UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Helicopter airborne electromagnetic survey (using the Dighem^{II*} system) of parts of the Lake City Caldera, Hinsdale County, Colorado

by

D. C. Fraser and Z. Dvorak

With an introduction by William D. Heran

Open-File Report 80-917

1980

*Registered trademark of Dighem Limited of Toronto, Canada. Use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey. This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards.

Introduction

The data presented herein is from an airborne electromagnetic-resistivity-survey conducted by Dighem Limited of Toronto Canada for the U.S. Geological Survey. The area surveyed is located in the western San Juan Mountains near Lake City, Colorado. The general area covered is between $37^{o}45'$ and 38^{o} latitude north and $107^{o}15'$ and $107^{o}35'$ longitude west. The survey flying was confined to nine valleys which surround the Lake City caldera. Four blocks were surveyed from October 22 to October 27, 1979 for a total of 535 line - kilometers. The survey was flown as part of a mineral appraisal study conducted in cooperation with Bureau of Land Management (BLM). The survey was done to detect massive mineralization, mainly copper, and to locate conductive faults that may be suitable sites for uranium mineralization.

To be useful, airborne electromagnetic measurements must be made within a few hundred feet of the surface. The area that was flown is so rugged that a helicopter rather than a fixed-wing aircraft was used.

Fraser and Dvorak summarize the data of the survey areas as follows: in the east and south, the ground resistivities varied over a broad range--, from 20 to 1000 ohm-m. The western and northern parts of the area were characterized by resistivities mostly in the 300 to 1000 ohm-m range. Several weak to moderate EM anomalies were located that may warrant ground follow-up work.

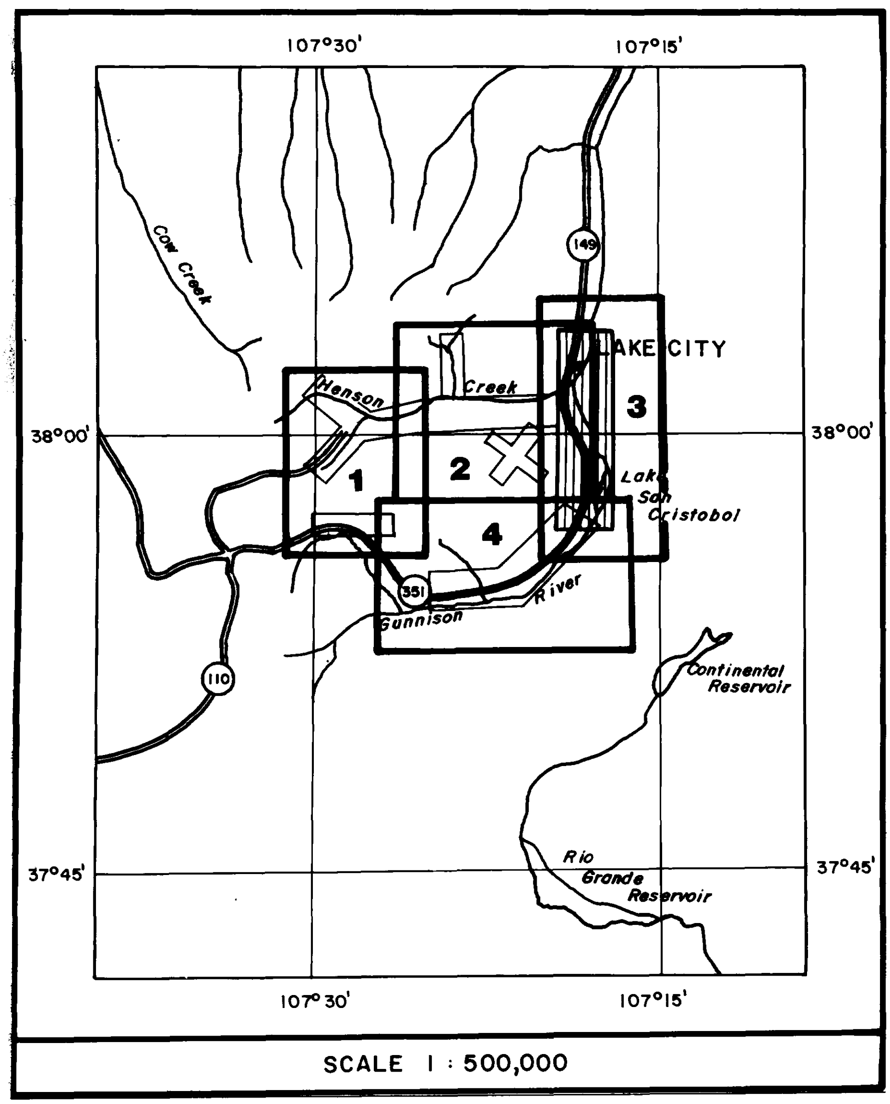

Figure 1. The western San Juan Mountain Survey Area, Lake City, Colorado. Map areas, are numbered 1, 2, 3, and 4. Blocks outlined within each are those areas actually surveyed. Resistivity and electromagnetic data for each block are presented as separate sheets (plates 1-8).

General Description of Dighem^{II} System

The Dighem^{II} System is a helicopter-towed electromagnetic system which employs two independent coil pairs, two orthogonal transmitter coils and two or three orthogonal receiver coils. The technique involves energizing conductors with two orthogonal transmitter coils, both operating at approximately the same frequency. In the standard coil pair both transmitter and receiver are coaxial, in the whaletail coil-pair both are coplanar. The system yields in-phase and quadrature channels, and by taking the difference of the response from the two coil pairs the effect of conductive overburden is suppressed, which may mask the response of bedrock conductors. The EM channels may indicate whether the conductor is thin (less than 3 m) or has substantial width (greater than 15 m). The inphase and quadrature signal from each channel along with other diagnostic information are recorded digitally. Apparent resistivity maps are produced from the horizontal coplanar data; these maps are of great assistance in the interpretation of low resistivity areas.

For a more detailed discussion of the Dighem^{II} system the reader may refer to: Fraser, D. C., 1979, The multicoil II airborne electromagnetic system, Geophysics, v. 44, no. 8, p. 1367-1394 or Fraser, D. C., 1978, Resistivity Mapping with an Airborne Multicoil Electromagnetic System; Geophysics, v. 43, no. 1, p. 144-172.

Equipment

A Lama C-6DEM jet helicopter was used in the survey and was flown with an average airspeed of 100 km/h. The EM bird was kept at an average height of 35 m above the Earth's surface. Other equipment consisted of a radio altimeter, sequence camera, 8-channel hot pen analog recorder, and a digital data acquisition system with a 7-track 200-bpi magnetic tape recorder. Due to the weight-altitude limitations of the helicopter, a magnetometer was not included in this survey. The analog equipment recorded four channels of EM data at approximately 900 Hz, two ambient EM noise channels (for the standard and whaletail receivers), and radio altitude. The digital equipment recorded the EM data at a maximum sensitivity of 0.2 ppm/bit.

General Geology

The Lake City caldera is located in the San Juan volcanic field, in the San Juan Mountains in southwestern Colorado. The general evolution of the San Juan volcanic field has been described by Lipman, Steven, and Mehnert (1970) and is outlined only briefly here.

In late Eocene or early Oligocene time, volcanic activity from many scattered stratovolcanoes produced a composite volcanic field covering more than 25,000 km^2 (Steven and Lipman, 1976). Early rocks are intermediate-composition lavas and breccias, followed by silicic ash flow tuff and later by a bimodal association of basalt and alkali rhyolite.

About 22.5 m.y. ago, ash-flow eruptions that produced the Sunshine Peak Tuff began in the Lake City area. (Lipman and others, 1973; Mehnert and others, 1973a). Concurrent with these eruptions, an elliptical block approximately 15 km across subsided to form the Lake City caldera, within the southern part of the older Uncompahgre caldera. The ring fault along which this collapse occurred is exposed for about 300^{o} of arc around the caldera, typically marked by a meter or so of gouge and minor hydrothermally altered rock.

Lava flows and domes of viscous silicic quartz latite, fed from vents along the ring fault, accumulated around the margins of the caldera floor, after the ash-flow eruptions ceased. Resurgence, resulting from upward movement of a shallow stock of granite porphyry, produced a simple dome on its flanks, and a northeast-trending graben over the caldera's distended crest.

The western San Juan Mountains have a complex history of mineralization with several distinct periods of ore deposition occurring over an interval of approximately 15 m.y. in late Tertiary time (Lipman and others, 1976). Scattered mineral deposits, in the Lake City area, occur in the intrusive cores of intermediate-composition stratovolcanoes. Significant vein and disseminated mineralization occurred within northern parts of the Uncompahgre caldera after it collapsed about 28 m.y. ago, but before collapse of the Lake City caldera about 22.5 m.y. ago. Additional vein and disseminated mineralization occurs within and adjacent to the Lake City caldera. Major veins also follow faults of the Eureka graben between the Lake City and Silverton calderas (Steven and Lipman, 1976). Detailed geology by Lipman (1976) may be used as an aid in the interpretation of the Dighem data presented here.

Following references, the text and data are from a report prepared by D. C. Fraser and Z. Dvorak of Dighem Ltd. for the U.S. Geological Survey.

Eight maps (plates 1-8) accompany this report, resistivity data (plates 1-4) are plotted on four map sheets, and electromagnetic data (plates 5-8) are plotted on four separate map sheets.

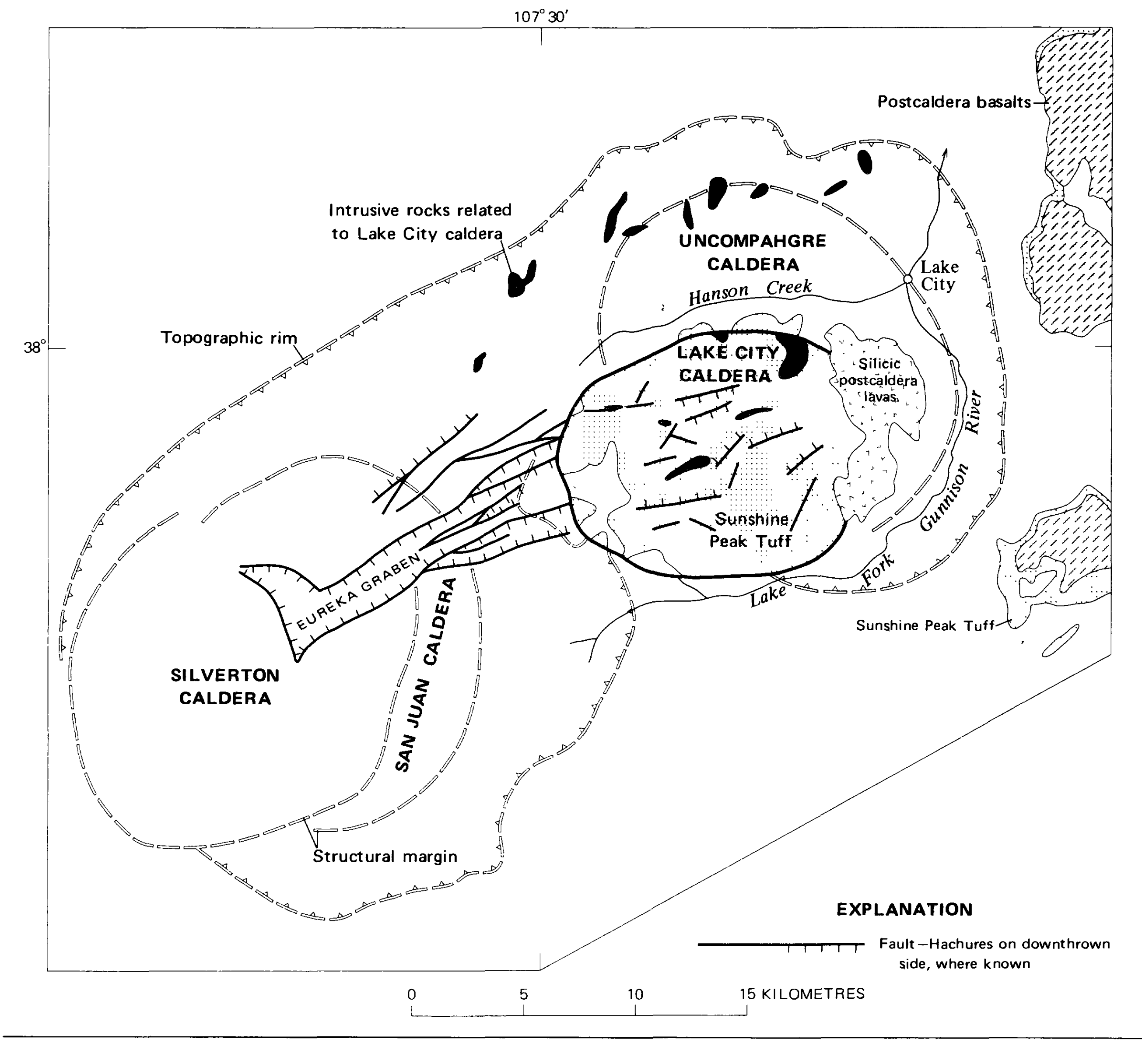

Figure 2. Generalized geologic map of San Juan caldera complex showing distribution of rocks related to the Lake City caldera (from Steven and Lipman, 1976).

References

Fraser, D. C., The multicoil II airborne electromagnetic system: Geophysics, v. 44, no. 8 (Aug 1979), p. 1367-1394.

______Resistivity Mapping with an Airborne Multicoil Electromagnetic System: Geophysics, v. 43, no. 1, (Feb 1978) p. 144-172.

Lipman, P. W., 1976, Geologic map of the Lake City caldera area, western San Juan Mountains, southwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-962.

Lipman, P. W., Steven, T. A., and Mehnert, H. H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geol. Soc. America Bull, v. 81, no. 8, p. 2329-2352.

Lipman, P. W., Steven, T. A., Luedke, R. G. and Burbank, W. S., 1973, Revised volcanic history of the San Juan, Uncompahgre, Silverton, and Lake City calderas in the western San Juan Mountains, Colorado: U.S. Geol. Survey Jour. Research, v. 1, no. 6, p. 627-642.

Lipman, P. W., Fisher, F. S., Mehnert, H. H., Naeser, C. W., Luedke, R. G., and Steven, T. A., 1976, Multiple ages of mid-Tertiary mineralization and alteration in western San Juan Mountains, Colorado: Econ. Geology (in press).

Mehnert, H. H., Lipman, P. W., and Steven, T. A., 1973a, Age of the Lake City caldera and related Sunshine Peak Tuff, western San Juan Mountains, Colorado: Isochron/West, no. 6,, p. 31-33.

Steven, T. A. and Lipman, P. W., Calderas of the San Juan Volcanic Field, Southwestern Colorado, Geological Survey Professional Paper 958, 1976, p. 1-35.

Data Presentation

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

The vertical sheet (half plane) model is the most common model used for the analysis of discrete conductors. All anomalies plotted on the electromagnetic map are interpreted 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 the most suitable model for broad conductors. Resistivity contour maps result from the use of this model. Resistivity contour maps should be prepared when the EM responses predominantly are of the broad class. A later section entitled Resistivity mapping describes the method further, including the effect of using it on anomalies caused by discrete conductors such as sulfide bodies.

Discrete conductor analysis

The EM anomalies appearing on the electromagnetic map are interpreted by computer to give the conductance (i.e., conductivity-thickness product) in mhos of vertical sheet model. DIGHEM anomalies are divided into six grades of conductance, as shown in Table I. The conductance in mhos is the reciprocal of resistance in ohms.

Table I. EM Anomaly Grades

Anomaly Grade	Mho Range
6	> 100
5	50 - 99
4	20 - 49
3	10 - 19
2	5 - 9
1	< 4

The mho value is a geological parameter because it is a characteristic of the conductor alone; it generally is independent of frequency, and of 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 mho values.

Conductive overburden generally produces broad EM responses which are not plotted on the EM maps. However, patchy conductive overburden in otherwise resistive areas can yield discrete-like anomalies with a conductance grade (cf. Table I) of 1, or even of 2 for conducting clays which have resistivities as low as 50 ohm-m. In areas where ground resistivities can be as low as 1 ohm-m, anomalies caused by weathering variations and similar causes can have conductance grades as high as 4. The anomaly shapes from the multiple coils often allow such surface conductors to be recognized, and these are indicated by the letter S on the map. The remaining anomalies in such areas could be bedrock conductors. The higher grades indicate increasingly higher conductances. Examples: DIGHEM's New Insco copper discovery (Noranda, Quebec, Canada) yielded a grade 4 anomaly, as did the neighbouring copper-zinc

*This statement is an approximation. DIGHEM, with its short coil separation, tends to yield larger and more accurate mho values than airborne systems having a larger coil separation.

Magusi River ore body; Mattabi (copper-zinc, Sturgeon Lake, Ontario, Canada) and Whistle (nickel, Sudbury, Ontario, Canada) gave grade 5; and DIGHEM's Montcalm nickel-copper discovery (Timmins, Ontario, Canada) yielded a grade 6 anomaly. Graphite and sulfides 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 5 and 6) are characteristic of massive sulfides or graphite. Moderate conductors (grades 3 and 4) typically reflect sulfides of a less massive character or graphite, while weak bedrock conductors (grades 1 and 2) can signify poorly connected graphite or heavily disseminated sulfides. Grade 1 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, New Brunswick, yielded a well defined grade 1 conductor. The 10 percent by volume of sphalerite occurs as a coating around the fine grained massive pyrite, thereby inhibiting electrical conduction.

On the electromagnetic map, the actual mho value and a letter are plotted beside the EM grade symbol. The letter is the anomaly identifier. The horizontal rows of dots, beside each anomaly symbol, indicate the anomaly amplitude of the flight record. The vertical column of dots gives the estimated depth. In areas where anomalies are crowded, the identifiers, dots and mho values 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 be accurate whereas one obtained from a small ppm anomaly (no dots) could be inaccurate.

The absence of amplitude dots indicates that the anomaly from the standard (coaxial maximum-coupled) coil is 5 ppm or less on both the inphase and quadrature channels. Such small anomalies could reflect a weak conductor at the surface, or a stronger conductor at depth. The mho value and depth estimate will illustrate which of these possibilities best fits the recorded data. The depth estimate, however, can be erroneous. The anomaly from a near-surface conductor, which exists only to one side of a flight line, will yield a large depth estimate because the computer assumes that the conductor occurs directly beneath the flight line.

Flight line deviations occasionally yield cases where two anomalies, having similar mho values but dramatically different depth estimates occur close together on the same conductor. Such examples illustrate the reliability of the conductance measurement while showing that the depth estimate can be unreliable. There are a number of factors which 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 further interpretation is presented on the EM map by means of the line-to-line correlation of anomalies. This provides conductor axes which may define the geological structure over portions of the survey area.

The majority of massive sulfide ore deposits have strike lengths of a hundred to a thousand metres. Consequently, it is important to recognize short conductors which may exist in close proximity to long conductive bands. The high resolution of the DIGHEM system, and the line-to-line correlation given on the EM map, are especially important for a proper strike length evaluation.

DIGHEM electromagnetic maps 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 mho values are plotted for those who wish quantitative data. The anomaly ppm and depth 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 direction, conductance and depth. The accuracy is comparable to an interpretation from a ground EM survey having the same line spacing.

An EM anomaly list attached to each survey report provides a tabulation of anomalies in ppm, and in mhos and estimated depth for the vertical sheet model. The anomalies are listed from top to bottom of the map for each line.

The EM anomaly list also shows the conductance in mhos and the depth for a thin horizontal sheet (whole plane) model, but only the vertical sheet, parameters appear on the EM map. The horizontal sheet model is suitable for a flatly dipping thin bedrock conductor such as a sulfide sheet having a thickness less than 15 m. The list also shows the resistivity and depth for a conductive earth (half space) model, which is suitable for thicker slabs such as thick conductive overburden. In the EM anomaly list, a depth value of zero for the conductive earth model, in an area of thick cover, warns that the anomaly may be caused by conductive overburden. Since discrete bodies normally are the targets of EM surveys, local base (or zero) levels are used to compute anomaly amplitudes rather than true zero levels. The use of local base levels may distort the horizontal sheet and conductive earth parameters. True zero levels, however, are used for resistivity mapping, discussed below.

Resistivity mapping

Areas of widespread conductivity have been encountered while surveying for base metals. In such areas, anomalies can be generated by decreases of only 5 m in survey altitude, as well as by increases in conductivity. The typical flight record in conductive areas is characterized by inphase and quadrature channels which are continuously active; local peaks reflect either increases in conductivity of the earth or decreases in survey altitude. For such conductive areas, apparent resistivity profiles and contour maps can aid the 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 those anomalies caused by conductivity changes. This helps the interpreter to differentiate between conductive trends in the bedrock and those patterns typical of conductive overburden. Discrete conductors will generally appear as narrow lows on the contour map and broad conductors will appear as wide lows.

Conductive overburden diminishes the ability of any EM system to effectively explore the bedrock. For example, the lower the resistivity of the cover, the more active the EM channels, and the less the likelihood of recognizing that a particular anomaly might be caused by a bedrock conductor. As a general rule of thumb, the effectiveness of most EM systems for base metal exploration is given in Table II.

Table II. Influence of Conductive Cover on Base Metal Surveys

Resistivity	Exploration effectiveness for most EM systems
> 300 ohm-m	excellent
100 to 300	good
30 to 100	moderate
< 30	poor

Apparent resistivity maps should always be constructed when the exploration effectiveness (Table II) is moderate to poor. DIGHEM^{II} surveys yield apparent resistivity maps as a standard product.

Channel 40 (see Appendix) presents the apparent resistivity using the so-called pseudo-layer half space model defined in Fraser (1978)* This model consists of a resistive layer overlying a conductive half space. Channel 41 (often not plotted) gives the apparent depth below surface of the conductive material. The apparent depth therefore is simply the apparent thickness of the overlying resistive layer. The apparent depth (or thickness) parameter will be positive when the upper layer is more resistive than the underlying material, in which case the apparent depth may be quite close to the true depth.

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

The apparent depth parameter is a useful indicator of simple layering in areas lacking a heavy tree cover. The DIGHEM^{II} system has been flown for the purpose of permafrost mapping, where positive apparent depths were used as a measure of permafrost thickness. However, little quantitative use has been made of negative apparent depths because the absolute value of the negative depth is not a measure of the thickness of the conductive upper layer and, therefore, is not meaningful physically. Thus, the apparent depth parameter is useful only in certain situations and so generally is not plotted.

X-type electromagnetic responses

DIGHEM^{II} maps contain x-type EM responses in addition to EM anomalies. An x-type response is below the noise threshold of 2 ppm, and reflects one of the following: a weak conductor near the surface, a strong conductor at depth (e.g., 100 to 120 m below surface), or noise. Those responses that have the appearance of valid bedrock anomalies on the flight profiles are mentioned in the report. The others should not be followed up unless their locations are of considerable geological interest.

The thickness parameter

DIGHEM^{II} can provide an indication of the thickness of a steeply dipping conductor. The ratio of the anomaly amplitude of channel 24/channel 22 generally increases as the apparent thickness increases, i.e., the thickness in the horizontal plane. This 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 can be high priority targets because most massive sulfide ore bodies are thick, whereas non-economic bedrock conductors are usually thin. An estimate of thickness cannot be obtained 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.

Reduction of conductive overburden response

The DIGHEM^{II} system yields four channels which generally are free of the response of conductive overburden. These are the inphase difference channel 33, the quadrature difference channel 34, and the two anomaly recognition functions of channels 35 and 36. Channels 35 and 36 are used to trigger the conductance channel 37 which identifies discrete conductors. In highly conducting environments, channel 36 is not generated because it is subject to some corruption by highly conductive earth signals.

Discrete conductors usually occur in the bedrock, such as sulfides or graphite, rather than in the overburden, such as conductive clay. Only discrete conductors are plotted on the EM map. Broad (i.e., non-discrete) conductors are not plotted on this map, but are identified by lows on the resistivity contour map.

Reduction of magnetite response

Magnetite produces a form of geological noise on the inphase channels of all EM systems. Rocks containing as little as 1% magnetite can yield negative inphase anomalies. When magnetite is widely distributed throughout a survey area, the inphase 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 magnetite generally vanishes on the inphase differences channel 33. This feature can be a significant aid in the recognition of conductors which occur in rocks containing accessory magnetite.

Western San Juan Mountains, Colorado

The survey flying was confined to nine valleys which surround the Lake City caldera. Due to the weight-altitude limitations of the Lama helicopter, a proton magnetometer was not included in the instrumentation package. Consequently, only EM and resistivity maps were produced. However, the presence of magnetite can be recognized on the EM traces. As an example, note the inphase channels 22 and 24 on line 124 in the vicinity of fiducial 1650. A negative inphase anomaly indicates that magnetite is present.

Difficulties were encountered in assembling the photomosaics due to the severe topography in the survey area. Consequently, ground overlaps appear on the maps in several places. The areas of overlap are indicated on the geophysical maps by hachured patterns.

The survey data are presented on four map sheets. The line identification and the amounts flown are shown below:

Sheet	Line-number	Line-km
1	21-29	40
	31-37	28
	51-56	23
2	41-46	55
	101-106	20
	109-114	32
	121-127	32
3	81-92	128
4	61-79	177
		535 km

Sheet 1

The area of Sheet 1 contains three flight blocks. The northern flight block (lines 31-37) covers the North Fork Henson Creek valley. Only one anomaly, 35A, was detected in this flight block. It has a conductance grade of 1 and occurs in the vicinity of several mine adits. The resistivity map displays an irregularly shaped zone of 750-1000 ohm-m which may reflect landslide material and colluvium.

The central flight block (lines 21-29) covers the Henson Creek valley. A grade 1 anomaly 28A appears to reflect a weak geologic conductor which extends toward 29xA. Two elongated resistivity zones exist in this flight block. The first one, which is characterized by 700-1000 ohm-m resistivities, occurs in the Henson Creek valley. It probably reflects sand and creek deposits. Resistivities in the 300-1000 ohm-m range were observed in the other zone, which runs along the southeastern slope of the valley. It appears to reflect landslide deposits which occur just inside the Lake City caldera.

The southern flight block (lines 51-56) covers the Lake Fork Gunnison River valley in the area of Burrows Park. A narrow zone of 230-1000 ohm-m resistivities correlates with the valley. It may reflect the landslide material, glacial moraine deposits and creek deposits. However, the sudden increase of resistivities in the mid-central part of the block, which correlates with the Lake City caldera boundary, suggests that most of the EM response may be due to conductivity within the weathered ash-flow rocks of the caldera.

Sheet 2

The area of Sheet 2 contains four flight blocks. The northern block (lines 121-127) extends along the lower part of the Nellie Creek valley. Several grade 1 and 2 anomalies, which occur on the eastern slopes of the valley, correlate with a low resistivity zone which may reflect the Eureka Member of the Sapinero Mesa Tuff. Anomalies 123A and 123B appear to occur along the margin of this low resistivity zone.

The central flight block (lines 41-46) extends east of Lake City, along the Henson Creek valley. This part of the survey area is quite featureless. The resistivity of the environment is high, mostly in excess of 1000 ohm-m). A noticeable exception is the northeasterly trending resistivity zone at the east end of the flight block, which may reflect tuff and tuffaceous sandstones. A small, low resistivity zone occurs in the western part of the flight block.

The two south-central flight blocks (lines 101-106 and 109-114) were flown in a cross-pattern fashion in the Alpine Gulch valley area. An irregularly shaped low resistivity zone in the eastern side of the flight blocks appears to coincide in part with a quartz latite flow.

Sheet 3

The survey area of Sheet 3 extends along the Lake Fork Gunnison River in the vicinity of the town of Lake City.

The resistivity of the geologic environment varies in the general range of 20 to 1000 ohm-m. Part of the resistivity variation is due to a number of cultural sources, e.g., anomalies along Highway 149. The majority of the EM responses, which have resulted in relatively complex resistivity patterns, were caused by geology.

Outcrops of the Fish Canyon Tuff, which occur mainly along the eastern slopes of the Lake Fork Gunnison River valley, have produced low resistivity zones with values less than 100 ohm-m. Several EM anomalies were detected in the areas of these resistivity lows, e.g., 81D, 82F, 89D, 89E.

Anomalies 81J, 81M, and 82K occur in an area of prominent low resistivities which appears to reflect conductive earthflow deposits at the mouth of Slumgullion Creek.

Flows of quartz latite produced an elongated zone of low resistivity in the central part of the flight block. This zone contains anomalies 86A and 87C, where the indicated line-to-line correlation is questionable.

An extensive zone of resistivities close to 100 ohm-m just west of Lake San Cristobal, which contains anomalies 84H and 85I, appears to reflect flows of quartz latite.

Among a group of anomalies, which occurs just northwest of Lake City and which may outline a zone of earthflow deposits, conductor 89B appears to be the most interesting one.

Anomalies 90C-92D and 91D occur in a quartz latite unit of Grassy

Mountain.

Sheet 4

The flight block of Sheet 4 extends along the Lake Fork Gunnison River Valley. The geologic environment in the western part of the valley is characterized by high resistivities, mostly in excess of 1000 ohm-m, probably reflecting sand and gravel deposits at the bottom of the valley. Somewhat lower resistivities were observed in a narrow band which runs along the northern slopes of the valley. It may reflect landslide material and glacial moraine deposits.

The margin of a low resistivity zone occurs along the southern slopes of the valley. This zone contains several weak anomalies, e.g. 79A, 79B, 79C, which may reflect geologic conductors which extend to the south beyond the survey boundary.

An oval-shaped low resistivity zone (centered on 73C) occurs in the north-central part of the flight block. It contains several grade 1 and 2 anomalies which appear to reflect geologic conductors. The low resistivity zone itself may partly reflect landslide debris.

The grade 1 anomalies 73E and 74D may reflect geologic conductors. They occur within a low resistivity zone which may in part reflect landslide deposits.

An irregularly shaped low resistivity zone (encompassing 69C, 72A, 72B) in the southeastern part of the flight block may reflect a mix of landslide deposits, conductive material deposited by the creek, and Tertiary volcanics. Anomalies confined to this zone appear to indicate geological conductors which occur along the slopes of the valley.

APPENDIX

THE FLIGHT RECORD AND PATH RECOVERY

The flight record is a roll of chart paper containing the geophysical profiles. The profiles are generated by computer at a scale identical to the geophysical maps. The flight record contains up to 17 channels of information, as follows:

Channel Number	Parameter	Scale units/mm	Noise
20	magnetics	10 gamma	2 gamma
21	altitude	3 m	2 m
22	standard* coil-pair inphase	1 ppm	1-2 ppm
23	standard coil-pair quadrature	1 ppm	1-2 ppm
24	whaletail** coil-pair inphase	1 ppm	1-2 ppm
25	whaletail coil-pair quadrature	1 ppm	1-2 ppm
28	ambient noise monitor (standard receiver)	1 ppm	1-2 ppm
29	ambient noise monitor (whaletail receiver)	1 ppm	1-2 ppm
31	sums function inphase***	1 ppm	1-2 ppm
32	sums function quadrature***	1 ppm	1-2 ppm
33	difference function inphase	1 ppm	1-2 ppm
34	difference function quadrature	1 ppm	1-2 ppm
35	first anomaly recognition function	1 ppm	1-2 ppm
36	second anomaly recognition function	1 ppm	1-2 ppm
37	conductance	1 mho	
40	log resistivity	.03 decade	
41	apparent depth to conductive half space***	3 m	

* coaxial
** horizontal coplanar
*** generally not plotted

The log resistivity scale of 0.03 decade/mm means that the resistivity changes by an order of magnitude in 33 mm. The resistivities at 0, 33, 67 and 100 mm up from the bottom of the chart are respectively 1, 10, 100 and 1000 ohm-m.

The fiducial marks on the flight record represent points on the ground which were recognized by the aircraft navigator. Continuous photographic coverage allowed accurate photo-path recovery locations for the fiducials, which were then plotted on the geophysical maps to provide the track of the aircraft.

The fiducial locations on both the flight records and flight path maps were examined by a computer for unusual helicopter speed changes. Such changes often denote an error in flight path recovery. The resulting flight path locations therefore reflect a more stringent checking than is provided by standard flight path recovery techniques.

The following brief description of DIGHEM^{II} illustrates the information content of the various profiles.

The DIGHEM^{II} system has two transmitter coils which are mounted at right angles to each other. (The transmitted frequency is given in the Introduction.) Thus, the system provides two completely independent surveys at one pass. In addition, the flight chart profiles (generated by computer) include an inphase channel and a quadrature channel which essentially are free of the response of conductive overburden. Also, the EM channels may indicate whether the conductor is thin (e.g., less than 3 m), or has a substantial width (e.g., greater than 15 m). Further, the EM channels include a channel of resistivity and another of conductance. A minimum of 10 EM channels are provided. The DIGHEM^{II} system therefore gives information in one pass which cannot be obtained by any other airborne or ground EM technique.

Figure A1 shows a DIGHEM^{II} flight profile over the massive pyrrhotite ore body in Montcalm Township, Ontario. It will serve to identify the various channels.

The two upper channels (numbered 20 and 21) are respectively the magnetics and the radio altitude. Channels 22 and 23 are respectively the inphase and quadrature of the coaxial coil-pair, which is termed the <u>standard</u> coil-pair. This coil-pair is equivalent to the standard coil-pair of all inphase-quadrature airborne EM systems. Channels 24 and 25 are the inphase and quadrature of the additional coplanar coil-pair which is termed the whaletail coil-pair.

Channels 31 and 32 are inphase and quadrature sums functions of the standard and whaletail channels; they provide a condensed view of the four basic channels 22 to 25. The sums channels normally are not plotted.

Channels 33 and 34 are inphase and quadrature differences functions of the standard and whaletail channels. The differences channels are almost free from the response of conductive overburden. Channel 37 is the conductance. The conductance channel essentially is an automatic anomaly picker calibrated in conductance units of mhos; it is triggered by the anomaly recognition functions shown as channels 35 and 36.

Channel 40 is the resistivity, which is derived from the whaletail channels 24 and 25. The resistivity channel 40 yields data which can be contoured, and so the DIGHEM^{II} system yields a resistivity contour map in addition to an electromagnetic map, a magnetic contour map, and an enhanced magnetic contour map. The enhanced magnetic contour map is similar to the filtered magnetic map discussed by Fraser.*

Figure A2 presents the DIGHEM^{II} results for a line flown perpendicularly to the Montcalm ore body. Channel 20 shows the 175 gammas magnetic anomaly caused by the massive pyrrhotite deposit. For the EM channels, the following points are of interest.

1. On channels 22-25 and 31-34, the ore body essentially yields only an inphase response. The quadrature response is almost completely caused by conductive overburden (which also gives a small inphse response). The hachures show the EM response from the overburden. The overburden

---

* Cdn. Inst. Mng., Bull., April 1974

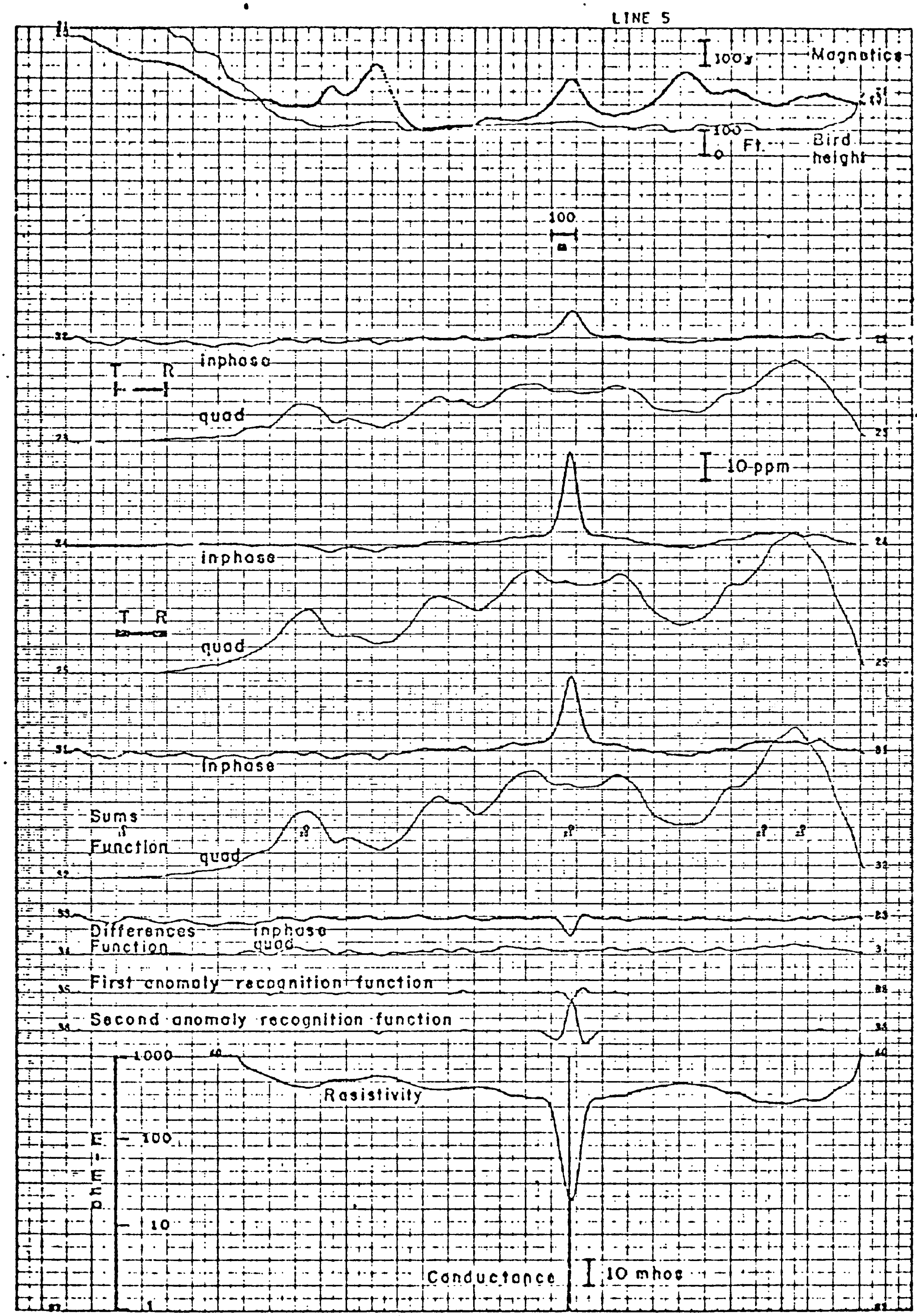

Fig. A1. Flight over Montcalm deposit, with line parallel to strike.

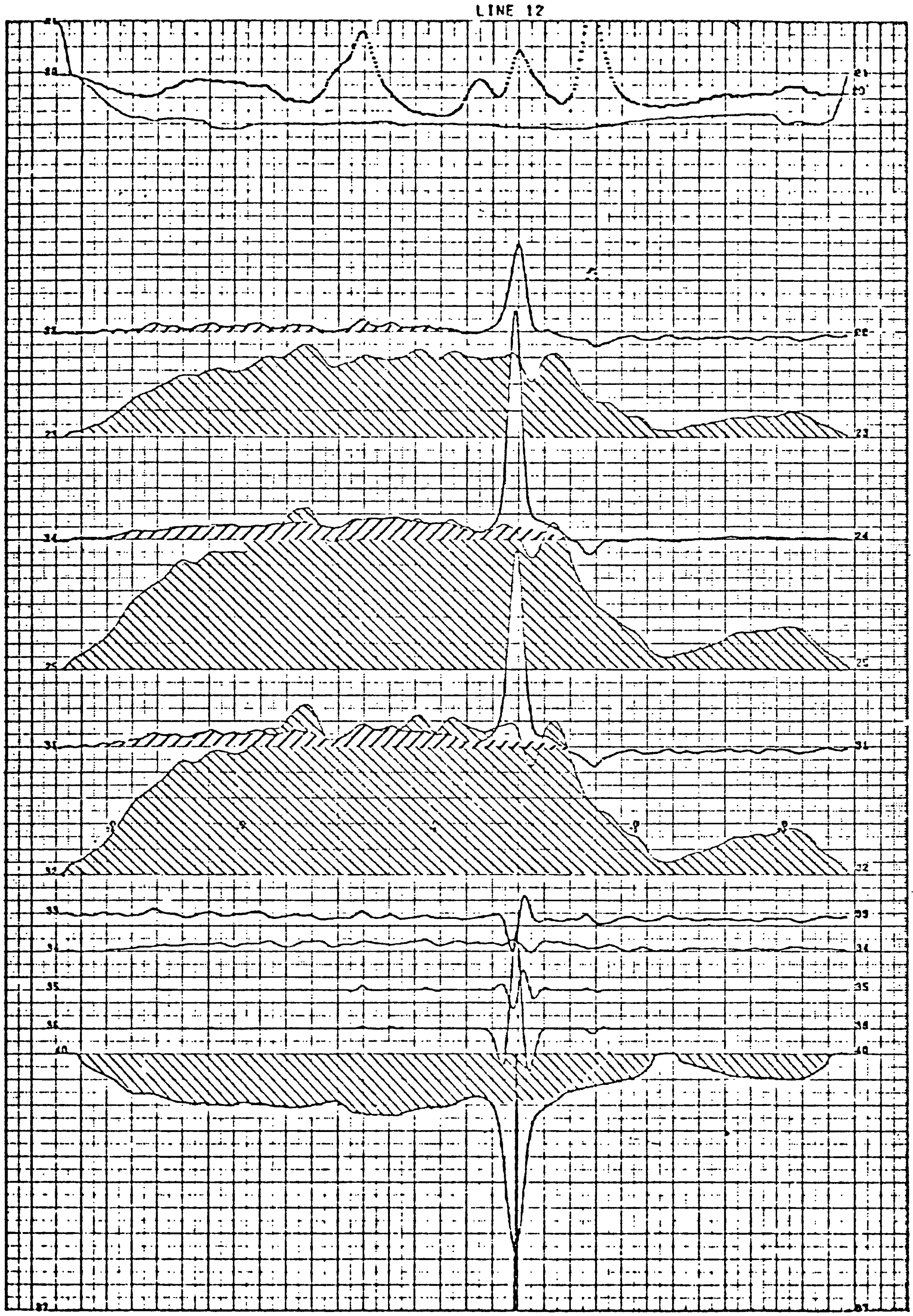

Fig. A2. Flight over Montcalm deposit, with line perpendicular to strike.

response vanishes on the difference EM channels, as can be seen by comparing the quadrature channels 25 and 34. This is an important point to note because DIGHEM^{II} is the only EM system which provides an inphase channel and a quadrature channel which are essentially free of conductive overburden response.

2. The whaletail anomaly of channel 24 has a single peak. This shows that the conductor has a substantial width. If the width had been under 3 m, the conductor would have produced a weak m-shaped anomaly on channel 24.
3. The ore body yields a resistivity of 5 ohm-m in a background of about 200 ohm-m (cf. channel 40). A dipole-dipole ground resistivity survey with an a-spacing of 50 m showed a similar background, but the ore body gave a low of only 53 ohm-m because of the averaging effect inherent in the ground technique.
4. The ore body has a conductance of 330 mhos according to its EM response on this particular flight line. The conductance channel 37 saturates at 100 mhos, and so the deposit is indicated by a 100-mho spike.

Figure A1 illustrates the DIGHEM^{II} results for a line flown subparallel to the ore body. The ore body anomaly is small on the standard coil-pair (channel 22) but shows up strongly on the whaletail coil-pair (channel 24).

111-SH.1 USGS SAN JUAN MTNS.,COL. NOV/79

LINE & ANOMALY	STANDARD COIL REAL PPM	STANDARD COIL QUAD PPM	WHALETAIL COIL REAL PPM	WHALETAIL COIL QUAD PPM	VERTICAL DIKE COND MHOS	VERTICAL DIKE DEPTH* FEET	HORIZONTAL SHEET COND MHOS	HORIZONTAL SHEET DEPTH FEET	CONDUCTIVE EARTH RESIS OHM-M	CONDUCTIVE EARTH DEPTH FEET
28A	0	7	0	4	1	13	1	245	1034	0
35A	0	3	0	2	1	0	1	481	1034	0
54A	2	4	4	7	3	93	1	381	156	198

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

	STANDARD COIL		WHALETAIL COIL		VERTICAL DIKE		HORIZONTAL SHEET		CONDUCTIVE EARTH	
LINE & ANOMALY	REAL PPM	QUAD PPM	REAL PPM	QUAD PPM	COND MHOS	DEPTH* FEET	COND MHOS	DEPTH FEET	RESIS OHM-M	DEPTH FEET
101A	0	6	0	14	1	11	1	189	1034	0
121A	9	17	19	35	5	0	1	161	57	52
121B	4	10	3	9	2	10	1	222	181	70
122A	2	17	10	44	1	0	1	93	224	0
122B	3	14	0	33	1	1	1	90	575	0
123A	6	7	9	15	5	0	1	220	70	86
123B	3	13	2	21	1	0	1	91	296	0
124C	0	2	0	1	5	243	1	682	1034	0
124D	3	5	1	5	2	40	1	313	231	124
126A	0	19	0	34	1	2	1	48	647	0

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

LINE & ANOMALY	STANDARD COIL REAL PPM	STANDARD COIL QUAD PPM	WHALETAIL COIL REAL PPM	WHALETAIL COIL QUAD PPM	VERTICAL DIKE COND MHOS	VERTICAL DIKE DEPTH* FEET	HORIZONTAL SHEET COND MHOS	HORIZONTAL SHEET DEPTH FEET	CONDUCTIVE EARTH RESIS OHM-M	CONDUCTIVE EARTH DEPTH FEET
81B	3	7	12	18	4	0	1	198	90	59
81C	1	0	0	0	5	222	1	622	807	0
81D	4	8	4	11	3	23	1	251	143	96
81F	4	8	10	17	4	15	1	234	89	95
81H	2	11	4	20	1	0	1	133	271	0
81J	12	24	23	50	5	0	1	108	56	9
81M	12	17	23	33	7	0	2	153	36	54
81N	13	5	14	15	16	0	4	247	13	163
81P	1	3	0	4	1	87	1	411	1034	0
82A	1	7	2	12	1	14	1	186	482	19
82B	4	3	5	2	12	153	3	539	23	425
82C	3	3	2	0	4	120	2	603	47	457
82D	5	16	7	29	2	0	1	137	147	14
82F	4	24	14	41	2	9	1	139	137	29
82I	8	21	11	36	3	0	1	111	105	3
82J	9	7	6	6	10	25	2	309	32	203
82K	14	35	34	79	5	0	1	66	53	0
82N	2	0	1	0	6	165	1	616	148	0
82O	2	2	1	3	3	122	1	489	191	271
82P	3	18	6	37	1	0	1	105	243	0
83A	1	0	5	2	11	237	2	704	46	0
83B	8	4	16	10	18	41	4	329	12	245
83C	1	5	0	6	2	57	1	259	942	0
83D	3	3	6	6	6	4	1	330	72	181
83E	2	22	5	53	1	0	1	53	418	0
83G	9	3	5	4	20	25	4	359	12	272
83H	1	11	1	17	1	0	1	59	759	0

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

	STANDARD COIL		WHALETAIL COIL		VERTICAL DIKE		HORIZONTAL SHEET		CONDUCTIVE EARTH	
LINE & ANOMALY	REAL PPM	QUAD PPM	REAL PPM	QUAD PPM	COND MHOS	DEPTH* FEET	COND MHOS	DEPTH FEET	RESIS OHM-M	DEPTH FEET
83I	5	9	4	11	3	6	1	226	128	77
84B	12	5	3	3	22	49	5	366	9	284
84C	12	9	5	5	11	0	3	257	26	158
84D	1	2	4	6	6	126	1	452	135	262
84E	15	5	25	14	33	31	6	281	4	218
84F	1	7	4	16	1	0	1	148	305	0
84G	3	9	4	15	2	0	1	168	237	16
84H	4	7	5	11	4	31	1	270	110	117
84I	2	2	0	3	2	62	1	392	508	89
85A	5	15	8	32	2	0	1	112	144	0
85B	8	2	6	4	23	0	5	330	9	242
85C	5	3	1	2	9	0	2	351	43	216
85D	5	1	1	2	25	0	4	437	15	324
85E	8	4	4	6	11	26	3	344	26	234
85F	3	2	0	0	7	12	2	516	35	0
85G	4	3	2	4	5	0	1	321	82	162
85H	2	13	4	28	1	0	1	67	309	0
85I	4	3	6	5	8	2	2	342	48	213
86A	4	7	6	14	3	0	1	179	117	30
86B	3	6	1	10	2	1	1	222	265	53
86E	3	7	5	13	2	23	1	241	191	85
87A	0	0	9	6	8	28	2	440	45	297
87B	2	2	9	6	9	4	2	361	40	233
87C	2	7	5	10	2	43	1	272	191	110
87D	3	10	6	21	2	0	1	132	185	0
87E	6	12	9	23	4	0	1	166	96	39
88A	7	20	11	40	3	0	1	76	115	0
88B	5	12	11	24	3	0	1	155	109	27

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

	STANDARD COIL		WHALETAIL COIL		VERTICAL DIKE		HORIZONTAL SHEET		CONDUCTIVE EARTH	
LINE & ANOMALY	REAL PPM	QUAD PPM	REAL PPM	QUAD PPM	COND MHOS	DEPTH* FEET	COND MHOS	DEPTH FEET	RESIS OHM-M	DEPTH FEET
88D	4	8	9	21	3	0	1	161	115	22
88E	4	16	6	27	2	0	1	106	204	0
89A	4	7	7	15	3	0	1	196	117	49
89B	6	8	10	9	7	54	2	315	43	199
89C	7	13	11	22	4	3	1	194	74	70
89D	2	11	4	26	1	0	1	120	315	0
89E	3	4	4	8	3	43	1	316	132	145
89F	3	10	1	15	1	0	1	139	379	0
89G	4	5	7	9	5	0	1	265	74	119
90A	3	17	10	32	2	0	1	109	167	0
90B	8	21	10	42	3	0	1	133	116	23
90C	3	4	1	7	3	26	1	298	187	116
91A	2	10	3	16	1	0	1	108	315	0
91B	8	21	16	43	3	0	1	104	90	0
91D	1	5	3	10	1	0	1	178	352	0
91E	9	26	13	53	3	0	1	92	103	0
92A	4	12	6	27	2	0	1	122	192	0
92B	5	18	9	35	2	0	1	92	141	0
92D	6	16	9	32	3	0	1	102	133	0

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

	STANDARD COIL		WHALETAIL COIL		VERTICAL DIKE		HORIZONTAL SHEET		CONDUCTIVE EARTH	
LINE & ANOMALY	REAL PPM	QUAD PPM	REAL PPM	QUAD PPM	COND MHOS	DEPTH* FEET	COND MHOS	DEPTH FEET	RESIS OHM-M	DEPTH FEET
62A	6	6	14	17	7	23	2	265	44	149
62B	6	7	10	15	6	0	2	224	57	97
64A	2	6	3	10	2	0	1	213	229	45
65C	9	9	2	6	7	0	2	236	53	109
65E	2	3	11	19	4	33	1	275	95	127
65G	2	6	7	11	3	7	1	247	143	87
65H	5	1	2	0	20	97	5	531	10	430
66A	3	2	3	4	7	97	2	475	58	332
66B	1	6	3	7	1	3	1	217	380	33
67A	2	3	0	4	4	12	1	309	261	94
68A	1	7	1	4	1	7	1	216	570	8
68B	2	3	1	3	2	75	1	408	267	183
68D	2	6	1	9	1	0	1	161	472	0
69A	0	2	0	3	1	0	1	460	1034	0
69C	4	11	8	22	3	0	1	151	139	18
70A	3	6	3	7	3	13	1	266	159	97
70B	2	13	1	25	1	0	1	81	428	0
72A	5	8	9	15	5	0	1	219	71	84
72B	6	14	9	26	3	0	1	146	115	22
73A	0	20	0	45	1	3	1	37	581	0

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.

111-SH.4 USGS SAN JUAN MTNS.,COL. NOV/79

LINE & ANOMALY	STANDARD COIL REAL PPM	STANDARD COIL QUAD PPM	WHALETAIL COIL REAL PPM	WHALETAIL COIL QUAD PPM	VERTICAL DIKE COND MHOS	VERTICAL DIKE DEPTH* FEET	HORIZONTAL SHEET COND MHOS	HORIZONTAL SHEET DEPTH FEET	CONDUCTIVE EARTH RESIS OHM-M	CONDUCTIVE EARTH DEPTH FEET
73B	4	9	7	15	3	0	1	206	123	62
73C	8	10	21	19	9	0	2	198	31	100
73E	2	3	4	7	3	14	1	315	138	133
74A	7	5	6	9	8	53	2	340	44	223
74D	7	19	13	37	3	30	1	184	97	74
74E	2	5	3	2	3	98	1	394	181	202
74H	2	18	4	34	1	0	1	52	370	0
76A	1	2	4	3	3	131	1	515	157	305
76B	2	11	4	16	1	0	1	152	329	6
77A	1	3	0	2	5	163	1	492	1034	0
77G	5	14	8	25	3	21	1	190	139	65
77H	3	11	2	15	1	0	1	139	290	0
79A	4	9	10	17	4	51	1	264	89	127
79B	2	4	5	8	3	89	1	361	160	183
79C	3	6	7	17	3	21	1	239	131	91
79D	1	7	1	7	1	22	1	214	824	0
79E	2	5	0	5	1	37	1	284	506	55

* ESTIMATED DEPTH MAY BE UNRELIABLE BECAUSE THE STRONGER PART OF THE CONDUCTOR MAY BE DEEPER OR TO ONE SIDE OF THE FLIGHT LINE, OR BECAUSE OF A SHALLOW DIP OR OVERBURDEN EFFECTS.