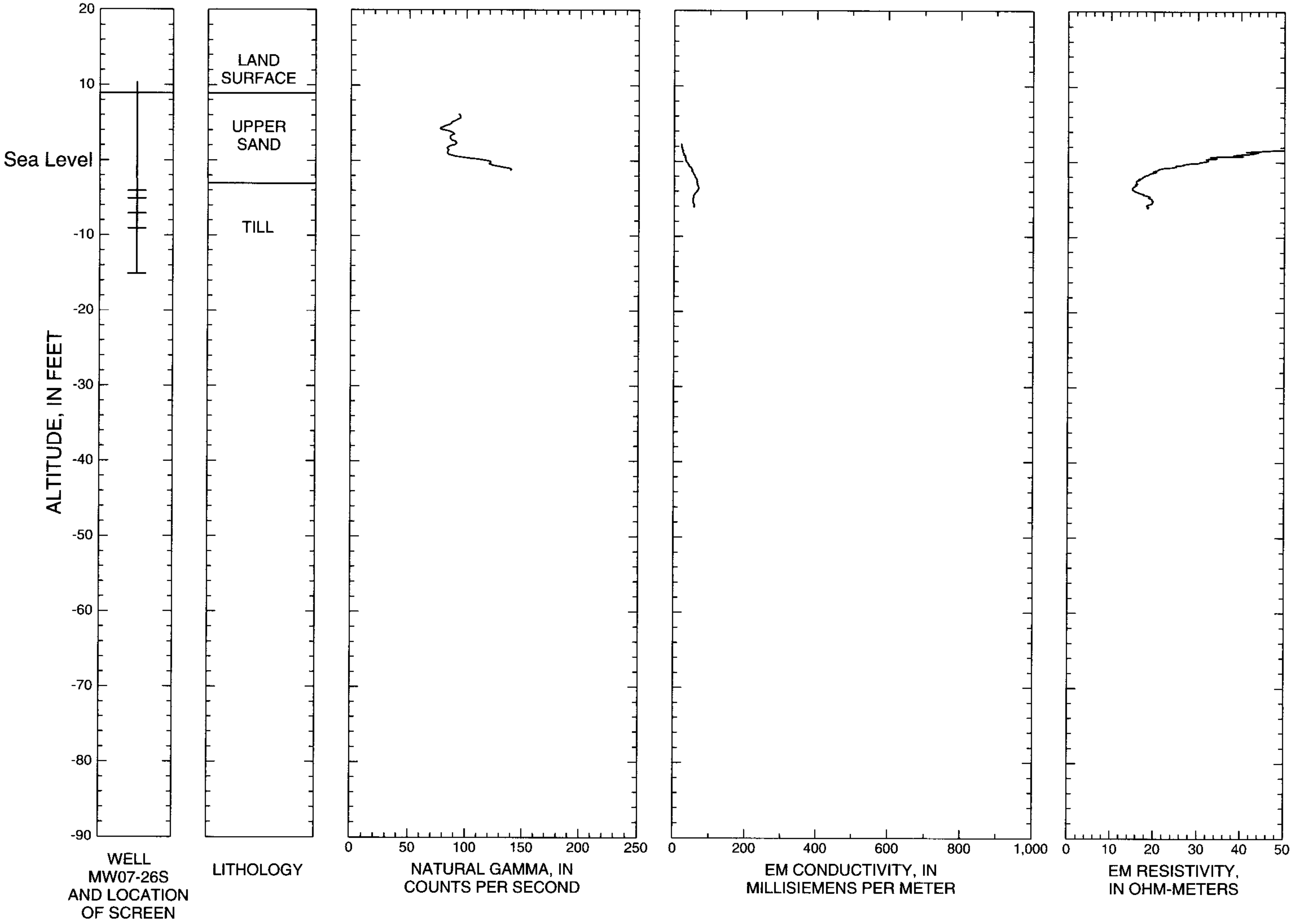
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

O. WELL CLUSTER MW07-24S,D



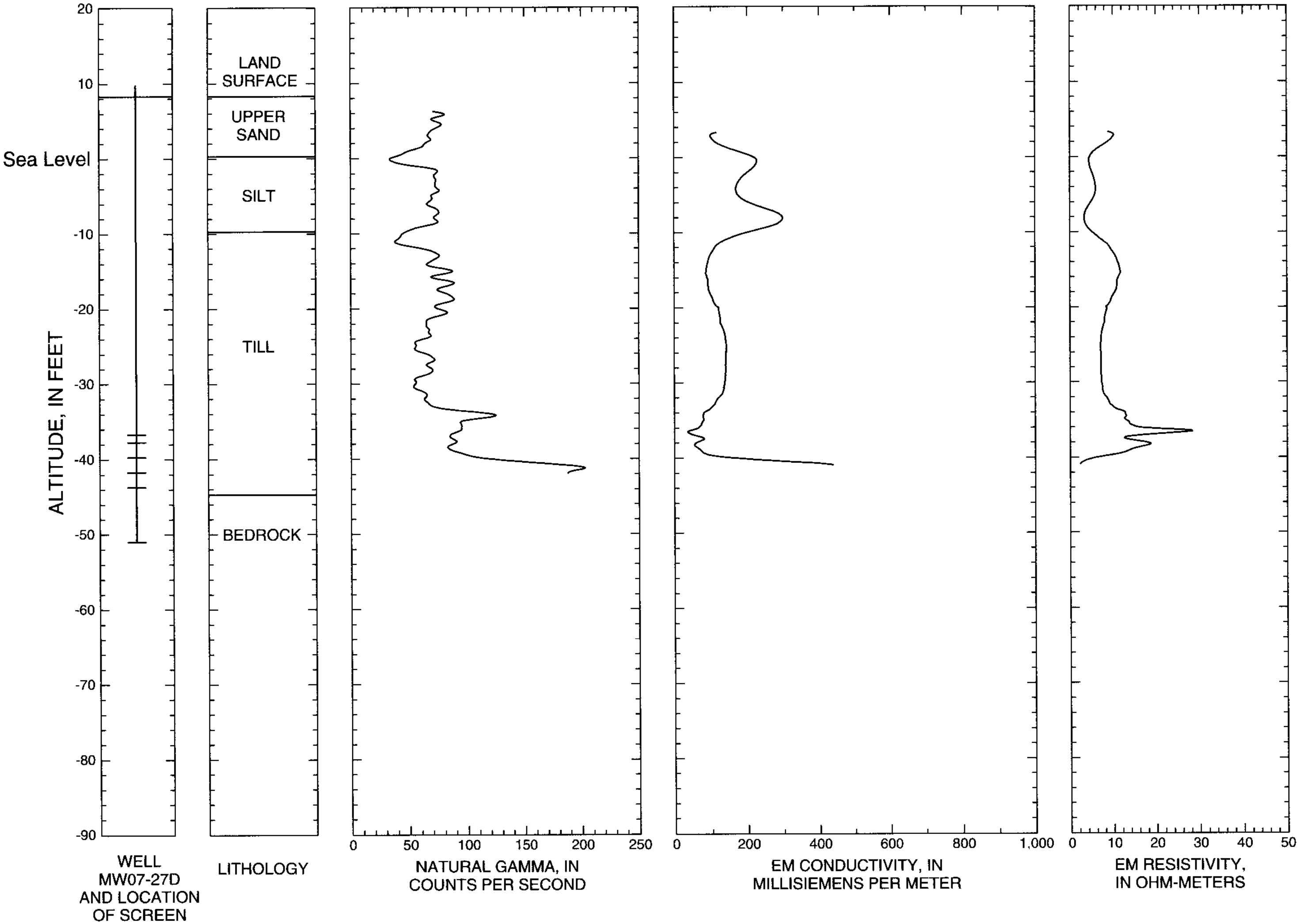
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

P. WELL MW07-26S



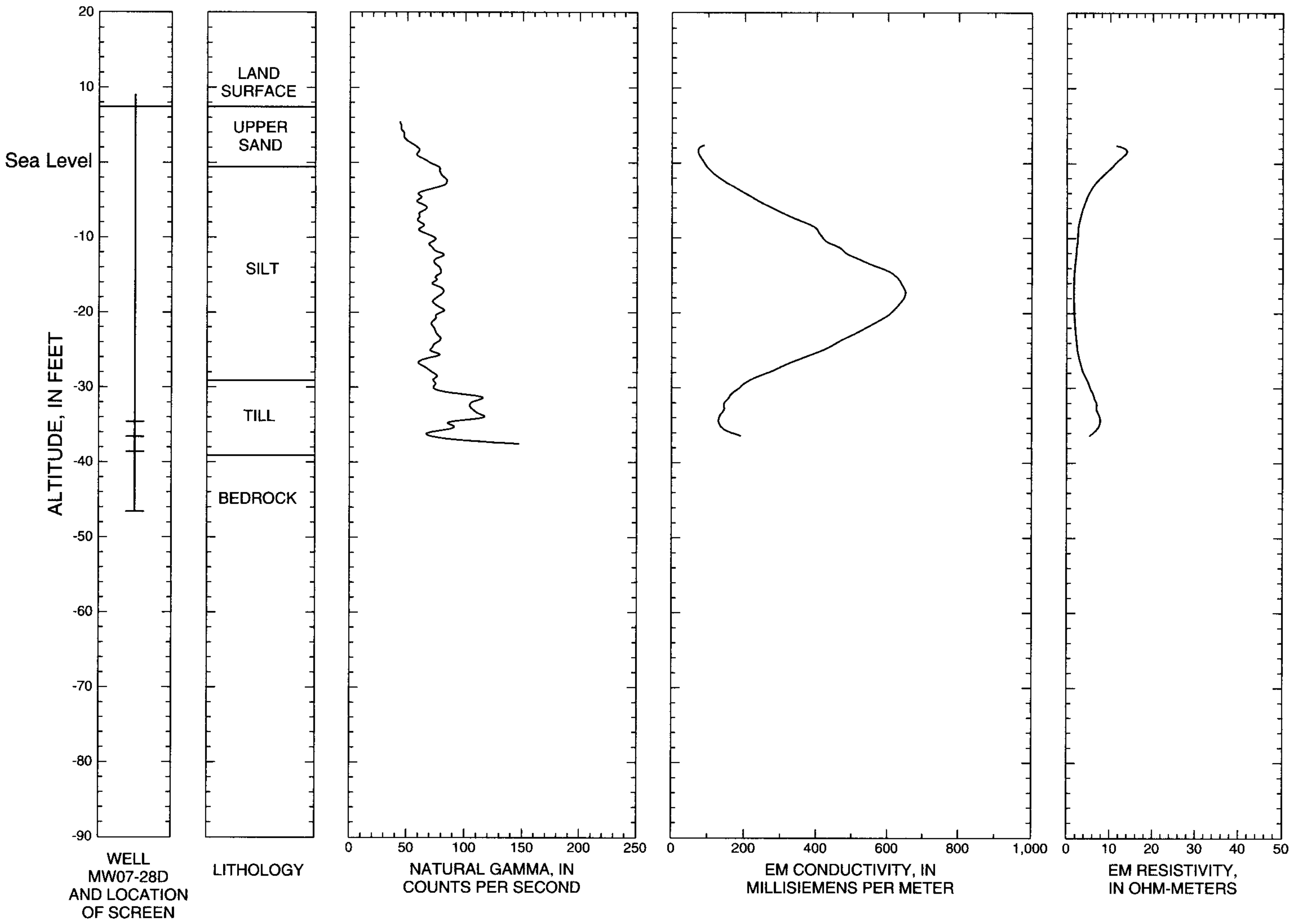
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

Q. **WELL MW07-27D**



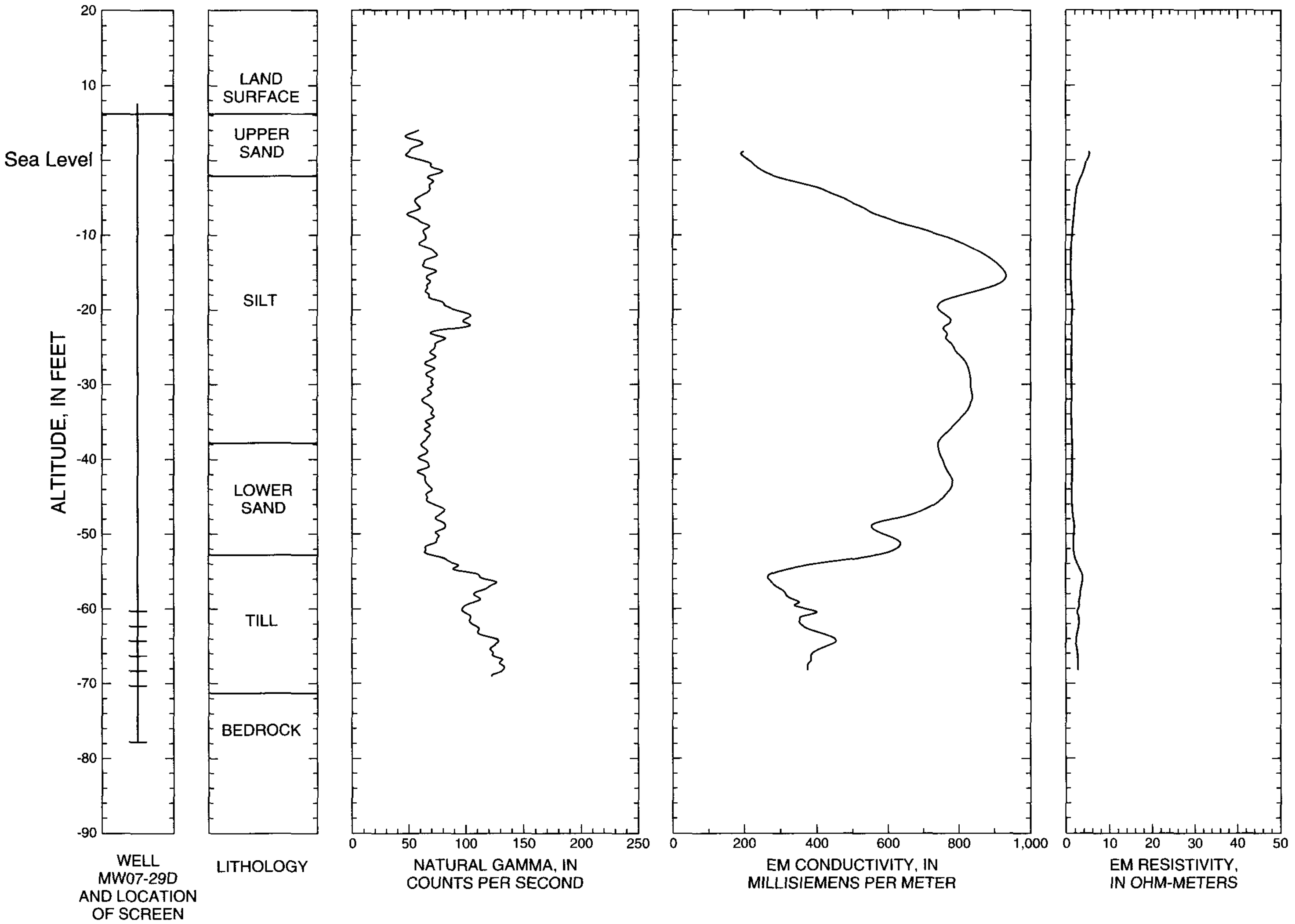
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

***R.* WELL MW07-28D**



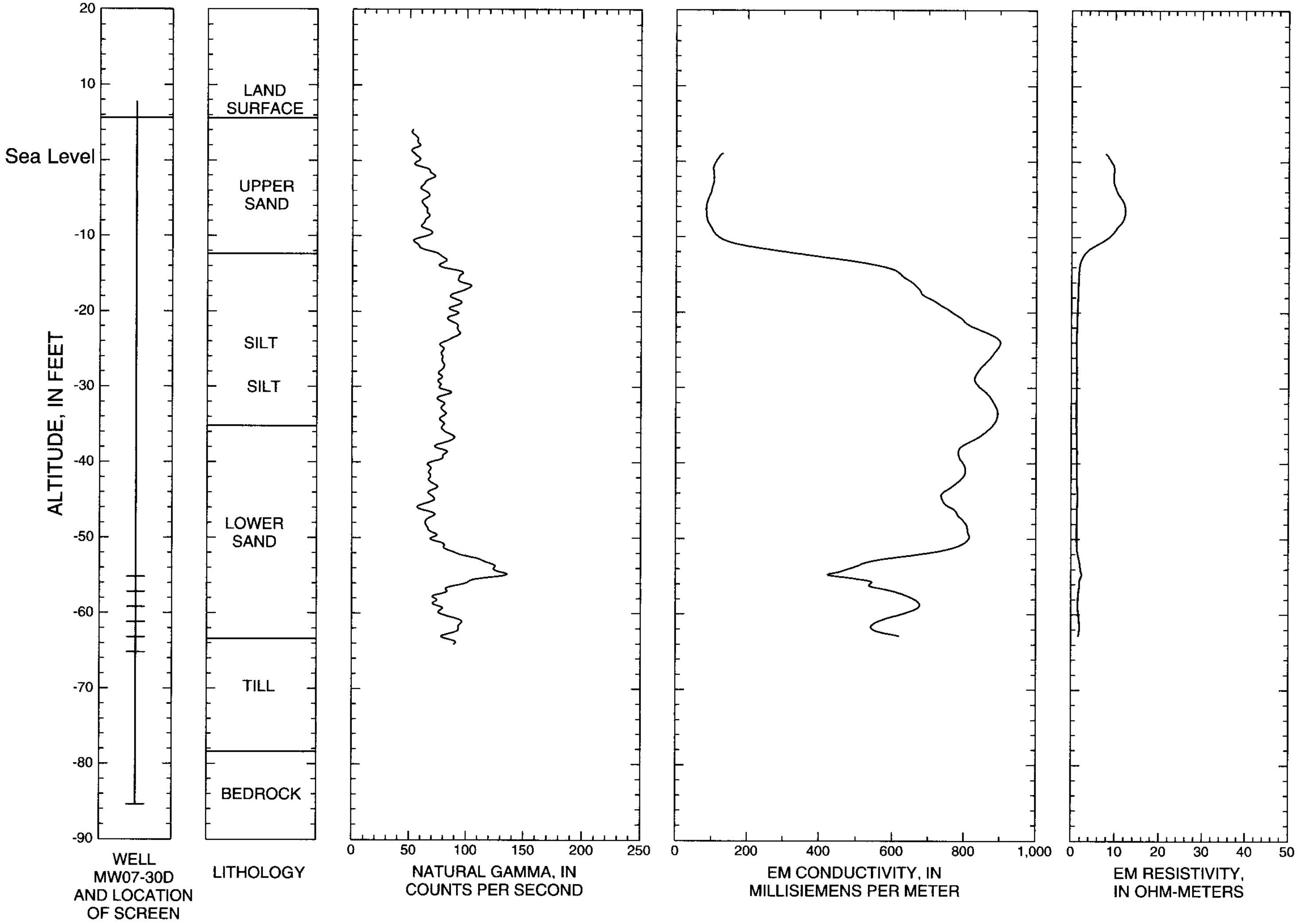
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

S. **WELL MW07-29D**



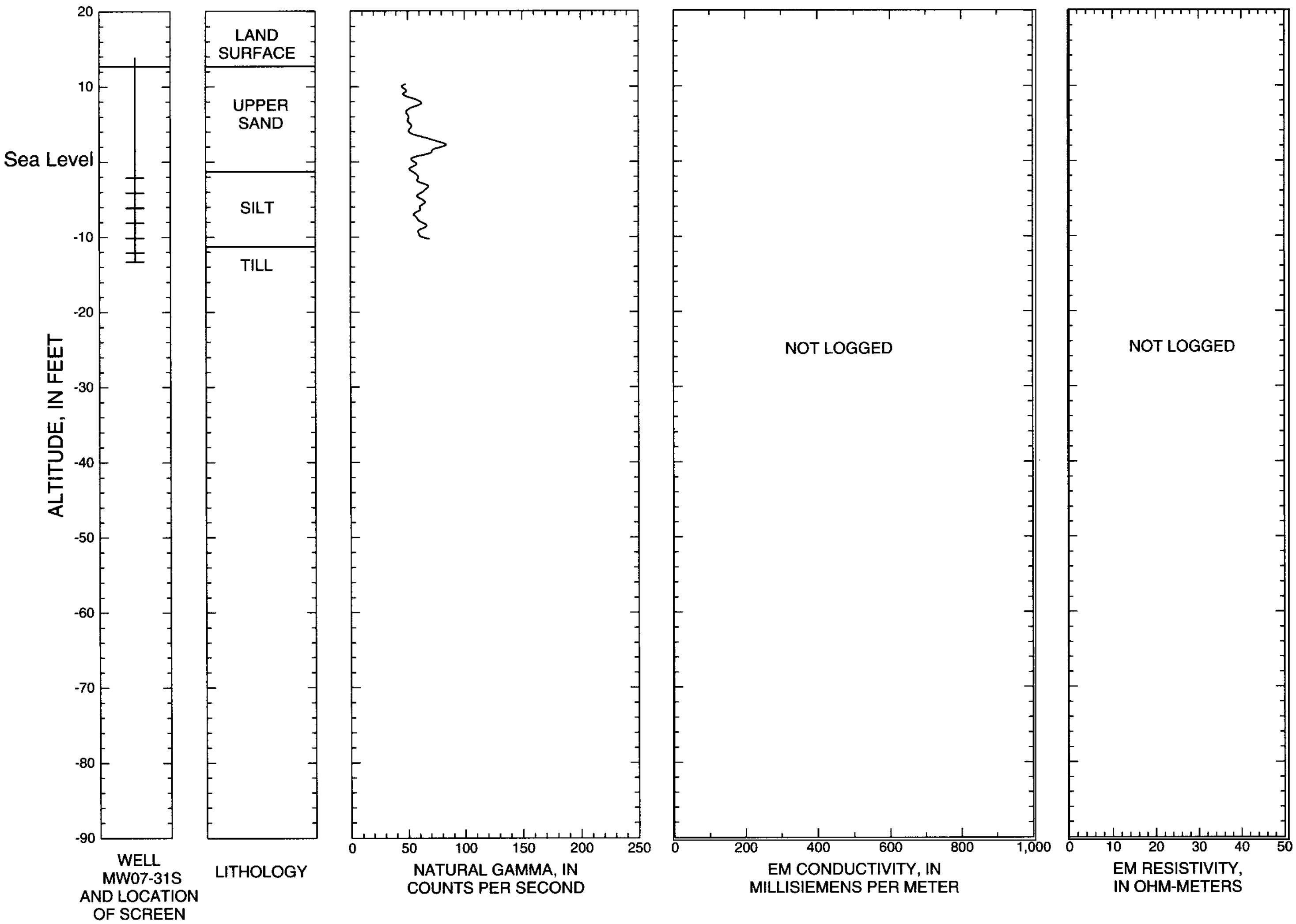
Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

T. WELL MW07-30D



Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

U. WELL MW07-31S



Appendix 1. Lithologic and borehole geophysical logs at Calf Pasture Point, Davisville, Rhode Island—*Continued.*

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