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Near-Surface Resistivity Variations on Kahoolawe Island, Hawaii

By

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Introduction

Kahoolawe Island has been used as a military target range since World War II and contains many types of unexploded ordnance at or near the surface. The U.S. Department of the Navy wishes to develop the technology to identify and locate ordnance hidden below the surface. To do this requires knowledge of the physical properties and their variations in the regolith and near-surface rocks in which the ordnance might be buried. During June 1981 a team of U.S. Geological Survey personnel spent five days on Kahoolawe Island to assist in defining the physical properties of the upper few meters of regolith and rock on the island. This report presents studies of the electrical resistivity of these materials. The work was funded by the Navy's Naval Explosive Ordnance Disposal Technology Center, Indian Head, Maryland, under military interdepartmental purchase request no. N0464A81MP00075.

Kahoolawe Island is located in the State of Hawaii about 11.5 km (7 miles) southwest of Maui (Figure 1). The island is 18 km (11 miles) long by 10 km (6 miles) across at its widest point. The summit of Lua Makika crater, the highest spot on the island, has an elevation of 450 m (1477 ft). On the summit of the island wind erosion has stripped most of the soil down to a brick-red partially indurated surface. This erosion was the result of overgrazing by livestock during the 1800's. The island is semi-arid, having an annual rainfall of about 24 inches (Stearns, 1940). There are no sources of potable water on the island.

Stearns' (1940) report is the last known published study of the geology of the island. He lists the principal rock units as late Tertiary or early Pleistocene pre-caldera basalts, caldera-filling basalts and basaltic andesites, post-caldera basalts and andesites, and Holocene basalts. He also noted a few thin vitric tuff beds. One such bed we observed exposed in the sides of gullies near site 2 (approximately 20°32'25" N. lat, 156°34'50" W. long). Post-caldera flows cover most of the surface and represent the bedrock in the areas we studied.

Electrical Measurements

Three separate electrical techniques were used to measure the resistivity of the upper few meters of earth on Kahoolawe: Schlumberger vertical electrical soundings using direct current; loop-loop electromagnetic measurements made at 39.2 kHz using a Geonics EM-31 system*; and electromagnetic resistivity measurements system made at 24.3 kHz using a Geonics EM-16 system*. Most work was done with the EM-31 system because measurements could be made rapidly at two exploration depths. This system permitted us to sample several different lithologies so as to assess the statistical variation of resistivity in the areas of interest to the Navy. We considered it important to obtain a fairly large number of measurements because we expected a very wide range of resistivities of the near-surface materials (Zohdy and Jackson, 1969; Hussong, 1967; Mattice, 1981).

Data sites are indicated in figure 1, which uses the USGS Kahoolawe 1:62,500 topographic map as a base. Reference is also made to locations shown on the U.S. Department of Defense Kahoolawe Training Area map, which is not reproduced in this report. In an attempt to sample a wide range of surficial deposits, measurements were made at five distinct areas on the island, numbered 1 to 5 in figure 1. Site no. 1, located at the Smugglers Cove (Hanakanaea), was on beach sand about 1 m above sea level, near archeological site 131 shown on the Kahoolawe Training Area map. This site is adjacent to the housing facilities.

*Use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Site 2 was within archeological site 110 at the upper end of a dry stream which reaches the sea by Kuakaiwa Point (Lae O Kuakaiwa). This site was at an elevation of approximately 335 m (1100 ft). Exposures in the gulch adjacent to the measuring site showed that the flows are essentially flat lying and include a vitric tuff at a depth of about 6.1 m (20 ft). Soil had been stripped from the surface down to a brick-red regolith, which was devoid of vegetation. Boulders in the surface adjacent to the wash showed extremely thick weathering rinds exceeding several inches.

Site 3 is located along this same dry stream. A traverse we ran here started at a place called the Adz quarry, 350 m (1150 ft) south of site 2, and proceeded downstream. This traverse permitted sampling of relatively unweathered rock exposed in the bottom of the stream. The fourth major area sampled was along a traverse in Kaulana Gulch starting near Moaula cone and extending about 2 km (1.3 mi) towards the sea. A wide range of surficial materials was sampled on this traverse.

Site 5 is situated just south of Puu Moiwi cone at about 305 m (1000 ft) elevation in the central part of the island, where a large amount of ordnance has disturbed the ground and litters the surface. In this area most of the soil has been stripped from the surface.

EM-31 data

Tables 1 through 8 list the data obtained using the EM-31 conductivity measuring instrument. Measurements were made with both the horizontal and vertical coplanar coil configurations, which give nominal measurement of earth conductivity to 6 meters (20 ft) and 3 meters (10 ft), respectively. The tables also give the mean, standard deviation, and range for each group of data. Examination of these data shows only a small variation in resistivity across all sites measured. The minimum resistivities observed were 7.1 ohm-meters for the horizontal and 6.1 ohm-meters for vertical coplanar configuration. The maximum observed resistivities were 62 ohm-meters and 91 ohm-meters, respectively. The maximum and minimum readings were both obtained on the Kaulana Gulch traverse, site 4. The low readings were obtained at the site of an abandoned clay quarry northeast of Moaula cone and adjacent to the old ranch road. The high readings were obtained on a bench of fine-grained alluvium deposited in the upper part of Kaulana Gulch. Low resistivities were also observed on the beach at Smuggler's Cove, site 2, and are due to sea-water saturation of the beach sand. Mean horizontal coplanar resistivity was 31.2 ohm-meters and 43.3 ohm-meters for the vertical coplanar configuration. Tables 1 through 4 list the data for sites 1 through 4, respectively. At site 5, four separate detailed traverses were run, and they are listed separately in tables 5 through 8. Examination of tables 1 through 8 shows that for most measurement sites the resistivity decreases with depth, although some sites showed essentially no change with depth at the nominal 3- and 6-m (10- and 20-ft) exploration range.

Schlumberger VES data

Three symmetric Schlumberger vertical electrical soundings (VES) were made to obtain better detail on the variation of resistivity with depth. One sounding was made on the beach at Smugglers Cove (site 1), and the other two were made at site 5 south of Puu Moiwi cone. Current electrode spacing (AB) started at 0.6 m (2 ft) and was extended to a maximum of 60 meters except at Smugglers Cove, where difficulties with electrode emplacement in the loose sand made it necessary to start at 1.6 m (5 ft) AB. The field data are given in tables 9-11, and figures 2-4 show the adjusted field data and a one-dimensional inversion of those data generated by a computer program of Zohdy (1974, 1975). The results are consistent with the EM-31 data. The VES data, however, show that resistivities in the upper several meters can rise abruptly as the surface is approached. This increase can be related to the loss of water from capillary spaces near the surface. Intrinsic resistivities are interpreted to reach values as high as 400 ohm-meters in the upper 20 cm (8 in.) in sounding 1 at site no. 5.

EM-16 data

An EM-16R VLF electromagnetic unit was used for a limited number of measurements to obtain data in the VLF frequency range. Station NPM, Hawaii, at 24.3 kHz, was used as a source because of its large field strength on Kahoolawe. For the average near-surface resistivities observed and the 24.3-kHz operating frequency the skin depth is about 20 m (66 ft). Thus, the maximum exploration depth with this unit is about 10 m (33 ft).

Measurements with the EM-16R were made at Smugglers Cove and at site 5. The results, given in table 12, are consistent with the other data. At Smugglers Cove the data are noisy because such low values are barely within the measuring range of the instrument.

Discussion

The data show a very narrow range of resistivities, particularly in view of what was expected from prior work done in the Hawaiian Islands. Exposures were sought which would represent the extreme values, yet the total range of observed resistivities was barely an order of magnitude using the EM-31 unit. A range of at least 3 orders of magnitude was expected. Table 13, adapted from Mattice (1981), summarizes the resistivities for various lithologic units observed by previous investigators on other islands in the Hawaiian chain. Lithologies representative of the high-resistivity units observed on other islands were not observed on Kahoolawe. Because such lithologic units were sought and not found, we believe that if they exist on

Kahoolawe they are of very limited areal extent or at depths greater than 6 m (20 ft).

Resistivities particularly in the upper meter of regolith can be expected to show temporal variations associated with rainy periods and the infiltration of rain water. Most of the rain comes from "Kona" storms, which occur from November to April (Stearns, 1940). The rain would tend to decrease the resistivity in the shallow horizons.

The low resistivities observed on Kahoolawe make the detection of buried ordnance by electrical or electromagnetic means difficult because of the small conductivity contrast between host and target. This effect is illustrated by the data presented in table 6, which are detailed readings taken on a traverse over a 500-pound bomb which had been detected by a ground radar unit. The bomb was undetectable with the EM-31 unit. The EM-31, of course, is not optimally designed for detection of such targets. However, the relatively narrow range of observed resistivities means that "geologic noise" contributed by lateral earth resistivity changes is not as severe as it might be, and thus the signal-to-noise ratio for ordnance discrimination might be improved.

Although not directly related to the electrical measurements discussed above, it should be noted that the mineral alunite, $KAl_3(SO_4)_2(OH)_6$, was found while making the traverse along Kaulana Gulch. This is the first reported occurrence of the mineral in the Hawaiian Islands (oral communication, K. Pankiwskyj, Univ. of Hawaii). Alunite is a hydrothermal-alteration product of igneous rocks high in feldspar.

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Table 1

EM-31 data for the southeast end of the beach at site 1. Data measured at 10-ft (3-m) intervals on the periphery of a 100-ft (30-m) square area. Station 0-0 is at the northwest corner of the 100-ft (30-m) square, and station 100-100 is at the southeast corner.

Station No. East-South	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)	Station No. East-South	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)
0-0	10	11	100-90	9.1	10
0-10	10	11	100-80	9.3	9.2
0-20	10	10	100-70	9.7	9.1
0-30	10	10	100-60	10	10
0-40	10	10	100-50	12	11
0-50	10	10	100-40	11	12
0-60	10	10	100-30	12	12
0-70	9.1	9.1	100-20	12	12
0-80	8.7	8.3	100-10	12	12
0-90	8.9	8.3	100-0	12	12
0-100	8.9	8.5	100-0	12	12
10-100	9.3	9.3	90-0	12	12
20-100	10	11	80-0	11	12
30-100	9.2	12	70-0	12	13
40-100	9.7	13	60-0	12	12
50-100	10	13	50-0	12	13
60-100	9.3	12	40-0	12	13
70-100	10	11	30-0	12	13
80-100	9.4	10	20-0	12	13
90-100	8.7	9.1	10-0	12	12
100-100	8.9	9.3	0-0	10	11

Horizontal coplanar--mean = 10.2, standard deviation = 2.0, range = 8.7-12

Vertical coplanar----mean = 11.0, standard deviation = 1.5, range = 8.3-13

Table 2

EM-31 data for site 2, located within archaeological site 110 and 350 meters northwest of the Adz quarry. Data measured at 10-ft (3-m) intervals on periphery of a 100-ft (30-m) square area. Station 0-0 is at the northwest corner of the 100-ft (30-m) square, and station 100-100 is at the southeast corner.

Station No. East-South	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)	Station No. East-South	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)
0-0	25	38	100-100	33	50
0-10	26	38	100-90	33	48
0-20	29	42	100-80	33	48
0-30	29	44	100-70	34	48
0-40	29	44	100-60	33	46
0-50	28	48	100-50	31	42
0-60	29	48	100-40	31	44
0-70	29	46	100-30	30	42
0-80	29	46	100-20	30	42
0-90	30	42	100-10	29	40
0-100	29	46	100-0	30	42
0-100	29	46	100-0	29	37
10-100	31	46	90-0	29	37
20-100	33	48	80-0	29	38
30-100	32	48	70-0	29	38
40-100	32	50	60-0	29	38
50-100	32	48	50-0	29	37
60-100	32	50	40-0	27	37
70-100	32	46	30-0	28	38
80-100	34	48	20-0	29	37
90-100	32	48	10-0	28	38
100-100	33	48	0-0	28	38

Horizontal coplanar - mean = 30.1, standard deviation = 2.1, range = 25-34

Vertical coplanar - mean = 43.5, standard deviation = 4.5, range = 37-50

Table 3

EM-31 data for site 3. Stations are located along a traverse from the Adz quarry south, along and within a dry wash. Measurements were made at intervals of approximately 50 m to station 19, after which a 3-m (10-ft) interval was used.

Station	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)	Remarks
1	30	48	Upper bench at Adz quarry
2	25	37	
3	12	18	
4	17	24	In bed of wash
5	10	14	At lower edge of vertical face
5	10	14	Rotate EM-31 unit 90°
6	31	53	
7	36	56	
8	17	22	In bed of wash on outcrop; outcrop sampled
8	23	33	Rotate EM-31 unit 90°
9	17	22	In bed of wash
10	22	22	"
11	18	23	"
12	28	36	"
13	34	56	" Outcrop sampled
14	37	53	"
15	25	40	"
16	46	62	On side of wash
17	44	59	Boulder field above wash
18	38	59	
19	46	-	Start closed traverse in boulder field at 3-m (10-ft) spacing. Soil predominantly red.
20	37	67	
21	40	59	
22	42	56	
23	42	52	
24	44	62	
25	38	67	

Table 3

EM-31 data for site 3--Continued.

Station	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)	Remarks
26	42	62	
27	48	59	
28	40	56	
29	40	59	
30	44	56	
31	37	56	
32	46	62	
33	44	62	
34	42	62	
35	38	62	
36	48	59	
37	34	38	Soil color change to greenish grey
38	31	36	"
39	33	38	"
40	29	38	"
41	36	44	"
42	40	56	"
43	34	62	Back to red-colored soil
44	43	62	
45	46	56	
46	37	46	
47	40	50	End closed traverse

Horizontal coplanar mean = 34.2 standard deviation = 10.3 range = 10-48

Vertical coplanar mean = 47.8 standard deviation = 15.5 range = 14-67

Table 4.

EM-31 data for site 4. Stations are located on a traverse along Kaulana Gulch. Traverse starts at helicopter landing pad LZ-2 at head of gulch and runs for about 2 km (1.3 mi) along the western margin of the gulch.

Station	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)	Remarks
1	38	59	On bare yellow soil
2	46	67	"
3	40	67	"
4	50	-	On landing pad
5	36	53	On bare red soil
6	34	50	"
7	31	44	"
8	33	53	Grass-covered soil
9	33	56	"
10	40	67	
11	46	77	
12	46	71	
13	34	62	Alongside outhouse
14	37	59	
15	36	43	
16	62	91	On about 10-m (30 ft) of fine grained alluvium
17	42	46	On yellow soil below red zone
18	40	62	
19	42	62	Pebble layer at surface
20	26	34	
21	28	42	On old road
22	44	67	
23	46	67	
24	28	42	On outcrop in small gully
25	38	53	On outcrop at top of rise
26	7.1	6.1	At old clay(?) quarry
27	9.7	16.1	
28	59.	71	On a high bench
29	33	50	Gravel-covered surface
30	56	77	On outcrop
31	25	-	On red soil
32	30	48	Chocolate-brown pluvial deposit
33	30	38	Alunite nodules in outcrop

Horizontal coplanar mean = 37.1, standard deviation = 11.6, range = 7.1-62
Vertical coplanar mean = 54.8, standard deviation = 17.4, range = 6.1-91

Table 5

EM-31 data for site 5. The traverse was run near the access road south of Puu Moiwe along radar traverse 1. The traverse runs east 20° south, and station interval is is 3m (10 ft).

Station	Resistivity Horizontal coplanar (ohm-meters)	Resistivity Vertical coplanar (ohm-meters)
1	29	42
2	29	40
3	29	42
4	32	46
5	31	48
6	33	46
7	33	46
8	33	48
9	38	53
10	37	51
11	40	48
12	37	46
13	37	49
14	36	50
15	37	48
16	40	48
17	36	48
18	40	48
19	40	50
20	40	49
21	46	51
22	44	53
23	46	56
24	43	57
25	44	57
26	42	57
27	42	56
28	38	53
29	38	53
30	38	53
31	38	53
32	40	56
33	44	74
34	46	53
35	48	62

Horizontal coplanar mean = 38.4, standard deviation = 5.0, range = 29-48
Vertical coplanar mean = 50.6, standard deviation = 6.4, range = 40-74

Table 6

EM-31 data for site 5. The traverse was run near the access road south of Puu Moiwi along radar traverse 2. The traverse runs north 19° west, and station interval is 3m (10 ft). Unexploded ordnance lies below station 4.5.

Station	EM-31 oriented N. 19° W. Resistivity (ohm-meters)		EM-31 oriented N. 71° E. Resistivity (ohm-meters)	
	Horizontal Coplanar	Vertical Coplanar	Horizontal Coplanar	Vertical Coplanar
1	48	67	48	71
1.5	46	67	46	71
2.0	46	67	46	67
2.5	46	62	46	62
3.0	44	59	44	62
3.5	44	59	46	67
4.0	44	59	46	67
4.5	48	59	48	62
5.0	46	62	46	67
5.5	46	67	48	67
6.0	48	71	48	71
6.5	50	71	50	71
7.0	48	71	50	67
Mean	46.0	64.7	46.7	67.2
Standard deviation	2.0	5.0	1.9	3.4
Range	44-50	59-71	44-50	62-71

Table 7

EM-31 data for site 5. The traverse was run along the line of expansion of VES 1. Station 0 is at center of expansion, and the measurement interval is 3m (10 ft).

Station	Resistivity (ohm-meters)	
	Horizontal Coplanar	Vertical Coplanar
0	31	44
10 NW	33	44
20	33	44
30	36	50
40	37	50
50	40	53
60	42	59
70	40	56
80	42	53
90	42	59
100 NW	42	59
10 SE	29	42
20	30	38
30	30	40
40	29	38
50	30	40
60	28	42
70	28	44
80	31	42
90	31	42
100 SE	32	44
Mean	34.2	46.7
Standard deviation	5.0	7.0
Range	28-42	38-59

Table 8

EM-31 data for site 5. The traverse was run along the line of expansion of VES-2. Station 0 is at center of expansion, and the measurement interval is 3m (10 ft).

Station	Resistivity (ohm-meters)	
	Horizontal Coplanar	Vertical Coplanar
0	24	33
10 NW	26	33
20	24	34
30	27	34
40	25	33
50	24	33
60	25	37
70	23	33
80	26	33
90	26	34
100 NW	25	34
10 SE	23	33
20	25	33
30	26	33
40	26	36
50	29	40
60	28	42
70	27	44
80	29	40
90	34	42
100 SE	25	36
Mean	26.2	35.9
Standard deviation	2.5	3.4
Range	23-34	33-44

Table 9, VES 1

Schlumberger VES data for site 5 northwest of dry stream. AB is the separation of the current electrodes and MN is the separation of the potential electrodes.

AB/2 meters	MN/2 meters	Apparent resistivity (ohm-meters)
.3	.06	370
.4	.06	264
.6	.06	152
.8	.06	108
1.0	.06	73.5
1.0	.20	60.0
1.4	.20	38.0
1.4	.06	43.5
2.0	.20	26.8
3.0	.20	23.7
4.0	.20	23.3
6.0	.20	19.0
6.0	1.0	20.7
8.0	1.0	22.5
8.0	.20	20.0
10	1.0	19.7
14	1.0	15.0
20	1.0	12.0
25	1.0	13.0
30	1.0	12.7

Table 10, VES 2

Schlumberger VES data for site 5 southeast of dry stream.

AB is the separation of the current electrodes and

MN is the separation of the potential electrodes.

AB/2 meters	MN/2 meters	Apparent resistivity (ohm-meters)
.3	.06	96.5
.4	.06	75.0
.6	.06	62.0
.8	.06	49.0
1.0	.06	45.0
1.0	.20	42.3
1.4	.20	35.6
1.4	.06	39.2
2.0	.20	29.4
3.0	.20	26.0
4.0	.20	25.2
6.0	.20	25.0
6.0	1.0	23.8
8.0	1.0	22.0
8.0	.20	23.0
10	1.0	23.3
14	1.0	24.2
20	1.0	26.2
25	1.0	29.6
30	1.0	31.4

Table 11, VES 3

Schlumberger VES data for Site 1, Smugglers Cove

AB is the separation of the current electrodes and

MN the separation of the potential electrodes.

AB/2 meters	MN/2 meters	Apparent resistivity (ohm-meters)
.8	.06	46
1.0	.06	42.5
1.0	.20	49
1.4	.20	37
1.4	.06	35
2.0	.20	25.5
3.0	.20	13.5
4.0	.20	7.8
4.0	.80	8.0
6.0	1.2	3.0
8.0	1.6	1.8
10	2.0	1.5
14	2.5	1.4
20	4.0	1.6
30	6.0	1.7

Table 12

EM-16 data at 24.3 kHz for site 1 (Smugglers Cove) and site 5

Station	Vertical in Phase (%)	Quad (%)	Resistivity (ohm-meters)	Phase (degrees)	Remarks
Site 1 (Station locations from table 2)					
0-0	-2	0	20	57	
0-50	-2	0	25	54	
0-100	-5	-2	20	43	
50-100	-4	+2	12.5	80	
100-100	-2	+4	10.2	76	
100-50	-2	+2	8.5	90	
100-0	-2	0	2.5	90	
50-0	-2	-3	10	90	
50-50	-2	+1	10	77	
Site 5					
1	-12	-1	45	50	Near radar tr. 1.
2	-12	0	35.5	76	Near radar tr. 2.
3	-11	0	55	49	
4	-9	-1	31.2	81	Bench by VES 1
5	-5	0	54.5	47	"
6	-2	0	38.7	75	
7	-2	-2	51.2	64	Lower bench northwest of gulch
8	-1	-2	70	44	Lower bench southeast of gulch

Table 13

Lithologies and Corresponding Resistivities for Representative Hawaiian Rocks from the Literature

Lithology	Resistivity (ohm-meters)
Zohdy and Jackson (1969)	
Clay with brackish to saline H_2O	< 3
Clay with brackish to fresh H_2O	5-8
Clay, silt, sand, and gravel with fresh H_2O	11-25
Sand and coral	40-400
Weathered basalt with fresh H_2O	30-60
Fresh basalt with fresh H_2O	300-700
Fresh basalt with saline H_2O	30-40
Hussong (1967)	
Unweathered	10,000-200,000
Unweathered pahoehoe	5,000-20,000
Weathered lavas	1,000-8,000
Dry soil	500-5,000
Wet soil	50-500
Lava with fresh H_2O	50-300
Mattice (1981)	
Dry alluvium	150-300
Wet alluvium	50-150
Dry basalt	2,000-20,000
Basalt with fresh H_2O	300-900
Weathered basalt with fresh H_2O	45-150
Basalt with saline H_2O	10-60
Basalt with warm fresh H_2O	25-100
Basalt with warm saline H_2O	3-8

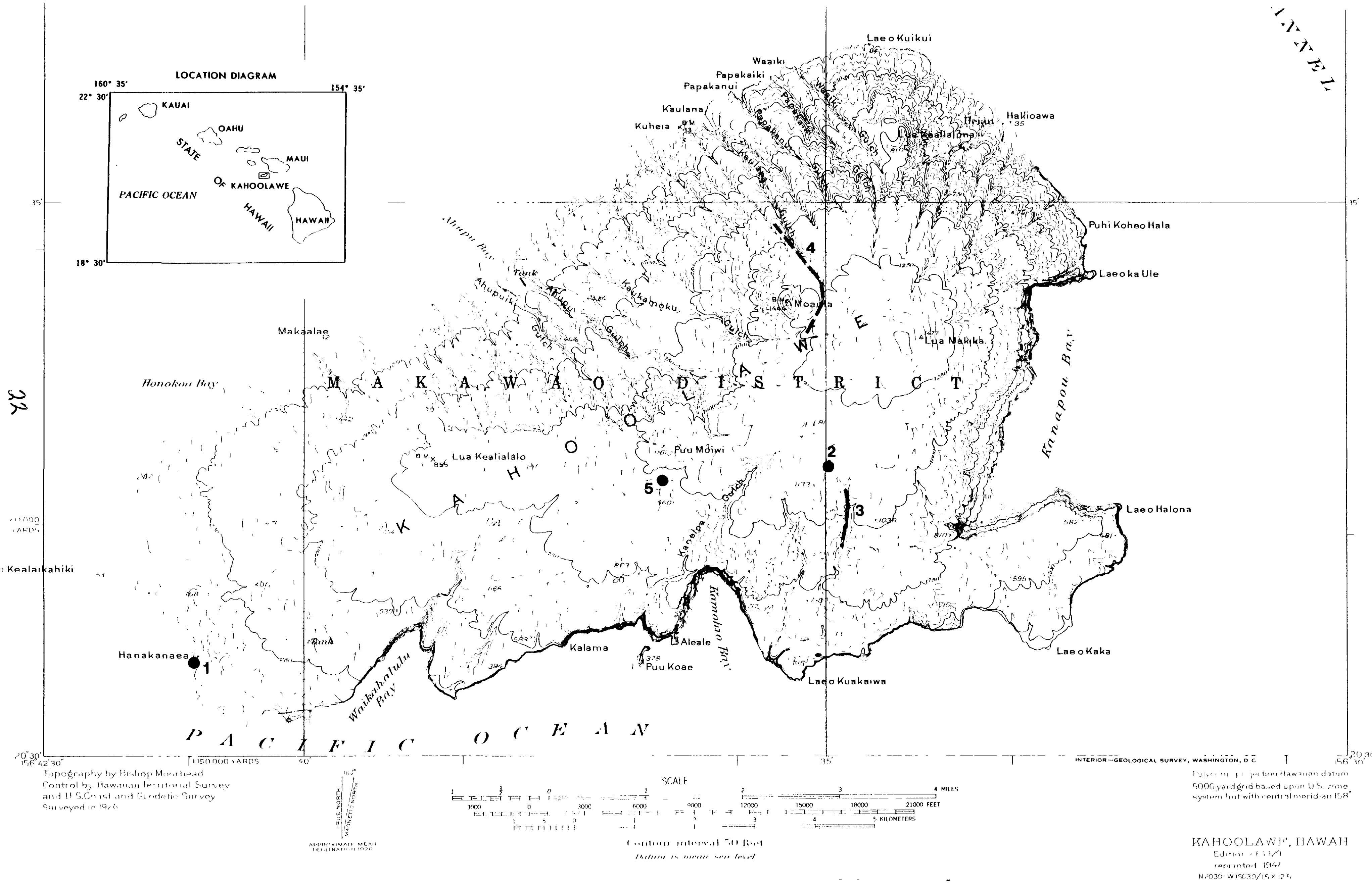

Figure 1. Location map showing five areas on Kahoolawe where electrical studies were conducted. Base from U.S. Geological Survey Kahoolawe quadrangle, 1929, 1:62,500.

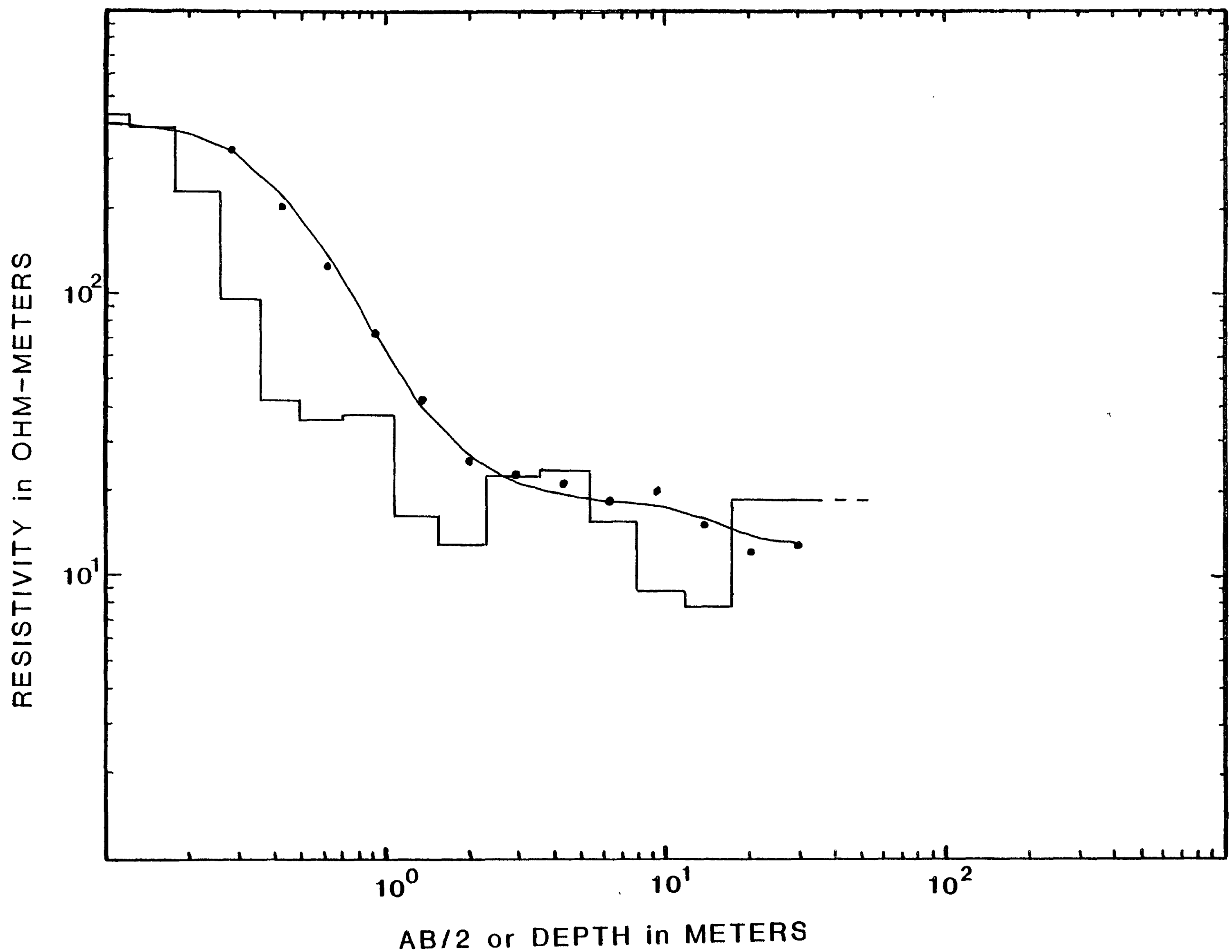

Figure 2. Schlumberger vertical electrical sounding 1 at site 5. The dots are the shifted field curve, the columnar graph is a one-dimensional model which fits the field data, and the solid line is the computed fit of the model.

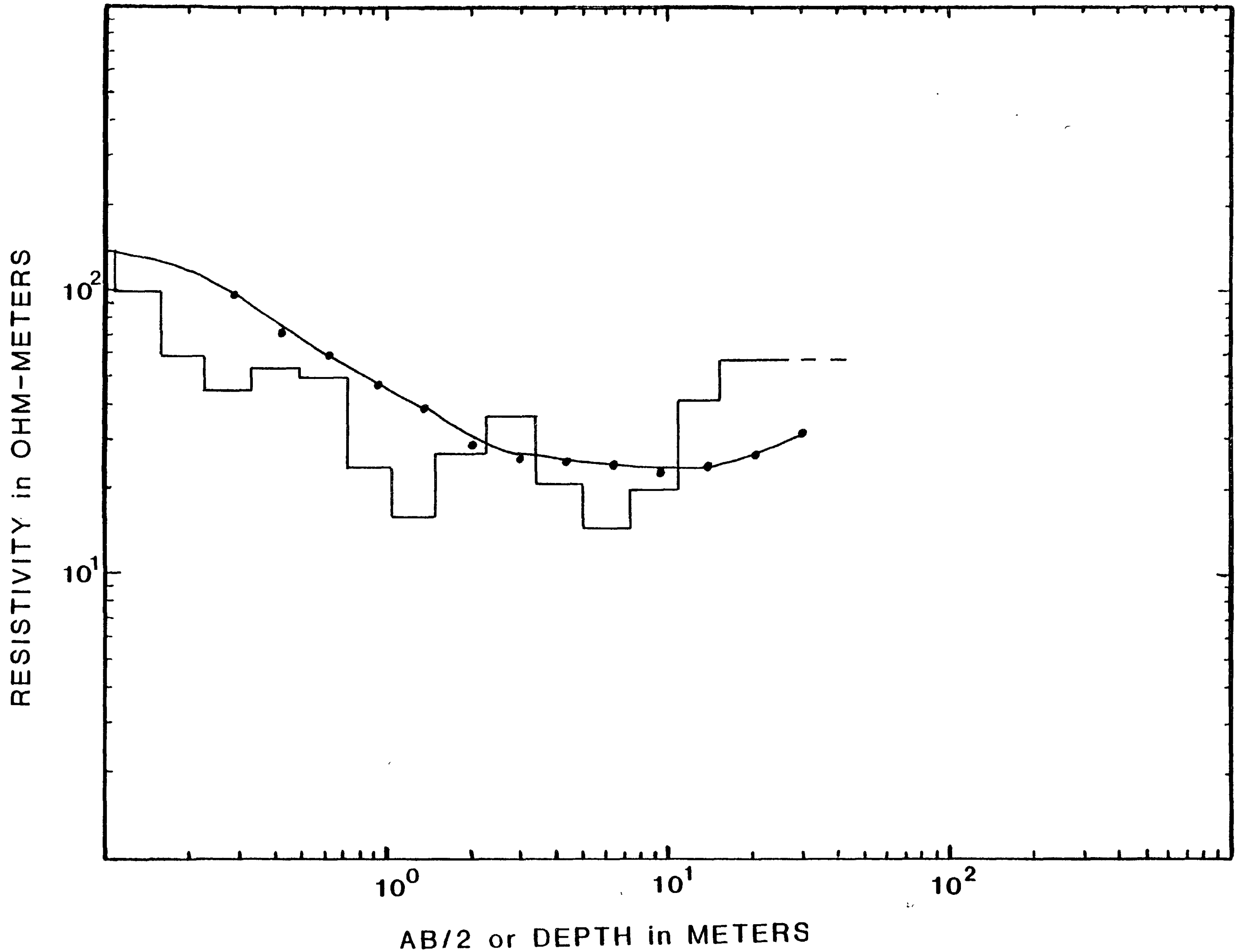

Figure 3. Schlumberger vertical electrical sounding 2 at site 5. The dots are the shifted field curve, the columnar graph is a one-dimensional model which fits the field data, and the solid line is the computed fit of the model.

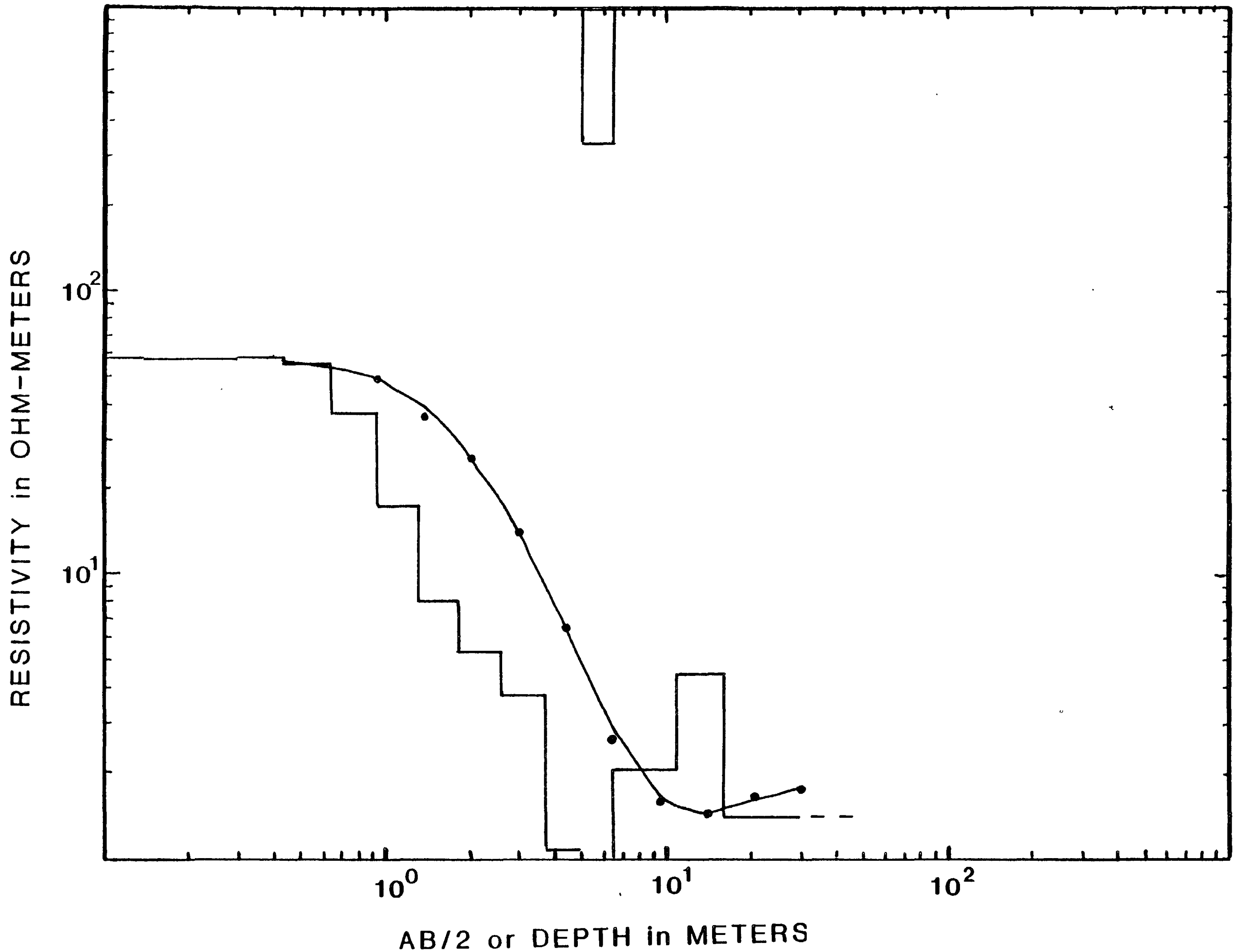

Figure 4. Schlumberger vertical electrical sounding 3 at site 1. The dots are the shifted field curve, the columnar graph is a one-dimensional model which fits the field data, and the solid line is the computed fit of the model.