Open-File Report 92-135

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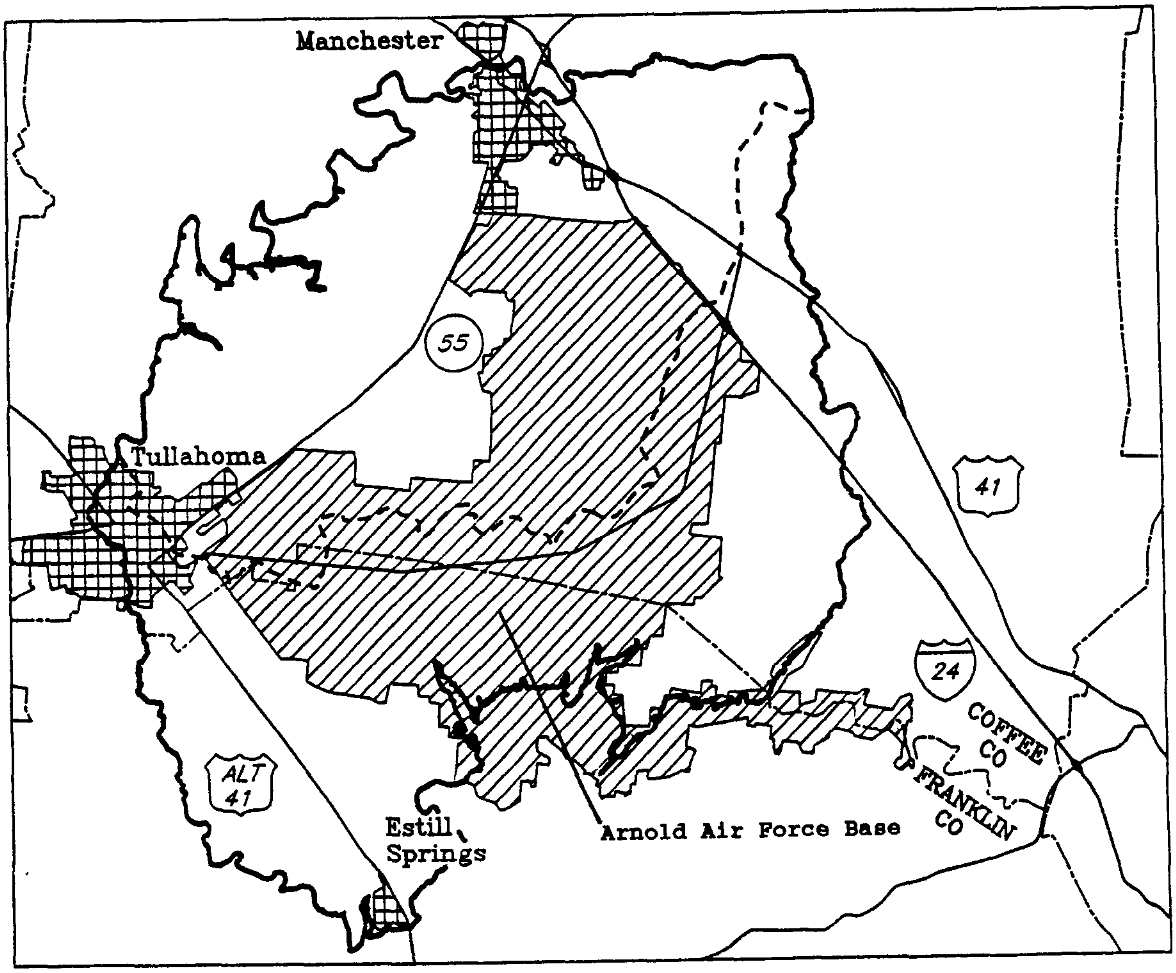

Prepared by the
U.S. GEOLOGICAL SURVEY

in cooperation with the
UNITED STATES AIR FORCE,
ARNOLD AIR FORCE BASE

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By CONNOR J. HAUGH, ELIZABETH N. MAHONEY, and JOHN A. ROBINSON

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Nashville, Tennessee

1992

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

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Multiply	*By*	*To obtain*
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06308	liter per second
microsiemens per centimeter at 25°C (μS/cm)	1	micromhos per centimeter at 25°C

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

$$°F = 1.8 \times °C + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum 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.

Site-numbering system: The U.S. Geological Survey assigns each site in this report a local Tennessee well number and a station identification number. The local well number is used as a concise label for a site. The station identification number is used as an identifier for site data stored in the national computer data base of the U.S. Geological Survey. These numbering systems are used in addition to the well numbers assigned by Arnold Engineering Development Center.

The local well number in Tennessee consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7½-minute topographic quadrangle on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Cf:G-010, for example, indicates that the well is located in Coffee County on the "G" quadrangle and is identified as well 10 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

The station identification number is a unique number for each site based on a latitude and longitude grid system. The number consists of 15 digits. The first 6 digits denotes the degrees, minutes, and seconds of latitude, the next 7 digits denotes degrees,minutes, and seconds of longitude, and the last 2 digits (assigned sequentially) identify the wells within a 1-second grid.

WELL-CONSTRUCTION, WATER-LEVEL, GEOPHYSICAL, AND WATER-QUALITY DATA FOR GROUND-WATER MONITORING WELLS FOR ARNOLD AIR FORCE BASE, TENNESSEE

By Connor J. Haugh, Elizabeth N. Mahoney, *and* John A. Robinson

ABSTRACT

Sixty-five wells were installed at 39 sites in the Arnold Air Force Base area in Coffee and Franklin Counties, Tennessee. The wells were installed to provide information on subsurface lithology, aquifer characteristics, ground-water levels, and ground-water quality. Well depths ranged from 11 to 384 feet.

Water-quality samples were collected from 60 wells and analyzed for common inorganic ions, trace metals, and volatile organic compounds. The median dissolved-solids concentrations were 60 milligrams per liter in the shallow aquifer, 48 million gallons per liter in the Manchester aquifer, 1,235 milligrams per liter in the Fort Payne aquifer, and 1,712 milligrams per liter in the upper Central Basin aquifer.

Caliper, temperature, natural gamma, electric, neutron porosity, gamma-gamma density, and acoustic velocity borehole-geophysical logs were obtained for the six deep wells completed below the Chattanooga Shale. Petrographic and modal analysis were performed on rock samples from each deep well. These six deep wells provide the first information in the study area on hydraulic head and water quality from below the Chattanooga Shale.

INTRODUCTION

As part of the U.S. Air Force Installation Restoration Program (IRP), numerous site-specific ground-water investigations have been conducted at sites of potential ground-water contamination on Arnold Air Force Base (AAFB). However, the regional hydrogeology of AAFB has not been defined in sufficient detail to provide quantification of the occurrence, direction, and velocities of ground-water flow. The U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force and Arnold Air Force Base (AAFB), is conducting a comprehensive investigation of the hydrogeology of the AAFB area.

The primary mission of AAFB is to support the development of aerospace systems. This is accomplished through test facilities at Arnold Engineering Development Center (AEDC). AEDC occupies about 4,000 acres in the center of AAFB. Ground-water contamination in selected areas of the AAFB facility has occurred as the result of base operations and past disposal practices. Ground-water investigations have been conducted or are currently in progress at several sites at AAFB.

The USGS identified locations outside the site-specific study areas where additional data were needed to understand the regional hydrogeologic system (J.V. Brahana, U.S. Geological Survey, written commun., 1990). Between October 1990 and February 1991, 65 wells were drilled at 39 sites to provide this hydrologic and geologic information including (1) subsurface lithology, (2) aquifer characteristics, (3) water levels, and (4) ground-water quality. Six of the wells were drilled through the Chattanooga Shale to provide information in the study area on the deep ground-water system.

Purpose and Scope

The report documents well-construction details and water-level measurements for 65 wells installed by the USGS. Water-quality analyses are reported for 60 wells that were sampled. Lithologic descriptions and borehole-geophysical data are presented for six deep wells. Continuous water-level data are presented for five wells drilled previous to this study.

Study Area

The AAFB occupies about 40,000 acres of Coffee and Franklin Counties, Tennessee (fig. 1). The study area extends beyond the boundaries of the AAFB to include major hydrologic and physiographic features important to the regional ground-water system. The study area includes about 180 square miles within six USGS $7^1/_2$-minute topographic quadrangles, including Normandy Lake, Manchester, Hillsboro, Tullahoma, Capital Hill, and Alto.

The AAFB area lies on the eastern Highland Rim physiographic province (Miller, 1974) and ranges from poorly drained, flat uplands to valley-dissected, sloping escarpments. Land surface altitudes within the study area range from greater than 1,100 feet above sea level at the Duck River-Elk River drainage divide to less than 890 feet above sea level in the valleys.

Hydrogeologic Setting

The study area is covered by regolith derived from the *in situ* weathering of Mississippian carbonates (in descending order): the St. Louis Limestone, the Warsaw Formation, and the Fort Payne Formation (Wilson, 1976). The regolith is typically 30 to 90 feet thick and consists primarily of clayey chert rubble with some silt and sand. Typically, the regolith grades upward from gravel-sized chert rubble at the top of bedrock into clay-sized chert particles at land surface (Burchett, 1977).

The bedrock underlying the regolith consists of the Fort Payne Formation. The Fort Payne Formation is an indurated siliceous limestone containing many chert nodules and platy chert stringers. The upper part of the Fort Payne bedrock contains many fractures and solution openings.

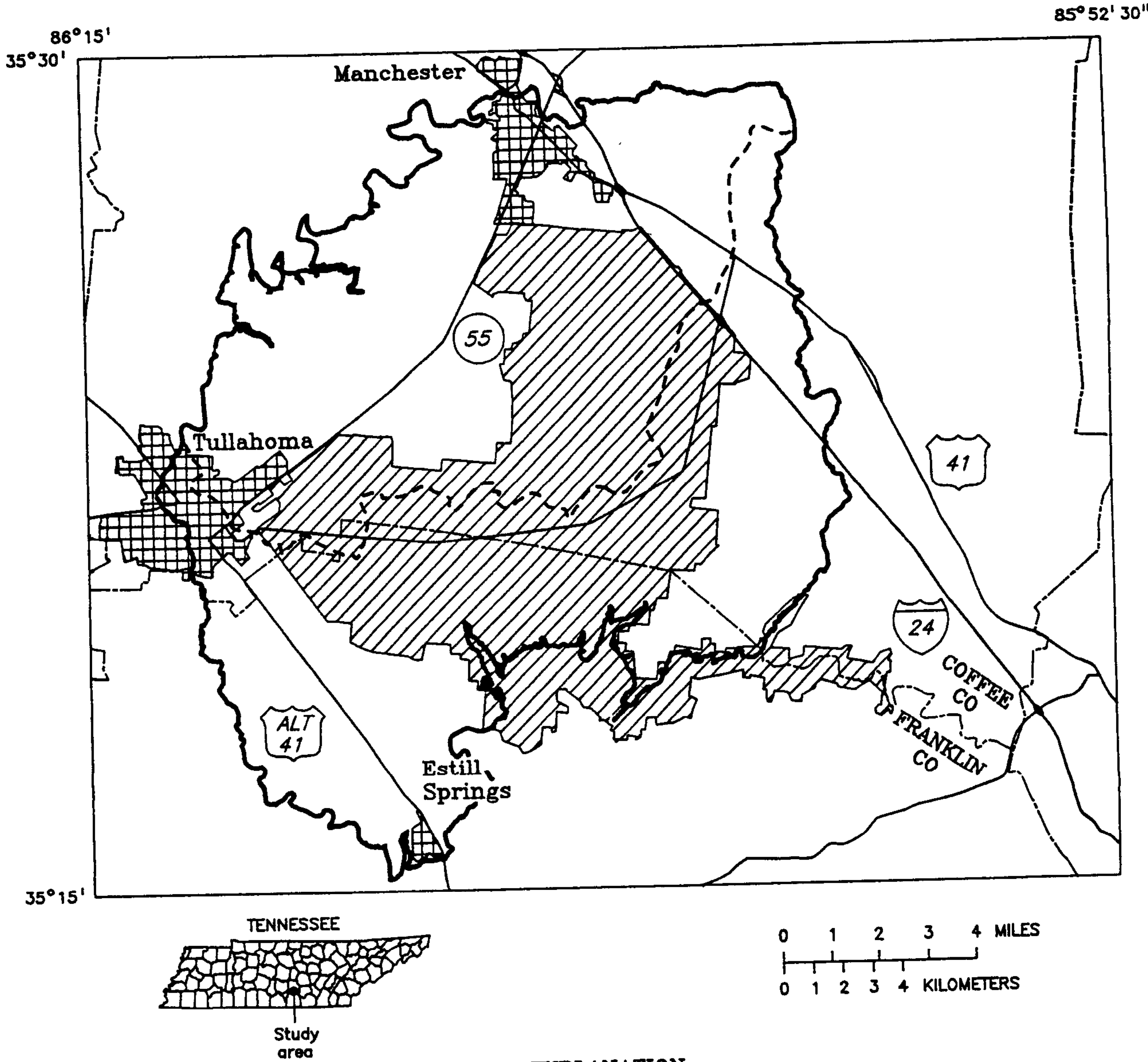
Underlying this bedrock unit is the Chattanooga Shale. The Chattanooga Shale consists of about 22 feet of a fissile, black, carbonaceous shale. Underlying the Chattanooga Shale are dark blue-gray bioclastic and argillaceous limestones of Late Ordovician age. Several different zones or aquifers can be identified in the study area. The Chattanooga Shale is considered to be the base of the freshwater ground-water system in the study area. The ground-water system above the Chattanooga Shale can be divided into three aquifers: the shallow aquifer, the Manchester aquifer, and the Fort Payne aquifer.

The shallow aquifer is described as alluvial, residual silt and sand deposits, and clayey chert particles. It is not continuous throughout the study area and is perched at some locations. The Manchester aquifer, the most productive of the zones, consists of chert rubble at the base of the regolith and solution openings in the upper part of the bedrock (Burchett and Hollyday, 1974). The Fort Payne aquifer corresponds to the lower part of the Fort Payne bedrock where solution openings are less developed.

The Ordovician limestones below the Chattanooga Shale comprise the upper Central Basin aquifer. The Chattanooga Shale isolates this deeper aquifer from the aquifers above it.

WELL CONSTRUCTION

Sixty-five wells were installed at 39 sites in the AAFB area (fig. 2). Eight of the wells were completed in the shallow aquifer, 41 were completed in the Manchester aquifer, 10 were completed in the Fort Payne aquifer,



EXPLANATION

ARNOLD AIR FORCE BASE

INCORPORATED TOWNS

HYDROLOGIC BOUNDARY--Delineation of regional ground-water flow system underlying Arnold Air Force Base

DRAINAGE DIVIDE--Surface water north and west of the divide flows to the Duck River. Surface water south and east of the divide flows to the Elk River

Figure 1.--Location of the study area.

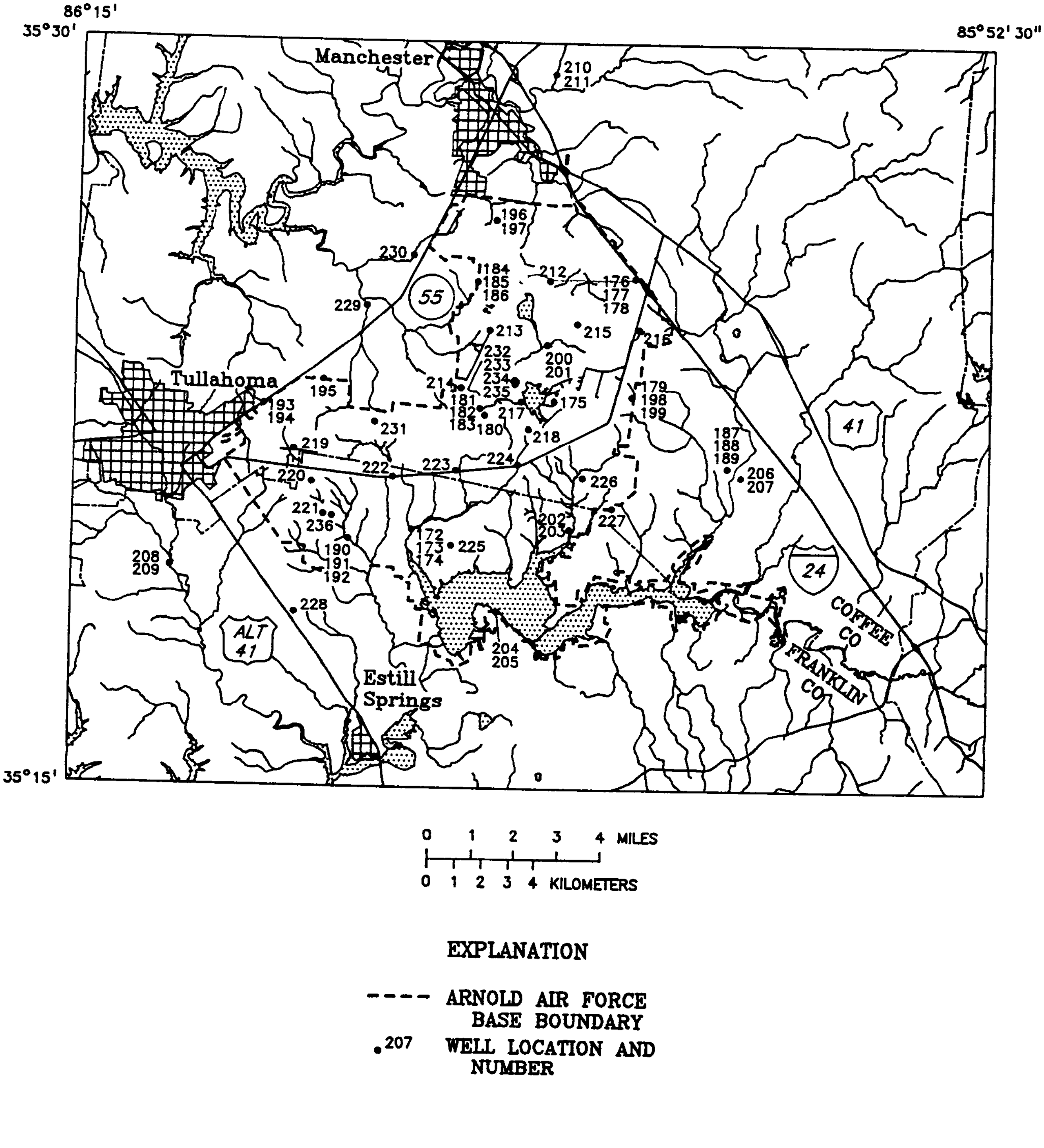


Figure 2.--Locations of the wells installed by the USGS in the Arnold Air Force Base area.

and six were completed in the upper Central Basin aquifer. Standard air-rotary techniques were used for drilling all wells. For wells completed in the regolith, either an 8- or 11-inch borehole was drilled to the desired depth. For wells completed in the rock, an 11-inch borehole was drilled through the regolith to a minimum of 2 feet into rock. Then, a nominal 8-inch-diameter steel surface casing was set into rock and the base sealed with bentonite clay. The borehole was advanced in bedrock with an 8-inch air-hammer bit to the desired depth.

Well-construction techniques used in this study followed guidelines outlined by the U.S. Environmental Protection Agency in the RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (1986). All wells were completed with 4-inch-diameter, schedule 40, threaded PVC casing and screen. A sand pack was installed from the bottom of the borehole to a minimum of 2 feet above the top of the screen. A 2-foot bentonite seal was placed above the sand pack. The annulus was then grouted from the top of the seal to land surface with a neat cement grout (fig. 3). Screen lengths for the regolith wells were either 5 or 10 feet. Screen lengths for the rock wells were either 10 or 20 feet. Slot sizes on all screens were 0.010 inch. Well-construction data are summarized in table 1.

GROUND-WATER LEVELS

The depth to ground water and water-level fluctuations at the AAFB were determined by collection of monthly and continuous ground-water levels. Monthly ground-water level measurements for the 65 wells drilled by the USGS were provided by the AAFB. These data are presented in table 2 for the period May 1991 through January 1992. The data indicate water-level fluctuations range from greater than 25 feet in well AEDC-213 to less than 2 feet in well AEDC-188. Water levels in several of the wells completed into rock took months to recover after sampling; therefore, water levels measured for some wells for certain months do not represent a static water level. These values are shown in parentheses in table 2.

Continuous ground-water levels were recorded in five wells (figs. 4, 5, and 6). The five wells, AEDC-91, -92, -93, -135, and -147, existed prior to well installation for this investigation. Three of the wells, AEDC-91, -92, and -93, are located in a cluster near the center of the AAFB and are completed at depths of about 121, 86, and 38 feet, respectively. They are screened in the lower part of the Manchester, the upper part of the Manchester, and the shallow aquifer, respectively. Water levels in this cluster indicate a downward vertical gradient. Well AEDC-135 is located in the northwestern corner of the AAFB and is completed in the lower part of the Manchester aquifer at a depth of about 55 feet. Well AEDC-147 is located in the southwestern part of the AAFB and is completed in the lower part of the Manchester aquifer at a depth of about 86 feet.

Rainfall data also were collected and are presented in table 3. Total rainfall measured for the water year October 1990 to September 1991 is 61.04 inches. Twenty-five percent of this total or 15.03 inches was recorded during the month of December.

BOREHOLE GEOPHYSICS

Borehole-geophysical logs provide a continuous record of the physical properties of the rocks encountered in a well and can provide indirect information on the lithology and hydraulic properties of the rock. Caliper, temperature, natural gamma, electric, neutron porosity, gamma-gamma density, and acoustic velocity logs were obtained on the six deep wells. The logs were run on the total depth of the open hole after the surface casing was set and before the PVC casing and screen were installed. Unstable borehole conditions near a cavity in well AEDC-176 prevented running acoustic velocity and electric logs past a depth of 112 feet.

The following discussion on the various types of logs is generalized. A more detailed discussion of the theory and interpretation of geophysical logs is beyond the scope of this report, but may be found in various texts on the subject, such as Keys and MacCary (1971) and Keys (1990).

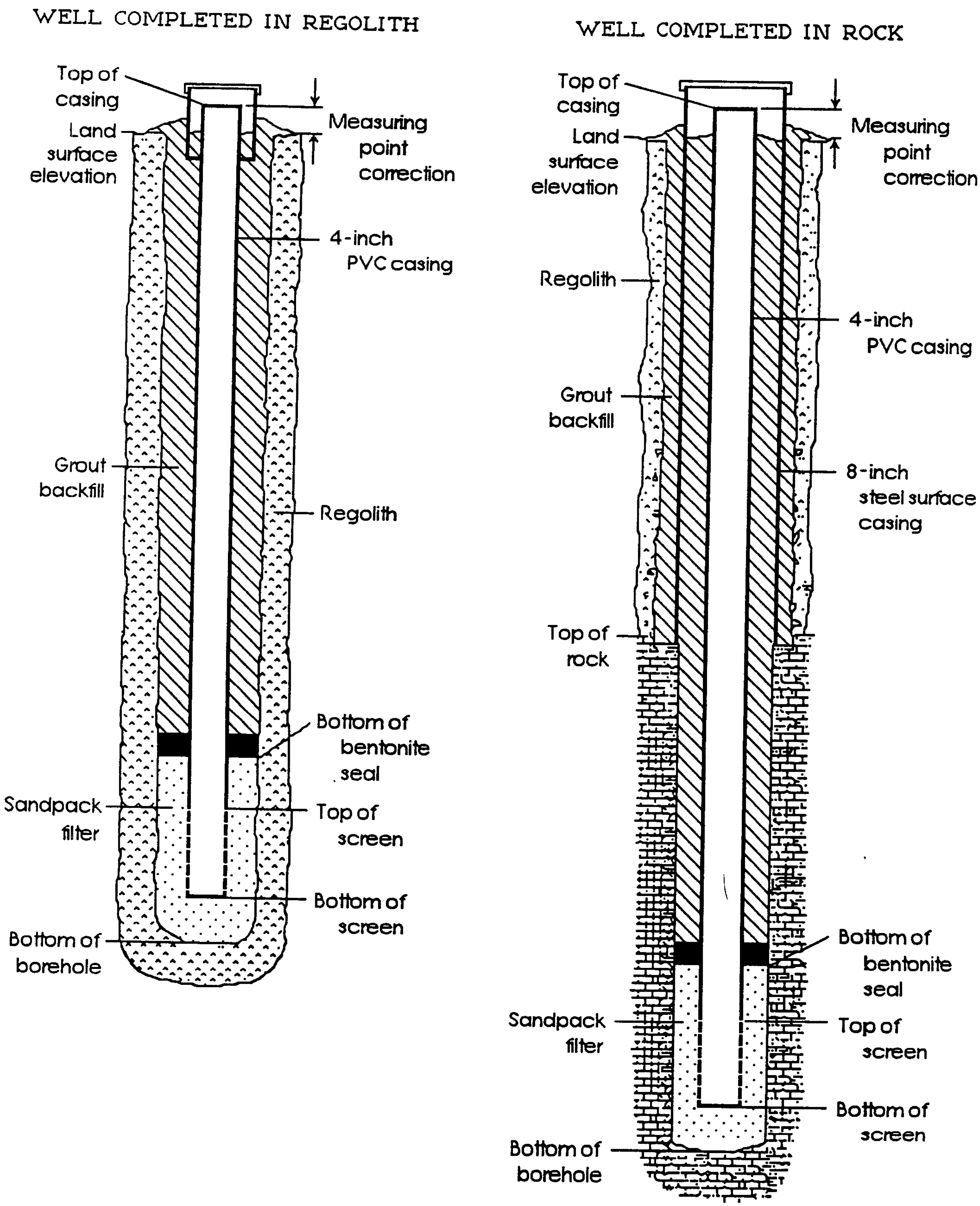


Figure 3.--Well-construction diagrams.

Table 1.--*Well-construction data for monitoring wells for Arnold Air Force Base*

[AEDC, Arnold Engineering Development Center; USGS, United States Geological Survey; --, no data; SH, shallow aquifer; MN, Manchester aquifer; FP, Fort Payne aquifer; UCB, Upper Central Basin aquifer]

AEDC well name	Local well number	USGS site identification	Land surface elevation (feet)	Measuring point height (feet)	Surface casing depth (feet)	Depth to bottom of seal (feet)	Screened interval (feet)	Depth to bottom of borehole (feet)	Hydro-geologic unit	Date of construction
AEDC-172	Fr:S-001	352011086063901	970.01	0.45	37	87	110 - 130	183	UCB	10-23-90
AEDC-173	Fr:S-004	352011086063902	971.17	.85	39	47	49 - 59	60	MN	12-18-90
AEDC-174	Fr:S-005	352011086063903	970.40	2.80	--	18	20 - 30	35	MN	12-19-90
AEDC-175	Cf:G-009	352247086031301	1,080.31	1.60	71	130	270 - 290	320	UCB	11-15-90
AEDC-176	Cf:G-006	352515086011701	1,088.51	1.95	24	288	340 - 360	384	UCB	10-29-90
AEDC-177	Cf:G-028	352515086011702	1,088.40	1.24	22	105	107 - 117	127	MN	02-28-91
AEDC-178	Cf:G-029	352515086011703	1,088.23	1.93	--	11	13 - 18	19	SH	02-28-91
AEDC-179	Cf:G-014	352253086011903	1,072.06	1.30	--	32	34 - 44	47	SH	01-10-91
AEDC-180	Cf:G-007	352229086045601	1,063.70	.75	67	118	120 - 130	131	UCB	10-31-90
AEDC-181	Cf:G-010	352237086050302	1,029.25	1.00	63	80	90 - 100	101	FP	11-21-90
AEDC-182	Cf:G-011	352237086050303	1,029.00	2.76	--	60	63 - 73	74	MN	11-20-90
AEDC-183	Cf:G-012	352237086050304	1,029.48	2.40	--	30	33 - 43	45	MN	11-26-90
AEDC-184	Cf:G-008	352509086051101	1,105.14	.64	29	240	250 - 270	320	UCB	11-02-90
AEDC-185	Cf:G-016	352509086051102	1,104.96	.30	27	47	50 - 60	61	MN	12-07-90
AEDC-186	Cf:G-018	352509086051103	1,104.82	1.40	--	15	17 - 27	27	MN	12-10-90
AEDC-187	Cf:D-001	352129085585501	1,009.86	1.10	91	200	220 - 240	300	UCB	01-07-91
AEDC-188	Cf:D-007	352129085585502	1,011.14	.90	92	98	101 - 111	112	FP	01-15-91
AEDC-189	Cf:D-003	352129085585503	1,010.57	2.16	--	57	59 - 69	85	MN	01-07-91
AEDC-190	Fr:R-007	351959086081301	977.23	.54	62	72	74 - 84	88	FP	11-29-90
AEDC-191	Fr:R-008	351959086081302	977.65	2.20	--	30	33 - 43	47	MN	11-30-90
AEDC-192	Fr:R-009	351959086081303	977.51	.92	--	26	29 - 39	42	SH	11-29-90
AEDC-193	Cf:F-003	352240086102101	1,036.49	.80	47	79	99 - 109	119	FP	02-14-91
AEDC-194	Cf:F-004	352240086102102	1,037.35	3.70	--	34	36 - 43	47	SH	02-14-91
AEDC-195	Cf:F-005	352310086085401	1,044.38	1.94	--	47	48 - 58	64	MN	02-26-91
AEDC-196	Cf:G-015	352624086044301	1,081.49	.65	48	70	98 - 108	167	FP	12-07-90
AEDC-197	Cf:G-017	352624086044302	1,082.80	2.52	--	28	32 - 42	48	SH	12-06-90
AEDC-198	Cf:G-032	352253086011901	1,072.12	1.12	106	115	122 - 132	133	FP	01-18-91
AEDC-199	Cf:D-009	352253086011902	1,073.06	2.00	--	88	90 - 100	100	MN	01-18-91
AEDC-200	Cf:G-021	352354086032501	1,067.46	1.24	56	72	74 - 84	84	MN	12-18-90
AEDC-201	Cf:G-022	352354086032502	1,067.09	2.74	--	39	41 - 51	58	MN	12-12-90
AEDC-202	Fr:S-002	352013086024701	981.34	2.82	73	71	72 - 82	91	MN	12-14-90
AEDC-203	Fr:S-003	352013086024702	977.84	1.42	--	41	43 - 53	53	MN	12-17-90
AEDC-204	Fr:S-006	351833086043301	964.63	.86	52	65	104 - 114	116	FP	12-19-90
AEDC-205	Fr:S-007	351833086043302	963.02	1.42	--	37	39 - 49	50	MN	01-02-91
AEDC-206	Cf:D-004	352118085583401	1,005.50	1.52	20	61	65 - 75	77	FP	01-10-91
AEDC-207	Cf:D-006	352118085583402	1,007.74	.09	--	4	4 - 9	11	MN	01-10-91
AEDC-208	Fr:R-012	351924086124601	1,029.16	-.90	89	100	108 - 118	119	FP	02-08-91
AEDC-209	Fr:R-013	351924086124602	1,028.98	-.18	--	66	69 - 79	79	MN	02-08-91
AEDC-210	Cf:G-024	352922086032101	1,046.17	1.80	42	70	90 - 100	130	FP	02-06-91
AEDC-211	Cf:G-025	352922086032102	1,046.81	2.42	--	28	30 - 40	40	MN	02-06-91
AEDC-212	Cf:G-020	352511086032301	1,098.12	2.80	--	12	17 - 27	29	MN	12-10-90
AEDC-213	Cf:G-033	352411086045101	1,070.47	2.76	--	43	49 - 59	61	MN	01-28-91
AEDC-214	Cf:G-023	352302086053201	1,059.49	1.12	--	65	69 - 79	79	MN	01-25-91
AEDC-215	Cf:G-019	352420086024101	1,075.75	1.75	--	46	48 - 58	61	MN	12-10-90
AEDC-216	Cf:G-013	352414086011001	1,054.37	1.66	--	46	49 - 59	62	MN	12-04-90
AEDC-217	Cf:C-002	352246086040201	1,045.97	3.30	--	41	47 - 57	57	MN	01-24-91
AEDC-218	Cf:C-001	352213086035001	1,083.20	2.20	--	60	66 - 76	76	MN	01-24-91
AEDC-219	Cf:B-002	352146086093601	1,070.09	1.96	--	60	63 - 73	87	MN	01-31-91
AEDC-220	Fr:R-010	352107086090901	1,105.76	2.04	--	72	74 - 84	88	MN	12-04-90
AEDC-221	Fr:R-012	352028086085101	1,025.51	3.08	--	63	68 - 78	80	MN	01-29-91
AEDC-222	Fr:S-009	352114086070801	1,046.08	2.10	--	75	83 - 93	93	MN	02-04-91
AEDC-223	Cf:C-005	352123086053701	1,046.90	2.02	--	54	59 - 69	71	MN	02-01-91
AEDC-224	Cf:C-004	352130086040501	1,079.74	1.62	--	67	73 - 83	85	MN	01-31-91
AEDC-225	Fr:S-008	351952086054201	1,046.42	2.70	--	53	55 - 65	66	MN	01-24-91
AEDC-226	Cf:C-006	352115086022901	1,057.97	2.38	--	70	79 - 89	91	MN	01-30-91
AEDC-227	Cf:C-003	352039086014501	1,060.04	2.82	--	73	79 - 89	91	MN	01-29-91
AEDC-228	Fr:R-015	351830086092501	1,030.96	-.50	--	63	65 - 75	78	MN	02-25-91
AEDC-229	Cf:F-002	352439086075201	977.82	2.24	--	10	13 - 18	22	MN	02-05-91
AEDC-230	Cf:F-001	352540086064501	1,019.44	2.42	--	11	15 - 20	22	MN	02-05-91
AEDC-231	Cf:B-001	352220086073701	1,046.92	1.94	--	54	61 - 71	74	MN	01-29-91
AEDC-232	Cf:G-026	352307086041201	1,092.47	1.90	--	66	71 - 81	81	MN	02-21-91
AEDC-233	Cf:G-027	352310086041401	1,094.90	1.55	--	37	42 - 52	53	SH	02-21-91
AEDC-234	Cf:G-030	352312086041201	1,090.30	1.65	--	38	43 - 53	53	SH	02-21-91
AEDC-235	Cf:G-031	352310086041001	1,093.56	1.32	--	44	48 - 58	58	SH	02-21-91
AEDC-236	Fr:R-016	352026086083801	1,022.86	2.10	--	75	78 - 88	92	MN	02-26-91

354 TLS=24 F7.

Table 2.--*Monthly water-level data for monitoring wells for Arnold Air Force Base*

[AEDC, Arnold Engineering Development Center; --, no data; water levels shown in parentheses are recovering from sampling and may not represent a static water level]

AEDC well number	Water level[1], in feet below land surface								
	May 1991	June 1991	July 1991	August 1991	September 1991	October 1991	November 1991	December 1991	January 1992
172	(33.68)	(28.59)	(25.79)	(23.43)	(21.69)	(21.03)	(20.41)	(19.97)	(19.08)
173	flowing	-0.03	0.79	1.19	1.51	1.56	1.83	0.29	-0.81
174	2.38	4.06	4.88	4.72	5.34	5.19	5.50	2.72	2.65
175	130.42	136.10	139.64	142.96	144.68	146.34	147.46	149.02	148.35
176	(122.40)	(110.91)	113.97	117.35	118.77	118.25	117.89	117.35	116.75
177	20.21	27.01	27.91	32.17	33.25	33.75	34.21	16.17	15.71
178	13.69	9.37	15.43	16.35	16.39	16.13	7.43	10.07	11.49
179	25.35	29.03	31.75	33.67	34.79	35.99	36.57	32.75	29.70
180	(111.25)	(111.15)	(111.07)	(110.97)	(110.93)	(110.89)	(110.87)	(110.85)	(110.80)
181	20.40	19.40	21.28	23.60	24.97	26.06	27.06	26.84	26.20
182	17.29	18.86	21.42	24.58	27.35	29.58	31.60	31.86	28.54
183	16.37	17.96	20.54	23.92	26.64	28.86	30.94	31.16	--
184	(139.61)	(137.90)	(136.80)	(135.76)	(135.02)	(134.74)	(134.34)	(134.04)	(133.46)
185	35.70	40.50	41.78	43.36	44.04	44.30	44.48	38.70	35.20
186	14.65	15.05	19.01	21.05	22.29	22.99	21.95	6.83	8.50
187	33.00	33.92	34.60	35.16	35.44	35.62	35.80	34.28	33.80
188	38.75	39.46	40.10	40.32	40.36	40.23	39.46	38.42	38.95
189	37.29	38.64	39.42	39.50	39.54	39.46	38.88	36.24	37.14
190	31.25	33.52	34.40	35.30	35.58	36.15	36.34	34.02	32.94
191	28.40	31.26	32.48	33.80	34.36	35.04	35.38	32.48	30.98
192	26.79	29.58	--	32.80	33.50	34.20	34.54	32.04	30.31
193	(87.50)	(84.40)	(81.50)	(80.40)	(80.04)	(80.02)	(80.02)	(80.04)	(79.90)
194	35.25	38.88	39.56	40.44	41.62	40.66	40.72	35.82	34.74
195	28.68	34.32	36.82	38.66	39.48	40.36	40.92	33.50	29.92
196	(66.90)	(53.85)	(48.64)	(43.80)	(41.62)	(79.42)	(67.80)	(61.56)	(56.00)
197	31.98	36.19	38.75	41.83	dry	dry	dry	31.37	30.68
198	27.38	32.98	36.02	38.22	39.68	41.54	41.72	34.52	32.78
199	27.10	32.64	35.64	37.76	39.28	41.06	41.30	34.50	32.55
200	4.86	9.62	12.50	17.36	20.62	22.40	24.10	9.82	6.26
201	4.41	9.21	12.11	17.01	20.23	22.01	23.71	9.41	5.81
202	14.39	15.77	16.42	17.34	18.00	18.39	19.16	18.62	17.82
203	9.58	10.90	11.58	12.62	13.38	13.84	14.60	14.00	13.02
204	(84.28)	(80.82)	(78.02)	(75.08)	(72.82)	(71.23)	(69.82)	(68.74)	(67.02)
205	1.98	2.72	3.06	3.36	3.38	3.69	4.40	3.94	--
206	32.73	33.47	33.93	34.15	34.19	34.17	33.53	31.77	32.83
207	dry	dry	dry	dry	dry	dry	dry	dry	dry
208	55.37	58.32	58.90	60.02	60.32	60.40	60.44	56.72	56.84
209	42.20	46.88	49.14	50.72	52.06	52.76	53.38	44.96	43.22
210	7.40	8.25	9.05	10.13	9.29	10.07	9.51	6.89	7.40
211	12.53	12.05	13.99	14.63	13.93	14.83	12.17	9.29	9.83
212	23.45	dry	dry	dry	dry	dry	dry	26.10	22.65
213	20.64	25.14	28.68	37.14	41.22	44.18	46.26	31.54	26.84
214	57.78	61.73	62.63	65.15	67.27	69.13	70.83	69.57	--
215	8.35	14.35	18.13	23.55	26.60	28.24	29.75	17.75	12.30
216	21.59	25.76	28.78	32.24	35.21	37.22	39.18	30.14	26.74
217	flowing	-1.50	-0.34	1.00	1.74	2.40	2.68	-1.20	-1.70
218	6.50	11.30	13.32	16.04	17.30	18.06	18.36	6.77	5.95
219	18.45	26.00	29.86	33.38	34.86	35.88	36.48	25.60	19.28
220	34.69	37.40	38.84	40.58	41.68	42.87	43.68	42.04	38.64
221	9.80	13.10	14.92	16.84	17.94	19.13	19.70	14.50	11.70
222	54.51	57.80	59.76	61.70	62.80	64.22	65.08	62.92	59.70
223	41.08	43.14	44.94	47.74	49.64	51.81	53.20	53.56	51.24
224	16.00	18.98	20.52	21.60	22.28	22.86	23.38	20.26	18.23
225	44.49	45.24	45.80	46.68	46.52	47.72	48.14	48.38	47.09
226	31.16	35.82	36.74	37.52	38.00	38.27	38.48	34.34	33.17
227	31.09	36.88	38.60	40.68	42.17	43.12	43.84	39.02	35.98
228	63.15	64.40	65.36	66.70	67.04	67.78	68.12	68.40	67.54
229	8.50	10.26	10.50	--	--	--	--	--	--
230	6.50	10.21	10.38	10.78	10.81	10.88	10.94	6.02	6.70
231	21.63	27.00	30.28	32.94	33.02	34.09	34.64	29.64	23.30
232	59.50	61.90	63.70	65.10	65.84	66.20	66.54	64.10	76.80
233	50.13	51.03	dry	dry	dry	dry	dry	dry	dry
234	52.43	dry	dry	dry	dry	dry	dry	dry	dry
235	58.81	dry	dry	dry	dry	dry	dry	dry	dry
236	68.34	71.32	72.38	74.12	74.88	75.96	76.46	74.76	71.97

[1]Water levels were measured each month within a 3-day period, generally during the third week of each month.

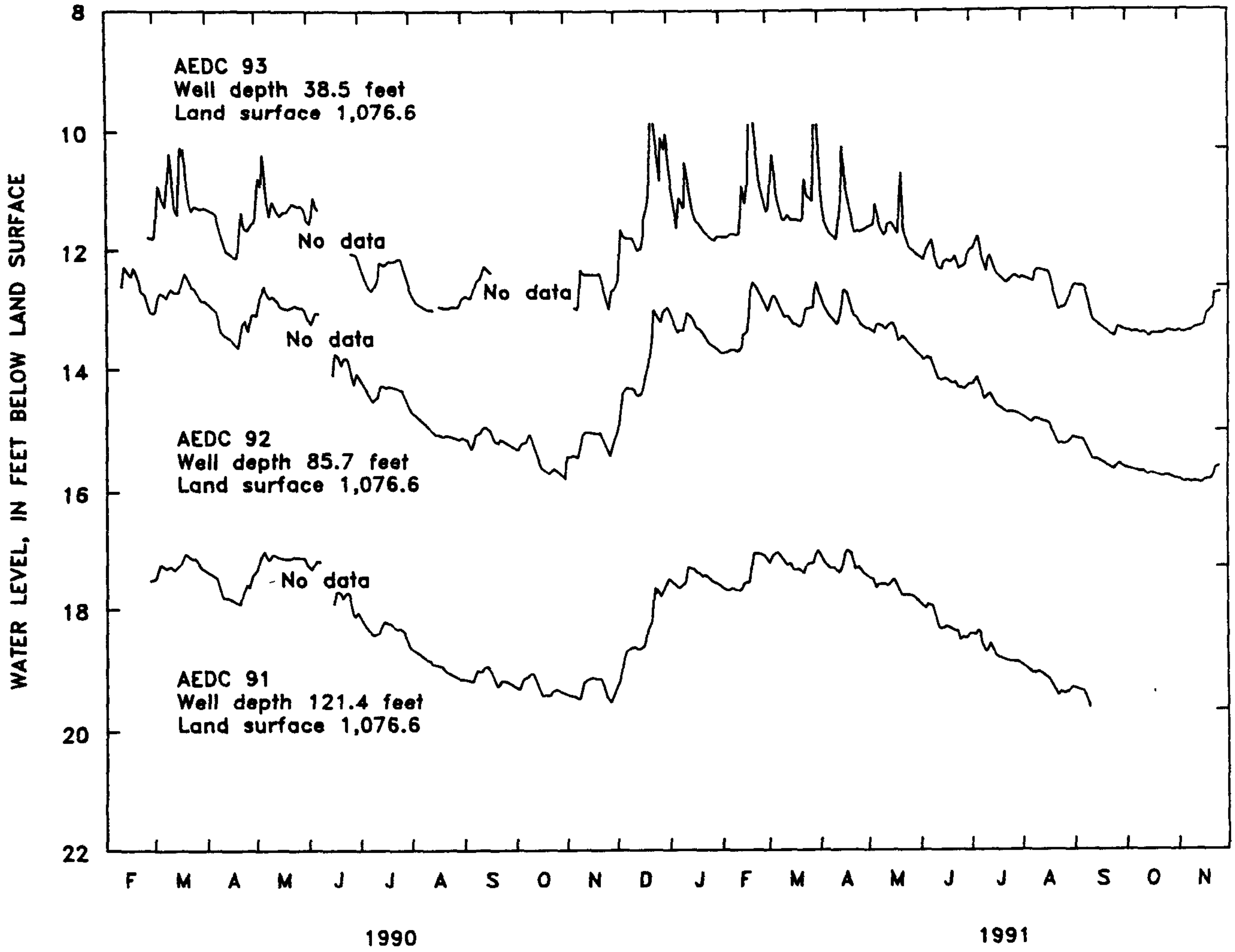


Figure 4.--Hydrographs for wells AEDC-91, -92, and -93 for the period February 1990 through November 1991.

Caliper logs provide a record of the diameter of the borehole. Increases in borehole diameter, such as those caused by large fractures or solution openings, appear as a deflection to the right on the caliper log. The caliper tool used in this study was the three-arm type that provides a more accurate measurement of the borehole diameter than single-arm calipers.

Temperature logs record the air or water temperature adjacent to the probe and can provide useful information on the movement of water through a borehole. The recorded temperature might indicate the temperature of adjacent rocks and their contained fluids. The temperature will increase with depth, as a function of the geothermal gradient if no flow exists in the borehole. If vertical flow of water occurs in a well, the temperature log through that interval will show little change. Similarly, gas entering the borehole also will disturb the geothermal gradient.

Natural gamma logs measure the amount of natural gamma radiation present in the rock. Increases in gamma radiation appear as deflections to the right on the log and are usually caused by clay or shale lithologies. Limestones and clean sandstones typically have low gamma values.

Neutron logs record the hydrogen content in the rocks and provide an indirect measurement of the water content or porosity of the rocks. Hydrogen in the rock attenuates the neutron activity resulting in a decrease in the number of counts per second recorded by the tool. In aquifers, the increased hydrogen is associated with increased water content (higher porosity) within the aquifer material. The tool used in this study was calibrated for quantitative measurement of porosity in percent.

Gamma-gamma logs provide information on the attenuation of gamma radiation through the aquifer material. The amount of attenuation is directly related to the bulk density of the aquifer. Bulk density is the mass of aquifer material per unit volume. An increase in attenuation (decrease in counts per second and deflection to the right on the log) is caused by an increase in bulk density. The tool used in this study was calibrated to read density directly in grams per cubic centimeter.

Acoustic-velocity logs record the travel time of an acoustic wave from transmitters to receivers in the probe. The acoustic energy travels through the fluid in the borehole and through surrounding rock at a velocity that is related to the matrix mineralogy and porosity of the rocks. An uncased borehole, filled with fluid is required to

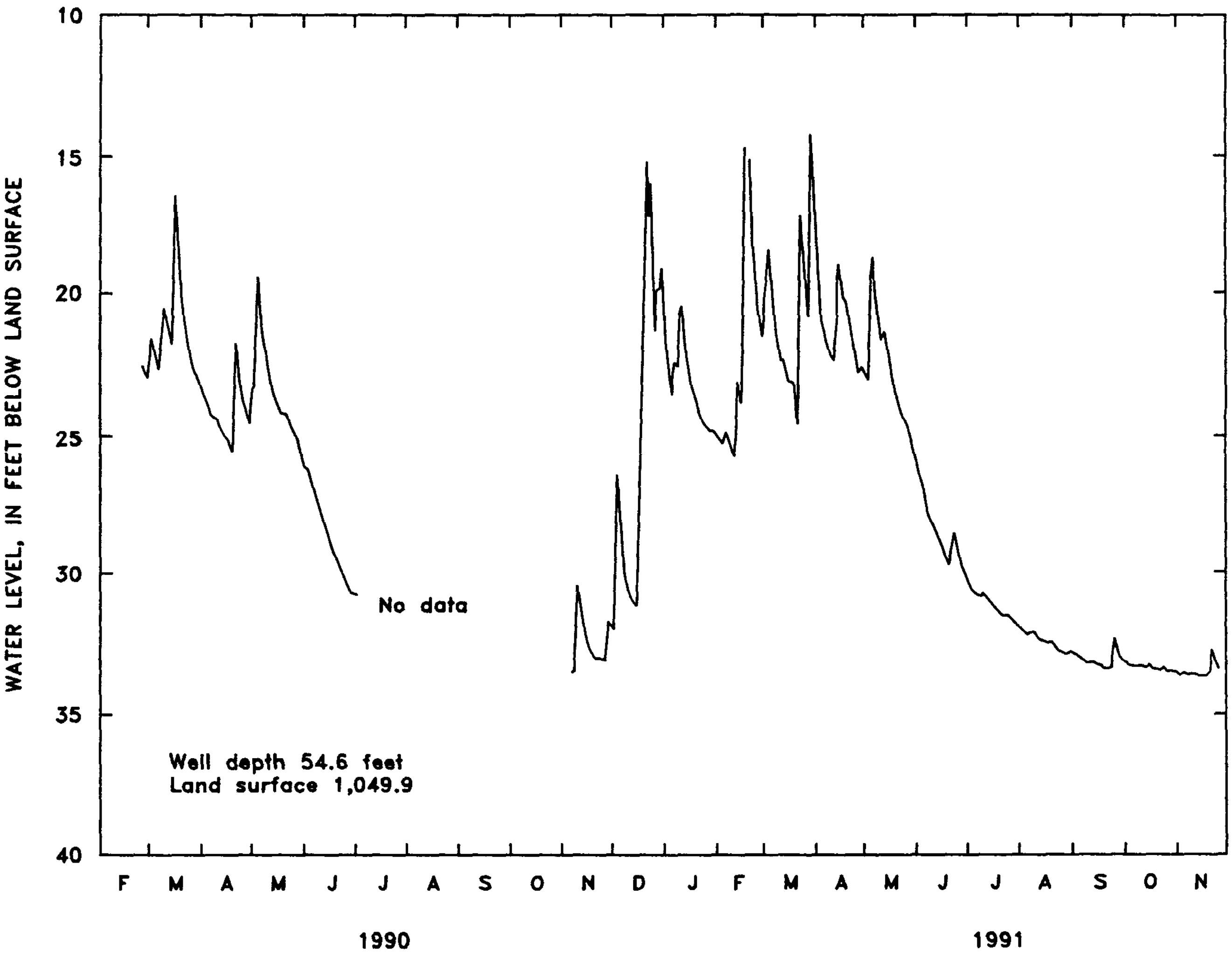


Figure 5.--Hydrograph for well AEDC-135 for the period February 1990 through November 1991.

couple the signal to the surrounding rocks. The acoustic velocity increases, or transit times decrease, with increasing rock hardness; therefore, the transit time can be related to primary porosity. Secondary porosity is not detected by acoustic-velocity logs as the acoustic wave travels the fastest path around solution openings. Many rock types will be characterized by a limited range of transit times; therefore, acoustic-velocity logs provide information on lithology. Lithologies of shale have longer transit times than limestones (Keys, 1990).

Electric logs measure the potential differences due to the flow of electric current in and adjacent to a well. Two common types of electrical logs are spontaneous-potential and resistivity logs. Spontaneous-potential logs can be useful in determining lithology and the salinity of formation water. If the borehole fluid is fresher than the native interstitial water, a negative spontaneous potential occurs. If the salinities are reversed, the response also is reversed. Resistivity logs measure apparent resistivity between electrodes. This information can be used to determine lithology and water quality. The tool used in this study recorded spontaneous-potential, long-normal resistivity, and short-normal resistivity.

Geophysical logs, lithologic descriptions, and analyses of rock samples from drilling for each of the six deep wells are presented in Appendix 1.

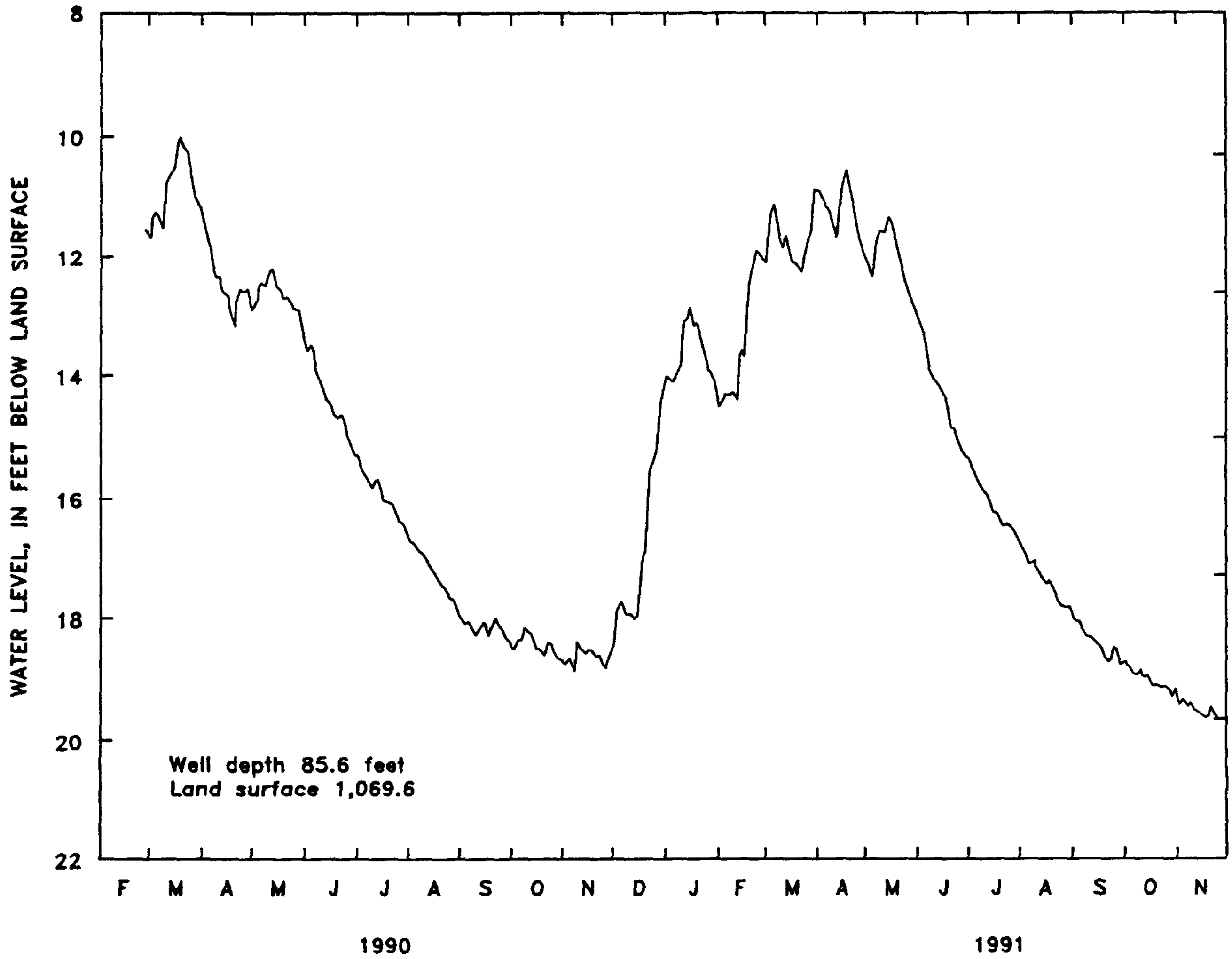


Figure 6.--Hydrograph for well AEDC-147 for the period February 1990 through November 1991.

Table 3.--*Rainfall data for Arnold Air Force Base area*

[--, no data]

DAY	Rainfall, in inches, water year October 1989 to September 1990											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	---	---	0.00	0.00	0.00	0.26	0.00	1.51	0.00	0.02	0.00	0.00
2	---	---	.00	.00	.47	.95	.00	.00	.00	.00	.00	.00
3	---	---	.00	.00	2.00	.02	.00	.00	1.71	.00	.00	.00
4	---	---	.00	.66	.25	.00	.00	.91	.00	.00	.02	.00
5	---	---	.00	.17	.00	.00	.00	.00	.00	.00	.07	.00
6	---	---	.00	.12	.03	.00	.52	.00	.00	.00	.00	.00
7	---	---	.23	.16	.05	.00	.00	.00	.00	.00	.00	.02
8	---	---	.38	.48	.00	.76	.00	.00	.00	.00	.00	.00
9	---	---	.00	.00	1.68	.69	.00	.21	.00	.70	.00	.00
10	---	---	.00	.04	.69	.00	.25	.57	.00	.07	.00	.25
11	---	---	.12	.00	.00	.00	.00	.00	.00	.00	.00	.29
12	---	---	.03	.00	.00	.00	.00	.00	.00	2.01	.00	1.19
13	---	---	.00	.00	.00	.00	.00	.00	.00	.29	.00	.12
14	---	---	.00	.00	.00	.00	.06	.00	.64	.00	.00	.14
15	---	---	.00	.00	1.74	.71	.00	.00	.00	.00	.00	.00
16	---	---	.00	.00	.19	1.46	.00	.00	.00	.00	.00	.00
17	---	---	.00	.45	.00	.04	.20	.67	.00	.00	.00	.00
18	---	---	.00	.17	.14	.00	.00	.00	.07	.01	.00	.00
19	---	---	.19	.00	.00	.01	.00	.12	.00	.00	.00	.32
20	---	---	.00	1.66	.00	.00	.00	.54	.00	.00	.00	.00
21	---	---	.00	.00	.00	.00	1.81	.51	.91	.11	.10	1.48
22	---	---	.00	.00	.21	.00	.00	.00	.07	.33	.00	.02
23	---	---	.00	.00	.02	.00	.00	.00	.00	.01	.00	.00
24	---	---	.00	.27	.01	.00	.00	.00	.00	.00	.00	.00
25	---	---	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
26	---	---	.00	.00	.00	.00	.00	.26	.00	.00	.00	.00
27	---	---	.00	.00	.00	.00	.00	.21	.00	.00	.00	.00
28	---	---	.00	.11	.00	.00	.53	.00	.00	.00	.00	.00
29	---	---	.19	1.53	---	.46	.00	.00	.00	.00	.36	.00
30	---	---	.77	.00	---	.07	.00	.00	.00	.00	.00	.00
31	---	---	.73	.00	---	.01	---	.00	---	.00	.00	---
TOTAL	---	---	2.64	5.82	7.48	5.44	3.37	5.51	3.40	3.55	0.55	3.83

DAY	Rainfall, in inches, water year October 1990 to September 1991											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.00	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00	0.00	0.00
2	.00	.00	.00	.00	.00	.06	.00	.00	.00	.35	.00	.00
3	.15	.00	1.44	.00	.00	.92	.00	.00	.00	.00	.00	.00
4	.78	.00	.00	.00	.01	.00	.00	.92	.50	.23	.00	.00
5	.00	.27	.00	.00	.26	.00	.32	.83	.00	.00	.00	.00
6	.00	.00	.00	.65	.12	.00	.00	.03	.00	.00	.00	.00
7	.02	.00	.00	1.66	.00	.00	.00	.00	.00	.00	.04	.00
8	1.72	.45	.00	.00	.00	.00	.48	.30	.00	.00	.00	.00
9	.00	1.05	.00	.00	.00	.00	.22	.00	.00	.05	.00	.00
10	.16	.00	.00	.87	.00	.00	.20	.02	.00	.14	.11	.28
11	.00	.00	.00	.12	.00	.00	.00	.00	.03	.03	.00	.30
12	.00	.00	.00	.00	.00	.63	.31	.78	.14	.00	.00	.12
13	.00	.00	.32	.00	1.22	.02	.66	.00	.00	.02	.00	.00
14	.00	.00	.00	.00	.00	.00	.47	.00	.00	.00	.00	.04
15	.00	.00	.18	.05	.00	.00	.76	.00	.00	.05	.00	.00
16	.00	.06	.30	.21	.00	.00	.00	.00	.00	.00	.00	.00
17	.00	.00	.51	.00	1.50	.38	.00	.00	.00	.02	.00	.00
18	.43	.00	.36	.00	3.24	.00	.00	.02	.00	.00	.09	.00
19	.00	.00	.00	.11	2.86	.00	.15	2.15	.00	.00	.10	.00
20	.00	.00	1.11	.04	.11	.00	.00	.01	.02	.00	.00	.00
21	.00	.00	3.22	.00	.00	.00	.00	.00	1.03	.00	.00	.00
22	.57	.06	5.49	.00	.15	.43	.00	.00	.06	.00	.00	.00
23	.48	.01	.10	.00	.01	.72	.00	.28	.00	.00	.00	.03
24	.01	.00	.00	.00	.00	.00	.00	.00	.00	.49	.00	1.71
25	.16	.00	.00	.00	.10	.00	.00	.00	.06	.00	.14	.00
26	.00	.00	.06	.00	.01	.00	.00	.16	.00	.00	.48	.00
27	.00	.93	1.13	.04	.00	.08	.12	.00	.00	.00	.00	.00
28	.00	.24	.09	.02	.00	.24	.30	.00	.02	.00	.00	.00
29	.00	.00	.08	.00	---	2.51	.68	.00	.00	.00	.53	.00
30	.00	.00	.64	.53	---	.42	.02	.00	.00	.00	.00	.00
31	.00	---	.00	.00	---	.00	---	.00	---	.00	.02	---
TOTAL	4.48	3.07	15.03	4.30	9.59	7.15	4.69	5.50	1.86	1.38	1.51	2.48

GROUND-WATER QUALITY

Water-quality samples were collected from 60 wells. Samples were analyzed for major inorganic constituents, trace metals, and volatile organic compounds. Samples were collected, treated, and preserved using procedures established and documented by the USGS (Claassen, 1982; Pritt and Jones, 1989; and Wood, 1976). Samples for dissolved analysis were filtered using an acetate membrane filter with a mean pore size of 0.45 micron. Samples for metal analysis were treated with one milliliter nitric acid to lower the pH to less than 2. Samples for volatile organic compound analysis were chilled immediately after collection and kept chilled until analyzed.

Wells were purged prior to sampling using a submersible pump. For most wells, specific conductance, temperature, pH, and Eh were monitored in a flow cell during well purging to determine when an appropriate amount of water had been purged from a well. Samples were collected after values of these monitored properties had stabilized. Samples for inorganic analysis were collected from the discharge line of the submersible pump. Samples for VOC analysis were collected with a 2-inch stainless-steel bailer. The bailer was field rinsed with a minimum of three bails full of well water before collecting the sample. Between wells, the bailer was cleaned by washing with laboratory detergent and tap water, then rinsing with tap water, and a final rinse with deionized water. The pump was cleaned by flushing with tap water.

Several of the wells had yields of less than 0.5 gallon per minute. For these wells, one casing volume was purged, then the well was allowed to recover before purging again. A minimum of three casing volumes were purged before sampling. These wells were AEDC-175, -179, -181, -186, -193, -198, -208, and -212. For these wells, physical properties were monitored with grab samples during purging.

A few of the wells drilled into rock had yields so low that the well would take several weeks or months to purge three casing volumes. These wells were purged as much as practical, then the sample collected at the midpoint of the well screen with either a submersible pump or a downhole sampler. These wells were AEDC-172, -176, -180, -184, -196, and -204.

All samples were analyzed for inorganic constituents and volatile organic compounds by the USGS National Water Quality Laboratory in Arvada, Colorado. Field quality-assurance samples also were collected for analysis for volatile organic compounds. These included field duplicates, equipment blanks, a trip blank, and an analysis of the AEDC tap water that was used to rinse sampling equipment.

Inorganic Constituents and Physical Properties

Samples were analyzed for major and trace inorganic constituents. The results of the water-quality analyses indicate the variation of geochemical processes affecting water from the various aquifers. The dissolved-solids concentrations ranged from 11 milligrams per liter (mg/L) in wells AEDC-216 and AEDC-217 to 8,810 mg/L in well AEDC-187. Wells AEDC-216 and AEDC-217 were completed in the upper part of the Manchester aquifer at depths of 59 and 57 feet below land surface, respectively. Well AEDC-187 is a deep well completed in the upper Central Basin aquifer at a depth of 240 feet below land surface. The median dissolved-solids concentrations were 60 mg/L in the shallow aquifer, 48 mg/L in the Manchester aquifer, 1,235 mg/L in the Fort Payne aquifer, and 1,712 mg/L in the upper Central Basin aquifer. The median values for each aquifer of other select constituents are shown in table 4. Most of the inorganic constituents followed a similar trend with the lowest concentrations in the shallow and Manchester aquifers and the highest concentrations in the upper Central Basin aquifer.

The complete analytical results for the inorganic constituents and physical properties of the ground-water samples are listed in Appendix 2. Values for the physical properties reported in Appendix 2 were measured in the field at the time ground-water samples were collected.

Table 4.--*Median values by aquifers of selected constituents in water from wells sampled at Arnold Air Force Base*

[µS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; mV, millivolts; °C, degrees Celsius; µg/L, micrograms per liter; Values given as < (less than) indicate that the concentration was below the detection level of the analytical method used and does not indicate the presence or absence of the constituent]

Constituent	Aquifer			
	Shallow	Manchester	Fort Payne	Upper Central Basin
Specific conductance (µS/cm)	104	87	1,635	2,365
pH (standard units)	6.2	6.0	7.2	7.5
Alkalinity (mg/L as $CaCO_3$)	38	39	181	159
Oxidation reduction potential (mV)	447	440	159	95
Hardness (mg/L as $CACO_3$)	47	40	840	360
Calcium (mg/L)	17	11	195	102
Magnesium (mg/L)	1.2	2.0	38	18
Sodium (mg/L)	1.5	1.0	58	365
Potassium (mg/L)	0.70	.30	3.1	20
Chloride (mg/L)	1.9	1.4	14	340
Sulfate (mg/L)	3.0	1.4	865	310
Fluoride (mg/L)	.10	.10	.45	.60
Silica (mg/L)	7.4	8.1	9.4	9.3
Dissolved solids (mg/L), residue at 180 °C	60	48	1,235	1,712
Solids (mg/L), sum of constituents	58	52	1,330	1,800
Barium (µg/L)	14	4.0	20	64
Iron (µg/L)	14	6.0	76	515
Lithium (µg/L)	<4.0	<4.0	180	650
Manganese (µg/L)	10	14	80	150
Strontium (µg/L)	44	15	1,900	2,000

Volatile Organic Compounds

Most of the volatile organic compounds analyzed for were below the detection limits (Appendix 3). However, some compounds were detected. Approximately one-half of the wells sampled showed the presence of aromatic hydrocarbons such as benzene, toluene, ethyl-benzene, and xylenes (BTEX). The highest concentrations of BTEX were found below the Chattanooga Shale in the upper Central Basin aquifer (table 5). These compounds occur naturally in association with petroleum deposits (natural gas and crude oil) and shale lithologies as well as in many refined petroleum products (Swanson, 1960; Slaine and Barker, 1990). When their presence is detected in ground water, it is often difficult to distinguish between naturally occurring BTEX and contamination from refined petroleum products from sources such as spills and landfill leachate (Barker and others, 1988). The median, maximum, and minimum values for these compounds for wells sampled in each aquifer are shown in table 5. None of these compounds were detected in any of the field blanks.

Three wells, AEDC-190, AEDC-199, and AEDC-216 contained water with chlorinated organic compounds such as tetrachloroethylene, 1,1,1-trichloroethane, 1,1-dichloroethane, and 1,1-dichloroethylene at concentrations of 1.1 µg/L or less. None of these compounds were detected in the field blanks. Well AEDC-190 also showed trichlorofluoromethane present at 15 µg/L. Trichlorofluoromethane was detected in several of the field blanks, but at levels of 0.3 and 0.2 µg/L, 50 times less than the level in well AEDC-190.

Table 5.--*Summary by aquifer of concentrations of BTEX compounds in water from wells sampled at Arnold Air Force Base*

[Values given as < (less than) indicate that the concentration was below the detection level of the analytical method used and does not indicate the presence or absence of the constituent; µg/L, micrograms per liter]

Constituent		Aquifers			
		Shallow	Manchester	Fort Payne	Upper Central Basin
Benzene (µg/L)	Median	<0.2	<0.2	2.0	700
	Maximum	.5	12	1,400	6,200
	Minimum	<.2	<.2	<.2	<0.2
Toluene (µg/L)	Median	<.2	.4	2.8	210
	Maximum	1.1	7.6	800	3,500
	Minimum	<.2	<.2	.2	<.2
Ethyl-benzene (µg/L)	Median	<.2	<.2	.6	5.6
	Maximum	.2	.6	94	180
	Minimum	<.2	<.2	<.2	<.2
Xylene (µg/L)	Median	<.2	<.2	2.4	27
	Maximum	.7	1.7	360	920
	Minimum	<.2	<.2	<.2	<.2

During the analysis for the volatile organic compounds, the presence of other organic compounds were detected and identified by the lab chemist (M.C. Noriega, U.S. Geological Survey, written commun., 1991). These results are discussed below, but are not listed in Appendix 3. Carbon disulfide was detected in several samples. The samples and levels for carbon disulfide are as follows: AEDC-195, 0.7 µg/L; AEDC-198, 1.7 µg/L; AEDC-199, 0.7 µg/L; AEDC-222, 1.5 µg/L; AEDC-226, 0.5 µg/L; and AEDC-227, 2.4 µg/L. Water from wells AEDC-179, -185, -186, -188, and -202 also contained detectable alkane compounds, but the individual compounds were not identified nor were the concentrations quantified.

Several of the samples for volatile organic compound analysis had hydrogen sulfide present. Hydrogen sulfide interferes with the analysis; therefore, the lab added cuprous chloride to the sample to precipitate out the sulfur product. The sample was then filtered through a 0.45-micron filter to remove the precipitate before analysis. Samples with hydrogen sulfide present included AEDC-181, -187, -190, -198, and -208.

Quality Assurance/Quality Control Samples

Approximately 10 percent of the field samples were quality assurance and quality control (QA/QC) samples. Field quality-assurance samples were collected and analyzed for volatile organic compounds. These samples included duplicates from wells AEDC-182, -230, and -236, equipment blanks for the downhole sampler and the bailer, a trip blank, and a sample of the AEDC tap water. The results of the analysis of the field quality-assurance samples are shown in Appendices 4 and 5.

The USGS laboratory follows standard QA/QC practices for all volatile organic analyses. These practices include lab blanks, quality-control check standards, surrogate spikes, matrix spikes, and duplicate analysis. Reagent blanks are run one daily or one for every 10 samples analyzed, whichever is greater. The analysis does not proceed unless the blank is free of contaminants.

Quality-control check standards are run daily for approximately 60 compounds. Recovery percentages are recorded for each compound and are expected to be within 60 to 140 percent. Recovery percentages for check standards for each day samples were analyzed are listed in Appendix 6.

Surrogate standards of D4 1,2-dichloroethane, D8 toluene, and 1,4-bromofluorobenzene are spiked into each sample analyzed. If the recovery results are less than 70 percent or greater than 130 percent, then a duplicate sample (if available) is analyzed. Surrogate spike recovery percentages are listed in Appendix 7.

Matrix spikes of five compounds, 1,1-dichloroethene, benzene, trichloroethene, toluene, and chlorobenzene, are analyzed 1 in every 20 samples. Low recoveries from matrix spikes indicate interferences from the sample matrix. Matrix spike results are listed in Appendix 8.

Duplicate samples are analyzed 1 in every 10 samples. If relative percent difference is greater than 30 percent, another replicate (if available) is analyzed. These data are presented in Appendix 9.

SUMMARY

Sixty-five wells were installed by the U.S. Geological Survey at 39 sites in the Arnold Air Force Base area. The wells are intended to provide information on subsurface lithology, aquifer characteristics, and water levels. Eight of the wells were completed in the shallow aquifer, 41 were completed in the Manchester aquifer, 10 were completed in the Fort Payne aquifer, and six were completed in the upper Central Basin aquifer. The six deep wells provide the first information in the study area on hydraulic head and water quality from below the Chattanooga Shale. Well depths ranged from 11 to 384 feet below land surface.

Caliper, temperature, natural gamma, electric, neutron porosity, gamma-gamma density, and acoustic velocity borehole-geophysical logs were obtained from the six deep wells. Petrographic and modal analyses also were performed on rock samples from each deep well.

Water-quality samples were collected from 60 wells and analyzed for common inorganic ions, trace metals, and volatile organic compounds. The median dissolved-solids concentrations were 60 mg/L in the shallow aquifer, 48 mg/L in the Manchester aquifer, 1,235 mg/L in the Fort Payne aquifer, and 1,712 mg/L in the upper Central Basin aquifer. Most of the inorganic constituents followed a similar trend with the lowest concentrations in the shallow and Manchester aquifers and the highest concentrations in the upper Central Basin aquifer.

Most of the volatile organic compounds analyzed for were below the detection limits. However, approximately one-half of the wells sampled showed the presence of BTEX compounds. The highest concentrations of BTEX were found below the Chattanooga Shale in the upper Central Basin aquifer. Three wells, AEDC-190, AEDC-199, and AEDC-216 contained water with chlorinated organic compounds such as tetrachloroethylene, 1,1,1-trichloroethane, 1,1-dichloroethane, and 1,1-dichloroethylene at concentrations of 1.1 μg/L or less. Well AEDC-190 also showed trichlorofluoromethane present at 15 μg/L.

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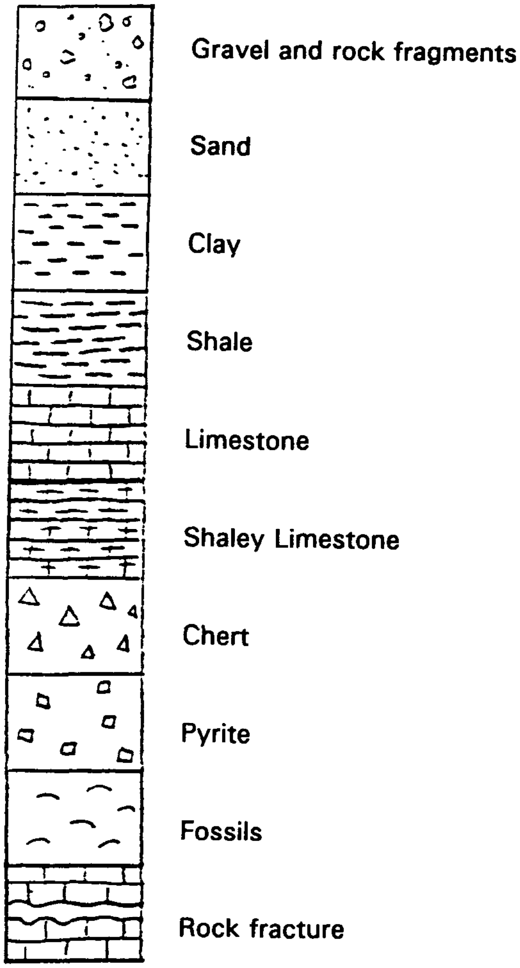
APPENDIX 1

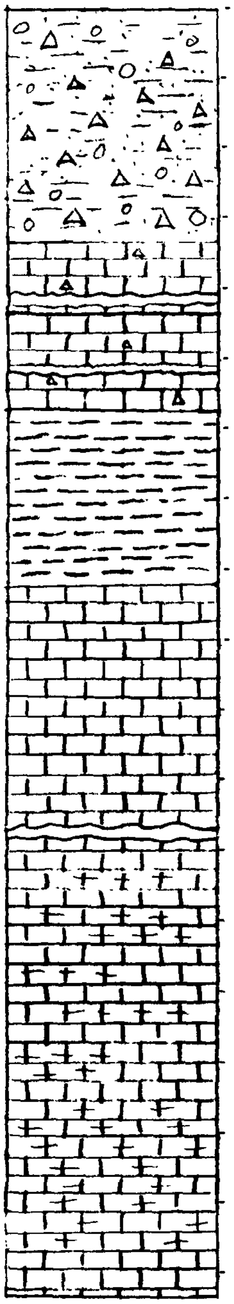
Lithologic descriptions, rock sample analyses, and geophysical

logs for wells AEDC-172, -175, -176, -180, -184, and -187

EXPLANATION: LITHOLOGY

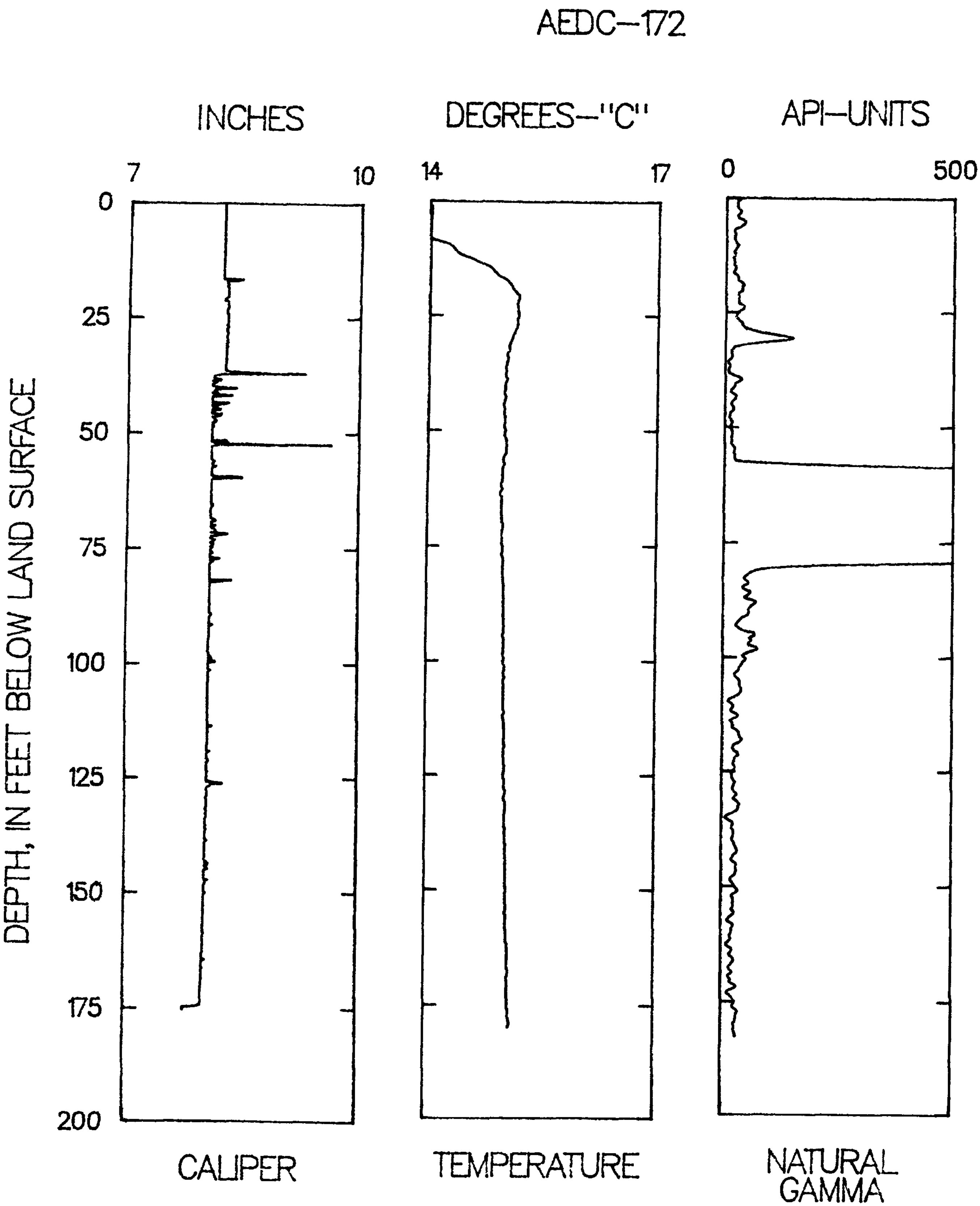


Explanation of symbols used for lithologic logs.

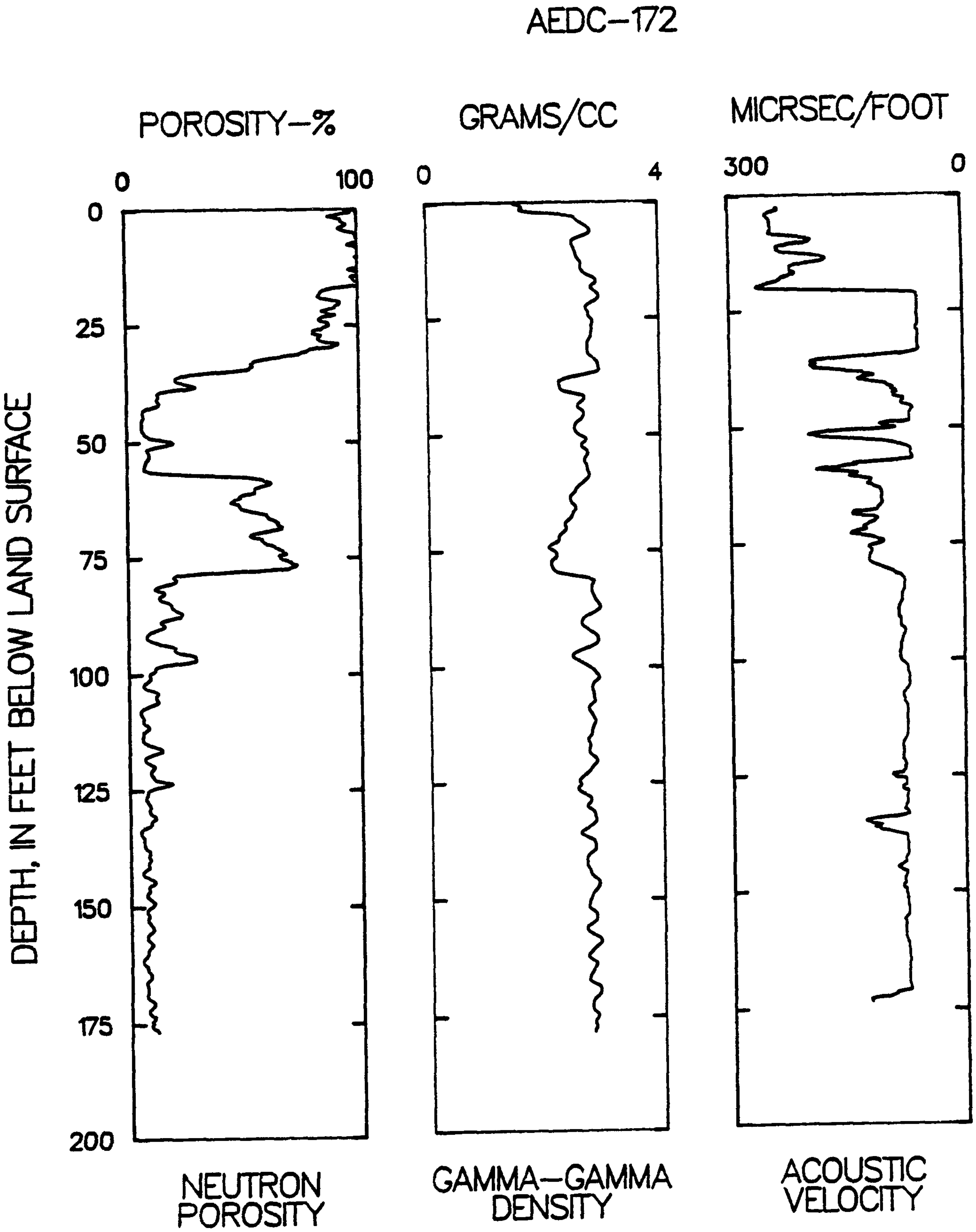


LITHOLOGY LAND SURFACE / DEPTH, IN FEET	DESCRIPTION	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Chert, rubble, gravel, and sand fragments in a brown clay matrix. Higher chert content at 10 feet.	
20		Chert: 90% quartz, 10% hematite.
30		
40	Fort Payne limestone at 33 feet, dark, dusky gray limestone with chert fragments. Hit fractured rock at 41 and 51 feet.	Chert: 90% quartz, 10% hematite.
50	Chattanooga Shale at 58 feet, black shale containing minor amounts of pyrite.	Chert: 85% quartz, 10% calcite, 5% hematite.
60		Shale: clay minerals, quartz, pyrite, black matrix material.
70		
80		Packstone: 85% calcite sparite, 10% matrix, 5% quartz, <1% clay.
90	Ordovician limestone at 82 feet, olive-gray limestone with minor red-brown limestone.	
100	Minor amounts of fossil fragments. Fracture at 117 feet.	Packstone: 60% calcite sparite, 20% matrix, 10% quartz, 10% pyrite.
110		Wackestone: 30% calcite spar cement, bioclasts, <1% pyrite.
120	Dark to medium gray limestone, fine-grained mixed with shaley limestone.	
130		
140		
150		
160	Mixed, dark gray, shaley limestone and minor fine-grained greenish-gray limestone. Strong sulfur odor.	Wackestone: 50% bioclasts 50% calcite spar cement.
170		
180	Bottom of hole at 183.	

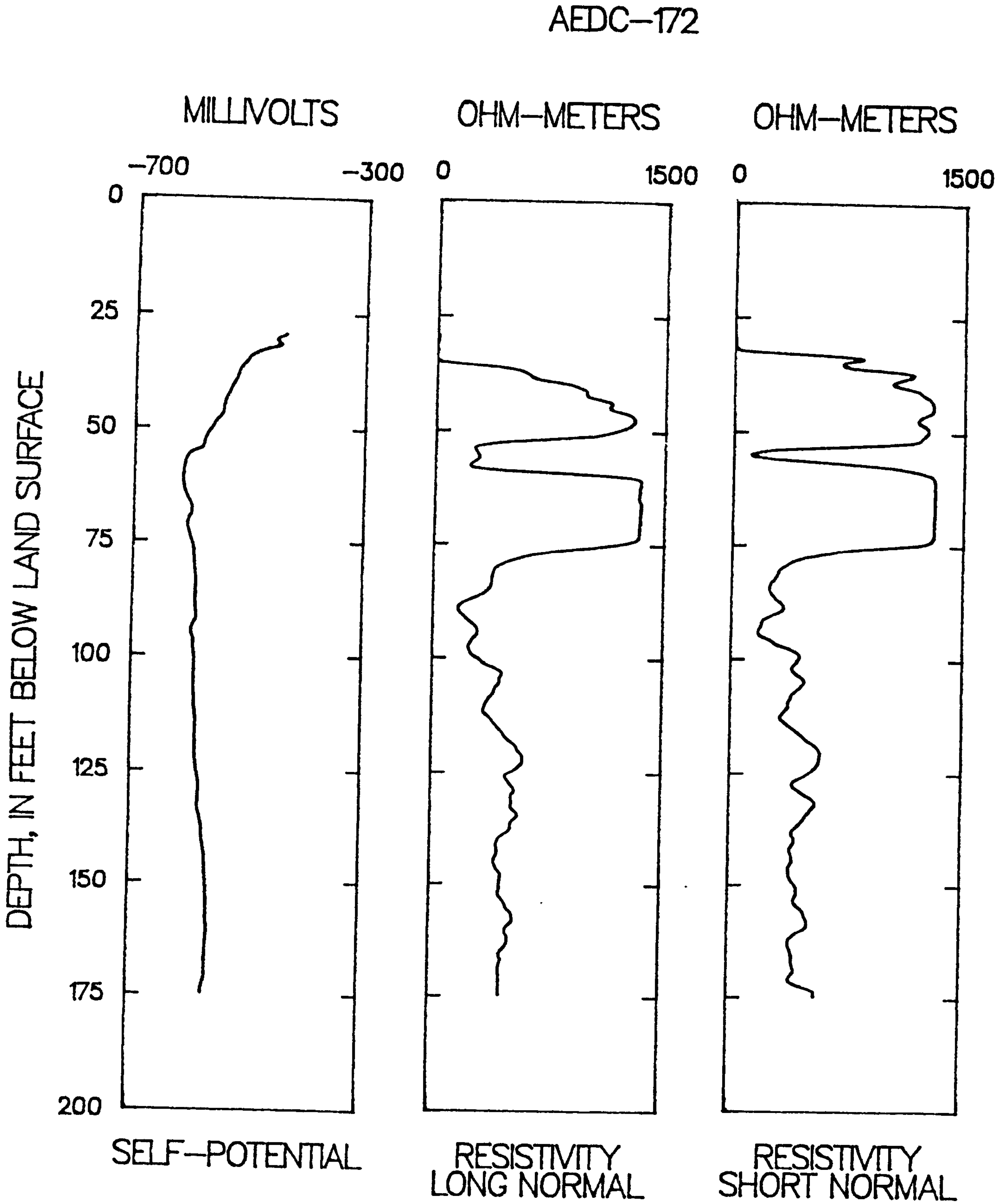
Lithologic descriptions and rock sample analysis for well AEDC-172.



Caliper, temperature, and natural gamma logs for well AEDC-172.

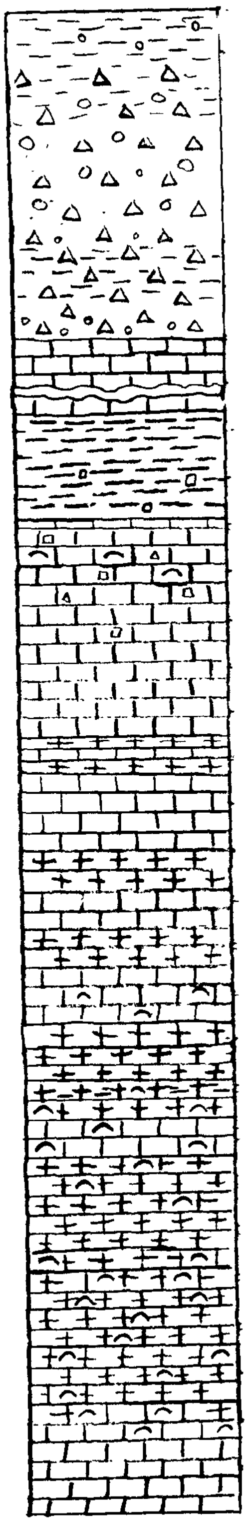


Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-172.



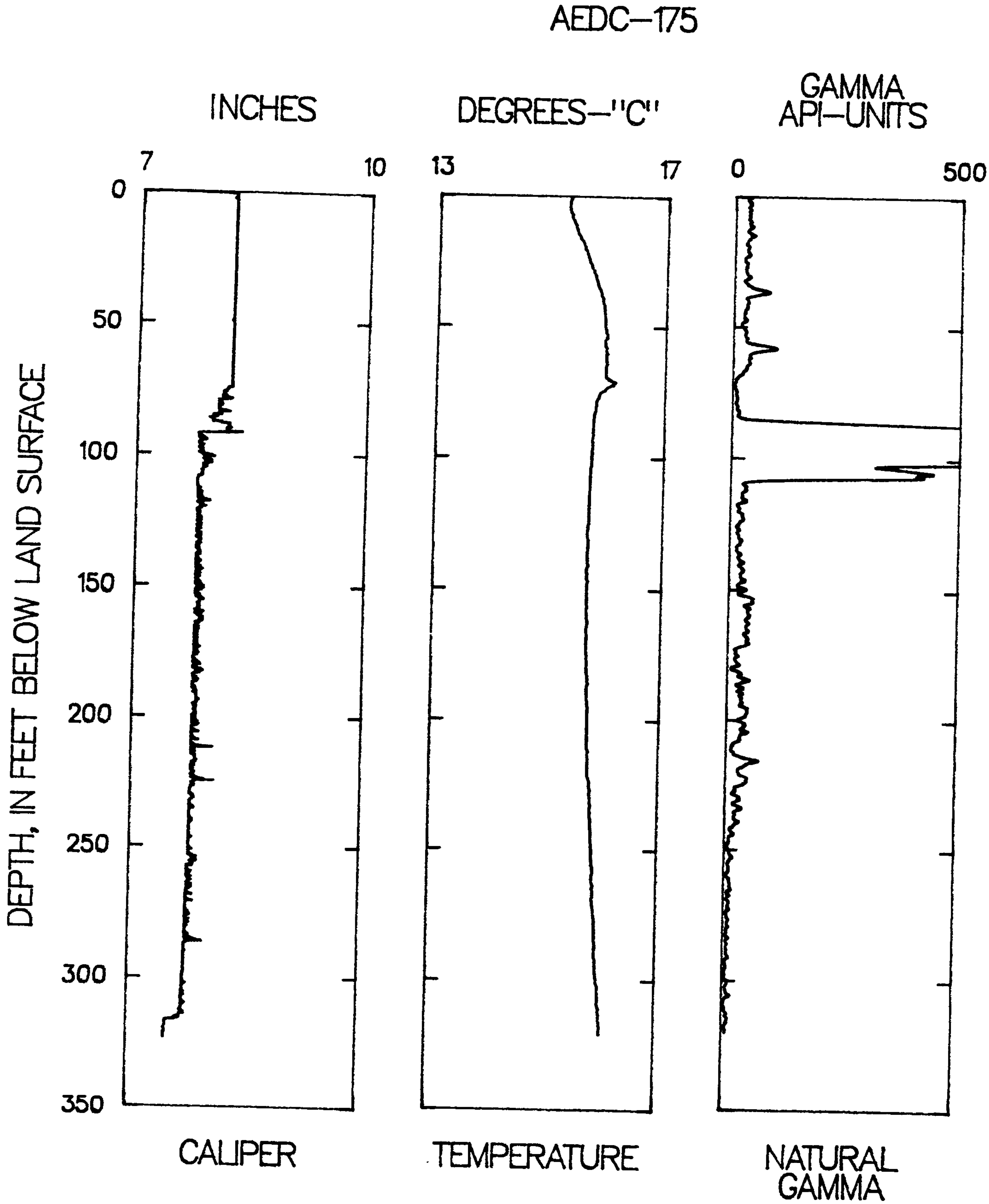
Electric logs for wells AEDC-172.

AEDC-175

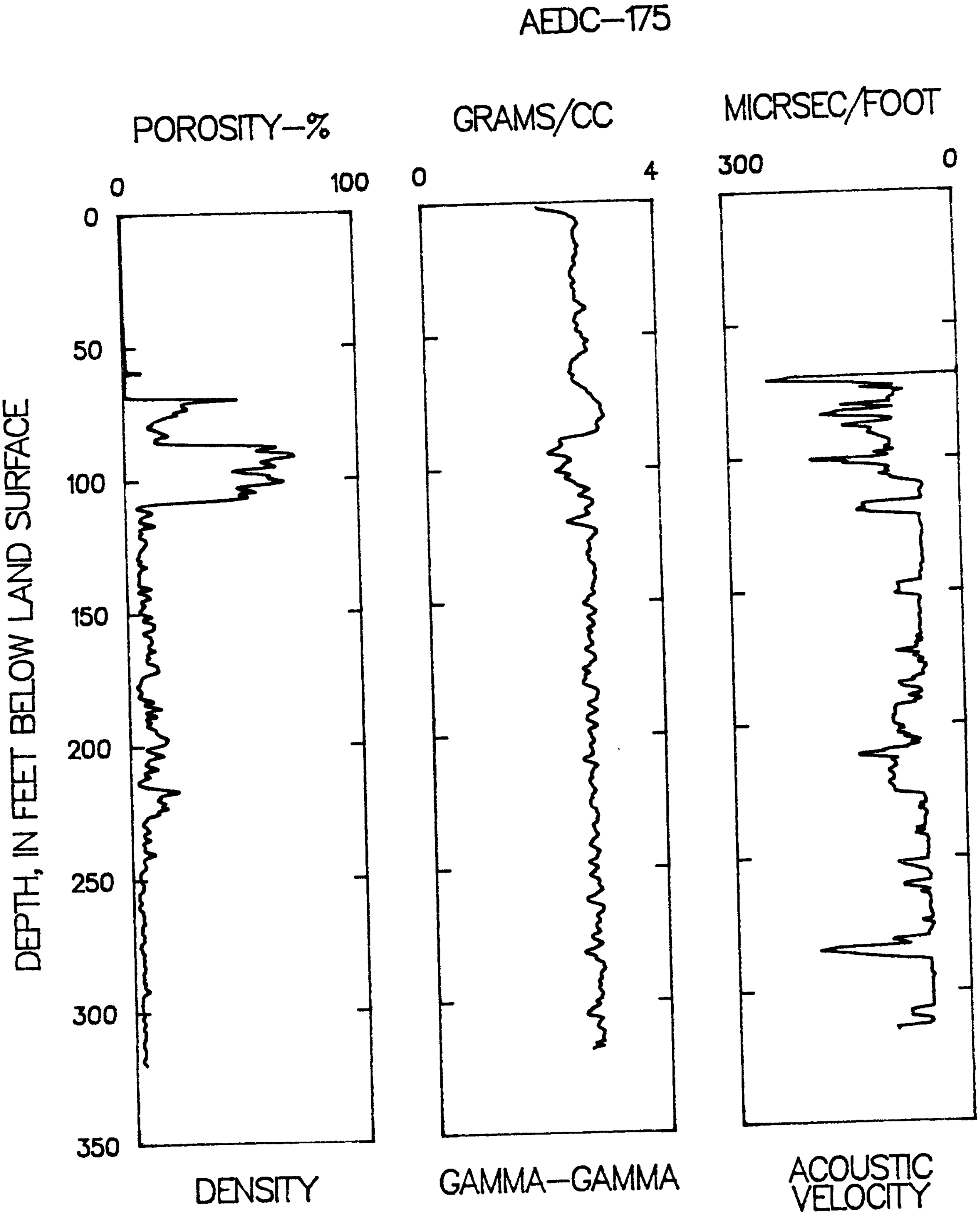


LITHOLOGY LAND SURFACE / DEPTH, IN FEET	DESCRIPTIONS	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Red clay matrix, rubbble.	
20	Red clay, rubble, and chert.	
30	Large chert and rock fragments.	
40	Brown color, large chert and rock fragments.	
50	Mostly chert fragments.	
60	Chert rubble with rock fragments. (90% chert with some clay.)	Chert: 80% quartz, 20% siliceous fossiil fragments, ~1% hematite.
70	Chert fragments and rock rubble. Limestone at 71 feet.	
80	Light gray-green limestone. Fracture at 80.1 feet. Water at 84 feet.	Packstone: 70% calcite sparite, 30% matrix. Chert (at 84 feet): 60% quartz, 30% calcite, 10% matrix, ~1% hematite.
90	Chattanooga Shale at 86 feet, black shale containing minor amounts of pyrite.	
100		Shale: Clay minerals, quartz, pyrite, black matrix material.
110	Dense dark and light gray limestone at 108 feet.	
120	Medium to dark gray limestone, minor chert, calcite, and fossil fragments.	Wackestone: 55% bioclasts, 30% calcite spar cement, 10% matrix, 5% pyrite.
130	Medium gray limestone, no fossils.	Wackestone: 60% bioclasts, 35% calcite spar cement, 5% pyrite.
140	Dark gray limestone.	
150	Medium gray limestone, fine-grained, intermixed with green shaley limestone, calcite specs, and some shale.	
160		Wackestone: 70% bioclasts, 30% calcite spar cement, ~1% quartz, <1% pyrite.
170		
180		
190	Light to medium gray limestone, green limestone, some calcite.	
200	Medium green-gray shaley limestone.	
210	Light gray limestone, some fossils.	
220	Dark gray shaley limestone.	
230	Medium to light gray fossiliferous Ordovician limestone (brachiopods and bryozoans), some limestone easily breakable, shale-like. Some calcite specs.	Wackestone: 65% bioclasts, 30% calcite spar cement, 5% quartz, ~1% pyrite.
240		
250		Packstone: 70% calcite sparite, 20% quartz, 10% matrix, ~1% pyrite.
260		
270		
280		Packstone: 80% calcite sparite, 15% quartz, 5% bioclasts.
290		
300		Wackestone: 70% bioclasts, 25% calcite spar cement, 5% pyrite, <1% quartz.
310		Wackestone: 60% bioclasts, 40% calcite spar cement, ~1% pyrite.
320	Bottom of hole at 320 feet.	

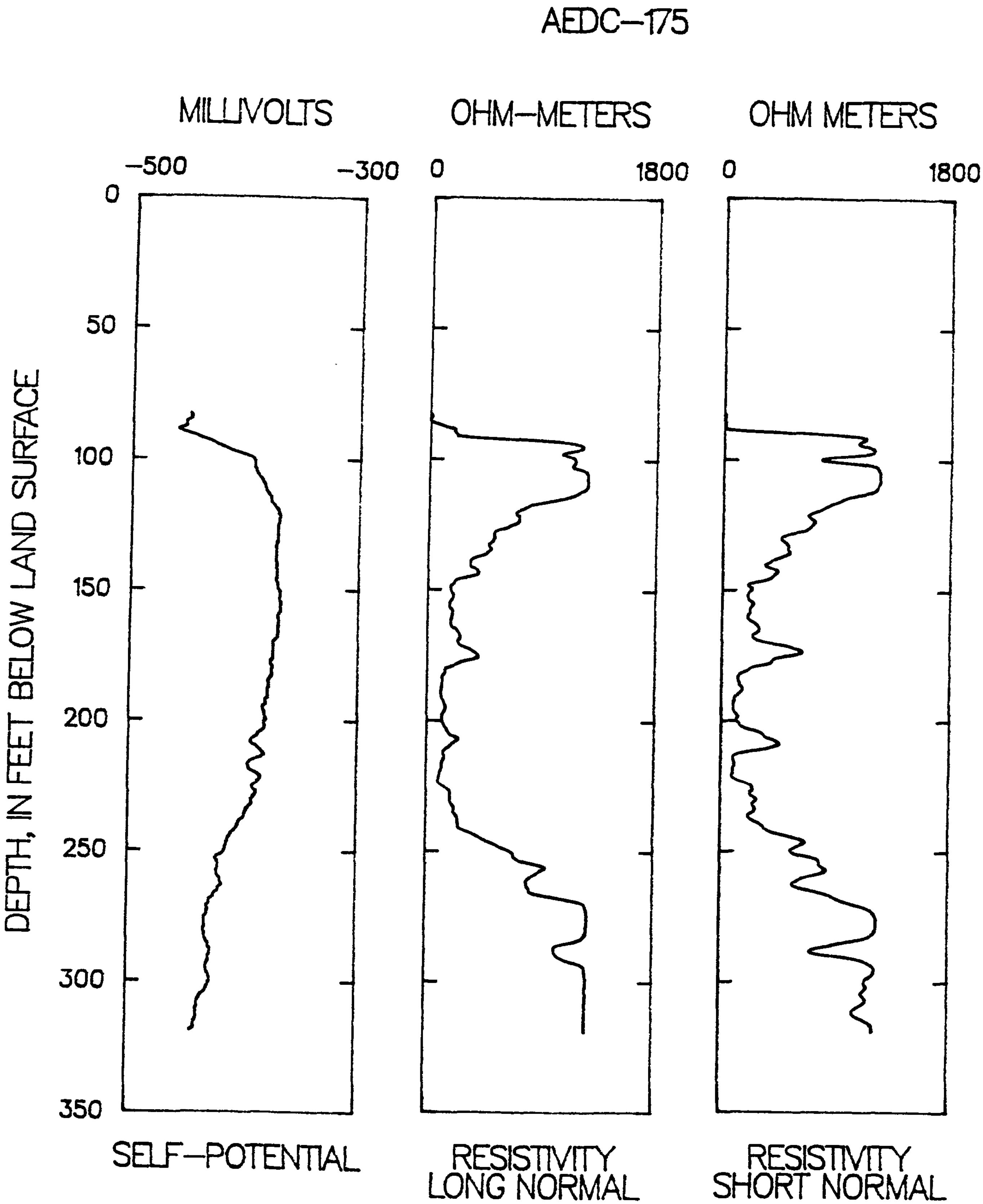
Lithologic descriptions and rock sample analysis for well AEDC-184.



Caliper, temperature, and natural gamma logs for well AEDC-175.



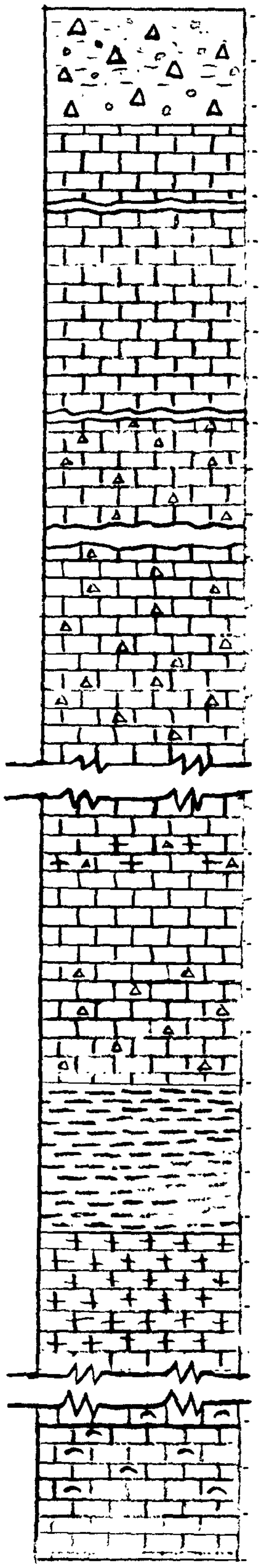
Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-175.



Electric logs for wells AEDC-175.

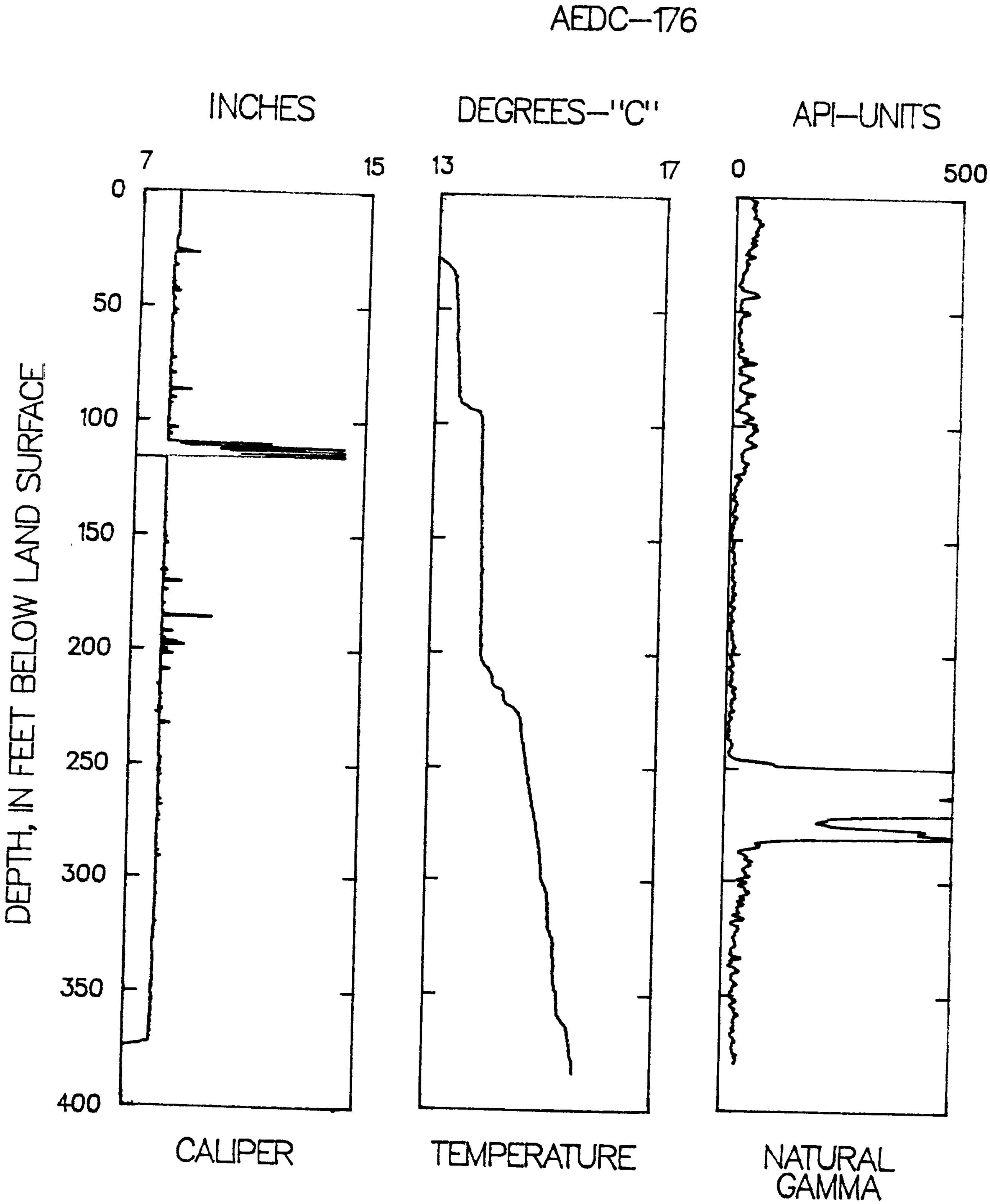
AEDC-176

LITHOLOGY LAND SURFACE

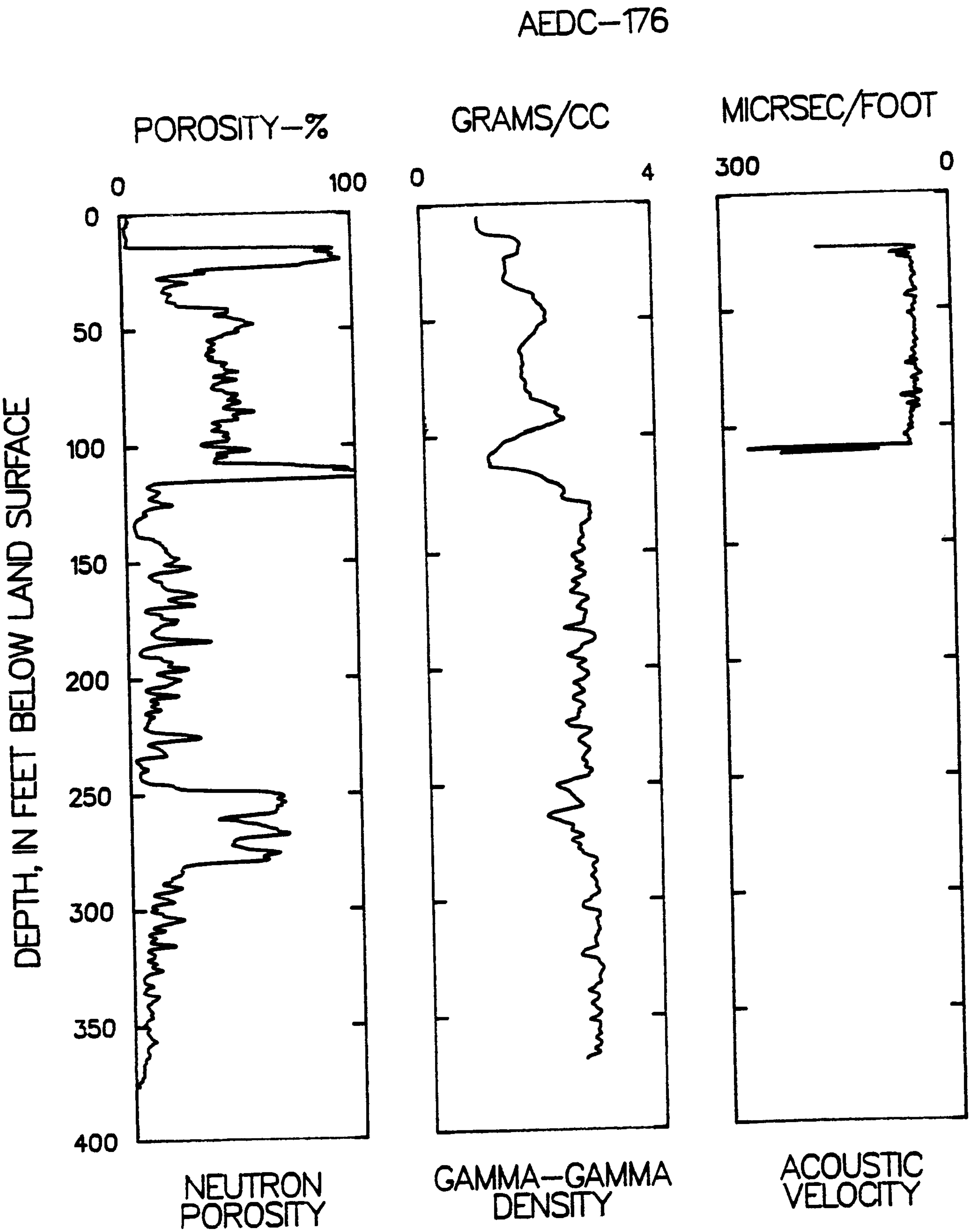


DEPTH, IN FEET	DESCRIPTION	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Mud, chert, and gravel.	
20	Chert and gravel.	Chert (at 22 feet): 85% quartz, 10% siliceous fossil fragments, 5% hematite.
30	Fort Payne limestone at 24 feet. Medium to light gray shaley limestone.	Wackestone: 70% bioclasts, 30% calcite spar.
40	Fracture at 41 feet.	
50	Medium gray limestone, coarse-grained.	
60		Wackestone: 60% bioclasts, 30% calcite spar cement, 10% quartz, ~1% pyrite.
70		
80		
90	Fractured limestone at 88-90 feet. Medium to dark gray limestone, some chert.	Wackestone (at 88 feet): 75% bioclasts, 20% calcite spar cement, 5% quartz, ~1% pyrite.
100		Chert: 65% quartz, 30% matrix, 5% hematite.
110	Fractured limestone at 110-118 feet, 4 foot cavity at 112-118 feet.	
120	Medium to light gray limestone, chert.	
130		
140	Cherty, medium to light gray limestone with calcite specs.	
150		Packstone: 65% calcite sparite, 35% matrix, <1% pyrite.
160	Light gray, fine-grained limestone, calcite and rock fragments.	
190		Packstone: 95% calcite, 5% matrix, <1% pyrite.
200	Light gray limestone, some shaley limestone, chert, some calcite.	
210		
220		
230	Dark to medium gray fine-grained limestone, chert, and calcite.	
240		
250	Chattanooga Shale at 252 feet. Sulfur odor.	Chert: 80% quartz, 15% matrix, 5% hematite. Shale: Clay minerals, quartz, pyrite, black matrix material.
260	Black shale, some green shale.	
270		
280	Light gray limestone at 284 feet.	Shale: Clay minerals, quartz, pyrite, black matrix material.
290	Dark gray shaley limestone.	
300	Green fine-grained limestone, mixed with gray limestone, calcite specs, and quartz pieces.	
310		Packstone: 85% calcite sparite, 10% matrix, 5% quartz, ~1% pyrite.
350	Dark and medium gray fossiliferous limestone, calcite pieces.	Wackestone: 60% bioclasts, 40% calcite spar cement, <1% quartz, <1% pyrite.
360		
370		
380	Bottom of hole at 384 feet.	Wackestone: 50% bioclasts, 50% calcite spar cement.

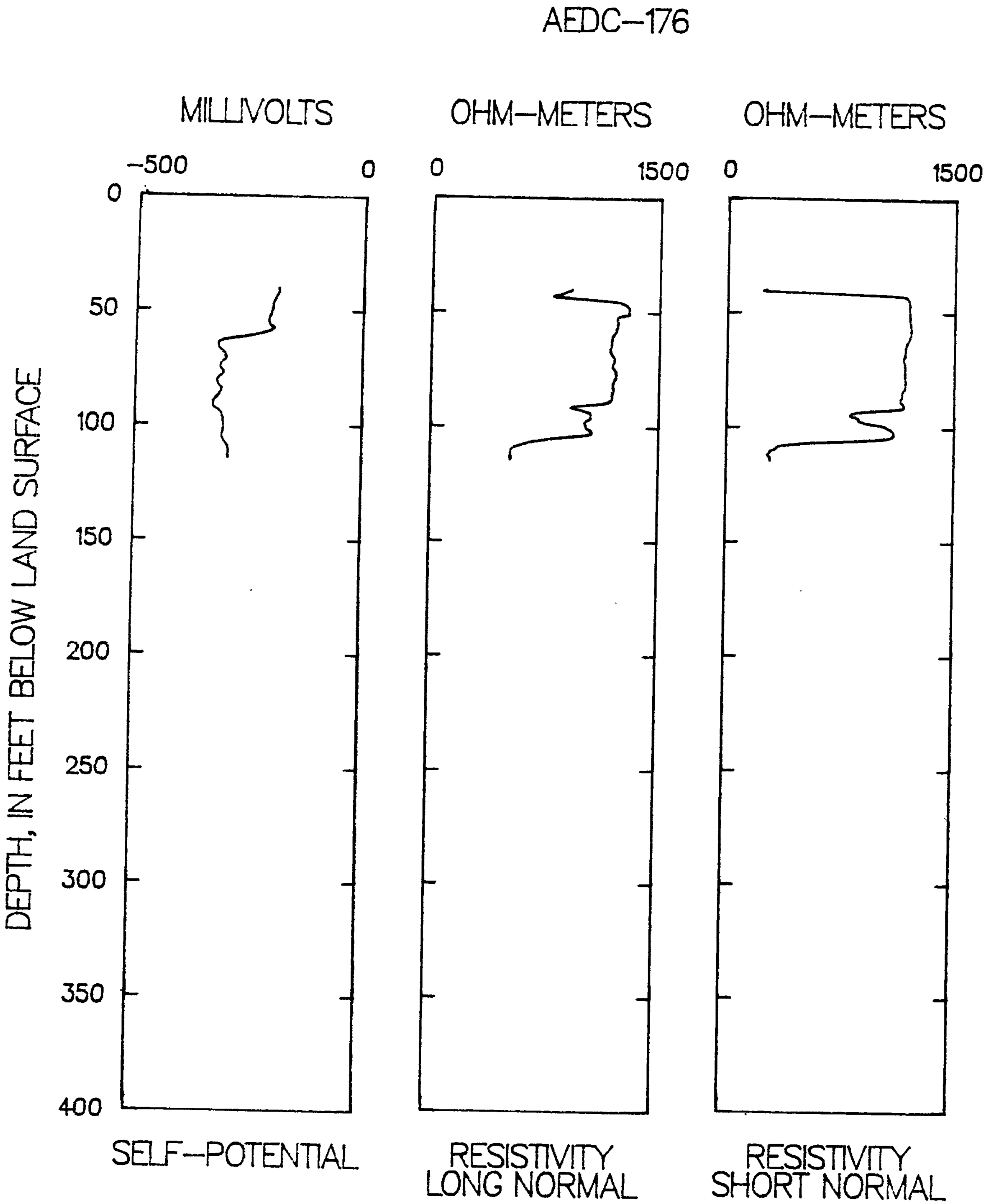
Lithologic descriptions and rock sample analysis for well AEDC-187.



Caliper, temperature, and natural gamma logs for well AEDC-176.



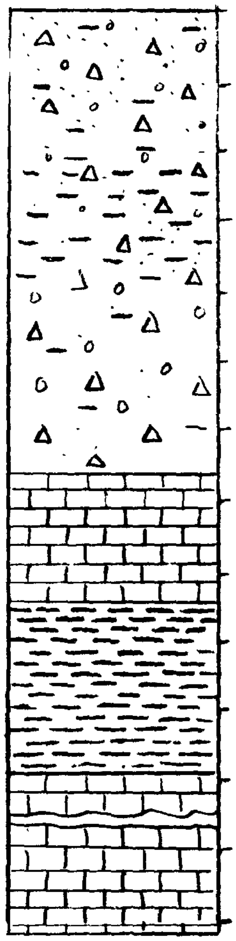
Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-176.



Electric logs for well AEDC-176.

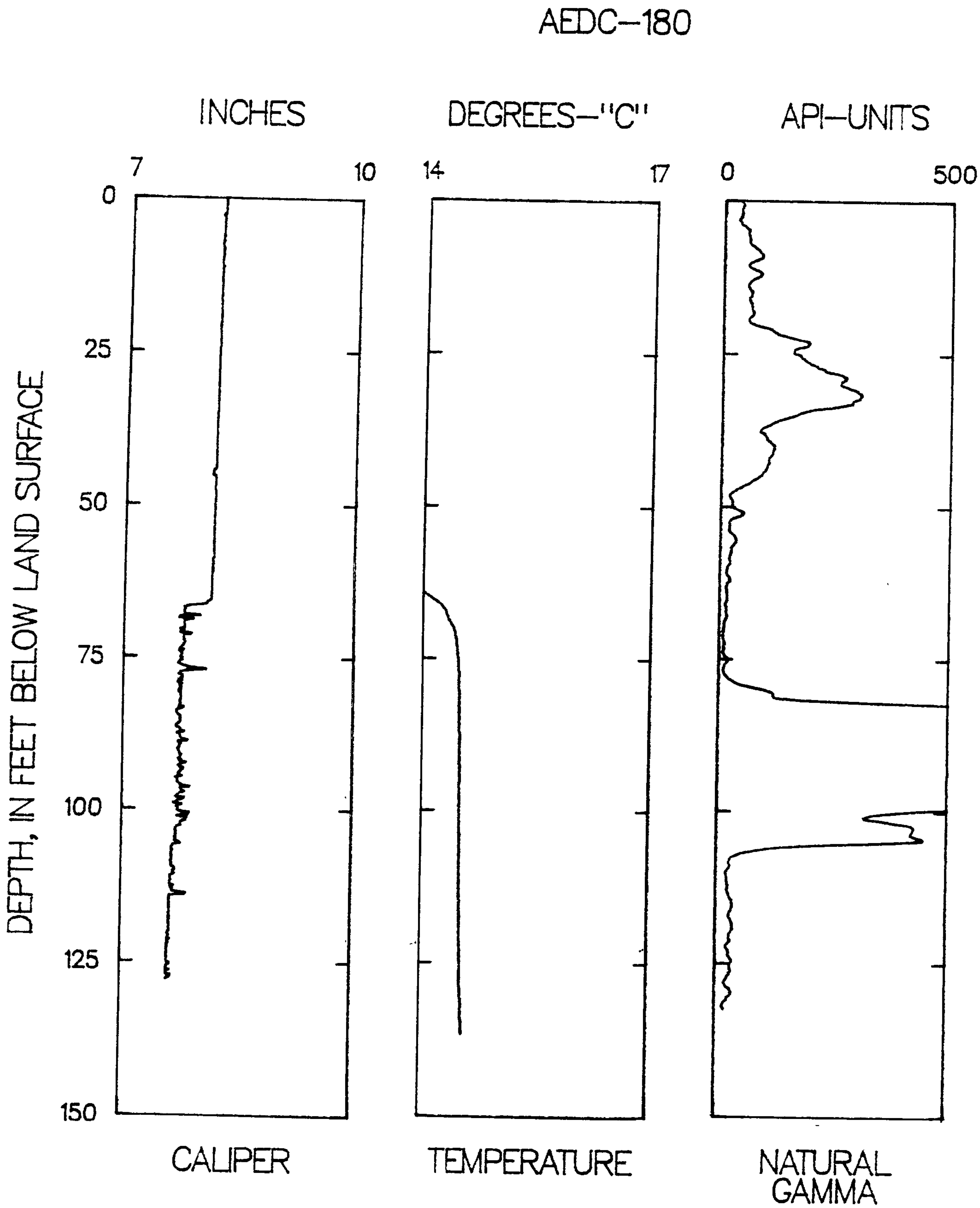
AEDC-180

LITHOLOGY LAND SURFACE

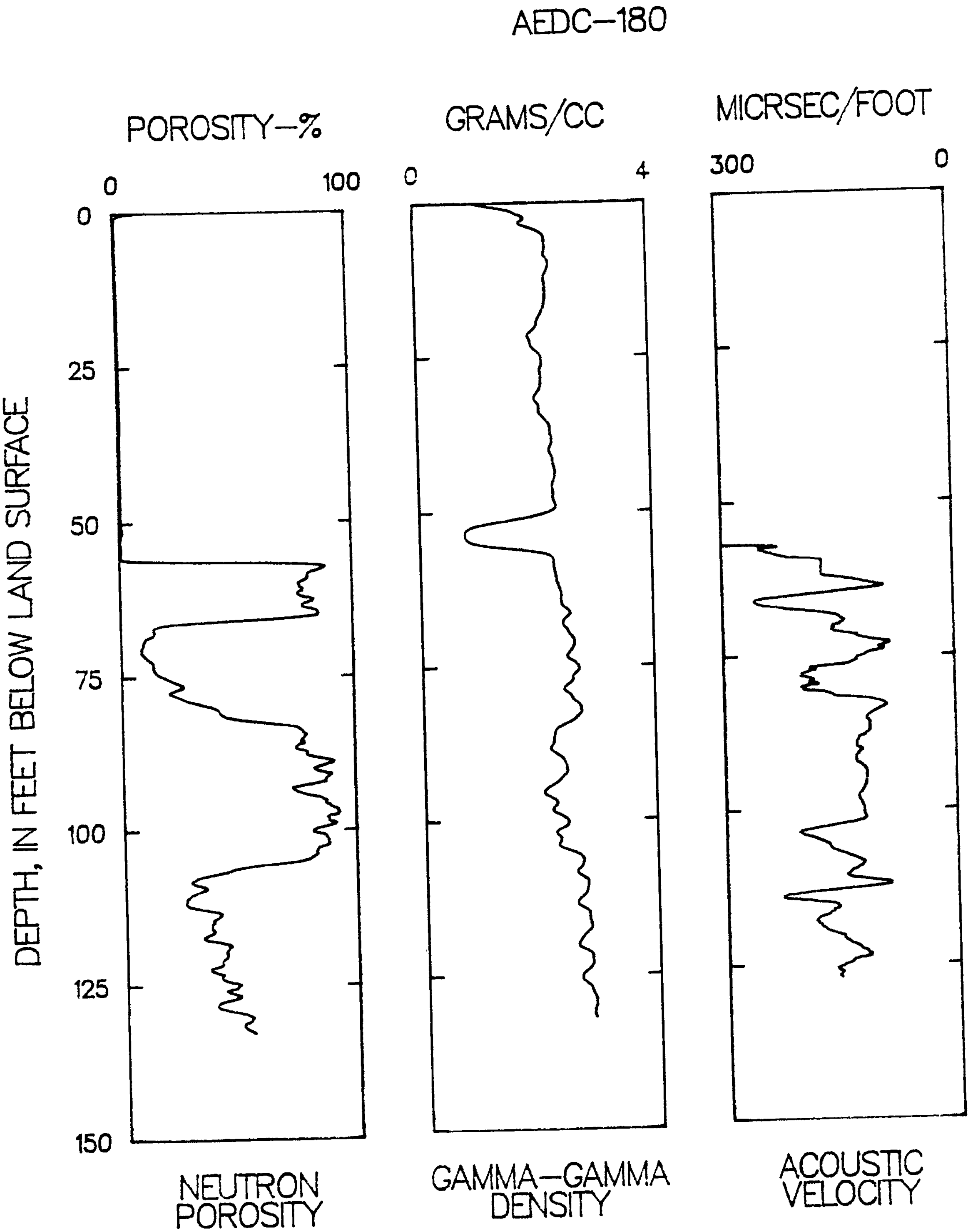


DEPTH, IN FEET	DESCRIPTIONS	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Rock and chert fragments, gravel mixed in a red-brown clay matrix.	Chert: 90% quartz, 5% matrix, 5% hematite.
20		
30		Chert: 85% quartz, 10% matrix, 5% hematite.
40	Higher chert content in matrix from 40 to 64.5 feet.	
50		
60	Light gray, fine-grained limestone. Changes to dark gray shaley limestone.	Chert: 85% quartz, 10% matrix, 5% hematite.
70		Wackestone: 30% bioclasts, 70% calcite spar cement.
80	Chattanooga Shale at 83 feet, black shale, strong sulfur odor.	Chert (at 183 feet): 90% quartz, 5% matrix, 5% hematite.
90		
100		Packstone: 60% calcite sparite, 20% matrix, 20% quartz, <1% pyrite.
110	Dark to light gray fine-grained Ordovician limestone at 108 feet.	Packstone: 75% calcite sparite, 20% quartz, 5% matrix, <1% pyrite.
	Hit fractured limestone at 115 feet.	
120		
130	Medium gray limestone, some calcite. Bottom of hole at 131 feet.	Wackestone: 40% bioclasts, 50% calcite spar cement, 10% matrix, <1% pyrite.

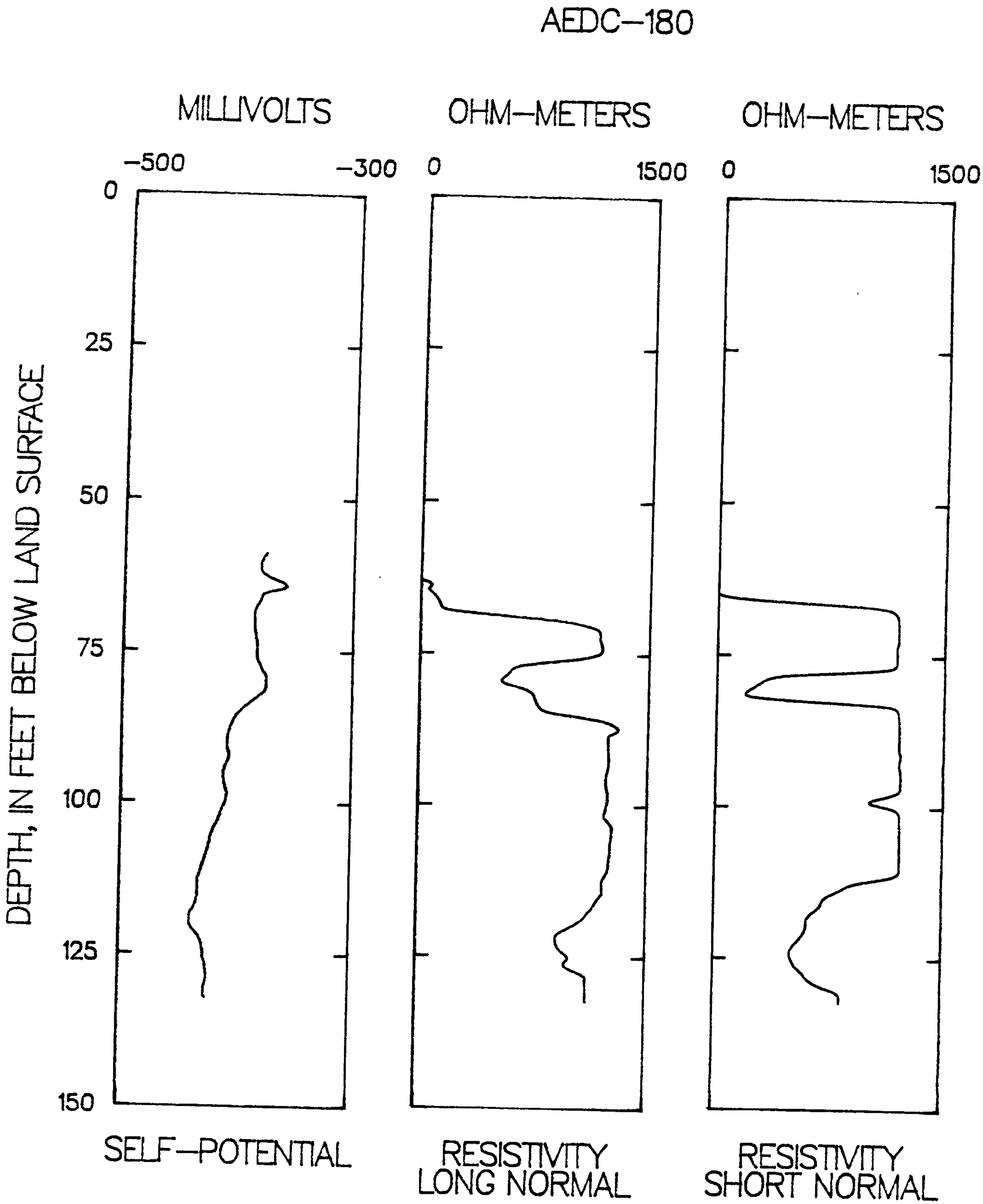
Lithologic descriptions and rock sample analysis for well AEDC-180.



Caliper, temperature, and natural gamma logs for well AEDC-180.

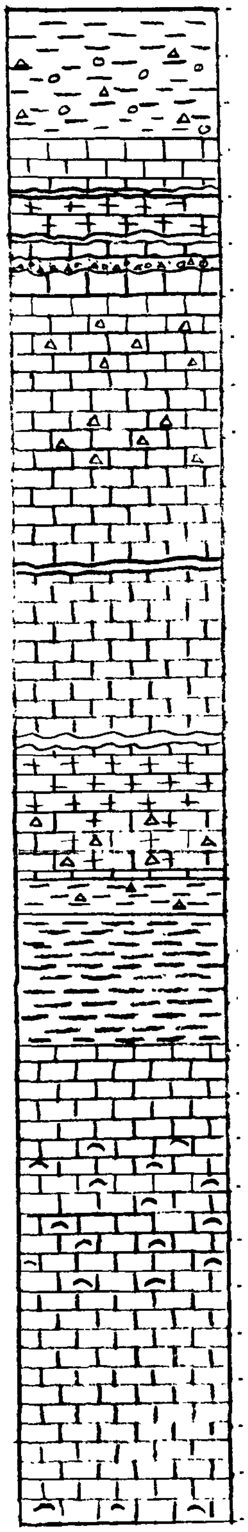


Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-180.



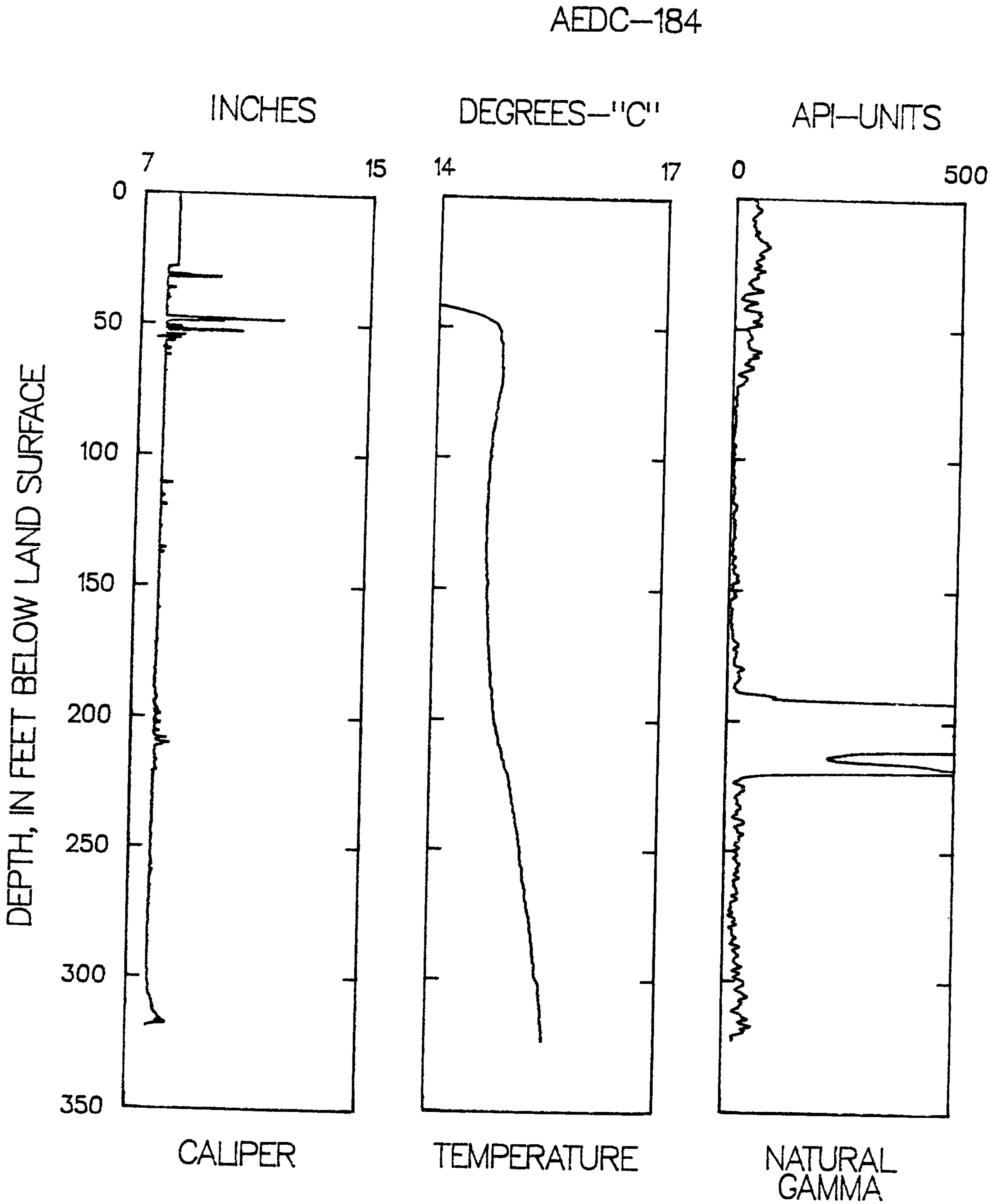
Electric logs for well AEDC-180.

AEDC-184

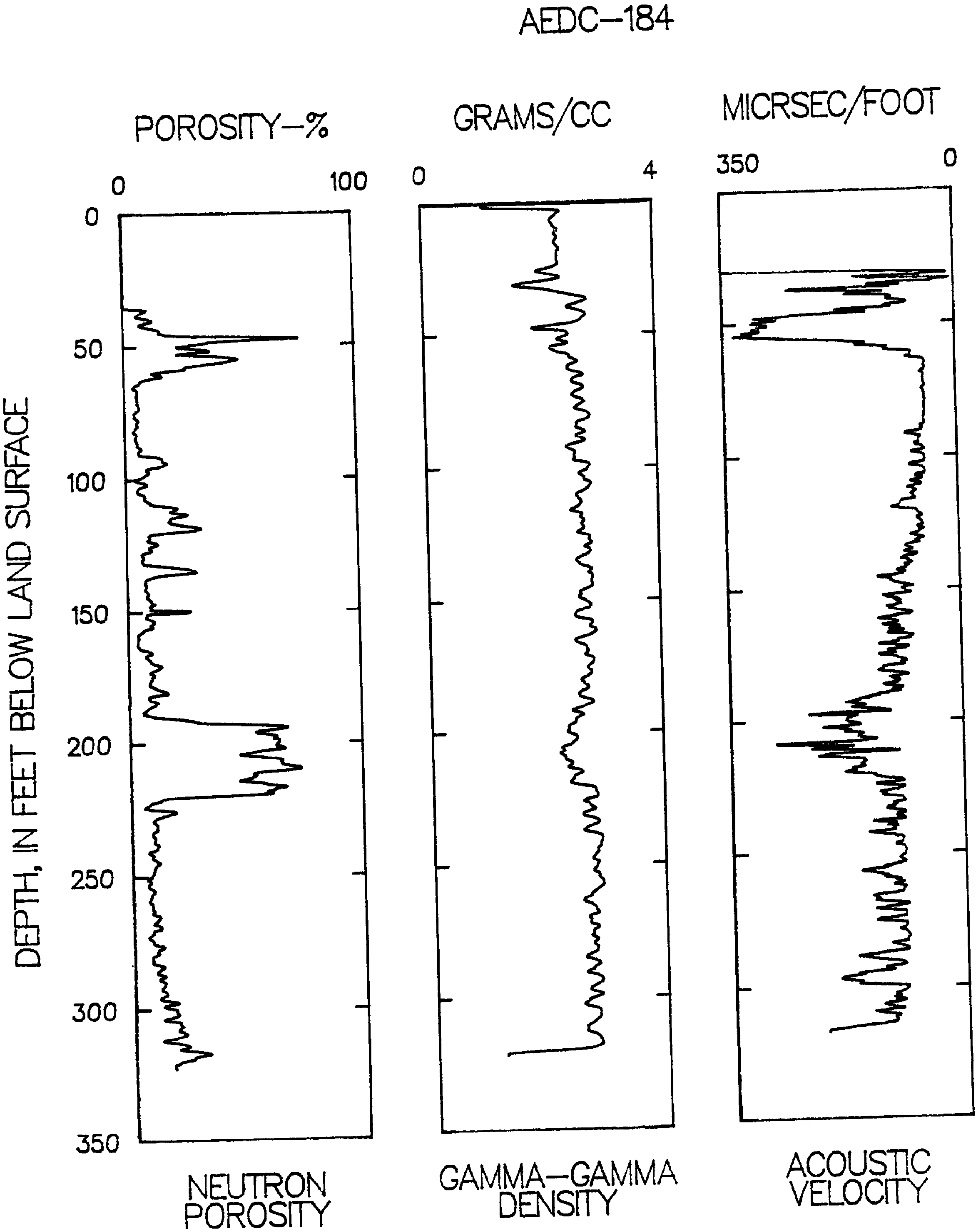


LITHOLOGY LAND SURFACE / DEPTH, IN FEET	DESCRIPTION	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Brown-red clay with chert and rock fragments.	
20		Chert: 95% quartz, 5% hematite.
30	Limestone at 27 feet. Medium gray limestone. Hit fracture at 38 feet (5 gpm).	Packstone: 80% calcite sparite, 20% matrix, ~1% pyrite.
40	Shaley, light to medium gray limestone. Hit fracture at 48 to 49 feet (25-30 gpm).	
50	Fracture at 50 to 54 feet. Mud, rock fragments, chert, and rubble included within fracture.	
60		
70	Light to dark gray limestone, chert.	
80	Medium gray limestone, rock fragments.	
90	Light to medium gray limestone, chert, calcite.	
100		
110		
120	Hit fractured limestone at 118 to 118.5 feet (40 gpm).	
130		
140		
150	Sulfur odor. Fracture at 152 feet.	Wackestone: 40% bioclasts, 50% calcite spar cement, 10% quartz, <1% pyrite.
160	Medium gray shaley limestone.	
170	Dark gray limestone, 50% chert, some green shale.	Wackestone: 50% bioclasts, 30% calcite spar cement, 20% quartz.
180	Green shale at 183 feet, limestone fragments and chert specs.	Wackestone (at 183 feet): 30% bioclasts, 70% calcite spar cement.
190		
200	Chattanooga Shale at 191 feet, black shale with sulfur odor.	Shale: Clay minerals, quartz, pyrite, black matrix material.
210		
220	Ordovician limestone at 219 feet. Dark to light gray fossiliferous limestone (brachiopods).	
230		
240		Wackestone: 50% bioclasts, 45% calcite spar cement, 5% pyrite.
250		
260		
270		Wackestone: 60% bioclasts, 40% calcite spar cement, 5% pyrite.
280	Medium to light gray limestone, some calcite, some fossils.	
290		
300		
310		
320	Bottom of hole at 320 feet.	Wackestone: 50% bioclasts, 50% calcite spar cement, ~1 pyrite.

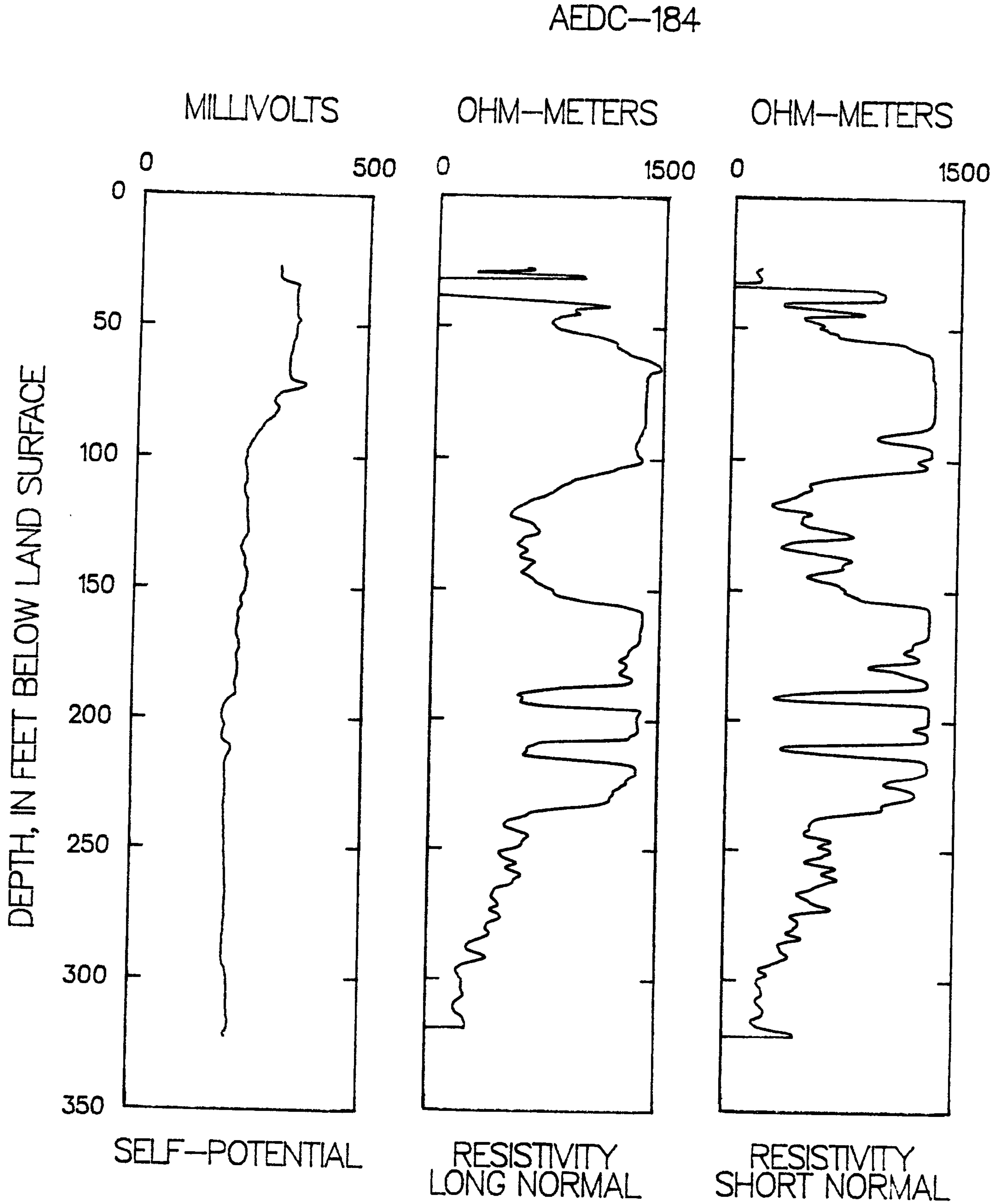
Lithologic descriptions and rock sample analysis for well AEDC-184.



Caliper, temperature, and natural gamma logs for well AEDC-184.



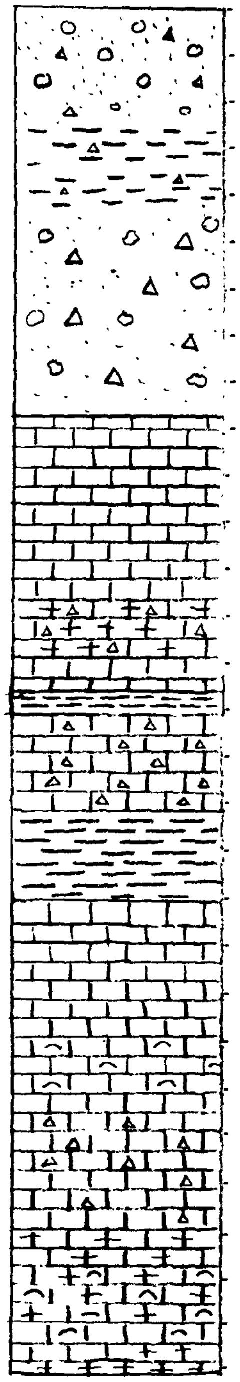
Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-184.



Electric logs for well AEDC-184.

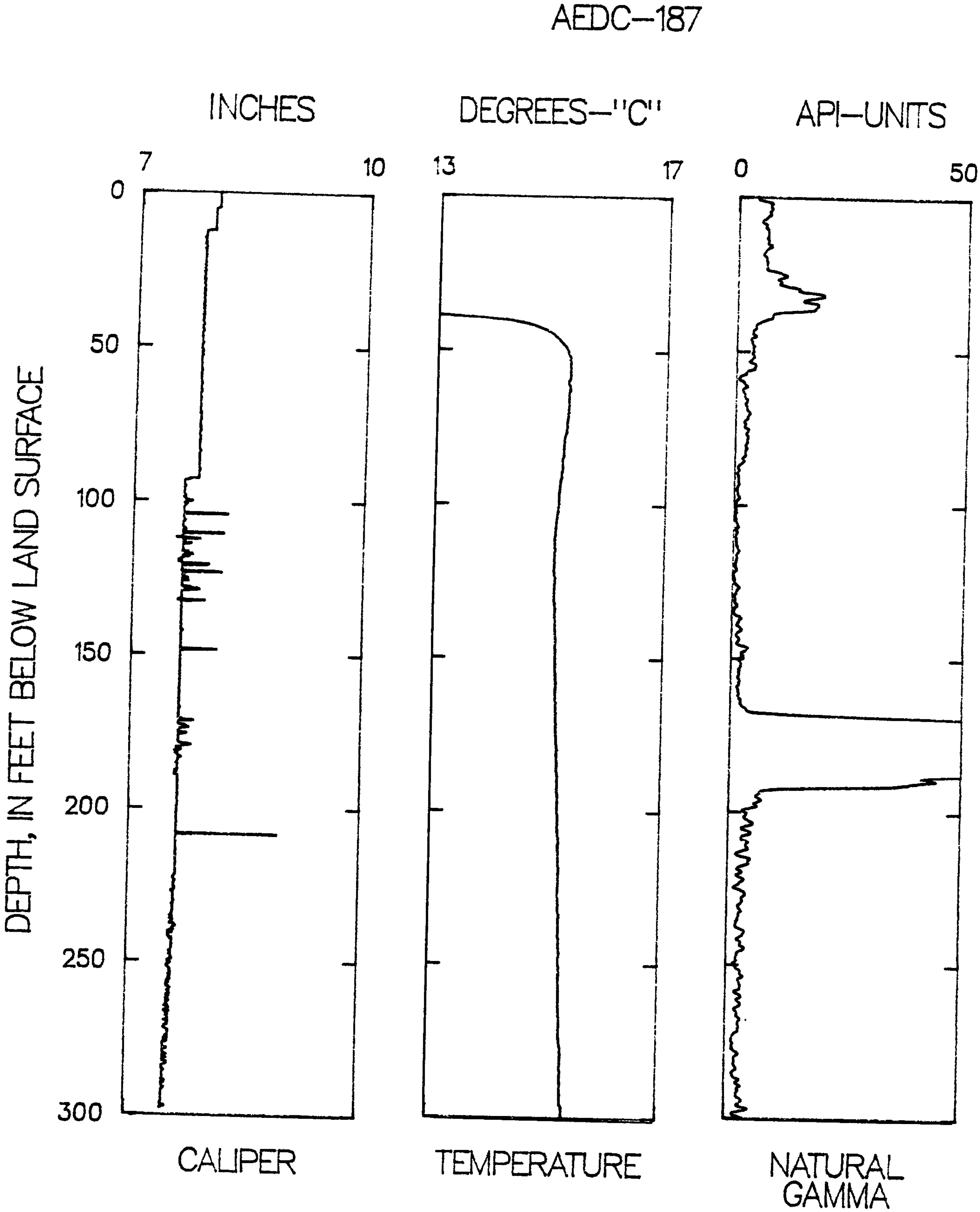
AEDC-187

LITHOLOGY LAND SURFACE

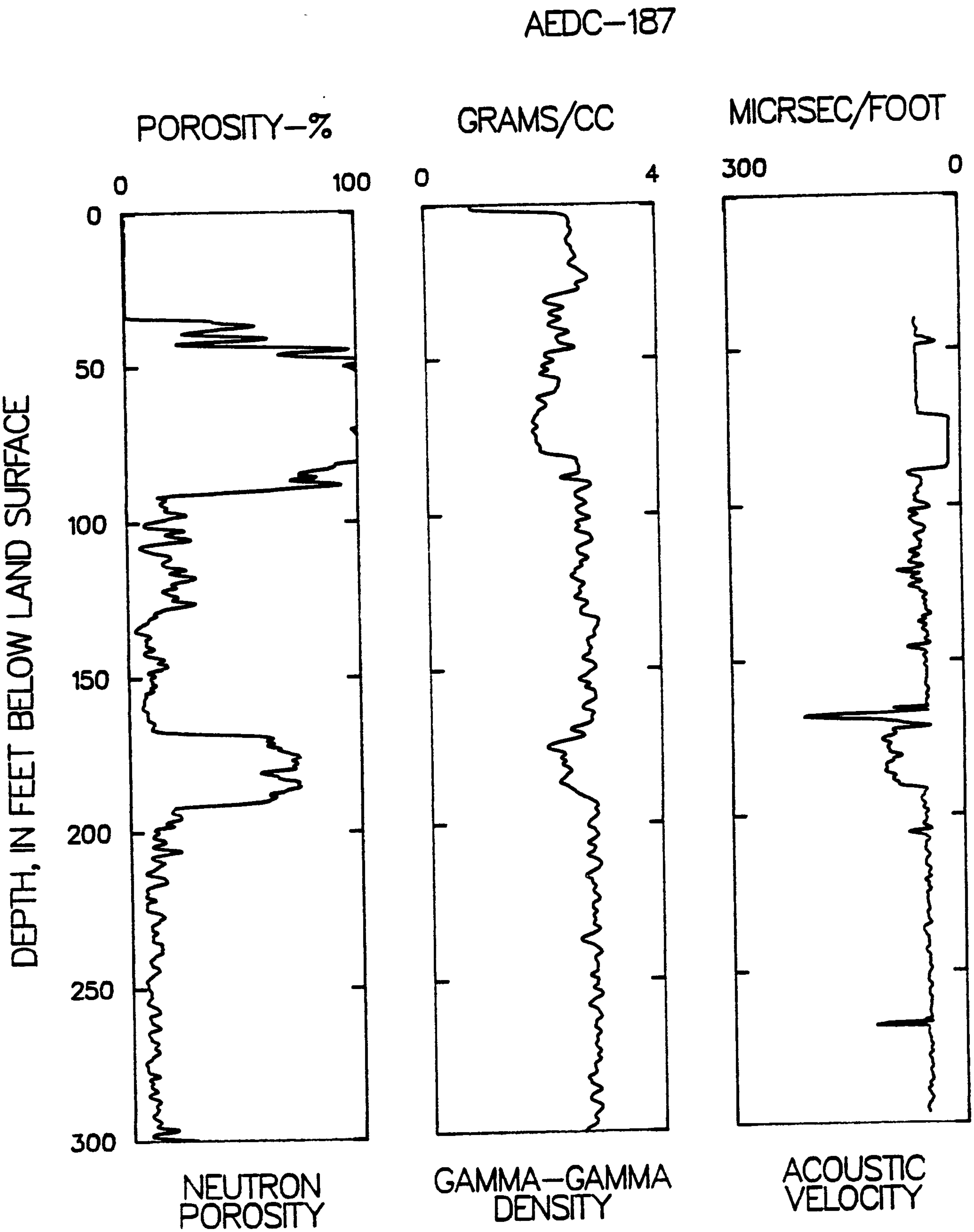


DEPTH, IN FEET	DESCRIPTION	ROCK SAMPLE ANALYSIS, IN PERCENT (%)
0		
10	Red-brown clay matrix containing rock rubble, sand, and chert.	
20		Chert: 85% quartz, 10% matrix, 5% hematite.
30		
40		
50	Medium gray limestone rock fragments with chert.	Chert: 70% quartz, 20% matrix, 10% hematite.
60		
70		
80		
	Hit limestone rock at 86 feet.	
90	Olive-gray limestone, micritic, some quartz fragments, sulfur odor.	Chert: 85% quartz, 10% matrix, 5% hematite.
100		
110		
120		Packstone: 95% calcite sparite, 5% matrix, <1% hematite.
130	Olive-gray chert and limestone, some clay, sulfur odor.	
140	Dark gray limestone, calcite crystals, green and black shale at 146 feet.	Wackestone: 35% bioclasts, 60% calcite spar cement, 5% hematite.
150	Olive-gray limestone and chert, few quartz chips.	
160	Green limestone, olive-gray chert, strong sulfur odor.	Wackestone: 50% bioclasts, 40% calcite spar cement, 10% quartz, <1% pyrite.
170	Chattanooga Shale.	
180		
190	Dark gray limestone at 189 feet.	Packstone (at 192 feet): 60% calcite sparite 20% matrix, 20% calcite vugs, <1% pyrite.
200	Olive-green to gray limestone, calcite chips.	Packstone: 65% calcite sparite, 15% matrix, 20% calcite vugs.
210		
220	Olive-gray limestone, some calcite, fossils.	Wackestone: 50% bioclasts, 30% calcite spar cement, 10% quartz, 10% matrix.
230	Olive-gray micritic limestone.	
240	Light to dark gray limestone, coarse-grained, some chert.	
250		Wackestone: 80% bioclasts, 20% calcite spar cement, <1% pyrite.
260	Light coarse to dark shaley limestone, some calcite specs.	Wackestone: 60% bioclasts, 40% calcite spar cement, <1% pyrite.
270	Medium gray coarse to dark gray shaley limestone, minor calcite specs and fossils (brachiopods).	Wackestone: 65% bioclasts, 35% calcite spar cement, <1% pyrite.
280		Wackestone: 80% bioclasts, 20% calcite spar cement, <1% pyrite.
300	Green shaley limestone. Bottom of hole at 300 feet.	Wackestone: 50% bioclasts, 50% calcite spar cement, <1% pyrite.

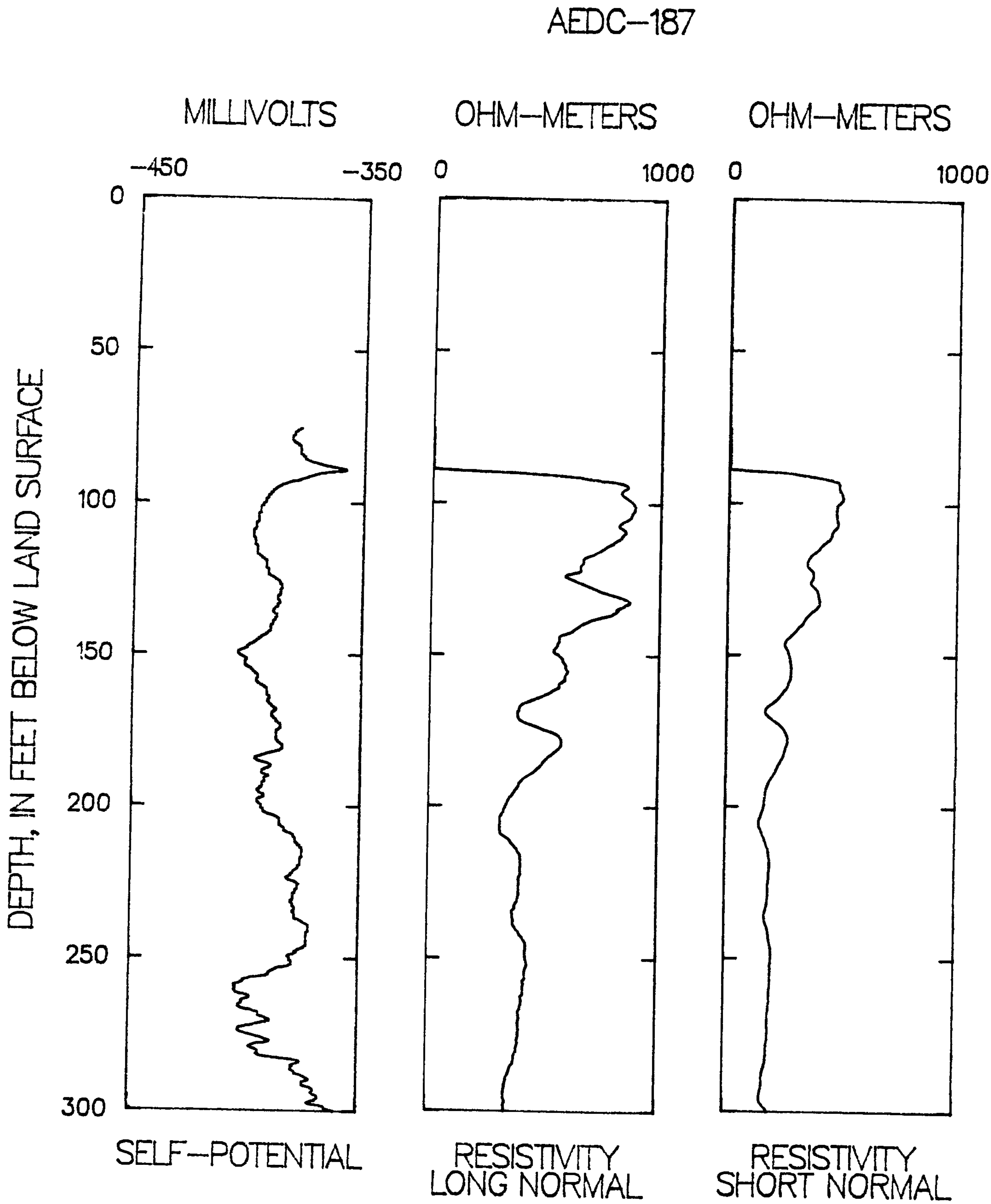
Lithologic descriptions and rock sample analysis for well AEDC-187.



Caliper, temperature, and natural gamma logs for well AEDC-187.



Neutron, gamma-gamma, and acoustic velocity logs for well AEDC-187.



Electric logs for well AEDC-187.