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Geological Survey

Mapping of a Buried Surface beneath Limestone in Agat, Territory of Guam using Electromagnetic profiling techniques

by

Jim Kauahikaua
Honolulu, Hawaii

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Abstract

Fixed-distance, horizontal-loop electromagnetic (EM) soundings were used to define the contact between an aquifer of Alifan limestone underlain by an impervious, clayey conglomerate in Agat, Guam. A Schlumberger resistivity sounding showed that the limestone has a resistivity of approximately 1500 ohm-m while the conglomerate appears to have a resistivity of less than 50 ohm-m. This resistivity structure presents an ideal situation for mapping by electromagnetic methods. The EM sounding measurements were not able to independently determine the resistivity of the limestone; however, they proved excellent for determining the depth to and resistivity of the conductive conglomerate beneath the limestone.

After compiling the results of the EM soundings, it appears that the base of the limestone generally dips to the northeast. A small basin interpreted to be beneath the northern end of the limestone outcrop may feed Bona Spring. No other basin configurations were found although one may exist northwest of Almagosa Spring beneath the southern portion of the outcrop.

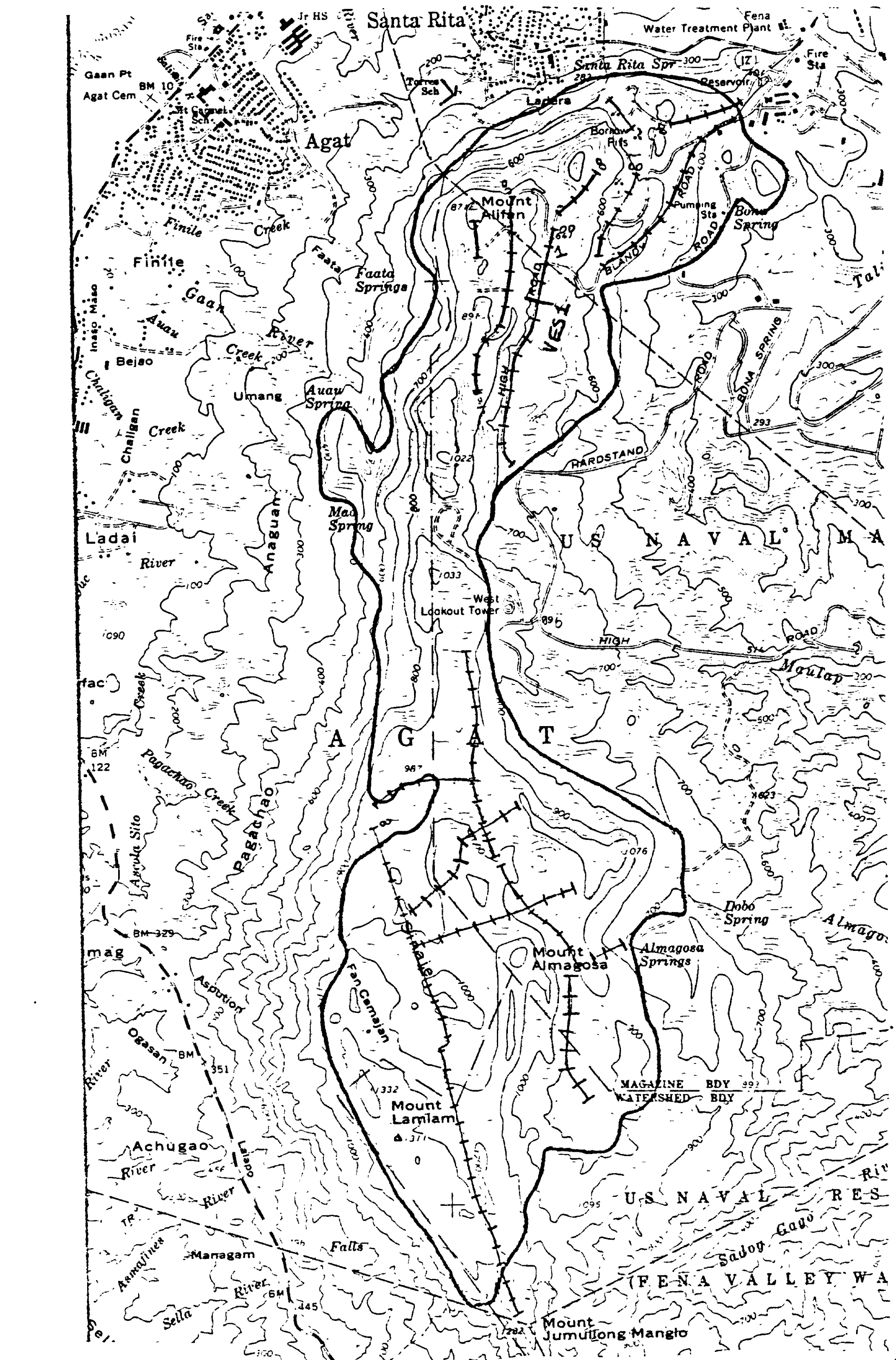
Introduction

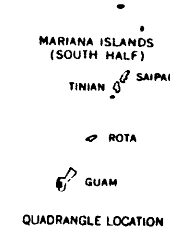
The purpose of this work was to map the subsurface contact between the Alifan limestone and the underlying clayey conglomerate in the hopes of finding basins in the conglomerate which may store water. The limestone is an aquifer while the conglomerate is an aquiclude. Several freshwater springs issue from places where the contact between these formations is at the ground surface. At present, the principal water user in this area (the US Naval Magazine) directly taps the output of these springs. Drilling into limestone-filled basins defined by geophysical surveys may allow increased amounts of water to be withdrawn.

Interpretation of a Schlumberger sounding (see Zohdy, 1974, for details of this technique) obtained in June, 1983 along the northern portion of High Road (Figure 1) showed that the limestone had a resistivity of about 1500 ohm-m while the rock immediately below had a resistivity of less than 50 ohm-m. No drill hole information is available to directly identify the low-resistivity rock beneath the limestone, therefore, contact relations at the base edge of the limestone outcrop were used to identify the material as clayey conglomerate. Data and interpretation of the Schlumberger sounding are given in Appendix A.

The large contrast between the resistivities of the limestone and the underlying conglomerate is more easily dealt with by electromagnetic (EM) profiling than with Schlumberger soundings. DC methods are primarily sensitive to the resistivity and thickness of the limestone and therefore, thickness estimates could be biased by variations in the resistivity of the limestone. On the other hand, EM techniques are relatively insensitive to the higher resistivity and are primarily sensitive to the thickness of the upper material and the resistivity of the conductive material beneath. Terrain was an equally important consideration; although the northern portion of the area was well covered by paved roads, the southern two-thirds of the study area was roadless and rather rugged. These logistics favored the EM technique because a portable, two-man loop-loop profiling system was available while available DC equipment was heavy and required vehicular transport.

Figure 1. A map of the Alifan limestone outcrop (thick solid line) showing geographical features named in the text (from USGS Agat quadrangle, 1:24,000 scale). Also shown are the profile lines (thin ticked lines).





Electromagnetic Profiling

Between January and April, 1984, the area was profiled with a Max/Min II loop-loop system in a horizontal coplanar mode at a 183 m (600 ft) distance between loops. Measurements were taken every 91.5 m (300 ft) along available roads and trails. This equipment allows measurement of the mutual coupling between the two loops at five frequencies - 222, 444, 888, 1777, and 3555 Hz. These readings take the form of an in-phase (IP) and an out-of-phase (OP) measurement at each frequency for a total of 10 measurements per location. Measurements were obtained at a total of 115 locations covering almost 11,600 line m (38,000 line ft) in 6 working days. The total effort required 118 man-days and 15 cans of mosquito repellant, most of it to cut trails through the dense vegetation and across very rugged terrain in the southern portion of the study area.

Although the measurement mode is described as fixed-distance, horizontal coplanar loops, deployment of these loops in densely vegetated, rugged terrain rarely resulted in the loops being exactly the same distance apart and exactly coplanar. Normally, sitings are taken from one loop to the other with a hand level to determine the elevation difference and the data are later corrected back to coplanar; however, siting between loops in this area was impossible owing to dense vegetation and rugged terrain. Elevations had to be estimated from a map (USGS 1:24,000 Agat quadrangle 1975) and the differences incorporated into the interpretation model. The true distance between loops is also estimated in the interpretation model.

Interpretation of Max/Min II Data

Each of the data sets was inverted using computer program MARQMAXMIN written in BASIC 2.1 for a Hewlett-Packard 9826 microcomputer. This program takes as input the ten measured values (5 IP, OP pairs), the elevation difference between loops, and an initial guess at the interloop distance and the parameters of a horizontally-layered halfspace. The program then automatically minimizes the difference between the data and the theoretical response of this type of halfspace model. At completion, the program outputs a best-fitting model with error estimates for each of the model parameters. As an example, Appendix B contains a detailed output listing from program MARQMAXMIN for a data set obtained near the location of the Schlumberger sounding detailed in Appendix A.

The parameters of the horizontally-layered halfspace model are the resistivity and thickness of each layer. All the data sets for this study were fit with a two-layer model, the first layer having a fixed resistivity of 5000 ohm-m (the equipment is not sensitive to resistivities above about 500 ohm-m in this configuration) and a variable thickness; the second layer also had a variable resistivity. The horizontal distance between the loops was also variable, but constrained so as not to exceed 183 m.

In general, the model fit the data well, as evidenced by the example in Appendix B. Second layer resistivities range from about 1.5 to 15 ohm-m while the first layer thicknesses range from 0 to over 80 meters (262 ft). A map of the first layer thicknesses subtracted from the lesser of the particular measurement loop elevations is shown in Figure 2 while a map of the second layer resistivities is shown in Figure 3. In these maps, the interpreted results have been plotted midway between the two loops used to take the measurements. The results are tabulated in Appendix C and the field data are tabulated in Appendix D.

Consistency of the results can be estimated by comparing interpretations at one location which has been measured on two different lines. There are two such locations, both along the line labeled 'Bush line #1'. Station 0 on the line labeled 'EW trail #3' lies between stations 2700 and 3000 on the line labeled 'Bush line #1'. The interpreted elevation of conglomerate is 261 m (855 ft) and its resistivity is 6.08 ohm-m for station 0 on the line labeled 'EW trail #3'. The corresponding quantities are 278 m (912 ft) and 253 m (829 ft) and 4.4 and 5.9 ohm-m for stations 2700 and 3000, respectively, on 'Bush line #1'. The second such location is station 100 on the line labeled 'EW trail #2 ->W' which almost lies between station 4200 and 4500 along 'Bush Line #1'. Station 100 on 'EW trail #2' yielded an interpreted elevation of 237 m (777 ft) and a resistivity of 4.9 ohm-m. The corresponding quantities are 240 m (787 ft) and 242 m (794 ft) and 4.1 and 5.6 ohm-m for stations 4200 and 4500, respectively. Both crosspoints show excellent agreement.

Significance of the EM Results

The resistivity structure is known to consist of two layers as interpreted from the Schlumberger sounding. The first layer is presumed to be the Alifan limestone and the second layer is presumed to be the clayey conglomerate. The results of the EM measurements support this structure because as an EM profile approaches or crosses the limestone/conglomerate contact as mapped by Tracey and others (1964), the thickness of the first layer approaches zero. This can be seen on three lines - the south end of High Road line, the west end of the line labeled 'EW trail to grassy area ->W', and the north and south end of the line labeled 'Bush line #2 ->S (Sinaje)'.

The map of conglomerate surface elevations beneath limestone (Figure 2) clearly shows a basin beneath the north end of the outcrop east of the Borrow Pits and north of Bona Spring. The base of the basin appears to be at about 88 m (290 ft) elevation while the edge might be around 98 m (320 ft) (the elevation of Bona Spring). Although not definitely a basin, the area northwest of Almagosa Spring might also be basin-like. Lack of data in that area because of very rugged terrain prevents definite conclusions about shape of its surface.

The map of the resistivity of the conglomerate (Figure 3) does not show any clear pattern except that the resistivities are generally higher in the southern portion of the limestone outcrop. This may reflect regional thinning of the clayey conglomerate between the resistive limestone and a resistive rock unit beneath the conglomerate.

Conclusions

EM profiling has mapped the depth to an electrical conductor beneath an electrically resistive rock unit presumed to be limestone. The electrical conductor is probably a clayey conglomerate known to underly the limestone in this area of Guam. Maps of the surface of the conductor show a definite basin north of Bona Spring and a possible basin north of Almagosa Spring.

Figure 2. A map of the elevations (feet) of the limestone/conglomerate contact interpreted from electromagnetic loop-loop profiling. Thick solid line is the limestone outcrop boundaries.

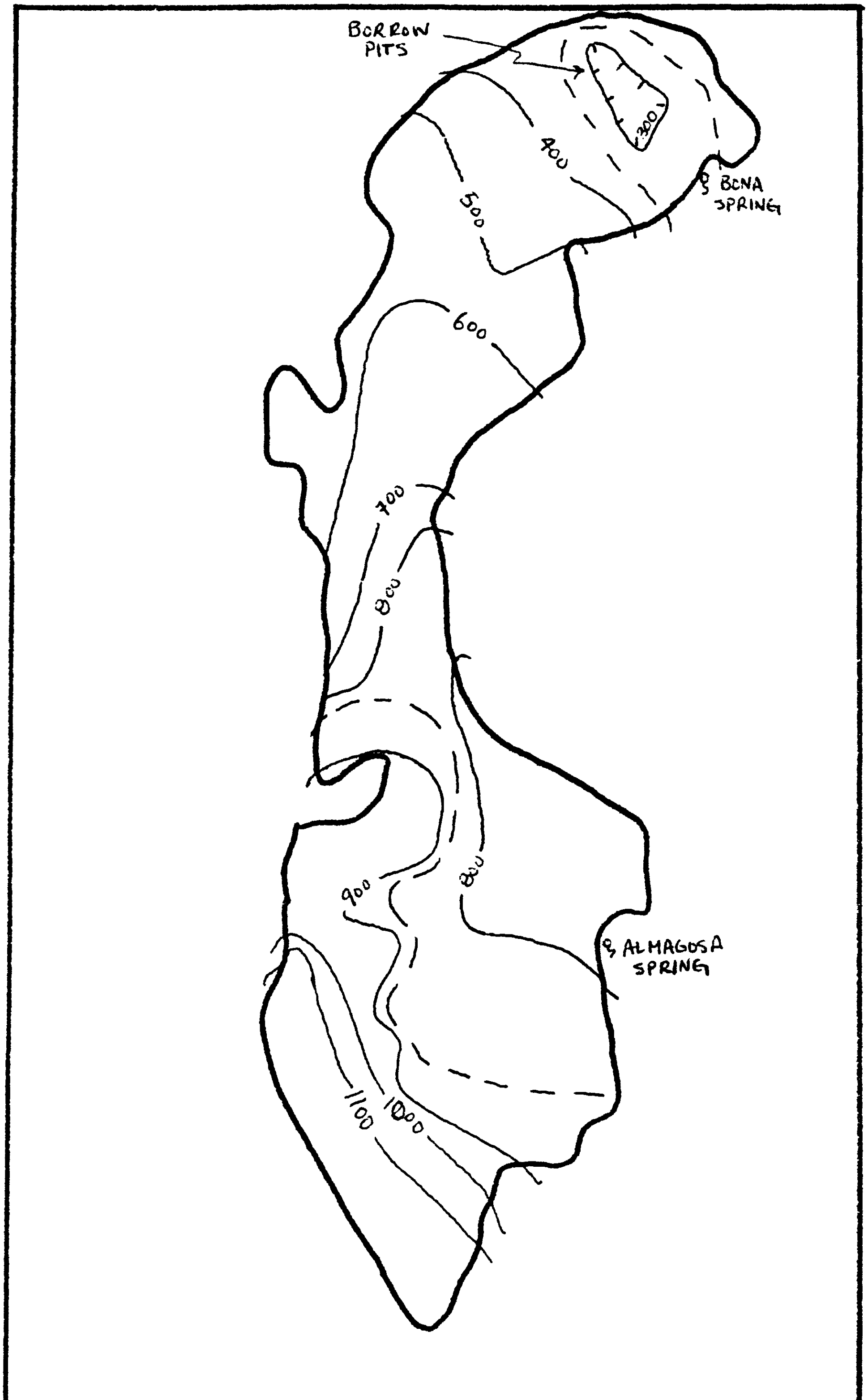
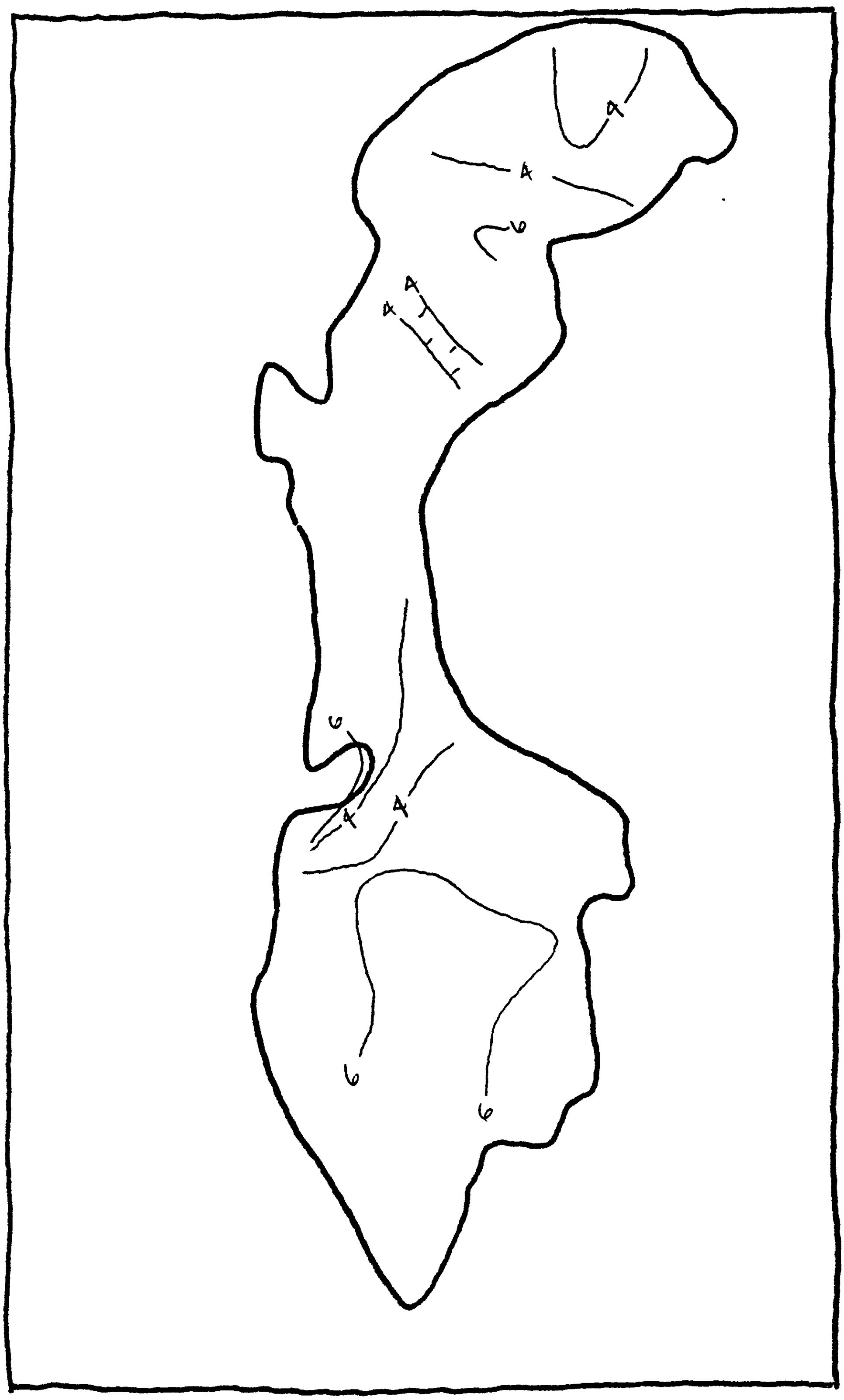


Figure 3. A map of the resistivity (ohm-m) of the conglomerate interpreted from electromagnetic loop-loop profiling. The thick solid line is the limestone outcrop boundary.



Further exploration should be carried out to confirm speculation in the latter area.

References

Anderson, W.L., 1979, Program MARQDCLAG -- Marquardt inversion of DC-Schlumberger soundings by lagged-convolution: USGS Open-File Report 79-1432, 58 p.

Tracey, J.I. Jr., Schlanger, S.O., Stark, J.T., Doan, D.B., and May, H.G., 1964, General Geology of Guam: USGS Professional Paper 403-A, 104 p.

Zohdy, A.A.R., 1974, Electrical Methods, in Applications of surface geophysics to ground-water investigations: Tech. of Water-Resources Inv. of the U.S. Geological Survey, ch. D1, p. 5-66.

Appendix A: Interpretation of Preliminary Schlumberger Sounding

Computer programs such as MARQDCLAG (Anderson, 1979) offer an automatic means by which sounding data sets can be inverted to their best-fitting horizontally-layered model parameters. These parameters are the resistivities and thicknesses of each of the layers in the earth model. Of course, approximate matching can be done by manually comparing the sounding data to theoretical curves in a standard album; however, the computer inversion offers an additional advantage, besides speed and automation, of parameter resolution estimates. They offer a means of assessing the reliability of parameters they estimate.

When input with the sounding data set and an initial guess of the model parameters, program MARQDCLAG_HP (a version of MARQDCLAG written in BASIC 2.1 for a Hewlett-Packard 9826 microcomputer used in this study) automatically minimizes the following quantity:

$$PHI = \sum_{i=1}^{N} \left[\frac{y_i - f(x_i)}{w_i} \right]^2$$

where

N is the number of data points in the sounding data set,

x_i is the i^{th} electrode spacing,

y_i is the apparent resistivity measured at x_i,

w_i is the apparent resistivity measurement error ($=y_i/100$), and

f(x) is the theoretical calculated apparent resistivities.

The number of layers cannot be automatically varied by the program so it is a common practice to invert each sounding data set for several models, each having a different number of layers. The best-fitting model is chosen to be the one which minimizes the following quantity, called the reduced chi-squared statistic:

$$X^2 = PHI / (N - 2 * m)$$

where * denotes multiplication, and m is the number of layers in the theoretical model.

During the inversion of this data set, the natural logarithm of the parameters was manipulated to avoid use of negative resistivities or thicknesses and to more accurately reflect the logarithmic resolution of these values. A detailed description of the headings and identifying terms used in the program output follows:

X	electrode spacing equal to half the distance between the two current electrodes, meters,
OBSERVED	shifted observed apparent resistivity values, ohm-meters,
PREDICTED	theoretical apparent resistivity values corresponding to the best-fitting model parameters,
%RESIDUALS	(OBSERVED-PREDICTED)*100,
WEIGHT FN	$1/(\text{error})^2$, where error is normally OBSERVED/100,
CORRELATION MATRIX	estimates of the correlation between each of the parameters and any other parameters of this particular model. Ones down the diagonal indicate that each parameter is 100% positively correlated with itself. Numbers between +1 and -1 off the diagonal indicate the magnitude of correlation between other pairs of parameters,
REDUCED CHI-SQUARED	= PHI / (N - 2 * m),
B-SD	exp[1] (PARAMETER-ERROR),

----

1. exp(x) represents e, the base of the natural logarithms, raised to the x power.

B	exp(PARAMETER),
B+SD	exp(PARAMETER+ERROR),

FINAL UNSCALED PARAMETERS:

RESISTIVITY	resistivity of layer i, in ohm-meters, and
DEPTH	depth from surface to bottom of layer i, in meters.

MARQUARDT STATISTICS: NAVAL MAG, GUAM VES 1

	X	OBSERVED	PREDICTED	%RESIDUALS	WEIGHT FN
1	+9.1440E+00	+1.4570E+03	+1.5675E+03	-7.5871E+00	+1.0330E-01
2	+1.2190E+01	+1.5440E+03	+1.5649E+03	-1.3560E+00	+9.1986E-02
3	+1.5240E+01	+1.5390E+03	+1.5607E+03	-1.4108E+00	+9.2585E-02
4	+1.9810E+01	+1.5300E+03	+1.5507E+03	-1.3519E+00	+9.3677E-02
5	+2.4380E+01	+1.5670E+03	+1.5355E+03	+2.0106E+00	+8.9306E-02
6	+3.0480E+01	+1.5640E+03	+1.5063E+03	+3.6921E+00	+8.9649E-02
7	+3.9620E+01	+1.5630E+03	+1.4426E+03	+7.7004E+00	+8.9764E-02
8	+4.8770E+01	+1.4620E+03	+1.3571E+03	+7.1738E+00	+1.0259E-01
9	+6.0960E+01	+1.1630E+03	+1.2179E+03	-4.7198E+00	+1.6213E-01
10	+7.6200E+01	+9.8400E+02	+1.0241E+03	-4.0770E+00	+2.2648E-01
11	+9.1440E+01	+8.6900E+02	+8.3266E+02	+4.1815E+00	+2.9039E-01
12	+1.2190E+02	+4.9900E+02	+5.1611E+02	-3.4296E+00	+8.8068E-01
13	+1.5240E+02	+3.1600E+02	+3.0925E+02	+2.1355E+00	+2.1961E+00
14	+1.9810E+02	+1.5200E+02	+1.5248E+02	-3.1699E-01	+9.4914E+00

CORRELATION MATRIX:

	1	2	3
1	+1.00	+.36	-.55
2	+.36	+1.00	-.89
3	-.55	-.89	+1.00

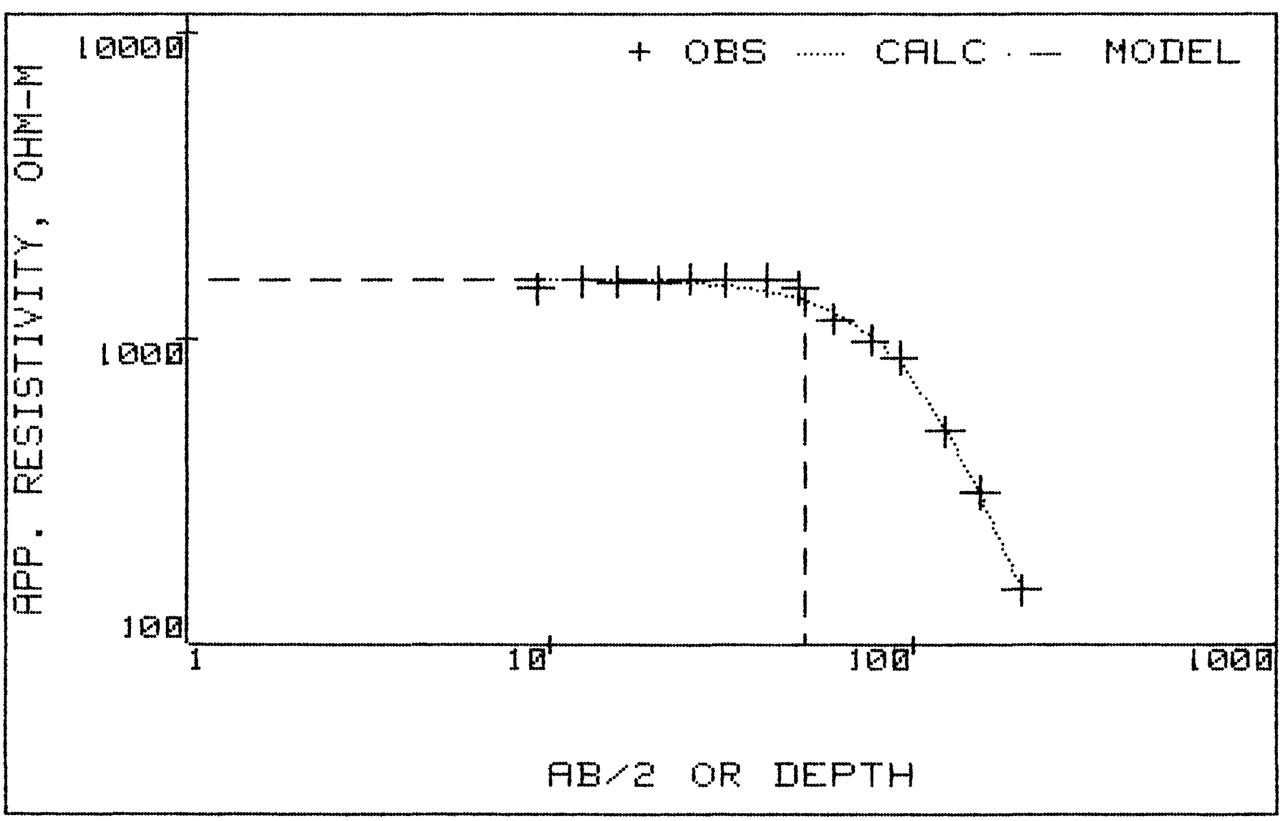
REDUCED CHI-SQUARED=26.45
PHI=264.46

DCLAG: ******** END ********   NAVAL MAG, GUAM VES 1
COORDINATES: 0 0
ELEVATION : 207 METER
AZIMUTH :

B-SD	B	B+SD
1.563E+003	1.569E+003	1.576E+003
5.110E+001	5.386E+001	5.678E+001
5.024E+001	5.057E+001	5.089E+001

FINAL UNSCALED PARAMETERS-- (* denotes fixed value)			RESISTIVITY		DEPTH
1	1.56948356E+03	1	1.56948356E+03		
2	5.38637970E+01	2	5.38637970E+01		
3	5.05653442E+01			1	5.05653442E+01

NAVAL MAG, GUAM VES 1



Appendix B: Example of MARQMAXMIN output

The discussion presented in Appendix A also holds true for the use of program MARQMAXMIN. The programs are functionally the same in that they fit horizontally-layered earth models to data observations. The outputs are identical in form with the following additions:

OFFSETS	reports output of a feature which has been turned off for this study.
actualR	reports the value that program MARQMAXMIN has assigned for the distance between loops, in meters.

MARQUARDT STATISTICS: FEENAMXMNA: High Road ->S RX: 300 TX: 900

	X	OBSERVED	PREDICTED	RESIDUALS	WEIGHT FN
1	+2.2200E+02	+1.2600E+00	+1.2617E+00	-1.6794E-03	+7.6923E-02
2	+2.2200E+02	+0.0000E+00	+1.0667E-02	-1.0667E-02	+1.9231E+00
3	+4.4400E+02	+1.2600E+00	+1.2399E+00	+2.0058E-02	+7.6923E-02
4	+4.4400E+02	-8.0000E-02	-8.5668E-02	+5.6681E-03	+1.9231E+00
5	+8.8800E+02	+1.1100E+00	+1.1539E+00	-4.3939E-02	+7.6923E-02
6	+8.8800E+02	-1.4000E-01	-1.4524E-01	+5.2379E-03	+1.9231E+00
7	+1.7770E+03	+1.0050E+00	+1.0589E+00	-5.3920E-02	+7.6923E-02
8	+1.7770E+03	-1.6000E-01	-1.4935E-01	-1.0647E-02	+1.9231E+00
9	+3.5550E+03	+7.7000E-01	+9.8746E-01	-2.1746E-01	+7.6923E-02
10	+3.5550E+03	-1.2000E-01	-1.2791E-01	+7.9060E-03	+1.9231E+00

CORRELATION MATRIX:

	2	3	6
2	+1.000	-.453	+.191
3	-.453	+1.000	+.266
6	+.191	+.266	+1.000

REDUCED CHI-SQUARED=.000785385899057

PARAMETER ERRORS:

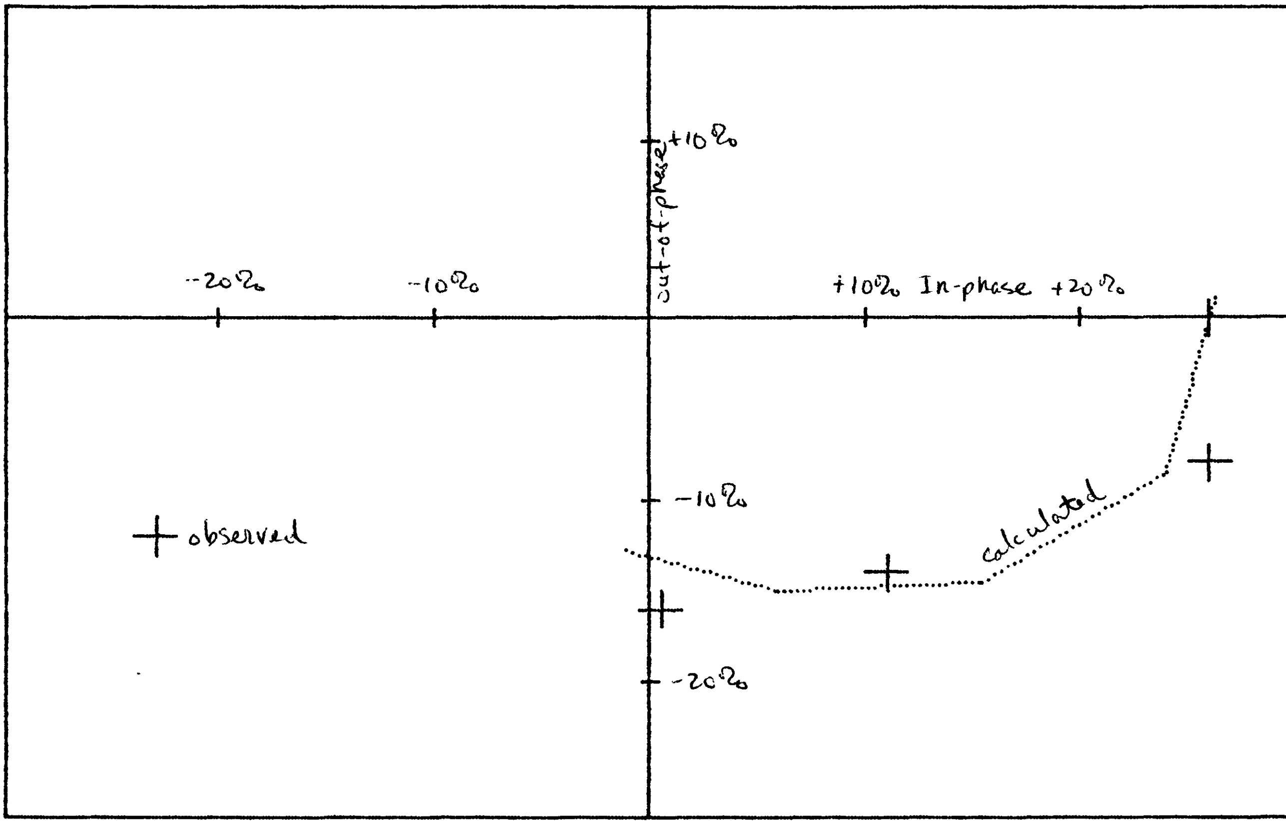
	PARAMETER	ERROR	%ERROR
1	+8.517E+00	+0.000E+00	0.00
2	+1.690E+00	+1.220E-01	7.22
3	+3.871E+00	+3.842E-02	.99
4	+0.000E+00	+0.000E+00	0.00
5	+0.000E+00	+0.000E+00	0.00
6	+1.000E+00	+5.639E-03	.56

LOOP: ******** END ******** FEENAMXMNA: High Road ->S RX: 300 TX: 900

B-SD	B	B+SD
5.000E+003	5.000E+003	5.000E+003
4.796E+000	5.418E+000	6.121E+000
4.616E+001	4.797E+001	4.985E+001

OFFSETS= 0.000 0.000
actualR= 182.7

FINAL UNSCALED PARAMETERS--		RESISTIVITY		DEPTH	
1	5.00000000E+03	1	5.00000000E+03		
2	5.41820053E+00	2	5.41820053E+00		
3	4.79691665E+01			1	4.79691665E+01


+10%
out-of-phase
-20%
-10%
+10%
In-phase
+20%
-10%
observed
calculated
-20%

Appendix C: Tabulated EM Profiling Results

The results of interpreting the EM profiling data using program MARQMAXMIN are tabulated here under the following headings:

STN	Station number, in feet along profile.
ELEV(FT)	Elevation of the limestone/conglomerate surface, in feet. Precisely, ELEV equals the topographic elevation minus D1, defined below and is subject to errors in both D1 and in the value used for topographic elevation.
RCHISQ	Reduced chi-squared value for the model-data fit. Locally large values indicate either a noisy data set or a geologic situation which departs significantly from the horizontally-layered model assumed here.
R(M)	Distance between loops, in meters, as determined by program MARQMAXMIN.
RHO2(OHM-M)	Resistivity of the layer underlying the limestone, in ohm-m. The three values under this heading are, from left to right, the lower limit, the best estimate, and the upper limit of this parameter using linear error estimates for one standard error.
D1(M)	Thickness of the limestone, in meters. The three values under this heading are, from left to right, the lower limit, the best estimate, and the upper limit of this parameter using linear error estimates for one standard error.

STN	ELEV(FT)	RCHISQ	R(M)	RHO2(OHM-M)			D1(M)		
High Road ->S									
-900	396	3.22E-004	182.9	1.676	2.155	2.772	74.2	77.3	80.5
-600	415	1.47E-004	182.9	1.796	2.081	2.411	70.1	71.8	73.5
300	451	1.28E-004	182.8	4.659	4.956	5.272	55.0	55.9	56.9
600	479	7.57E-004	182.7	4.756	5.356	6.032	45.9	47.7	49.5
900	496	1.73E-004	182.7	5.842	6.132	6.437	41.8	42.5	43.3
1200	496	1.61E-004	182.8	5.243	5.549	5.873	49.1	50.0	50.9
1500	500	1.51E-004	182.8	4.701	4.979	5.272	49.6	50.4	51.3
1800	524	7.93E-004	182.9	4.007	4.490	5.032	44.3	46.0	47.7
2100	569	1.01E-003	182.3	4.354	4.774	5.234	32.4	33.8	35.4
2400	611	4.52E-004	180.1	4.957	5.184	5.423	20.2	21.0	21.8
2700	636	3.36E-004	182.4	4.578	4.733	4.893	12.9	13.5	14.2
3000	636	1.23E-003	182.9	3.244	3.472	3.716	12.3	13.5	14.9
3300	664	5.39E-003	180.4	3.068	3.459	3.901	3.2	5.0	7.9
3600	653	8.78E-003	179.3	4.022	4.660	5.398	0	1	155
Mt. Alifan NS									
300	512	4.70E-004	182.7	2.852	3.802	5.069	76.3	81.7	87.6
NS road #2 ->S									
300	440	3.75E-004	182.8	2.340	3.124	4.169	80.1	85.3	90.8
600	476	7.84E-004	182.9	2.328	3.228	4.477	72.4	77.4	82.7
900	507	6.56E-004	182.7	2.554	3.286	4.229	66.1	69.6	73.4
1200	518	5.28E-004	182.8	3.524	4.261	5.152	64.8	67.8	70.8
1500	528	3.97E-004	182.9	3.549	4.206	4.986	68.0	70.7	73.5
1800	530	3.87E-004	182.8	3.326	3.955	4.703	67.3	70.0	72.8
2100	568	2.82E-005	175.4	3.885	4.046	4.214	59.4	60.0	60.6
2400	587	1.30E-004	176.6	3.973	4.295	4.643	56.0	57.2	58.4
2700	602	2.17E-004	180.6	3.310	3.660	4.047	59.0	60.5	61.9
3000	608	3.18E-004	182.9	3.461	3.881	4.353	59.9	61.6	63.4
Alifan Quarry ->SW									
300	365	2.25E-004	181.6	3.405	3.655	3.924	40.2	41.1	42.0
600	376	5.07E-004	182.5	3.019	3.423	3.880	48.5	50.0	51.7
900	389	1.22E-003	182.9	3.078	3.745	4.556	52.5	55.2	58.0
1200	432	7.90E-004	182.8	3.450	3.805	4.197	37.5	38.9	40.3
Alifan Quarry Borrow Pit ->NW									
300	294	1.26E-003	182.9	3.457	4.035	4.709	45.2	47.4	49.8
Blandy Road ->NE									
300	470	1.78E-003	182.6	4.029	4.332	4.658	12.4	13.8	15.3
600	423	5.46E-004	181.5	4.081	4.326	4.586	21.1	22.0	23.1
900	368	7.64E-004	182.2	3.407	3.753	4.134	32.7	34.1	35.6
1200	338	4.42E-004	182.7	3.400	3.676	3.975	39.1	40.2	41.3
1500	311	5.27E-004	182.8	3.371	3.720	4.105	44.1	45.4	46.8
1800	295	5.44E-005	181.1	3.364	3.476	3.592	40.6	41.1	41.5
2100	303	5.69E-004	178.6	3.304	3.615	3.955	34.3	35.6	36.9
2400	291	3.07E-004	179.1	3.402	3.617	3.847	35.2	36.1	37.1
2700	311	9.80E-004	177.3	3.256	3.552	3.874	25.8	27.1	28.5

Bush line #2 (Sinaje)->S

300	930	4.91E-004	166.6	4.291	4.460	4.636	2.6	3.0	3.5
600	923	3.17E-003	176.4	3.887	4.370	4.912	15.3	17.3	19.5
900	920	1.97E-004	171.7	3.683	3.802	3.925	22.4	22.9	23.4
1200	885	3.59E-004	177.3	4.207	4.455	4.717	34.0	34.9	35.8
1500	911	2.87E-003	179.6	4.976	5.630	6.369	25.1	27.2	29.6
1800	908	2.24E-003	180.9	5.056	5.713	6.455	27.6	29.6	31.8
2100	924	2.06E-003	175.3	5.428	6.029	6.696	21.4	23.1	25.0
2400	910	2.53E-003	172.0	6.332	7.152	8.078	23.9	25.9	28.0
2700	843	3.71E-004	173.9	5.033	5.544	6.107	49.4	50.8	52.3
3000	835	7.36E-004	171.7	5.896	6.709	7.635	46.7	48.6	50.7
3300	919	2.86E-003	150.2	4.881	5.776	6.836	25.6	27.8	30.2
3600	938	1.55E-003	160.4	4.713	5.297	5.953	20.2	21.8	23.6
3900	890	4.66E-004	178.9	4.898	5.486	6.143	47.1	48.9	50.7
4200	962	6.56E-004	177.2	8.122	8.814	9.566	31.5	32.8	34.2
4500	1029	6.23E-003	182.4	4.995	5.833	6.812	17.3	20.0	23.2
4800	1071	5.78E-003	182.2	5.891	6.646	7.499	9.7	12.0	14.9
5100	1074	1.69E-003	176.5	10.00	10.99	12.08	18.5	20.1	21.8
5400	1077	2.61E-003	178.6	7.758	8.780	9.936	23.1	25.2	27.5
5700	1106	1.72E-003	181.6	7.857	8.592	9.396	21.0	22.6	24.3
6000	1121	5.11E-004	181.3	9.76	10.21	10.69	18.5	19.4	20.2
6300	1143	3.01E-003	173.8	10.51	11.60	12.80	12.6	14.3	16.2
6600	1146	2.13E-003	175.3	9.69	10.53	11.44	13.6	15.1	16.7
6900	1156	4.09E-003	180.1	7.007	7.810	8.705	11.2	13.3	15.7
7200	1183	3.84E-003	180.7	8.216	9.063	9.998	3.6	5.3	7.6
7500	1199	7.06E-003	170.2	13.68	15.52	17.61	0	0	257
7800	1209	2.36E-004	177.3	14.77	15.13	15.50	.2	.4	.8

EW trail #2 ->W

-530	763	3.43E-004	180.9	6.854	7.528	8.269	49.3	50.8	52.4
-300	780	6.41E-004	179.1	7.222	8.027	8.923	47.1	48.8	50.7
100	777	6.70E-004	179.6	4.275	4.875	5.559	44.7	46.7	48.8
300	791	3.25E-005	180.0	5.468	5.665	5.869	44.9	45.4	46.0
600	822	1.72E-005	182.2	5.010	5.134	5.262	53.7	54.1	54.5
900	816	1.19E-002	182.7	2.001	4.335	9.393	51.5	62.1	74.9
1200	850	1.01E-003	180.5	5.126	5.930	6.861	43.5	45.8	48.2
1500	917	3.60E-004	178.2	6.443	6.752	7.077	27.6	28.4	29.2
1650	922	5.60E-004	180.9	6.282	6.626	6.990	25.9	26.9	28.0

EW trail #3 ->W

-300	847	3.51E-004	182.9	4.190	4.408	4.637	30.6	31.4	32.3
0	855	9.35E-004	170.1	5.570	6.080	6.636	23.1	24.4	25.9
300	928	4.05E-004	165.0	5.291	5.540	5.800	5.9	6.6	7.4
600	996	2.38E-003	181.1	5.134	5.500	5.893	.6	1.3	2.6
900	947	1.30E-003	160.4	5.037	5.580	6.180	26.8	28.3	29.9
1200	915	1.09E-003	162.3	5.790	6.476	7.244	24.4	26.0	27.8
1500	874	1.36E-003	178.4	5.640	6.431	7.332	33.4	35.5	37.7
1800	869	7.57E-004	178.7	5.325	5.814	6.349	38.4	39.8	41.4

EW trail #4 (Almagosa Springs) ->E

300	857	3.72E-003	160.8	7.770	8.471	9.236	.2	.9	4.5
700	724	1.59E-003	176.2	5.339	5.933	6.593	3.4	4.9	7.0

Road NE of Alifan Quarry ->NE

300	341	5.50E-004	182.1	3.800	4.078	4.376	25.9	27.0	28.1
600	368	3.90E-004	181.4	3.290	3.435	3.587	13.6	14.4	15.1
900	387	6.34E-004	177.5	3.011	3.155	3.306	6.2	6.9	7.7

Bush line #1 ->S

300	817	8.52E-004	180.5	4.316	4.674	5.062	28.5	29.8	31.2
600	821	8.90E-004	177.7	3.948	4.291	4.663	31.8	33.2	34.6
900	831	2.27E-003	167.3	3.814	4.297	4.841	25.3	27.1	29.0
1200	849	3.59E-004	175.5	3.599	3.759	3.926	21.1	21.8	22.5
1500	868	3.49E-004	176.8	3.546	3.681	3.822	15.2	15.9	16.5
1800	883	2.80E-003	175.0	3.263	3.604	3.980	9.9	11.4	13.2
2100	906	8.64E-004	176.3	3.512	3.701	3.900	5.1	5.9	6.8
2400	910	1.87E-003	176.4	3.371	3.645	3.942	3.5	4.5	5.8
2700	912	1.44E-003	173.3	4.135	4.411	4.705	10.4	11.6	12.8
3000	829	2.35E-003	170.4	4.917	5.890	7.055	37.3	40.0	42.9
3100	824	1.07E-003	170.7	6.134	6.990	7.965	39.4	41.4	43.5
3900	825	1.12E-003	179.3	2.592	3.080	3.660	42.0	44.2	46.6
4200	787	2.05E-004	179.3	3.761	4.069	4.403	45.4	46.6	47.8
4500	794	1.54E-004	177.3	5.263	5.581	5.917	49.6	50.5	51.4
4800	781	3.37E-004	178.4	5.735	6.293	6.905	47.1	48.6	50.1
5100	765	7.03E-005	173.7	5.127	5.362	5.608	49.7	50.4	51.1
5400	807	4.52E-004	176.7	5.546	5.957	6.398	27.2	28.3	29.5

Bush Line 1NS extension ->S

300	816	9.15E-004	169.5	6.929	7.400	7.903	24.4	25.5	26.7
600	811	6.25E-004	174.2	6.484	6.860	7.257	26.0	27.0	28.1
900	813	1.29E-004	178.4	5.830	5.980	6.133	25.9	26.4	26.9
1200	804	2.07E-003	179.2	4.278	4.763	5.302	21.4	23.2	25.2
1500	819	4.83E-003	178.0	4.073	4.667	5.347	4.6	6.4	9.0
1800	851	7.36E-004	172.3	4.973	5.186	5.409	2.2	2.7	3.2

EW trail #1 ->W

300	896	1.73E-003	176.4	4.034	4.324	4.636	3.3	4.1	5.2
600	924	2.28E-003	169.2	9.85	10.50	11.20	.1	.4	2.5
900	909	2.24E-002	176.9	7.23	9.05	11.33	4.00E-001		
1200	919	3.78E-003	176.8	8.91	9.73	10.62	0.0	.4	41.2
1500	909	3.88E-003	180.7	6.573	7.277	8.057	4.8	6.5	8.7

Appendix D: Tabulated EM Profiling Data

Each line of this data set consists of one of the following three groups of information:

1. Line title

2. two pairs of station numbers and topographic elevations corresponding to the locations of each of the two loops used to obtain a particular set of data. The exact format is four fields of five in the order (from left to right) transmitter station number, elevation of transmitter, receiver station number, and elevation of receiver. Blanks for the elevation fields are treated as 'no data'.

3. five pairs of in-phase and out-of-phase data values measured with the Max/Min equipment. The exact format is 10 field of five, or five pairs of two fields of five. Each pair is in the order (left to right) in-phase measurement and out-of-phase measurement. Each pair corresponds to one of five frequencies in the order (again left to right) 222, 444, 888, 1777, and 3555 Hertz.

4.

Each line is headed by a line title and each measurement consists of two lines, one with the station numbers and elevations and the other with the data. One unique type of measurement is denoted with the word 'CALIBRATION' in the first 11 columns of the line title. Such a title is followed with a data line consisting of values by which all following measurements are normalized.

The calibration equation is as follows:

$$A + iB = [(1+C/100) + i*D/100] / [(1+E/100) + i*F/100]$$

$$\text{corrected in-phase} = 100*(A-1)$$
$$\text{corrected out-of-phase} = 100*B$$

where C = field in-phase measurement,
D = field out-of-phase measurement,
E = calibration in-phase measurement, and
F = calibration out-of-phase measurement.

```
High Road ->S
-600  650 -1200  650
+12.0  0.0+20.0 -3.0+18.0 -5.0+15.0 -4.5+13.0 -2.5
-300  650  -900  650
+16.0 -2.0+20.0 -4.0+17.0 -5.0+13.0 -5.5+12.0 -5.5
 00   650   600  635
+27.0 +2.0+19.0 -5.5+13.0-11.0 +6.0-11.0 +2.0-10.0
 300  635   900  660
+26.0  0.0+26.0 -8.0+11.0-14.0 +0.5-16.0-23.0-12.0
 600  635  1200  665
+26.0  0.0+26.0 -9.0 +9.5-18.0 -3.0-19.0 -9.0-15.0
 900  660  1500  675
+27.0 +1.0+26.0 -8.0+11.0-14.0 +2.0-14.0 -3.0-14.0
1200  665  1800  685
+28.0 +1.0+26.0 -9.0+10.0-14.0 +0.5-13.0 -3.0-12.0
1500  675  2100  685
+28.0 -3.0+23.0-14.0 +3.0-22.0 -8.0-15.0-12.0-12.0
1800  685  2400  680
+30.0 -9.0+12.0-27.0 -8.0-33.0-17.0-25.0-24.0-15.0
2100  685  2700  680
+30.0-19.0 +5.0-43.0-19.0-47.0-39.0-32.0-48.0-21.0
2400  680  3000  680
+15.5-36.0-17.0-60.0-52.0-52.0-64.0-31.0-73.0-18.0
2700  680  3300  680
 -4.0-48.0-37.0-62.0-72.0-40.0-75.0-23.0-82.0-12.0
3000  680  3600  680
 -9.0-58.0-52.0-72.0-91.0-39.0-85.0-11.0-87.0 -4.5
3300  680  3900  655
+13.0-52.0-27.0-83.0-90.0-60.0-92.0-14.0-85.0 -5.0
Mt. Alifan NS
  00  810   600  780
+12.0 +5.0+13.5 +1.0+13.5 -1.0+11.0 -2.0+11.5 -2.0
NS road #2 ->S
 600  735    00  720
+14.0 +4.0+15.5 +0.5+15.0 -1.5+12.0 -2.0+13.0 -1.5
 900  740   300  730
+14.5 +3.0+15.0 -1.5+13.0 -5.0 +8.0 -4.0 +8.0 -2.0
1200  760   600  735
+14.5 +2.0+15.5 -2.0+13.0 -6.0 +6.5 -5.5 +5.5 -3.0
1500  760   900  740
+15.0 +4.0+15.5 -2.0+13.0 -5.5 +7.0 -6.0 +6.5 -4.5
1800  765  1200  760
+15.0 +3.0+16.0 -1.0+14.5 -5.0+10.0 -5.0 +9.0 -5.5
2100  775  1500  760
 15.0 +3.0+16.5 -1.5+14.0 -5.0 +9.0 -5.5 +9.0 -4.5
2400  800  1800  765
+35.0 +3.0+38.0 -2.0+35.0 -6.0+28.0 -7.0+26.0 -6.0
2700  810  2100  775
+34.0 +3.0+38.0 -3.0+34.0 -8.0+26.0 -8.0+15.0 -6.5
3000  810  2400  800
+27.0 -0.5+32.0 -4.5+27.0 -9.0+11.0 -9.0 +9.0 -7.5
3300  810  2700  810
+25.0 +1.0+23.0 -6.5+10.0-10.0 +3.0 -9.0  0.0 -7.0
Alifan Quarry ->SW
 600  570    00  500
+27.0 -3.0+14.0-13.0 +3.0-16.0 -5.0-12.5 -8.0-10.0
 900  580   300  540
+23.0 -3.0+10.0-10.5 +2.0-12.5 -5.5-11.0 -9.5 -9.5
1200  580   600  570
+14.5 -3.0+10.0-11.0 +1.0-13.0 -6.0-12.0-11.0-10.0
1500  560   900  580
+17.0 -9.0 +7.0-23.0 -8.5-25.0-12.0-18.0-17.0-13.0
Alifan Quarry Borrow Pit ->NW
```

```
 600  460    00  450
+25.0 -4.0+12.0-15.0 -1.0-21.0-12.0-14.5-16.0-10.0
Blandy Road ->NE
 600  515    00  550
+13.0-30.0-11.5-51.0-42.0-48.0-58.0-27.0-63.0-14.0
 900  495   300  530
+28.0-19.0 +2.0-38.0-18.0-39.0-34.0-27.0-42.0-17.0
1200  480   600  515
+29.0-10.0 +9.0-26.0 -8.0-26.0-12.0-18.0-17.0-15.0
1500  470   900  495
+27.0 -8.0 +9.0-21.0 -4.0-22.0-13.0-16.0-13.0-14.0
1800  460  1200  480
+26.0 -7.5 +9.5-15.0 -1.0-17.0-11.0-16.0-17.0-14.0
2100  430  1500  470
+29.0 -7.0+20.0-17.0 +8.0-18.0 -2.0-15.0 -7.0-13.0
2400  420  1800  460
+32.0 -8.0+22.0-22.0 +7.0-24.0 -3.0-16.0 -9.0-14.0
2700  410  2100  430
+31.0-11.0+19.0-24.0 +3.0-26.0 -7.0-18.0-14.0-15.5
3000  400  2400  420
+33.0-18.0+14.0-37.0-11.0-33.0-22.0-23.0-28.0-15.0
Road NE of Alifan Quarry ->NE
 600  430    00  480
+23.0-13.0+11.0-30.0 -9.0-31.0-22.0-23.0-28.0-15.0
 900  415   300  440
+14.0-40.0-19.0-53.0-51.0-42.0-59.0-24.0-64.0-15.0
1200  410   600  430
+12.0-55.0-34.0-65.0-70.0-40.0-73.0-19.0-77.0-12.0
Bush line #1 ->S
 600  930    00  915
+28.0-13.0+15.0-30.0 -6.0-32.0-18.0-25.0-26.0-24.0
 900  930   300  930
+33.0-14.0+20.0-28.0 +2.0-29.0 -9.0-25.0-18.0-23.0
1200  920   600  930
+56.0-11.0+42.0-32.0+21.0-34.0 +7.0-24.0 -2.0-27.0
1500  920   900  930
+34.0-26.0+11.0-44.0-19.0-40.0-32.0-26.0-38.0-21.0
1800  925  1200  920
+27.0-37.0 -5.0-56.0-42.0-44.0-53.0-26.0-58.0-18.0
2100  925  1500  920
+28.0-42.0-11.0-64.0-54.0-46.0-61.0-21.0-65.0-11.0
2400  950  1800  925
+23.0-48.0-21.0-68.0-65.0-46.0-69.0-22.0-73.0-14.5
2700  960  2100  925
+18.0-48.0-23.0-67.0-65.0-47.0-70.0-20.0-70.0-11.0
3000  950  2400  950
+37.0-36.0 +7.0-60.0-39.0-55.0-60.0-29.0-64.0-12.5
3300  980  2700  960
+53.0 +7.5+52.0-10.0+38.0-23.0+24.0-17.0+16.0-13.0
3400  985  2800  960
+51.0 +9.5+53.0 -6.0+42.0-17.0+28.0-17.0+18.0-14.0
4200  970  3600 1010
+33.0 -5.0+27.0-15.0+14.0-18.0 +2.0-13.0 -3.0 -6.0
4500  940  3900 1000
+30.0 +1.0+28.0 -9.0+19.0-13.0+11.0-10.5+11.0 -9.0
4800  960  4200  970
+34.0 +2.5+34.0 -6.5+27.0-12.5+19.0-13.0+16.0-14.0
5100  980  4500  940
+30.0 +4.0+32.0 -4.0+26.0-10.0+19.0-11.0+17.0-14.0
5400  930  4800  960
+40.0 +4.5+42.0 -4.0+38.0-11.0+27.0-11.0+24.0-10.0
5700  900  5100  980
+33.0  0.0+32.0-12.5+19.0-25.0 +3.0-22.0 -2.0-16.0
EW trail #1 ->W
 600  910    00  925
+23.0-48.0-18.0-72.0-70.0-55.0-78.0-20.0-77.0-12.0
```

```
 900  930   300  925
+60.0 -7.0+54.0-51.0 +2.0-78.0-63.0-70.0-82.0-26.0
1200  940   600  910
+38.0-26.0+19.0-65.0-39.0-88.0-98.0-58.0-99.9-13.0
1500  920   900  930
+41.0-18.0+28.0-57.0-23.0-85.0-83.0-64.0-99.9-17.0
1800  930  1200  940
+27.0-23.0+11.0-55.0-38.0-68.0-75.0-45.0-80.0-12.0
Bush line #2 (Sinaje)->S
 600  995    00  940
+51.0-35.0+22.0-60.0-23.0-57.0-43.0-33.0-48.0-23.0
 900 1000   300  980
+32.0-29.0+10.0-46.0-22.0-43.0-36.0-32.0-48.0-30.0
1200 1000   600  995
+41.0-25.0+20.0-40.0 -6.0-40.0-20.0-30.0-26.0-20.0
1500 1005   900 1000
+35.0-10.5+24.0-24.0 +8.0-27.0 -5.0-24.0-13.0-21.0
1800 1000  1200 1000
+32.0-15.0+18.0-32.0 -3.0-36.0-20.0-32.0-32.0-31.0
2100 1015  1500 1005
+28.0-12.5+16.0-26.0 -1.0-31.0-18.0-31.0-22.0-28.0
2400 1025  1800 1000
+38.0-11.0+28.0-29.0 +8.0-36.0 -9.0-33.0-23.0-31.0
2700  995  2100 1015
+45.0 -3.0+40.0-22.0+25.0-31.0 +8.0-31.0 -5.0-33.0
3000 1010  2400 1025
+42.0 +6.0+42.0 -5.5+35.0-13.0+26.0-11.5+23.0-10.5
3300 1010  2700  995
+47.0 +9.0+52.0 -4.5+43.0-10.5+28.0-15.0+24.0-10.5
3600 1050  3000 1010
102.0 +8.0103.0 -7.0100.0-25.0+77.0-26.0+70.0-14.0
3900 1090  3300 1010
+68.0 +1.0+68.0-13.5+55.0-29.0+33.0-26.0+25.0-15.0
4200 1095  3600 1050
+31.0 +5.5+33.0 -5.5+24.0-13.0+15.0-11.0+13.0 -9.0
4500 1110  3900 1070
+32.0 +3.0+33.0 -8.0+26.0-20.0+19.0-23.0 -1.0-25.0
4800 1140  4200 1095
+24.0-10.0+18.0-31.0 -9.0-45.0-39.0-34.0-47.0-10.5
5100 1160  4500 1110
+22.0-13.0+14.0-38.0-18.0-54.0-55.0-40.0-62.0-13.0
5400 1180  4800 1140
+35.0 +6.5+42.0 -9.5+30.0-35.0 -2.0-42.0-25.0-28.0
5700 1185  5100 1160
+33.0 +2.5+37.0-14.0+22.0-37.0-11.0-38.0-27.0-21.0
6000 1190  5400 1180
+28.0 -3.0+28.0-23.0 +9.0-44.0-28.0-43.0-45.0-23.0
6300 1195  5700 1185
+28.0 -1.0+30.0-22.0+12.0-45.0-26.0-48.0-50.0-30.0
6600 1200  6000 1190
+33.0 +2.0+37.0-18.0+20.0-50.0+23.0-55.0-52.0-36.0
6900 1200  6300 1195
+37.0 +1.5+42.0-23.0+23.0-52.0-23.0-55.0-48.0-30.0
7200 1200  6600 1200
+28.0-15.0+20.0-40.0-15.0-62.0-57.0-48.0-70.0-17.0
7500 1210  6900 1200
+29.0-17.5+20.0-46.0-21.0-70.0-72.0-56.0-85.0-16.5
7800 1240  7200 1200
+38.0 -1.0+43.0-24.0+27.0-60.0+23.0-75.0-75.0-56.0
8100 1250  7500 1210
+33.0 -1.0+37.0-25.0+19.0-57.0-30.0-72.0-75.0-48.0
EW trail #2 ->W
 400  980  -200  930
+25.0 -1.0+27.0 -6.0+22.0-11.0+15.0-12.5+13.0-14.0
 600 1045    00  940
+23.0 +5.0+25.0 -2.0+21.0 -8.0+13.0 -9.0+12.0 -8.0
```

```
 900 1040   300 1000
+24.0 +3.0+26.0 -4.0+20.0 -9.5+13.0-10.0+10.0 -9.0
1200 1020   600 1045
+28.0  0.0+27.0 -7.5+21.0 +9.0+11.0-14.0 +6.0-14.0
1500 1000   900 1040
+32.0 -0.5+30.0 -2.5+21.0-15.0 +9.0-15.0 +4.0-12.5
1800 1010  1200 1020
+34.0 -6.0+28.0-23.0+11.0-34.0 -9.0-32.0-23.0-27.0
1950 1010  1350 1010
+31.0-10.0+21.0-29.0 -1.0-38.0-22.0-35.0-36.0-28.0
```