Geonics Limited Technical Note TN-35

Archaeological Mapping Using the Geonics EM38B to Map Terrain Magnetic Susceptibility (With Selected Case Histories)

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1. Introduction

The Geonics Limited EM38B has been used for many years to map terrain conductivity, for example for identifying areas of groundwater contamination and soil salinity. Less widely realized is that this instrument also simultaneously maps terrain magnetic susceptibility (defined as the magnetic response of the ground when subjected to an inducing magnetic field) which makes it particularly useful for mapping archaeological sites. In this Technical Note we will first outline why magnetic susceptibility plays such an important role in locating and mapping sites that have been occupied by humans for hundreds of years. We will show that the EM38B offers important advantages over other geophysical instruments such as magnetic gradiometers for this application. We then describe survey data from a large number of case-histories carried out in Eastern Canada.

The decision was made to format this Note as a computer document as well as the printed page since it contains a large amount of survey data most easily presented in this format.

2. Why Would Soil Magnetic Susceptibility Be of Interest to Archaeologists?

In this section we briefly describe various aspects of the spatial distribution of magnetically active soils that make such soils of great interest to archaeologists. But first, what do we mean by magnetically active (susceptible) soils?

If we induce a local (primary) magnetic field into the ground (for example with an electrical coil) this magnetic field acts on microscopic iron-oxide bearing mineral grains in the soil, causing them to align themselves with the primary magnetic field. These aligned mineral grains in turn generate a (secondary) magnetic field, much smaller than the primary magnetic field and usually in the same direction as it. The ratio of the secondary magnetic field to the primary magnetic field is defined as the magnetic susceptibility of the soil.

There are many different factors that determine the strength of the soil susceptibility, however, as Aspinall et al. (2008) state, many researchers (and these authors give a large number of references) have clearly demonstrated over the years the remarkable fact that ‘anthropogenically influenced’ topsoils have a high concentration of iron oxides that lead to enhanced magnetic susceptibility.

The most important iron oxides for archaeologists are hematite (α-Fe_2O_3), magnetite (Fe_3O_4), and maghemite (γ-Fe_2O_3). In all of these minerals the different locations of the iron and oxygen ions in their different crystal structures result in quite different magnetic properties. Of note is the fact that, while the commonly occurring mineral hematite is not magnetically active, both magnetite and maghemite are strongly magnetic, even in very small concentrations (of the order of 1% or less). Of particular interest to archaeologists is the fact that, under certain conditions, often associated with human habitation, the less magnetic hematite can be converted (chemically reduced) to strongly magnetic magnetite, and then further converted (chemically oxidized) to the only slightly less magnetic maghemite. Moreover, both of these substances, being oxides, are highly resistant to weathering and persist in the ground for very long periods of time, and over a variety of environmental conditions.

Aspinall et al. (2008) list five factors that enhance soil magnetic susceptibility as a result of human occupation; the list below is quoted directly from their book.

(1) The 'La Borgne effect' associated with the heating and burning of soils. They state "that the burning of vegetation in most surface fires is sufficient to exclude oxygen, thus producing a reducing atmosphere. Under these conditions temperatures of about 200 degrees Celsius are sufficient to reduce hematite in the topsoil to magnetite. When the fires abate, oxygen becomes available, and, in cooling, the magnetite can re-oxidize as maghemite, leading to permanently enhanced magnetic susceptibility of the soil."

An interesting demonstration of the power of this effect is given by Anthony Clark, who was very active in the 1980's in exploring the use of various chemical and geophysical techniques for archaeological mapping. Clark (2000) states that "the strength of the burning effect on occupied sites is such that it seems always to be readily distinguishable when superimposed on any magnetic enhancement present in the generality of soil, and normally on any effect from modern stubble burning, which is very quick and superficial. It has been demonstrated that the burning effect can be enhanced in the presence of organic material, which must provide the necessary initial reducing conditions…" He continues "The burning effect can be readily simulated. One of my lecture demonstrations is to increase the magnetic susceptibility of a sample of soil—usually taken from the nearest flowerbed to the lecture theatre to impress the audience that there is nothing special about the sample—simply by heating it with a butane torch. The strength of the effect, in the absence of any precautions, shows that the conditions for enhancement are by no means critical".

(2) Aspinall et al. state that "human habitation is also linked with organic waste. Domestic waste heaps, or middens, and detritus are home for many microorganisms that propagate decay. These bacteria create the reducing or oxidizing conditions necessary for waste digestion. In these conditions magnetic minerals may also be converted, leading to enhancement of the magnetic susceptibility in the soil".

(3) "Certain bacteria are able to create micron-sized magnetite crystals within their bodies by using iron oxides naturally occurring in soil".

(4) "The addition of magnetic material such as broken pottery or brick fragments obviously enhances the susceptibility. Such material was often simply discarded, incorporated into middens by farmers who spread it on arable fields with other manure. Metalworking debris, for example

hammer scale and slag, also becomes incorporated into soil layers to greatly increase the susceptibility".

(5) "Enhancement of soil magnetic susceptibility also occurs during soil formation processes (pedogenesis)".

This list amply illustrates the potential that measurement of the terrain magnetic susceptibility has for archaeological mapping. And in fact, indirect measurement of the soil susceptibility is already proving very useful to archaeologists, who often employ magnetometers or, more recently, magnetic gradiometers for this purpose. These devices infer changes in the terrain susceptibility by measuring local changes in the earth's magnetic field (or its gradient) that are caused by changes in the soil susceptibility. Thus they offer an indirect measurement of the susceptibility.

Measurements made with the EM38B, on the other hand, directly measure the susceptibility by applying a localized, primary magnetic field to each part of the soil and measuring the localized secondary magnetic field caused by the inducing local, primary field. Unlike the magnetometer or gradiometer, which use the earth's magnetic field (more or less uniform over the whole survey area) as the primary or inducing field, the EM38B applies its own inducing field (the direction of which varies as the surveyor moves across the ground) and measures changes in the secondary magnetic field arising directly from changes in the local susceptibility at each location. The result is excellent spatial resolution.

Before leaving the subject of magnetic susceptibility there is another aspect of the susceptibility that will be of interest to archaeologists.

Laboratory measurements of the magnetic susceptibility of a soil sample are made by placing the sample inside a coil of wire through which an electrical current is passed to generate the primary, inducing magnetic field in the soil sample. The resultant secondary magnetic field arising from the specimen is simultaneously measured to determine the magnetic susceptibility of the specimen, defined simply as the ratio of the secondary magnetic field to the primary magnetic field (and thus a dimensionless quantity usually expressed as parts per million (ppm) or parts per thousand (ppt)). Such a measurement can be made either by passing a direct electrical current (DC) through the coil, in which case the susceptibility that is measured is known as the DC susceptibility, or by using an alternating current (AC) which simplifies the measurement but has another interesting effect. In this case it is often observed that as the frequency of the alternating current (and thus primary magnetic field) is increased, the measured susceptibility actually decreases with increasing frequency. The reason is that it can take a finite amount of time for the magnetism in the sample (that is causing the secondary magnetism) to respond to the primary or inducing magnetic field. At very low frequencies, where the primary magnetic field is also changing very slowly with time, this response time will be negligible and the sample susceptibility at these frequencies will be the same as that measured with a constant or DC inducing field. As the source frequency is increased however, it will often be found that the induced magnetism becomes smaller than the DC value since the sample magnetism is simply too slow to follow the more rapidly time-varying primary magnetic field. We say that the induced magnetism, which has a frequency-dependent magnetic susceptibility, is showing a ‘relaxation effect’.

Now as discussed by Clark (2000) the theory for this behaviour is complicated, but it shows that the relaxation is strongly dependent on the actual physical dimensions of the microscopic iron oxide mineral grains that are causing the magnetic response. Larger mineral grains, such as are apparently found in magnetic rocks such as basalt, show little relaxation and their magnetic response does not vary significantly with frequency. On the other hand, when small mineral grains (such as those produced by pedogenic enhancement) predominate in a soil sample the frequency dependence can become, as we shall see, quite measureable and it appears possible that, when better understood, this phenomena will prove useful in differentiating the responses and thus the causes of the response from different materials and/or materials in different stages of development. This matter is discussed further in Appendix 1.

Having described the many ways that a contour map of magnetic susceptibility can be of use to the archaeologists the question arises as to how terrain susceptibility varies with depth. Dalan (2008) has been investigating the uses of susceptibility in archaeology for many years and more recently, following a collaborative effort with Bartington Instruments (English manufacturers of both laboratory and survey instruments for measuring the susceptibility of rock and soil samples and gradient magnetometers), that company has introduced their MS2H one-inch diameter borehole sensor for measuring terrain susceptibility to depths of the order of a meter (a presumed depth of interest to archaeologists). Results from using this equipment (Dalan, 2006, 2008) show that high-resolution measurements of magnetic susceptibility to this depth can yield useful archaeological (and environmental) information. Examples include locating buried paleosols, elucidation of the source of susceptibility anomalies detected by surface geophysical surveys, and the improved mapping of stratigraphic correlations based on susceptibility.

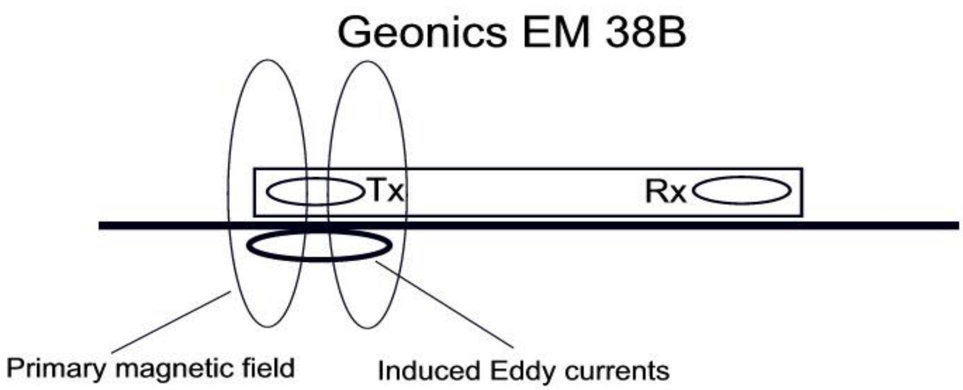
A great deal of useful archaeological information is clearly available from high-resolution surface and depth mapping of magnetic susceptibility. For those wishing further information on the subject as well as more technical details and a complete bibliography, readers are referred to Dalan & Bannerjee (1998).

It is apparent from the material presented above that, as suggested by Tabbagh (1986), a slingram-type (employing self-contained transmitter and receiver coils) electromagnetic instrument, measuring both the inphase component (for susceptibility) and quadrature-phase component (for conductivity) to depths of the order of a meter should be particularly useful to archaeologists.

3. Why Use Inductive Conductivity-Susceptibility Meters to Measure Terrain Susceptibility?

(a) Instrumentation Operational Characteristics

All of the case-histories in this Technical Note were performed with the Geonics EM38B and our description will focus on that unit, which has an effective depth of exploration of about one-half meter for susceptibility. A newer version of this instrument, the EM 38 Mark 2 (which simultaneously measures to depths of 0.25 and 0.50 meters) is now available and Geonics also manufactures the EM31-SH (depth of 1 meter) and the EM31 (depth of 2 meters). All of these instruments work on the same principle: the only variable is the depth of exploration.

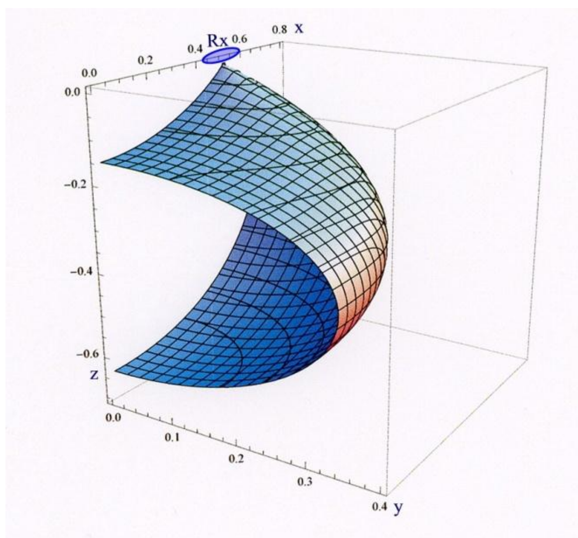


In all of these instruments a small transmitter coil is energized with an alternating current at an audio frequency. This current generates, in turn, an alternating primary magnetic field in the ground, as shown in the figure. The time-varying magnetic field causes two important effects.

The first effect is that, if the ground is electrically conductive (and most ground is, to some extent) the magnetic field induces extremely small eddy currents in the ground, as also shown in the figure. If the instrument is correctly designed, the strength of these eddy currents is proportional to the ground electrical conductivity. Just as the transmitter current generated the primary magnetic field, these eddy currents, which are proportional to the ground conductivity, generate a secondary magnetic field which, along with the primary magnetic field, is sensed and measured by the receiver coil. By measuring the secondary magnetic field these devices are able to accurately measure the ground conductivity without electrical contact with the ground.

The second effect is that the alternating primary magnetic field also magnetically polarizes the ground, and the secondary magnetic field from this magnetic polarization is also measured by the receiver coil. If the instrument is correctly designed, it is possible to separate these two secondary magnetic fields, and to design an instrument that simultaneously measures the terrain electrical conductivity (σ) as well as the magnetic susceptibility (κ) defined in the previous section. The remainder of this Technical Note will concern itself with the measurement of terrain susceptibility.

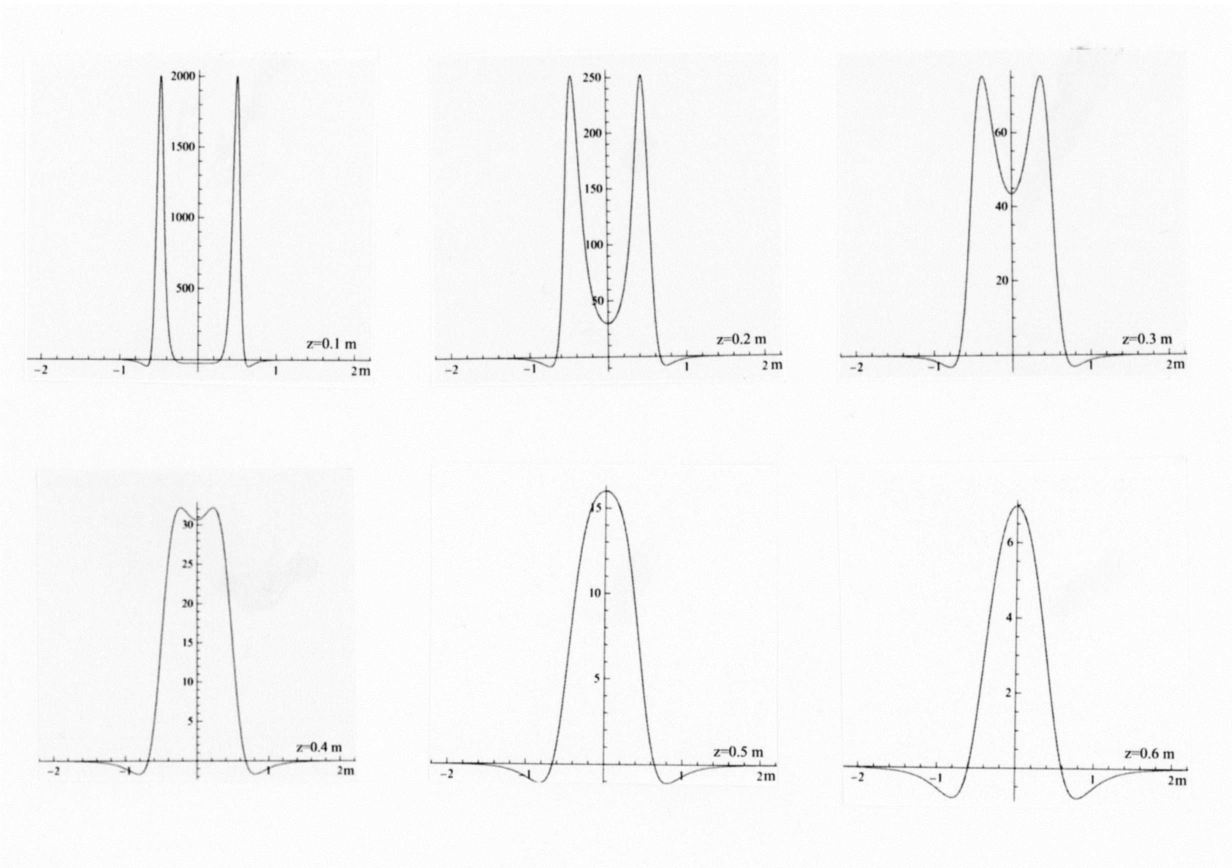
What are the characteristics of the spatial response for these instruments? The figure below, for the EM38B with one-meter intercoil spacing, shows a quarter-section of coarse contours of the response for a small target located at various positions beneath the earth's surface. The long axis of the instrument is along the x-axis on the graph; the receiver coil is located at x=0.5 meters and the transmitter coil at x= -0.5 meters.



We see that the response peaks sharply under the receiver coil (in fact, under either the transmitter or the receiver coil, since it can be shown that the response is symmetrical with respect to both coils), that it extends down to a depth of about 0.6 meters, and sideways out to about 0.35 meters on either side of the instrument. We also see that the 'down-the-line' spatial resolution will be of the order of one meter, and, furthermore, that a 'between-the-line' survey spacing of one meter will catch most anomalies.

Equally important, however, are the profile shapes that the instrument produces as the surveyor moved across a small buried, susceptible sphere (or roughly spherical, since the response shape is not profoundly sensitive to the shape of an approximately spherical body). The figure below shows, for vertical dipole mode of operation, that the profile shapes are strongly dependent on body depth and allow an approximate estimate of target depth. We see that a body at shallow depth shows a large response as each of the two coils passes over the body, and that this phenomenon decreases with increasing depth. At a depth of about 0.4 meters the two responses have melded into a single response, directly over the body. Similar calculations for the horizontal dipole mode show similar behaviour except that now the shallow responses have one-half the amplitude and are always of negative polarity.

It should be added that the information available from these profiles requires that the data logger recording the survey data must take readings at a rate of at least three readings per meter, and when this is done we will see this behavior on the case-history survey profiles.



The fact that the spatial response changes quickly as the sphere depth increases suggests that when searching for deeper targets one might do the survey with the instrument at a height of about 0.25 meters above the ground rather than right on the ground, a procedure also used for magnetic gradiometer surveys. However the survey data shown in Section 4 shows that such a procedure would remove a great deal of useful survey information from the data. In some cases, however, it might be desirable to simply do a survey twice, once on the ground followed by a repeat of interesting regions with an instrument height of 0.25 meters.

Furthermore the following table shows that, although though the response to a spherical target of constant radius decreases rapidly with depth, since the response to a sphere also increases rapidly with sphere radius, it does not take a large increase in sphere radius to give an appreciable response at greater depths. The table (which is approximate) shows, for a sphere susceptibility of 10 ppt, the required sphere radius necessary to generate a quite detectable response of 0.3 ppt .

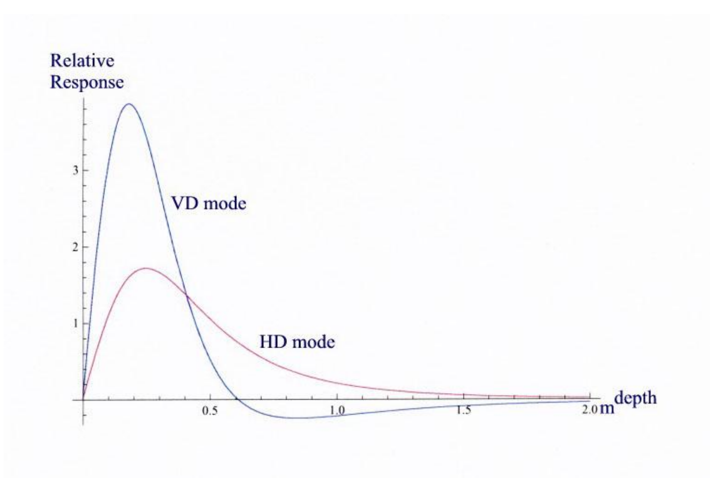
Depth to sphere centre (cm)	Approximate sphere radius (cm)
100	4
200	7
300	11
400	14
500	18

To continue with the subject of survey profiles which contain much useful information, it is the usual practice to contour geophysical survey data, but it should be kept in mind that contouring greatly filters the data and much of the valuable information in the survey profiles is lost. The DAT-38BW program, supplied with the EM38B instrument to facilitate profile handling, is itself an extremely valuable aid to data interpretation. Indeed interpreters will find themselves continually going backwards and forwards between the profiles and the contours to maximize survey information.

Moreover this program also facilitates adjustments of the instrument zero levels, corrects for thermal drift in the zero level, and formats the data for entry into the Surfer contouring program (which has been used for all the data shown in this Technical Note).

An important comment is appropriate here. It is well-known that total-field and gradient magnetometers are insensitive to relatively thin, flat lying susceptible media, and therein lies one of the significant advantages of inductive conductivity-susceptibility meters. We shall see that conductivity-susceptibility meters allow detailed inspection of the geophysical connections between areas of different susceptibility as well as extending the surroundings of susceptibility anomalies themselves. Incidentally, it follows that the choice of colour scale used in the contouring program is very important since the variations in colour at different susceptibility levels will control the visibility of the inter-relating connections. It is usually worth spending time and effort to experiment with the colour scale to bring out maximum information.

To date we have discussed the system response to a small susceptible sphere located at various positions in the earth. What about variations of bulk susceptibility with depth? Here again the inductive conductivity-susceptibility meter offers an important advantage. It is possible to calculate the relative response of the instrument to a horizontal, thin layer of susceptible material as a function of depth, as shown in the figure below.



This diagram gives the relative response from material at different depths for the EM38B used in either the vertical dipole mode (instrument upright on the ground) or horizontal dipole mode (lying flat on the ground). For both modes it is observed that the response to a horizontal thin layer lying at a depth of zero (i.e. right under the instrument) is zero, however as the depth increases the response rapidly increases, more rapidly for the vertical dipole mode, and in general this mode of operation is most sensitive to near-surface material.

For the vertical dipole mode this response peaks at a depth of about 0.2 meters, whereupon it decreases rapidly, actually becoming negative at a depth of about 0.6 meters. While this behavior looks alarming it should not cause concern since, except over thick, buried susceptible layers one does not usually see negative responses with the instrument in the vertical dipole mode. When it might be a concern, surveys can be carried out with the instrument in the horizontal dipole mode, whereupon the effect disappears; it should be noted however that the noise level of the instrument will often be higher in the horizontal dipole mode due to increased sensitivity to stray electromagnetic fields from radio transmitters, power lines etc.

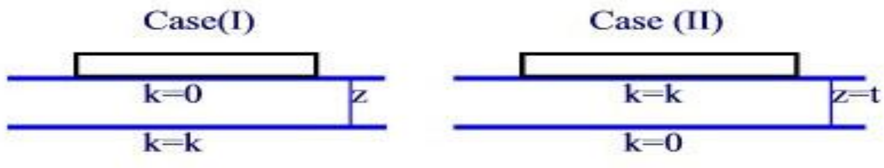
In the horizontal dipole mode the response with depth also increases initially, but peaks at a slightly greater depth, and decreases to zero rather slowly thereafter. Not shown in this figure is the fact that in the horizontal dipole mode the response is always negative (the polarity of the horizontal dipole mode response has been reversed in the figure to facilitate comparison of the different response shapes).

Although the graphs above show that the instrument response is zero at a depth of zero it is easily shown that for either dipole mode the response to a near-surface horizontal thin sheet is in fact proportional to the product of the susceptibility and the square of the sheet thickness, so is quite diagnostic of changes in this parameter.

The total area under each curve is the same since for a homogeneous half-space (which is what geophysicists call an earth where the susceptibility does not vary with depth) the instrument must, by definition, read the same in both modes of operation and this is exactly what happens. When situated on a uniform half-space the instrument correctly reads the half-space susceptibility with the instrument in either VD or HD mode. The only difference is that in the VD mode the instrument will numerically read $+\kappa$ and in the HD mode, $-\kappa$.

Indeed, the converse is true. If the instrument reading does not change numerically (apart from the above mentioned change of sign) when the instrument is shifted from the vertical dipole to the horizontal dipole position, the operators know that they are situated at a spot where the susceptibility does not vary with depth down to the penetration depth of the instrument (about 0.5 meters), an important piece of information.

What happens if the earth is vertically layered? Can we use the two pieces of information (the readings in both the vertical and horizontal dipole modes) to identify this case?



Since we have only two pieces of information we can deal only with an assumed two-layered earth. It will be either Case (I) where the upper layer has κ=0 and the lower layer, at depth z, has susceptibility κ, or Case (II) which is the converse, upper layer of susceptibility κ and lower layer at depth z=t, with κ=0.

Suppose, for example, that our surveyor is walking down the survey line, having started at a location where he/she knows that the ground was homogeneous with depth (having made measurements in both the vertical and horizontal dipole modes and measured the same susceptibility κ in both modes). Further down the line, however, the apparent (measured) susceptibility has decreased to κ/2. Does this mean that (a) there is now material with κ=0 overlying the original material, or (b) that the thickness of the original material has now decreased, and there is material of κ=0 beneath it, or (c) neither of the above, the material is still uniform with depth but the susceptibility has decreased to κ/2? It turns out to be a simple matter to resolve this issue and the procedure is described in the Appendix 2. Naturally the procedure works well only if the susceptibility structure in the ground reasonably resembles a two-layered earth as shown in the figure.

We will not deal with it further in this Technical Note, but it is another useful characteristic of the depth response of inductive conductivity-susceptibility meters that simple calculations allow the response to be calculated in either mode for any layered earth model. Thus although the instruments may not be able to resolve a multi-layered earth it is often useful to be able to model the resulting apparent susceptibility as layer thicknesses and susceptibilities are changed to learn whether these changes will even be perceptible in the survey data.

A problem with both gradient magnetometers and inductive conductivity/susceptibility meters is that both measure very small changes in a larger quantity (the earth's magnetic field and the transmitter primary magnetic field, respectively). This makes them sensitive to changes in the equipment temperature, which in turn alters the equipment zero setting. The EM38B incorporates sensitive drift elimination circuitry to eliminate thermal drift. Furthermore if the EM38B is elevated to a height of about 1 ½ meters above the earth in the horizontal dipole mode, these calculations show that the instrument reading will be less than 3% of the value that would be read with the instrument on the surface over the corresponding homogeneous half-space, less if it is a layered earth. Thus, if temperature drift is a problem, at the beginning and end of each line the operator should simply raise the instrument as described and let the logger continue to record for a few seconds.

For even greater accuracy in setting or obtaining the correct zero level, at the end of the line the instrument can be held at a height of 1 ½ meters, first in the vertical dipole mode, recording the data, then in the horizontal dipole mode, recording the data. It can be shown that in virtually all cases the first reading will be twice the second, from which the correct zero level can then be calculated. The DAT38BW program offers a simple procedure for removing linear drift.

Having explored the various factors that control the spatial response of the EM38B we turn to the question of typical values for normal (i.e. unenhanced) soil susceptibility? Fifty years ago Cook & Carts (1962) measured the magnetic properties of the upper 25 cm of soil samples collected from 250 sites scattered across the United States and Panama (to include both temperate and tropical climatic zones). They found (after converting their data to the more modern SI units of susceptibility) that susceptibility values ranged from a low of less than 0.01 ppt to 10 ppt, with the majority of forest, plains, and desert soils between 0.01 ppt and 0.30 ppt. The noise level of the EM38B is of the order of 0.02 ppt and the maximum signal level is 100 ppt, so typical values for unenhanced soils fall nicely within the instrumental range, particularly when we remember that an archaeological survey will often be looking for enhanced values of soil susceptibility.

Finally and importantly, in Section 2 above it was mentioned that soils with very small iron oxide mineral grains often display a frequency or relaxation effect. This effect is quite evident in surveys carried out with inductive conductivity-susceptibility instruments which measure both the inphase (susceptibility) response and the quadrature phase (conductivity) phase response of the earth. Specifically, when traversing a susceptibility anomaly (for example, as was shown on a susceptibility profile), the parallel conductivity profile (which normally responds only to the ground conductivity, normally quite different than the susceptibility) sometimes also shows an additional anomaly component whose profile shape is clearly related to the susceptibility, but whose profile is the mirror image of the associated inphase susceptibility profile. Examples of this quite common effect will be shown in the case histories in Section 4.

It is hoped that as more is learned about the relationship of this relaxation effect to the sources of other soil magnetic properties it will have important interpretational value.

The discussion to date has focused entirely on the use of the EM38B for surface surveys, but it should be noted that the instrument can also be used to determine the behavior of susceptibility with depth in existing archaeological trenches simply by holding the instrument against the trench wall and observing or recording the apparent susceptibility as the instrument is slowly shifted down the wall face.

3. Why Use Inductive Conductivity-Susceptibility Meters to Measure Terrain Susceptibility?

(b) Summary of Conductivity-Susceptibility Meter Advantages

The only real competition to the inductive conductivity-susceptibility meters is the gradient magnetometer, so of necessity this section will be a comparison of these two instrument techniques.

The magnetometer measures changes in the essentially uniform earth's magnetic field to measure changes in terrain susceptibility. On the other hand conductivity-susceptibility meters directly measure changes in susceptibility by moving both transmitter and receiver to accomplish this, so are better indicators of anomaly shape. This is an important difference; it means that there is more, often useful, information in the profiles. Unlike the magnetometer, the conductivity-susceptibility meter is sensitive to thin horizontal layers of susceptible material so is easily able to detect such material that may exist between or surrounding more other anomalies, thus yielding structural information that is otherwise lost. Since the response for horizontal thin sheets is proportional to the square of the sheet thickness it is a sensitive measurer of this parameter, information that is not available to the magnetometer.

As seen from the sphere profile plots, the conductivity-susceptibility meter yields depth information about localized targets directly.

The conductivity-susceptibility meters also respond to thick horizontal layers, and by measuring in both the vertical and horizontal modes useful information as to layer thickness and/or depth can be obtained.

The response shapes from the conductivity-susceptibility meters do not depend on the angle of incidence of the earth's magnetic field, so are independent of the measurement location on the earth's surface. Since the response from these devices measures only the induced component of terrain magnetism they can often be used in situations where the magnetometer response would be dominated by remanent magnetism.

By measuring both inphase and quadrature phase responses, inductive conductivity-susceptibility meters respond to both ferrous and non ferrous metals: the fact that they measure both responses greatly improves the chance of identifying the source and nature of metallic responses.

Moreover since they measure the terrain conductivity as well as susceptibility, a completely different type of information is made available. For example, in previous surveys done in archaeological areas the conductivity data has shown the location of deeper plastic irrigation pipes by the conductive plumes associated with water flow.

And it is, of course, the conductivity channel which shows the magnetic relaxation effect described in section 2 above, which may turn out to be an important diagnostic tool and which is hidden to the magnetometer.

With a depth of exploration ideally suited to many archaeological sites, a dynamic measurement range well suited to typical values of soil susceptibility (both normal and enhanced), and versatile interpretation programs the EM38B is a very useful archaeological tool.

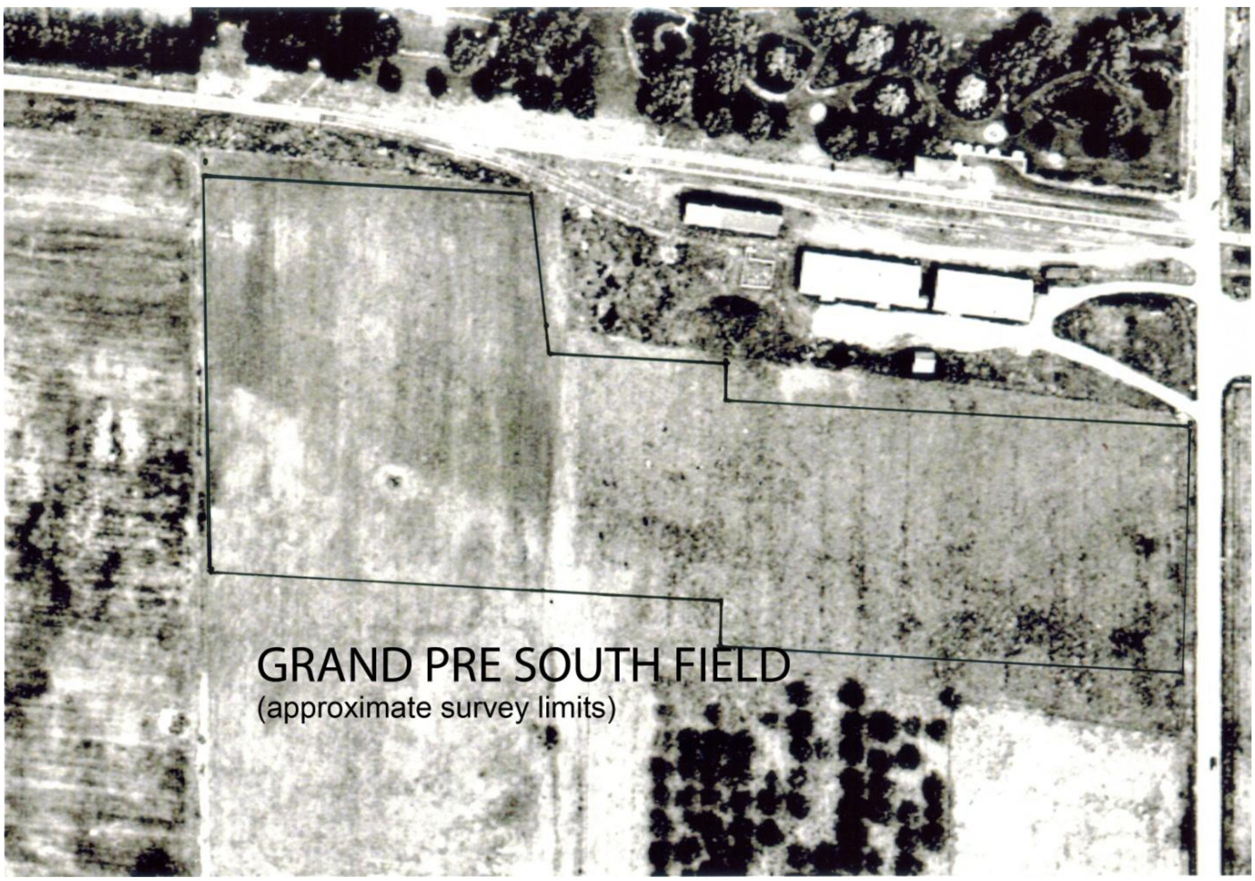
Most important is simplicity of operation and ease of data interpretation. If in doubt as to whether geophysics will help solve an archaeological problem, try the EM38B. A small survey with a few survey lines over a test site, followed by a quick download of the data and examination of the data profiles will quickly confirm whether the system will be of use.

4. Case Histories

In this section we give several case-histories of EM38B surveys taken in the Maritime Provinces over the past ten years. All surveys are plotted with north at the top of the sheet.

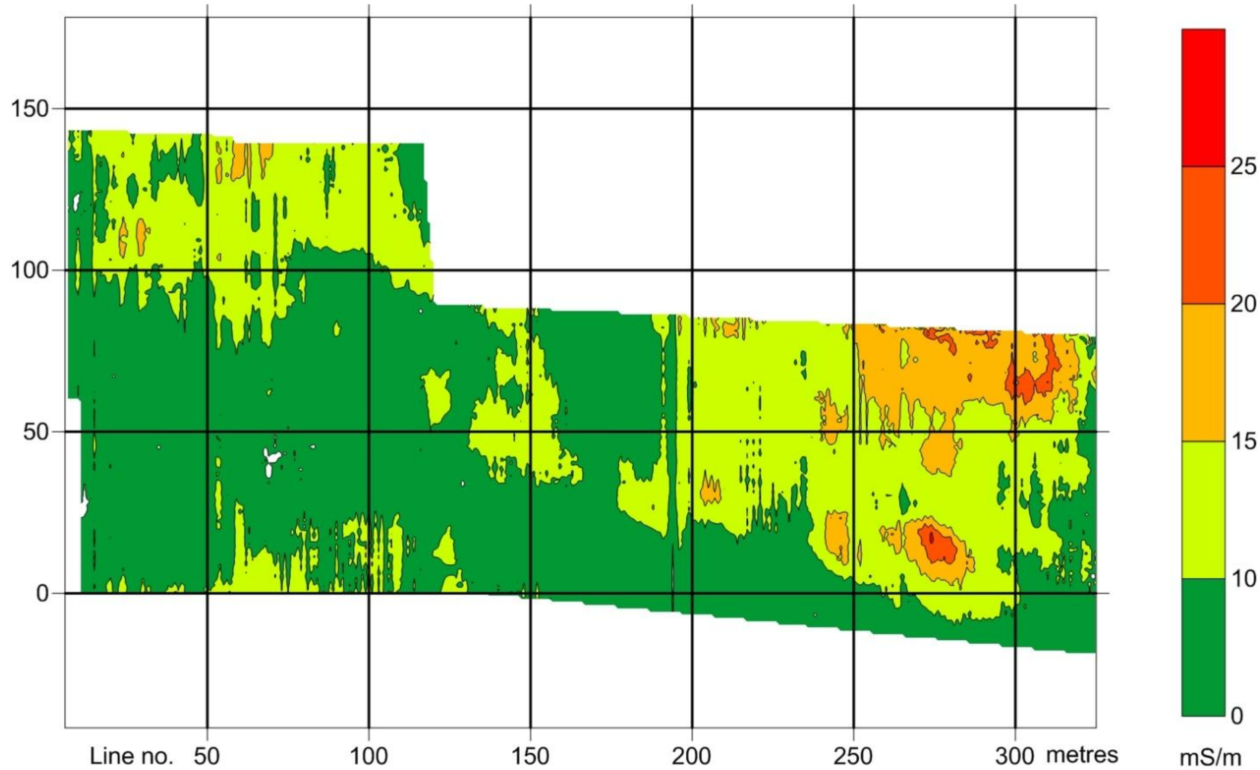
(a) South Field, Grand Pré, Nova Scotia

An airphoto of this site is shown below. This survey was carried out for Parks Canada, who wished to avoid intrusion into archaeologically potentially sensitive ground as they constructed a new visitor centre for Grand Pré.

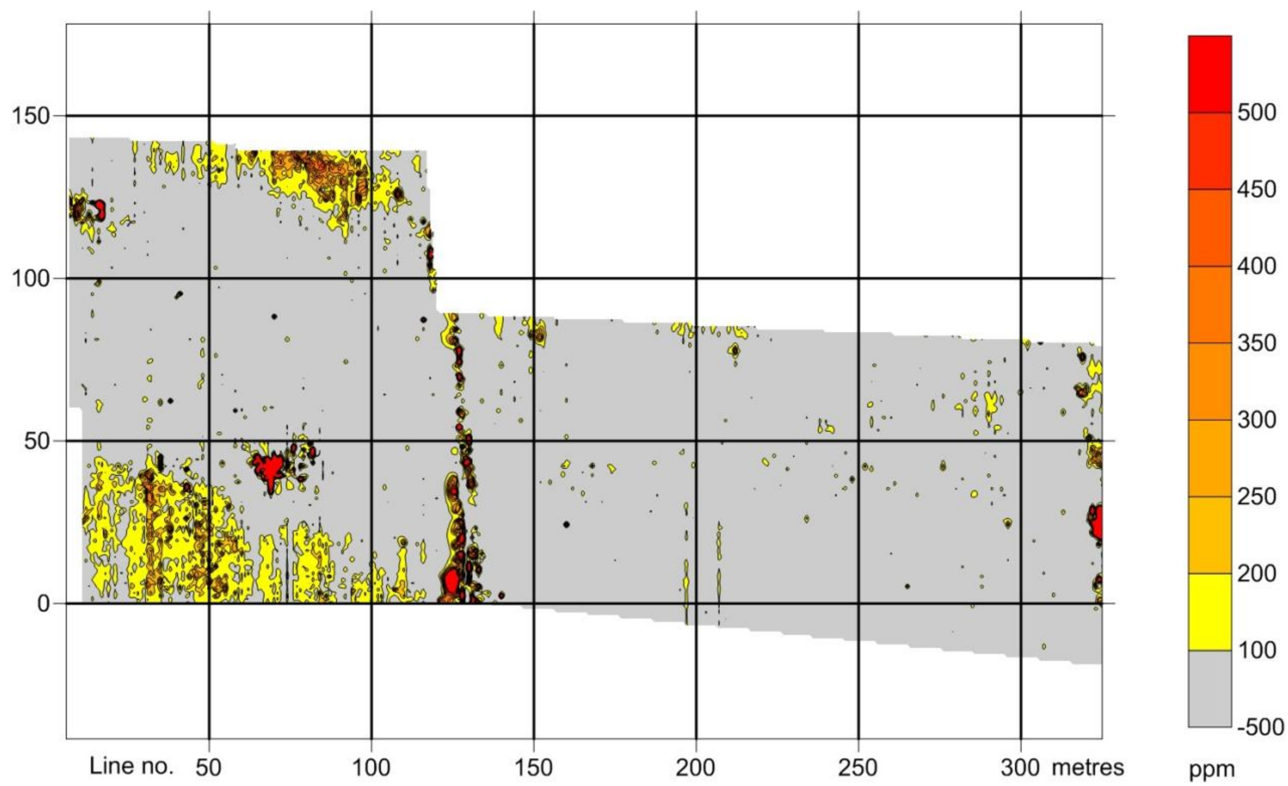


The portion of the survey area to the south-east is a ridge, gently rising to the south and underlain by the Carboniferous Horton formation,. The area to the north, underlain by Triassic Wolfville formation, is flat-lying and forms the floor of the Annapolis Basin.

The first figure below shows contours of the electrical conductivity in millisiemens/meter, the second figure the magnetic susceptibility in ppm. Both parameters were measured simultaneously by the EM38B, using an interline spacing of 1 meter.



GRAND PRE SOUTH FIELD: CONDUCTIVITY



GRAND PRE SOUTH FIELD: SUSCEPTIBILITY

The electrical conductivity is basically a function of soil moisture content (the more moisture the higher the soil conductivity), the electrical conductivity of this moisture, and of the soil clay content and type. As the first plot shows, the drainage generally increases from south to north, with the moisture content becoming quite high to the east. The pattern is reflecting the topography and there seems to be nothing of archaeological interest in this plot.

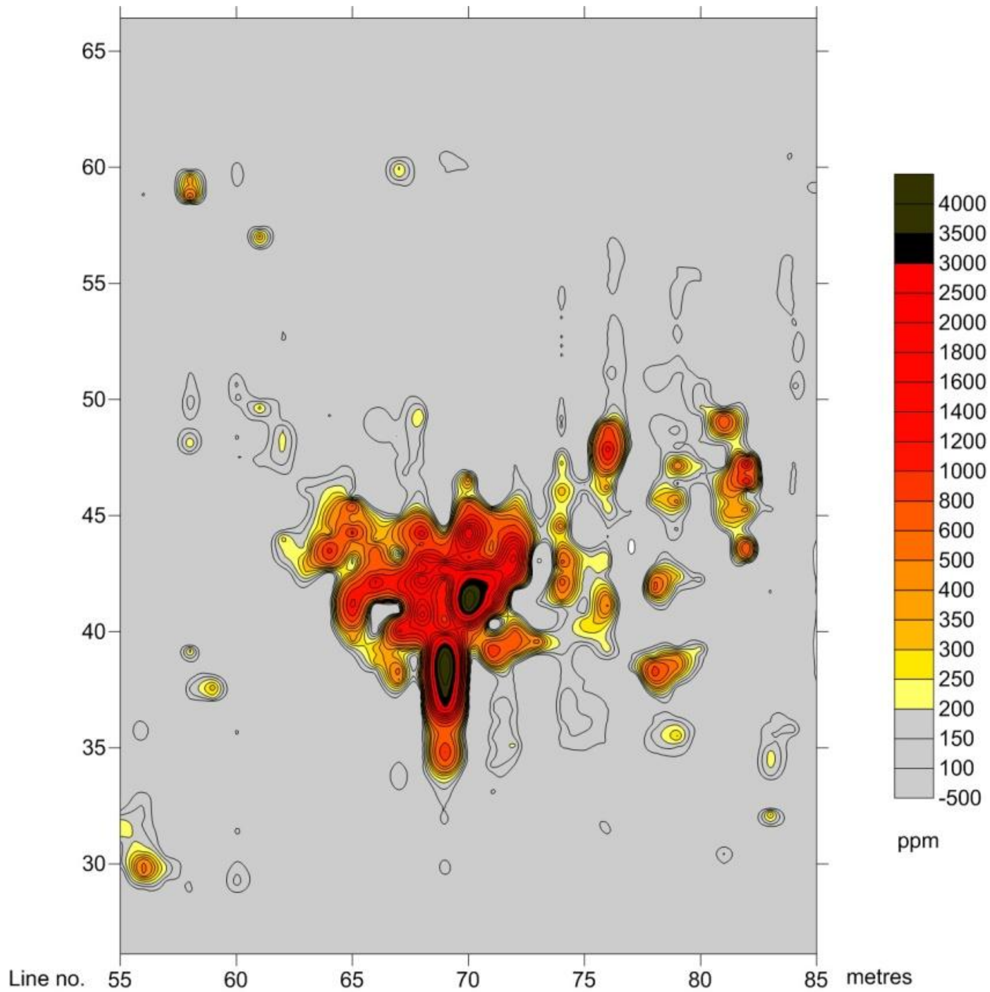
As we have seen, the magnetic volume susceptibility can reflect a variety of material properties. These include the nature of the bedrock (for example mafic rocks such as basalt), the occurrence of mineralization in sedimentary rocks, the nearly always present magnetite or maghemite in the surface soil, the effects of agricultural working of the soil (both mechanical such as plowing, and chemical such as the conversion of non-magnetic oxides to a magnetic form), burning of the soil, mineralization in the clay content of the soil, the presence of buried metal (either ferrous or non-ferrous) etc. etc. Of particular interest for this site is the fact that the Grand Pré region lay glacially downstream of the North Mountain basalts with the result that an abundance of good quality (and, happily for the archaeologists, high magnetic susceptibility) building stone could be obtained conveniently.

We see, then, that there are good reasons why susceptibility maps generally show little or no resemblance to conductivity maps although sometimes a given cause can affect both sets of responses. Like soil conductivity, the survey response from magnetic susceptibility is not unique, and like conductivity we must rely on the morphological shape of survey anomalies (as shown in the profiles and contours) to infer the cause of the anomaly.

The biggest surprise of this survey was that such a large area, so closely located to where history places the Parish Church of St. Charles-des-Mines, had so few responses that might be caused by dwellings. In fact, there are only two such responses; both of these show up very clearly on the survey, so one can be optimistic that there are no more (at least of the amplitudes of these two). This low concentration of dwellings tends to confirm historical records that the Acadian houses were far apart rather than clustered together.

The main features of probable archaeological interest shown on the contours, then, are the four high susceptibility anomalies centred at (x=15, y=120), at (x=70, y=40), at (x=325, y=25) and distributed along line126. The first two of these anomalies (and perhaps the third) are probably old building sites, suspected to be of Acadian origin. The last, long anomaly has been conjectured to be associated with an old Acadian road leading north to the Grand Pré (Great Meadow).

We focus our attention first on anomaly (x=70, y=40, which also shows up on the air photo) and is shown in more detail on the next page. This plot demonstrates that the choice for a colour bar that has been optimized for the original large survey area may need to be redefined for detailed examination of any specific anomalous region. The complexity of this particular site is now clearly demonstrated. Of particular interest is the small but strong anomaly at the south end of the main anomalous region.



GRAND PRE SOUTH FIELD: SUSCEPTIBILITY
DETAILS OF LINES 55-85

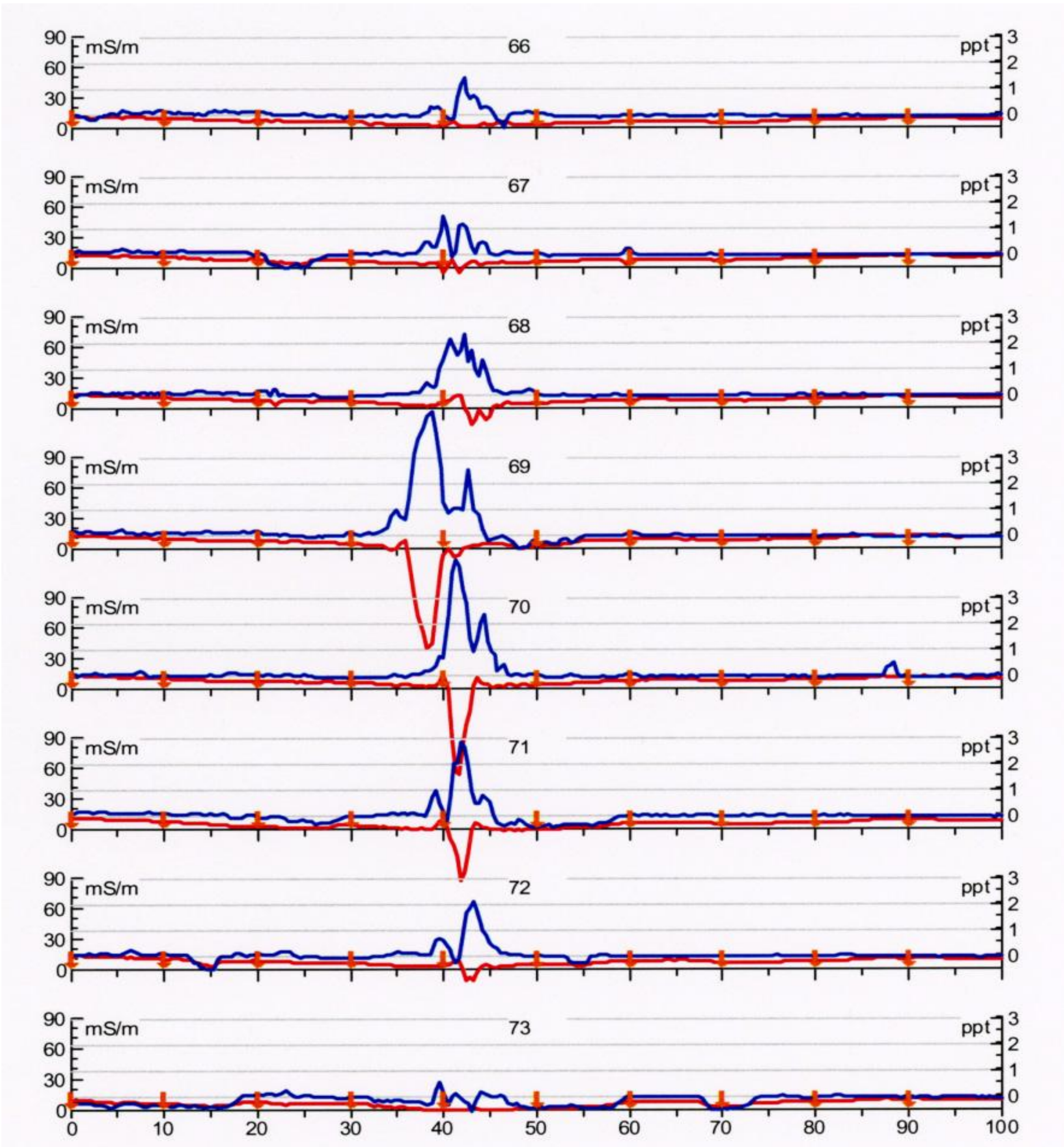
Is there more information to be derived from the profiles? The next page shows profiles from survey lines 66 to 73 taken directly from the DAT38BW program.

The blue profiles are those of magnetic susceptibility. The scale bar is on the right, and unlike the colour bar for the susceptibility contours, which were in units of ppm, this scale bar is in units of ppt, which are of course easily converted using ppt=ppm/1000.

The red profiles are those of electrical conductivity. The scale bar is on the left and is still in millisiemens per meter. Note that all of the conductivity profiles have been equally shifted vertically downwards to place them near the susceptibility profiles to facilitate comparison with the susceptibility profiles for reasons that we will see.

The horizontal scale bar is in meters, as for all of the surveys in this Technical Note.

And finally, the choice of 90 mS/m and 3 ppt for the two scale bars has been chosen to make the inphase and quadrature phase scales physically equal to each other so they are directly comparable (remember that the conductivity too is measured in ppt and then converted numerically to conductivity).



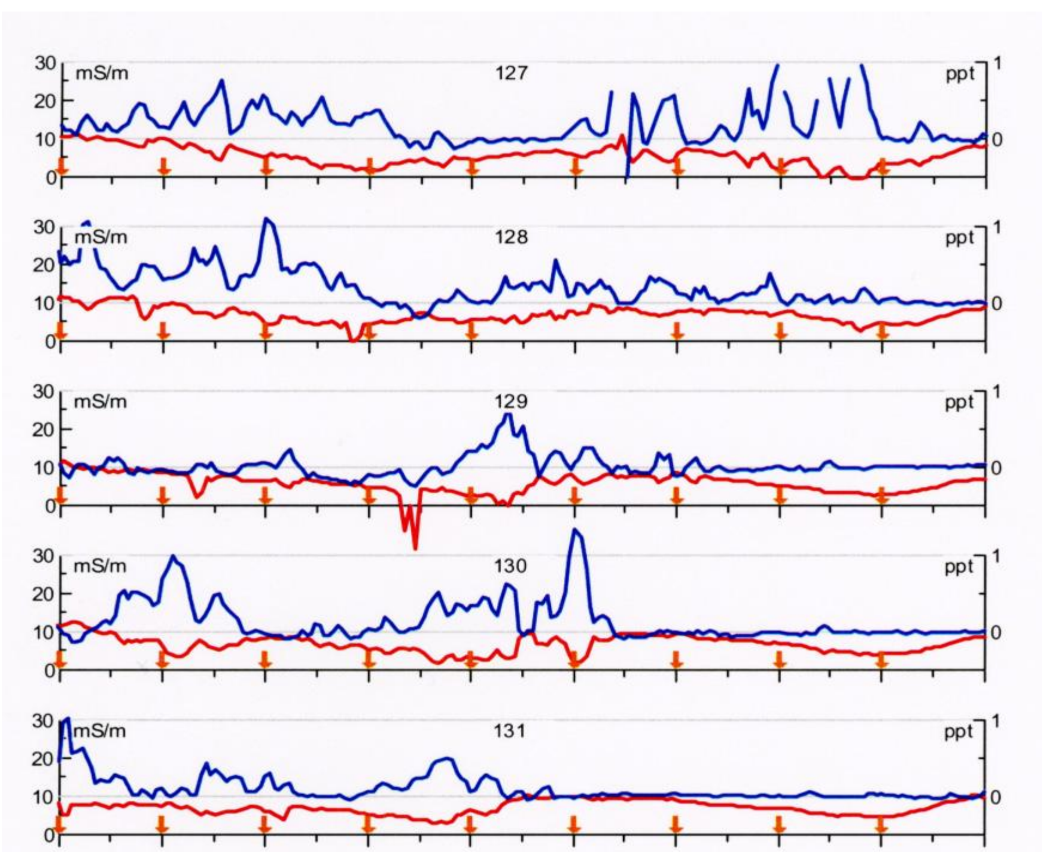
The first thing to note is that the anomaly amplitudes are much larger than the background fluctuations in both susceptibility and conductivity (the geological signal-to-noise ratio is excellent). The next thing is the complexity of the profiles, and the how quickly their shape changes both down the lines and from line to line (i.e. over a lateral distance of one meter).

Also to be noticed is the different but often related behavior of the inphase and quadrature phase responses. For example on line 69 at station 37 there is a very large susceptibility (inphase) peak, associated with which is an almost equally large negative quadrature peak. This is an excellent example of the relaxation phenomena referred to in Section 2 above, and indicates that, at this location, the susceptibility response is having a hard time responding to the sinusoidal variations in the primary magnetic field. Recall that this effect is caused by the causative iron oxide mineral grains being of very small size. Moving just a short distance down the line to station 42 we see that the susceptibility anomaly amplitude has decreased somewhat whereas the quadrature phase anomaly has virtually disappeared. The relaxation effect has disappeared.

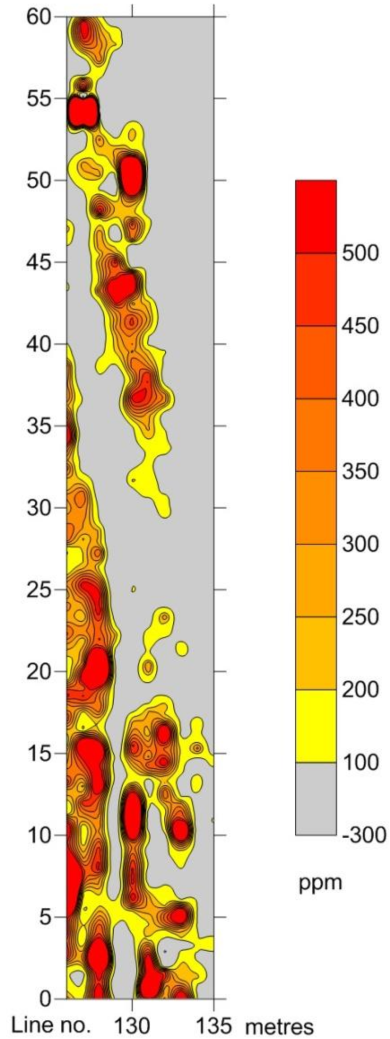
We note that most anomaly widths are equal to or greater than 1 meter and thus probably at depths of a few tenths of a meter or greater, although there is evidence of 'near-surface chatter' on line 68 between stations 40-45.

The figure below shows profiles for lines 127 to 131 at a more sensitive scale. Clearly shown is that the conductivity (quadrature phase) response varies slowly along the line; superimposed on it are the relaxation responses with different 'quadrature phase/inphase response' ratios at different locations. In this example the ratios are relatively constant at quadrature phase/inphase ratio ~1/4 but we will see in other surveys that they often vary more than this.

The above profiles have been shown at reduced sensitivity to keep the anomaly amplitudes on scale. Normal profile examination is carried out at a full scale deflection of 1 ppt or less, as shown below. Many more, smaller anomalies show up at this scale of course, and there is often a distinct correlation between the local inphase and quadrature phase anomaly responses as shown below for lines 127-131.



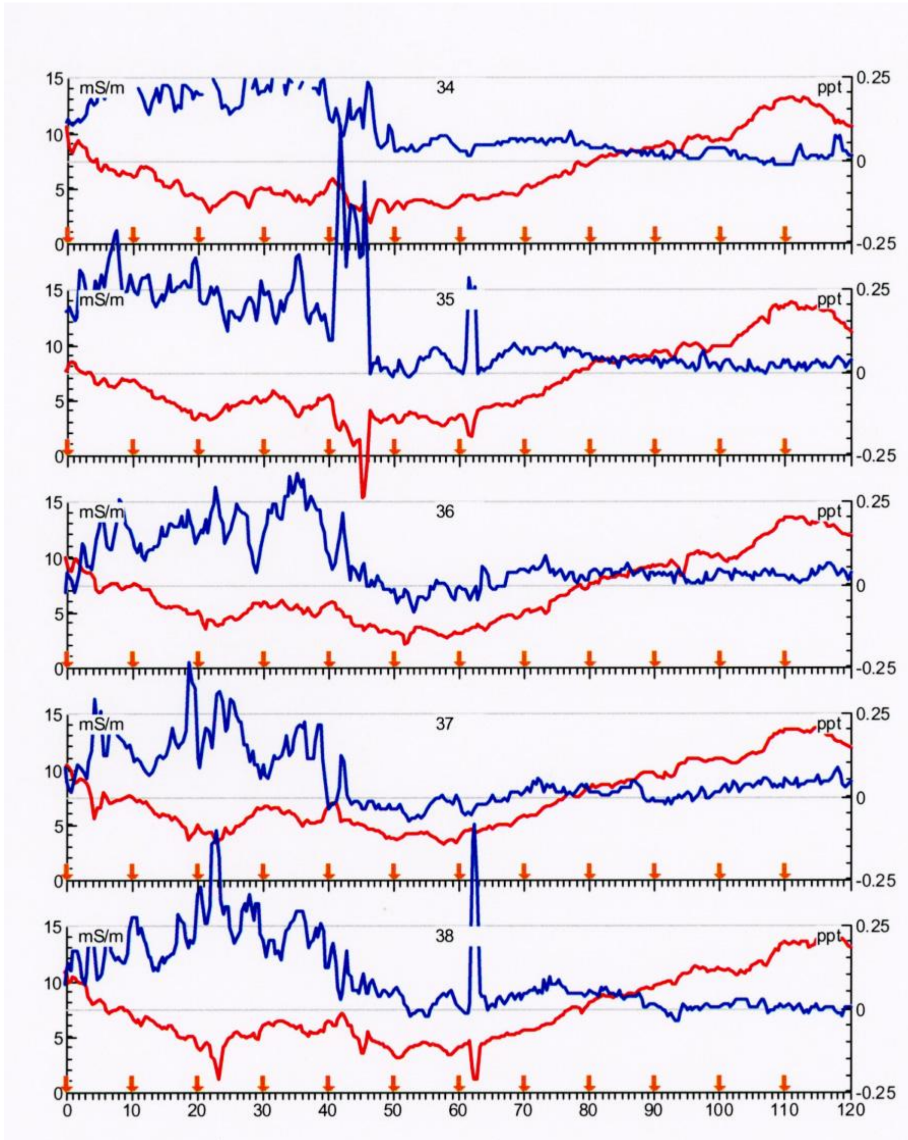
The contours for this area are shown below.



GRAND PRE SOUTH FIELD: SUSCEPTIBILITY
DETAILS OF LINES 126-135

As mentioned above it has been conjectured that this is an old Acadian road leading to the Grand Pré. The contour details illustrate the spatial resolution that is achieved with EM38B. As is well known to geophysicists the world over the worst orientation for a survey feature is one that is long and thin and is parallel to the survey lines since such a feature challenges both the accuracy of the survey grid and the spatial resolution of the survey instrument. The fact that the EM38B has a resolution of about 1 meter is well illustrated by these contours.

Finally, profiles for the diffuse geological feature at the south-east end of the survey area, the nature of which is not understood, are shown below for a 120 meter length of lines 34 to38.

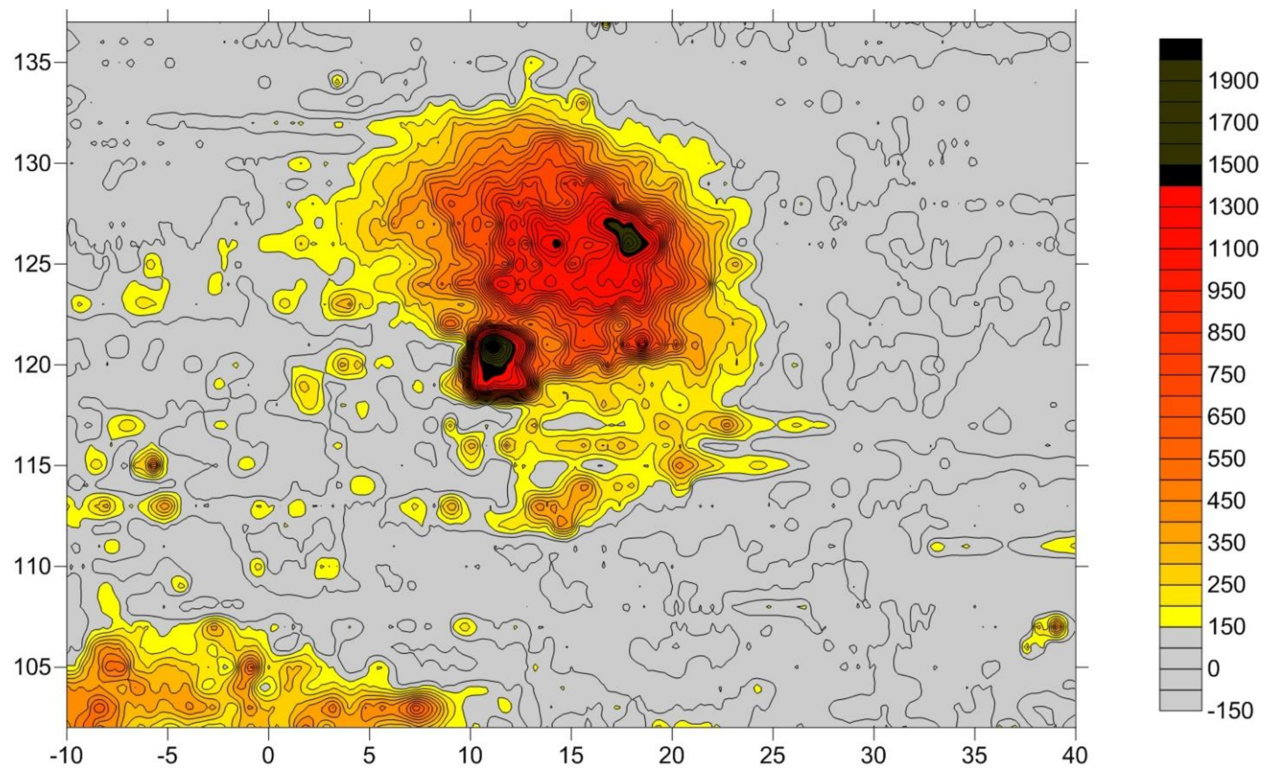


The feature of interest here is the behavior of the 'high-frequency chatter' on the susceptibility profile for the first 50 meters or so, superimposed on a more slowly spatially varying susceptibility component. As discussed in Section 2 this chatter (with a component of about 1 meter in length) will be caused by very near-surface variations in the susceptibility as each of the two coils, spaced 1 meter apart) goes past a given location. It is surmised that the bedrock is very near surface and that the instrument is sensing small fractures in the near-surface bedrock.

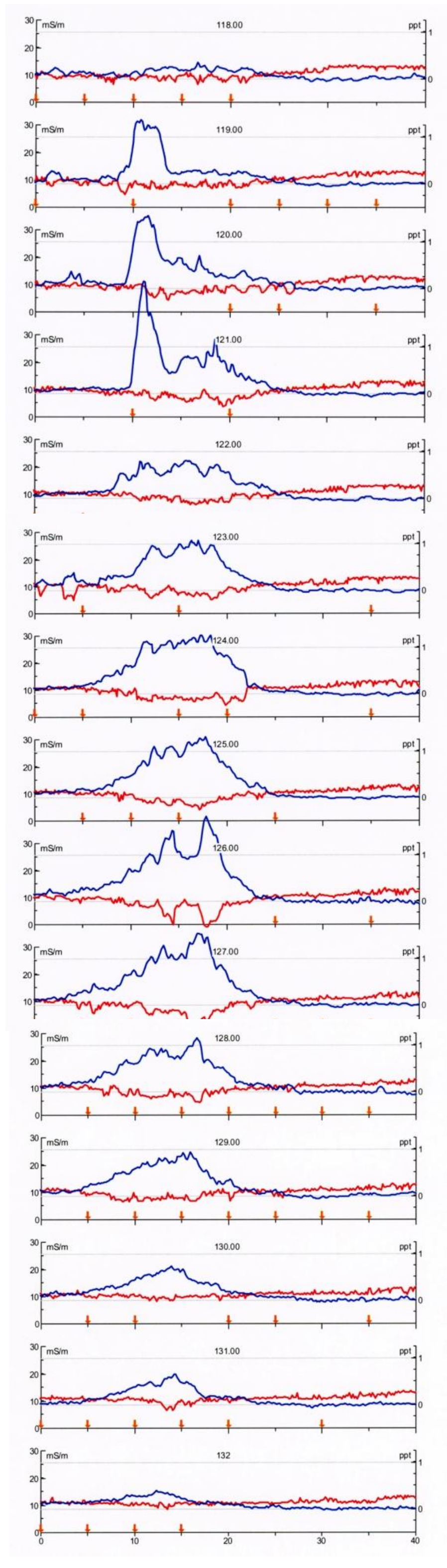
(b) Area 8B52, South Field, Grand Pré, Nova Scotia

Contours for a more recent survey, also in the South Field of the previous survey but further west, are shown below. Once again the interline survey distance was 1 meter but this time the lines were in an E/W direction.

The main anomalous region can be divided into two parts. The southernmost part is essentially rectangular in shape, 2 by 2 meters in size, with well-defined boundaries and very high susceptibility amplitude (over 1500 ppm). The northernmost part is much larger, of the order of 10 by 10 meters in size, with less well-defined boundaries but still showing high susceptibility amplitudes of the order of 1000 ppm. This part incorporates a small amount of internal structure but the most significant feature is the large, spatially slowly varying high-susceptibility signature.



The great detail shown by the contours is evident, as is the detail of the underlying profiles shown on the next page. Note the extremely high geological signal-to-noise ration in these profiles. Unlike the earlier South Field survey profiles, the profile data from this site shows only a very small but unmistakable quadrature phase component compared with the inphase response.


118.00
119.00
120.00
121.00
122.00
123.00
124.00
125.00
126.00
127.00
128.00
129.00
130.00
131.00
132
mS/m
ppt

Duggan (2011) reports that the two parts of the anomaly have been partially excavated to test the results of the magnetic susceptibility survey. A 2½ by 4 meter trench (long axis E/W) was located on the top half of the southern anomaly and a nearby 1 by 4 meter trench (long axis N/S) sampled the south edge of the diffuse anomaly.

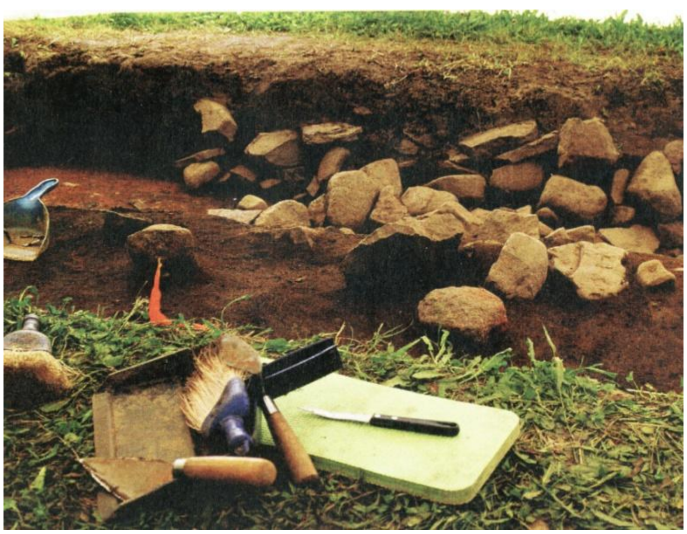
The E/W trench revealed some (but relatively few) cultural artifacts indicating (Acadian) occupation dating back to early 18th century but no evidence of later (post 1770 Planter) occupation. There were significant indications of internal structure such as trenches and a buried, thick clay layer, and as well, as a large scattering of boulders (presumed to be from later agricultural clearing of field stone) with a significant basaltic component. The N/S trench also revealed some cultural artifacts indicating (Acadian) occupation.

Most surprising, however, were a very large number (over five hundred) pieces of metallic slag (typically quasi-cylindrical, of size a few cm long) and scrap iron fragments scattered throughout both excavations. More specifically, those in the N/S trench showed an increasing concentration to the north.

These artifacts were tested with the EM38B and to no one's surprise gave significant inphase response (with very little quadrature phase response). Likewise, testing of the in-situ basalt boulders with the EM38B also showed good inphase and no quadrature phase response. However, similar testing of a large pile (about a cubic meter) of carefully filtered excavation detritus also showed very high susceptibility response, again of the order of 1000 ppm.

The susceptibility contours show that background levels of susceptibility in the area surrounding the anomaly were generally less than 150 ppm. That fact, and the fact that there was a good deal of charcoal, occurring both as flecks and chunks, in the smaller excavation strongly suggests that the site had been subjected to burning.

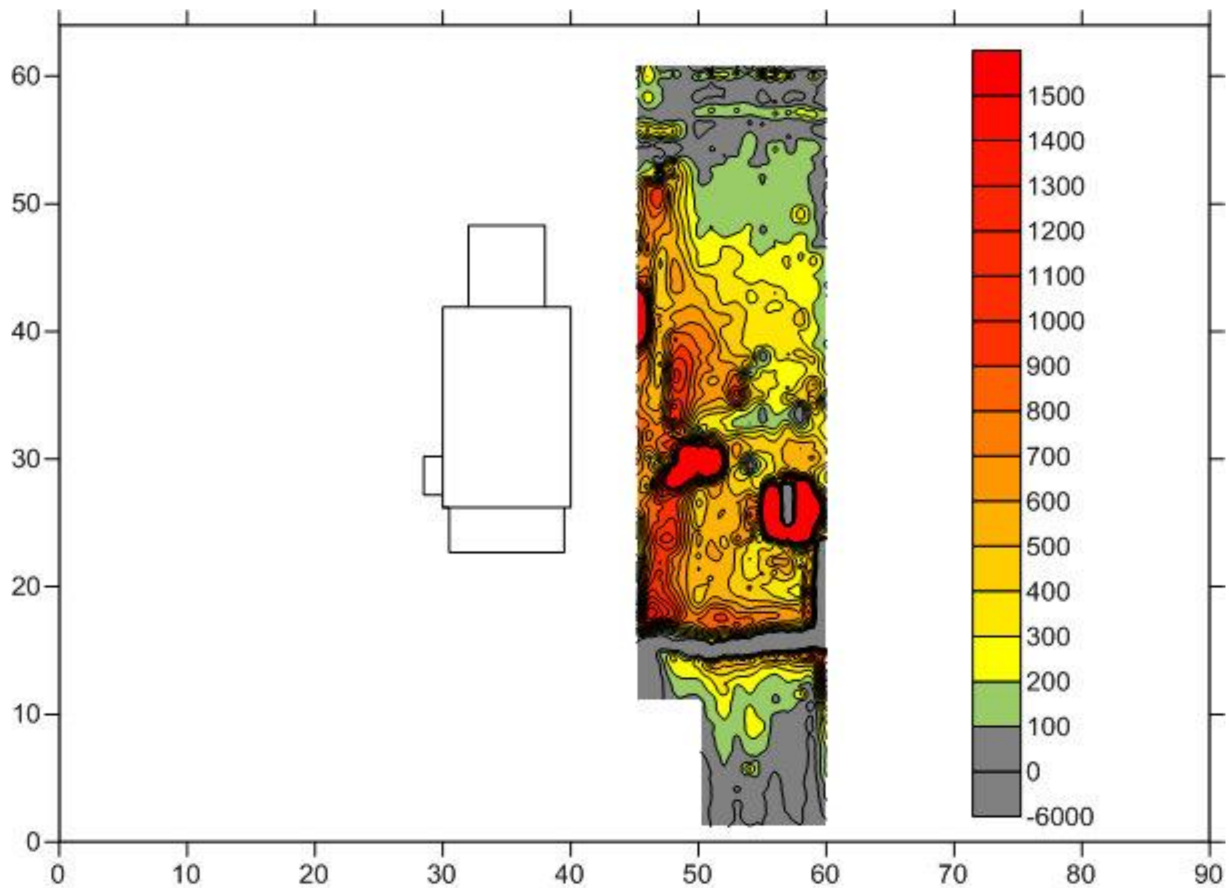
The conclusion is reached that the 8B52 site susceptibility anomaly can be attributed in part to the presence of near-surface basalt boulders, in part to the extensive scattered slag and iron fragments, and in major part to extensive burning of the whole area.



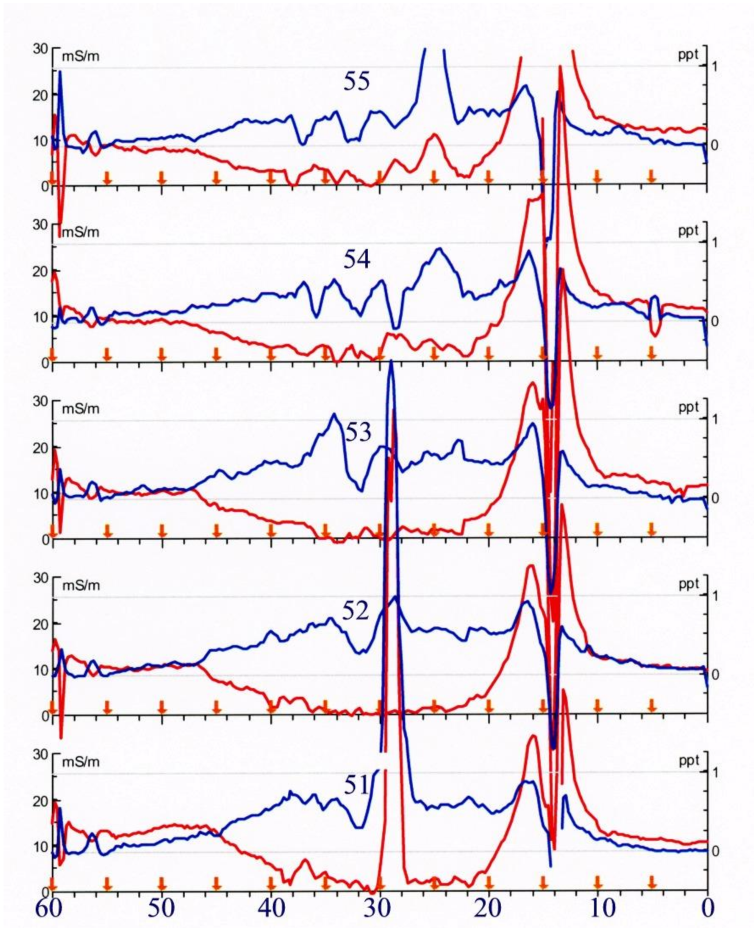
(c) Memorial Church, Grand Pré, Nova Scotia

The next case-history comes from a series of geophysical surveys attempting to locate the foundations of the Acadian Parish Church of St. Charles-des-Mines, in which 418 males were incarcerated prior to the expulsion of the Acadian population of Grand Pré in 1755 (McNeill, 2012).

The figure below shows the outline of the modern Memorial Church and, to the right, contours of susceptibility resulting from a survey of 15 north/south lines, spaced 1 meter apart. There are many metal pipes crossing this region and their effect is obvious in the figure. Basically visible, however, is a broad, E/W trending susceptibility anomaly (yellow contours) of width about 35 meters in the N/S direction. Having over the years surveyed the entire Park and found no other anomalies of this type my conclusion is that, if the Parish Church was located in what is now the Park area, there is a reasonably good chance that this anomaly is related to the foundations of the Parish Church, which is reported to have been burnt to the ground following deportation of the Acadian population.

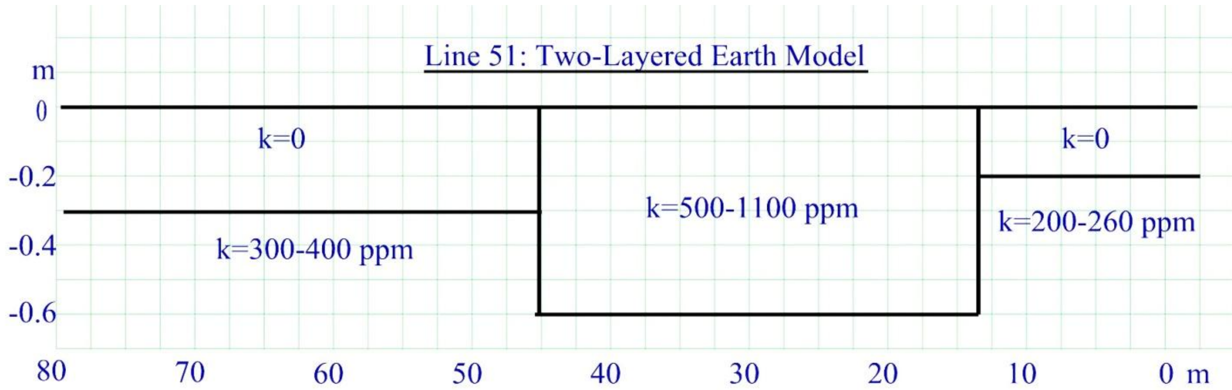


The next figure shows the profiles for lines 51-55.



The pipe responses appear at station 14 for all lines, and at station 25 for line 55. In addition, unfortunately some metal appears to have been left on the surface in the survey area at station 29 for lines 51 and 52 (it's not there now). Ignoring these responses we see the broad susceptibility anomaly referred to above extending from stations 10 to 45. We also note that, as seen in earlier surveys, an equally broad negative quadrature response reflects the susceptibility (inphase) response, and furthermore that in this case the ratio of quadrature/inphase response is about one; the negative quadrature phase response is essentially of the same amplitude as the inphase response. This is a large relaxation effect, about the largest that we have seen in surveys in the entire Grand Pré area.

In Section 2 and Appendix 2 we described a technique in which measurements made along a survey line in both the vertical dipole and horizontal dipole modes could be inverted to give a two-layer model for the underlying susceptibility. Such a series of measurements was made at 5 meter intervals along line 51 from stations 0 to 60 (and continued to station 80 to get a better idea of the constancy of the off-anomaly readings). The results of the inversion are shown below.



The two-layered model actually fit the data reasonably well. For both regions at the north and south ends of the survey the depths to a susceptible homogeneous half-space were as shown and the values of the homogeneous half-space were consistent at the values shown. The anomalous central region (modeled as a thick sheet) was more variable in both depth (average of 0.6 meters) and susceptibility. Not shown on the plot is the fact that there was no data for 10 meters in the central anomalous region due to a (successful) archaeological excavation.

Whilst a two-layered earth model is definitely an oversimplification of reality it does give a bit more insight into approximate behavior of the susceptibility beneath the surface.

(d) Oudy Farm, Greenwich, Prince Edward Island National Park

In 1720, the Compagnie d l'Isle Saint-Jean established the first European settlements on Isle Saint-Jean (now Prince Edward Island/PEI) at Port la Joye and Havre Saint-Pierre (now Greenwich).

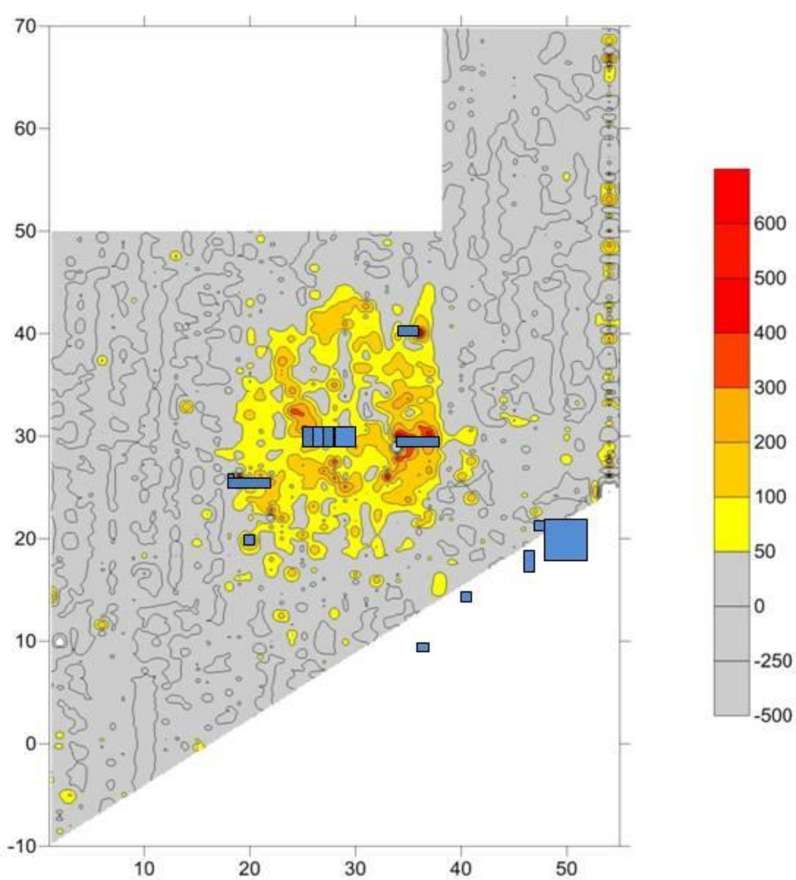
A census of the area in 1752 lists seven families on the north side of the bay, within the survey area. A map by Thomas Wright, 1765, shows nine houses along the shore, with farm fields stretching inland. By the end of 1758, these families had been deported from the island by its new claimants, the British.

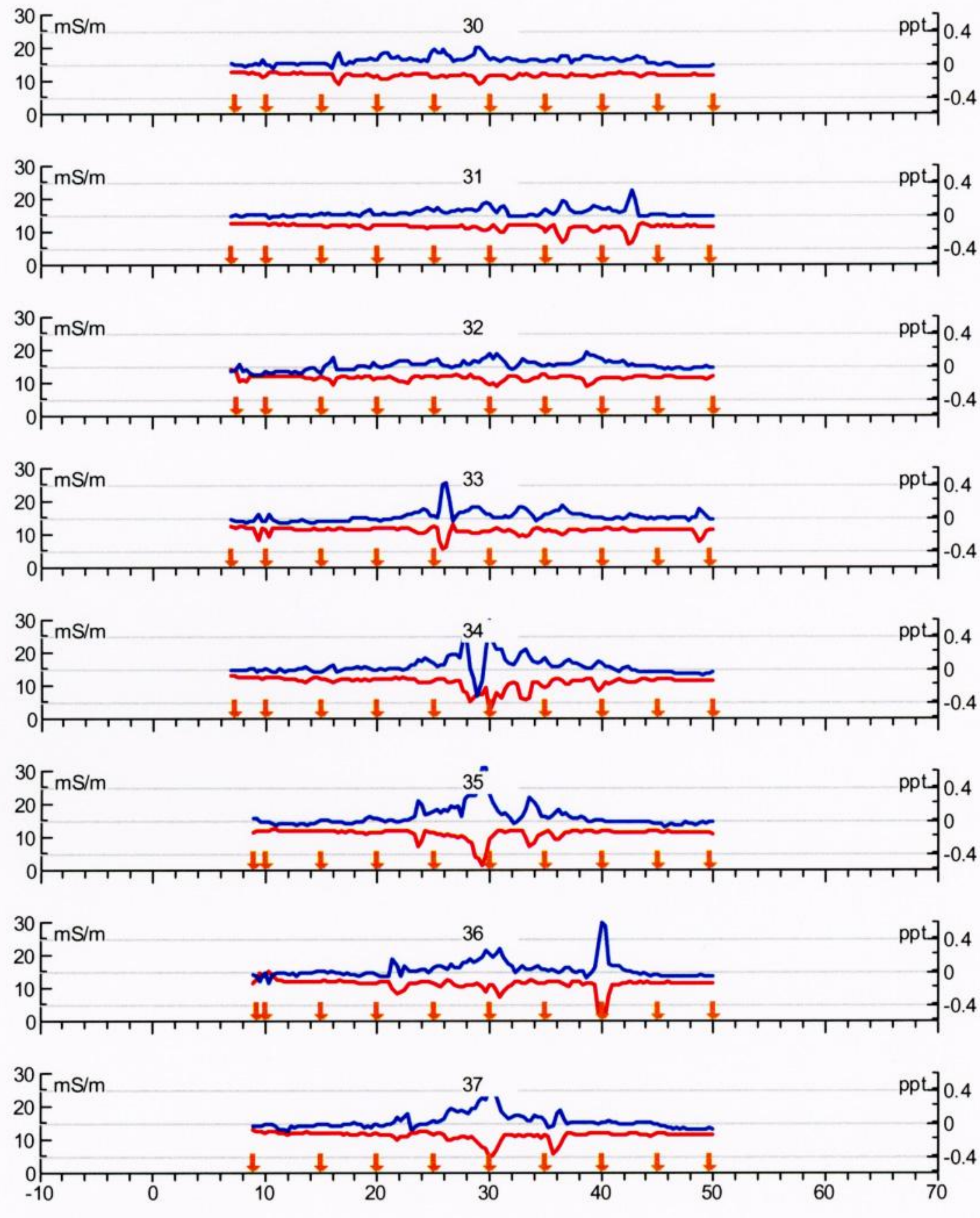
To inventory the site, a geophysical survey with the EM-38B (with one meter interline spacing) was undertaken between 2000 and 2006. This large survey covers a distance of 2.5 kilometers of shoreline, stretching inland from 50 to 100 meters.

A French farmstead likely included one or two wood-frame houses, a barn and/or byre, a small family garden plot and a well, within a fenced enclosure, with the agricultural fields beyond. Two hundred and fifty years of land use have removed all traces of the buildings.

Seven farm sites are suspected to lie within the area surveyed (one other lies on a rock ridge and the final one is within a densely overgrown rose briar, both west of the survey). Archaeological testing of susceptibility anomalies in 2000, 2004 and 2008 has verified four sites and suggests a probable fifth. .

The most dramatic results appeared in the first summer of surveys. A detailed picture of a farm site, named the Oudy Site after the family that settled most of the farms, was recorded. (The family emigrated from Beaubassin, in Acadia, to Havre Saint-Pierre some time prior to 1729, and continued to build their farms on the north shore until their forced removal in 1758.) Unlike the other farms located by anomalies, with varying degrees of clarity, this one is particularly detailed, even suggesting the fenced boundaries of the farmyard. We now know that this particular field was not ploughed by later farmers but must have been left in pasture. Its susceptibility response thus clearly reflects the French-period occupation. It indicates a broad, L-shaped anomaly, roughly 20 m E/W by 20 m N/S, within which are two large intense anomalies, and a smaller one. Just outside the presumed farmstead limits are a second smaller anomaly and a high point anomaly. The point anomaly was quickly determined to be two large pieces of a cast iron cooking pot, unassociated with any feature and perhaps tossed over the fence by a frustrated cook.





mS/m
ppt
30
31
32
33
34
35
36
37
0.4
0
-0.4
0
10
20
30
-10
0
10
20
30
40
50
60
70

The most intense anomaly (largest blue E/W rectangle) has been identified as the root cellar of a house. Virtually all excavated Acadian sites of this period exhibit a small cellar for food storage, usually 3-4 m square. Only a small section of the south edge has been exposed, revealing a pit excavated into the sandy subsoil. After the deportation of the Oudy family, the cellar began filling with wind-blown sands. Sometime in the 20th century, a mass of large boulders was dumped into the depression, doubtless to get rid of unwanted field stones from one of the ploughed fields. The discovery of partially charred framing timbers tossed into a well suggests that the British may have burned the dwelling after removing its occupants. (The well was discovered eroding from the shoreline and was just outside the survey lines.)

The second major anomaly, 4 m east of the cellar, results from the organic waste of a large midden, rich in animal bones, seeds, charcoal, and artifacts of iron, ceramics and glass. This is the domestic refuse of the family. Presumably the high organic content of the midden has created the oxidizing conditions for enhanced magnetic susceptibility.

A second, smaller midden was uncovered at the lesser anomaly southwest of the cellar. Again, a high organic content may have created the enhanced susceptibility. The other lesser anomaly, located just outside the apparent boundaries of the farmyard, is associated with a pile of small rocks, undoubtedly from clearing the adjacent field.

The Oudy Site is a rare example of an Acadian-period archaeological site undisturbed by later farming. As such, it is one of the most significant archaeological sites of the period, revealed by the EM-38B. Root cellars with period artifacts have been identified at three of the other farm sites, and period artifacts have been excavated at a fourth. The potential for future research into the island's French heritage is enormous.

Summary

Over the past decade the author has been directly involved in well over a dozen EM38B geophysical surveys in Eastern Canada, either as principal surveyor or in helping other archaeologists format and interpret their own survey data. In virtually every case these surveys have produced interesting and useful archaeological information about the sites. Why was this?

Firstly, in all of the survey areas, which were carried out in soils overlying a variety of different bedrock geologies, the all-important geological signal-to-noise ratio was excellent. We saw in Section 2 that Cook and Carts (1962) found that susceptibility for the majority of forest, plains, and desert soils varied between 0.01 and 0.3 ppt, which suggests that the random fluctuations in the susceptibility should generally be of the same magnitude. Under these conditions, with an instrumental random noise level of about 0.02 ppt the EM38B should be limited by the geological noise level, and this is precisely what we have usually seen.

Secondly, such a low geological noise level means that we should generally be able to detect anomalous areas that have susceptibilities in excess of about 0.2 ppt, and once again, this has been the case. Much of our contouring has started using brighter colours at 0.2 ppt.

Thirdly, and this has been quite a surprise (and pleasure), in the areas that we have surveyed, particularly those in the lowest geological noise areas, we have never encountered what looked like significant archaeological responses at levels below about 0.2 ppt, and indeed they have usually been substantially higher, and thus well resolved. Moreover, the signal levels of significant anomalies in all of the areas (with the exception of soils originating in areas of highly magnetic bedrock) are in the 0.3 to 1.5 ppt range and occasionally much greater.

What about more magnetically active areas? A survey done in soils near North Mountain with its basalt sheets showed noticeably higher geological noise levels of about 0.25 ppt (along with higher but easily differentiated signals from residual basalt boulders). Surveys done at Louisbourg show quite a variation and it is suspected that depth to the volcanic bedrock varies widely, becoming very near-surface in parts. Where this appears to be the case the geological noise levels can be up to 0.4 ppt but where bedrock appears to be deeper the noise reduces to about 0.2 ppt or less. So sometimes a problem, but usually not prohibitive (the main problem in this area is a serious lack of knowledge about subsurface conditions which will improve as more experience is gained).

Fourthly, the basaltic boulders, and the fact they were used for construction, was certainly fortuitous. It was a surprise how often one came across such boulder responses, even in Prince Edward Island, where the underlying geology is strictly sedimentary.

Fifthly, is the fact that soil susceptibility certainly appears to be enhanced by human occupation. Of the various forms that this influence might take, burning is almost certainly one of them, although we still do not have definitive proof from our surveys that this is the case. Where we know buildings have been burnt, there are strong anomalies. Moreover, in areas presumed to have been burnt, strong anomalies occur even when such areas have been heavily excavated and the soil seriously disturbed.

Unfortunately it may be true that the firebrands of the past have left a legacy for the geophysically-inclined archaeologists of today.

And last but not least, as shown in Section 3(b) above, conductivity-susceptibility meters such as the EM38B offer many other technical advantages, all of which come into play when the instruments are used for archaeological exploration.

Acknowledgements

I would like to thank Rob Ferguson, recently retired archaeologist with Parks Canada, for introducing me to the delights of archaeology combined with geophysics, for his continuing use of geophysics for archaeology in the Maritimes over the past two decades, and for supplying the write-up for the Oudy Farm. I would also like to thank Jonathan Fowler, Assistant Professor of Archaeology at St. Mary's University in Halifax for his enthusiasm, advice and ongoing support for the geophysical survey work at Grand Pré over the past decade. Last, but not least, I would like to thank my wife Sylvia who has assisted me in carrying out all of the many surveys, and who has done much, much more, as I poured over survey data.

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Appendix 1

The cause of the relaxation effects often seen in the measured EM38B terrain response was briefly described in Section 2, and the effects themselves are shown in several of the case-histories of Section 4. There, it was seen for example that, at a place where an isolated target might give a peak inphase (susceptibility) response of 1 ppt, it could, at the same place, give a corresponding negative quadrature (conductivity) response of -20 mS/m.

Briefly also referred to above was the fact that, for the EM38B, a conductivity reading of 30 mS/m was actually equivalent to a quadrature phase signal of 1 ppt. Thus when the chart scales on the profile plots from the DAT38BW programs are set to full scale deflection of 30 mS/m on the left hand scale and full scale deflection of 1 ppt on the right hand scale, both scales are in effect reading ppt and we can directly compare the amplitudes of the quadrature phase response (called Q) and the inphase response (called I). In the case above where the supposed conductivity reading was -20 mS/m (=-0.67 ppt) and the susceptibility reading was 1 ppt, the numerical ratio of Q/I is 0.67/1.00=0.67.

We give here a simple way of calculating the approximate time duration of the susceptibility response to a rapidly applied primary magnetic field, using the measured ratio of the quadrature phase (Q) response to the inphase (I) response.

We use the approach of Mullins and Tite (1973) who in turn use the Néel theory for susceptibility response time calculations. Néel shows that, under certain conditions, small magnetic mineral grains exhibit an exponential time response to a suddenly applied magnetic field, the time-constant of which is sensitively dependent on the grain volume. Since there will be a large number of grains with different volumes the overall response will be the sum of the many exponential responses with different time-constants.

Our many field surveys, with the EM38B operating at a frequency of 15 kHz and showing many anomalies with a Q/I ratio (defined above) varying between 0.1 and 1, suggest that a number of these time-constants lie in the vicinity of between 1 and 10 µsec. We therefore use simple, single time-constant theory to calculate these time-constants as being given by

$$\tau=(1/\omega)\text{x}(Q/I), \text{ where}$$

$\omega=2\pi f$, and f=operating frequency.

Some results are shown in the following table.

(Q/I) Ratio	τ (μsecs)
0.1	1.1
0.2	2.2
0.5	5.5
0.8	8.8
1.0	11

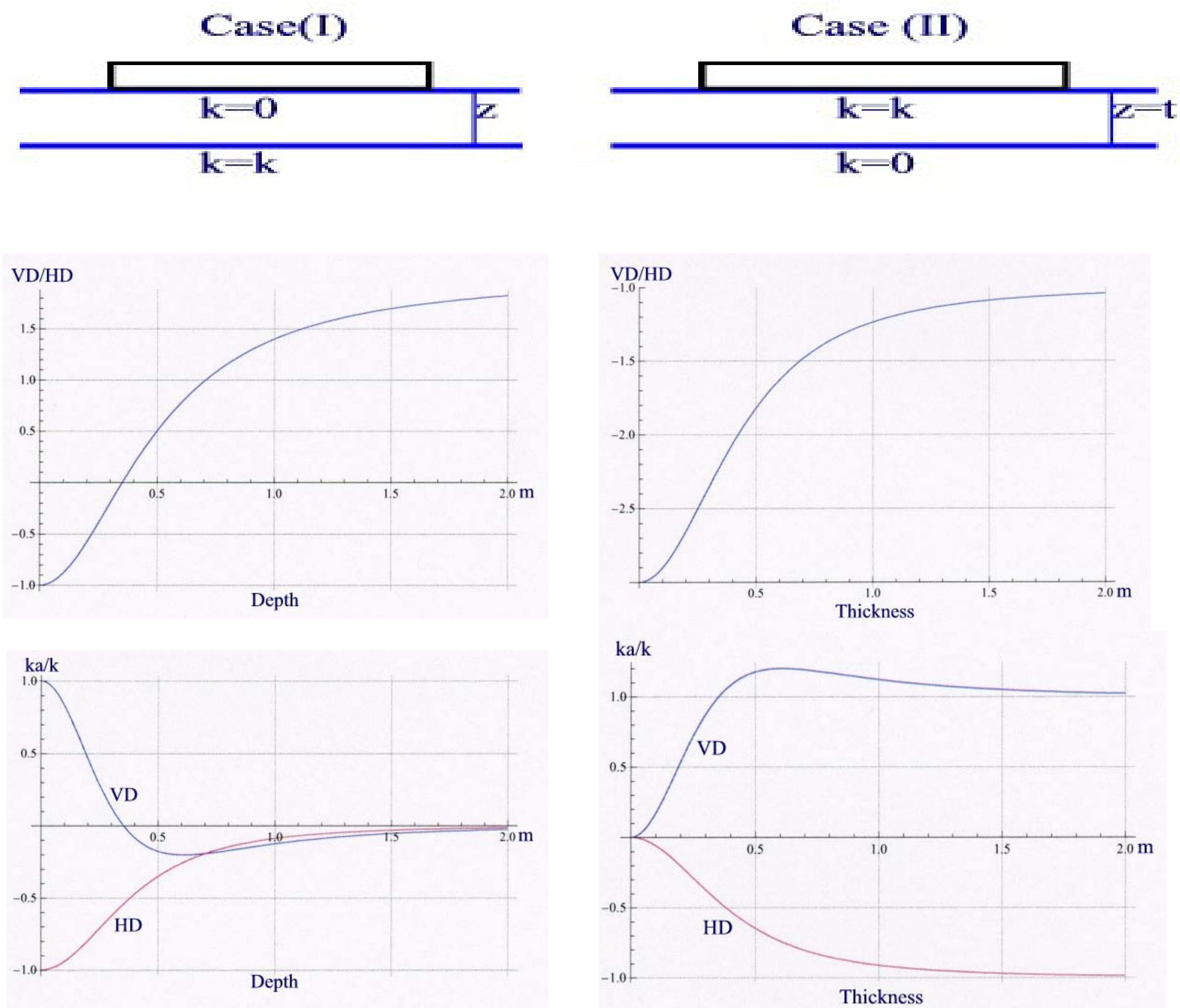
Whilst these quantities are undoubtedly approximate they are related to real response times, and may well form a basis for quantifying the different Q/I ratios in a meaningful way.

Mullins, C.E., and Tite, M.S., (1973). Magnetic Viscosity, Quadrature Susceptibility, and Frequency Dependence of Susceptibility in Single-Domain Assemblies of Magnetite and Maghemite. J.Geophysical Res. 78, 5; pp 804-809.

Appendix 2

Calculations for a Two-Layered Earth—The Problem

Given that at a certain location, using the vertical dipole mode (VD), the surveyor measures a terrain susceptibility κ; does this susceptibility increase, decrease or stay constant with depth?



The above graphs answer this question for two useful cases of archaeological interest. The two left hand graphs (Case I) apply to the geometry where beneath the EM38B the ground has susceptibility κ=0 down to a depth z, and a susceptibility κ for all greater depths. The two right hand graphs (Case II) apply to the geometry where beneath the EM38B the ground has a susceptibilityκ down to thickness t, and susceptibility κ=0 for all greater depths.

It was stated in Section 3 in the Note that whereas the EM38B measures a positive terrain susceptibility in the vertical dipole (VD) mode, when the instrument is placed on its side in the horizontal dipole mode (HD) the indicated susceptibility is always a negative value, and this fact is incorporated in the lower graph for both Case I and Case II.

To answer the question of how the susceptibility varies with depth using these two models, the procedure is as follows. At every survey location of interest, the EM38B operator measures the apparent susceptibility in the vertical dipole (VD) mode (which is usually a positive number but may be negative) and then measures the apparent susceptibility in the horizontal dipole (HD) mode (which will be a negative number) and records each number. The operator then calculates the ratio VD/HD (which can be a positive or negative number).

If this ratio is greater than -1 and less than +2 the left hand pair of graphs is used. If it is greater than -3 and less than -1 the right hand pair of graphs is used..

Suppose that the measured values of susceptibility are 0.10 ppt in the VD mode and -0.31 ppt in the HD mode. Then VD/HD=-0.32 (which is greater than -1) and the graphs on the left side of the page are to be used. From the top graph we see that the depth to the susceptible layer is given by 0.27 meters (the answer for the first unknown quantity). For this value of depth, the bottom graph shows that κa/κ is -0.68, from which, using the -0.31 ppt HD reading, the lower layer susceptibility is given as κ=κa/-0.68=-0.31/-0.68 =0.46 ppt (the answer for the second unknown quantity) and the problem is fully resolved.

Clearly this technique can only be used when the layered earth model is valid (and not, for example when it is clear that the EM38B response is caused by a localized body) but, on the other hand, one advantage of the Inductive C-S meter is that the lateral spatial resolution is quite high, i.e. a small volume is being sampled, with the result that the parameters of the layered earth model can change fairly quickly with distance down the survey line and a layered model may well still apply. Finally the top two graphs show that the instrument provides good layered earth resolution for this type of layering down to depth of about a meter.