UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Description of digital data from a helicopter geophysical survey to map brine contamination--Brookhaven Oil Field, Lincoln County, Mississippi

by

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and

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NOTICE

Introduction

The Branch of Geophysics of the U.S. Geological Survey (USGS) has contracted airborne geophysical studies near Brookhaven, Mississippi, (fig. 1). The Brookhaven oil field and parts of the surrounding area in Mississippi were selected as a test area for this Applied Research and Development Project funded by the Environmental Protection Agency (EPA). This study is part of a program to evaluate the use of various geophysical methods in the detection and delineation of near-surface brine pollution associated with oil fields. This project was specifically designed to evaluate the use of airborne electromagnetic (AEM) methods to map subsurface distribution of brine. Additionally, the signal-to-noise capabilities of the AEM system were evaluated since the area has many sources of cultural noise. Sources of electrical noise typically associated with oil fields are powerlines, pipe lines, radio transmissions, rail lines, and fences.

Previous ground electrical surveys in the area (Nacht and Barrows, 1985) were studied to design optimum parameters for the AEM survey. Another objective of the survey was to use total field magnetic measurements in estimating the locations of abandoned cased wells that may play a role in the distribution of subsurface brine contamination.

The survey was carried out by DIGHEM Surveys and Data Processing Inc. of Ontario, Canada, using a helicopter airborne geophysical system. The helicopter-borne geophysical system consisted of an active electromagnetic system using horizontal coil configurations at 56000, 7200, and 900 Hz for resistivity mapping of the predominantly layered-earth study area. Passive electromagnetic systems (measuring VLF and 60 Hz signals) and a total-field cesium magnetometer were used to help locate sources of cultural noise and steel cased oil wells.

This report presents general background information of the survey area and the geophysical survey. The contractors report is included as Appendix A, reference to the digital data archive and the description of the digital data format are given. Reprocessed apparent resistivity data from the original data received from the contractor, are given as grey scale contoured maps for each frequency (figs. 2-4). Magnetic data are given as a contoured reduced (IGRF and local gradient removed) total field map (fig. 5). VLF data are given as a contoured filtered total field map (fig. 6). An evaluation of the survey results is given in a report to the Environmental Protection Agency (Interagency Agreement DW-14932583) (Smith and others, 1988).

General Background

In the early days of petroleum production, well locations were not always recorded, or only described in general terms. Some of the recorded locations are erroneous or records are not readily available. Abandoned, dormant or unknown well locations can present a significant problem in petroleum regions where the density of wells can be high. In addition, faulty wells where casings are cracked or corroded may cause problems in leakage, and in many cases their locations are unknown.

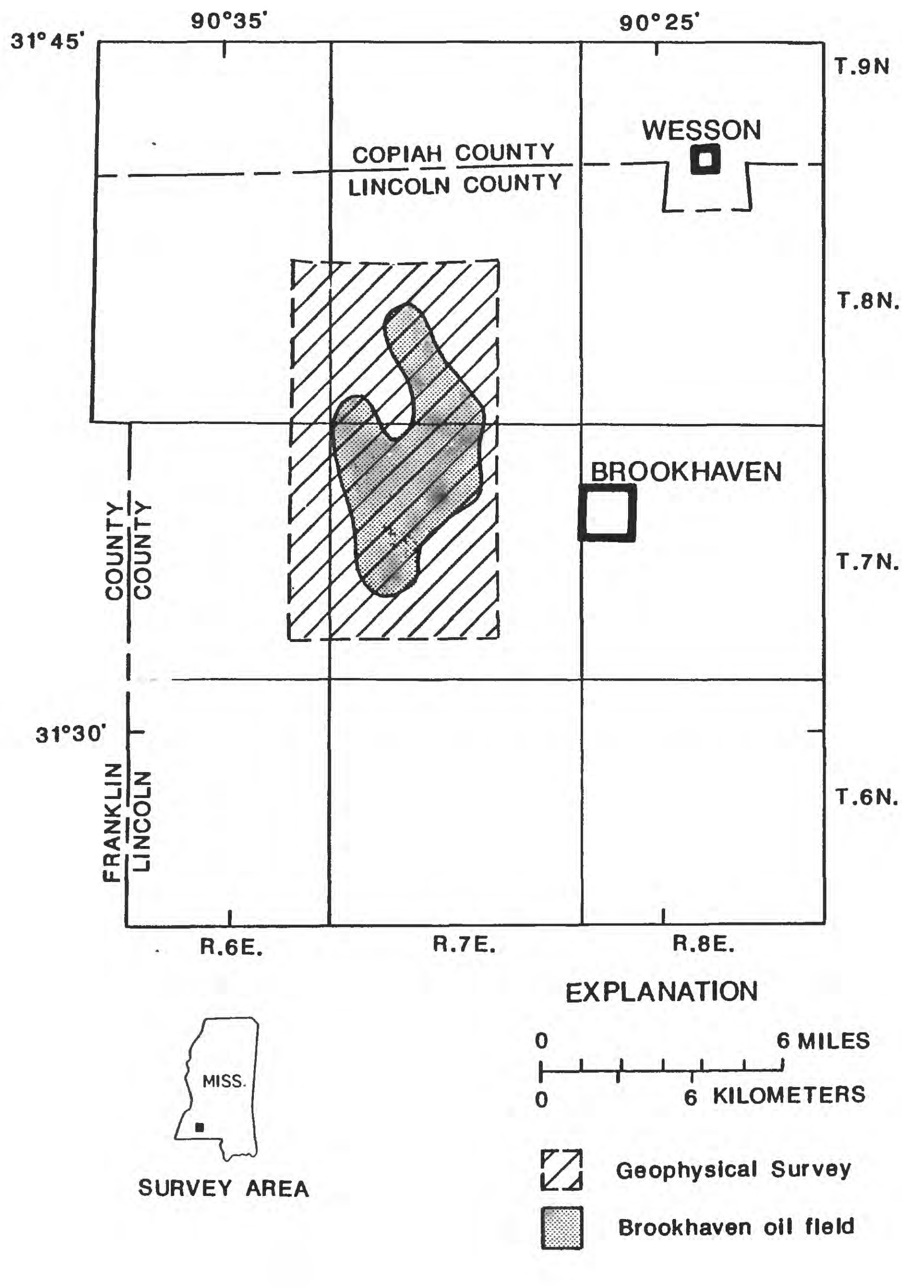

Figure 1. Map showing the location of the Brookhaven oil field and the coverage of the helicopter geophysical survey.

A general estimate done by the EPA in 1979 determined that there were about 500,000 industrial, commercial, agricultural, municipal and domestic wells in the United States injecting fluids into the subsurface. Also it was estimated that at least 5,000 new injection wells were being constructed every year. Injection pressures can reach high levels depending on the depth of injection and the porosity and permeability of the formation at the injection zone. Injection of fluids can contaminate freshwater aquifers by at least two methods. If the injection well is improperly constructed or maintained it can allow leakage of fluids at various levels directly into shallow freshwater aquifers. Secondly, nearby dormant wells, improperly plugged wells, or vertical fault zones can act as conduits that allow saline connate water or injected fluid to migrate upwards from the injection zone to overlying freshwater aquifers, due to the increased pressures.

The Environmental Protection Agency (EPA), as required by the Safe Drinking Water Act (1979), issued the Underground Injection Control Regulations (UIC) which regulate injection wells for the protection of actual or potential underground sources of drinking water. The UIC regulations state that for all new or proposed injection well sites, a radius of review must be established within which a search must be made, for possible conduits between the injection stratum and the overlying aquifers containing potable water.

The Brookhaven Oil Field is located in northwestern Lincoln County, west of Brookhaven, Mississippi and covers an area of about 15 mi^2. The oil field came into production in 1943 and its peak production from about 80 wells occurred in 1949. Production gradually decreased to about 20 producing wells in 1984. Brines or connate waters containing high concentrations of dissolved solids are extracted along with oil from the lower part of the Cretaceous Tuscaloosa Formation. The predominate ions in the brines are sodium and chloride but there may be relatively large concentrations of the minor ions, bromide, strontium, and barium present. The brines in the oil producing formations characteristically have dissolved solids contents that range from 157,000 to 163,000 milligrams per liter as compared to less than 20 mg/l for uncontaminated water on the surface (Kalkhoff, 1986).

Since oil production began, disposal of approximately 54.2 million barrels of brine has posed a threat of contamination to shallow freshwater aquifers and streams in and near the oil field (Kalkhoff, 1986). Surface dumping of brine in the past has threatened the water quality in streams. Evaporation ponds pose a threat by leakage into shallow ground-water aquifers and by migration into nearby streams. Injection methods for disposal can contaminate freshwater sources by several mechanisms including defective or inadequate casing in the well causing brine to leak directly into shallow aquifers. Additionally deep saline waters may migrate upward due to increased pressure in the injection zone along abandoned or improperly plugged production wells or subsurface vertical fractures (Kalkhoff, 1986).

General Geology and Hydrology

The near-surface geologic units in the Brookhaven area consist of unconsolidated sedimentary deposits of Tertiary and Quaternary age. The major oil producing formation is the lower part of the Cretaceous Tuscaloosa Formation. The two units that serve as aquifers are the Hattiesburg Formation of Miocene age and the Citronelle Formation of Pliocene age. Two Quaternary units overlying the Citronelle Formation consist of loess and alluvium.

The Hattiesburg Formation in this area consists of discontinuous sands separated by confining layers. The sands are fine-to-coarse-grained and the confining layers are composed of silt and clay. The Citronelle Formation overlies the Hattiesburg Formation and is exposed at places on the surface. It consists of discontinuous sand and gravel units separated by sandy clay lenses (Kalkhoff, 1986).

Gravels of the Citronelle Formation and three sand layers in the Hattiesburg Formation are the main sources of freshwater for domestic supplies in this area. A hydrologic investigation to define areas of brine contamination in the shallow aquifers and streams that drain the Brookhaven Oil Field was conducted by the USGS from October 1983 to September of 1984 (Kalkhoff, 1986). This study concluded that the history of brine disposal has contaminated the Citronelle aquifer and the Hattiesburg aquifers to a depth of at least 300 ft. Approximately five square miles of the shallow Citronelle Formation contains water with higher than normal (greater than 20 mg/l) chloride concentrations. Contaminated water has moved from the source laterally through the Citronelle aquifer to discharge into streams draining the oil field and has moved vertically into the underlying Hattiesburg aquifer (Kalkhoff, 1986).

Previous Geophysical Surveys

Ground Electromagnetic (EM) surveys have demonstrated that brine within a sequence of sedimentary rocks is characterized by higher electrical conductivity (low resistivity) (Nacht and Barrows, 1985). Concentrated brine generally has a lower resistivity than other earth material. Thus the replacement of freshwater by concentrated brine lowers the resistivity of rocks due to sodium chloride content of the brine. This electrical contrast makes it possible for EM methods to be useful in mapping conductive brine bearing units within less conductive units.

Previous ground electrical surveys made in and near the oil field by Nacht and Barrows (1985) were studied to plan the helicopter electromagnetic (HEM) survey. A set of 44 Wenner DC resistivity soundings were reinterpreted using algorithms of Zohdy and Bisdorf (1975). Along a north-south profile the depth/resistivity section shows extremely low interpreted resistivities extending to a depth of about 10 meters correlating with an area of known shallow brine contamination (Kalkhoff, 1986). Becker and Morrison (1987) interpreted the shallow resistivity soundings in order to input parameters for theoretical modeling of different airborne EM methods. They concluded that brine contaminated lithologies have a lower resistivity by a factor of 10 than areas that are uncontaminated.

Airborne Geophysical Survey

The U.S. Geological Survey accepted proposals and awarded the contract to DIGHEM Surveys and Data Processing of Canada for a helicopter airborne survey of the Brookhaven, Mississippi area. The survey area, located west of Brookhaven (fig. 1), covering the Brookhaven Oil Field and adjacent areas is about 54 square miles in dimension. The survey was specifically designed to evaluate the use of electromagnetic measurements for mapping near-surface brine pollution, although total field magnetic measurements were also taken to evaluate the utility of the magnetic method for locating cased wells. The helicopter survey was flown using a 1/8 mile flight-line spacing in an east-west direction. Two lines were flown north-south through the survey area in order to check and adjust base level changes in the data. The average flight elevation during the survey was 150 ft above terrain. The bird containing the magnetic sensor was towed 50 ft below the aircraft. The Lama turbine helicopter used in this survey flew at an average air speed of 70 mph. The navigation system used was a ultra high frequency (UHF) radio system. The system uses two to three transponders located outside the survey area. Real-time navigation information is displayed for the helicopter pilot and digitally recorded. A video camera recorded images directly below the aircraft.

Geophysical Instrumentation

Active Source Electromagnetic System

The term active source used in connection with airborne EM surveys indicates that both the EM transmitter and receiver are part of the geophysical system. The DIGHEM 4 EM system employed in the geophysical survey, is the primary EM system that was tested for possible mapping of subsurface brine bearing water. In this system the transmitter and receiver are horizontal coil pairs operated at frequencies of 56000, 7200 and 900 Hz. The horizontal coil configuration is ideally suited to mapping variations in subsurface resistivities in the Brookhaven area since these variations are confined to horizontal layers. EM measurements were also made with a vertical coaxial tranmsitter-receiver coil system which was not specified in the final contract. This coil system is typically used in mineral exploration to define narrow vertical areas of low resistivity. Further processing of these data will be neeeded to determine possible applications to mapping lateral boundaries between fresh and brine bearing waters.

The broad range of frequencies in the EM system yield information about resistivity variations from near surface (10's of feet) to depths on the order of 200 to 300 feet. The depth-of-penetration or mapping generally is deepest for the lower frequencies (900 Hz) and shallowest for the higher frequencies (56,000 Hz).

Calibration of Airborne EM Measurements

Calibration and system checks of the magnitude of in-phase and quadrature measurements of the AEM system is accomplished by the following methods. In the first method, the system is calibrated on the ground before and after each flight. The transmitter-receiver system is turned on and a small ferrite rod is placed near the receiver coil at a position marked on the bird. The rod produces a known EM signal at each frequency and coil configuration used in the survey.

A second method of calibration uses a small transmitter located approximately half way between the larger transmitter and receiver coils. During the survey, the system operator uses this internal calibration to check for drifts in system electronics.

The third system check is also performed during the survey by flying the system at an altitude sufficient to be out of the influence of the conductive earth. This is primarily a check of the zero levels and is done at the end of each flight line.

Other methods of calibration, not used in this survey, involve flying the system over an area where the electrical structure of the earth is known. The measured responses are then compared to theoretical calculations.

Total Field Magnetometer System

The magnetic field measurement system consists of a magnetometer towed beneath the helicopter and a base station recording magnetometer. The magnetometer used in this survey is a high sensitivity (0.01 nT) Cesium sensor towed about 50 ft. below the helicopter. The sample rate of the Cesium magnetometer was set at 10 per second. The base station magnetometer is a standard proton precession system with a sensitivity of 0.50 nT. The base station magnetometer, located near the Brookhaven airport, provided an analog record of changes in the total magnetic field every five seconds during the geophysical survey. Time dependent variations in the earth's magnetic field were removed from the airborne data using records from the base station magnetometer. During periods when the variations are too fast or too large for proper removal, the survey is interrupted until conditions improve.

Passive Electromagnetic Systems

These systems passively sense electromagnetic signals generated from sources external to the helicopter instrumentation. The two passive systems used in this survey sense very low frequency EM signals transmitted by Navy stations (VLF) and 60 Hz EM signals generated by powerlines. The VLF measurements were made from three transmitting stations located at Cutler, ME, Seattle, WA, and Annapolis, MD. These stations transmit signals at frequencies ranging from 21 kHz to 25 kHz.

The 60 Hz passive EM system is traditionally used in most airborne EM surveys to monitor the location of powerlines which produce signals that corrupt the measurements of other EM systems. However, in this survey, the amplitude of the horizontal and vertical components for the 60 Hz magnetic field was measured and digitally recorded to take advantage of developing technology in EM mapping methods. Recent research by the USGS (Frischknecht and others, 1986) has resulted in a prototype system which uses 60 Hz signals from powerlines to map variations in subsurface resistivity. Based on experience from this research, an informal arrangement was made with the contractor to modify their normal measurement procedure for the 60 Hz system. Normally the gain or amplification of the signals is minimal so that the EM system has significant response only when flown over a powerline or other corrupting EM source. However, for this survey, gains for these channels were increased so that variations in the 60 Hz magnetic field could be measured further away from powerlines. Preliminary inspection of the data in the field and on the digital profile shows that there are significant variations in amplitude of the magnetic fields which may be associated with either subsurface or surficial (cultural) conductive features. Further processing and interpretation needs to be done in order to determine how useful the 60 Hz data might be for mapping subsurface brine.

Data Archive

The data received from DIGHEM have been reprocessed for integrated analysis, and are given in this report as figures 2-6. A report to the Environmental Protection Agency (Interagency Agreement DW-14932583) (Smith and others, 1988) contains an evaluation of the survey and a summary of the results. Digital data on nine track magnetic tape, as received from DIGHEM, are archived at the National Geophysical Data Center (NOAA), 325 Broadway, Boulder, Colorado, 80303, under Brookhaven project number 4153. These data are digital files of all the geophysical data and auxiliary data recorded along each flight line, given as observed parameters and computed parameters. The tapes of the digital profiles contain the following information:

ARCHIVE TAPE DATA STRUCTURE:

RECORDING -	:9-TRACK
DENSITY	:1600 BPI
CHARACTER CODE	:ASCII
RECORD FORMAT	:FIXED BLOCK
LOGICAL RECORD LENGTH	:326 Bytes
BLOCK SIZE	:6520 Bytes
NUMBER OF TAPE VOLUMES	:1

VOL.	LABEL	LENGTH-FEET	# OF FILES
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FILE	# OF BLOCKS	DESCRIPTION OF FILE CONTENTS
1	5127	SURVEY LINES 10010-10731, TIE LINES 19010, 19020

SURVEY DATA FORMAT:

#	PARAMETER	TIME (SEC)	UNITS	MULTI-PLYER	SUB TRACTOR	DEFAULT	FORMAT	BYTES	POSITION
1	LINE						(I8)	8	1- 8
2	FLIGHT						(I8)	8	9- 16
3	FID						(F8.2)	8	17- 24
4	LONG	0.20	DEGREES	1.0	0	-15500	(FLL.5)	11	25- 35
5	LAT	0.20	DEGREES	1.0	0	-15500	(FLL.5)	11	36- 46
6	MAGT	1.00	GAMMAS	10.0	50000	-15500	(I8)	8	47- 54
7	MAG	1.00	GAMMAS	10.0	50000	-15500	(I8)	8	55- 62
8	ALT	0.20	FEET*10	10.0	0	-15500	(I8)	8	63- 70
9	CXIT900	0.20	PPM *10	10.0	0	-15500	(I8)	8	71- 78
10	CXQT900	0.20	PPM *10	10.0	0	-15500	(I8)	8	79- 86
11	CPIT900	0.20	PPM *10	10.0	0	-15500	(I8)	8	87- 94
12	CPQT900	0.20	PPM *10	10.0	0	-15500	(I8)	8	95-102
13	CPIT7200	0.20	PPM *10	10.0	0	-15500	(I8)	8	103-110
14	CPQT7200	0.20	PPM *10	10.0	0	-15500	(I8)	8	111-118
15	CPIT56K	0.20	PPM *10	10.0	0	-15500	(I8)	8	119-126
16	CPQT56K	0.20	PPM *10	10.0	0	-15500	(I8)	8	127-134
17	CXI900	0.20	PPM *10	10.0	0	-15500	(I8)	8	135-142
18	CXQ900	0.20	PPM *10	10.0	0	-15500	(I8)	8	143-150
19	CPI900	0.20	PPM *10	10.0	0	-15500	(I8)	8	151-158
20	CPQ900	0.20	PPM *10	10.0	0	-15500	(I8)	8	159-166
21	CPI7200	0.20	PPM *10	10.0	0	-15500	(I8)	8	167-174
22	CPQ7200	0.20	PPM *10	10.0	0	-15500	(I8)	8	175-182
23	CPI56K	0.20	PPM *10	10.0	0	-15500	(I8)	8	183-190
24	CPQ56K	0.20	PPM *10	10.0	0	-15500	(I8)	8	191-198
25	CXPL	0.20	PPM *10	10.0	0	-15500	(I8)	8	199-206
26	CPPL	0.20	PPM *10	10.0	0	-15500	(I8)	8	107-214
27	CXS	0.20	PPM *10	10.0	0	-15500	(I8)	8	215-222
28	RES56K	0.20	OHM-M	1.0	8000	-155500	(F8.1)	8	223-230
29	DP56K	0.20	M	1.0	0	-155500	(F8.1)	8	231-238
30	RES7200	0.20	OHM-M	1.0	0	-155500	(F8.1)	8	239-246

#PARAMETER		TIME (sec)	UNITS	MULTI- PLYER	SUB TRACTOR	DEFAULT	FORMAT	BYTES	POSITION
31	DP7200	0.20	M	1.0	0	-15500	(F8.1)	8	247-254
32	RES900	0.20	OHM-M	1.0	0	-15500	(F8.1)	8	255-262
33	DP900	0.20	M	1.0	0	-15500	(F8.1)	8	263-270
34	CDT	0.20	MHOS	1.0	0		(I8)	8	271-278
35	VTNAA	0.20	% *10	10.0	0	-15500	(I8)	8	279-286
36	VQNAA	0.20	% *10	10.0	0	-15500	(I8)	8	287-294
37	VENAA	0.20	% *10	10.0	0	-15500	(I8)	8	295-302
38	VTNSS	0.20	% *10	10.0	0	-15500	(I8)	8	303-310
39	VQNSS	0.20	% *10	10.0	0	-15500	(I8)	8	311-318
40	VENSS	0.20	% *10	10.0	0	-15500	(I8)	8	319-326

NOTES FLAG -9999 DENOTES END OF SURVEY LINE

PARAMETER DESCRIPTIONS:

LINE	- SURVEY LINE NUMBER
FLIGHT	- SURVEY FLIGHT NUMBER
FID	- FIDUCIAL COUNTER
LONG	- LONGITUDE LOCATION COORDINATE IN DEGREES
LAT	- LATITUDE LOCATION COORDINATE IN DEGREES
MAGT	- RAW TOTAL FIELD MAGNETICS
MAGE	- PROCESSED TOTAL FIELD MAGNETICS
ALT	- BIRD TO EARTH-SURFACE CLEARANCE
CXIT900	- RAW COAXIAL INPHASE 900 HERTZ
CXQT900	- RAW COAXIAL QUADRATURE 900 HERTZ
CPIT900	- RAW COPLANAR INPHASE 900 HERTZ
CPQT900	- RAW COPLANAR QUADRATURE 900 HERTZ
CPIT7200	- RAW COPLANAR INPHASE 7200 HERTZ
CPQT7200	- RAW COPLANAR QUADRATURE 7200 HERTZ
CPIT56K	- RAW COPLANAR INPHASE 56000 HERTZ
CPQT56K	- RAW COPLANAR QUADRATURE 56000 HERTZ
CXI900	- COAXIAL INPHASE 900 HERTZ
CXQ900	- COAXIAL QUADRATURE 900 HERTZ
CPI900	- COPLANAR INPHASE 900 HERTZ
CPQ900	- COPLANAR QUADRATURE 900 HERTZ
CPI7200	- COPLANAR INPHASE 7200 HERTZ
CPQ7200	- COPLANAR QUADRATURE 7200 HERTZ
CPI56K	- COPLANAR INPHASE 56000 HERTZ
CPQ56K	- COPLANAR QUADRATURE 56000 HERTZ
CXS	- COAXIAL SPHERICS ENVIRONMENTAL MONITOR
CXPL	- COAXIAL POWER LINE MONITOR
CPPL	- COPLANAR POWER LINE MONITOR
RES900	- APPARENT RESISTIVITY 900 HERTZ
DP900	- APPARENT DEPTH 900 HERTZ
RES7200	- APPARENT RESISTIVITY 7200 HERTZ
DP7200	- APPARENT DEPTH 7200 HERTZ
RES56K	- APPARENT RESISTIVITY 56000 HERTZ
DP56K	- APPARENT DEPTH 56000 HERTZ
CDT	- ANOMALY CONDUCTIVITY THICKNESS
VTNAA	- VLF TOTAL FIELD USING CUTLER TRANSMITTER
VQNAA	- VLF QUADRATURE USING CUTLER TRANSMITTER
VENAA	- FILTERED VLF USING CUTLER TRANSMITTER
VTNSS	- VLF TOTAL FIELD USING ANNAPOLIS TRANSMITTER
VQNSS	- VLF QUADRATURE USING ANNAPOLIS TRANSMITTER
VENSS	- FILTERED VLF USING ANNAPOLIS TRANSMITTER

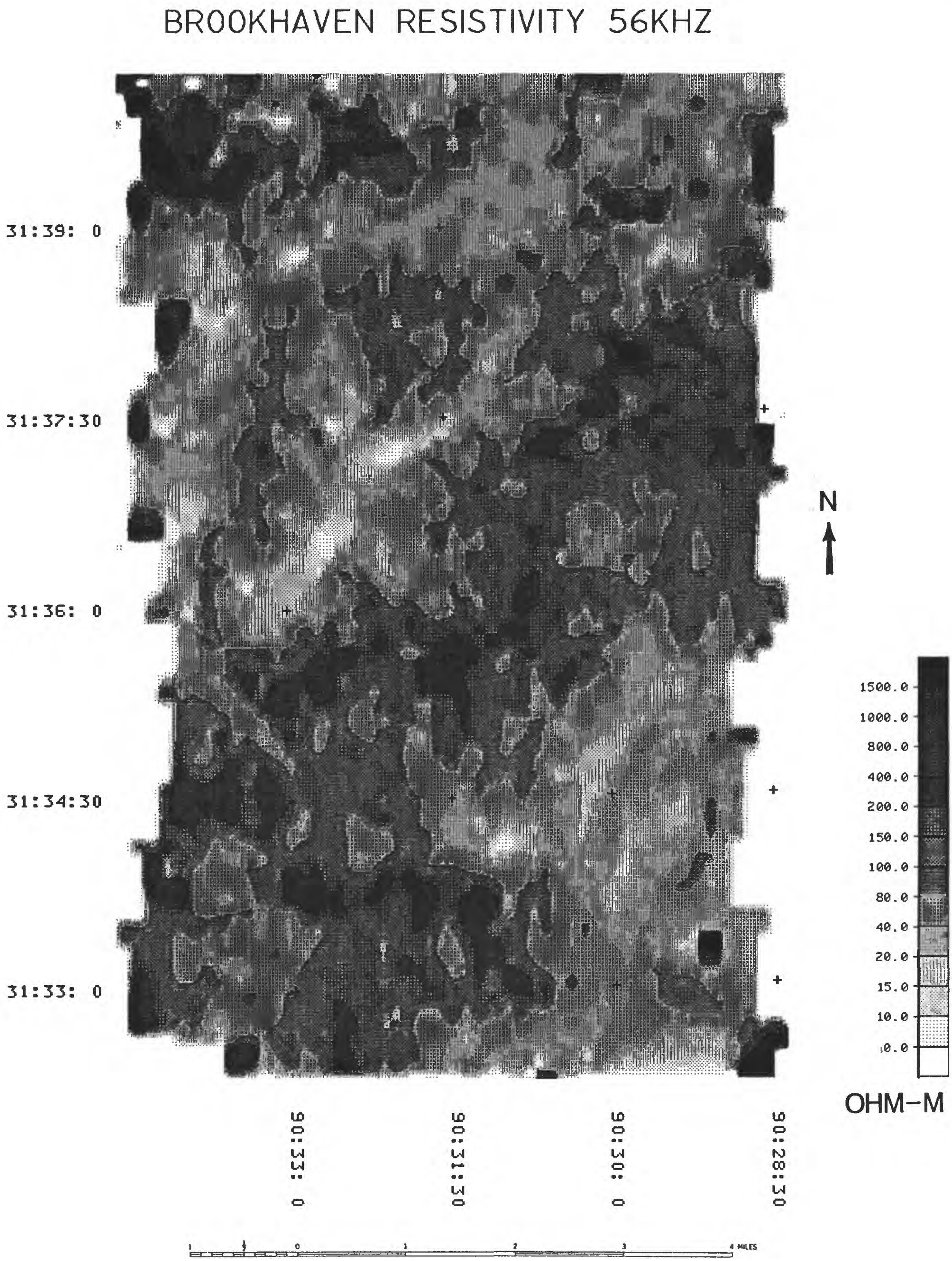

Figure 2. Grey scale apparent resistivity map computed from 56,000 Hz EM data.

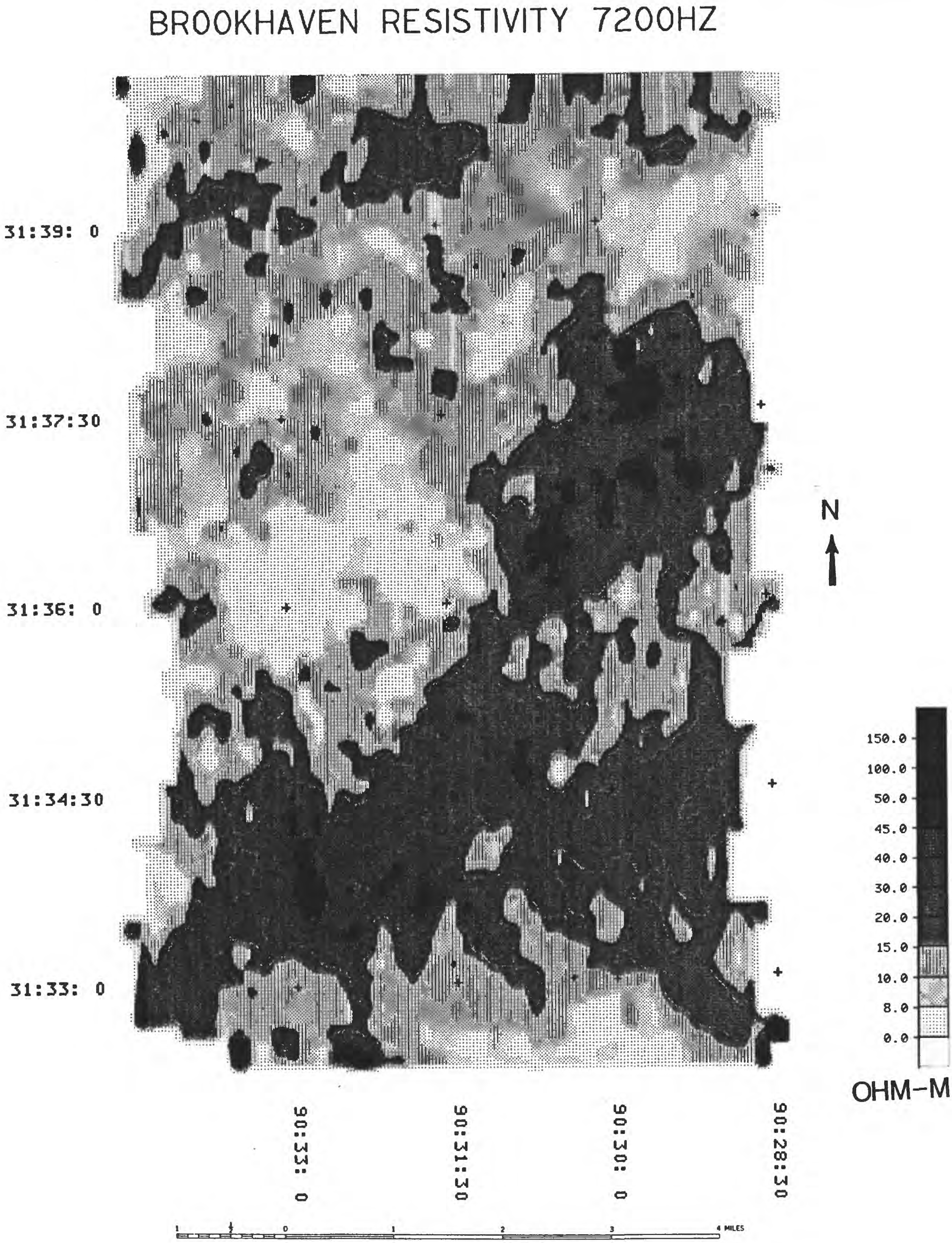

Figure 3. Grey scale apparent resistivity map computed from 7200 Hz EM data.

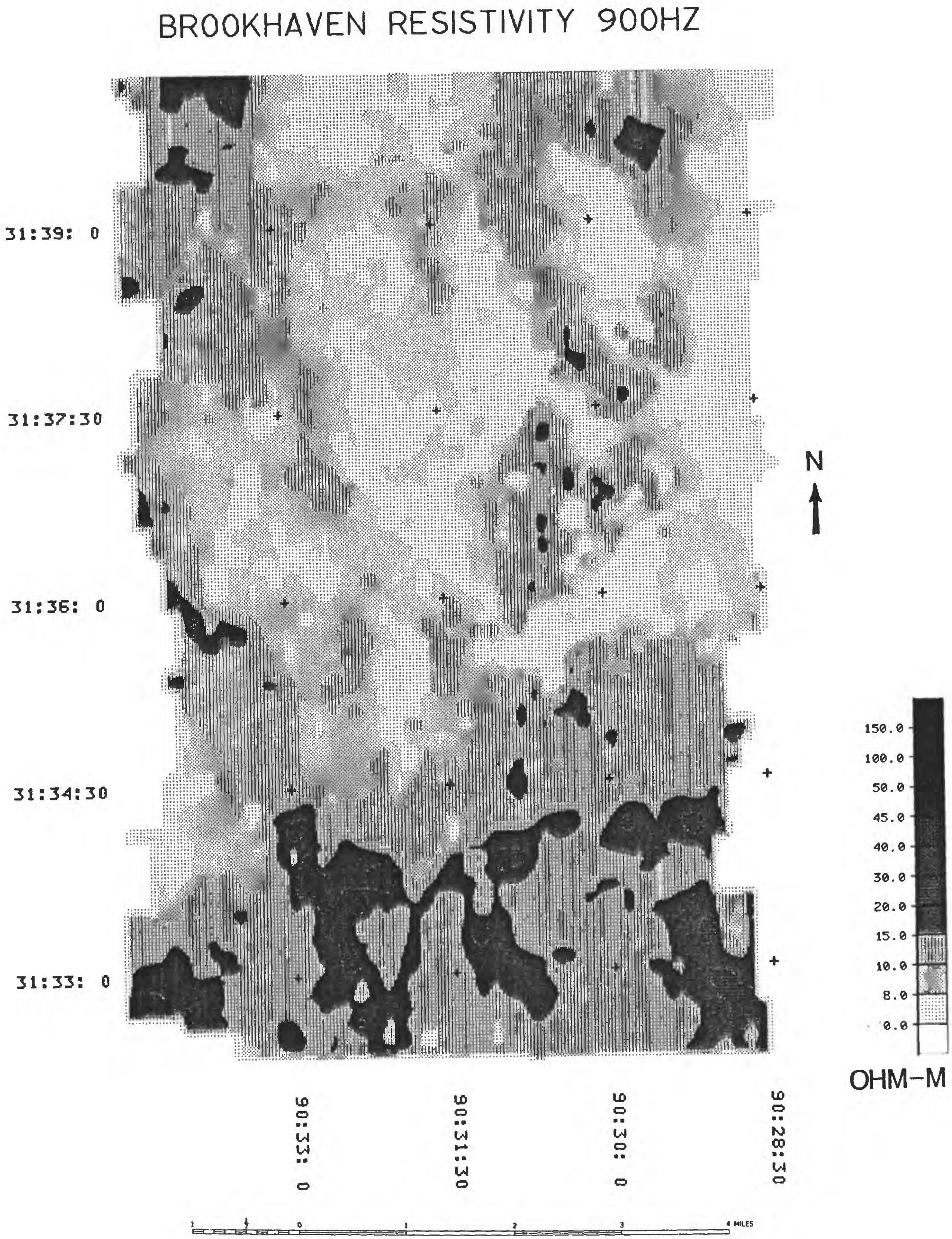

Figure 4. Grey scale apparent resistivity map computed from 900 Hz EM data.

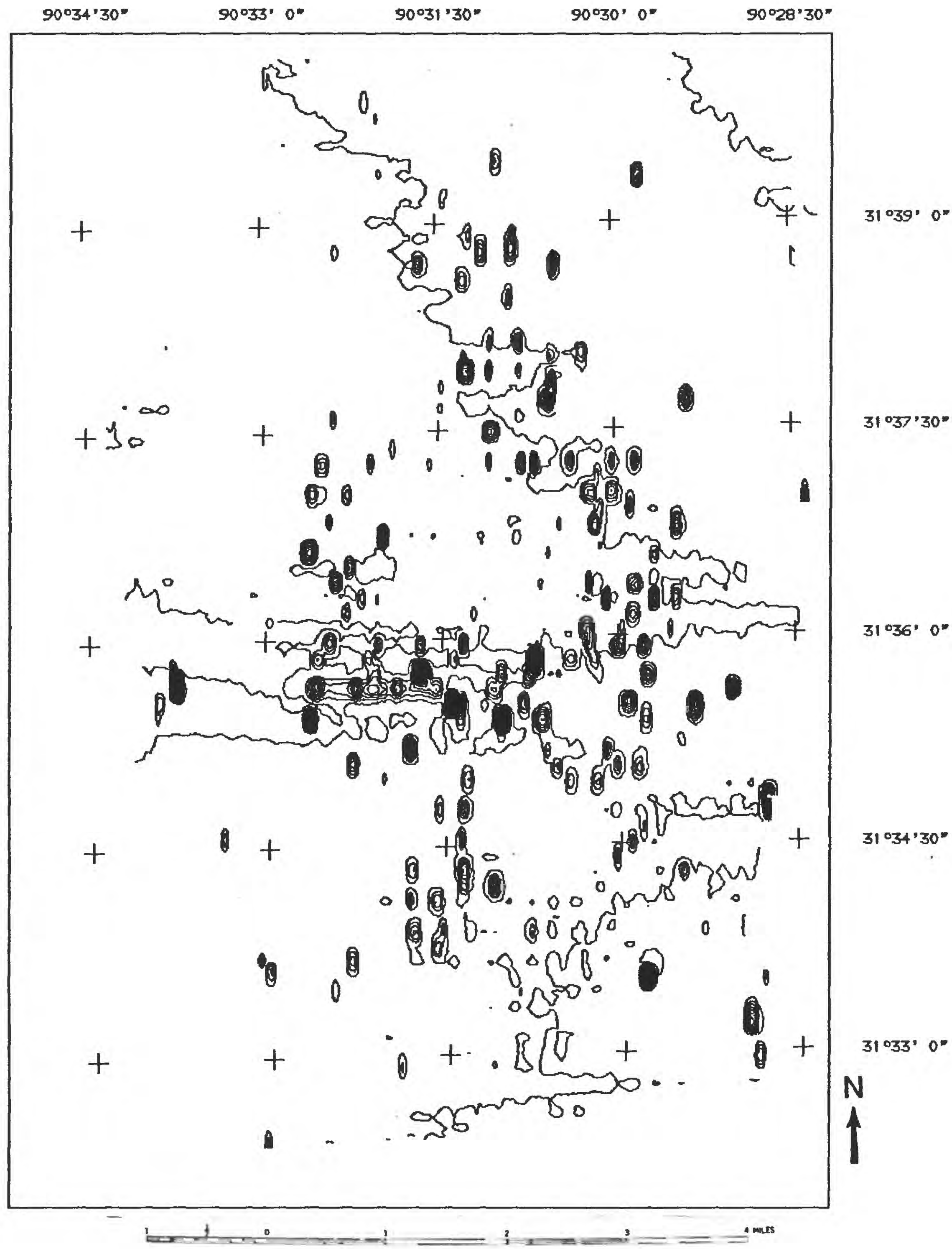

Figure 5. Contour map of reduced total field magnetic data, contour interval is 2nT.

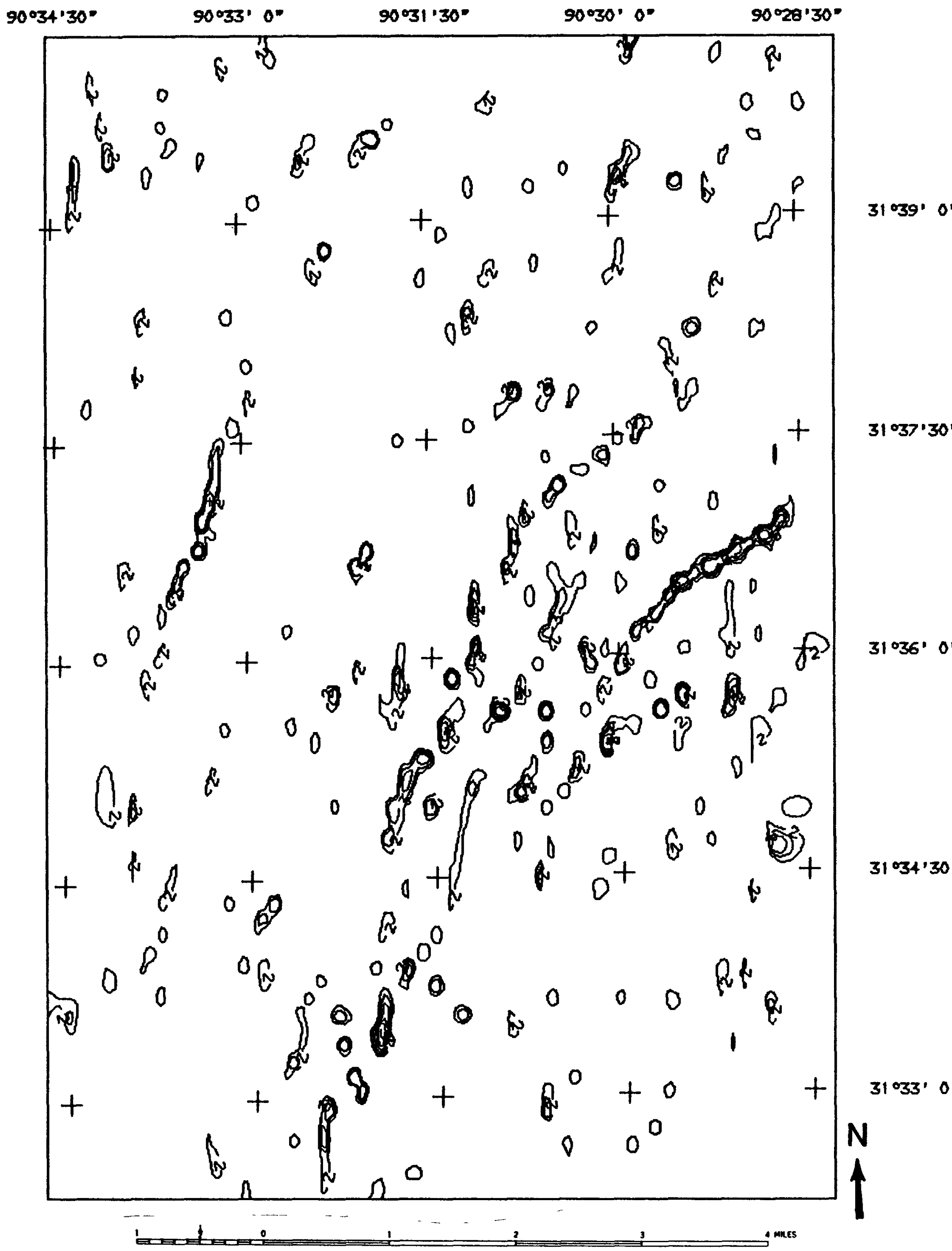

Figure 6. Contour map of filtered VLF total field data

References

Becker, A., and Morrison, H.F., 1987, Detection of brine contamination in the Brookhaven oil field with airborne electromagnetic: EPA Administrative Report, Environmental Monitoring and Systems Laboratory, Las Vegas, Nevada, 29 p.

Frischknecht, F.C., Smith, B.D., Hoover, D.B., and Long, C.L., 1987, New application of geoelectrical methods in mineral resource assessment: U.S. Geological Survey Circular 960, p. 221-247.

Kalkhoff, S., 1986, Brine contamination of shallow ground water and streams in the Brookhaven oil field, Lincoln County, Mississippi: U.S. Geological Survey Water-Resources Investigations Report 86-4087, 57 p.

Nacht, S.J., and Barrows, L.J., 1985, Electrical reconnaissance survey of the Brookhaven Oil Field, Lincoln County, Mississippi: EPA Administrative Report, Environmental Monitoring and Systems Laboratory, Las Vegas, Nevada, 43 p.

Smith, B.D., Mazzella, A., Heran, W.D., and Bisdorf, R.J., 1988, Evaluation of airborne geophysical methods to map brine contamination, Brookhaven oil field, Lincoln County, Mississippi: Environmental Protection Agency.

Zohdy, A.A.R., and Bisdorf, R.J., 1975, Computer programs for the forward calculation and automatic inversion of Wenner sounds curves: National Technical Information Service PB-247-265,27.

Appendix A

Contractors report from DIGHEM Surveys and Processing Inc.

Report #537

DIGHEM IV SURVEY
FOR
U.S. GEOLOGICAL SURVEY
PROJECT 8-9380-4038
MISSISSIPPI

DIGHEM SURVEYS & PROCESSING INC.
MISSISSAUGA, ONTARIO
September 6 1988

Douglas L. McConnell
Geophysicist

A0537SEP.89R

CONTENTS

SUMMARY

A DIGHEM^{IV} survey was flown for the United States Geological Survey, over a survey block near Brookhaven, Mississippi.

The purpose of the survey was to detect resistivity contrasts in order to map the contamination of fresh water acquifers with brine. A secondary objective was to make high resolution magnetic measurements to locate abandoned oil wells.

The 900, 7,200 and 56,000 Hz data were used to produce resistivity maps. The different levels of penetration of the three frequencies through conductive earth, results in resistivity maps that show the conductive properties at different depths. The total field magnetic contours show numerous bull's-eye anomalies due to cultural sources. The VLF contours have also been influenced by cultural sources.

A comparison of the three resistivity parameters, and additionally the calculated depth channels, should be useful in determining the depths and extent of conductive sources below surface.

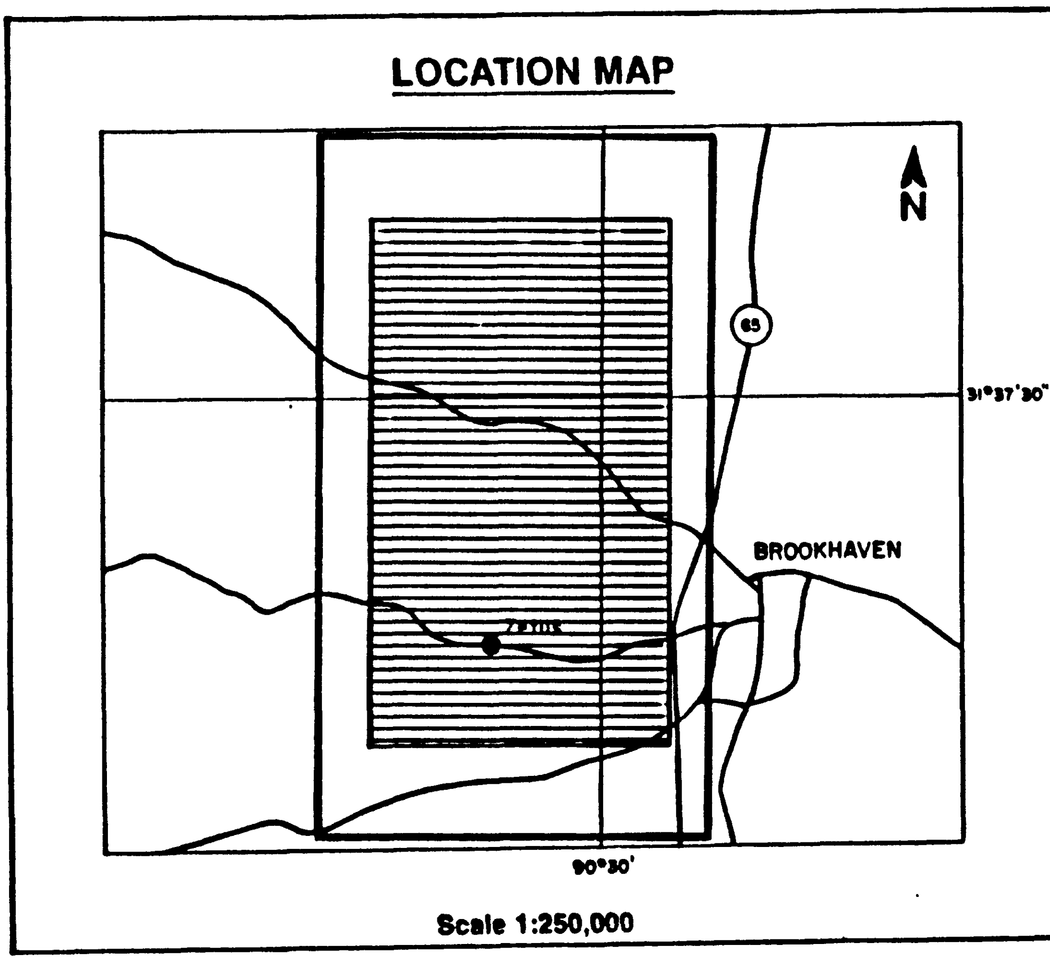

FIGURE 1

THE SURVEY AREA

INTRODUCTION

A DIGHEM^{IV} electromagnetic/resistivity/magnetic/VLF survey was flown for the U.S. Geological Survey, from May 12 to May 16, 1988, over a survey block near Brookhaven, Mississippi. This block is located on the Zetus and Brookhaven, Mississippi, U.S.G.S. map sheets (Figure 1).

Survey coverage consisted of approximately 422 line-miles. Flight lines were flown with a line separation of approximately 1/8 of a mile (200 metres) in an azimuthal direction of 090°/270°. Tie lines were flown perpendicular to the flight line direction.

The survey employed the DIGHEM^{IV} electromagnetic system. Ancillary equipment consisted of a magnetometer, radio altimeter, video camera, analog and digital recorders, a VLF receiver and an electronic navigation system.

This report is divided into six sections. Section 2 provides details on the equipment used in the survey and lists the recorded data and computed parameters. Section 3 reviews the data processing procedures, with further information on the various parameters provided in Section 5. Section 4 describes the geophysical results.

The survey results are shown on 1 separate map sheet for each parameter. Table 1-1 lists the products which can be obtained from the survey. Those which are part of the contract are indicated in this table by showing the presentation scale. These total 6 maps.

Recommendations for additional products are included in Table 1-1. These recommendations are based on the information content of products that would contribute to meeting the objectives of the survey.

Table 1-1 Plots Available from the Survey

MAP	NO. OF SHEETS	ANOMALY MAP	PROFILES ON MAP	CONTOURS INK	CONTOURS COLOR	SHADOW MAP
Flight Lines	1	N/A	-	24,000	-	-
Electromagnetic Anomalies	-	-	-	N/A	N/A	N/A
Probable Bedrock Conductors	-	-	N/A	N/A	N/A	N/A
Resistivity (900 Hz)	1	N/A	-	24,000	**	-
Resistivity (7,200 Hz)	1	N/A	-	24,000	**	-
Resistivity (56,000 Hz)	1	N/A	-	24,000	**	-
EM Magnetite	-	N/A	-	-	-	-
Total Field Magnetics	1	N/A	-	24,000	-	-
Enhanced Magnetics	-	N/A	-	-	-	-
Vertical Gradient Magnetics	-	N/A	-	-	-	-
2nd Vertical Derivative Magnetics	-	N/A	-	-	-	-
Magnetic Susceptibility	-	N/A	-	-	-	-
VLF	1	N/A	-	24,000	-	-
Electromagnetic Profiles(900 Hz)	-	N/A	-	-	-	-
Electromagnetic Profiles(7200 Hz)	-	N/A	-	-	-	-
Overburden Thickness	-	N/A	-	-	-	-
Digital Profiles		Worksheet profiles				-
		Interpreted profiles				12,000

N/A Not available
*** Highly recommended due to its overall information content
** Recommended
* Qualified recommendation, as it may be useful in local areas
- Not recommended
24,000 Scale of delivered map, i.e, 1:24,000

SURVEY EQUIPMENT

This section provides a brief description of the geophysical instruments used to acquire the survey data:

Electromagnetic System

Model:	DIGHEM^{IV}
Type:	Towed bird, symmetric dipole configuration, operated at a nominal survey altitude of 100 feet. Coil separation is 26.2 feet.
Coil orientations/frequencies:	coaxial / 900 Hz coplanar/ 900 Hz coplanar/ 7,200 Hz coplanar/56,000 Hz
Sensitivity:	0.2 ppm at 900 Hz 0.4 ppm at 7,200 Hz 1.0 ppm at 56,000 Hz
Sample rate:	10 per second

The electromagnetic system utilizes a multi-coil coaxial/coplanar technique to energize conductors in different directions. The coaxial transmitter coil is vertical with its axis in the flight direction. The coplanar coils are horizontal. The secondary fields are sensed simultaneously by means of receiver coils which are maximum coupled to their respective transmitter coils. The system yields an inphase and a quadrature channel from each transmitter-receiver coil-pair. The system is also equipped to provide two environment noise monitor channels.

Magnetometer

Model: Picodas Cesium

Sensitivity: 0.01 nT

Sample rate: 10 per second

The magnetometer sensor is towed in a bird 50 ft. below the helicopter.

Magnetic Base Station

Model: Geometrics G-826A

Sensitivity: 0.50 nT

Sample rate: once per 5 seconds

An Epson recorder is operated in conjunction with the base station magnetometer to record the diurnal variations of the earth's magnetic field. The clock of the base station is synchronized with that of the airborne system to permit subsequent removal of diurnal drift.

VLF System

Manufacturer: Herz Industries Ltd.

Type: Totem-2A

Sensitivity: 0.1%

The VLF receiver measures the total field and vertical quadrature components of the secondary VLF field. Signals from two separate transmitters can be measured simultaneously. The VLF sensor is towed in a bird 33 feet below the helicopter.

Radar Altimeter

Manufacturer: Honeywell/Sperry

Type: AA 220

Sensitivity: 1 ft

The radar altimeter measures the vertical distance between the helicopter and the ground. This information is used in the processing algorithm which determines conductor depth.

Analog Recorder

Manufacturer: RMS Instruments

Type: GR33 dot-matrix graphics recorder

Resolution: 4x4 dots/mm

Speed: 1.5 mm/sec

The analog profiles were recorded on chart paper in the aircraft during the survey. Table 2-1 lists the geophysical data channels and the vertical scale of each profile.

Digital Data Acquisition System

Manufacturer: Scintrex

Type: CDI-6

Tape Deck: RMS TCR-12, 6400 bpi, tape cartridge recorder

The digital data were used to generate several computed parameters.

Tracking Camera

Type: Panasonic Video

Model: AG 2400/WVCD132

Fiducial numbers are recorded continuously and are displayed on the margin of each image. This procedure ensures accurate correlation of analog and digital data with respect to visible features on the ground.

Navigation System

Model: Del Norte 547

Type: UHF electronic positioning system

Sensitivity: 3 feet

Sample rate: 0.5 per second

The navigation system uses ground based transponder stations which transmit distance information back to the helicopter. The ground stations are set up well away from the survey area and are positioned such that the signals cross the survey block at an angle between 30° and 150°. After site selection, a baseline is flown at right angles to a line drawn through the transmitter sites to establish an arbitrary coordinate system for the survey area. The onboard Central Processing Unit takes any two transponder distances and determines the helicopter position relative to these two ground stations in cartesian coordinates.

Aircraft

The instrumentation was installed in an Aerospatiale Lama 315B turbine helicopter. The helicopter flew at an average airspeed of 70 mph with an EM bird height of approximately 100 feet.

Table 2-1. The Analog Profiles

Channel Name	Parameter	Sensitivity per mm	Designation on digital profile
CX1I	coaxial inphase (900 Hz)	2.5 ppm	CXI (900 Hz)
CX1Q	coaxial quad (900 Hz)	2.5 ppm	CXQ (900 Hz)
CP2I	coplanar inphase (900 Hz)	2.5 ppm	CPI (900 Hz)
CP2Q	coplanar quad (900 Hz)	2.5 ppm	CPQ (900 Hz)
CP3I	coplanar inphase (7200 Hz)	5.0 ppm	CPI (7200 Hz)
CP3Q	coplanar quad (7200 Hz)	5.0 ppm	CPQ (7200 Hz)
CP4I	coplanar inphase (56 kHz)	10.0 ppm	CPI (56 kHz)
CP4Q	coplanar quad (56 kHz)	10.0 ppm	CPQ (56 kHz)
CXSP	coaxial sferics	2.5 ppm	
CPSP	coplanar sferics	2.5 ppm	
ALT	altimeter	3 m	ALT
VL1T	VLF-total: primary station	5%	
VL1Q	VLF-quad: primary station	5%	
VL2T	VLF-total: secondary stn.	5%	
VL2Q	VLF-quad: secondary stn.	5%	
MAGC	magnetics, coarse	20 nT	MAG
MAGF	magnetics, fine	2.0 nT	MAG

Table 2-2. The Digital Profiles

Channel <u>Name (Freq)</u>	<u>Observed parameters</u>	Scale <u>units/mm</u>
MAG	magnetics	2 nT
ALT	bird height	6 m
CXI (900 Hz)	vertical coaxial coil-pair inphase	2 ppm
CXQ (900 Hz)	vertical coaxial coil-pair quadrature	2 ppm
CPI (900 Hz)	horizontal coplanar coil-pair inphase	2 ppm
CPQ (900 Hz)	horizontal coplanar coil-pair quadrature	2 ppm
CPI (7200 Hz)	horizontal coplanar coil-pair inphase	4 ppm
CPQ (7200 Hz)	horizontal coplanar coil-pair quadrature	4 ppm
CPI (56 kHz)	horizontal coplanar coil-pair inphase	10 ppm
CPQ (56 kHz)	horizontal coplanar coil-pair quadrature	10 ppm
CXPL	vertical coaxial power line monitor	4 ppm
	<u>Computed Parameters</u>	
CDT	conductance	1 grade
RES (900 Hz)	log resistivity	.06 decade
RES (7200 Hz)	log resistivity	.06 decade
RES (56 kHz)	log resistivity	.06 decade
DP (900 Hz)	apparent depth	6 m
DP (7200 Hz)	apparent depth	6 m
DP (56 kHz)	apparent depth	6 m

PRODUCTS AND PROCESSING TECHNIQUES

The following products are available from the survey data. Those which are not part of the survey contract may be acquired later. Refer to Table 1-1 for a summary of the maps which accompany this report and those which are recommended as additional products. Most parameters can be displayed as contours, profiles, or in colour.

Base Maps

Base maps of the survey area were prepared from 1:24,000 topographic maps.

Flight Path

The cartesian coordinates produced by the electronic navigation system were transformed into UTM grid locations during data processing. These were tied to the UTM grid on the base map. In the case of a photomosaic base map, the UTM grid must be transferred from a topographic map to the photomosaic.

Prominent topographical features were correlated with the navigational data points, to ensure that the data is accurately registered on the base map.

Electromagnetic Anomalies

Anomalous electromagnetic responses are selected and analysed by computer to provide a preliminary electromagnetic anomaly map. This preliminary EM map is used, by the geophysicist, in conjunction with the computer generated digital profiles, to produce the final interpreted EM anomaly map. This map includes bedrock, surficial and cultural conductors. A map containing only bedrock conductors can be generated, if desired.

Resistivity

The apparent resistivity in ohm-m may be generated from the inphase and quadrature EM components for any of the frequencies, using a pseudo-layer halfspace model. A resistivity map portrays all the EM information for that frequency over the entire survey area. This contrasts with the electromagnetic anomaly map which provides information only over interpreted conductors. The large dynamic range makes the resistivity parameter an excellent mapping tool.

EM Magnetite

The apparent percent magnetite by weight is computed wherever magnetite produces a negative inphase EM response.

The results are usually displayed on a contour map.

Total Field Magnetics

The aeromagnetic data are corrected for diurnal variation using the magnetic base station data. The regional IGRF gradient is removed from the data, if required under the terms of the contract.

Enhanced Magnetics

The total field magnetic data are subjected to a processing algorithm. This algorithm enhances the response of magnetic bodies in the upper 1,500 feet and attenuates the response of deeper bodies. The resulting enhanced magnetic map provides better definition and resolution of near-surface magnetic units. It also identifies weak magnetic features which may not be evident on the total field magnetic map. However, regional magnetic variations, and magnetic lows caused by remanence, are better defined on the total field magnetic map. The technique is described in more detail in Section 5.

Magnetic Derivatives

The total field magnetic data may be subjected to a variety of filtering techniques to yield maps of the following:

vertical gradient

second vertical derivative

magnetic susceptibility with reduction to the pole

upward/downward continuations

All of these filtering techniques improve the recognition of near-surface magnetic bodies, with the exception of upward continuation. Any of these parameters can be produced on request. Dighem's proprietary enhanced magnetic technique is designed to provide a general "all-purpose" map, combining the more useful features of the above parameters.

VLF

The VLF data can be digitally filtered to remove long wavelengths such as those caused by variations in the transmitted field strength. The results are usually presented as contours of the filtered total field.

Digital Profiles

Distance-based profiles of the digitally recorded geophysical data are generated and plotted by computer.

These profiles also contain the calculated parameters which are used in the interpretation process. These are produced as worksheets prior to interpretation, and can also be presented in the final corrected form after interpretation. The profiles display electromagnetic anomalies with their respective interpretive symbols. The differences between the worksheets and the final corrected form occur only with respect to the EM anomaly identifier.

Contour, Colour and Shadow Map Displays

The geophysical data are interpolated onto a regular grid using a cubic spline technique. The resulting grid is suitable for generating contour maps of excellent quality.

Colour maps are produced by interpolating the grid down to the pixel size. The distribution of the colour ranges is normalized for the magnetic parameter colour maps, and matched to specific contour intervals for the resistivity and VLF colour maps.

Monochromatic shadow maps are generated by employing an artificial sun to cast shadows on a surface defined by the geophysical grid. There are many variations in the shadowing technique, as shown in Figure 3-1. The various shadow techniques may be applied to total field or enhanced magnetic data, magnetic derivatives, VLF, resistivity, etc. Of the various magnetic products, the shadow of the enhanced magnetic parameter is particularly suited for defining geological structures with crisper images and improved resolution.

Dighem software provides several shadowing techniques. Both monochromatic (commonly green) or polychromatic (full color) maps may be produced. Monochromatic shadow maps are often preferred over polychromatic maps for reasons of clarity.

Spot Sun

The spot sun technique tends to mimic nature. The sun occupies a spot in the sky at a defined azimuth and inclination. The surface of the data grid casts shadows. This is the standard technique used by industry to produce monochromatic shadow maps.

A characteristic of the spot sun technique is that shadows are cast in proportion to how well the sunlight intersects the feature. Features which are almost parallel to the sun's azimuth may cast no shadow at all. To avoid this problem, Dighem's hemispheric sun technique may be employed.

Hemispheric Sun

The hemispheric sun technique was developed by Dighem. The method involves lighting up a hemisphere. If, for example, a north hemispheric sun is selected, features of all strikes will have their north side in sun and their south side in shadow. The hemispheric sun lights up all features, without a bias caused by strike. The method yields sharply defined monochromatic shadows.

The hemispheric sun technique always improves shadow casting, particularly where folding and cross-cutting structures occur. Nevertheless, it is important to center the hemisphere perpendicular to the regional strike. Features which strike parallel to the center of the hemisphere result in ambiguity. This is because the two sides of the feature may yield alternating patterns of sun and shadow. If this proves to be a problem in your survey area, Dighem's omni sun technique may be employed.

Omni Sun

The omni sun technique was also developed by Dighem. The survey area is centered within a ring of sunlight. This lights up all features without any strike bias. The result is brightly defined monochromatic features with diffuse shadows.

Multi Sun

Two or three spot suns, with different azimuths, may be combined in a single presentation. The shadows are displayed on one map by the use of different colors, e.g., by using a green sun and a red sun. Some users find the interplay of colors reduces the clarity of the shadowed product.

Polychromatic Maps

Any of the above monochromatic shadow maps can be combined with the standard contour-type solid color map. The result is a polychromatic shadow map. Such maps are esthetically pleasing, and are preferred by some users. A disadvantage is that ambiguity exists between changes in amplitude and changes in shadow.

Fig. 3-1 Shadow Mapping

SURVEY RESULTS

Resistivity

Apparent resistivity maps were prepared from the 900, 7,200 and 56,000 Hz coplanar EM data. These maps show the conductive properties of the survey area.

The 56,000 Hz data has the greatest dynamic range but is biased towards surficial conductivity. In general, the 56,000 Hz map shows higher resistivities than either the 900 or 7,200 Hz maps. This is indicative of a relatively resistive upper layer overlying a conductive layer or layers. This resistive cover may be thinner where the 56,000 Hz resistivity agrees closely with the lower frequencies. For example, a low resistivity trend of 10 to 15 ohm-m extends from fiducial 2200 on line 10270, to fiducial 3640 on line 10410 on the 56,000 Hz map.

The 7,200 Hz data is likely penetrating through the surficial layer to a greater extent than the 56,000 Hz resistivity. It generally agrees with the 900 Hz resistivity, except in a few isolated areas. In areas where it yields higher resistivities the relatively resistive surficial layer may be thicker.

The resistivity contours do not appear to have been affected to a high degree by cultural sources. EM anomalies due to cultural sources, such as power lines, are primarily the result of current channelling. This yields a high amplitude response but little phase shift and therefore no appreciable change in the inphase to quadrature ratio. As the resistivity calculation is based on the phase, which is changed as a result of inductive coupling, the cultural sources do not usually distort the resistivity map to a high degree. In some areas excessive noise in the form of spiking or hash on the EM channels resulted from culture. In such areas the data was left out of the resistivity calculation to ensure that the resistivity contours were not distorted.

Magnetics

The total field magnetic data have been presented as contours on the base map using a contour interval of 1 nT where gradients permit. The IGRF gradient across the survey block has not been removed. The maps show the magnetic properties of the rock units underlying the survey area. The isolated bull's-eye anomalies are likely due to cultural sources. Some of these may be attributed to oil wells. The narrow response yielded by such a source may easily be missed at a 1/8 mile line spacing, therefore many of these sources may not have been detected.

VLF

VLF results were obtained from three transmitting stations, Cutler, Maine (NAA - 24.0 kHz), Seattle, Washington (NLK - 24.8 kHz) and Annapolis, Maryland (NSS - 21.4 kHz). The use of three different stations was necessitated by signal interruptions at the source of transmission. Results from the transmitter at Annapolis, Maryland were presented as contours of the filtered total field. The contour patterns are greatly influenced by cultural sources.

The VLF method is quite sensitive to the angle of coupling between the conductor and the proposed EM field. Consequently, conductors which strike towards the VLF station will usually yield a stronger response than conductors which are nearly orthogonal to it.

Closely-spaced conductors, conductors of short strike length or conductors which are poorly coupled to the VLF field, may escape detection with this method. Erratic signals from the VLF transmitters can also give rise to strong, isolated anomalies which should be viewed with caution.

Electromagnetic Anomalies

The electromagnetic anomalies are displayed on the digital profiles. Corresponding to each anomaly identifier is either an "L" or "H" interpretive symbol. The "L" symbol reflects an anomaly that is due to a line source or culture. The "H" interpretive symbol is used to denote a response from a conductor which fits a half space model, such as a buried, flat lying layer. The coplanar EM channels will be maximum coupled to these flat lying conductors, and therefore these sources are best represented on the resistivity parameters. Refer to the sections on "Recognition of Culture" and "Resistivity Mapping" in section 5 for more information.

BACKGROUND INFORMATION

This section provides background information on parameters which are available from the survey data. Those which have not been supplied as survey products may be generated later from raw data on the digital archive tape.

ELECTROMAGNETICS

Resistivity mapping

Areas of widespread conductivity are commonly encountered during surveys. In such areas, anomalies can be generated by decreases of only 5 m in survey altitude as well as by increases in conductivity. The typical flight record in conductive areas is characterized by inphase and quadrature channels which are continuously active. Local EM peaks reflect either increases in conductivity of the earth or decreases in survey altitude. For such conductive areas, apparent resistivity profiles and contour maps are necessary for the correct interpretation of the airborne data. The advantage of the resistivity parameter is that anomalies caused by altitude changes are virtually eliminated, so the resistivity data reflect only those anomalies caused by conductivity changes. The resistivity analysis also helps the interpreter to differentiate between conductive trends in the bedrock and those patterns typical of conductive overburden. For example, discrete conductors will generally appear as narrow lows on the contour map and broad conductors (e.g., overburden) will appear as wide lows.

The resistivity profiles and the resistivity contour maps present the apparent resistivity using the so-called pseudo-layer (or buried) half space model defined by Fraser (1978)[1]. This model consists of a resistive layer overlying a conductive half space. The depth channels give the apparent depth below surface of the conductive material. The apparent depth is simply the apparent thickness of the overlying resistive layer. The apparent depth (or thickness) parameter will be positive when the upper layer is more resistive than the underlying material, in which case the apparent depth may be quite close to the true depth.

The apparent depth will be negative when the upper layer is more conductive than the underlying material, and will be zero when a homogeneous half space exists. The apparent depth parameter must be interpreted cautiously because it will contain any errors which may exist in the measured altitude of the EM bird (e.g., as caused by a dense tree

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1 Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, v. 43, p.144-172

cover). The inputs to the resistivity algorithm are the inphase and qaudrature components of the coplanar coil-pair. The outputs are the apparent resistivity of the conductive half space (the source) and the sensor-source distance are independent of the flying height. The apparent depth, discussed above, is simply the sensor-source distance minus the measured altitude or flying height. Consequently, errors in the measured altitude will affect the apparent depth parameter but not the apparent resistivity parameter.

The apparent depth parameter is a useful indicator of simple layering in areas lacking a heavy tree cover. The DIGHEM system has been flown for purposes of permafrost mapping, where positive apparent depths were used as a measure of permafrost thickness. However, little quantitative use has been made of negative apparent depths because the absolute value of the negative depth is not a measure of the thickness of the conductive upper layer and, therefore, is not meaningful physically. Qualitatively, a negative apparent depth estimate usually shows that the EM anomaly is caused by conductive overburden. Consequently, the apparent depth channel can be of significant help in distinguishing between overburden and bedrock conductors.

The resistivity map often yields more useful information on conductivity distributions than the EM map. In comparing the EM and resistivity maps, keep in mind the following:

(a) The resistivity map portrays the absolute value of the earth's resistivity, where resistivity = 1/conductivity.

(b) The EM map portrays anomalies in the earth's resistivity. An anomaly by definition is a change from the norm and so the EM map displays anomalies, (i) over narrow, conductive bodies and (ii) over the boundary zone between two wide formations of differing conductivity.

The resistivity map might be likened to a total field map and the EM map to a horizontal gradient in the direction of flight[2]. Because gradient maps are usually more sensitive than total field maps, the EM map therefore is to be preferred in resistive areas. However, in conductive areas, the absolute character of the resistivity map usually causes it to be more useful than the EM map.

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2 The gradient analogy is only valid with regard to the identification of anomalous locations.

Recognition of culture

Cultural responses include all EM anomalies caused by man-made metallic objects. Such anomalies may be caused by inductive coupling or current gathering. The concern of the interpreter is to recognize when an EM response is due to culture. Points of consideration used by the interpreter, when coaxial and coplanar coil-pairs are operated at a common frequency, are as follows:

1. Channel CXPL monitors 60 Hz radiation. An anomaly on this channel shows that the conductor is radiating power. Such an indication is normally a guarantee that the conductor is cultural. However, care must be taken to ensure that the conductor is not a geologic body which strikes across a power line, carrying leakage currents.

2. A flight which crosses a "line" (e.g., fence, telephone line, etc.) yields a center-peaked coaxial anomaly and an m-shaped coplanar anomaly. When the flight crosses the cultural line at a high angle of intersection, the amplitude ratio of coaxial/coplanar response is 4. Such an EM anomaly can only be caused by a line. The geologic body which yields anomalies most closely resembling a line is the vertically dipping thin dike.

Such a body, however, yields an amplitude ratio of 2 rather than 4. Consequently, an m-shaped coplanar anomaly with a CXI/CPI amplitude ratio of 4 is virtually a guarantee that the source is a cultural line.

3. A flight which crosses a sphere or horizontal disk yields center-peaked coaxial and coplanar anomalies with a CXI/CPI amplitude ratio (i.e., coaxial/coplanar) of 1/4. In the absence of geologic bodies of this geometry, the most likely conductor is a metal roof or small fenced yard.[3] Anomalies of this type are virtually certain to be cultural if they occur in an area of culture.

4. A flight which crosses a horizontal rectangular body or wide ribbon yields an m-shaped coaxial anomaly and a center-peaked coplanar anomaly. In the absence of geologic bodies of this geometry, the most likely conductor is a large fenced area.[5] Anomalies of this type are virtually certain to be cultural if they occur in an area of culture.

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[3] It is a characteristic of EM that geometrically similar anomalies are obtained from: (1) a planar conductor, and (2) a wire which forms a loop having dimensions identical to the perimeter of the equivalent planar conductor.

5. EM anomalies which coincide with culture, as seen on the camera film or video display, are usually caused by culture. However, care is taken with such coincidences because a geologic conductor could occur beneath a fence, for example. In this example, the fence would be expected to yield an m-shaped coplanar anomaly as in case #2 above. If, instead, a center-peaked coplanar anomaly occurred, there would be concern that a thick geologic conductor coincided with the cultural line.

6. The above description of anomaly shapes is valid when the culture is not conductively coupled to the environment. In this case, the anomalies arise from inductive coupling to the EM transmitter. However, when the environment is quite conductive (e.g., less than 100 ohm-m at 900 Hz), the cultural conductor may be conductively coupled to the environment. In this latter case, the anomaly shapes tend to be governed by current gathering. Current gathering can completely distort the anomaly shapes, thereby complicating the identification of cultural anomalies. In such circumstances, the interpreter can only rely on the radiation channel CPS and on the camera film or video records.

MAGNETICS

The magnetometer data are digitally recorded in the aircraft to an accuracy of 0.01 nT for cesium magnetometers. The digital tape is processed by computer to yield a total field magnetic contour map. When warranted, the magnetic data may also be treated mathematically to enhance the magnetic response of the near-surface geology, and an enhanced magnetic contour map is then produced. The response of the enhancement operator in the frequency domain is illustrated in Figure 5-1. This figure shows that the passband components of the airborne data are amplified 20 times by the enhancement operator. This means, for example, that a 100 nT anomaly on the enhanced map reflects a 5 nT anomaly for the passband components of the airborne data.

The enhanced map, which bears a resemblance to a downward continuation map, is produced by the digital bandpass filtering of the total field data. The enhancement is equivalent to continuing the field downward to a level (above the source) which is 1/20th of the actual sensor-source distance.

Because the enhanced magnetic map bears a resemblance to a ground magnetic map, it simplifies the recognition of trends in the rock strata and the interpretation of

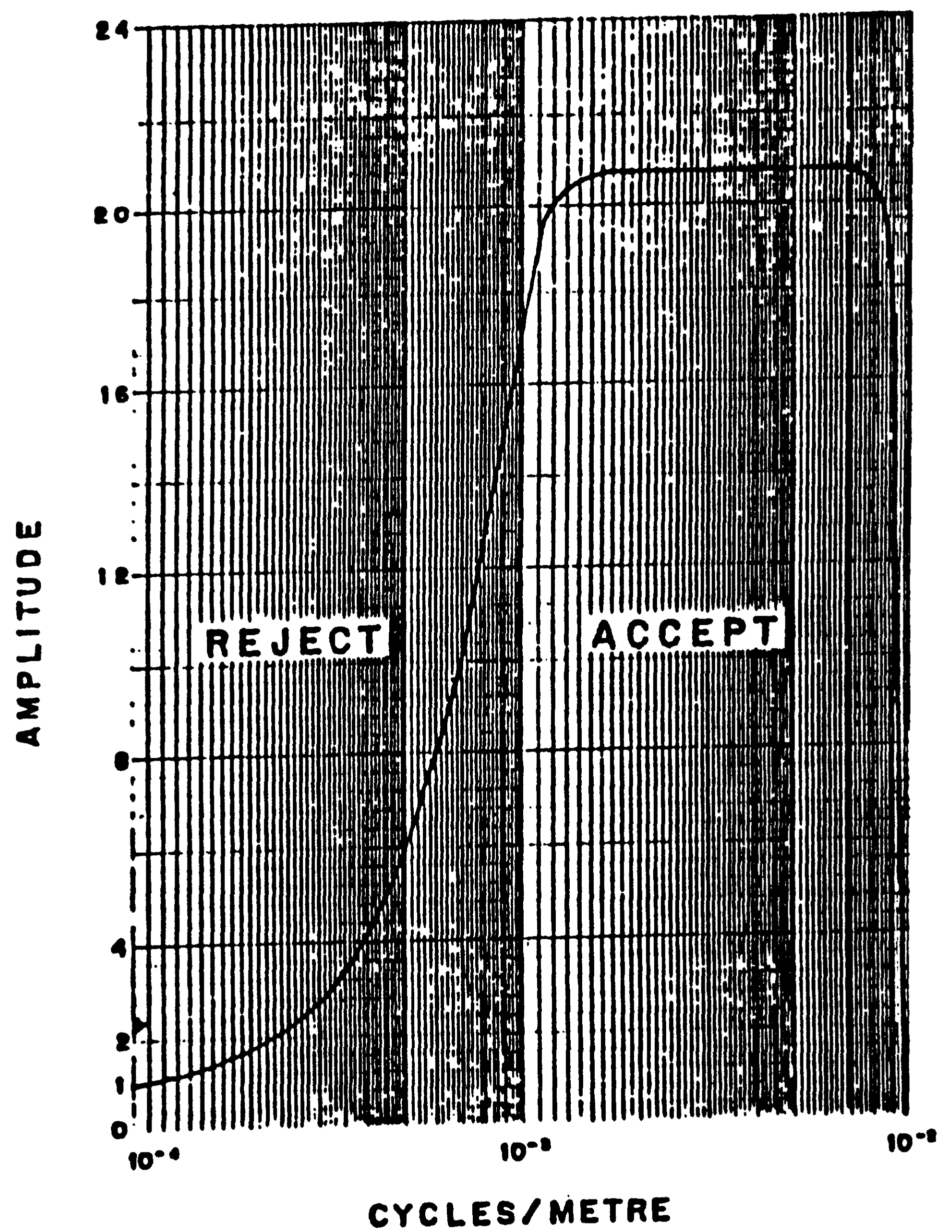

Fig. 5-2 Frequency response of magnetic enhancement operator for a sample interval of 50 m.

geological structure. It defines the near-surface local geology while de-emphasizing deep-seated regional features. It primarily has application when the magnetic rock units are steeply dipping and the earth's field dips in excess of 60 degrees.

Any of a number of filter operators may be applied to the magnetic data, to yield vertical derivatives, continuations, magnetic susceptibility, etc. These may be displayed in contour, colour or shadow.

VLF

VLF transmitters produce high frequency uniform electromagnetic fields. However, VLF anomalies are not EM anomalies in the conventional sense. EM anomalies primarily reflect eddy currents flowing in conductors which have been energized inductively by the primary field. In contrast, VLF anomalies primarily reflect current gathering, which is a non-inductive phenomenon. The primary field sets up currents which flow weakly in rock and overburden, and these tend to collect in low resistivity zones. Such zones may be due to massive sulfides, shears, river valleys and even unconformities.

The VLF field is horizontal. Because of this, the

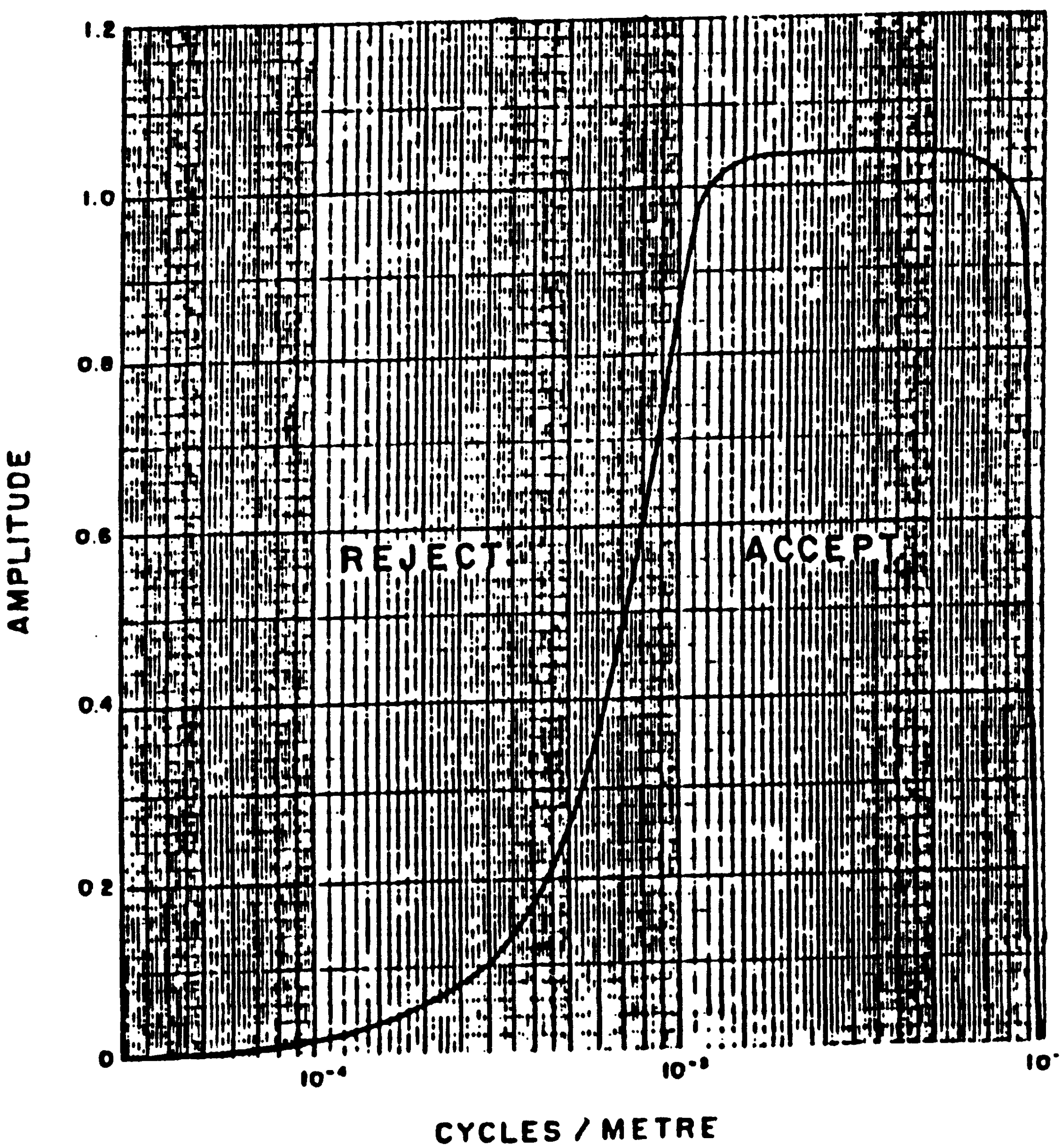

Fig. 5-3 Frequency response of VLF operator.

method is quite sensitive to the angle of coupling between the conductor and the transmitted VLF field. Conductors which strike towards the VLF station will usually yield a stronger response than conductors which are nearly orthogonal to it.

The Herz Industries Ltd. Totem VLF-electromagnetometer measures the total field and vertical quadrature components. Both of these components are digitally recorded in the aircraft with a sensitivity of 0.1 percent. The total field yields peaks over VLF current concentrations whereas the quadrature component tends to yield crossovers. Both appear as traces on the profile records. The total field data are filtered digitally and displayed as contours to facilitate the recognition of trends in the rock strata and the interpretation of geologic structure.

The response of the VLF total field filter operator in the frequency domain (Figure 5-2) is basically similar to that used to produce the enhanced magnetic map (Figure 5-1). The two filters are identical along the abscissa but different along the ordinant. The VLF filter removes long wavelengths such as those which reflect regional and wave transmission variations. The filter sharpens short wavelength responses such as those which reflect local geological variations.

CONCLUSIONS AND RECOMMENDATIONS

This report provides a brief description of the survey results and describes the equipment, procedures and logistics of the survey.

The various maps included with this report display the magnetic and conductive properties of the survey area. The survey results should be reviewed in detail, in conjunction with all available geological, geophysical and geochemical information.

It is also recommended that additional processing of existing geophysical data be considered, in order to extract the maximum amount of information from the survey results. Resistivity colour plots may aid in identification of resistivity contrasts.

Respectfully submitted,

DIGHEM SURVEYS & PROCESSING INC.

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DLM/mg

A0537SEP.89R