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THE CAVENDISH TEST SITE:
A UTEM SURVEY
PLUS A COMPILATION OF
OTHER GROUND GEOPHYSICAL DATA

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NOTE

This report is presented here in preliminary form. It is anticipated that the main body of the data herein presented, after revision, will be formally published during 1981. Together with this, additional data, particularly airborne data, is to be compiled. Any reader who has access to, or is aware of, any geophysical data of interest that is not covered or referenced in this preliminary report is asked to write to me, should they desire, before September 1980 at the latest. Material arriving before this date will be considered for inclusion in the final compilation.

On a different subject, it appears that the Cavendish test site may very soon be closed, and no longer be available for use by geophysicists due to cottage construction. The land on which the grid is located is privately owned, and thus the geophysical community in Toronto will soon have to locate another suitable test site.

J.C. Macnae
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ABSTRACT

This report presents data from three recent University of Toronto surveys at the Cavendish geophysical test site, namely UTEM, horizontal loop (HLEM) and ground magnetic surveys. Interpretation of the UTEM survey has clearly defined the presence of a short strike-length pod of high conductance within the regional zone A conductor, present on Line C. The pod is interpreted to have a conductance in excess of 400 Siemens, compared to about 10 Siemens for the regional zone A conductor extending across the grid. HLEM data interpretation strongly confirm this conclusion. Zone B is interpreted to have the top of its main conductivity at some depth. This conclusion, if true would indicate that the crosscutting westerly dip for zone B postulated by Williams et al. (on the basis of one drill hole that did not intersect sulphides) may no longer be necessary to explain the drill data. The detailed magnetic field data collected, when contoured, show a very different picture to that of earlier data. On the basis of UTEM late-time limit interpretation it was possible here to determine the nature of the source of the near surface static magnetic anomalies i.e. whether induced or remanent magnetization is predominant. The second part of the report presents a compilation of ground geophysical data at Cavendish, obtained from a variety of sources. This data set is by no means complete, and due to the constraints of the original surveys, no valid inter-system comparisons can be made. A reference list
of other, easily available, data on the Cavendish test site is also included. In an appendix the vector diffusion process of EM induction is illustrated in the UTEM E field case for the Cavendish test site.

ACKNOWLEDGEMENTS

Financial support for parts of this project was provided by grants from the Ontario Geological Survey and from the (then) National Research Council of Canada to Professor G.F. West. The following people collected data specifically for this compilation: Ganpat Lodha (magnetics), Tom Eadie and Boris Lum (HLEM). Yves Lamontagne and Tim Farquhar assisted in the UTEM survey. Tapio Varre arranged for the loan of a MAXMIN II HLEM unit. Data for the compilation were kindly provided by Harry Siegal, Phil Hallof, Miro Bosnar, Andrew Rogozinski and Duncan Crone. Alf Dyck and Bill Scott reviewed the draft manuscript, and made many valuable suggestions as to improvements, which for reasons of time will only be fully implemented in the final version of this paper. Khader Khan did the typing.
THE CAVENDISH TEST SITE

INTRODUCTION

The Cavendish test site in Ontario, Canada (Figure 1), has been the location of many geophysical surveys, and a wealth of published data is available from these tests. However, not all of this data is easily obtainable. This paper consists of two parts: firstly an interpretation of an extensive UTEM survey over the Cavendish test site, and secondly, a compilation of other ground geophysical data, such as from manufacturer's data sheets and sales literature, university theses and reports, and other sources. Complete interpretation of this compiled data will not be attempted, however some aspects of the various system's responses will be discussed, particularly in relation to known geology.

Included with the references to this paper is a bibliography of publications known to contain data about the geophysical response at Cavendish. This compilation is as complete as could be easily obtained but undoubtedly does not include all available reports.

GEOLOGY

The geology of the Cavendish township test range has been described by Williams, Scott and Dyck (1975), based on surface mapping and geological logs of thirty-three drillholes. The area is located within the Grenville geological province of Canada.
Bedrock consists of granite-gneiss, mafic gneiss, and crystalline limestone (Figure 2). Bedrock dips are generally steep to the east as shown in Figure 3.

Two zones of sulphide mineralization, mainly pyrrhotite and pyrite, cut across the grid and are interpreted from the drilling results to dip at different angles than the bedrock contacts. Each zone has a wide 'halo' region with about 2% sulphides, and may have an inner 'core' region containing up to 10% sulphides (Figure 3).

Shallow, irregular overburden is present over portions of the grid, and has been to some extent delimited by the drilling as well as previous seismic surveys reported by Scott (1971) and Hobson (1975).

REPORT ON THE UTEM SURVEY AT CAVENDISH

The Survey

A UTEM survey was carried out at the Cavendish geophysical test site during 12 days in July, 1977. Of this time two days were used for loop layout and retrieval, two days were lost due to equipment malfunction, one day to bad weather, and one day was used for rechaining the cut lines and flagging intermediate lines using chain and compass. During the six days of actual surveying over 10,000 readings were obtained.

On each line, generally five components of the electromagnetic (H) field, and two horizontal components of the electric (E) field. For the detailing of zone A near line C only the
vertical H field and the horizontal E fields were measured. Using a second loop, three lines of reversed data were obtained over a portion of the original survey. The locations of the transmitter loops and survey lines are shown in Figure 4.

For each component at any station 10 readings at different delay times were recorded, although due to bandwidth limitations in the transmitter, usually only 9 channels were plotted.

THE UTEM SYSTEM

The UTEM system was developed by Y. Lamontagne and G.F. West of the University of Toronto. A short description of the system is included in appendix A. A more complete description may be found in Lamontagne (1975), or Lamontagne, Lodha, Macnae and West (1978). For those readers not familiar with the system it is suggested that the appendix be read before continuing.

DATA PRESENTATION

Data may be presented in a number of formats. The most common is that of a multitrace plot, for example that of Figure 8. In many cases, the early and late-time channels are plotted at different scales for ease of interpretation. The normalization scheme used is as follows:

\[
\frac{\text{Reading (Channel no.)-base field}}{\text{normalizing field}} \times 100\%
\]

For channels 2 to 10 of the H field data the base field is the measured channel 1 reading, while for channel 1 it is the calculated
primary field, while $H_x$ and $H_y$ data the normalizing field is the calculated total primary field at that station. (The x direction is along the survey line, y is perpendicular to the line, and z is vertical as shown in Appendix A). The plotted channel 1 anomalies thus normalized have a slightly 'bumpy' appearance due mainly to geometrical errors, and anomalies caused by magnetic susceptibility effects. These effects are removed to first order by the normalization used for channels 2 to 10.

The Electric field data have had no base field subtracted, and are normalized by the total calculated primary E field.

The expected H profile shapes from some simple shapes are shown in Figure 5, and the response of the five measured E and H components to a dyke-like conductor are shown in Figure 6. The plotting symbols for the different channels are shown in Figure 7.

UTEM RESULTS AND INTERPRETATION

H FIELD

The $H_x$ and $H_z$ components of the UTEM survey along line 8S (commonly known as line C) are shown in Figure 8. The most distinct anomaly present is that at about station 16W. Both components indicate that the source is a thin, steeply dipping, dyke-like conductor coming very close to surface. The crossover of H from maximum positive to maximum negative in a distance of less than 25' at early times indicates that the current flow,
and hence top of conductor, is virtually at surface. At later delay times the crossover is somewhat smoothed out indicating that the top of the current vortex is slightly deeper, this behaviour is to be expected for induction in a plate-like body.

Also visible on the $H$ data earliest time channels, (channels 10 and 9) a second crossover can be seen 50' east of the main conductor. This is exhibited on the $H_x$ data as a broadening of the positive anomaly to the east at early times. The source of these effects is interpreted thus to be a poor conductor located east of the main body. By comparing this interpretation with the drill section (Figure 3) on line C, it can be seen that the main conductor correlates with the 2% to 10% sulphide core zone, with the poor conductor detected just to the east corresponding to the 'halo' zone of about 2% sulphides. The main anomaly on this line corresponds in location to what has been referred to as zone A in previous surveys.

The response of another conductor can also be seen on this line, appearing as a crossover-type anomaly on the $H$ data, with its centre at about station 9W. The 'blanking' effect of zone A has distorted the shape of this anomaly. The comparatively smooth anomaly shape indicates that the source is at a greater depth than zone A. The interpretation of this conductor, previously defined as zone B, will be left until results of the second loop are introduced. Figures 9, 10 and 11 present the three components of the $H$ field surveyed over 6 lines at Cavendish. Stations from 4W to 20W were surveyed on lines B, C, D and E of the grid,
with two intermediate lines also surveyed on each side of line C as shown in Figure 4. The most obvious feature on the early time \( H_x \) and \( H_z \) data (Figure 9 and 11) is the zone A anomaly, which strikes at about 75° to the lines, crossing line 16S (line E) at about station 18W and extending across the grid to cross line 4S (line B) at about station 14+50W. Within this long zone there are small regions of greater conductance. Two such zones are clear on lines 8S (C) and 16S (E), as evidenced by the sharp anomalies present at late times, say channels 2 to 5.

Also evident on the \( H_x \) and \( H_z \) data is the response of the zone B conductor, which can be seen on all lines except line 16S. The response of this conductor is fairly uniform from line to line and is particularly clear on the \( H_z \) late-time data. The location of this conductor is at about station 8W on line 4S and station 9W on line 8S.

The \( H_y \) data over the grid can be used to estimate the direction of current flow as will be described later.

E FIELD

Figures 12 and 13 present the electric E field obtained over the grid. The x direction is along the line and the y direction is perpendicular to the lines. If, in the x direction, the late-time limit (best estimated by channel 1) crosses over the axis, such a crossover must indicate a net inflow/outflow of current in the x direction (Because of continuity conditions this current goes to/comes from the y direction). The E field
can thus be used as a current direction indicator as will be shown in later vector plots.

On line 8S (Figure 12), zone A is indicated by a clear crossover (inflow type) at about station 16W, and zone B by another clear crossover at about station 9W. The reversed crossover at station 10+50W would indicate a net outflow of current and hence a resistive horizon in the y direction. The $E_y$ data (Figure 13) also clearly indicates the zone A conductor at about station 16W on line 8S. The $E_y$ component can be thought of as being 'shorted out' by the conductor. On line 16S, the local conductor at station 18W is again shallow, and thus the $E_y$ component is virtually zero here too. On the other lines, the zone A conductor can be detected, but is less clear.

The zone B anomaly is located just east of a reversal in the $E_y$ field. Such a reversal is totally unexpected and can not be explained at present. Zone B on line 16S is very clear on the $E_y$ data as a low.

When looking at $E$ field data it should be kept in mind that the late-time limit response is controlled by conductivity contrasts, as opposed to the late-time $H$ field response which is controlled by magnetic susceptibility. Since in the earth large conductivity variations are much more common than large susceptibility variations, the late-time $E$ field limits look much more active than late-time $H$ field limits. It should be noted that poor geometrical control can lead to what might appear to be late-time anomalies, but these are usually resolvable, and
never approach in amplitude the common E field variations observed.

THE ZONE A CONDUCTOR AT LINE C

Detailing was performed to map out the strike extent of the good conductor within zone A on line C. The data shown in figure 14 clearly indicate the presence of a long time-constant anomaly with its source at station 16W on line 7S, which correlates with the zone A core conductor on line 8S (line C). On line 9S however, the response observed indicates a much lower conductance is causing the anomaly and therefore that only the regional zone A conductor is present on this line. Using the data for line 10S (Figure 11), it can thus be seen that the strike-length of the good conductor is much less than 300 feet, and is probably in the range 150' to 200'.

The anomaly observed over the zone A conductor has in this region essentially two contributing components. This is best illustrated by the time-decay plot of the peak-to-peak $H_z$ anomaly over the zone, as shown in figure 15. The short time constant component is similar in amplitude and time to the response of the regional zone A conductor present on other lines of the grid. This regional zone is also interpreted to be about 75' wide on line 7S due to the width of the negative peak on the early-time channels (9, 8, 7). The second component of the time-decay plot (Figure 15) is a long-time constant anomaly with a much smaller inductive limit—around 50% as opposed to the short-time constant component inductive limit of about 300%. This 50% value would
agree well with a depth/strike length ratio of about .1, here say, depth to top =20', strike length=200' for this zone. Using these values, the conductivity thickness of the 'core' conductor is calculated to be in excess of 400 Ωm. The conductance interpretation technique used to obtain this value is described in Lamontagne (1975). Lamontagne, in an interpretation of an earlier UTEM survey at Cavendish, estimated the σt to be only 40 Siemens for the zone A core; however, the data upon which he based this estimate was not as detailed as that available for the present interpretation. The regional conductor has an interpreted conductance of about 5 Siemens at line 7S.

COMPARISON OF RESPONSE TO DIFFERENT TRANSMITTER LOOPS

In Figures 16 to 20 there are shown comparisons of response of UTEM data surveyed from two loops, one to the west of the grid and the other to the east with locations as shown in Figure 4. On line 4S (Figure 16), the regional zone A conductor is located at about 13+50W. The migrating nature of the crossover from early to late time on the loop-501 data indicates that the source is a wide conductor similar to the example in Figure 5D. So too, zone B appears to be a wide zone from the loop-502 data. It should be remembered that the positive peak of a normal H2 crossover-type anomaly is nearest the loop. Because of blanking, that is the shielding effect of any large conductor located between the zone of interest and the source, the conductor located away from the loop in each case is less well defined.
Figures 17 compares the two transmitter loop locations for the H anomalies on line 8S. Again both zones A and B are clearly detected from both loops, with blanking effects altering the shape and amplitude of the anomaly far from the loop. Line 12S (Figure 18) is somewhat different in character with a clear zone A anomaly at about stations 16W but a much less well defined zone B anomaly. To explain the migration of crossover locations with delay time seen on this line, it would seem necessary to postulate that some conductive material is present at depth between zones A and B.

Figures 19 and 20 present the comparison of the E field responses to the two transmitter loops. The close similarity in general shape of each component compared to the same component from the other loop is to be expected in this case, as the shape of the response is essentially controlled by the conductivity contrasts on vertical or steeply dipping contacts.

INTERPRETATION

The crossover-type H responses of both loops were interpreted in terms of a finite-dyke model to yield estimated conductivity thickness and depths, and a compilation of these values is shown in Figure 21. For any migrating or inferred crossover on the map, the plotted location may be subject to some error, and the depths shown are generally an estimate of maximum depth to top of source. For the sharply defined anomalies more confidence can be placed in location, conductance and depth.
Generally both the regional zone A and zone B are similar in character, with poor conductivity over a width of typically 50 to 100' indicated. The total conductance of zone B appears to be slightly greater than that of zone A, and the zone B conductor has its top at a greater depth. Within zone A there are two isolated regions of much greater conductance, one on line C with a strike length of less than 200', and another on line E, whose strike length has not been defined by the present survey coverage.

It is interesting to consider the $E_x$ crossover in relation to the mapped geology. In a system of parallel conductors, it is to be expected that the regional current induced in the ground will be channelled into the more conductive horizons. This would manifest itself on the $E_x$ data as a crossover in the late-time limit in a current inflow sense. As can be seen in Figure 22, the conductive zones A and B generally have a current inflow associated with them; as well there is a third zone of net current inflow which corresponds with a band of biotite gneiss running in between zones A and B. Reversed crossovers representing a net current outflow occur generally in association with the hornblende gneiss although this correlation is in some doubt. Nonetheless the geological control of $E_x$ crossover locations is evident.

THE DIFFUSIVE PROCESS IN EM INDUCTION

Figures 23, 24 and 25 show E field vector plots at 3 different delay times. The general shape of the primary E field consists of
vectors circling the loop, with a geometrical shape essentially shown in Figure 26, ignoring the anomalous region. Normalization of amplitudes has been performed to local strength of primary field.

The diffusion process of EM induction is quite well illustrated in these three vector plots. Figure 23 shows the total E field shortly after a discontinuity in the waveform. The primary field direction has thus just reversed, and is now pointing up on the map rather than down. It can be seen that it is only close to the loop that the vectors are up, while behind the zone A conductor they are still pointing down. As time goes on, the field diffuses through zone A and it can be seen in Figure 24 that at a later delay time the field direction is now up as far as zone B, but that behind zone B the vectors are still generally down and have not fully responded to the change in primary field direction. Finally, the field diffuses through zone B and in Figure 25 it can be seen that essentially everywhere the E field has become positive, or approximately in the same direction as the primary field. A complete set of vector plots of this diffusion is shown in Appendix B.

Note that even at the late-time limit, the E field vector plot does not look like a primary field plot. This is due to the presence of boundaries A with a conductivity contrast that may be crossed by steady current flow, leading to static E field anomalies. An example of such an anomaly is given in Figure 26, showing the theoretical response of a conductive oblate hem-
ispheroid in a resistive medium. The shape of the body is circular in section and thus looks somewhat like a half disc. A clear late-time limit E field anomaly exists over such a body. The pattern of current inflow seen at the edge of the body should be compared with the zone A core conductor on line C as shown in Figure 25.

Further details on E fields may be found in Macnae (in preparation)

Figures 27 and 28 show a map of equivalent surface current vectors that would produce the observed (horizontal) \( H_x \) and \( H_y \) UTEM anomalies.

The concept of equivalent surface current is similar to the equivalent stratum concept in gravity interpretation (See Grant and West, 1965, p. 214). Although the real earth current will be quite different in form it should be similar in direction and thus the close correspondence between the direction of the vectors and regional strike is expected. Note also that the response of the good pod-like conductors in zone A is clearer at intermediate-time delays as expected. The high response in the general area between lines A and B shows that extensive conductivity other than purely zone A and zone B is probably present, and it is postulated that a third conductor is present at depth between the two zones. This would agree with the data of other EM surveys (Ward et al., 1974, Koziar, 1976, Lamontagne, 1975).
CONCLUSIONS FROM THE UTEM SURVEY

The UTEM survey has clearly detected and mapped zones A and B at Cavendish, and outlined two highly conductive pods within zone A. It may be of interest to consider the result that the top of the zone B conductor is interpreted to be at some depth. Williams et al. (1975) postulated a crosscutting west dip for zone B on the basis of one drillhole that did not cut any sulphides as shown in Figure 3. If the zone B conductor is at the calculated depths, then it may be reasonable that neither of the holes at 9W or 9+40W actually is truly representative of the zone and thus it is quite feasible that the zone B conductor may have a dip similar to the bedrock dip.

A third zone at greater depth between zones A and B is also postulated on the basis of the H-field data.

U OF T MAGNETIC AND HLEM SURVEYS

Magnetic surveys over Cavendish have previously been published by McPhar (1967) and Charbonneau and McGrath (1975). However, these surveys consisted of readings every 100' on lines A to E. A detailed (25' station spacing) magnetic survey on 100' foot lines was performed at Cavendish during the annual University of Toronto field camp for undergraduate students in 1975. The contour map of these results is shown in Figure 29, which is very different in form to the earlier published contour maps, particularly around zone B. The good conductor in zone A at line C can be seen to have a directly coincident 3000 nT
magnetic anomaly, while there is no clear magnetic expression for the regional zone A conductor.

The magnetic response in the vicinity of zone B is highly variable, with several isolated features present. The UTEM \( H_z \) data can be used to determine the nature of near-surface magnetization if no strongly conductive features are in the immediate vicinity. If the static magnetic anomaly in the presence of the nearly vertical earths magnetic field, is an induced anomaly with no permanent component, and has an amplitude of 5% of the value of the earth's field, then we would expect a static UTEM anomaly of 5% too in the primary field direction. This anomaly would not decay with time and thus in the standard UTEM reduction would only appear on the plotted channel 1 response. Figure 30 shows the channel 1 \( H_z \) UTEM data after a "regional" linear correction has been applied, and the measured vertical magnetic field expressed in percent of total earth's inducing magnetic field. The "regional" correction above will remove to first order the amplitude effects of any conductor whose source geometry is such that its response is not changing rapidly along the line, for example, distant and/or deep conductors. This fairly smooth behaviour can be seen in the eastern portion of the grid as shown in Figure 11. The correction applied is similar in intent to regional-residual separation in gravity (See Grant and West 1965, p. 243-248). As can be seen in Figure 30, there is almost perfect correlation of the earth's vertical magnetic field anomaly with the UTEM magnetic field anomaly on lines 10S, 12S and 16S.
This would indicate that the source of these magnetic anomalies is purely induced magnetization.

Charbonneau and McGrath (1975) measured susceptibilities of rocks collected from the site, and found that indeed on line D (12S), the susceptibility contrast of rocks on the anomaly at about 9+50W with those in the host on either side explained the source. This conclusion is in agreement with the UTEM interpretations. On line C (8S), the measured susceptibilities of their rock samples were not much different from the host environment, which they interpreted either to mean that their samples were not representative, or that the source of the magnetic anomaly was deep. The detailed magnetic survey indicates that the source of the line C anomaly at station 9W is very shallow, but the absence of a Channel 1 UTEM response provides evidence that the source must be due almost entirely to remanent magnetization. This hypothesis does not seem to have been considered by Charbonneau and McGrath (1975). In the same way, the static magnetic anomalies on lines 4S and 6S are interpreted to be caused mainly by remanent magnetization.

The Horizontal Loop EM (HLEM) data at Cavendish presented here was collected to supplement the less complete coverage given by McPhar (1967). The survey was conducted with a MAX-MIN II HLEM unit kindly loaned by Apex Parametics Ltd. Figures 31, 32 and 33 present four-frequency maximum-coupled HLEM data for three coil separations surveyed on Line C. Clearly evident on these lines are the zone A and zone B conductors. Based on a standard,
steeply dipping half-plane model, (Grant and West, 1965, p. 554), interpreted conductances and depths are shown in the tables below.

**TABLE 1**

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<tr>
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<td>100' 200' 400'</td>
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<td>7 4</td>
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<td>10 7 2</td>
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The variation in interpreted values, particularly of zone A
indicates that neither of the conductive sources is a simple, thin, half-plane. In particular, on zone A, the increase in conductance with decrease of either coil separation or frequency indicates the presence of a small conductive core within a large halo zone. This agrees very well with the UTEM interpretation, although less detail is available with the HLEM data. It is also interesting that the interpreted conductance at lowest frequency and smallest coil separation is 400 Siemens, indicating again a very close agreement with the interpreted UTEM conductance. The halo conductor can be seen to cause a broadening of the quadrature response to the east of zone A compared to the in-phase response, noticable at all frequencies and coil separations.

Zone B appears more consistent with a half-plane model, but nonetheless there must be some localized areas of greater conductivity within the general zone to explain the variations of interpreted conductance with coil separation.

Data from lines B and D, surveyed with a 400' spacing, are also presented in figures 34 and 35. The half-plane model provides a consistent fit to the two zones on these two lines.

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At the large (400) coil separation used for line-to-line comparison, the anomaly of the regional conductors is enhanced compared to local variations, and this will explain the more consistent results above. However, the interpreted conductances and depths to the source are consistently less than those interpreted from the UTEM data. This probably is a result of the different system geometries, and complexity of the geology. The HLEM will tend to energize near surface features more strongly than UTEM and thus it is possible that zone B has a higher conductance at depth than near surface, which would tentatively explain both HLEM and UTEM data.

Compilation of Other Data

This section of the report will not go into any detail of interpretation from the data to be presented. The reason for this is that the data was collected by many different individuals, showing different degrees of care, depending on the aim of their
particular survey. In addition, much of the data was primarily obtained with prototype instruments still in the debugging process. Thus with the constraints that survey data was often collected in a non-optimum manner with instruments that are now outdated, it is clear that no valid inter-technique comparisons can be made from this data set. However, the following data is indeed of interest, and some short notes on each data section will be given, but no attempt will be made to provide a detailed interpretation.

System descriptions will not be given here, and the reader unfamiliar with any system is referred to one of the standard texts (e.g. Grant and West, 1965) or manufacturer's data sheets.

AFMAG

An interpretation of this data appears in the McPhar (1967) case-history. Clearly indicated in the data (Figure 36) are the regional zone A and B conductors, and also the shallow isolated regions of conductivity within zone A on lines C and E. It is interesting to note the similarity in anomaly shape of the Afmag data and the UTEM Hz data from the loop to the west. (There is a difference in presentation and normalization, but for small anomalies dip angle and vertical-amplitude anomalies are proportional to each other).

TURAM

The data obtained in the Turam survey clearly shows an anomaly
over the local zone A conductor at station 16S, and the less well conducting regional zone B conductor. Some rather tenuous evidence for the regional zone A conductor can be seen in the phase angle data, noticeable in the assymmetry of the anomalous response. However, the density of data points here is not really sufficient to resolve this. The loop for this survey was located east of the survey lines, of size 2000' square, running from lines A to A+400 (OS to 2000S) with its near side along the Base Line.

VLF-EM

The VLF-EM technique generally uses a distant VLF transmitter as a source, and thus the measured response over a conductor will depend on the particular station used. Fig. 38 shows the azimuths of the VLF stations from which data were collected, and in addition the regional strike direction. The VLF source field at a distance has a horizontal electric field component in a radial direction. Thus, ideally, for maximum coupling, the VLF source should be located in a direction along the regional strike, and for best results the survey lines should be perpendicular to strike.

Fig. 39 shows a comparison of the Line C response using 3 different transmitters. The dip angles and field strengths were read perpendicular to field direction, and clearly show the expected variation in response. A complete VLF survey using a fourth transmitter over the Cavendish grid is presented in Figures
40 and 41. The regional zones A and B conductors show up clearly on all the data lines. However, no absolute conductivity determinations are feasible using this technique. An estimate of depth to anomaly source may be made but this is not presented here.

EM16R

The Geonics EM16R uses VLF transmissions as a source, and measures the strength of both the horizontal electric and vertical magnetic fields, and thus can be used to determine an apparent resistivity of the ground as in magnetotelluric measurements. The zone A conductor is clearly indicated by this survey (Figure 42). Zone B does not appear to be clearly indicated in the apparent resistivity data.

EM31

The Geonics EM31 is a rigid-boom-mounted EM system operating at 39.2 kHz with a coil separation of 4.0M which measures apparent ground resistivities using the resistive-limit approximation (Grant & West, 1965, p. 489). The survey on line C clearly indicates the isolated zone A conductor, as well a small anomaly over the regional disseminated conductor can be seen just east of the high-conductivity zone (Figure 43). Zone B at about 9W is also clearly indicated, with the response at 7W corresponding to an overburden thickening in the region of a swamp, as shown in the drill section on Figure 3.
EMR16

Figure 44 shows a pseudo-section of apparent resistivities as determined by a multifrequency Geoprobe EMR-16 survey. The technique is based on measurements of the vertical and horizontal magnetic fields obtained from a dipole source. Clearly indicated are both zones A and B. This data was obtained with a 400' TX-RX coil separation. These results appear very similar to the audio-frequency magnetotellurics survey results published by Strangway and Koziar (1979), but are derived from quite different measurements.

PEM

The Crone PEM survey over line C is shown in Figure 45. The poorly conducting zone B shows up only at early time delays. The anomaly from the zone A is isolated conductor is very clear, and the broadening of the response to the east at early delay times is evidence for the lesser conducting regional zone A conductor located east from the main anomaly.

INDUCED POLARIZATION AND RESISTIVITY

This compilation has been oriented towards ground EM methods, however for comparison one line of IP and resistivity data from McPhar (1967) is presented in Figure 46. More complete data is obtainable in McPhar (1967), Scott (1971) and Smith et. al. (undated report).
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Crone, D.J.
Geonics Limited,

Data Sheet A: EM31 Accurate Electrical Conductivity Measurements and technical note TN-3: Electromagnetic non-contacting ground resistivity mapping.

Geonics Limited,

1973: EM16R Direct Reading Ground Resistivity meter.

Geonics Limited,

Data Sheet B: TX27 VLF-Portable Transmitter

Geonics Limited,


Ghosh, M.K.


Goldstein, M.A.


Goldstein, M.A. and Strangway, D.W.


Grant, F.S. and West, G.F.

Hobson, G.D.

Hood, P.J.

Koziar, A.

Koziar, A.

Lamontagne, Y.L.

Lamontagne, Y., Lodha, G., MacNae, J., and West, G.F.
Macnay, J.C.


McPhar,

1967: A geophysical case history, Cavendish Township, Ontario, Canada: Toronto, McPhar Geophysics Ltd.

Mwenifumbo, D.J., and Mansinka L.


Paterson, N.R.


Pheonix Geophysics Limited

Data sheet A: VLF-2 Electromagnetic Unit.

Scintrex Limited


Scott, W.J.


Smith, R.J. Hallof, P.G. and Stevenhuysen, J.

Sobczak, L.W. and Jacoby, W.R.


Siegel, H.O.


Strangway, D.W. and Koziar, A.


Williams, D.A., Scott, W.J., and Dyck, A.V.


TABLE OF PRIMARY GROUND DATA SOURCES
(including data not presented or referenced in the text)

**GENERAL DATA**

<table>
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<th>Topic</th>
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<tbody>
<tr>
<td>Topography</td>
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<td>Geology and</td>
<td>Williams et. al. (1975).</td>
</tr>
<tr>
<td>Seismic</td>
<td>Hobson (1975), Scott (1971).</td>
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<tr>
<td>Gravity</td>
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**ELECTRICAL DATA**

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<td>Magnetic Induced</td>
<td>Seigal (1974).</td>
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<tr>
<td>Polarization</td>
<td></td>
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<tr>
<td>Mise-a-la-masse</td>
<td>Mwenifumbo and Mansinha (1980).</td>
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</table>
TABLE OF PRIMARY GROUND DATA SOURCES (cont.)

ELECTROMAGNETIC DATA

UTEM
Horizontal Loop
PEM
Vertical Loop
Tilt angle/ellipticity
VLF

This report, Lamontagne (1975)
This report, McPhar (1967)
McPhar (1967).
Ward et. al. (1974).
Geonics (1973, data sheet B), Phoenix
(data sheet B), Crone (1967c).
This report, Scintrex (data sheet).
Geoprobe (data sheet).
Geonics (data sheet A).
Strangway and Koziar (1979), Koziar (1976)
Goldstein and Strangway (1975), Koziar (1972),
Goldstein (1971).
McPhar (1967)
Figure 1. Location map of the Cavendish test site (from Williams et al., 1975).
Figure 2. Interpreted geological map of the Cavendish test site (after Williams et. al., 1975).
Figure 3. Geological section from drilling and surface mapping at Cavendish (after Williams et. al., 1975).
Figure 4. Location map for the UTEM survey at Cavendish.
Figure 5. The form of UTEM $H_z$ anomalies over some simple shapes. Examples A-D are drawn for conductors far from the loop. Near the loop, where the primary field intensity varies rapidly, the form of the profiles may be somewhat altered. Diagram from Lamontagne, 1975.
Figure 6. Schematic diagram to show two E and three H field component anomaly shapes over a conducting dyke. The examples are for a conductor not too close to the transmitter loop.
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<td>10</td>
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</table>

Primary Field

Figure 7. Plotting symbols for UTEM channels. Channel 10 data at 30 Hertz are not plotted. Delay times are approximate mean delay times for each channel.
Figure 8. Horizontal along line (x) and vertical (z) components of the magnetic (H) field along line C from loop 501 as shown in Figure 4. Base frequency 15 Hertz.
Figure 9. UTEM $H_x$ results over the Cavendish grid. Frequency used is 30 Hertz for all lines except 8S, for which the base frequency was 15 Hertz. Standard normalization.
Figure 10. UTEM $H_y$ (perpendicular to line) component survey at Cavendish. Base frequency 15 Hertz for 8S, all others at 30 Hertz.
Figure 11. UTEM vertical $H_z$ magnetic field at Cavendish. All lines surveyed at 30 Hertz. Standard Channel 1 normalization.
Figure 12. UTEM $E_x$ response at Cavendish. Data are normalized to total primary $E$ field. All lines surveyed at 30 Hertz, except 8S surveyed at 15 Hertz.
Figure 13. UTEM $E_y$ response at Cavendish. Data are normalized to primary $E$ field. All lines at 30 Hertz, except 8S at 15 Hertz base frequency.
Figure 14. Detail lines, 100' either side of line 8S at Cavendish.

30 Hertz base frequency.
Figure 15. Log-amplitude log time plot of the peak-to-peak $H_z$ anomaly of the zone A conductor on line 7S. Note the dual nature of the decay. The short time-constant component is interpreted to be caused by the regional 'halo' conductor, and the long time-constant portion by a local, very good, conductor.

$\tau_{\text{short}} = 4.0 \times 10^{-4}$ seconds

$\tau_{\text{long}} = 1.2 \times 10^{-2}$ seconds
Figure 16. Comparison of UTEM $H_z$ response over line 4S using two different transmitter loops. Base frequency 30 Hertz.
Figure 17. Comparison of UTEM $H_z$ response over line 8S using two different transmitter loops with a 30 Hertz base frequency.
Figure 18. Comparison of UTEM $H_z$ response over Line 12S using two different transmitter loops. Base frequency 30 Hertz.
Figure 19. Comparison of UTEM $E_x$ response over line 8S using two different transmitter loops. Base frequency 30 Hertz.
Figure 20. Comparison of UTFTM E_y response over line 85 using two different transmitter loops. Base frequency 30 Hertz.
LOOP 501

Figure 21. Interpreted conductivity-thickness (Siemens) and depth to source (feet) from UTEM H crossover type anomalies at Cavendish. The location of sulphide zones according to Williams et al. is also shown.

UTEM SURVEY CAVENDISH

Loop 502

Hz crossovers

△ △ LOOP 501

▽ ▽ LOOP 502

▲ sharply defined crossover
▼ Migrating or inferred crossover

Loop 502

200 FT
Figure 22. UTEM $E_x$ crossovers and geological contacts of the hornblende gneiss. The mapped sulphide zones are also shown.
UTEM SURVEY CAVENDISH

Figure 23. Total E field vectors at a short delay time after the discontinuity, corresponding to channel 8 at 30 Hertz.

E
VECTORS
100 μs delay

200 FT
UTEM SURVEY CAVENDISH

Figure 24: Total E field vectors at an intermediate delay time, corresponding to channel 5 at 30 Hertz.

VECTORS
800 µs delay

100%

200 FT
Figure 25. Total E field vectors after a long delay, corresponding to channel 2 at 30 Hertz.
Figure 26. Theoretical late time limit E field response for an oblate hemispheroid with conductivity 10 times that of the host medium. Note that the primary field circles the transmitter loop, and current is channelled into one end and out of the other. A resistive body would have an anomalously large E field directly over it.
Vector plot of equivalent surface current that would produce the observed horizontal H field at a short delay time. The 100% vector represents the magnitude that would produce a 100% horizontal H field anomaly when normalized to local, total primary field.
Figure 28. Intermediate delay time equivalent surface current vectors. Note the expanded scale compared to Figure 27.
Magnetic field contour map, vertical component, contour interval 500 nT. Data was collected at a 25' spacing on the lines shown, and on 6 additional lines spaced 100' apart between lines B and C, and C and D. These lines have not been plotted to improve clarity.

Figure 29.
Figure 30. Comparison of UTEM Channel 1 $H_z$ and natural vertical magnetic field anomalies. Plotting scale for $H_z$ is in percent of primary field, and for the magnetic field in percent of the vertical component of the earths total magnetic field.
Figure 31. 100' spacing HLEM data over line C. The bumpiness of the in-phase profiles compared to the quadrature profiles is due to small chainage and orientation errors.
Figure 32. 200' spacing HLEM data over line C.
Figure 33. 400' spacing HLEM data over line C
CAVENDISH LINE B

Frequency (Hz)

222
444
888
1777

MAXMIN II HLEM
400' SPACING

20% IN PHASE
0 QUADRATURE
-20%
Figure 35. 400' spacing HLEM data over line D.
Figure 36. Two frequency AFMAG data at Cavendish (from McPhar, 1967).
Figure 37. Five frequency Turam profiles along line C. Data courtesy Androtex Ltd., with interpolated points from a survey by Scintrex Limited. The loop front was located at station 0, with sides 2000'x2000'; 100' coil sep.
Figure 38. Source direction of VLF transmissions and regional strike compared to the Cavendish grid.
Figure 39. Comparison of VLF responses over line C for different transmitters. Data courtesy of Pheonix Geophysics.
Figure 40. VLF dip angle profiles over the Cavendish grid, using the Panama station as a source. Data courtesy Crone Geophysics Limited.
Figure 41. VLF field strength over the Cavendish grid, source in Panama. Data courtesy Crone Geophysics Limited.
Figure 42. Apparent resistivity and phase from electric and magnetic field VLF measurements using the EM16R instrument. Data courtesy Geonics Limited.
Figure 43. Electromagnetic non-contacting apparent conductivities over Line C obtained with the EM31.
CAVENDISH LINE C EMR 16 APPARENT RESISTIVITIES

Figure 44:
Apparent resistivities obtained over line C using the Geoprobe EMR16 instrument. Data obtained with a 400' coil separation, courtesy Geological Survey of Canada.

Frequency (Hz)

- 43 K
- 21.5 K
- 10.8 K
- 5.38 K
- 2698
- 1344
- 672
- 336
- 168
- 64
- 42
- 21
- 10.5
Figure 45. PEM results over line C obtained with a prototype instrument. Data courtesy Crone Geophysics Limited.
Figure 46. Induced Polarization and Resistivity survey, Dipole-Dipole array a=100', n=1 to 4 over Line C. Data from McPhar (1967).
UTEM is a wide band, time-domain ground, EM prospecting system developed in the Geophysics Laboratory, University of Toronto by Yves Lamontagne and G.F. West. It provides the sensitivity and interpretative power of a research style system in handling problems of deep exploration and conductive environments with reasonable surveying rates and a small crew size.

The UTEM system: UTEM employs a large, fixed, horizontal, transmitter loop as source. The field of this loop is then mapped with the receiver system, normally by measuring the vertical component of the magnetic field, but also measuring the horizontal magnetic and electric field components in some circumstances (Fig.1). The size of the transmitter loop and the associated survey area depends on the prospecting problem but might easily be as large as 5,000 x 3,000 ft. with surveying to a distance of 4,000 ft. from the loop in resistive terrain or as small as 1,000 x 1,000 ft. with surveying to a distance of about 2,000 ft. in a conductive area.

The UTEM transmitter passes a low frequency current of precise triangular waveform through the transmitter loop. The receiver magnetic sensor is a wideband coil. Thus, in "free space" a precise squarewave voltage would be induced in the receiver, while on conductive ground the waveform is substantially distorted. The UTEM receiver system measures the distortion of the waveform by determining 10 amplitudes (averages over time windows) at binary spaced times between the waveform transitions. The sampling scheme is shown in Fig. 2. The base frequency of the waveform is set somewhere in the range 9 - 30 Hz (usually 30 or 15 Hz in 60 cycle countries, 25 or 12.5 Hz in 50 Hz countries). This frequency is low enough that the ground response has usually vanished by the end of the half cycle. When this is the case, the UTEM system essentially determines the step response of the ground over the time range 50 µs - 25 ms (15 Hz base frequency).
The optimum field crew for a typical UTEM survey is three men: a geophysicist, a trained operator, and a helper. The geophysicist spends part of his time on the survey and part on data reduction and interpretation. Measurement is usually best done with a two man crew especially if E fields are to be recorded. However, surveying can still proceed with a single operator. The helper is thus available for loop repair, layout and pickup. The transmitter is normally operated unattended.

**Design philosophy.** The UTEM system was designed with four geophysical objectives in mind.

1. System must be truly wide band ( > 100:1 frequency coverage), to enable all the various possible induction phenomena to be recognized in interpretation.
2. The system must have maximum possible depth sensitivity.
3. The system must have good geometrical resolving power for shallow or deep conductors.
4. The data should be obtained in such a way that interpretation is simplified by allowing frequency or time scaling.

These were to be obtained within the constraint that survey costs with the system should be minimized and must certainly not exceed those of IP.

It is not sufficient just to increase receiver sensitivity to obtain greater depth penetration. It is necessary to increase the scale of the prospecting system in order that the fall-off of target response with increasing depth not be excessive. Otherwise, small near surface features will mask any possible deep responses. When a large scale system is employed (e.g. 200 m HLEM, 400 m VL dip angle methods) resolution is a problem. A system where the receiver maps the field of a fixed transmitter was therefore chosen as it provides the requisite depth sensitivity with minimum loss of resolution for deep or shallow features.
scaled up in amplitude inversely proportional to their time constant. Since even in the step response, the short time constant overburden anomalies have very large amplitudes (inductive limits) in comparison to the low amplitude longer time constant responses of target conductors, any amplification of these short time constant anomalies is undesirable.

Step switching in the transmitter can also present a problem. Transmitter loops are somewhat inductive (∼10 mH) and resist a sudden shut off of large currents. In practice, a ramp shut off over a period of some 100 μs or so is required. Thus, the system function of the total measuring system does not approximate either a step or an impulse response until delay times of about half or one millisecond are reached. This causes problems in interpretation for two reasons - firstly, it prevents simple time scaling in the interpretation, where model data can be rescaled to fit the observations. Secondly, the system function may not be entirely constant, so that interpretation models have to be altered for different transmitter loop sizes etc.

To avoid the foregoing problems, UTCM uses a triangular current waveform in the transmitter. The receiver coil differentiates this to a square waveform, which approximates an ideal step. Because of the reduced high frequency content of the triangular waveform, the current in a typical transmitter loop can be slewed around the discontinuity in some 5 - 20 μs. Thus the waveform approximates a true square for delay times as short as 50 μs.

Generating a precise triangular current waveform requires more complicated electronics than does a simple step, in that a linear, wide band amplifier must be employed. The present UTCM transmitter can supply a peak current of about 4 amps and a peak voltage of about 250 volts. It would be difficult to raise the voltage limit with the present technology, although the current output could quite possibly be increased.
Fig 1  The usual UTEM survey configuration

Fig 2  (a): UTEM transmitter current waveform

(b): The sampling scheme in the UTEM receiver. The amplitudes A1, A2 etc. are measures of the total field. The shaded areas represent secondary field due to induction.
Fig. 3. The inductive limit of response is directly dependent on conductor size, geometry, proximity but not on conductivity.
APPENDIX B

An example of inductive diffusion of the UTEM electric field.

The diagrams presented are free of notation; for scales, line numbers etc., refer to Figures 4, 23, 24, 25 of the main text. Amplitude normalization of vectors is to the magnitude of the primary electric field at the measuring point.
Figure B1. Late-time measured E field at Cavendish plotted in vector format with primary field reversed (pointing down). The transmitting loop is \#501 as shown in Figure 4 of the text.
Figure B2. At time $t=0$ the primary field of the source reverses to point up as shown. Size of vectors indicates 100%. True amplitudes change by about 2 orders of magnitude over the grid.
Figure B3. The E field after 50 μs delay. Very little effect of the change is primary field directions can be seen behind zone A.
Figure B4. The E field after 100 $\mu$s delay.
Figure B5. The E field after 200 μs delay.
Figure B6. The E field after $400 \, \mu s$ delay. The field has now penetrated zone A and the direction of the actual field between zones A and B is now up.
Figure B7. The E field after 800 μs delay.
Figure B8. The E field after 1.6 ms delay. The field has now almost completely penetrated to zone B.
Figure B9. The E field after 3.2 ms delay. The E field can now be seen to be upwards behind zone B.
Figure B10. The E field after 6.4 ms delay
Figure B11. The E field after 12.8 ms delay. A total of 20ms after the discontinuity (at a base frequency of 30 Hertz). The primary field will then reverse again and the cycle will restart. Note - the large amplitudes of the E field close to the loop in the top left corner of the plot are due to an inadvertent ground contact where the loop was buried under a road.