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Helicopter Electromagnetic and Magnetic Geophysical Survey Data, Oakland, Ashland, and Firth Study Areas, Eastern Nebraska, March 2007

By Bruce D. Smith, Jared A. Abraham, James C. Cannia, Gregory V. Steele, and Patricia Hill



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Front Cover: Photo shows helicopter EM system flying over part of the eastern Nebraska water resource project survey area. Photo by Jesse T. Korus, Lower Platte South Natural Resources District, Lincoln, NE

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Conversion Factors, Datum, and Acronyms

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km ²)	247.1	acre
liter (L)	0.2642	gallon (gal)
nanotesla (nT)	1	gamma
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
 $^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$

Electrical conductivity is given in millisiemens per meter (mS/m) unless otherwise specified
Electrical resistivity is given in ohm meters unless otherwise specified
1 mS/m = 1000/ (1ohm meter) thus 10 mS/m = 100 ohm meters

Vertical coordinate information is referenced to the "North American Vertical Datum of 1988 (NAVD 88)" except as noted in text
Horizontal coordinate information is referenced to the "North American Datum of 1984, Universal Transverse Mercator Zone 14 (NAD 84 UTM Zone 14N)" except as noted in text
Airborne geophysical survey reference for GPS data is WGS84 as explained in the text
Main text gives description of data projections use din acquisition and processing

ACRONYMS USED IN THIS REPORT:

EM Electromagnetic
DTM Digital Terrain Model
GPS Global Positioning System
HEM Helicopter Electromagnetic
RTP Reduced-to-Pole
USGS U.S. Geological Survey
UTM Universal Transverse Mercator

ABBREVIATIONS USED IN THIS REPORT:

Hz hertz
kHz kilohertz

Helicopter Electromagnetic and Magnetic Geophysical Survey Data, Oakland, Ashland, and Firth Study Areas, Eastern Nebraska, March 2007

By Bruce D. Smith¹, Jared A. Abraham¹, James C. Cannia², Gregory V. Steele², and Patricia L. Hill¹

Abstract

This report is a digital data release for a helicopter electromagnetic and magnetic survey that was conducted during March 2007 in three 93 square kilometer (36 square mile) areas of eastern Nebraska as part of a joint State of Nebraska and U.S. Geological Survey study. The objective of the survey is to improve the understanding the relationship between surface water and groundwater systems critical to developing management programs for water resources. The electromagnetic equipment consisted of six different coil-pair orientations that measured resistivity at separate frequencies from about 400 hertz to about 115,000 hertz. The electromagnetic data were converted to electrical resistivity geo-referenced grids and maps, each representing different approximate depths of investigation for each area. The range of subsurface investigation is comparable to the depth of shallow aquifers. The three areas selected for the study, Ashland, Firth, and Oakland have glacial terrains and bedrock that typify different hydrogeologic settings for surface water and ground water in Nebraska. The geophysical and hydrologic information from U.S. Geological Survey studies are being used by resource managers to develop ground-water resource plans for the area.

Introduction

Airborne geophysical studies have been effectively used by the U.S. Geological Survey (USGS) in a variety of ground-water resource projects and programs (Smith and others, 2007). Electrical geophysical methods can be used to image the subsurface of the earth using techniques very similar to a medical CAT (computed axial tomography) scan of the human body (Won, 1990). A specific example is the HEM survey conducted for the USGS in the upper Missouri River Basin (Poplar, Montana) to study ground-water quality in a similar hydrologic setting to Nebraska (Smith and others, 2006). Based on the success of these and other ground-water studies utilizing airborne geophysical methods, the USGS received funding from Nebraska state agencies to evaluate the subsurface mapping application eastern Nebraska. The project has been described by Abraham and others (2007) in a poster session at the 2007 annual Geological Society of America Meeting. The abstract and poster (PDF file) is included in Appendix I. The airborne geophysical data described in this report were collected by Fugro Airborne using a helicopter electromagnetic (HEM) system under contract to the USGS. The contractor's report is included as a PDF file (Appendix B). The

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digital airborne geophysical data collected along flight lines was processed by the contractor to produce digital maps. Additional data processing was done by the USGS and supplemental maps were produced. These digital line data and maps are also included as part of the digital data release.

The general objectives of the Eastern Nebraska Water Resources Assessment (ENRWA) have been recently described by Korus and Divine (2007) and is summarized here: The Eastern Nebraska Water Resources Assessment (ENWRA) is a cooperative effort involving ten local, state, and federal agencies to develop a three-dimensional geologic framework and water budget for the glaciated region, or eastern 1/5th of Nebraska. This region contains 70 percent of the state's population but is most limited in terms of the state's ground water supplies. Locally governed Natural Resources Districts (NRDs), charged with ground water management in Nebraska, seek to improve their management plans in response to growing populations, hydrologic drought, and new conjunctive management laws. Detailed mapping and characterization is necessary to delineate aquifers, assess their degree of hydrologic connection with streams and other aquifers, and better predict water quality and quantity.

This is a large, multi-faceted study requiring successful coordination and planning between multiple levels of government. Public involvement and funding of water resources studies at the local, state, and federal levels have been and will continue to be vital to its long-term success.

Purpose and Scope

This report presents HEM and magnetic maps and data that were collected for the U.S. Geological Survey by Fugro Airborne during March 22 to 26, 2007, in eastern Nebraska. The survey consisted of 1170 line kilometers (727 line miles). In general the survey covered three areas, about one township each. The objective of the survey is to improve the understanding the relationship between surface water and groundwater systems critical to developing management programs for water resources. The airborne geophysical survey data can be used to map subsurface electrical and magnetic properties of the earth that can be related to geologic and hydrologic features.

Description of Study Areas

Three study areas of about one township size were chosen for evaluation of the HEM method in mapping glaciated terrains of eastern Nebraska (Figure 1). Pilot studies at three different sites are being conducted to test the effectiveness of potential investigative tools. Sites are located near Firth, Ashland, and Oakland, Nebraska, each representing a different hydrogeologic setting. The pilot studies, initiated in 2006, are planned to continue for three years and will be used to assess the feasibility of applying the tools to broader areas. In the first year one, helicopter electromagnetic (HEM) surveys were completed over approximately one township at each pilot study site. Test hole drilling, borehole geophysics, and time domain electromagnetic (TDEM) surveys were conducted for 'ground truth' data to support the HEM interpretations. In years 2 and 3, additional tools supporting water quality studies, ground water age dating, hydrologic monitoring, and estimation of recharge to aquifers will be tested at the sites. The long-term vision

is to apply the suite of tools developed in the pilot studies to provide data, interpretations, and models for improved water resources management.

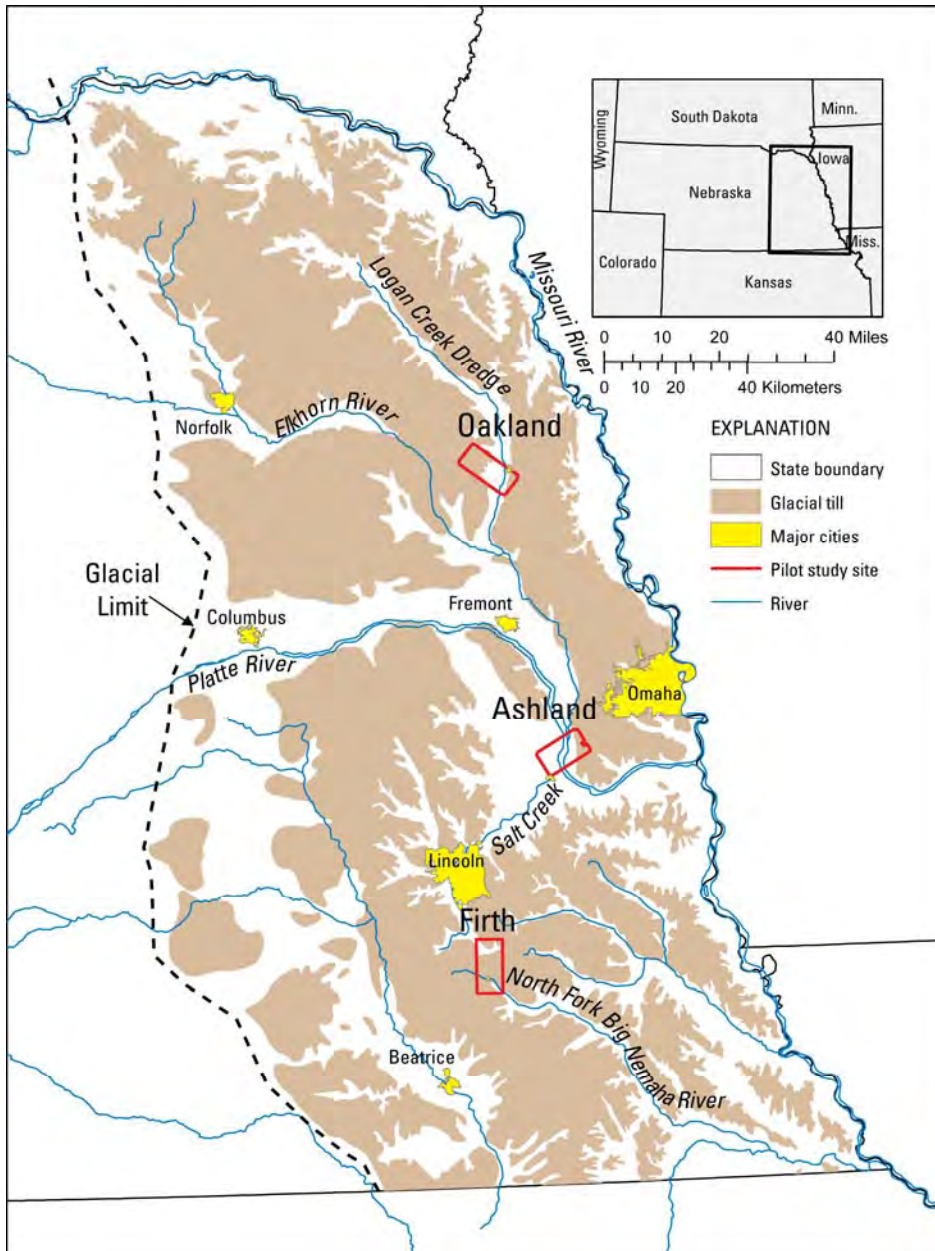
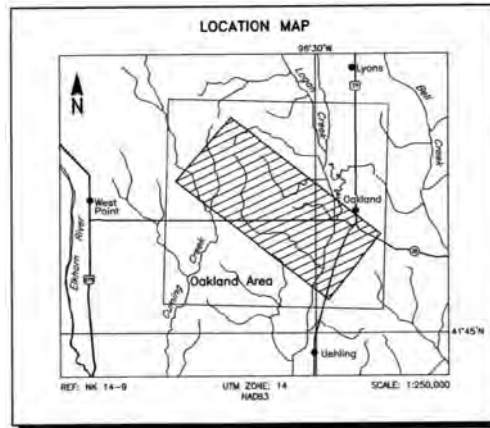
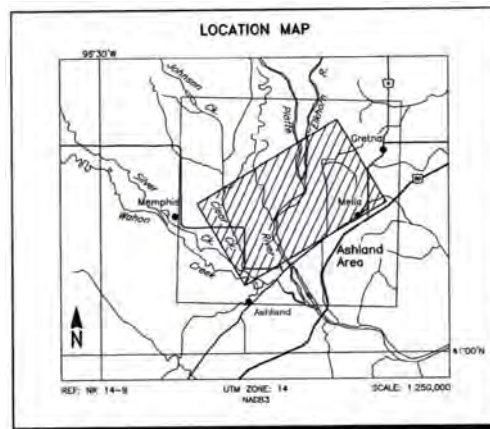


Figure 1. Location of study area and helicopter electromagnetic and magnetic survey.

a)



b)



c)

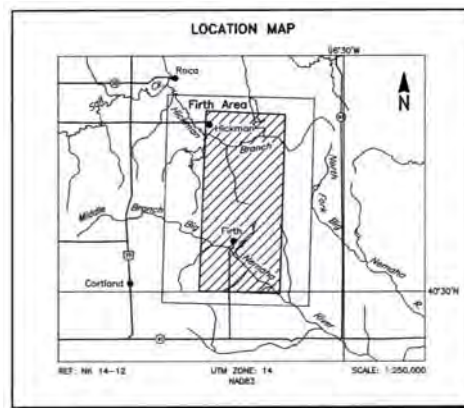


Figure 2. Detailed location maps for pilot study areas: a) location map for the Oakland area, b) location map for the Ashland area, and c) location map for the Firth area (adapted from Fugro Airborne report (Appendix II)).

Geophysical Data Overview

The digital data from the airborne survey was acquired and processed by the contractor, Fugro Airborne LTD, as described in Appendix II. The USGS did quality control of the contractor's data acquisition, processing, and report. In addition the USGS did some reprocessing of the data to meet specific requirements of this project. Both the contractor and USGS digital data is included in the present data release. Table 1 contains links to the digital data and a brief description of the files and directories.

Table 1. Digital data organization and description for files and directories

Directory	Description
<u>METADATA</u>	Metadata description of digital data
<u>GIS SURVEY</u>	Geographic information such as digital topographic map and survey areas
<u>GRIDS</u>	Grids of the electromagnetic and magnetic field data for the horizontal coplanar coil pairs are in this directory. The grids are in Geosoft OASIS MONTAJ (http://www.geosoft.com/) format, a 'standard' of the geophysical industry used in many map display programs. Programs are included with this data release to view, export, and import the grid files in ARCMAP9.2.
<u>LINEDATA</u>	Flight-line data are in ascii standard and Geosoft OASIS MONTAJ (http://www.geosoft.com/) database in this directory. The readme file in this directory contains a description of the channels of the digital line data.
<u>PLOTS</u>	Geotiff (UTM14N, NAD83 projected ".tif" files) of the grids are in this directory. Each file has an associated world file (".tfw"). The digital version of plate 1 can be found in this directory. The original images of the airborne apparent resistivity maps generated by the contractor are included in the IMAGES/CONTRACTOR_PDF_MAPS.
<u>REPORT</u>	This report and appendix 1 are in this directory as ".pdf" and Microsoft Word files.

Helicopter Electromagnetic and Magnetic Survey

Method

Kirsh (2006) and Hubbard and Rubin (2005) give good overviews of geophysical principles and applications to ground-water studies. Airborne geophysical surveys are usually made along regularly spaced flight lines within specified survey areas (Figure 1 and 2). Flight lines can be as close as 50 m, though closer spacing is possible in special circumstances. The USGS has generally flown HEM surveys with 200-400 m spacing (1/8 to 1/4 mile: Smith and others, 2007) though flight lines with 800 m separation have been used to map regional structures in a carbonate aquifer setting (Smith and others, 2007b). One objective of the present study is to evaluate the flight line spacing in terms of resolution of hydrogeologic features in the glaciated terrain of eastern Nebraska. Table 2 gives the flight line specifications for each survey area.

Table 2. Flight line direction and spacing for each survey area.

Block	Traverse line azimuth	Tie Line azimuth	Traverse line spacing (m)	Tie line spacing (m)	Traverse Line Distance (km)	Tie Line Distance (km)	Total
Oakland	127°/307°	37°/217°	270	14 000	371.0	14.0	385.0
Ashland	58°/238°	148°/328°	270	12 000	361.6	24.3	385.9
Firth	90°/270°	0°/180°	280	6 000	367.8	30.1	397.9
TOTAL					1100.4	68.4	1168.8

The main part of the geophysical system is housed in a cylindrical tube or “*bird*” that is towed beneath the helicopter. In the system flown by Fugro Airborne all of the measurement systems in the *bird* are transmitted via a cable to a processing and digital recording system in the helicopter. Measurements of the geophysical data (EM and total field magnetic) are made approximately every three meters along the flight line. Figure 3 shows the instrumentation used by the German Geological Survey (Siemon, 2006) for HEM surveys similar to that used for this survey. The helicopter used by Fugro is different (see Appendix II) and radiometric measurements were not made.

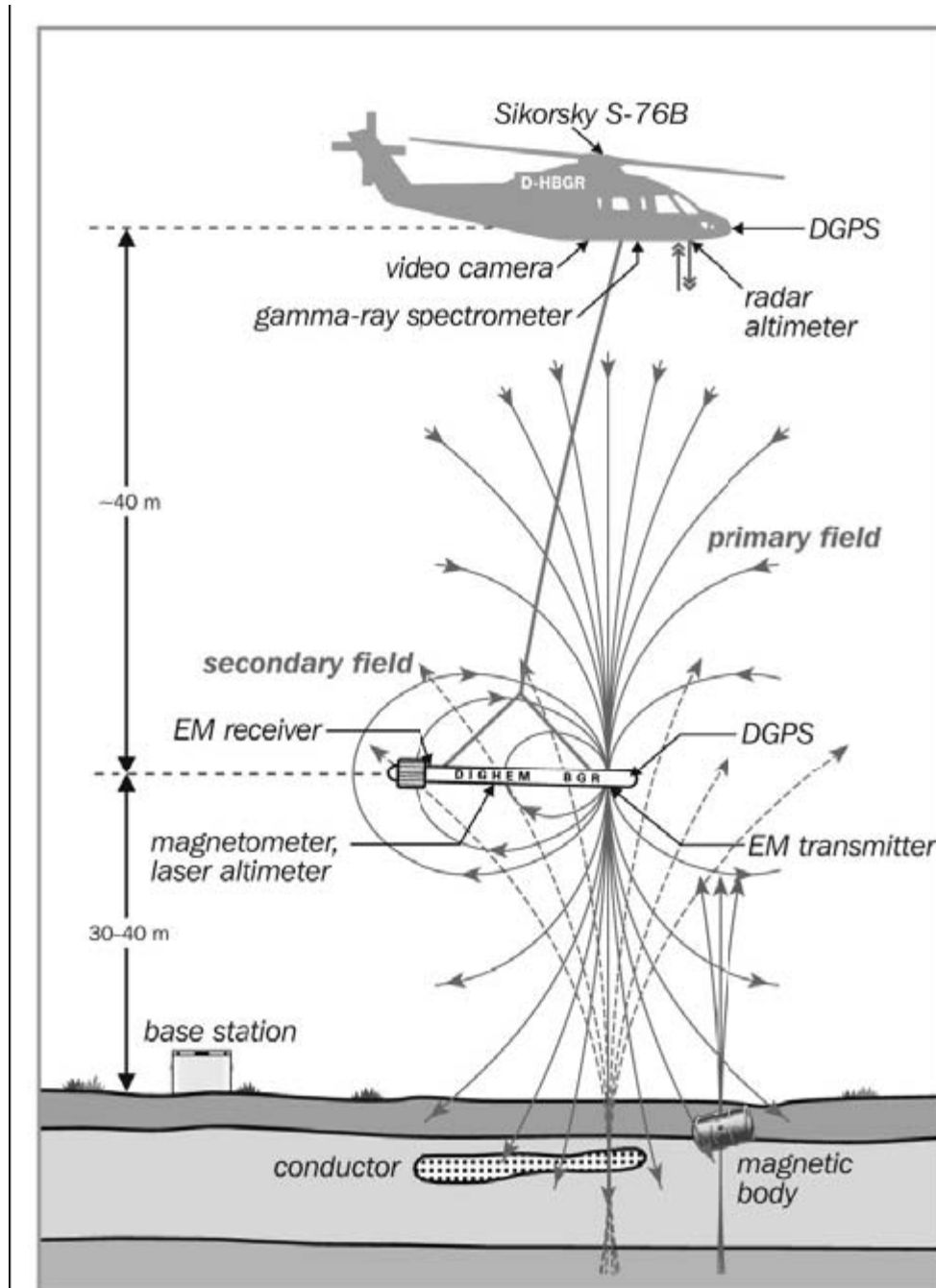


Figure 3. Helicopter-borne Resolve geophysical system similar that used in the Nebraska survey as implemented by the Geological Survey of Germany (after Siemon, 2006): Electromagnetic, magnetic, GPS and laser altimeter sensors are housed in a “bird”, a cigar-shaped 9 m long tube, which is kept at about 30–40 m above ground level. The gamma-ray spectrometer (not used in the Nebraska survey), additional altimeters and the navigation system are installed in the helicopter. The base station records the time varying parameters diurnal magnetic variations.

HEM Measurements

The principles of HEM methods are well summarized by Siemon (2006) and Paine and Minty (2005). The RESOLVE[®] HEM system flown by Fugro Airborne is described in detail in Appendix II. The electromagnetic (EM) measurements are made using six coil pairs that measure EM signals at separate frequencies from about 400 hertz (Hz) to about 115,000 Hz (115 kHz). Five of the coil pairs were oriented in a horizontal, coplanar position and one of the coil pairs was oriented in a vertical, coaxial position. The specific frequencies, separation, orientation of the coil pairs are given in Table 3.

Table 3. Frequencies and sensitivities for the HEM survey. The coil pair separation is 7.9 meters for all except for the 3300 Hz coil-pair which is 9.0 meters.

Coil Configuration	Nominal Frequency Hertz	Actual Frequency Hertz	Sensitivity parts per million
Coplanar	400	380	0.12
Coplanar	1,500	1,760	0.12
Coaxial	3,300	3,270	0.12
Coplanar	6,500	6,520	0.24
Coplanar	26,000	25,300	0.60
Coplanar	115,000	114,940	0.60

The EM measurements made approximately every three meters (ten feet) along flight lines are reduced to apparent resistivity values as described in the contractor's report (Appendix II). One important consideration of the HEM earth subsurface imaging is that the depth of imaging is dependent on the frequency and resistivity of the earth. One estimate of the depth of exploration (depth of mapping) for the frequencies used in the RESOLVE[®] system is shown in figure 6. In this figure, the depth of exploration is defined as 0.5 of the skin depth (point at which a plane electromagnetic wave has attenuated to 37 per cent of the initial amplitude). The depths of

exploration estimates shown in figure 6 are conservative since one skin depth generally is considered to be the depth limit of HEM measurements (Fraser, 1978). Generally, at the highest frequency, depths of exploration are just a few meters. At the lowest frequency, 400 Hz, the depth of exploration may be on the order of 80-m. This aspect of HEM resistivity measurements is the basic principle that allows depth images to be constructed.

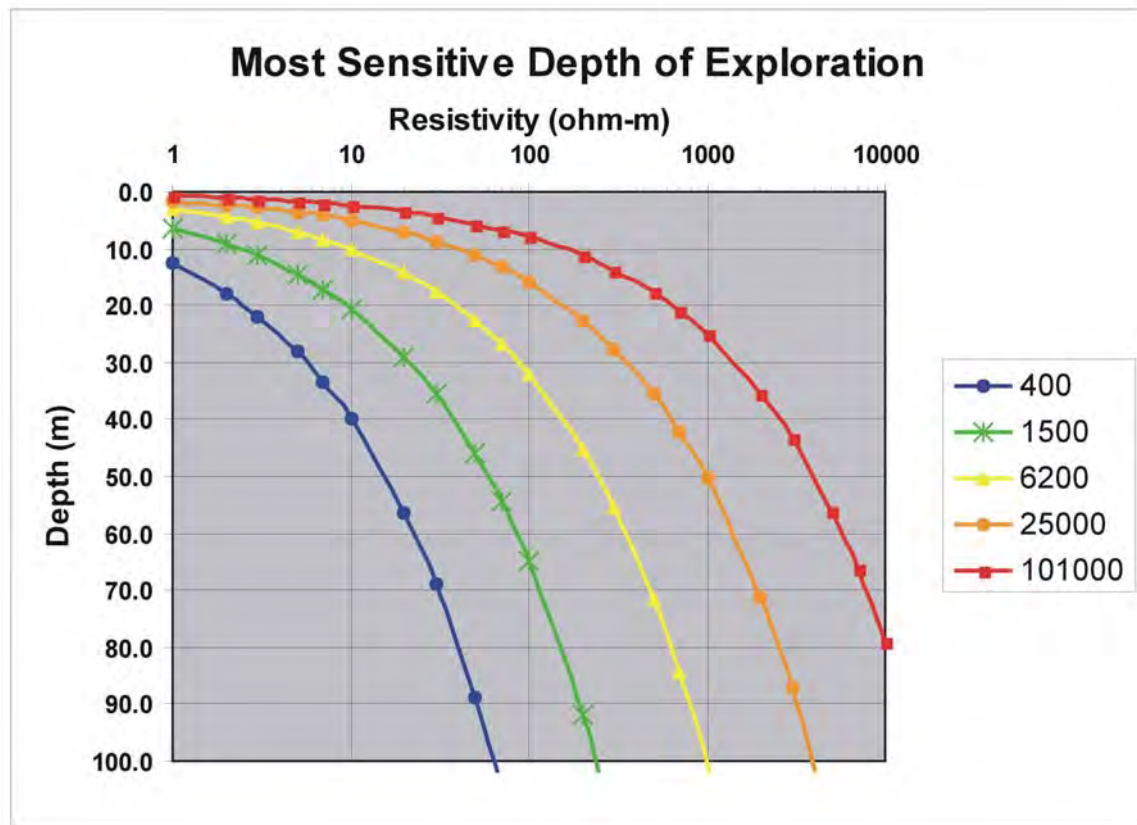


Figure 4. Depth of penetration or imaging as a function of frequency and earth resistivity for the RESOLVE© system (Hodges, Fugro Airborne, 2004, written communication).

The EM signals are recorded for each frequency as in-phase and quadrature (out-of-phase) as referenced to the transmitted signal. These signals are post-processed to apparent resistivity for each frequency and a corresponding apparent depth as described in Appendix II and by Fraser (1978). The apparent resistivity is, as the name implies, not the intrinsic electrical resistivity of the earth but a value estimated based on assumptions of the measurement and of a homogeneous earth (Fraser, 1978). Estimates of the intrinsic resistivity are obtained through a variety of imaging methods that are described by Seimon (2006) and Hodges (2003). The differential resistivity and depth transformation (Haung and Fraser, 1996) is one simple depth imaging method that has proven effective for HEM survey data (Smith and others, 2003). Both the apparent resistivity and differential data are given in the digital line data files (see Table 1).

An important part of the data processing is leveling the EM signals for system drift and calibrations. The specific steps used in the data processing are described in Appendix II. The digital line data gives the raw in-phase and quadrature data and the processed data from which the apparent resistivities are computed. The final leveled data is also given. These data are included in the data base in case the original data is used for reprocessing.

Total Magnetic Field Measurements

The magnetic system measured the Earth's total field to an accuracy of 0.01 nanoTesla (nT). The magnetic field consists of the Earth's main magnetic field and the local magnetic field due to sources within the crust and ferromagnetic metallic sources at the surface. The total field measurements are influenced by short term variations in the magnetic field which are independent of local sources and are caused mainly by solar activity. A total magnetic field base station, set up by the contractor near the base of operations, is used to record these short term variations in the earth's total magnetic field which subtracted from the measurements made during the survey.

The contractor also processed the total magnetic field to remove the spatial variation from the Earth's main magnetic field. This spatial variation is defined by the International Geomagnetic Reference Field or IGRF (Sharma, 2002, describes the basic principles of the main magnetic field removal from magnetometer measurements).

An additional processing step has been applied by the USGS to the magnetic-field data to reduce the data to the magnetic north pole. This reduction to the pole (RTP) shifts magnetic highs directly over the causative body instead of being located slightly to the south. The RTP magnetic data processing was done using Oasis Montaj software (Geosoft, Inc., 2006).

Ancillary Measurements

The airborne electromagnetic system also monitors 60 Hz signals in coaxial and coplanar coil configurations. The data is given as CXPL CPPL channels in the line database (LINEDATA). The data are given as arbitrary voltage levels, which generally increase over power lines. The expression of power lines is quite variable due to a number of factors such as the size of the line, how well it is "grounded", and the electrical resistivity of the earth. In general the infrastructure around urban development, transmission towers, and along major roads has a higher cultural noise level resulting in high 60 Hz signals.

Positioning measurements of the *bird* and the helicopter are critical in processing and making accurate maps. Location data from the GPS system in both the *bird* and helicopter are given in the files in the LINEDATA directory. Elevation data from the laser altimeter on the *bird* as well as the radar and barometric altimeters on the helicopter are given in the LINEDATA files. An important aspect of the contractor's data processing is the elevation data are given in the WGS84 Spheroid and have NOT been reduced to an ellipsoid. The contractor's report explains that additional processing needed to do this data reduction was not part of the USGS contract.

Digital Data

Digital data is given in the directories described in Table 1. The following describes the digital data in each subdirectory.

Metadata

The metadata directory contains files that describe the Ashland, Oakland, and Firth geophysical survey blocks (Figure 1). These survey blocks are the boundaries for line data, digital grids, and plots. The metadata also describes the projection used for all of the digital plots which is briefly NDAD83 UTM14 (meters).

GIS Data

The GIS directory contains various files that may be useful in map preparation. The flight line location files are in dxf (AUTOCAD). Outlines for each survey area are given as ESRI shape files (.shp and ancillary files).

Grids

Flight line data is interpolated onto a regular grid (gridded) to produce map plots. One of the challenges of gridding airborne geophysical data is that the spacing between flight lines is much greater than the sampling along the line (a few meters). Specialized gridding methods have been developed to deal with this aspect of processing airborne geophysical data. The contractor has used a modified Akima spline method (Appendix II, and also in a Fugro technical note: http://www.fugroairborne.com/resources/technical_notes/time_domain_em/pdfs/Akima_tension_III.pdf). The contractor grids are given in the GRIDS directory in the FUGRO subdirectory. These grids have not been modified. The nomenclature for the grid names is given in the readme.txt file.

An alternate gridding method is the minimum curvature method implemented by Webring (1981) for geophysical airborne data. This gridding method is used in the GEOSOFT OASIS MONTAJ program (<http://www.geosoft.com/resources/papers/pdfs/topicsingriddingworkshop.pdf>). We have used this algorithm to produce grids from selected channels of the flight line data. File naming convention is given in the readme.txt file.

The resistivity data has been gridded with a variable cell size to reflect both the increasing size of the footprint of the HEM measurements (Rubin and others, 2005) and the higher noise levels of the lower frequencies (400 and 1500 Hz) due to cultural sources. The lower frequencies have been gridded with a cell size of 100 meters and the higher frequencies with a cell size of 50 meters.

The USGS grids also include the magnetic RTP data, digital elevation, and powerline monitor data. These grids have 50 meter cell size.

The grids are in the GEOSOFT OASIS MONTAJ format commonly used in many geophysical software packages. The grids can be viewed in free software distributed by GEOSOFT (<http://www.geosoft.com/pinfo/oasismontaj/free/montajviewer.asp>). The grids can also be imported into ESRI ARCMAP applications with a plug-in provided by GEOSOFT (<http://www.geosoft.com/resources/releasenotes/plugins/arcGISplugin.asp>). Plug-ins for other software packages can be found on the GEOSOFT web site (<http://www.geosoft.com/downloads/>). Plots produced from the grid files are described below.

Plots

The contractor provided plots for each survey area of the apparent resistivity data at each frequency and plots of the total magnetic field corrected for the earth's main magnetic field (IGRF described above). These plots are given as PDF files in PLOTS directory (Table 1). Note that for the apparent resistivity, the color scales have been stretched for each frequency to emphasize the maximum (red) and minimum (blue) range. Consequently the color scales are not directly comparable between maps with different frequencies. The plots were done from the data as gridded by the contractor using methods described in the project report (Appendix II).

The USGS has produced plots of the gridded data described above as geo-referenced tiff format (geotiff) plots. The projection used for the geotiff plots is the same as the grids, NAD83 UTM14N. The geotiff images have been made as both flat colors (clr files) and as color shaded relief (csr). The color scale for all of the resistivity maps is the same and given as the *RES.jpg file. The color scale gives high resistivity as warm colors (reds) and low resistivity as cool colors (blues). Color scales for the magnetic and digital elevation maps are also given as bitmap .jpg files.

Digital Flight line Data

The flight line data for each area is given in the directory LINEDATA. The files are given in ascii format with column headings as described in the readme file. The contractors report in APPENDIX II also describes the digital flight line data.

Acknowledgments

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APPENDIX I 2008 Geological Society of America Annual Meeting ABSTRACT

Preliminary Results of Hydrogeological Framework Studies of Surface Water - Ground Water Systems in Eastern Nebraska Using Airborne and Ground Geophysics

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Understanding the relationship between surface water and groundwater systems in Eastern Nebraska is critical to understanding water resources and developing management programs. The U.S. Geological Survey (USGS) conducted an airborne resistivity and magnetic (helicopter electromagnetic, HEM) survey and follow up ground surveys in order to characterize and map the hydrogeology in three glacial terrains in Eastern Nebraska during the spring of 2007. The project is part of the Eastern Nebraska Water Resources Assessment (ENWRA), a joint State of Nebraska and USGS study including the Conservation and Survey Division (University of Nebraska) and the following Natural Resource Districts: Lower Platte South, Lower Platt North, Lower Elkhorn, Lewis and Clark, Nemaha, and Papio-Missouri River. The three areas selected for the study, Ashland, Firth, and Oakland have glacial terrains and bedrock that typify different hydrogeologic settings for surface water and ground water in Nebraska.

Approximately 600 line km were flown with HEM in each of the three glacial terrains with a line spacing of approximately 270 m and samples every three meters. Earth resistivities in the Oakland area are the lowest, ranging from 8 to 23 ohm-m, yielding a general depth of penetration of 50 - 60 m. The Ashland area centered on the Platte River exhibited earth resistivities from 6 to 100 ohm-m with an effective depth of penetration from 50 – 100 m. Within the Firth area, earth resistivities range from 5 to 40 ohm-m with a depth of penetration of 50 – 80 m. These HEM results correlate with ground time domain electromagnetic soundings and borehole geophysical logs. The total field magnetics in each area show significant anomalies (in cases, 1000 nT) from crystalline basement features such as mafic dikes and intrusives as well as structures. These may correlate with shallower features that could control the distribution of ground water. Three-dimensional models of the resistivity and magnetic field data indicate buried hydrogeologic features and structure that may control the surface- and ground-water interactions. Follow up drilling efforts coupled with ground-water modeling will use the airborne and ground geophysical models to build a better ground-water management program for Eastern Nebraska.

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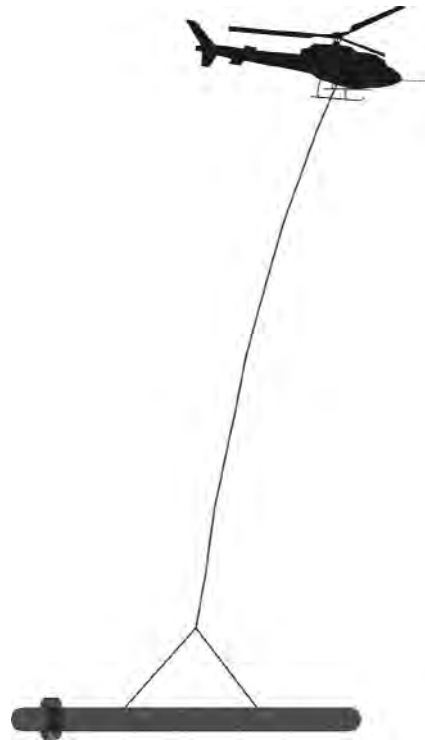
The GSA POSTER is given in [REPORTS](#) directory.

Appendix II: Fugro Geophysical Report

The contractors report is given in the [REPORTS](#) directory.

**RESOLVE SURVEY
FOR
U. S. GEOLOGICAL SURVEY
OAKLAND, ASHLAND and FIRTH AREAS
FREMONT, NEBRASKA**

REF: NK 14-9; NK 14-12



Fugro Airborne Surveys Corp.
Mississauga, Ontario

May 25th, 2007

SUMMARY

This report describes the logistics, data acquisition, processing and presentation of results of a RESOLVE airborne geophysical survey carried out for the U. S. Geological Survey, over the Oakland, Ashland and Firth properties located near Fremont, Nebraska. Total coverage of the survey blocks amounted to 1168.8 km. The survey was flown from March 22nd to March 26th, 2007.

The purpose of the survey was to define conductivity contrasts within the survey blocks and to provide information that could be used to map the geology and structure of the survey areas. This was accomplished by using a RESOLVE multi-coil, multi-frequency electromagnetic system, supplemented by a high sensitivity cesium magnetometer. The information from these sensors was processed to produce maps that display the magnetic and conductive properties of the survey areas. A GPS electronic navigation system ensured accurate positioning of the geophysical data with respect to the base maps.

The survey data were processed and compiled in the Fugro Airborne Surveys Toronto office. Map products and digital data were provided in accordance with the scales and formats specified in the Survey Agreement.

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1. INTRODUCTION

A RESOLVE electromagnetic/resistivity/magnetic survey was flown for the U. S. Geological Survey, from March 22nd to March 26th, 2007, over the Oakland, Ashland and Firth properties located near Fremont, Nebraska. The survey areas are shown in Figures 2 through 4.

Survey coverage consisted of approximately 1168.8 line-km, including 68.4 line-km of tie lines. The breakdown of kilometres flown per block as well as the line direction and line spacing is given below in Table 1-1.

Table 1-1

Block	Traverse line azimuth	Tie Line azimuth	Traverse line spacing (m)	Tie line spacing (m)	Traverse Line (km)	Tie Line (km)	Total
Oakland	127°/307°	37°/217°	270	14 000	371.0	14.0	385.0
Ashland	58°/238°	148°/328°	270	12 000	361.6	24.3	385.9
Firth	90°/270°	0°/180°	280	6 000	367.8	30.1	397.9
TOTAL					1100.4	68.4	1168.8

The survey employed the RESOLVE electromagnetic system. Ancillary equipment consisted of a magnetometer, radar and laser altimeters, video camera, digital data recorder, and an electronic navigation system. The instrumentation was installed in an AS350-B3 turbine helicopter (Registration C-FYZF) that was provided by Great Slave Helicopters Ltd. The

helicopter flew at an average airspeed of 127 km/h with an EM sensor height of approximately 30 metres



Figure 1: Fugro Airborne Surveys RESOLVE EM bird with AS350-B3

2. SURVEY OPERATIONS

The base of operations for the survey was established in Fremont, Nebraska. The survey areas can be seen in Figures 2 through 4.

Table 2-1 lists the corner coordinates of the survey areas in NAD83, UTM Zone 14, central meridian 99°W.

Table 2-1

Block	Corners	X-UTM (E)	Y-UTM (N)
07026-1	1	696693	4636599
Oakland	2	700825	4641659
	3	712641	4632876
	4	708754	4627700
07026-2	1	717397	4553704
Ashland	2	728027	4560504
	3	732027	4554186
	4	721229	4547425
07026-3	1	700186	4500736
Firth	2	706634	4500596
	3	706614	4485999
	4	700006	4486019

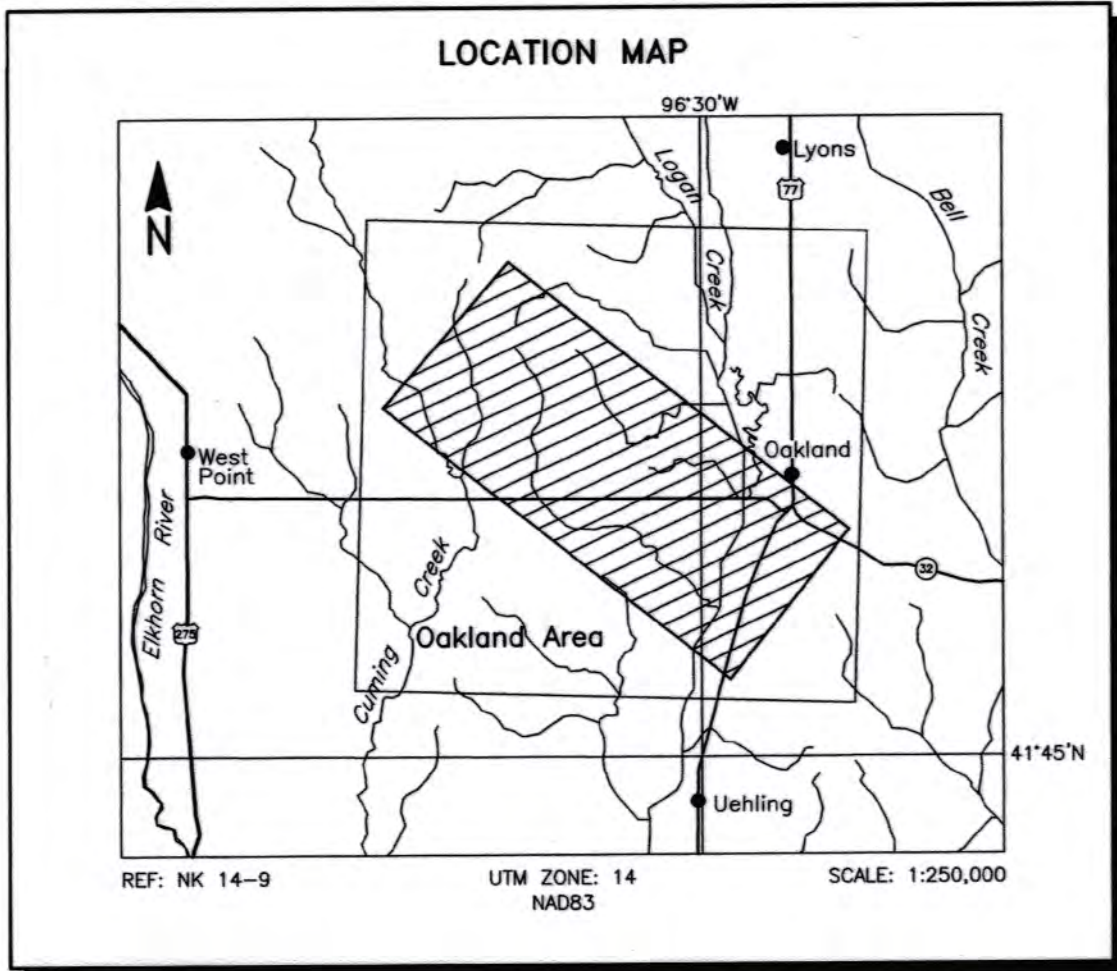


Figure 2
Location Map and Sheet Layout
Oakland Area
Job # 07026-A

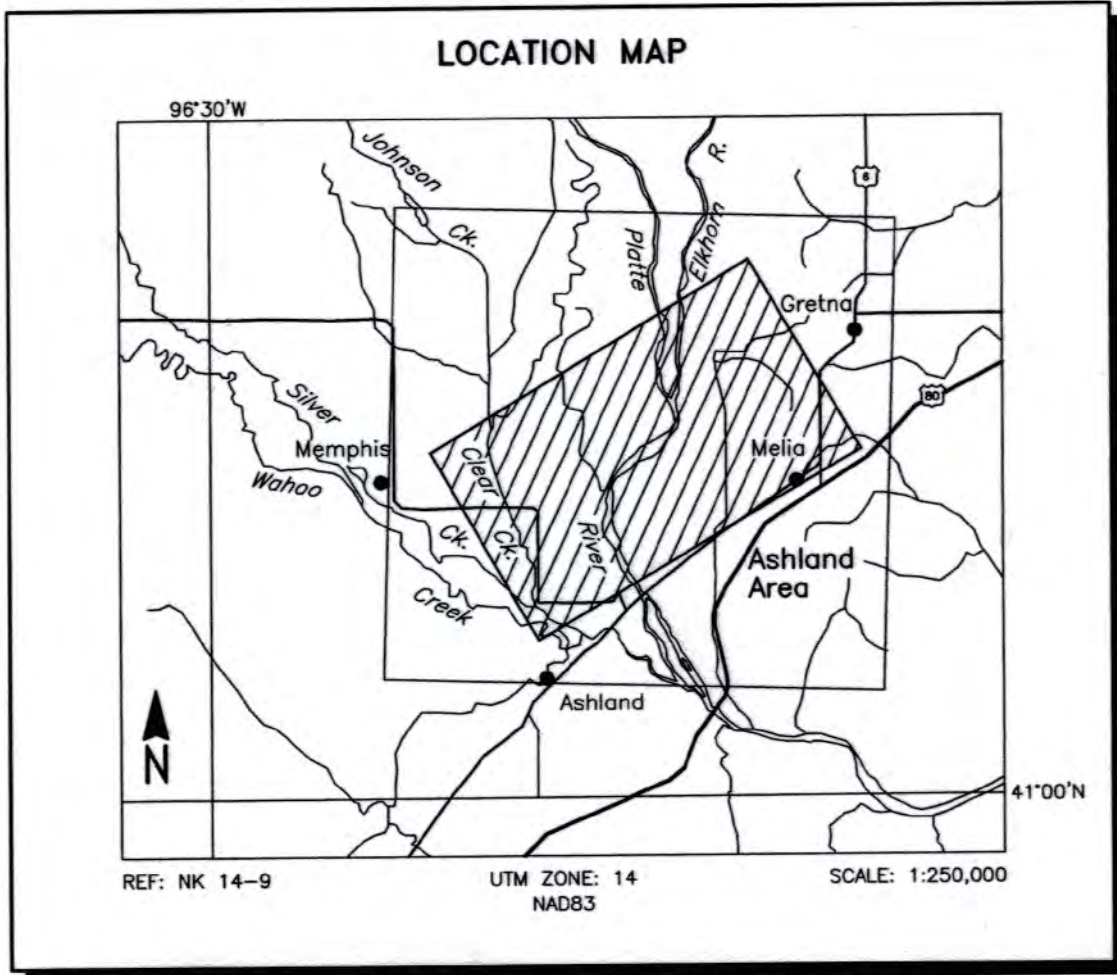


Figure 3
Location Map and Sheet Layout
Ashland Area
Job # 07026-B

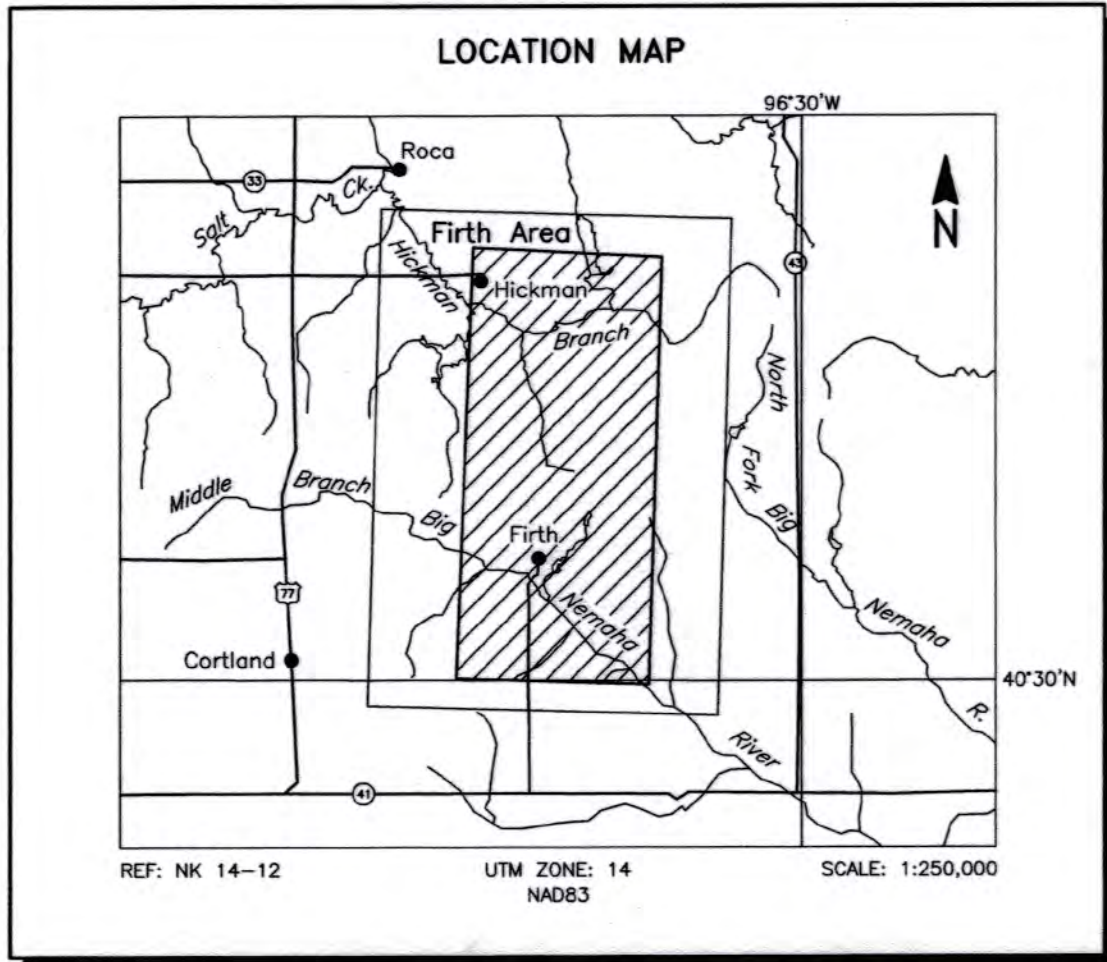


Figure 4
Location Map and Sheet Layout
Firth Area
Job # 07026-C

The survey specifications were as follows:

Parameter	Specifications
Traverse line direction:	
Oakland	127°/307°
Ashland	58°/238°
Firth	90°/270°
Traverse line spacing:	
Oakland	270 m
Ashland	270 m
Firth	280 m
Tie line direction:	
Oakland	37°/217°
Ashland	148°/328°
Firth	0°/180°
Tie line spacing:	
Oakland	14 000 m
Ashland	12 000 m
Firth	6 000 m
Sample interval	10 Hz, 3.3 m @ 120 km/h
Aircraft mean terrain clearance	58 m
EM sensor mean terrain clearance	30 m
Mag sensor mean terrain clearance	30 m
Average speed	127 km/h
Navigation (guidance)	±5 m, Real-time GPS
Post-survey flight path	±2 m, Differential GPS

3. SURVEY EQUIPMENT

This section provides a brief description of the geophysical instruments used to acquire the survey data and the calibration procedures employed. The geophysical equipment was installed in an AS350-B3 helicopter. This aircraft provides a safe and efficient platform for surveys of this type.

Electromagnetic System

Model: RESOLVE

Type: Towed bird, symmetric dipole configuration operated at a nominal survey altitude of 30 metres. Coil separation is 7.9 metres for 385 Hz, 1500 Hz, 6200 Hz, 25,000 Hz and 115,000 Hz, and 9.0 metres for the 3300 Hz coil-pair.

Coil orientations, frequencies and dipole moments	<u>Atm²</u>	<u>orientation</u>	<u>nominal</u>	<u>actual</u>
	310	coplanar	385 Hz	380 Hz
	175	coplanar	1500 Hz	1760 Hz
	211	coaxial	3300 Hz	3270 Hz
	70	coplanar	6200 Hz	6520 Hz
	35	coplanar	25,000 Hz	26 640 Hz
	18	coplanar	115,000 Hz	116 400 Hz

Channels recorded: 6 in-phase channels
6 quadrature channels
2 monitor channels

Sensitivity: 0.12 ppm at 385 Hz Cp
0.12 ppm at 1500 Hz Cp
0.12 ppm at 3300 Hz Cx
0.24 ppm at 6200 Hz Cp
0.60 ppm at 25,000 Hz Cp
0.60 ppm at 115,000 Hz Cp

Sample rate: 10 per second, equivalent to 1 sample every 3.3 m, at a survey speed of 120 km/h.

The electromagnetic system utilizes a multi-coil coaxial/coplanar technique to energize conductors in different directions. The coaxial coils are vertical with their axes in the flight direction. The coplanar coils are horizontal. The secondary fields are sensed simultaneously by means of receiver coils that are maximum coupled to their respective transmitter coils. The system yields an in-phase and a quadrature channel from each transmitter-receiver coil-pair.

In-Flight EM System Calibration

Calibration of the system during the survey uses the Fugro AutoCal automatic, internal calibration process. At the beginning and end of each flight, and at intervals during the flight, the system is flown up to high altitude to remove it from any “ground effect” (response from the earth). Any remaining signal from the receiver coils (base level) is measured as the zero level, and is removed from the data collected until the time of the next calibration. Following the zero level setting, internal calibration coils, for which the response phase and amplitude have been determined at the factory, are automatically triggered – one for each frequency. The on-time of the coils is sufficient to determine an accurate response through any ambient noise. The receiver response to each calibration coil “event” is compared to the expected response (from the factory calibration) for both phase angle and amplitude, and any phase and gain corrections are automatically applied to bring the data to the correct value.

In addition, the outputs of the transmitter coils are continuously monitored during the survey, and the gains are adjusted to correct for any change in transmitter output.

Because the internal calibration coils are calibrated at the factory (on a resistive halfspace) ground calibrations using external calibration coils on-site are not necessary for system calibration. A check calibration may be carried out on-site to ensure all systems are working correctly. All system calibrations will be carried out in the air, at sufficient altitude that there will be no measurable response from the ground.

The internal calibration coils are rigidly positioned and mounted in the system relative to the transmitter and receiver coils. In addition, when the internal calibration coils are calibrated at the factory, a rigid jig is employed to ensure accurate response from the external coils.

Using real time Fast Fourier Transforms and the calibration procedures outlined above, the data are processed in real time, from measured total field at a high sampling rate, to in-phase and quadrature values at 10 samples per second.

Airborne Magnetometer

Model:	Fugro D1344 processor with Scintrex CS2 sensor
Type:	Optically pumped cesium vapour
Sensitivity:	0.01 nT
Sample rate:	10 per second

The magnetometer sensor is housed in the EM bird, 28 m below the helicopter.

Magnetic Base Station

Primary

Model:	Fugro CF1 base station with timing provided by integrated GPS		
Sensor type:	Geometrics GR822A		
Counter specifications:	Accuracy:	± 0.1 nT	
	Resolution:	0.01 nT	
	Sample rate	1 Hz	
GPS specifications:	Model:	Marconi Allstar	
	Type:	Code and carrier tracking of L1 band, 12-channel, C/A code at 1575.42 MHz	
	Sensitivity:	-90 dBm, 1.0 second update	
	Accuracy:	Manufacturer's stated accuracy for differential corrected GPS is 2 metres	

Environmental

Monitor specifications:	Temperature:	
	• Accuracy:	$\pm 1.5^{\circ}\text{C}$ max
	• Resolution:	0.0305 $^{\circ}\text{C}$
	• Sample rate:	1 Hz

- Range: -40°C to +75°C

Barometric pressure:

- Model: Motorola MPXA4115A
- Accuracy: $\pm 3.0^{\circ}$ kPa max (-20°C to 105°C temp. ranges)
- Resolution: 0.013 kPa
- Sample rate: 1 Hz
- Range: 55 kPa to 108 kPa

A digital 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, using GPS time, to permit subsequent removal of diurnal drift. The magnetic base station was located at latitude 41° 26.95525'N, longitude 96° 30.81197'W at an elevation of 335.60 metres.

Navigation (Global Positioning System)

Airborne Receiver for Guidance

Model:	PNAV 2100
Type:	SPS (L1 band), 24-channel, C/A code at 1575.42 MHz, S code at 0.5625 MHz, Real-time differential
Sensitivity:	-132 dBm, 0.5 second update
Accuracy:	Manufacturer's stated accuracy is better than 5 metres real-time
Antenna:	Mounted on tail of aircraft

Airborne Receiver for Flight Path Recovery

Model: Novatel OEM4

Type: Code and carrier tracking of L1-C/A code at 1575.42 MHz and L2-P code at 1227.0 MHz. Dual frequency, 24-channel

Sample rate: 10 Hz update

Accuracy: Better than 1 metre in differential mode

Antenna: Mounted on nose of EM bird

Primary Base Station for Post-Survey Differential Correction

Model: Novatel Millennium

Type: Code and carrier tracking of L1 band, 12-channel, dual frequency C/A code at 1575.2 MHz, and L2 P-code 1227 MHz

Sample rate: 0.5 second update

Accuracy: Manufacturer's stated accuracy for differential corrected GPS is better than 1 metre

Secondary GPS Base Station

Model: Marconi Allstar OEM, CMT-1200

Type: Code and carrier tracking of L1 band, 12-channel, C/A code at 1575.42 MHz

Sensitivity: -90 dBm, 1.0 second update

Accuracy: Manufacturer's stated accuracy for differential corrected GPS is 2 metres.

The Novatel OEM4 is a line of sight, satellite navigation system that utilizes time-coded signals from at least four of forty-eight available satellites. Both Russian GLONASS and

American NAVSTAR satellite constellations are used to calculate the position and to provide real time guidance to the helicopter. For flight path processing an Ashtech Z-surveyor was used as the mobile receiver. A similar system was used as the primary base station receiver. The mobile and base station raw XYZ data were recorded, thereby permitting post-survey differential corrections for theoretical accuracies of better than 2 metres. A Marconi Allstar GPS unit, part of the CF-1, was used as a secondary (back-up) base station.

Each base station receiver is able to calculate its own latitude and longitude. For this survey, the primary GPS station was located at latitude $41^{\circ} 26' 59.51405''N$, longitude $96^{\circ} 30' 45.51876''W$ at an elevation of 341.87 metres above the ellipsoid. The secondary GPS unit was located at latitude $41^{\circ} 26.95525'N$, longitude $96^{\circ} 30.81197'W$ at an elevation of 335.60 metres. The GPS records data relative to the WGS84 ellipsoid, which is the basis of the revised North American Datum (NAD83). Conversion software is used to transform the WGS84 coordinates to the UTM system displayed on the maps.

Radar Altimeter

Manufacturer:	Honeywell/Sperry
Model:	RT330 or AT220
Type:	Short pulse modulation, 4.3 GHz
Sensitivity:	0.3 m
Sample rate:	2 per second

The radar altimeter measures the vertical distance between the helicopter and the ground.

This information is used in the processing algorithm that determines conductor depth.

Barometric Pressure and Temperature Sensors

Model:	DIGHEM D 1300	
Type:	Motorola MPX4115AP analog pressure sensor AD592AN high-impedance remote temperature sensors	
Sensitivity:	Pressure:	150 mV/kPa
	Temperature:	100 mV/°C or 10 mV/°C (selectable)
Sample rate:	10 per second	

The D1300 circuit is used in conjunction with one barometric sensor and up to three temperature sensors. Two sensors (baro and temp) are installed in the EM console in the aircraft, to monitor pressure (1KPA) and internal operating temperatures (2TDC).

Laser Altimeter

Manufacturer:	Optech
Model:	G150
Type:	Fixed pulse repetition rate of 2 kHz
Sensitivity:	±5 cm from 10°C to 30°C ±10 cm from -20°C to +50°C
Sample rate:	2 per second

The laser altimeter is housed in the EM bird, and measures the distance from the EM bird to ground, except in areas of dense tree cover.

Digital Data Acquisition System

Manufacturer: Fugro
Model: HELIDAS
Recorder: Compact Flash Card

The stored data are downloaded to the field workstation PC at the survey base, for verification, backup and preparation of in-field products.

Video Flight Path Recording System

Type: Axis 2420 Digital Network Camera
Recorder: Tablet computer

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

4. QUALITY CONTROL AND IN-FIELD PROCESSING

Digital data for each flight were transferred to the field workstation, in order to verify data quality and completeness. A database was created and updated using Geosoft Oasis Montaj and proprietary Fugro Atlas software. This allowed the field personnel to calculate, display and verify both the positional (flight path) and geophysical data on a screen or printer. Records were examined as a preliminary assessment of the data acquired for each flight.

In-field processing of Fugro survey data consists of differential corrections to the airborne GPS data, verification of EM calibrations, drift correction of the raw airborne EM data, spike rejection and filtering of all geophysical and ancillary data, verification of flight videos, calculation of preliminary resistivity data, diurnal correction, and preliminary levelling of magnetic data.

All data, including base station records, were checked on a daily basis, to ensure compliance with the survey contract specifications. Reflights were required if any of the following specifications were not met.

Navigation - Positional (x,y) accuracy of better than 10 m, with a CEP (circular error of probability) of 95%.

- Flight Path - Deviations from the planned (pre-flight) paths could not exceed 10 percent of the designated flight line spacing. Gaps between adjacent flight lines greater than 1.5 times the designated flight line spacing for more than 2 linear miles (3.2 km) required fill-in intermediate flight lines. However, if the flight-line spacing deviation was caused by a safety requirement, FAA regulation, or military requirement, a fill-in line was not required. Aircraft air speed maintained at a constant during surveying operations.
- Clearance - Mean terrain sensor clearance of 30 m, ± 10 m, except where precluded by safety considerations, e.g., restricted or populated areas, severe topography, obstructions, tree canopy, aerodynamic limitations, etc.
- Airborne Mag - Airborne survey data were not acceptable when gathered during magnetic storms or short term disturbances of magnetic activity at the ground station used that exceeded the following:
- Monotonic changes in the magnetic field of 5 nT in any five-minute period.
 - Pulsations having periods of 5 minutes or less did not exceed 2 nT.

- 4.3 -

- Pulsations having periods between 5 and 10 minutes did not exceed 4 nT.
- Pulsations having periods between 10 and 20 minutes did not exceed 8 nT.

The period of a pulsation is defined as the time between adjacent peaks or troughs. The amplitude of a pulsation is one-half the sum of the positive and negative excursions from trough to trough or peak to peak.

Total intensity magnetometer used to perform the surveys had a sensitivity of 0.1 nT or better. Values were obtained along flight lines at intervals no greater than 33 feet (10 m). The error envelope due to turbulence and the internal magnetometer noise did not exceed ± 0.1 nT for more than 10% of any flight line.

Base Mag - Diurnal variations not to exceed 10 nT over a straight line time chord of 1 minute.

EM - Spheric pulses may occur having strong peaks but narrow widths. The EM data area considered acceptable when their occurrence is less than 10 spheric events exceeding the stated noise specification for a given

frequency per 100 samples continuously over a distance of 2,000 metres.

Frequency	Coil Orientation	Peak to Peak Noise Envelope (ppm)
385 Hz	horizontal coplanar	5.0
1500 Hz	horizontal coplanar	10.0
3300 Hz	vertical coaxial	10.0
6200 Hz	horizontal coplanar	10.0
25,000 Hz	horizontal coplanar	20.0
115,000 Hz	horizontal coplanar	40.0

5. DATA PROCESSING

Flight Path Recovery

The raw range data from at least four satellites are simultaneously recorded by both the base and mobile GPS units. The geographic positions of both units, relative to the model ellipsoid, are calculated from this information. Differential corrections, which are obtained from the base station, are applied to the mobile unit data to provide a post-flight track of the aircraft, accurate to within 2 m. Speed checks of the flight path are also carried out to determine if there are any spikes or gaps in the data.

The corrected WGS84 latitude/longitude coordinates are transformed to the coordinate system used on the final maps. Images or plots are then created to provide a visual check of the flight path.

Electromagnetic Data

EM data are processed at the recorded sample rate of 10 samples/second. Spheric rejection median and Hanning filters are then applied to reduce noise to acceptable levels.

Apparent Resistivity

The apparent resistivities in ohm-m are generated from the in-phase and quadrature EM components for all of the coplanar frequencies, using a pseudo-layer half-space model. The inputs to the resistivity algorithm are the in-phase and quadrature amplitudes of the secondary field. The algorithm calculates the apparent resistivity in ohm-m, and the apparent height of the bird above the conductive source. Any difference between the apparent height and the true height, as measured by the radar altimeter, is called the pseudo-layer and reflects the difference between the real geology and a homogeneous halfspace. This difference is often attributed to the presence of a highly resistive upper layer. Any errors in the altimeter reading, caused by heavy tree cover, are included in the pseudo-layer and do not affect the resistivity calculation. The apparent depth estimates, however, will reflect the altimeter errors. Apparent resistivities calculated in this manner may differ from those calculated using other models.

In areas where the effects of magnetic permeability or dielectric permittivity have suppressed the in-phase responses, the calculated resistivities will be erroneously high. Various algorithms and inversion techniques can be used to partially correct for the effects of permeability and permittivity.

Apparent resistivity maps portray all of the information for a given frequency over the entire survey area. The preliminary apparent resistivity maps and images are carefully inspected to identify any lines or line segments that might require base level adjustments. Subtle changes between in-flight calibrations of the system can result in line-to-line differences that are more

recognizable in resistive (low signal amplitude) areas. If required, manual level adjustments are carried out to eliminate or minimize resistivity differences that can be attributed, in part, to changes in operating temperatures. These levelling adjustments are usually very subtle, and do not result in the degradation of discrete anomalies.

Dielectric Permittivity and Magnetic Permeability Corrections¹

In resistive areas having magnetic rocks, the magnetic and dielectric effects will both generally be present in high-frequency EM data, whereas only the magnetic effect will exist in low-frequency data.

The magnetic permeability is first obtained from the EM data at the lowest frequency, because the ratio of the magnetic response to conductive response is maximized and because displacement currents are negligible. The homogeneous half-space model is used. The computed magnetic permeability is then used along with the in-phase and quadrature response at the highest frequency to obtain the relative dielectric permittivity, again using the homogeneous half-space model. The highest frequency is used because the ratio of dielectric response to conductive response is maximized. The resistivity can then be determined from the measured in-phase and quadrature components of each frequency, given the relative magnetic permeability and relative dielectric permittivity.

¹ Huang, H. and Fraser, D.C., 2001 Mapping of the Resistivity, Susceptibility, and Permittivity of the Earth Using a Helicopter-borne Electromagnetic System: Geophysics 106 pg 148-157.

Resistivity-depth Sections (optional)

The apparent resistivities for all frequencies can be displayed simultaneously as coloured resistivity-depth sections. Usually, only the coplanar data are displayed as the close frequency separation between the coplanar and adjacent coaxial data tends to distort the section. The sections can be plotted using the topographic elevation profile as the surface. The digital terrain values, in metres a.m.s.l., can be calculated from the GPS Z-value or barometric altimeter, minus the aircraft radar altimeter.

Resistivity-depth sections can be generated in three formats:

- (1) Sengpiel resistivity sections, where the apparent resistivity for each frequency is plotted at the depth of the centroid of the in-phase current flow²; and,
- (2) Differential resistivity sections, where the differential resistivity is plotted at the differential depth³.
- (3) Occam⁴ or Multi-layer⁵ inversion.

² Sengpiel, K.P., 1988, Approximate Inversion of Airborne EM Data from Multilayered Ground: Geophysical Prospecting 36, 446-459.

³ Huang, H. and Fraser, D.C., 1993, Differential Resistivity Method for Multi-frequency Airborne EM Sounding: presented at Intern. Airb. EM Workshop, Tucson, Ariz.

⁴ Constable et al, 1987, Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics, 52, 289-300.

⁵ Huang H., and Palacky, G.J., 1991, Damped least-squares inversion of time domain airborne EM data based on singular value decomposition: Geophysical Prospecting, 39, 827-844.

Both the Sengpiel and differential methods are derived from the pseudo-layer half-space model. Both yield a coloured resistivity-depth section that attempts to portray a smoothed approximation of the true resistivity distribution with depth. Resistivity-depth sections are most useful in conductive layered situations, but may be unreliable in areas of moderate to high resistivity where signal amplitudes are weak. In areas where in-phase responses have been suppressed by the effects of magnetite, or adversely affected by cultural features, the computed resistivities shown on the sections may be unreliable.

Both the Occam and multi-layer inversions compute the layered earth resistivity model that would best match the measured EM data. The Occam inversion uses a series of thin, fixed layers (usually 20 x 5m and 10 x 10m layers) and computes resistivities to fit the EM data. The multi-layer inversion computes the resistivity and thickness for each of a defined number of layers (typically 3-5 layers) to best fit the data.

Total Magnetic Field

A fourth difference editing routine was applied to the magnetic data to remove any spikes.

The aeromagnetic data were corrected for diurnal variation using the magnetic base station data. The results were then levelled using tie and traverse line intercepts. Manual adjustments were applied to any lines that required levelling, as indicated by shadowed images of the gridded magnetic data. The manually levelled data were then subjected to a microlevelling filter.

Calculated Vertical Magnetic Gradient (optional)

The diurnally-corrected total magnetic field data can be subjected to a processing algorithm that enhances the response of magnetic bodies in the upper 500 m and attenuates the response of deeper bodies. The resulting vertical gradient map provides better definition and resolution of near-surface magnetic units. It also identifies weak magnetic features that may not be evident on the total field map. However, regional magnetic variations and changes in lithology may be better defined on the total magnetic field map.

Residual Magnetic Intensity (optional)

The residual magnetic intensity (RMI) is derived from the total magnetic field (TMF), the diurnal, and the regional magnetic field. The total magnetic intensity is measured in the aircraft, the diurnal is measured from the ground station, and the regional magnetic field is calculated from the international geo-referenced magnetic field (IGRF). The low frequency component of the diurnal is extracted from the filtered ground station data and removed from the TMF. The average of the diurnal is then added back in to obtain the resultant total magnetic intensity. The regional magnetic field, calculated for the specific survey location and the time of the survey, is then removed from the resultant total magnetic intensity to yield the residual magnetic intensity.

Magnetic Derivatives (optional)

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

- second vertical derivative
- reduction to the pole/equator
- magnetic susceptibility with reduction to the pole
- upward/downward continuations
- analytic signal

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.

Digital Elevation (optional)

The radar altimeter values (ALTR – aircraft to ground clearance) are subtracted from the differentially corrected and de-spiked GPS-Z values to produce profiles of the height above the ellipsoid along the survey lines. These values are gridded to produce contour maps showing approximate elevations within the survey area. The calculated digital terrain data are then tie-line levelled and adjusted to mean sea level. Any remaining subtle line-to-line discrepancies are manually removed. After the manual corrections are applied, the digital terrain data are filtered with a microlevelling algorithm.

The accuracy of the elevation calculation is directly dependent on the accuracy of the two input parameters, ALTR and GPS-Z. The ALTR value may be erroneous in areas of

heavy tree cover, where the altimeter reflects the distance to the tree canopy rather than the ground. The GPS-Z value is primarily dependent on the number of available satellites. Although post-processing of GPS data will yield X and Y accuracies in the order of 1-2 metres, the accuracy of the Z value is usually much less, sometimes in the ± 10 metre range. Further inaccuracies may be introduced during the interpolation and gridding process.

Because of the inherent inaccuracies of this method, no guarantee is made or implied that the information displayed is a true representation of the height above sea level. Although this product may be of some use as a general reference, THIS PRODUCT MUST NOT BE USED FOR NAVIGATION PURPOSES.

Contour, Colour and Shadow Map Displays

The geophysical data are interpolated onto a regular grid using a modified Akima spline technique. The resulting grid is suitable for image processing and generation of contour maps. The grid cell size is 20% of the line interval.

Colour maps are produced by interpolating the grid down to the pixel size. The parameter is then incremented with respect to specific amplitude ranges to provide colour "contour" maps.

Monochromatic shadow maps or images 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. These techniques can be applied to total field or enhanced magnetic

data, magnetic derivatives, resistivity, etc. The shadowing technique is also used as a quality control method to detect subtle changes between lines.

6. PRODUCTS

This section lists the final maps and products that have been provided under the terms of the survey agreement. Other products can be prepared from the existing dataset, if requested.

Base Maps

Base maps of the survey area were produced by scanning published topographic maps to a bitmap (.bmp) format. This process provides a relatively accurate, distortion-free base that facilitates correlation of the navigation data to the map coordinate system. The topographic files were combined with geophysical data for plotting the final maps. All maps were created using the following parameters:

Projection Description:

Datum:	NAD83
Ellipsoid:	GRS 1980
Projection:	UTM (Zone: 14)
Central Meridian:	99°W
False Northing:	0
False Easting:	500000
Scale Factor:	0.9996
WGS84 to Local Conversion:	Molodensky
Datum Shifts:	DX: 0 DY: 0 DZ: 0

Final Products

The following parameters are presented on three map sheets, at a scale of 1:24 000. All maps include flight lines and topography, unless otherwise indicated.

Table 6-1 Final Map Products

	Final Map Products	
	Mylar	Colour (.PDF)
Total Magnetic Field	1	1
Apparent Resistivity 400 Hz	-	1
Apparent Resistivity 1500 Hz	-	1
Apparent Resistivity 6200 Hz	-	1
Apparent Resistivity 25 000 Hz	-	1
Apparent Resistivity 115 000 Hz	-	1

Additional Products

Digital Archive (see Archive Description)
Survey Logistics Report

1 CD-ROM
2 copies

APPENDIX A

LIST OF PERSONNEL

The following personnel were involved in the acquisition, processing and presentation of data, relating to a RESOLVE airborne geophysical survey carried out for the U. S. Geological Survey, over the Oakland, Ashland and Firth properties located in the Fremont area, Nebraska.

David Miles	Manager, Helicopter Operations
Emily Farquhar	Manager, Data Processing and Interpretation
Andy Semple	Geophysical Operator
Robert Loder	Geophysical Operator
Igor Sram	Field Geophysicist
Glen Charbonneau	Pilot (Great Slave Helicopters Ltd.)
Russell Imrie	Geophysical Data Processor
Ruth Pritchard	Interpretation Geophysicist
Lyn Vanderstarren	Drafting Supervisor
Susan Pothiah	Word Processing Operator
Albina Tonello	Secretary/Expeditor

The survey consisted of 1168.8 km of coverage, flown from March 22nd to March 26th, 2007.

All personnel are employees of Fugro Airborne Surveys, except where indicated

APPENDIX B

BACKGROUND INFORMATION

BACKGROUND INFORMATION

Electromagnetics

Fugro electromagnetic responses fall into two general classes, discrete and broad. The discrete class consists of sharp, well-defined anomalies from discrete conductors such as sulphide lenses and steeply dipping sheets of graphite and sulphides. The broad class consists of wide anomalies from conductors having a large horizontal surface such as flatly dipping graphite or sulphide sheets, saline water-saturated sedimentary formations, conductive overburden and rock, kimberlite pipes and geothermal zones. A vertical conductive slab with a width of 200 m would straddle these two classes.

The vertical sheet (half plane) is the most common model used for the analysis of discrete conductors. All anomalies plotted on the geophysical maps are analyzed according to this model. The following section entitled **Discrete Conductor Analysis** describes this model in detail, including the effect of using it on anomalies caused by broad conductors such as conductive overburden.

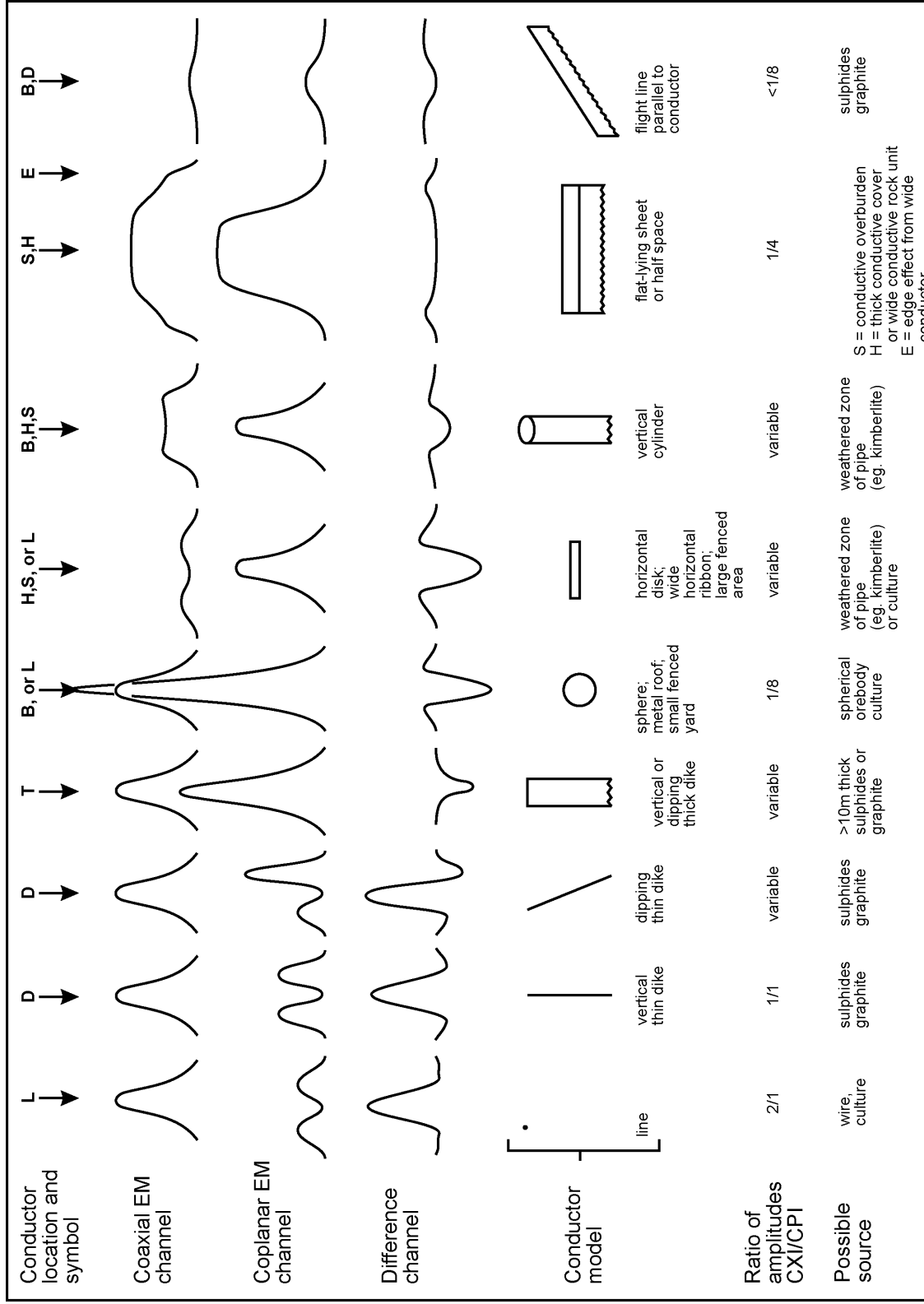
The conductive earth (half-space) model is suitable for broad conductors. Resistivity contour maps result from the use of this model. A later section entitled **Resistivity Mapping** describes the method further, including the effect of using it on anomalies caused by discrete conductors such as sulphide bodies.

Geometric Interpretation

The geophysical interpreter attempts to determine the geometric shape and dip of the conductor. Figure B-1 shows typical HEM anomaly shapes which are used to guide the geometric interpretation.

Discrete Conductor Analysis

The EM anomalies appearing on the electromagnetic map are analyzed by computer to give the conductance (i.e., conductivity-thickness product) in siemens (mhos) of a vertical sheet model. This is done regardless of the interpreted geometric shape of the conductor. This is not an unreasonable procedure, because the computed conductance increases as the electrical quality of the conductor increases, regardless of its true shape. DIGHEM anomalies are divided into seven grades of conductance, as shown in Table B-1. The conductance in siemens (mhos) is the reciprocal of resistance in ohms.



Typical HEM anomaly shapes
Figure B-1

- Appendix B.3 -

The conductance value is a geological parameter because it is a characteristic of the conductor alone. It generally is independent of frequency, flying height or depth of burial, apart from the averaging over a greater portion of the conductor as height increases. Small anomalies from deeply buried strong conductors are not confused with small anomalies from shallow weak conductors because the former will have larger conductance values.

Table B-1. EM Anomaly Grades

Anomaly Grade	Siemens
7	> 100
6	50 - 100
5	20 - 50
4	10 - 20
3	5 - 10
2	1 - 5
1	< 1

Conductive overburden generally produces broad EM responses which may not be shown as anomalies on the geophysical maps. However, patchy conductive overburden in otherwise resistive areas can yield discrete anomalies with a conductance grade (cf. Table B-1) of 1, 2 or even 3 for conducting clays which have resistivities as low as 50 ohm-m. In areas where ground resistivities are below 10 ohm-m, anomalies caused by weathering variations and similar causes can have any conductance grade. The anomaly shapes from the multiple coils often allow such conductors to be recognized, and these are indicated by the letters S, H, and sometimes E on the geophysical maps (see EM legend on maps).

For bedrock conductors, the higher anomaly grades indicate increasingly higher conductances. Examples: the New Inco copper discovery (Noranda, Canada) yielded a grade 5 anomaly, as did the neighbouring copper-zinc Magusi River ore body; Mattabi (copper-zinc, Sturgeon Lake, Canada) and Whistle (nickel, Sudbury, Canada) gave grade 6; and the Montcalm nickel-copper discovery (Timmins, Canada) yielded a grade 7 anomaly. Graphite and sulphides can span all grades but, in any particular survey area, field work may show that the different grades indicate different types of conductors.

Strong conductors (i.e., grades 6 and 7) are characteristic of massive sulphides or graphite. Moderate conductors (grades 4 and 5) typically reflect graphite or sulphides of a less massive character, while weak bedrock conductors (grades 1 to 3) can signify poorly connected graphite or heavily disseminated sulphides. Grades 1 and 2 conductors may not respond to ground EM equipment using frequencies less than 2000 Hz.

The presence of sphalerite or gangue can result in ore deposits having weak to moderate conductances. As an example, the three million ton lead-zinc deposit of Restigouche Mining Corporation near Bathurst, Canada, yielded a well-defined grade 2 conductor. The 10 percent by volume of sphalerite occurs as a coating around the fine grained massive pyrite, thereby inhibiting electrical conduction. Faults, fractures and shear zones may produce anomalies that typically have low conductances (e.g., grades 1 to 3). Conductive rock formations can yield

- Appendix B.4 -

anomalies of any conductance grade. The conductive materials in such rock formations can be salt water, weathered products such as clays, original depositional clays, and carbonaceous material.

For each interpreted electromagnetic anomaly on the geophysical maps, a letter identifier and an interpretive symbol are plotted beside the EM grade symbol. The horizontal rows of dots, under the interpretive symbol, indicate the anomaly amplitude on the flight record. The vertical column of dots, under the anomaly letter, gives the estimated depth. In areas where anomalies are crowded, the letter identifiers, interpretive symbols and dots may be obliterated. The EM grade symbols, however, will always be discernible, and the obliterated information can be obtained from the anomaly listing appended to this report.

The purpose of indicating the anomaly amplitude by dots is to provide an estimate of the reliability of the conductance calculation. Thus, a conductance value obtained from a large ppm anomaly (3 or 4 dots) will tend to be accurate whereas one obtained from a small ppm anomaly (no dots) could be quite inaccurate. The absence of amplitude dots indicates that the anomaly from the coaxial coil-pair is 5 ppm or less on both the in-phase and quadrature channels. Such small anomalies could reflect a weak conductor at the surface or a stronger conductor at depth. The conductance grade and depth estimate illustrates which of these possibilities fits the recorded data best.

The conductance measurement is considered more reliable than the depth estimate. There are a number of factors that can produce an error in the depth estimate, including the averaging of topographic variations by the altimeter, overlying conductive overburden, and the location and attitude of the conductor relative to the flight line. Conductor location and attitude can provide an erroneous depth estimate because the stronger part of the conductor may be deeper or to one side of the flight line, or because it has a shallow dip. A heavy tree cover can also produce errors in depth estimates. This is because the depth estimate is computed as the distance of bird from conductor, minus the altimeter reading. The altimeter can lock onto the top of a dense forest canopy. This situation yields an erroneously large depth estimate but does not affect the conductance estimate.

Dip symbols are used to indicate the direction of dip of conductors. These symbols are used only when the anomaly shapes are unambiguous, which usually requires a fairly resistive environment.

A further interpretation is presented on the EM map by means of the line-to-line correlation of bedrock anomalies, which is based on a comparison of anomaly shapes on adjacent lines. This provides conductor axes that may define the geological structure over portions of the survey area. The absence of conductor axes in an area implies that anomalies could not be correlated from line to line with reasonable confidence.

The electromagnetic anomalies are designed to provide a correct impression of conductor quality by means of the conductance grade symbols. The symbols can stand alone with geology when planning a follow-up program. The actual conductance values are printed in the attached anomaly list for those who wish quantitative data. The anomaly ppm and depth

- Appendix B.5 -

are indicated by inconspicuous dots which should not distract from the conductor patterns, while being helpful to those who wish this information. The map provides an interpretation of conductors in terms of length, strike and dip, geometric shape, conductance, depth, and thickness. The accuracy is comparable to an interpretation from a high quality ground EM survey having the same line spacing.

The appended EM anomaly list provides a tabulation of anomalies in ppm, conductance, and depth for the vertical sheet model. No conductance or depth estimates are shown for weak anomalous responses that are not of sufficient amplitude to yield reliable calculations.

Since discrete bodies normally are the targets of EM surveys, local base (or zero) levels are used to compute local anomaly amplitudes. This contrasts with the use of true zero levels which are used to compute true EM amplitudes. Local anomaly amplitudes are shown in the EM anomaly list and these are used to compute the vertical sheet parameters of conductance and depth.

Questionable Anomalies

The EM maps may contain anomalous responses that are displayed as asterisks (*). These responses denote weak anomalies of indeterminate conductance, which may reflect one of the following: a weak conductor near the surface, a strong conductor at depth (e.g., 100 to 120 m below surface) or to one side of the flight line, or aerodynamic noise. Those responses that have the appearance of valid bedrock anomalies on the flight profiles are indicated by appropriate interpretive symbols (see EM legend on maps). The others probably do not warrant further investigation unless their locations are of considerable geological interest.

The Thickness Parameter

A comparison of coaxial and coplanar shapes can provide an indication of the thickness of a steeply dipping conductor. The amplitude of the coplanar anomaly (e.g., CPI channel) increases relative to the coaxial anomaly (e.g., CXI) as the apparent thickness increases, i.e., the thickness in the horizontal plane. (The thickness is equal to the conductor width if the conductor dips at 90 degrees and strikes at right angles to the flight line.) This report refers to a conductor as thin when the thickness is likely to be less than 3 m, and thick when in excess of 10 m. Thick conductors are indicated on the EM map by parentheses "()". For base metal exploration in steeply dipping geology, thick conductors can be high priority targets because many massive sulphide ore bodies are thick. The system cannot sense the thickness when the strike of the conductor is subparallel to the flight line, when the conductor has a shallow dip, when the anomaly amplitudes are small, or when the resistivity of the environment is below 100 ohm-m.

Resistivity Mapping

- Appendix B.6 -

Resistivity mapping is useful in areas where broad or flat lying conductive units are of interest. One example of this is the clay alteration which is associated with Carlin-type deposits in the south west United States. The resistivity parameter was able to identify the clay alteration zone over the Cove deposit. The alteration zone appeared as a strong resistivity low on the 900 Hz resistivity parameter. The 7,200 Hz and 56,000 Hz resistivities showed more detail in the covering sediments, and delineated a range front fault. This is typical in many areas of the south west United States, where conductive near surface sediments, which may sometimes be alkalic, attenuate the higher frequencies.

Resistivity mapping has proven successful for locating diatremes in diamond exploration. Weathering products from relatively soft kimberlite pipes produce a resistivity contrast with the unaltered host rock. In many cases weathered kimberlite pipes were associated with thick conductive layers that contrasted with overlying or adjacent relatively thin layers of lake bottom sediments or overburden.

Areas of widespread conductivity are commonly encountered during surveys. These conductive zones may reflect alteration zones, shallow-dipping sulphide or graphite-rich units, saline ground water, or conductive overburden. In such areas, EM amplitude changes 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 in-phase and quadrature channels that 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 bedrock and 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 apparent resistivity is calculated using the pseudo-layer (or buried) half-space model defined by Fraser (1978)⁶. 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 that might

⁶ Resistivity mapping with an airborne multicoil electromagnetic system: Geophysics, v. 43, p.144-172

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exist in the measured altitude of the EM bird (e.g., as caused by a dense tree cover). The inputs to the resistivity algorithm are the in-phase and quadrature components of the coplanar coil-pair. The outputs are the apparent resistivity of the conductive half-space (the source) and the sensor-source distance. The flying height is not an input variable, and the output resistivity and sensor-source distance are independent of the flying height when the conductivity of the measured material is sufficient to yield significant in-phase as well as quadrature responses. 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. Depth information has been used for 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.

Interpretation in Conductive Environments

Environments having low background resistivities (e.g., below 30 ohm-m for a 900 Hz system) yield very large responses from the conductive ground. This usually prohibits the recognition of discrete bedrock conductors. However, Fugro data processing techniques produce three parameters that contribute significantly to the recognition of bedrock conductors in conductive environments. These are the in-phase and quadrature difference channels (DIFI and DIFQ, which are available only on systems with “common” frequencies on orthogonal coil pairs), and the resistivity and depth channels (RES and DEP) for each coplanar frequency.

The EM difference channels (DIFI and DIFQ) eliminate most of the responses from conductive ground, leaving responses from bedrock conductors, cultural features (e.g., telephone lines, fences, etc.) and edge effects. Edge effects often occur near the perimeter of broad conductive zones. This can be a source of geologic noise. While edge effects yield anomalies on the EM difference channels, they do not produce resistivity anomalies. Consequently, the resistivity channel aids in eliminating anomalies due to edge effects. On the other hand, resistivity anomalies will coincide with the most highly conductive sections of conductive ground, and this is another source of geologic noise. The recognition of a bedrock conductor in a conductive environment therefore is based on the anomalous responses of the two difference channels (DIFI and DIFQ) and the resistivity channels (RES). The most favourable situation is where anomalies coincide on all channels.

The DEP channels, which give the apparent depth to the conductive material, also help to determine whether a conductive response arises from surficial material or from a conductive zone in the bedrock. When these channels ride above the zero level on the depth profiles

(i.e., depth is negative), it implies that the EM and resistivity profiles are responding primarily to a conductive upper layer, i.e., conductive overburden. If the DEP channels are below the zero level, it indicates that a resistive upper layer exists, and this usually implies the existence of a bedrock conductor. If the low frequency DEP channel is below the zero level and the high frequency DEP is above, this suggests that a bedrock conductor occurs beneath conductive cover.

Reduction of Geologic Noise

Geologic noise refers to unwanted geophysical responses. For purposes of airborne EM surveying, geologic noise refers to EM responses caused by conductive overburden and magnetic permeability. It was mentioned previously that the EM difference channels (i.e., channel DIFI for in-phase and DIFQ for quadrature) tend to eliminate the response of conductive overburden.

Magnetite produces a form of geological noise on the in-phase channels. Rocks containing less than 1% magnetite can yield negative in-phase anomalies caused by magnetic permeability. When magnetite is widely distributed throughout a survey area, the in-phase EM channels may continuously rise and fall, reflecting variations in the magnetite percentage, flying height, and overburden thickness. This can lead to difficulties in recognizing deeply buried bedrock conductors, particularly if conductive overburden also exists. However, the response of broadly distributed magnetite generally vanishes on the in-phase difference channel DIFI. This feature can be a significant aid in the recognition of conductors that occur in rocks containing accessory magnetite.

EM Magnetite Mapping

The information content of HEM data consists of a combination of conductive eddy current responses and magnetic permeability responses. The secondary field resulting from conductive eddy current flow is frequency-dependent and consists of both in-phase and quadrature components, which are positive in sign. On the other hand, the secondary field resulting from magnetic permeability is independent of frequency and consists of only an in-phase component which is negative in sign. When magnetic permeability manifests itself by decreasing the measured amount of positive in-phase, its presence may be difficult to recognize. However, when it manifests itself by yielding a negative in-phase anomaly (e.g., in the absence of eddy current flow), its presence is assured. In this latter case, the negative component can be used to estimate the percent magnetite content.

A magnetite mapping technique, based on the low frequency coplanar data, can be complementary to magnetometer mapping in certain cases. Compared to magnetometry, it is far less sensitive but is more able to resolve closely spaced magnetite zones, as well as providing an estimate of the amount of magnetite in the rock. The method is sensitive to 1/4% magnetite by weight when the EM sensor is at a height of 30 m above a magnetitic half-space. It can individually resolve steep dipping narrow magnetite-rich bands which are separated by 60 m. Unlike magnetometry, the EM magnetite method is unaffected by remanent magnetism or magnetic latitude.

The EM magnetite mapping technique provides estimates of magnetite content which are usually correct within a factor of 2 when the magnetite is fairly uniformly distributed. EM magnetite maps can be generated when magnetic permeability is evident as negative in-phase responses on the data profiles.

Like magnetometry, the EM magnetite method maps only bedrock features, provided that the overburden is characterized by a general lack of magnetite. This contrasts with resistivity mapping which portrays the combined effect of bedrock and overburden.

The Susceptibility Effect

When the host rock is conductive, the positive conductivity response will usually dominate the secondary field, and the susceptibility effect⁷ will appear as a reduction in the in-phase, rather than as a negative value. The in-phase response will be lower than would be predicted by a model using zero susceptibility. At higher frequencies the in-phase conductivity response also gets larger, so a negative magnetite effect observed on the low frequency might not be observable on the higher frequencies, over the same body. The susceptibility effect is most obvious over discrete magnetite-rich zones, but also occurs over uniform geology such as a homogeneous half-space.

High magnetic susceptibility will affect the calculated apparent resistivity, if only conductivity is considered. Standard apparent resistivity algorithms use a homogeneous half-space model, with zero susceptibility. For these algorithms, the reduced in-phase response will, in most cases, make the apparent resistivity higher than it should be. It is important to note that there is nothing wrong with the data, nor is there anything wrong with the processing algorithms. The apparent difference results from the fact that the simple geological model used in processing does not match the complex geology.

Measuring and Correcting the Magnetite Effect

Theoretically, it is possible to calculate (forward model) the combined effect of electrical conductivity and magnetic susceptibility on an EM response in all environments. The difficulty lies, however, in separating out the susceptibility effect from other geological effects when deriving resistivity and susceptibility from EM data.

Over a homogeneous half-space, there is a precise relationship between in-phase, quadrature, and altitude. These are often resolved as phase angle, amplitude, and

⁷ Magnetic susceptibility and permeability are two measures of the same physical property. Permeability is generally given as relative permeability, μ_r , which is the permeability of the substance divided by the permeability of free space ($4\pi \times 10^{-7}$). Magnetic susceptibility k is related to permeability by $k = \mu_r - 1$. Susceptibility is a unitless measurement, and is usually reported in units of 10^6 . The typical range of susceptibilities is -1 for quartz, 130 for pyrite, and up to 5×10^5 for magnetite, in 10^6 units (Telford et al, 1986).

altitude. Within a reasonable range, any two of these three parameters can be used to calculate the half space resistivity. If the rock has a positive magnetic susceptibility, the in-phase component will be reduced and this departure can be recognized by comparison to the other parameters.

The algorithm used to calculate apparent susceptibility and apparent resistivity from HEM data, uses a homogeneous half-space geological model. Non half-space geology, such as horizontal layers or dipping sources, can also distort the perfect half-space relationship of the three data parameters. While it may be possible to use more complex models to calculate both rock parameters, this procedure becomes very complex and time-consuming. For basic HEM data processing, it is most practical to stick to the simplest geological model.

Magnetite reversals (reversed in-phase anomalies) have been used for many years to calculate an "FeO" or magnetite response from HEM data (Fraser, 1981). However, this technique could only be applied to data where the in-phase was observed to be negative, which happens when susceptibility is high and conductivity is low.

Applying Susceptibility Corrections

Resistivity calculations done with susceptibility correction may change the apparent resistivity. High-susceptibility conductors, that were previously masked by the susceptibility effect in standard resistivity algorithms, may become evident. In this case the susceptibility corrected apparent resistivity is a better measure of the actual resistivity of the earth. However, other geological variations, such as a deep resistive layer, can also reduce the in-phase by the same amount. In this case, susceptibility correction would not be the best method. Different geological models can apply in different areas of the same data set. The effects of susceptibility, and other effects that can create a similar response, must be considered when selecting the resistivity algorithm.

Susceptibility from EM vs Magnetic Field Data

The response of the EM system to magnetite may not match that from a magnetometer survey. First, HEM-derived susceptibility is a rock property measurement, like resistivity. Magnetic data show the total magnetic field, a measure of the potential field, not the rock property. Secondly, the shape of an anomaly depends on the shape and direction of the source magnetic field. The electromagnetic field of HEM is much different in shape from the earth's magnetic field. Total field magnetic anomalies are different at different magnetic latitudes; HEM susceptibility anomalies have the same shape regardless of their location on the earth.

In far northern latitudes, where the magnetic field is nearly vertical, the total magnetic field measurement over a thin vertical dike is very similar in shape to the anomaly from the HEM-derived susceptibility (a sharp peak over the body). The same vertical dike at

the magnetic equator would yield a negative magnetic anomaly, but the HEM susceptibility anomaly would show a positive susceptibility peak.

Effects of Permeability and Dielectric Permittivity

Resistivity algorithms that assume free-space magnetic permeability and dielectric permittivity, do not yield reliable values in highly magnetic or highly resistive areas. Both magnetic polarization and displacement currents cause a decrease in the in-phase component, often resulting in negative values that yield erroneously high apparent resistivities. The effects of magnetite occur at all frequencies, but are most evident at the lowest frequency. Conversely, the negative effects of dielectric permittivity are most evident at the higher frequencies, in resistive areas.

The table below shows the effects of varying permittivity over a resistive (10,000 ohm-m) half space, at frequencies of 56,000 Hz (DIGHEM^V) and 102,000 Hz (RESOLVE).

Apparent Resistivity Calculations Effects of Permittivity on In-phase/Quadrature/Resistivity

Freq (Hz)	Coil	Sep (m)	Thres (ppm)	Alt (m)	In Phase	Quad Phase	App Res	App Depth (m)	Permittivity
56,000	CP	6.3	0.1	30	7.3	35.3	10118	-1.0	1 Air
56,000	CP	6.3	0.1	30	3.6	36.6	19838	-13.2	5 Quartz
56,000	CP	6.3	0.1	30	-1.1	38.3	81832	-25.7	10 Epidote
56,000	CP	6.3	0.1	30	-10.4	42.3	76620	-25.8	20 Granite
56,000	CP	6.3	0.1	30	-19.7	46.9	71550	-26.0	30 Diabase
56,000	CP	6.3	0.1	30	-28.7	52.0	66787	-26.1	40 Gabbro
102,000	CP	7.86	0.1	30	32.5	117.2	9409	-0.3	1 Air
102,000	CP	7.86	0.1	30	11.7	127.2	25956	-16.8	5 Quartz
102,000	CP	7.86	0.1	30	-14.0	141.6	97064	-26.5	10 Epidote
102,000	CP	7.86	0.1	30	-62.9	176.0	83995	-26.8	20 Granite
102,000	CP	7.86	0.1	30	-107.5	215.8	73320	-27.0	30 Diabase
102,000	CP	7.86	0.1	30	-147.1	259.2	64875	-27.2	40 Gabbro

Methods have been developed (Huang and Fraser, 2000, 2001) to correct apparent resistivities for the effects of permittivity and permeability. The corrected resistivities yield more credible values than if the effects of permittivity and permeability are disregarded.

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

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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. Channels CXPL and CPPL monitor 60 Hz radiation. An anomaly on these channels 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 that strikes across a power line, carrying leakage currents.
2. A flight that crosses a "line" (e.g., fence, telephone line, etc.) yields a centre-peaked coaxial anomaly and an m-shaped coplanar anomaly.⁸ When the flight crosses the cultural line at a high angle of intersection, the amplitude ratio of coaxial/coplanar response is 2. Such an EM anomaly can only be caused by a line. The geologic body that yields anomalies most closely resembling a line is the vertically dipping thin dike. Such a body, however, yields an amplitude ratio of 1 rather than 2. Consequently, an m-shaped coplanar anomaly with a CXI/CPI amplitude ratio of 2 is virtually a guarantee that the source is a cultural line.
3. A flight that crosses a sphere or horizontal disk yields centre-peaked coaxial and coplanar anomalies with a CXI/CPI amplitude ratio (i.e., coaxial/coplanar) of 1/8. In the absence of geologic bodies of this geometry, the most likely conductor is a metal roof or small fenced yard.⁹ Anomalies of this type are virtually certain to be cultural if they occur in an area of culture.
4. A flight that crosses a horizontal rectangular body or wide ribbon yields an m-shaped coaxial anomaly and a centre-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.
5. EM anomalies that 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 centre-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

⁸ See Figure B-1 presented earlier.

⁹ 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.

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 channels and on the camera film or video records.

Magnetic Responses

The measured total magnetic field provides information on the magnetic properties of the earth materials in the survey area. The information can be used to locate magnetic bodies of direct interest for exploration, and for structural and lithological mapping.

The total magnetic field response reflects the abundance of magnetic material in the source. Magnetite is the most common magnetic mineral. Other minerals such as ilmenite, pyrrhotite, franklinite, chromite, hematite, arsenopyrite, limonite and pyrite are also magnetic, but to a lesser extent than magnetite on average.

In some geological environments, an EM anomaly with magnetic correlation has a greater likelihood of being produced by sulphides than one which is non-magnetic. However, sulphide ore bodies may be non-magnetic (e.g., the Kidd Creek deposit near Timmins, Canada) as well as magnetic (e.g., the Mattabi deposit near Sturgeon Lake, Canada).

Iron ore deposits will be anomalously magnetic in comparison to surrounding rock due to the concentration of iron minerals such as magnetite, ilmenite and hematite.

Changes in magnetic susceptibility often allow rock units to be differentiated based on the total field magnetic response. Geophysical classifications may differ from geological classifications if various magnetite levels exist within one general geological classification. Geometric considerations of the source such as shape, dip and depth, inclination of the earth's field and remanent magnetization will complicate such an analysis.

In general, mafic lithologies contain more magnetite and are therefore more magnetic than many sediments which tend to be weakly magnetic. Metamorphism and alteration can also increase or decrease the magnetization of a rock unit.

Textural differences on a total field magnetic contour, colour or shadow map due to the frequency of activity of the magnetic parameter resulting from inhomogeneities in the distribution of magnetite within the rock, may define certain lithologies. For example, near surface volcanics may display highly complex contour patterns with little line-to-line correlation.

Rock units may be differentiated based on the plan shapes of their total field magnetic responses. Mafic intrusive plugs can appear as isolated "bulls-eye" anomalies. Granitic intrusives appear as sub-circular zones, and may have contrasting rings due to contact

- Appendix B.14 -

metamorphism. Generally, granitic terrain will lack a pronounced strike direction, although granite gneiss may display strike.

Linear north-south units are theoretically not well-defined on total field magnetic maps in equatorial regions due to the low inclination of the earth's magnetic field. However, most stratigraphic units will have variations in composition along strike that will cause the units to appear as a series of alternating magnetic highs and lows.

Faults and shear zones may be characterized by alteration that causes destruction of magnetite (e.g., weathering) that produces a contrast with surrounding rock. Structural breaks may be filled by magnetite-rich, fracture filling material as is the case with diabase dikes, or by non-magnetic felsic material.

Faulting can also be identified by patterns in the magnetic total field contours or colours. Faults and dikes tend to appear as lineaments and often have strike lengths of several kilometres. Offsets in narrow, magnetic, stratigraphic trends also delineate structure. Sharp contrasts in magnetic lithologies may arise due to large displacements along strike-slip or dip-slip faults.

APPENDIX C

DATA ARCHIVE DESCRIPTION

APPENDIX C

ARCHIVE DESCRIPTION

CCD02517

This final data archive contains XYZ files and grids of an airborne geophysical survey conducted by FUGRO AIRBORNE SURVEYS CORP. on behalf of the U.S.G.S in Nebraska over the Oakland Block A, Ashton Block B and Firth Block C areas flown from March 22-26, 2007

Job # 07026

ReadMe.TXT - This file

Grids in Geosoft format with corresponding .GI files

\Grids\

MAG-*.GRD	- Residual Magnetic Field nT Block *
RES400-*.GRD	- Apparent Resistivity 380 Hz coplanar ohm.m Block *
RES1500-*.GRD	- Apparent Resistivity 1760 Hz coplanar ohm.m Block *
RES3300-*.GRD	- Apparent Resistivity 3270 Hz coaxial ohm.m Block *
RES6200-*.GRD	- Apparent Resistivity 6520 Hz coplanar ohm.m Block *
RES25K-*.GRD	- Apparent Resistivity 26640 Hz coplanar ohm.m Block *
RES100K-*.GRD	- Apparent Resistivity 116400 Hz coplanar ohm.m Block *
DTM-*.GRD	- Digital Terrain Model Z-LASER m Block *

\Linedata\

Geosoft format Line Data ASCII XYZ files

Block-A.GDB	- Final data archive in Geosoft XYZ format Block A
Block-B.GDB	- Final data archive in Geosoft XYZ format Block
Block-C.GDB	- Final data archive in Geosoft XYZ format Block C

\Plots\

Final colour maps in PDF format

MAGBW_*.PDF	- Black and white Residual Magnetic Field nT Blocks *
MAG_*.PDF	- Residual Magnetic Field nT Blocks *
RES400-*.PDF	- Apparent Resistivity 380 Hz coplanar ohm.m Blocks *
RES1500-*.PDF	- Apparent Resistivity 1760 Hz coplanar ohm.m Blocks *
RES3300-*.PDF	- Apparent Resistivity 3270 Hz coaxial ohm.m Blocks *
RES6200-*.PDF	- Apparent Resistivity 6520 Hz coplanar ohm.m Blocks *
RES25K-*.PDF	- Apparent Resistivity 26640 Hz coplanar ohm.m Blocks *
RES100K-*.PDF	- Apparent Resistivity 116400 Hz coplanar ohm.m Blocks *

\Report\

07026rep.pdf	- Logistics report
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The channels in the Block-*.XYZ files are as follows;

1 – X	m	Final bird easting (NAD83) UTM Z14N
2 – Y	m	Final Bird Northing (NAD83) UTM Z14N
3 – FID		Fiducial counter
4 – Z	m	Leveled height of EM bird above WGS84 ellipsoid
5 – BALT	m	Leveled barometric altitude of helicopter
6 – LASER	m	Em Bird to Earth-Surface, Laser Altimeter
7 – ALTRADAR	m	Helicopter to Earth-Surface, Radar Altimeter
8 – DTM	m	Digital Terrain Model ZFIN-LASER
9 – MAGSP	nT	Despiked total magnetic field
10 – DIURNAL	nT	Base level removed diurnal magnetic correction
11 – MAGLD	nT	Lagged diurnal corrected total magnetic field
12 – IGRF	nT	International Geomagnetic Reference Field 2005 based on date and ZFIN
13 – MAG	nT	Leveled residual magnetic field
14 – CPPL		Coplanar powerline monitor
15 – CXSP		Coaxial powerline monitor
16 – CPSP		Coplanar atmospheric monitor
17 - CPI400_CAL	ppm	Raw Inphase-Coplanar 380 Hz
18 - CPQ400_CAL	ppm	Raw Quadrature-Coplanar 380 Hz
19 - CPI1500_CAL	ppm	Raw Inphase-Coplanar 1760 Hz
20 - CPQ1500_CAL	ppm	Raw Quadrature-Coplanar 1760 Hz
21 - CXI3300_CAL	ppm	Raw Inphase-Coaxial 3270 Hz
22 - CXQ3300_CAL	ppm	Raw Quadrature-Coaxial 3270 Hz
23 - CPI6200_CAL	ppm	Raw Inphase-Coplanar 6520 Hz
24 - CPQ6200_CAL	ppm	Raw Quadrature-Coplanar 6520 Hz
25 - CPI25K_CAL	ppm	Raw Inphase-Coplanar 26640 Hz
26 - CPQ25K_CAL	ppm	Raw Quadrature-Coplanar 26640 Hz
27 - CPI100K_CAL	ppm	Raw Inphase-Coplanar 116400 Hz
28 - CPQ100K_CAL	ppm	Raw Quadrature-Coplanar 116400 Hz
29 - CPI400_R	ppm	Background leveled, lagged Inphase-Coplanar 380 Hz
30 - CPQ400_R	ppm	Background leveled, lagged Quadrature-Coplanar 380 Hz
31 - CPI1500_R	ppm	Background leveled, lagged Inphase-Coplanar 1760 Hz
32 - CPQ1500_R	ppm	Background leveled, lagged Quadrature-Coplanar 1760 Hz
33 - CXI3300_R	ppm	Background leveled, lagged Inphase-Coaxial 3270 Hz
34 - CXQ3300_R	ppm	Background leveled, lagged Quadrature-Coaxial 3270 Hz
35 - CPI6200_R	ppm	Background leveled, lagged Inphase-Coplanar 6520 Hz
36 - CPQ6200_R	ppm	Background leveled, lagged Quadrature-Coplanar 6520 Hz
37 - CPI25K_R	ppm	Background leveled, lagged Inphase-Coplanar 26640 Hz
38 - CPQ25K_R	ppm	Background leveled, lagged Quadrature-Coplanar 26640 Hz
39 - CPI100K_R	ppm	Background leveled, lagged Inphase-Coplanar 116400 Hz
40 - CPQ100K_R	ppm	Background leveled, lagged Quadrature-Coplanar 116400 Hz
41 - CPI400	ppm	Final leveled Inphase-Coplanar 380 Hz
42 - CPQ400	ppm	Final leveled Quadrature-Coplanar 380 Hz
43 - CPI1500	ppm	Final leveled Inphase-Coplanar 1760 Hz
44 - CPQ1500	ppm	Final leveled Quadrature-Coplanar 1760 Hz
45 - CXI3300	ppm	Final leveled Inphase-Coaxial 3270 Hz
46 - CXQ3300	ppm	Final leveled Quadrature-Coaxial 3270 Hz
47 - CPI6200	ppm	Final leveled Inphase-Coplanar 6520 Hz
48 - CPQ6200	ppm	Final leveled Quadrature-Coplanar 6520 Hz

49 - CPI25K	ppm	Final leveled Inphase-Coplanar 26640 Hz
50 - CPQ25K	ppm	Final leveled Quadrature-Coplanar 26640 Hz
51 - CPI100K	ppm	Final leveled Inphase-Coplanar 116400 Hz
52 - CPQ100K	ppm	Final leveled Quadrature-Coplanar 116400 Hz
53 - RES400	ohm·m	Apparent Resistivity 380 Hz
54 - RES1500	ohm·m	Apparent Resistivity 1760 Hz
55 - RES3300	ohm·m	Apparent Resistivity 3270 Hz Coaxial
56 - RES6200	ohm·m	Apparent Resistivity 6520 Hz
57 - RES25K	ohm·m	Apparent Resistivity 26640 Hz
58 - RES100K	ohm·m	Apparent Resistivity 116400 Hz
59 - DEP400	m	Apparent Depth 380 Hz
60 - DEP1500	m	Apparent Depth 1760 Hz
61 - DEP3300	m	Apparent Depth 3270 Hz Coaxial
62 - DEP6200	m	Apparent Depth 6520 Hz
63 - DEP25K	m	Apparent Depth 26640 Hz
64 - DEP100K	m	Apparent Depth 116400 Hz
65 - UTC	sec	Time
66 - FLIGHT		Flight number
67 - DATE		yyyy/mm/dd Date
68 - LATWGS84	deg	Bird latitude WGS 84 UTM Z14N
69 - LONWGS84	deg	Bird longitude WGS 84 UTM Z14N
70 - ALTL_FP	m	Raw bird laser altitude
71 - ALTR	feet	Raw Helicopter radar altitude
72 - KPA	kPa	Raw air pressure at helicopter
73 - Z_BIRD	m	Raw GPS bird height above WGS84 ellipsoid

The coordinate system for all grids and the data archive is projected as follows

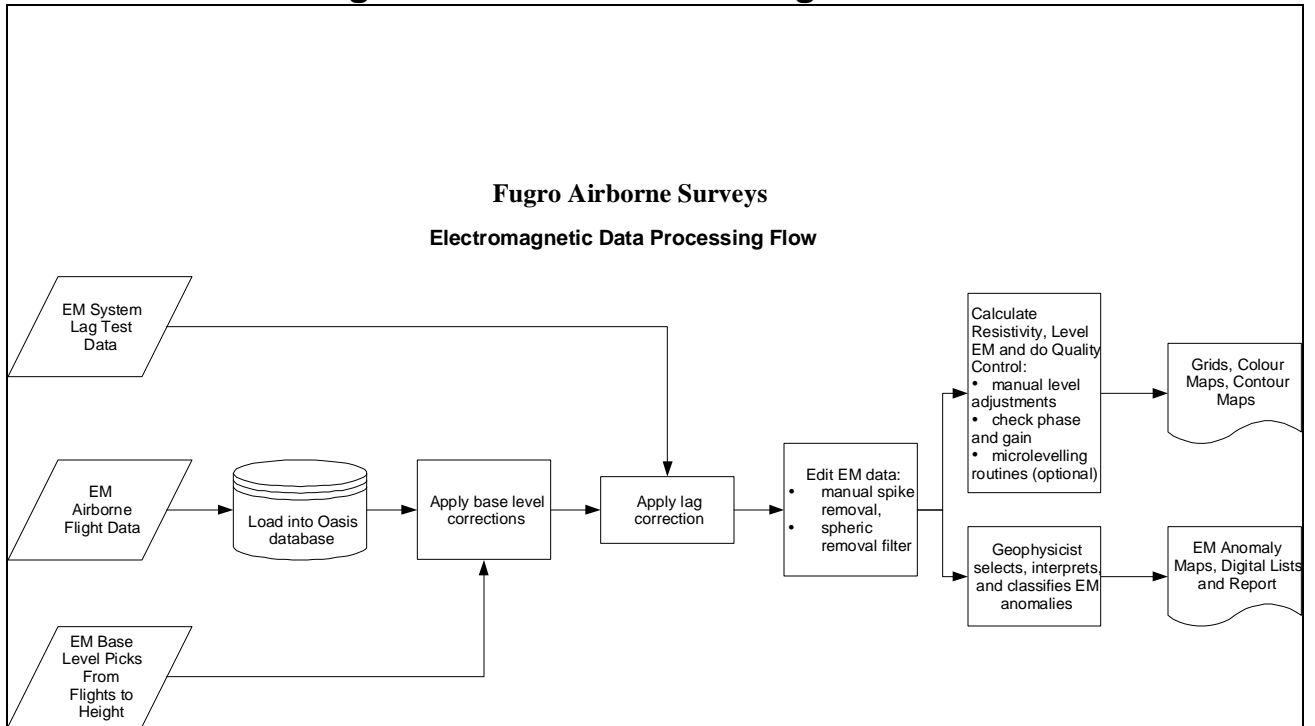
Datum	NAD83
Spheroid	WGS84
Projection	UTM
Central meridian	99 West (Z14N)
False easting	500000
False northing	0
Scale factor	0.9996
Northern parallel	N/A
Base parallel	N/A
WGS84 to local conversion method	Molodensky
Delta X shift	0
Delta Y shift	0
Delta Z shift	0

APPENDIX D

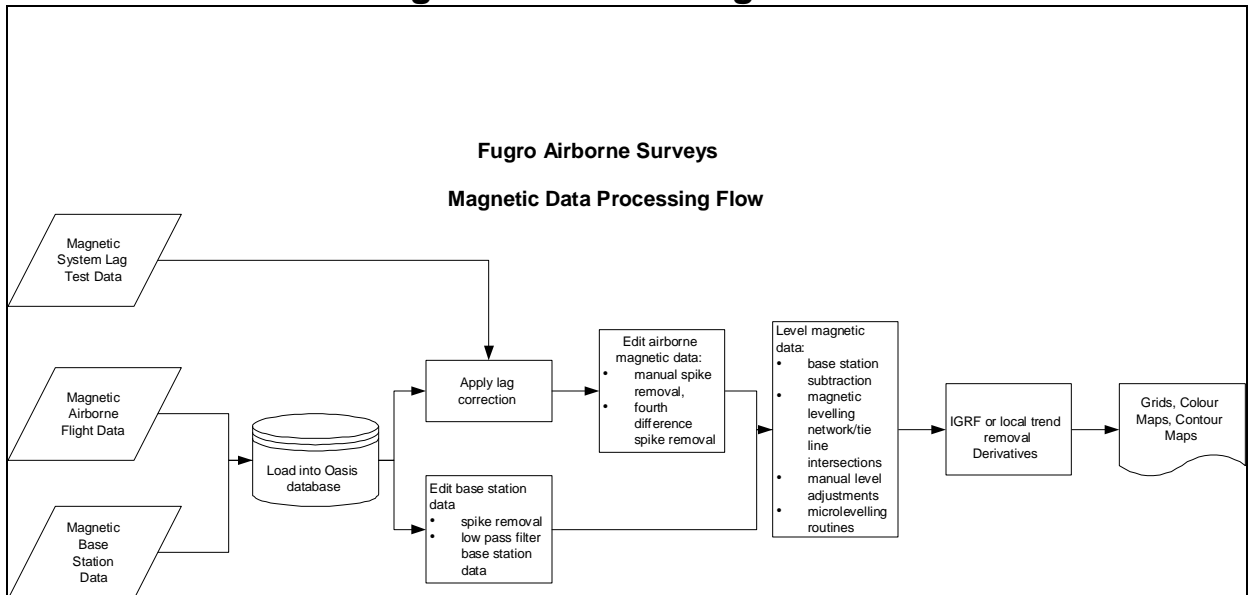
**DATA PROCESSING
FLOWCHARTS**

APPENDIX D

Processing Flow Chart - Electromagnetic Data



Processing Flow Chart - Magnetic Data



APPENDIX E

GLOSSARY

APPENDIX E

GLOSSARY OF AIRBORNE GEOPHYSICAL TERMS

Note: The definitions given in this glossary refer to the common terminology as used in airborne geophysics.

altitude attenuation: the absorption of gamma rays by the atmosphere between the earth and the detector. The number of gamma rays detected by a system decreases as the altitude increases.

apparent- : the *physical parameters* of the earth measured by a geophysical system are normally expressed as apparent, as in “apparent *resistivity*”. This means that the measurement is limited by assumptions made about the geology in calculating the response measured by the geophysical system. Apparent resistivity calculated with *HEM*, for example, generally assumes that the earth is a *homogeneous half-space* – not layered.

amplitude: The strength of the total electromagnetic field. In *frequency domain* it is most often the sum of the squares of *in-phase* and *quadrature* components. In multi-component electromagnetic surveys it is generally the sum of the squares of all three directional components.

analytic signal: The total amplitude of all the directions of magnetic *gradient*. Calculated as the sum of the squares.

anisotropy: Having different *physical parameters* in different directions. This can be caused by layering or fabric in the geology. Note that a unit can be anisotropic, but still **homogeneous**.

anomaly: A localized change in the geophysical data characteristic of a discrete source, such as a conductive or magnetic body: something locally different from the **background**.

B-field: In time-domain **electromagnetic** surveys, the magnetic field component of the (electromagnetic) **field**. This can be measured directly, although more commonly it is calculated by integrating the time rate of change of the magnetic field dB/dt , as measured with a receiver coil.

background: The “normal” response in the geophysical data – that response observed over most of the survey area. **Anomalies** are usually measured relative to the background. In airborne gamma-ray spectrometric surveys the term defines the **cosmic**, radon, and aircraft responses in the absence of a signal from the ground.

base-level: The measured values in a geophysical system in the absence of any outside signal. All geophysical data are measured relative to the system base level.

- Appendix E.2 -

base frequency: The frequency of the pulse repetition for a *time-domain electromagnetic* system. Measured between subsequent positive pulses.

bird: A common name for the pod towed beneath or behind an aircraft, carrying the geophysical sensor array.

bucking: The process of removing the strong *signal* from the *primary field* at the *receiver* from the data, to measure the *secondary field*. It can be done electronically or mathematically. This is done in *frequency-domain EM*, and to measure *on-time* in *time-domain EM*.

calibration coil: A wire coil of known size and dipole moment, which is used to generate a field of known *amplitude* and *phase* in the receiver, for system calibration. Calibration coils can be external, or internal to the system. Internal coils may be called Q-coils.

coaxial coils: [CX] Coaxial coils in an HEM system are in the vertical plane, with their axes horizontal and collinear in the flight direction. These are most sensitive to vertical conductive objects in the ground, such as thin, steeply dipping conductors perpendicular to the flight direction. Coaxial coils generally give the sharpest anomalies over localized conductors. (See also *coplanar coils*)

coil: A multi-turn wire loop used to transmit or detect electromagnetic fields. Time varying *electromagnetic* fields through a coil induce a voltage proportional to the strength of the field and the rate of change over time.

compensation: Correction of airborne geophysical data for the changing effect of the aircraft. This process is generally used to correct data in *fixed-wing time-domain electromagnetic* surveys (where the transmitter is on the aircraft and the receiver is moving), and magnetic surveys (where the sensor is on the aircraft, turning in the earth's magnetic field).

component: In *frequency domain electromagnetic* surveys this is one of the two *phase* measurements – *in-phase or quadrature*. In “multi-component” electromagnetic surveys it is also used to define the measurement in one geometric direction (vertical, horizontal in-line and horizontal transverse – the Z, X and Y components).

Compton scattering: gamma ray photons will bounce off electrons as they pass through the earth and atmosphere, reducing their energy and then being detected by *radiometric* sensors at lower energy levels. See also *stripping*.

conductance: See *conductivity thickness*

conductivity: [σ] The facility with which the earth or a geological formation conducts electricity. Conductivity is usually measured in milli-Siemens per metre (mS/m). It is the reciprocal of *resistivity*.

conductivity-depth imaging: see **conductivity-depth transform**.

conductivity-depth transform: A process for converting electromagnetic measurements to an approximation of the conductivity distribution vertically in the earth, assuming a **layered earth**. (Macnae and Lamontagne, 1987; Wolfgram and Karlik, 1995)

conductivity thickness: [σt] The product of the **conductivity**, and thickness of a large, tabular body. (It is also called the “conductivity-thickness product”) In electromagnetic geophysics, the response of a thin plate-like conductor is proportional to the conductivity multiplied by thickness. For example a 10 metre thickness of 20 Siemens/m mineralization will be equivalent to 5 metres of 40 S/m; both have 200 S conductivity thickness. Sometimes referred to as conductance.

conductor: Used to describe anything in the ground more conductive than the surrounding geology. Conductors are most often clays or graphite, or hopefully some type of mineralization, but may also be man-made objects, such as fences or pipelines.

coplanar coils: [CP] In HEM, the coplanar coils lie in the horizontal plane with their axes vertical, and parallel. These coils are most sensitive to massive conductive bodies, horizontal layers, and the **halfspace**.

cosmic ray: High energy sub-atomic particles from outer space that collide with the earth’s atmosphere to produce a shower of gamma rays (and other particles) at high energies.

counts (per second): The number of **gamma-rays** detected by a gamma-ray **spectrometer**. The rate depends on the geology, but also on the size and sensitivity of the detector.

culture: A term commonly used to denote any man-made object that creates a geophysical anomaly. Includes, but not limited to, power lines, pipelines, fences, and buildings.

current channelling: See current gathering.

current gathering: The tendency of electrical currents in the ground to channel into a conductive formation. This is particularly noticeable at higher frequencies or early time channels when the formation is long and parallel to the direction of current flow. This tends to enhance anomalies relative to inductive currents (see also **induction**). Also known as current channelling.

daughter products: The radioactive natural sources of gamma-rays decay from the original “parent” element (commonly potassium, uranium, and thorium) to one or more lower-energy “daughter” elements. Some of these lower energy elements are also radioactive and decay further. **Gamma-ray spectrometry** surveys may measure the gamma rays given off by the original element or by the decay of the daughter products.

- Appendix E.4 -

dB/dt: As the **secondary electromagnetic field** changes with time, the magnetic field [B] component induces a voltage in the receiving **coil**, which is proportional to the rate of change of the magnetic field over time.

decay: In **time-domain electromagnetic** theory, the weakening over time of the **eddy currents** in the ground, and hence the **secondary field** after the **primary field** electromagnetic pulse is turned off. In **gamma-ray spectrometry**, the radioactive breakdown of an element, generally potassium, uranium, thorium, or one of their **daughter** products.

decay constant: see time constant.

decay series: In **gamma-ray spectrometry**, a series of progressively lower energy **daughter products** produced by the radioactive breakdown of uranium or thorium.

depth of exploration: The maximum depth at which the geophysical system can detect the target. The depth of exploration depends very strongly on the type and size of the target, the contrast of the target with the surrounding geology, the homogeneity of the surrounding geology, and the type of geophysical system. One measure of the maximum depth of exploration for an electromagnetic system is the depth at which it can detect the strongest conductive target – generally a highly conductive horizontal layer.

differential resistivity: A process of transforming **apparent resistivity** to an approximation of layer resistivity at each depth. The method uses multi-frequency HEM data and approximates the effect of shallow layer **conductance** determined from higher frequencies to estimate the deeper conductivities (Huang and Fraser, 1996)

dipole moment: [NIA] For a transmitter, the product of the area of a **coil**, the number of turns of wire, and the current flowing in the coil. At a distance significantly larger than the size of the coil, the magnetic field from a coil will be the same if the dipole moment product is the same. For a receiver coil, this is the product of the area and the number of turns. The sensitivity to a magnetic field (assuming the source is far away) will be the same if the dipole moment is the same.

diurnal: The daily variation in a natural field, normally used to describe the natural fluctuations (over hours and days) of the earth's magnetic field.

dielectric permittivity: [ϵ] The capacity of a material to store electrical charge, this is most often measured as the relative permittivity [ϵ_r], or ratio of the material dielectric to that of free space. The effect of high permittivity may be seen in HEM data at high frequencies over highly resistive geology as a reduced or negative **in-phase**, and higher **quadrature** data.

- Appendix E.5 -

drape: To fly a survey following the terrain contours, maintaining a constant altitude above the local ground surface. Also applied to re-processing data collected at varying altitudes above ground to simulate a survey flown at constant altitude.

drift: Long-time variations in the base-level or calibration of an instrument.

eddy currents: The electrical currents induced in the ground, or other conductors, by a time-varying **electromagnetic field** (usually the **primary field**). Eddy currents are also induced in the aircraft's metal frame and skin; a source of **noise** in EM surveys.

electromagnetic: [EM] Comprised of a time-varying electrical and magnetic field. Radio waves are common electromagnetic fields. In geophysics, an electromagnetic system is one which transmits a time-varying **primary field** to induce **eddy currents** in the ground, and then measures the **secondary field** emitted by those eddy currents.

energy window: A broad spectrum of **gamma-ray** energies measured by a spectrometric survey. The energy of each gamma-ray is measured and divided up into numerous discrete energy levels, called windows.

equivalent (thorium or uranium): The amount of radioelement calculated to be present, based on the gamma-rays measured from a **daughter** element. This assumes that the **decay series** is in equilibrium – progressing normally.

exposure rate: in radiometric surveys, a calculation of the total exposure rate due to gamma rays at the ground surface. It is used as a measurement of the concentration of all the **radioelements** at the surface. See also: **natural exposure rate**.

fiducial, or fid: Timing mark on a survey record. Originally these were timing marks on a profile or film; now the term is generally used to describe 1-second interval timing records in digital data, and on maps or profiles.

Figure of Merit: (FOM) A sum of the 12 distinct magnetic noise variations measured by each of four flight directions, and executing three aircraft attitude variations (yaw, pitch, and roll) for each direction. The flight directions are generally parallel and perpendicular to planned survey flight directions. The FOM is used as a measure of the **manoeuvre noise** before and after **compensation**.

fixed-wing: Aircraft with wings, as opposed to “rotary wing” helicopters.

footprint: This is a measure of the area of sensitivity under the aircraft of an airborne geophysical system. The footprint of an **electromagnetic** system is dependent on the altitude of the system, the orientation of the transmitter and receiver and the separation between the receiver and transmitter, and the conductivity of the ground. The footprint of a **gamma-ray spectrometer** depends mostly on the altitude. For all geophysical systems, the footprint also depends on the strength of the contrasting **anomaly**.

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frequency domain: An *electromagnetic* system which transmits a *primary field* that oscillates smoothly over time (sinusoidal), inducing a similarly varying electrical current in the ground. These systems generally measure the changes in the *amplitude* and *phase* of the *secondary field* from the ground at different frequencies by measuring the *in-phase* and *quadrature* phase components. See also *time-domain*.

full-stream data: Data collected and recorded continuously at the highest possible sampling rate. Normal data are stacked (see *stacking*) over some time interval before recording.

gamma-ray: A very high-energy photon, emitted from the nucleus of an atom as it undergoes a change in energy levels.

gamma-ray spectrometry: Measurement of the number and energy of natural (and sometimes man-made) gamma-rays across a range of photon energies.

gradient: In magnetic surveys, the gradient is the change of the magnetic field over a distance, either vertically or horizontally in either of two directions. Gradient data is often measured, or calculated from the total magnetic field data because it changes more quickly over distance than the *total magnetic field*, and so may provide a more precise measure of the location of a source. See also *analytic signal*.

ground effect: The response from the earth. A common calibration procedure in many geophysical surveys is to fly to altitude high enough to be beyond any measurable response from the ground, and there establish *base levels* or *backgrounds*.

half-space: A mathematical model used to describe the earth – as infinite in width, length, and depth below the surface. The most common halfspace models are *homogeneous* and *layered earth*.

heading error: A slight change in the magnetic field measured when flying in opposite directions.

HEM: Helicopter ElectroMagnetic, This designation is most commonly used for helicopter-borne, *frequency-domain* electromagnetic systems. At present, the transmitter and receivers are normally mounted in a *bird* carried on a sling line beneath the helicopter.

herringbone pattern: A pattern created in geophysical data by an asymmetric system, where the *anomaly* may be extended to either side of the source, in the direction of flight. Appears like fish bones, or like the teeth of a comb, extending either side of centre, each tooth an alternate flight line.

homogeneous: This is a geological unit that has the same *physical parameters* throughout its volume. This unit will create the same response to an HEM system anywhere, and the HEM system will measure the same apparent *resistivity* anywhere. The response may change with system direction (see *anisotropy*).

- Appendix E.7 -

HTEM: Helicopter Time-domain ElectroMagnetic, This designation is used for the new generation of helicopter-borne, **time-domain** electromagnetic systems.

in-phase: the component of the measured **secondary field** that has the same phase as the transmitter and the **primary field**. The in-phase component is stronger than the **quadrature** phase over relatively higher **conductivity**.

induction: Any time-varying electromagnetic field will induce (cause) electrical currents to flow in any object with non-zero **conductivity**. (see **eddy currents**)

induction number: also called the “response parameter”, this number combines many of the most significant parameters affecting the **EM** response into one parameter against which to compare responses. For a **layered earth** the response parameter is $\mu\omega\sigma h^2$ and for a large, flat, **conductor** it is $\mu\omega\sigma h$, where μ is the **magnetic permeability**, ω is the angular **frequency**, σ is the **conductivity**, t is the thickness (for the flat conductor) and h is the height of the system above the conductor.

inductive limit: When the frequency of an EM system is very high, or the **conductivity** of the target is very high, the response measured will be entirely **in-phase** with no **quadrature** (phase angle =0). The in-phase response will remain constant with further increase in conductivity or frequency. The system can no longer detect changes in conductivity of the target.

infinite: In geophysical terms, an “infinite” dimension is one much greater than the **footprint** of the system, so that the system does not detect changes at the edges of the object.

International Geomagnetic Reference Field: [IGRF] An approximation of the smooth magnetic field of the earth, in the absence of variations due to local geology. Once the IGRF is subtracted from the measured magnetic total field data, any remaining variations are assumed to be due to local geology. The IGRF also predicts the slow changes of the field up to five years in the future.

inversion, or inverse modeling: A process of converting geophysical data to an earth model, which compares theoretical models of the response of the earth to the data measured, and refines the model until the response closely fits the measured data (Huang and Palacky, 1991)

layered earth: A common geophysical model which assumes that the earth is horizontally layered – the **physical parameters** are constant to **infinite** distance horizontally, but change vertically.

magnetic permeability: [μ] This is defined as the ratio of magnetic induction to the inducing magnetic field. The relative magnetic permeability [μ_r] is often quoted, which is the ratio of the rock permeability to the permeability of free space. In geology and geophysics, the **magnetic susceptibility** is more commonly used to describe rocks.

- Appendix E.8 -

magnetic susceptibility: [**k**] A measure of the degree to which a body is magnetized. In SI units this is related to relative **magnetic permeability** by $k = \mu_r - 1$, and is a dimensionless unit. For most geological material, susceptibility is influenced primarily by the percentage of magnetite. It is most often quoted in units of 10^{-6} . In HEM data this is most often apparent as a negative ***in-phase*** component over high susceptibility, high **resistivity** geology such as diabase dikes.

manoeuvre noise: variations in the magnetic field measured caused by changes in the relative positions of the magnetic sensor and magnetic objects or electrical currents in the aircraft. This type of noise is generally corrected by magnetic **compensation**.

model: Geophysical theory and applications generally have to assume that the geology of the earth has a form that can be easily defined mathematically, called the model. For example steeply dipping **conductors** are generally modeled as being **infinite** in horizontal and depth extent, and very thin. The earth is generally modeled as horizontally layered, each layer infinite in extent and uniform in characteristic. These models make the mathematics to describe the response of the (normally very complex) earth practical. As theory advances, and computers become more powerful, the useful models can become more complex.

natural exposure rate: in radiometric surveys, a calculation of the total exposure rate due to natural-source gamma rays at the ground surface. It is used as a measurement of the concentration of all the natural **radioelements** at the surface. See also: **exposure rate**.

noise: That part of a geophysical measurement that the user does not want. Typically this includes electronic interference from the system, the atmosphere (***sferics***), and man-made sources. This can be a subjective judgment, as it may include the response from geology other than the target of interest. Commonly the term is used to refer to high frequency (short period) interference. See also ***drift***.

Occam's inversion: an ***inversion*** process that matches the measured **electromagnetic** data to a theoretical model of many, thin layers with constant thickness and varying resistivity (Constable et al, 1987).

off-time: In a ***time-domain electromagnetic*** survey, the time after the end of the ***primary field pulse***, and before the start of the next pulse.

on-time: In a ***time-domain electromagnetic*** survey, the time during the ***primary field pulse***.

overburden: In engineering and mineral exploration terms, this most often means the soil on top of the unweathered bedrock. It may be sand, glacial till, or weathered rock.

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Phase, phase angle: The angular difference in time between a measured sinusoidal electromagnetic field and a reference – normally the primary field. The phase is calculated from $\tan^{-1}(\textit{in-phase} / \textit{quadrature})$.

physical parameters: These are the characteristics of a geological unit. For electromagnetic surveys, the important parameters are **conductivity**, **magnetic permeability** (or **susceptibility**) and **dielectric permittivity**; for magnetic surveys the parameter is magnetic susceptibility, and for gamma ray spectrometric surveys it is the concentration of the major radioactive elements: potassium, uranium, and thorium.

permittivity: see **dielectric permittivity**.

permeability: see **magnetic permeability**.

primary field: the EM field emitted by a transmitter. This field induces **eddy currents** in (energizes) the conductors in the ground, which then create their own **secondary fields**.

pulse: In time-domain EM surveys, the short period of intense **primary** field transmission. Most measurements (the **off-time**) are measured after the pulse. **On-time** measurements may be made during the pulse.

quadrature: that component of the measured **secondary field** that is phase-shifted 90° from the **primary field**. The quadrature component tends to be stronger than the **in-phase** over relatively weaker **conductivity**.

Q-coils: see **calibration coil**.

radioelements: This normally refers to the common, naturally-occurring radioactive elements: potassium (K), uranium (U), and thorium (Th). It can also refer to man-made radioelements, most often cobalt (Co) and cesium (Cs)

radiometric: Commonly used to refer to **gamma ray** spectrometry.

radon: A radioactive daughter product of uranium and thorium, radon is a gas which can leak into the atmosphere, adding to the non-geological background of a gamma-ray spectrometric survey.

receiver: the **signal** detector of a geophysical system. This term is most often used in active geophysical systems – systems that transmit some kind of signal. In airborne **electromagnetic** surveys it is most often a **coil**. (see also, **transmitter**)

resistivity: [ρ] The strength with which the earth or a geological formation resists the flow of electricity, typically the flow induced by the **primary field** of the electromagnetic transmitter. Normally expressed in ohm-metres, it is the reciprocal of **conductivity**.

resistivity-depth transforms: similar to **conductivity depth transforms**, but the calculated **conductivity** has been converted to **resistivity**.

resistivity section: an approximate vertical section of the resistivity of the layers in the earth. The resistivities can be derived from the **apparent resistivity**, the **differential resistivities**, **resistivity-depth transforms**, or **inversions**.

Response parameter: another name for the **induction number**.

secondary field: The field created by conductors in the ground, as a result of electrical currents induced by the **primary field** from the **electromagnetic** transmitter. Airborne **electromagnetic** systems are designed to create and measure a secondary field.

Sengpiel section: a **resistivity section** derived using the **apparent resistivity** and an approximation of the depth of maximum sensitivity for each frequency.

sferic: Lightning, or the **electromagnetic** signal from lightning, it is an abbreviation of "atmospheric discharge". These appear to magnetic and electromagnetic sensors as sharp "spikes" in the data. Under some conditions lightning storms can be detected from hundreds of kilometres away. (see **noise**)

signal: That component of a measurement that the user wants to see – the response from the targets, from the earth, etc. (See also **noise**)

skin depth: A measure of the depth of penetration of an electromagnetic field into a material. It is defined as the depth at which the primary field decreases to 1/e of the field at the surface. It is calculated by approximately $503 \times \sqrt{(\text{resistivity}/\text{frequency})}$. Note that depth of penetration is greater at higher **resistivity** and/or lower **frequency**.

spectrometry: Measurement across a range of energies, where **amplitude** and energy are defined for each measurement. In gamma-ray spectrometry, the number of gamma rays are measured for each energy **window**, to define the **spectrum**.

spectrum: In **gamma ray spectrometry**, the continuous range of energy over which gamma rays are measured. In **time-domain electromagnetic** surveys, the spectrum is the energy of the **pulse** distributed across an equivalent, continuous range of frequencies.

spheric: see **sferic**.

stacking: Summing repeat measurements over time to enhance the repeating **signal**, and minimize the random **noise**.

stripping: Estimation and correction for the gamma ray photons of higher and lower energy that are observed in a particular **energy window**. See also **Compton scattering**.

susceptibility: See **magnetic susceptibility**.

tau: [τ] Often used as a name for the **time constant**.

TDEM: **time domain electromagnetic**.

thin sheet: A standard model for electromagnetic geophysical theory. It is usually defined as a thin, flat-lying conductive sheet, **infinite** in both horizontal directions. (see also **vertical plate**)

tie-line: A survey line flown across most of the **traverse lines**, generally perpendicular to them, to assist in measuring **drift** and **diurnal** variation. In the short time required to fly a tie-line it is assumed that the drift and/or diurnal will be minimal, or at least changing at a constant rate.

time constant: The time required for an **electromagnetic** field to decay to a value of 1/e of the original value. In **time-domain** electromagnetic data, the time constant is proportional to the size and **conductance** of a tabular conductive body. Also called the decay constant.

Time channel: In **time-domain electromagnetic** surveys the decaying **secondary field** is measured over a period of time, and the divided up into a series of consecutive discrete measurements over that time.

time-domain: **Electromagnetic** system which transmits a pulsed, or stepped **electromagnetic** field. These systems induce an electrical current (**eddy current**) in the ground that persists after the **primary field** is turned off, and measure the change over time of the **secondary field** created as the currents **decay**. See also **frequency-domain**.

total energy envelope: The sum of the squares of the three **components** of the **time-domain electromagnetic secondary field**. Equivalent to the **amplitude** of the secondary field.

transient: Time-varying. Usually used to describe a very short period pulse of **electromagnetic** field.

transmitter: The source of the **signal** to be measured in a geophysical survey. In airborne **EM** it is most often a **coil** carrying a time-varying electrical current, transmitting the **primary field**. (see also **receiver**)

traverse line: A normal geophysical survey line. Normally parallel traverse lines are flown across the property in spacing of 50 m to 500 m, and generally perpendicular to the target geology.

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vertical plate: A standard model for electromagnetic geophysical theory. It is usually defined as thin conductive sheet, *infinite* in horizontal dimension and depth extent. (see also *thin sheet*)

waveform: The shape of the *electromagnetic pulse* from a *time-domain* electromagnetic transmitter.

window: A discrete portion of a *gamma-ray spectrum* or *time-domain electromagnetic decay*. The continuous energy spectrum or *full-stream* data are grouped into windows to reduce the number of samples, and reduce *noise*.

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Common Symbols and Acronyms

k	Magnetic susceptibility
ϵ	Dielectric permittivity
μ, μ_r	Magnetic permeability, relative permeability
ρ, ρ_a	Resistivity, apparent resistivity
σ, σ_a	Conductivity, apparent conductivity
σt	Conductivity thickness
τ	Tau, or time constant
Ωm	ohm-metres, units of resistivity
AGS	Airborne gamma ray spectrometry.
CDT	Conductivity-depth transform, conductivity-depth imaging (Macnae and Lamontagne, 1987; Wolfgram and Karlik, 1995)
CPI, CPQ	Coplanar in-phase, quadrature
CPS	Counts per second
CTP	Conductivity thickness product
CXI, CXQ	Coaxial, in-phase, quadrature
FOM	Figure of Merit
fT	femtoteslas, normal unit for measurement of B-Field
EM	Electromagnetic
keV	kilo electron volts – a measure of gamma-ray energy
MeV	mega electron volts – a measure of gamma-ray energy 1MeV = 1000keV
NIA	dipole moment: turns x current x Area
nT	nanotesla, a measure of the strength of a magnetic field
nG/h	nanoGreys/hour – gamma ray dose rate at ground level
ppm	parts per million – a measure of secondary field or noise relative to the primary or radioelement concentration.
pT/s	picoteslas per second: Units of decay of secondary field, dB/dt
S	siemens – a unit of conductance
x:	the horizontal component of an EM field parallel to the direction of flight.
y:	the horizontal component of an EM field perpendicular to the direction of flight.
z:	the vertical component of an EM field.

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