Geophysics in Mineral Exploration: Fundamentals and Case Histories
Ni-Cu Sulphide Deposits with examples from Voisey's Bay

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INTRODUCTION

To the geologist interested in geophysical exploration for Ni-Cu sulphide deposits it is helpful to begin with some basic principles of electromagnetic (EM) theory because EM methods have been so successful in the discovery and delineation of these deposits. EM methods are capable of detecting Ni-Cu sulphide to depths of several hundred meters based on the extreme contrast in conductivity between the dominant sulphide pyrrhotite and the resistive host rock. High resolution methods such as helicopter EM/magnetic and HLEM are excellent for detection of conductors and estimation of their conductance within the upper 100 m. Deeper penetrating methods like fixed-wing airborne EM (to 400 m depth), time-domain EM (to 800 m) and magnetotellurics (to 1500 m) offer superior depth of exploration but with a corresponding drop in target resolution and conductance estimates.

Electromagnetic theory

In EM prospecting, a time-varying electromagnetic field called the ***primary field*** is generated by a transmitter. The primary field travels through resistive host rock by the process of ***induction*** and interacts with a conductor by generating eddy currents over the conductor's surface. The eddy currents create a secondary magnetic field called the ***secondary field*** which travels back through the resistive host rock and is measured by the EM receiver (e.g. Grant and West, 1965). All EM methods measure and record this secondary field. It is the role of the geophysicist to interpret the secondary field response and identify those conductors related to Ni-Cu sulphide occurrences. The transmitter waveforms for some typical EM systems are shown in Figure 1.

Geophysicists refer to the magnetic component of the electromagnetic field as the B-field and use a coil of wire, known as an induction receiver, to measure it. Induction receivers do not measure the B-field directly but instead measure the rate of change in the B-field as a function of time or *dB/dt*. The units of measurement of the B-field are nanoTeslas (nT) and for *dB/dt* nanoTeslas per second (nT/s). In order to measure *dB/dt* of the primary field the current in the transmitter must be changing.

The secondary field from a conductor changes as the primary field from the transmitter changes, but it is a time-related response and there is a delay. This allows the secondary field to be divided into two components - one component is ***in-phase*** with the primary field and the other is out-of-phase or ***quadrature*** with the primary field. Systems that separate the secondary field into the in-phase and quadrature components use a constant frequency as the transmitted waveform and are called frequency-domain systems with the readings termed ***harmonic*** measurements. These systems are also known as ***on-time*** systems because the primary field from the transmitter is turned on while the measurement is being made.

EM methods were greatly improved with the development of time-domain EM systems in which ***transient*** measurements of the secondary field decay are recorded as a function of time after the primary field from the transmitter has been turned off. These are the so-called ***off-time*** systems. Today transient EM systems record both the primary and secondary fields (i.e. full waveform recording) and can be referred to as either on-time or off-time depending on what part of the recorded secondary field is being interpreted. Measurements in the on-time are better at detecting highly conductive targets like Ni-Cu sulphide deposits because the EM responses from such targets are essentially in-phase with the primary field from the transmitter. Measurement of the in-phase component from a transient EM system requires accurate knowledge of the transmitter-receiver geometry that ultimately increases the complexity and cost of the survey.

A general misconception of the EM methods is that they can be used to identify massive sulphide and can differentiate massive from disseminated sulphide. EM systems do not identify massive sulphide in as much as they merely detect conductors. A mineralized zone averaging 10% sulphide will produce a strong EM response if the sulphide is electrically connected over a large enough surface area for eddy currents to form. This is typical in Ni-Cu sulphide systems where a large halo of low percent sulphide surrounds the smaller more-massive deposits. The term “disseminated” is normally used by geophysicists to describe mineralization that is not conductive but is electrically polarizable (using an IP survey for example) whereas geologists often use “disseminated” to describe that portion of the mineralization that is composed of low percent sulphide. For an EM response to be present the mineralization must be electrically connected (not disseminated) and does not have to be massive to be an excellent conductor.

Properties of Ni-Cu-Fe sulphide conductors

Typical Ni-Cu-Fe sulphide mineralization is composed mainly of pyrrhotite, pentlandite, and chalcopyrite. In EM prospecting the properties of Ni-Cu sulphide are essentially the properties of pyrrhotite because pyrrhotite is usually the dominant mineral.

Units of conductivity are Seimens/meter (S/m). Changes in either conductivity or conductor thickness have the same effect on the EM response and cannot be separated. For this reason the term conductance (conductivity times thickness) measured in Seimens (S) is used to describe conductor strength. Pyrrhotite has a high conductivity ranging from 10^4 to 10^6 S/m. While a 1 m section of massive pyrrhotite can have a conductance of 10^4 S, a 50 m section of low percent pyrrhotite can also have a conductance of 10^4 S (200 S/m x 50 m). Both the 1 m massive zone and the 50 m low percent sulphide zone can produce the same EM response. Of course both conductors can also be totally devoid of Ni-Cu (i.e. barren pyrrhotite). It is important that the geologist understand the limitations of EM methods because these techniques can only lead toward the more conductive portion of a Ni-Cu sulphide system and not necessarily to an ore-grade intersection. Table 1 serves as a rough guide to categorize the strength of a conductor.

Pyrrhotite can be magnetic and coincident magnetic and EM responses are often used in an attempt to separate sulphide conductors from conductive graphite. However, graphitic rock units can contain magnetite and will also produce a magnetic response. The possibility that magnetite can occur with either graphite or sulphide, and the fact that pyrrhotite can also be non-magnetic limits the usefulness of magnetics in helping to screen Ni-Cu sulphide targets.

Strength	Conductance (S)	In-phase response	Quadrature response	Possible cause
poor	< 1	weak	moderate	- overburden response
moderate	1 - 10	moderate	strong	- pyrite
good	10 - 1000	strong	strong to moderate	- clay-rich overburden - graphite - salt-water sediment - pyrrhotite-sulphide
excellent	> 1000	very strong	weak	- pyrrhotite-sulphide - graphite - salt-water

Table 1. The strength of EM responses in relation to the conductance estimates.

VOISEY'S BAY GEOLOGICAL SETTING

The Voisey's Bay deposits (Figure 2) discovered since 1994 represent mineral reserves and resources in excess of 116 million metric-tonnes (MMT). The shallow mineralization associated with the Discovery Hill gossan was easily detected with HLEM and ground magnetic surveys (Crebs, 1997) and resulted in the discovery of the Ovoid (31.7 MMT measured resource) and the Discovery Hill Zone (7.3 MMT indicated resource). The Reid Brook Zone (19.0 MMT indicated resource) was discovered after a helicopter EM/magnetic survey further extended the strike length of the mineralized Western Extension. Surface TDEM surveys mapped the Eastern Deeps Main Zone (47 MMT indicated resource) to a depth of 800 m and a regional AMT survey mapped the Far Eastern Deeps Zone (5.6 MMT indicated resource) to a depth of 1300 m (Balch *et al*, 1998). Both the latter deposits had been discovered previously during a stratigraphic drilling program designed to explore the basal contact of a large troctolite magma chamber located east of the Ovoid deposit.

The deposits are hosted by troctolite dike(s) that are thought to be feeder conduit(s) for the Voisey's Bay intrusion of the Nain Plutonic Suite (Naldrett *et al*, 1996). The Western Extension which includes the Reid Brook and Discovery Hill deposits is a near-vertical troctolite dike over 3 km in strike length, extending from near-surface to almost 2 km at depth where it remains open. Mineralization within the dike is composed of lenses of disseminated and semi-massive to massive sulphide. The Ovoid deposit is located under 20 m of overburden at the eastern end of the Western Extension and is 70% massive sulphide. The Eastern Deeps deposit is located at the mouth of a feeder dike along the entry point where the dike opens into a large troctolite magma chamber. The overlying troctolite of the Eastern Deeps deposit is barren of sulphide in the upper 300-400 m at the western margin and in the upper 800-1000 m near the eastern limit.

Five profiles across the Voisey's Bay deposits have been selected to highlight the geophysical signatures of these deposits. The responses are shown within a geological context for each zone starting with the most westerly located deposit, the Reid Brook Zone (Figure 3), and continuing east to the Discovery Hill Zone (Figure 4), the Ovoid (Figure 5), and the Main Eastern Deeps Zone (Figures 6 and 7).

The discussion on geophysical methods which follows describes the different methods for the three basic platforms - airborne, ground, and borehole - that have been used at Voisey's Bay. Geophysical exploration examples from other major Ni-Cu deposits can be found in King *et al* (1994) and Watts (1997).

AIRBORNE GEOPHYSICAL METHODS

Exploration of Ni-Cu sulphide deposits by airborne EM (AEM) surveys involves measurement of the earth's total magnetic field and of the EM field from some transmitter-receiver configuration attached to the aircraft. AEM systems were developed in the 1950's (Fountain, 1998) and were substantially improved with the introduction of digital technology in the 1970's. Two basic configurations have emerged - the rigid transmitter-receiver systems mounted in helicopters and the large separation towed bird systems mounted on fixed-wing aircraft.

Total magnetic field (Magnetic)

Total magnetic field (magnetic) images have become so commonplace that many geologists no longer regard them as a geophysical measurement. Magnetic images are a standard tool for geological mapping. Measured in nanoTeslas (nT), magnetic field variations result mainly from changes in the concentration of magnetite within rock units. In Ni-Cu sulphide exploration, a processed magnetic map can define the contacts of the host rock as well as linear features that may represent magnetic dikes containing sulphide. Interpreted near-surface magnetic linears must always have a corresponding EM response for Ni-Cu sulphide to be present. A processed magnetic map over the Voisey's Bay deposits is shown along with surface geology in Figure 8.

Helicopter-towed electromagnetic (HEM)

Helicopter electromagnetic (HEM) systems are designed to detect conductors within the first 100 m below surface with very high resolution (Fraser, 1972). The transmitter and receiver coils are mounted inside a bird that is towed below the helicopter 30 m above ground. The transmitter coils operate at three fixed frequencies (e.g. low: 900 Hz, medium: 7200 Hz, high: 50000 Hz) for two different coil configurations (coaxial and coplanar). Measurements of the in-phase and quadrature components of the secondary field are recorded for the three frequencies and two coil configurations. The primary use of HEM measurements is of course detection but some other key points to consider are:

1. **Discrimination:** Highly conductive sources have a strong in-phase response and a weak quadrature response. Also the EM response from a conductor decreases as the frequency is lowered. At the lowest frequency the responses are more likely to come from highly conductive sulphide or graphite and less likely to come from weakly conductive overburden.

2. **Depth estimation:** Lower frequencies penetrate deeper into the ground. By comparing the responses from the three different frequencies it is possible to estimate the approximate depth to a conductor.

3. **Orientation:** The coaxial coil configuration is more sensitive to vertically oriented conductors, and the coplanar coil configuration is more sensitive to flat-lying conductors. It is possible to estimate the orientation of a conductor by comparing the responses of these configurations.

The unit of measurement for HEM systems is parts per million (or ppm) of the primary field. A peak amplitude of 10 ppm represents a weak response but is well above the noise level of 1 ppm. For example the Reid Brook Zone, buried beneath 90 m of overburden, is detected by the HEM survey as an in-phase response at 10 ppm in the lowest frequency (Figure 3).

Using the in-phase and quadrature components for a given frequency and coil configuration it is possible to calculate an apparent resistivity in ohm-m. For each flight line, a geophysicist might interpret responses for up to 5 pairs of profiles to estimate depth, conductance, and orientation. For the geologist a plan map of apparent resistivity is the most useful interpretive tool. In combination with a processed magnetic image, apparent resistivity plan map images are useful for relating conductors to important geologic / magnetic features. At Voisey's Bay the computed apparent resistivity (Figure 10a) mapped all the known deposits located within 100 m of surface.

Fixed-wing time-domain EM (TDEM)

Airborne EM systems mounted on fixed-wing aircraft (e.g. Palacky and West, 1991) have three times the depth penetration of HEM systems but with less resolution because of the large transmitter-receiver separation. Fixed-wing time-domain EM (TDEM) systems normally operate in the off-time and are less sensitive to highly conductive Ni-Cu sulphide compared to on-time systems. Attempts have been made at reducing this problem by introduction of the B-field measurement where the secondary field is measured and integrated during the on-time (Smith and Annan, 1998). Use of the B-field measurement increases the maximum conductance that TDEM airborne systems are capable of detecting. Another advantage is the improved detection of higher conductance sources within a weakly conductive overburden response.

Comparison of the off-time *dB/dt* responses and the on-time B-field responses for 3 flight lines is shown in Figure 9 over the Eastern Deeps Zone. The survey was flown using the GEOTEM system operated by Geoterrex-Dighem. From Figure 9 it is apparent that the B-field measurement detects conductive mineralization associated with the Eastern Deeps on each of the three flight lines shown including the eastern-most line 23+50E where the mineralization is greater than 400 m below surface. The *dB/dt* measurement detects the Eastern Deeps mineralization on the first two lines where the mineralization is within 320 m of surface but the *dB/dt* response over the deeper mineralization (23+50E) is not obvious in late time. The B-field measurement may offer improved detection in the search for deeper conductors when compared with the standard *dB/dt* profiles.

The response of fixed-wing EM systems is asymmetric due to the transmitter-receiver geometry that causes the shape of a conductor response to be dependent on the flight-line direction. Color imaging of fixed-wing survey data results in a pronounced herringbone effect. This effect is absent in HEM surveys because there is symmetry between the transmitter-receiver. Symmetry in an EM system exists when the transmitter and receiver positions can be interchanged at any point along the survey line without affecting the measured response.

In fixed-wing surveys two components of the secondary field are measured. The "X" component is horizontal and is more sensitive to steeply dipping conductors, and the "Z" component is vertical and is more sensitive to sub-horizontal conductors. As the depth to a subsurface conductor increases, the "X" component response decreases rapidly. Very deep conductors are characterized by a "Z"-only response. Standard products delivered by the airborne contractor include a plan map of conductance, time window profiles of the "X" and "Z" components, and conductor picks that include conductance and depth estimates.

The unit of measurement for fixed-wing systems is parts per million (or ppm) of the primary field. A peak amplitude of 200 ppm would be well above the 10 ppm noise level and would represent a weak response. The strong peak response of 1250 ppm over the Reid Brook Zone

(Figure 3) shows the superior depth penetration of fixed-wing systems in areas of deeper overburden cover.

GROUND GEOPHYSICAL METHODS

The ground-based methods are the most versatile and range from the high-resolution portable systems to the deep penetrating large loop systems. Virtually all of these systems are suitable for Ni-Cu sulphide exploration. For example, the low cost and portable HLEM method is ideal for small projects restricted to the near-surface while the large loop EM methods like UTEM and Pulse EM can detect conductors as deep as 800 m below surface. More recently the magnetotelluric method has been integrated into exploration programs which explore to depths of 1500 m (usually within known mine environments).

Horizontal loop electromagnetic (HLEM)

The horizontal loop electromagnetic (HLEM) method (Ketola, 1968), commonly referred to as MaxMin™, is a fixed frequency technique which measures the in-phase and quadrature components of the primary plus secondary field for frequencies at 440, 880, 1760, 3520, and 7040 Hz. The units of measurement are percent (%) of the primary field. Estimates of conductance are made from the ratio of the in-phase to quadrature components at a given frequency. Higher conductance sources have a higher ratio of in-phase to quadrature. HLEM surveys are used for grass-roots exploration programs where no previous HEM surveys have been completed. The depth of exploration with HLEM is similar to HEM at 100 m. This technique provides excellent discrimination of Ni-Cu sulphide, particularly at the low 440 Hz frequency, and was instrumental in the discovery of the shallow Voisey’s Bay deposits.

Time-domain electromagnetic (TDEM)

Surface TDEM methods like UTEM and Pulse EM are commonly applied in many geophysical exploration programs. Pulse EM is an off-time system that measures the decay of the secondary field over 20 time windows after the primary field has been turned off. The Pulse EM system also has a single on-time measurement called the primary pulse (PP) located near the end of the ramp. UTEM is an on-time system that measures the decay of the primary plus secondary field (called the total field) over 10 time windows. The disadvantage of on-time systems is the requirement that the position between the transmitter and receiver be accurately known. For a UTEM survey, each receiver station must be positioned, either by chaining or GPS, and the transmitter loop position must also be measured. Borehole geometry is measured using a gyroscope. Because off-time systems are less sensitive to highly conductive sulphide, the use of on-time systems is preferred when it is a matter of discrimination of conductance within a conductive system rather than mere detection of a conductor.

Directly over the Ovoid, the UTEM channel 1 response suggests a flat-lying conductor and not a dipping conductor as indicated in the off-time (or decaying) channels (see Figure 5). Over the deeper mineralization of the Eastern Deeps Zone, the large loop UTEM, Crone Pulse EM, and Geonics EM-37 systems show anomalous secondary field responses along lines where the mineralization is known to be 800 m below surface (Figures 6 and 7).

Magnetotellurics (MT) and Audio Magnetotellurics (AMT)

The magnetotelluric (MT) method has seen major improvements in both acquisition hardware and data processing that hold great promise for the technique as a deep-seeking exploration tool and is one of the few methods that relies on a natural transmitter. The earth's ionosphere and magnetosphere generate natural EM fields that are the low frequency primary fields that interact with subsurface conductors. The secondary fields from these interactions are measured on the earth's surface as electric fields (using current dipoles) and magnetic fields (using induction receivers). From these sets of readings impedance tensors are calculated and phase shift (in degrees) and apparent resistivity (in ohm-m) are computed. Changes in both the phase and apparent resistivity are used to identify subsurface conductors (Livelybrooks *et al*, 1996). Plan maps can be generated at a fixed frequency, or depth pseudo-sections that invert frequency to depth can be used with the lower frequencies representing deeper conductors.

Recording of the natural MT field is in the form of a time series and extends over a frequency range that can be varied depending on the survey design. For example, at Voisey's Bay measurements have been recorded at frequencies from 8 Hz to 20,000 Hz. Limiting the recording to this frequency range allows more stations to be recorded (e.g. 30 minutes per station which equates to 1.5 line-km/day). Because these frequencies lie within the audio range the method is called audio magnetotellurics (AMT). The major cause of the primary fields in AMT prospecting is from world wide thunderstorm activity. An impedance phase image from Voisey's Bay is shown in conjunction with the HEM apparent resistivity in Figure 10. The phase image shows the Eastern Deeps mineralization that reaches a depth of over 1300 m at its eastern limit.

The MT/AMT method offers the promise of locating very deep conductors (to 1500 m). With this deeper penetration comes two serious problems - a lack of spatial resolution, and poor estimation of conductance. For these reasons caution is required when spotting boreholes directly on MT conductors.

BOREHOLE GEOPHYSICAL METHODS

Borehole EM techniques have the advantage of placing the EM receiver closer to the conductor. These methods are based on the same EM techniques as the ground-based methods and with the recent development of 3-component borehole EM probes, interpretation of the direction to a conductor is now more reliable.

When a borehole is collared to intersect a conductor interpreted from either a surface or airborne EM survey, the first hole can often intersect inside the Ni-Cu sulphide system. The drillcore from that first hole may not represent an economic intersection, but the sulphide may be connected to a thicker more massive zone of mineralization only a few tens of meters away. A borehole EM survey can confirm whether the conductor was intersected (an "in-hole" response) or how far away and in what direction the missed conductor is located (an "off-hole" response). Because discrimination of the conductor is so important at this stage of exploration only on-time borehole EM systems should be considered for Ni-Cu sulphide exploration.

Borehole UTEM

The UTEM system was developed by Yves Lamontagne and Gordon West in the early 1970's at the University of Toronto (West *et al*, 1984). The UTEM waveform is unique in that the primary field with its triangular shape never shuts off. Because EM receivers measure the rate of change in the magnetic field *dB/dt*, the UTEM receiver coils measure a step response from the transmitted primary field (i.e. the derivative of the triangular waveform is a step function). Step response systems energize conductors more uniformly than do impulse response or Pulse EM systems that concentrate more of the primary field into the early time and as a result enhance poor conductors like overburden. For this reason step response systems are considered more desirable for Ni-Cu sulphide exploration.

Borehole Pulse EM

The Pulse EM system was developed in the 1960's and was originally intended as an off-time system. Companies such as Crone Geophysics and Geonics have long recorded at least one time window in the on-time initially for reasons of calibration. Because of the linearity of the Crone transmitter waveform during shutoff, the combined on-time and off-time can be used to calculate the step response in a form similar to UTEM (Ravenhurst, 1998). A comparison between the Crone calculated step response and the UTEM measured step response for hole 97-400 near the Reid Brook Zone is shown in Figure 11. Both holes define an off-hole conductor as represented by the building in-phase secondary field at 980 m. Hole 97-400 encountered 9.3 m of weak mineralization within the troctolite host rock. The follow-up hole 97-412 drilled to test the off-hole conductor interpreted from a Crone borehole EM survey of hole 97-400 intersected 20.4 m of mineralization including 8.25 m of massive sulphide. Borehole EM systems like the Geonics EM-37 which do not use a linear ramp can still be used as on-time systems by integration of the primary plus secondary field for the duration of the ramp shut-off and throughout the off-time (Smith and Balch, 1998). An example of the Geonics borehole EM system for hole 97-400 is shown in Figure 12.

A key point to on-time measurements is normalization of the data to the theoretical primary field. For example, in the UTEM system the latest time channel (i.e. channel 1) is subtracted from the theoretical primary field in the direction of the measured component and normalized to the total theoretical primary field with the measurement expressed in percent (%). It is possible to subtract and normalize both the Crone and Geonics data using the same procedure. The result is a measurement that identifies the conductor with the highest conductance. When exploring within a mineralized Ni-Cu sulphide system where more than one conductor is present, such discrimination of higher conductance is critical.

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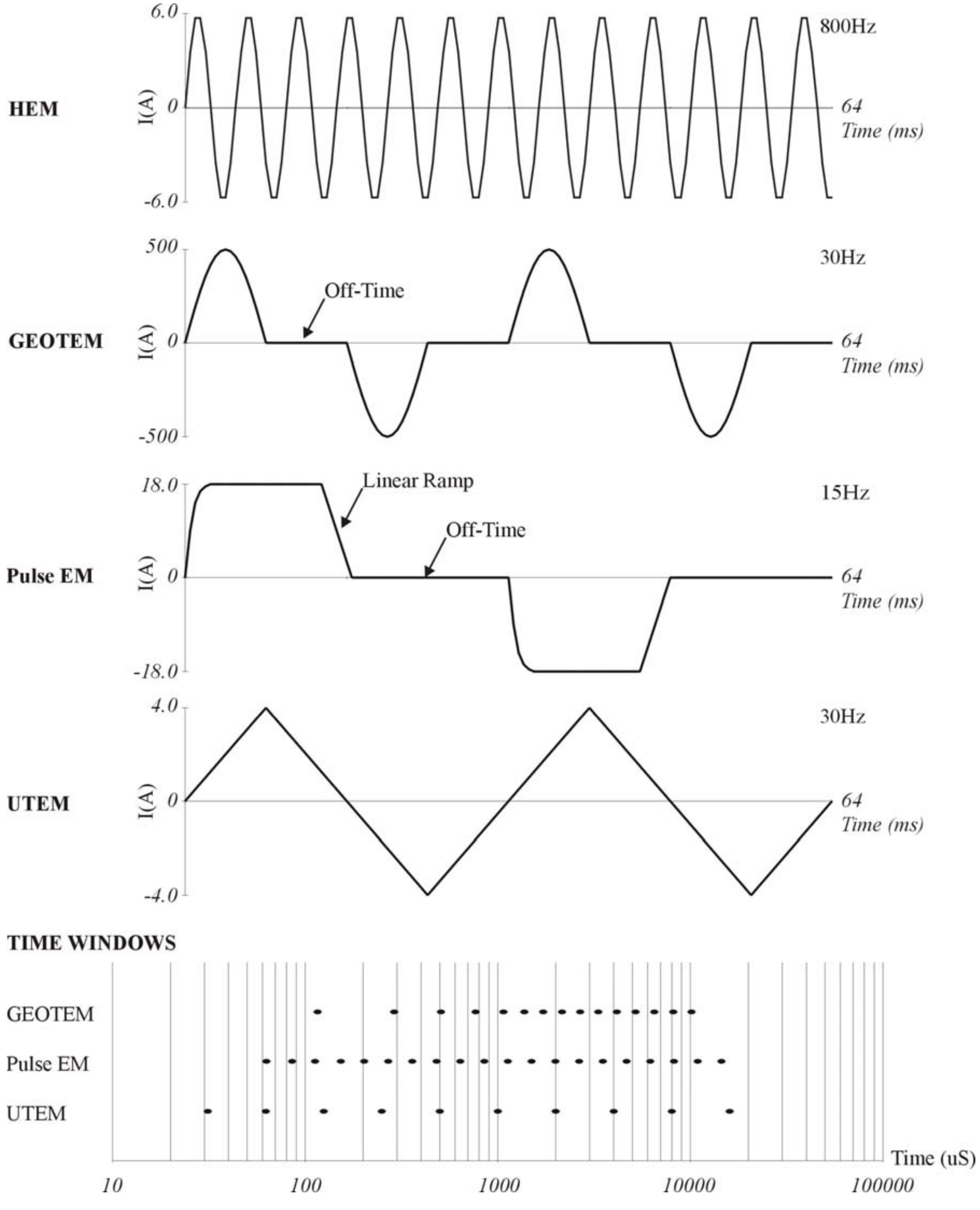
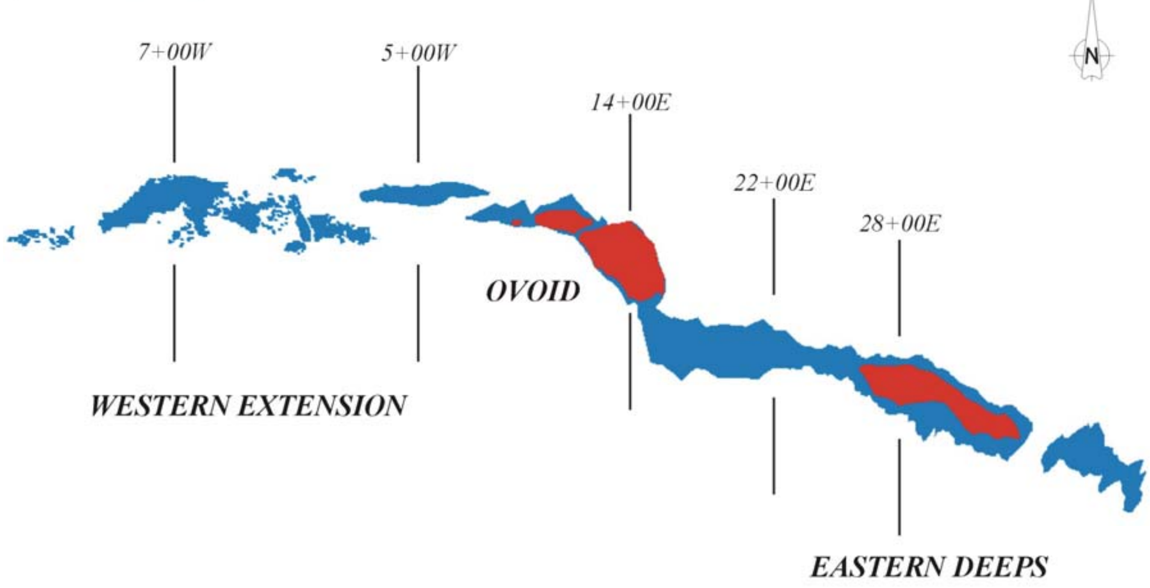


Figure 1. The idealized transmitter waveforms for some common EM systems are shown as a function of current versus time. The HEM system is the only constant frequency method shown. The time-domain EM systems use a repetitive wave form which switches from positive to negative current once for each cycle. Several cycles are averaged to form a single reading. The GEOTEM waveform shown for 2 complete cycles consists of a cosine pulse in the on-time, followed by zero current in the off-time, and repeated in the second half of the cycle for the opposite current direction. The Pulse EM system uses a linear ramp to shut-off the current from on-time to off-time, while the UTEM waveform operates in the on-time always. The time windows for GEOTEM, Pulse EM, and UTEM are shown for the typical base frequencies used.

a) Plan Map



b) North-facing longitudinal section

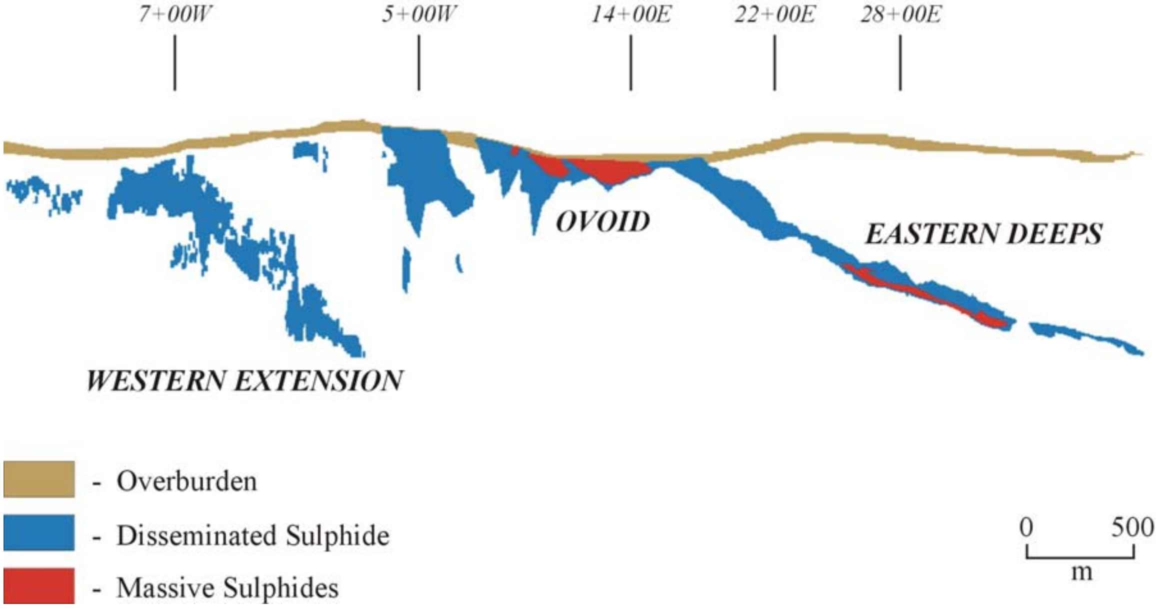


Figure 2. The Voisey's Bay Ni-Cu-Co deposits have a dominant east-west strike direction as seen in the plan map (2a), and an eastward plunge as seen in the longitudinal section map (2b). Five profiles have been chosen over the deposits to highlight the geophysical responses across the different geological settings.

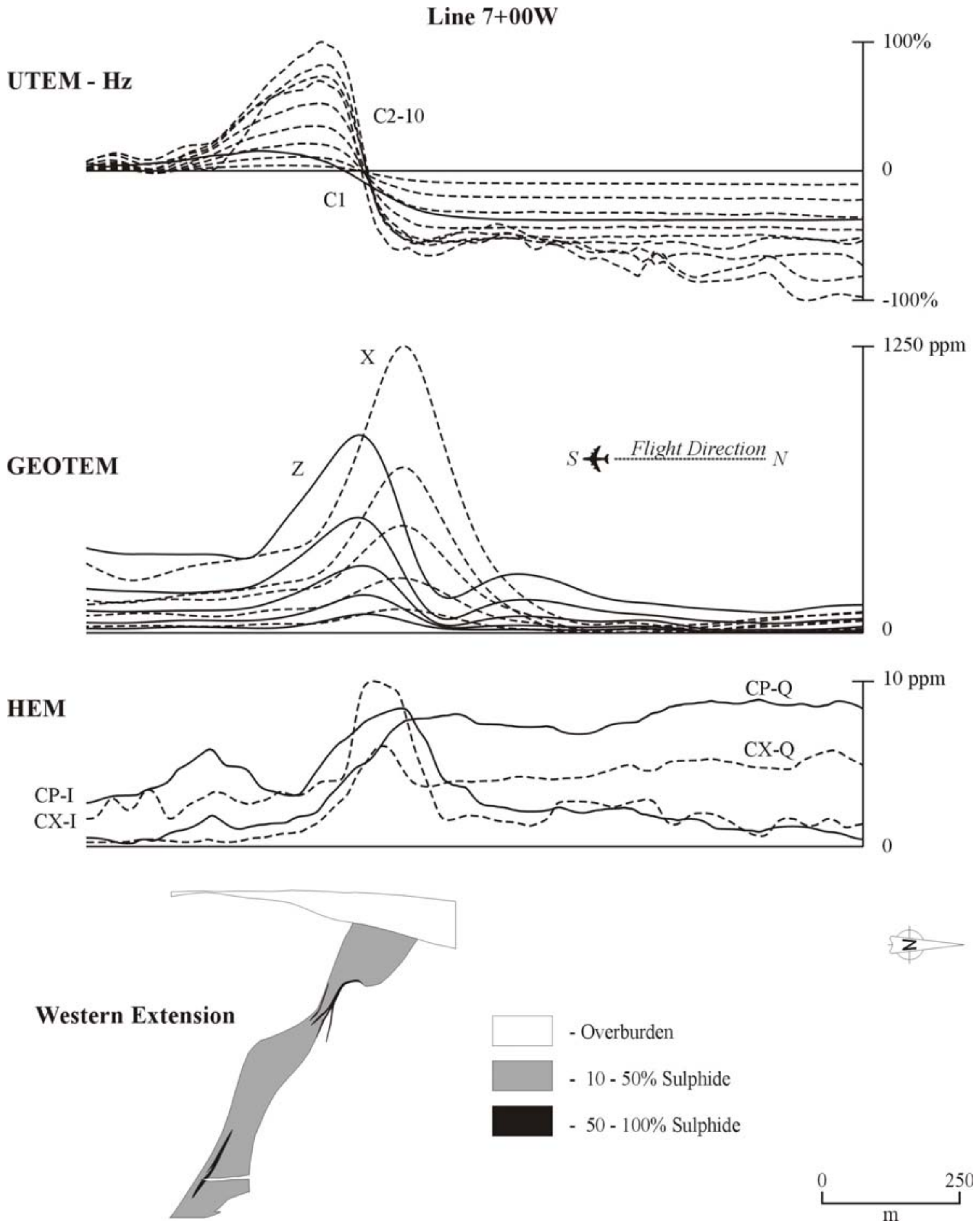


Figure 3. On line 7+00W the Western Extension mineralization dips steeply to the south, covered by 90 m of overburden. The UTEM Hz cross-over response detects the mineralization as a steeply dipping conductor of great depth extent and high conductance. GEOTEM also shows a strong response with the X component peaking at 1250 ppm. The HEM response is only 10 ppm in the in-phase components (CP-I and CX-I) reflecting the limited depth penetration of this method. The quadrature components (CP-Q and CX-Q) are strongly affected by the thick overburden cover.

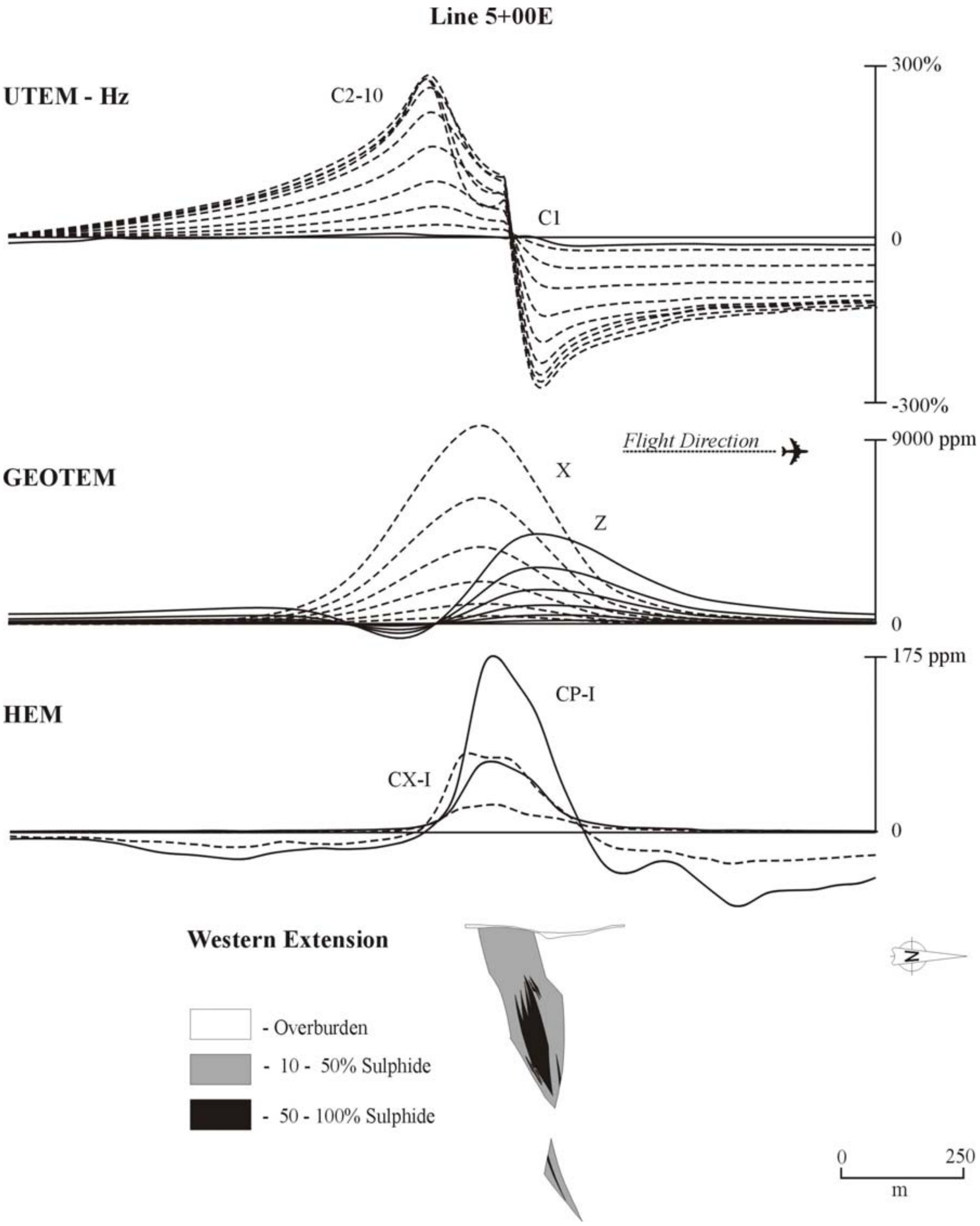


Figure 4. On line 5+00E the Western Extension mineralization dips steeply to the north under only a few meters of overburden. The UTEM Hz cross-over response suggests a near-surface conductor of good depth extent as seen by the "hanging response" on the north side of the mineralization. Both the GEOTEM and HEM responses show strong peaks over the shallow mineralization. Note the strong negative tail in the HEM in-phase (CP-I) component caused by the highly magnetic enderbite unit to the north.

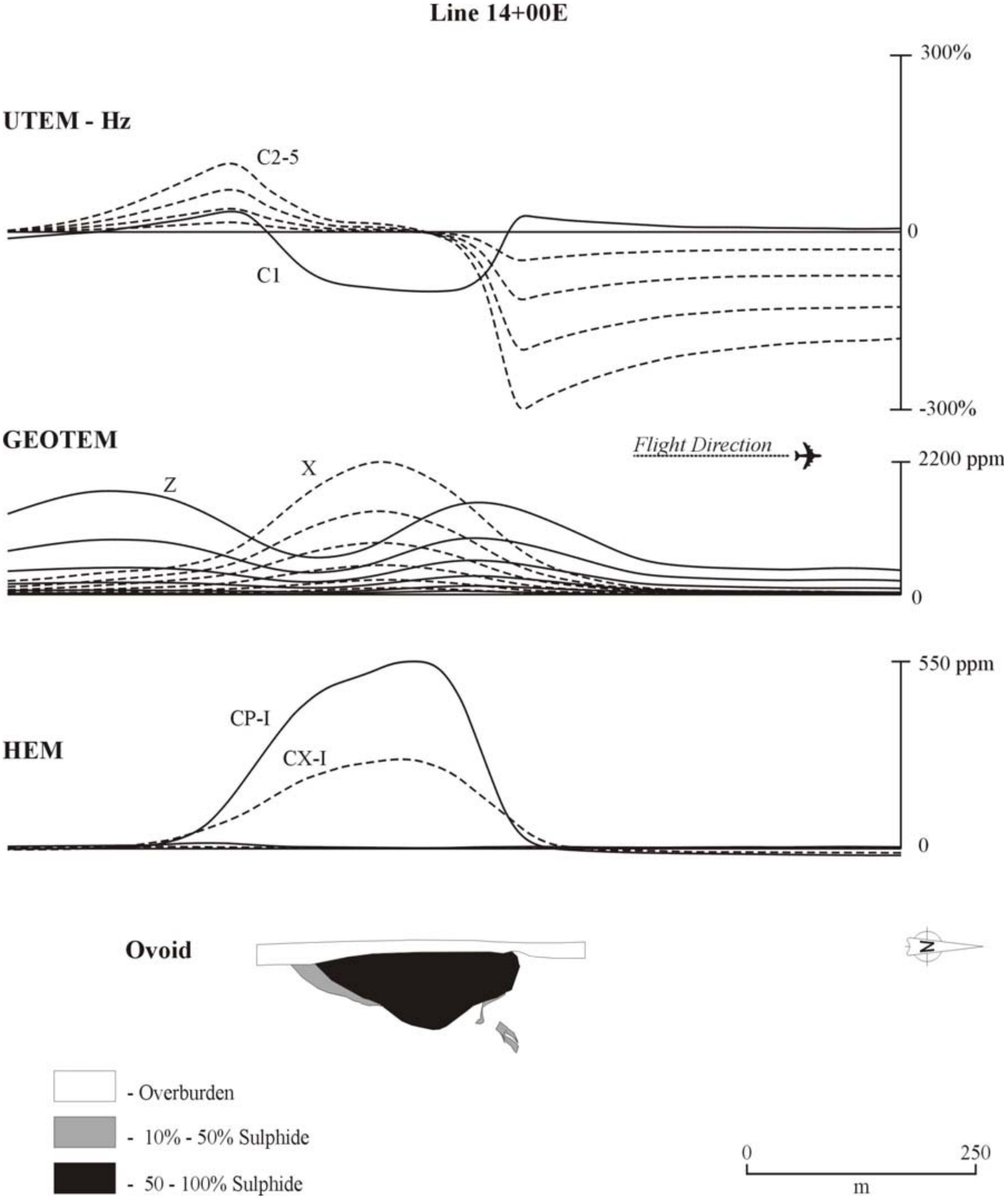


Figure 5. The OVOID is a flat-lying body composed of 70% massive sulphide and is located under 20 m of overburden. While the OVOID has been easy to detect by EM methods, the on-time systems more clearly identify its flat-lying geometry. The UTEM channel 1 response is that of a flat-lying conductor of extreme conductance. The GEOTEM responses are anomalous over the OVOID but do not suggest a flat-lying orientation. The HEM response is strongly in-phase with the coplanar coil (CP-I) peaking at twice the amplitude of the coaxial coil (CX-I) with no corresponding quadrature responses. The HEM method clearly identifies a flat-lying conductor of extreme conductance.

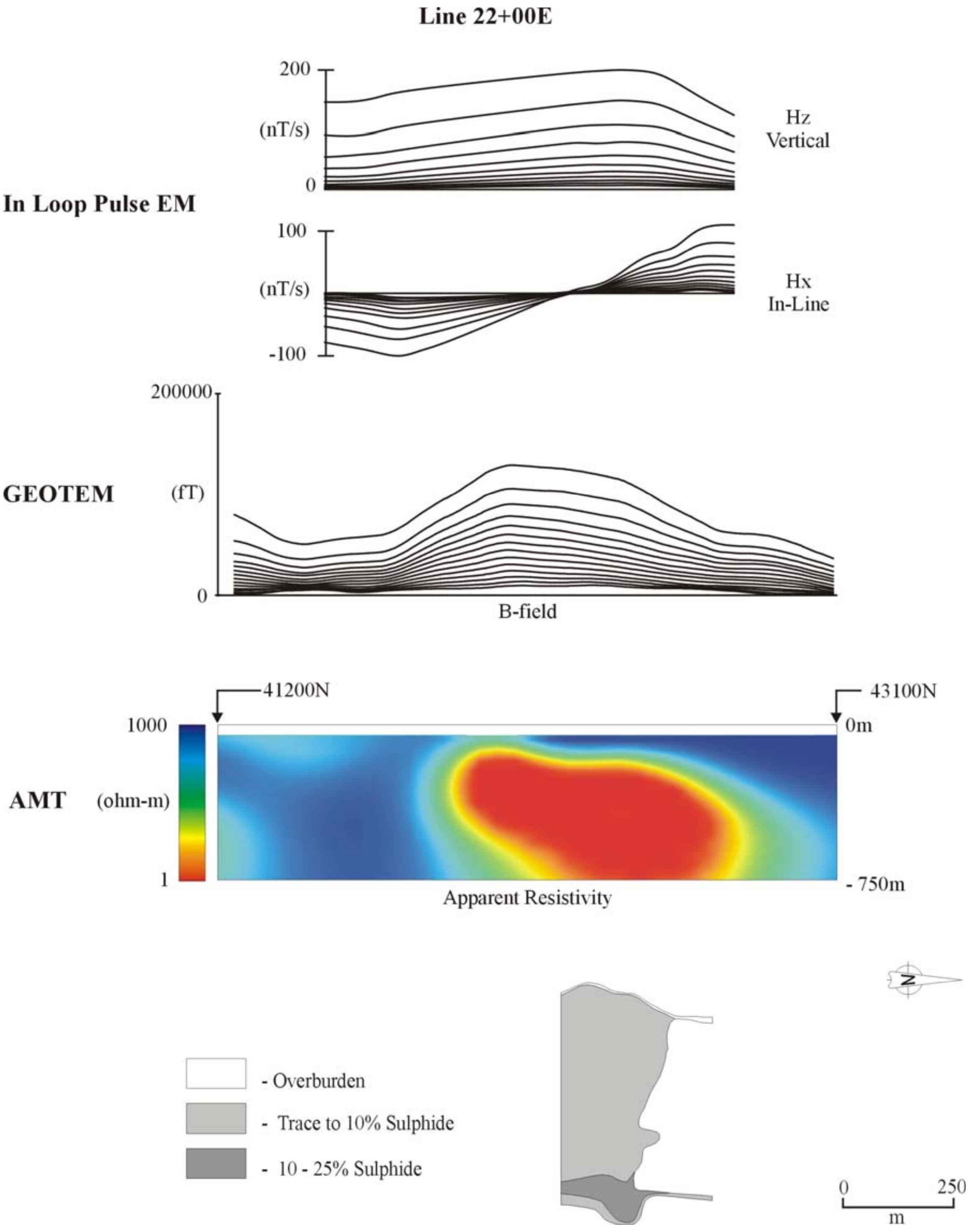


Figure 6. At over 400 m below surface the Eastern Deeps is detected by the GEOTEM survey as a broad "Z" component response. Deeper penetrating methods like in-loop Pulse EM, UTEM and AMT have no problem locating the mineralization. The broad responses from these deeper conductors makes it difficult to recommend precise drillhole locations.

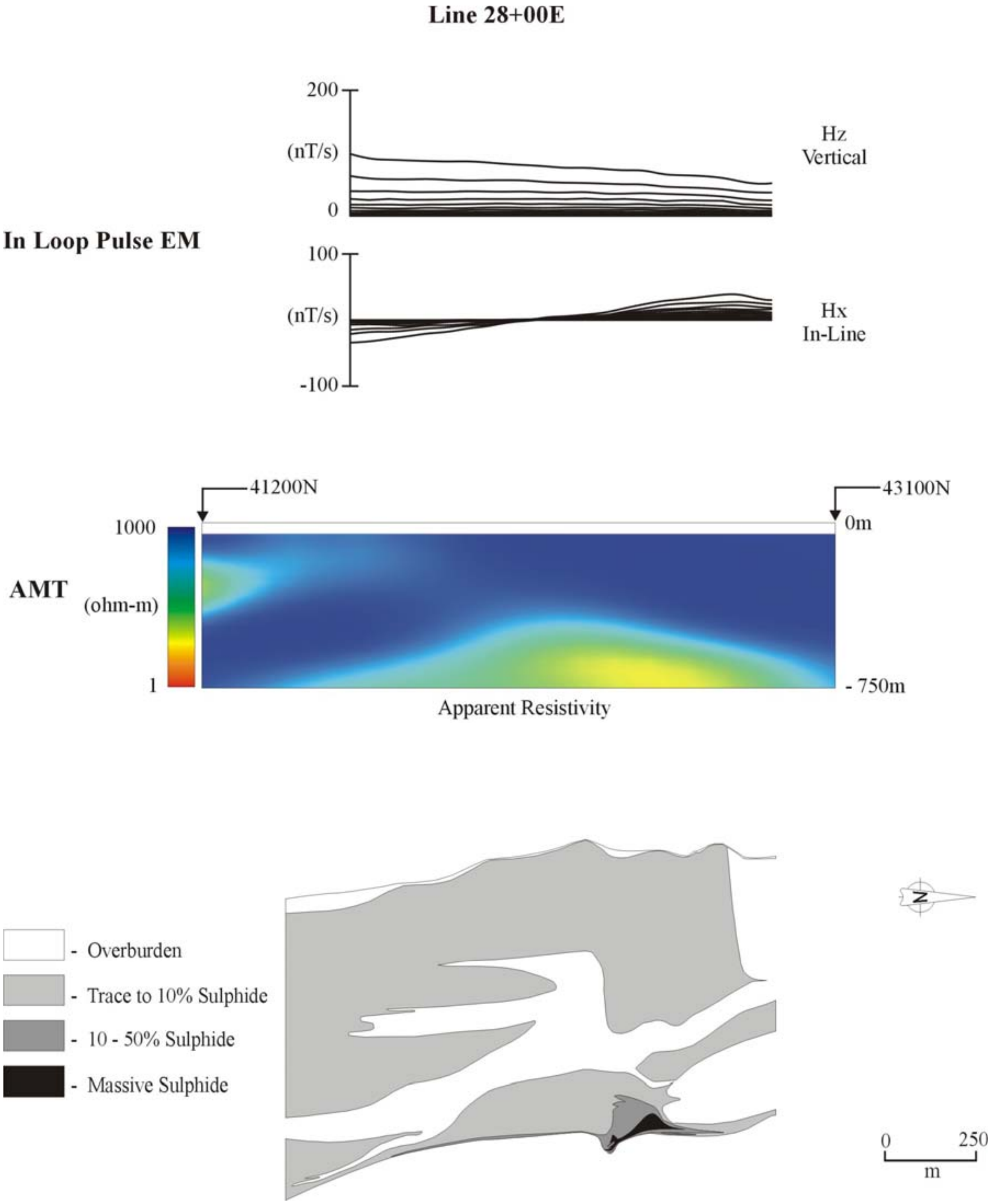


Figure 7. At over 700 m below surface the Eastern Deeps is beyond the reach of any airborne EM system and is difficult to detect even with large loop EM methods. The in-loop Pulse EM response suggests a deep flat-lying conductor but the response could also be interpreted as conductive overburden. But the AMT method clearly shows the response of a deep conductor.

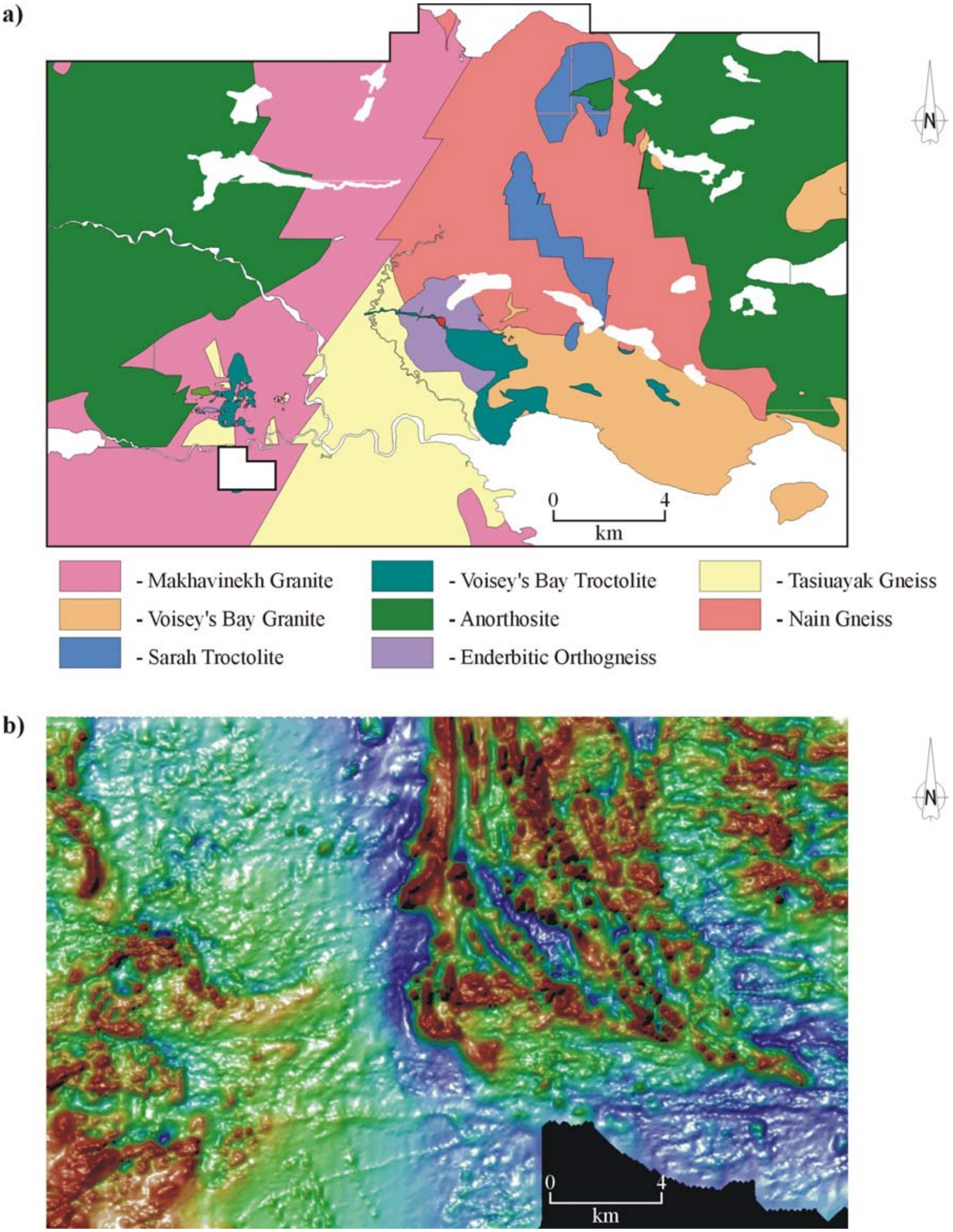


Figure 8. The Voisey's Bay Troctolite as shown on the Main Block geology map (8a) contains all the currently known Ni-Cu deposits at Voisey's Bay. There is no strong correlation between the total magnetic field, shown here as a hue-intensity-saturation image (8b), and the known mineralization. The Enderbitic Orthogneiss and Nain Gneiss units are strongly magnetic, while the Tasiuayak Gneiss, the Makhavinekh and Voisey's Bay Granites, and the Voisey's Bay and Sarah Troctolites are, for the most part, non-magnetic.

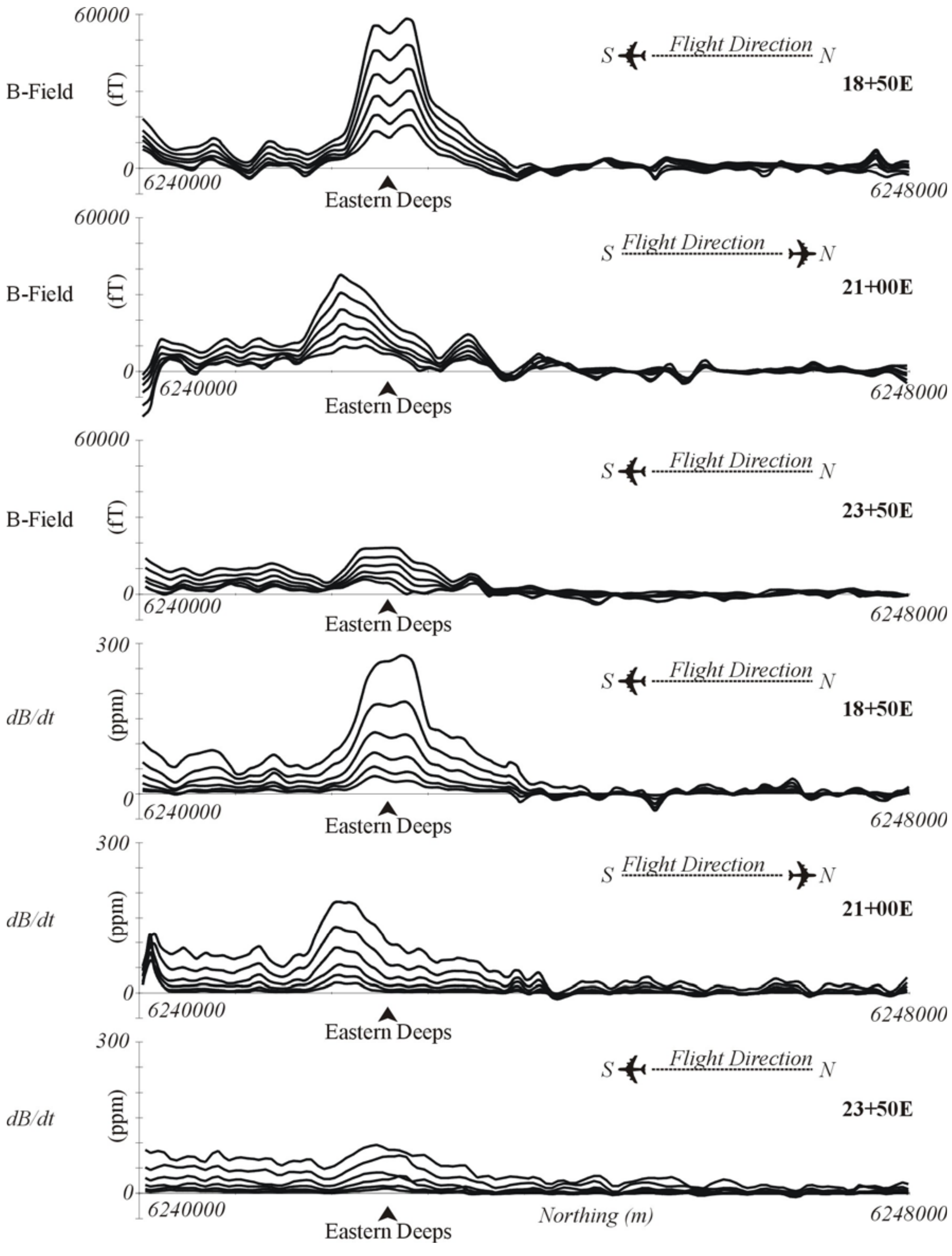
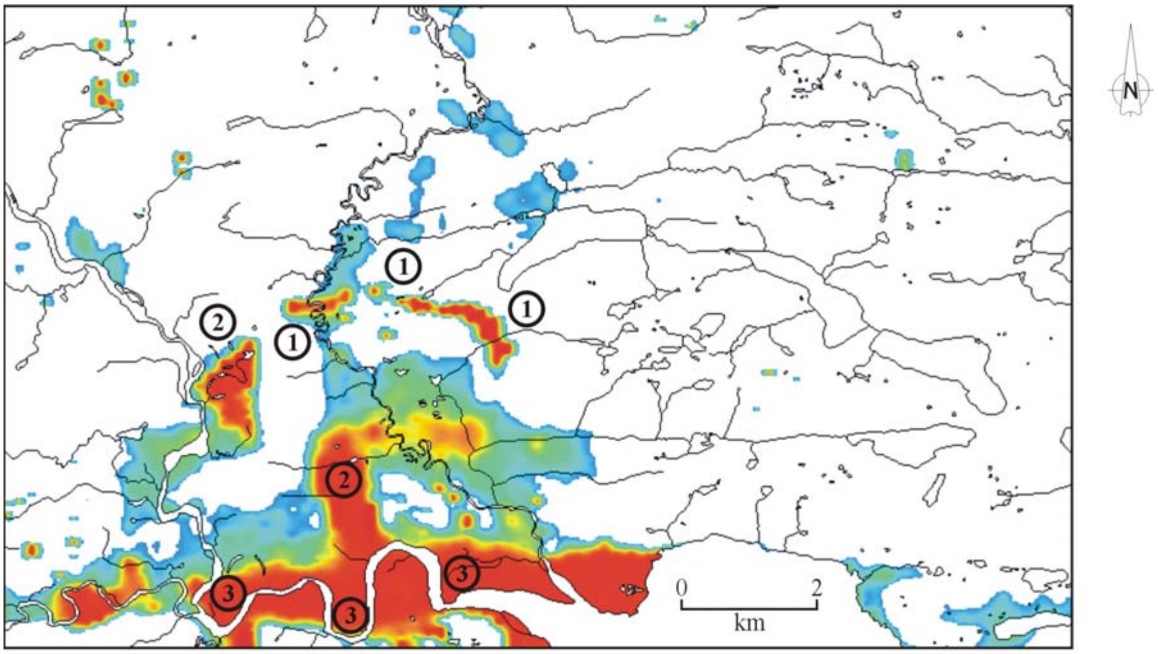


Figure 9. The GEOTEM "Z" component responses (shown here for the 6 latest time channels) are more sensitive to deeper conductors when compared with the X component. The B-field measurement clearly detects the Eastern Deeps mineralization across the 3 consecutive flight lines. The *dB/dt* measurement also detects the mineralization on the three lines, but over the deepest portion of the mineralization (LINE 23+50E) the *dB/dt* profiles have fallen into the system noise level in late-time. The B-field measurement appears more effective at identifying deeper conductors.

a) **HEM apparent resistivity**



b) **AMT impedance phase**

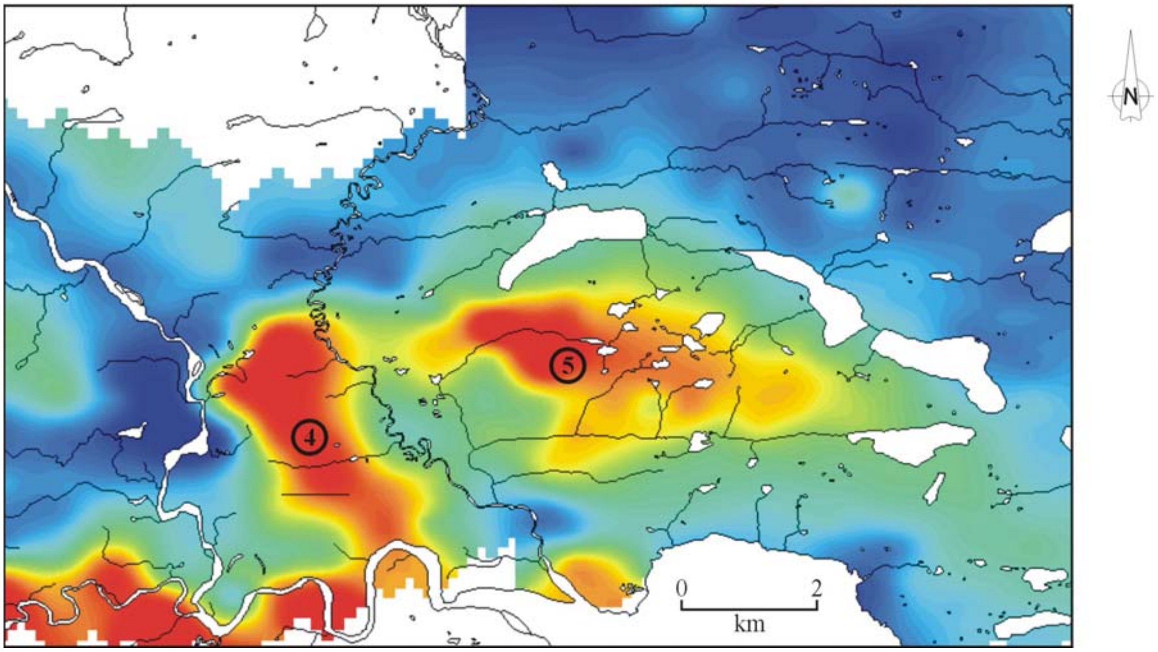
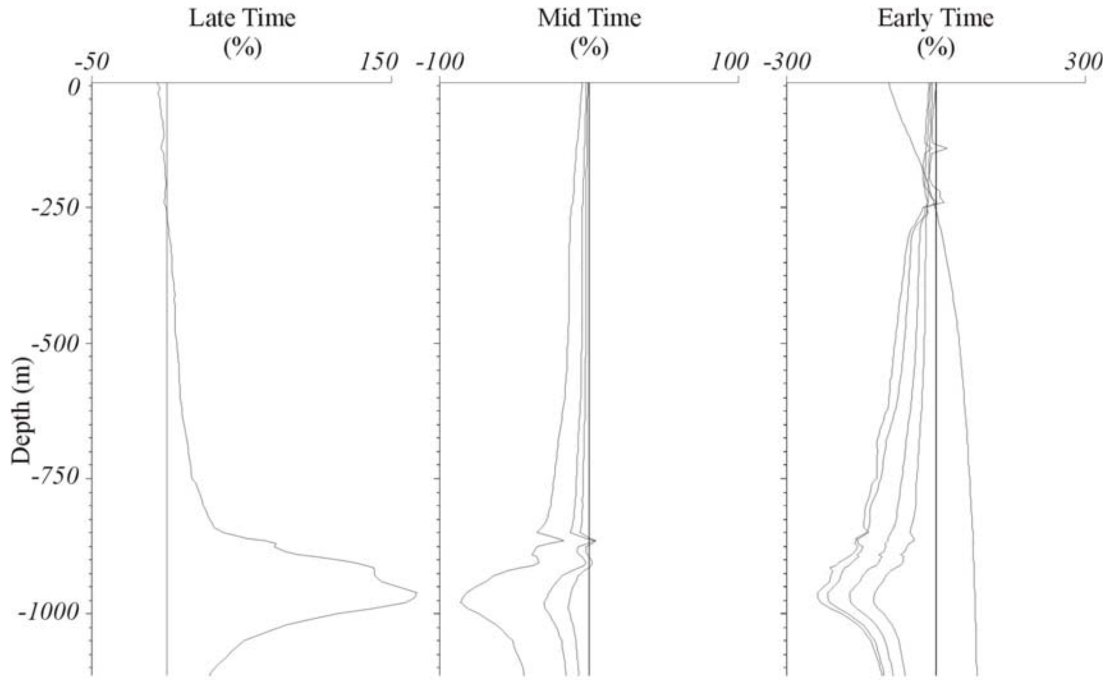


Figure 10. The HEM apparent resistivity image (10a) accurately locates the known mineralization (1), as well as large regional graphite conductors (2), and conductive sediment associated with Voisey's Bay (3). The AMT impedance phase image (10b) suggests the graphite is continuous at depth (4). The Eastern Deeps mineralization is seen as a large diffuse conductive system (5).

a) Crone Pulse EM step response



b) UTEM step response

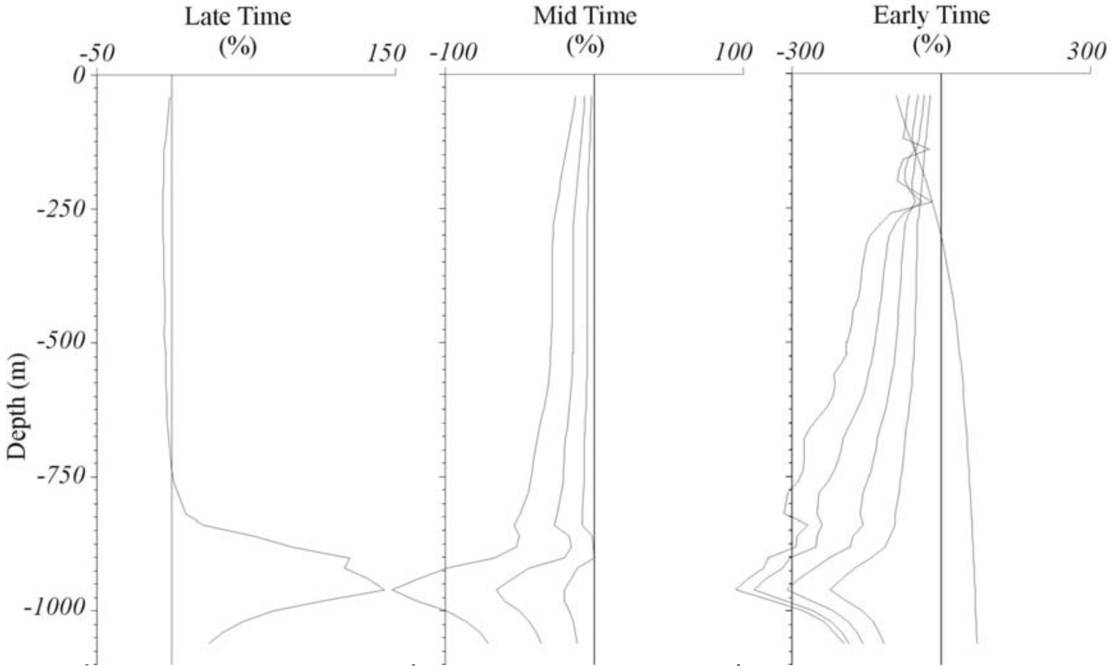


Figure 11. Both the Crone and UTEM step response profiles identify a strong off-hole response at 980 m downhole. The early-time responses suggest a lower conductance unit has been intersected at the same depth interval. The hole intersected 9.3 m of weakly mineralized troctolite. The change from an in-hole to off-hole response in late-time within a known Ni-Cu sulphide system is a strong indication of better mineralization nearby. Based on the directional components of the EM survey, a second hole was drilled on-section and up-dip and intersected 20.4 m of mineralization including 8.25 m of massive sulphide.

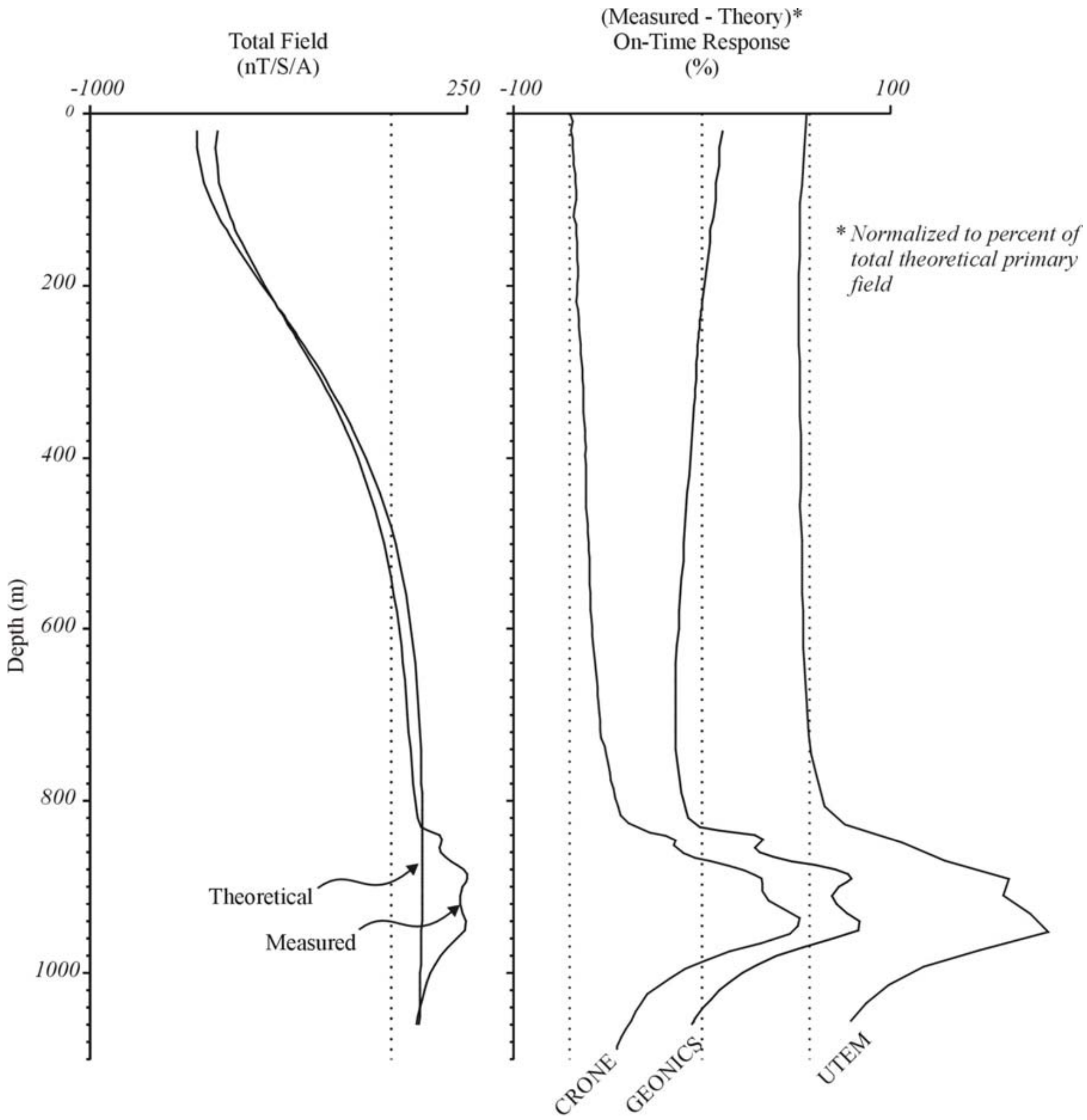


Figure 12. For the detection of highly conductive Ni-Cu sulphide, it is not so important that the step response as opposed to the impulse response of the ground be measured as it is the in-phase component of the secondary magnetic field be compared to the theoretical primary field . Systems like the GEONICS impulse EM system can be useful in Ni-Cu sulphide exploration through integration of the on-time and off-time measurements. A comparison between the channel 1 UTEM and Crone step response profiles and the GEONICS integrated B-field response confirms a close correlation.