Exploring for Nickel in the 90s, or 'til depth us do part'

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ABSTRACT

Since the last great nickel exploration boom of the 1960s, which took place in the wake of the Thompson discovery, advances in geophysical instrumentation, especially in large-loop time-domain electromagnetic (TEM) systems, and PC-aided interpretation, have revolutionized mineral exploration geophysics. The Sudbury Igneous Complex (SIC), host to the largest concentration of nickel sulphide ore in the world, continues to provide an ideal testing ground for geophysical instrumentation both surface and borehole, and refinement of the rigourous processing of time-domain EM required to ensure that high conductance ore bodies are not missed. In addition to the traditional exploration tools for nickel of EM and magnetics, non-traditional techniques such as audio-magnetotellurics, and 3-D seismics for massive sulphide detection, and ground-penetrating radar for massive-sulphide and nickel laterite delineation are meeting with increased acceptance.

INTRODUCTION

With the discovery of the Voisey's Bay Ni/Cu deposit in 1994, the search for giant sulphide nickel deposits has been revitalised worldwide. This discovery, coupled with the belated recognition of the true dimensions of the Norilsk Ni deposit in Russia, has helped spur a nickel exploration boom last seen in the post-Thompson discovery era of the 1960s.

Geophysics has played a key role in the discovery of the Ovoid deposit at Voisey's Bay (Crebs 1996), and gravity and magnetics helped isolate the Lower Talnakh intrusion which is host to Talnakh "ore-junction" at Norilsk (V. Lulko, pers. comm.). Geophysics continues to be a crucial component of the ongoing follow-up exploration programs in these mining camps. While the geologic settings of the four premier Ni sulphide mining camps worldwide, i.e., the Sudbury Basin, Thompson, Norilsk and now Voisey's Bay may differ, the one constant in all four locations is that the dominant sulphide ore-hosting mineral is pyrrhotite. This sulphide mineral has long been recognised as displaying the highest conductivity of the common sulphide minerals. Conductivity values of Sudbury ore are typically in the range of 10^4–10^6 siemens/metre. What may have been neglected until fairly recently, certainly in the case of Sudbury, is the detectability of significant thicknesses of massive pyrrhotite using traditional impulse-type time-domain borehole EM methods. Included in this paper is a cautionary case-history detailing problems encountered initially using a typical impulse TEM system in Sudbury exploration, and what measures have subsequently been implemented to ensure an economic ore deposit is not missed.

Other case-histories presented exemplify the depth penetration capabilities of modern-day fixed-loop TEM methods (Sudbury), the utility of 3-D magnetic inversion and 3-D computer visualization techniques in complex geologic terrains (Raglan Project), and finally the use of the ground penetrating radar (GPR) method in mapping a typical Ni laterite profile at the Falcondo Mine (Loma Caribe Deposit) in the Dominican Republic.

THE NORTH RANGE DEPTH PROJECT, SUDBURY

Discovery of the Craig Depth Ore Zone—Crone and UTEM borehole EM system response in the vicinity of a "perfect" conductor

The objective of the on-going North Range Depth exploration program (Figures 1 and 2) is to evaluate the downdip potential between Falconbridge's Craig and Onaping mines. During the period 1991–1993 a total of ten deep holes were drilled to depths of between 2.0 and 2.5 km in an east-west tier approximately 600 m downdip of these two mines.

During the period from 1984 to 1992 Falconbridge used the Crone Pulse EM (PEM) borehole system exclusively in the Sudbury Basin, most notably in the exploration program leading up to the discovery of Lindsley deposit (Crone 1991). In September, 1992, a series of comparative tests were initiated between the Crone system and the UTEM system, manufactured by Lamontagne Geophysics of Kingston, Ontario.

These tests were carried out downdip of Inco's Victor Depth deposit (Figure 1), ground that Falconbridge owns. The results of these tests will not be discussed in this paper. Suffice it to say that sufficient discrepancy existed between the results from the two systems, as presented by contractors, that it was decided to continue these comparative tests on the Falconbridge's North Range Depth exploration program in the Sudbury Igneous Complex.

The advantage that the Crone system had over most other borehole EM systems at the time was a reliable three-component measurement

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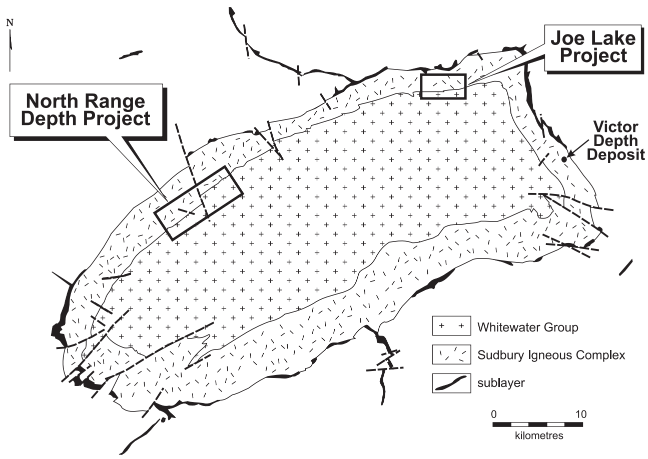

Figure 1: *Location map of North Range Depth and Joe Lake projects, Sudbury Igneous Complex. (modified after Naldrett, Hweins et al., 1984)*

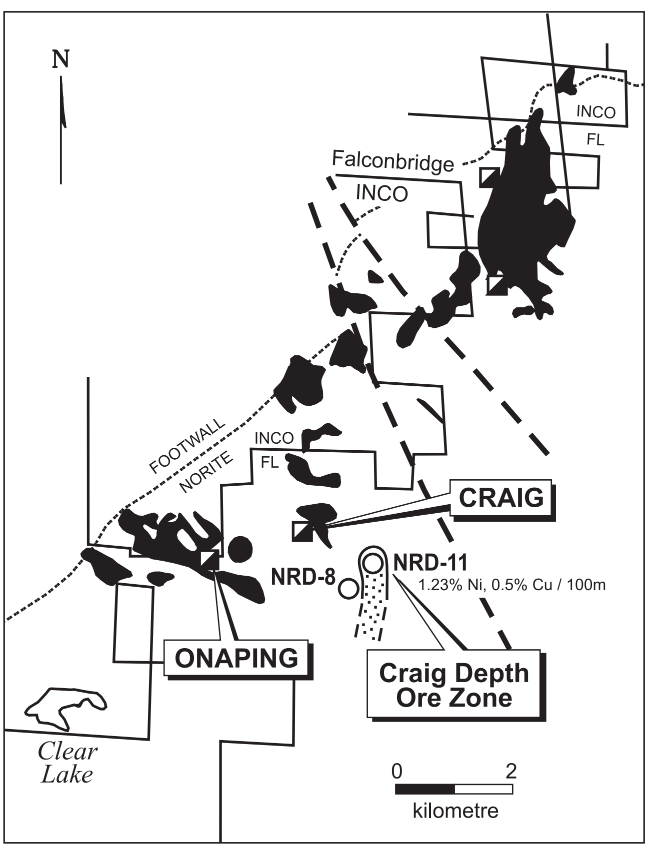

Figure 2: *Location of NRD-8 and NRD-11 relative to Onaping and Craig Mines, SIC.*

capability, a capability which until recently the UTEM system, and most other commercially available EM systems, did not have. The added directional information provided by a three-component system is crucial when drilling holes that cost between $200,000–300,000. It was felt by Falconbridge's exploration staff that perhaps only a combination of the two techniques would provide the total package of information required to follow-up on prospective targets.

The first case history presented will compare the results from the two borehole EM (BHEM) systems for a single hole, NRD-8 (Figure 2), a crucial hole in the North Range Depth project and one which played a key role in the subsequent discovery of the Craig Depth ore zone. Before comparing the results from NRD-8 for the two systems, a brief description of some of the basic differences and similarities between the two systems is required.

Crone PEM

The Crone PEM system belongs to a family of time-domain EM systems which use an impulse-type transmit waveform and measure the rate of change in decay of the induced secondary EM field during the transmitter off-time (Figure 3). The major advantage of measuring the secondary field in the absence of the primary is that the exact geometrical relationship between transmitter and receiver is not required. Another advantage is that a pulsed transmitter waveform is amenable to large current output—transmitting 20 A into a 1×1 km loop is routine in present day PEM surveys. A well-known drawback to any present-day impulse-based TEM system which measures the time derivative of the secondary field decay, rather than the secondary field decay itself, is that the initial amplitude of the off-time response falls off at a rate of $1/\tau$ (Grant and West, 1965). Since τ (time constant) values of more than 100 milliseconds are common in Sudbury, this fall-off can be quite significant.

The Crone PEM system also has an accurately controlled linear shut-off ramp, which allows for a stable measurement of the so-called 'primary-pulse'. The shut-off ramp can be varied from 0.5 milliseconds to 1.5 millseconds. This measurement is normally made between 200 and 100 microseconds before the initiation of the off-time measurement (Figure 3), and can be thought of as similar to a UTEM measurement in that it is sampling the sum of the primary EMF generated in the receiver coil by the rapid shut-off of the transmitter current and any secondary field build-up caused by local conductors. Until recently this parameter was frequently overlooked as a diagnostic tool and generally presented in a 'raw' format only, if at all. It is hoped that this case-history will serve to emphasise that proper processing of the 'primary-pulse' parameter is an essential component to any comprehensive interpretation of Crone PEM data, and can compensate for the significant attenuation in off-time measurements in proximity to very high conductivity (>>10^4s) targets.

The UTEM system

The UTEM system is unique amongst time-domain EM systems in that it is designed to measure the step rather than impulse response of the ground, which entails measurement of the secondary EM field in the presence of the primary field (West *et al.*, 1984). The step response can be vizualised as the sum of a primary, inducing EM field of constant amplitude, and a secondary field produced by the build-up of eddy currents in a local conductor.

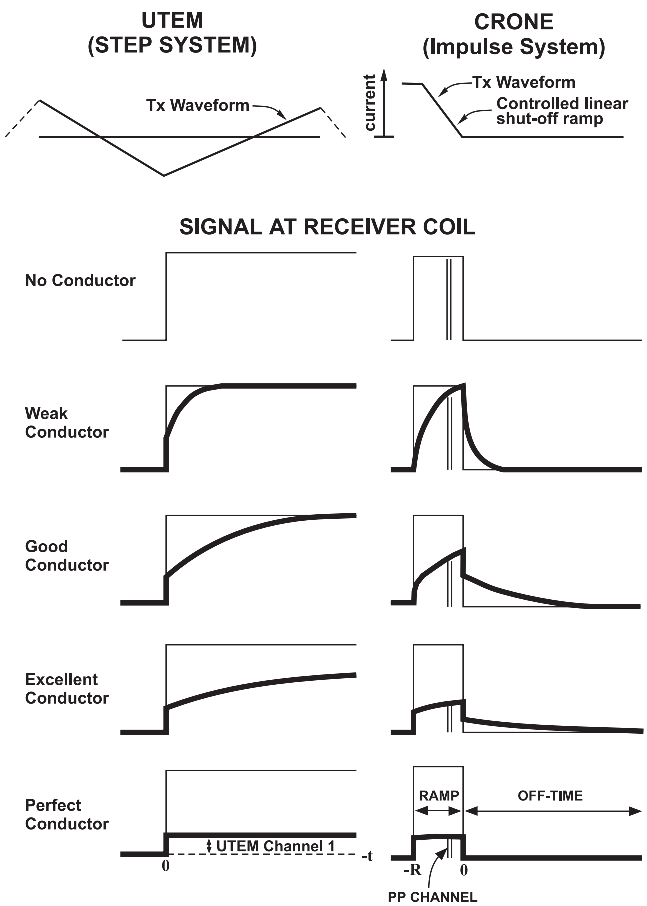

Figure 3: *Idealized system response for Crone PEM and UTEM for increasing target conductance (after W. Ravenhurst, 1996).*

This is accomplished by using a modified triangular transmit waveform, and measuring the resultant total magnetic field response across 10 delay time channels during each half-cycle of the transmitter waveform. Secondary field contribution from a local conductor (Figure 3) is calculated by subtracting the theoretical primary field signal from the measured total field response. To calculate the theoretical primary field value at any given measurement point, the precise location of that point relative to the transmitter loop must be known.

NRD-8 BHEM results

Crone survey

The off-time and unprocessed 'primary-pulse' data, as presented in 1993 for the axial component, is shown in Figure 4. A 16 Hz base-frequency and 1.5 millisecond shut-off ramp were employed. Note that the main feature of the off-time data is a moderate conductivity (10 siemens) in-hole response centered on 2000 m, which is a typical PEM response from weakly mineralized Sub-layer in Sudbury. There is no discernible response, either in-hole or off-hole, at the base of the SIC at 2100 m in either the off-time or primary-pulse data, and the late off-time channel (Ch 15-20) profiles are flat for the length of the hole, with no indication of any off-hole high conductance target.

UTEM survey

The UTEM survey was carried out at approximately the same time as the Crone survey. Similar transmit loop positions and dimensions were utilised for both surveys, i.e., approximately 1.5 × 1.5 km, with the front edge immediately south of the drill hole collar location. Base-frequency for the survey was 31 Hz. The results of this survey are shown in Figure 6. The same long-wavelength moderate conductivity (10 siemens) in-hole response as observed in the Crone data is evident, centered on 1900 m. Of more relevance, however, is the off-hole response in the Channel 1 profile (latest UTEM channel) at 2100 m. The UTEM Channels 2-10 have Channel 1 response subtracted, so that the lack of corresponding deflection on these earlier channels is indicative of a conductor at the inductive limit, i.e., a perfect conductor, and a conductance greater than 10 000 siemens was estimated for this feature. This type of response would be analogous to obtaining an in-phase only response of equal amplitude across multiple frequencies with a a horizontal-loop EM (HLEM) surface survey system.

General comments

The detection of the UTEM off-hole conductor was considered to be one of the highlights of the the 1993 drill program on the North Range Depth Project, which had otherwise not been particularly successful in intersecting mineralization. Two holes, NRD-9 and -10, were drilled west of NRD-8, in early 1994, before NRD-11 intersected 99 m of 1.23% Ni approximately 300 m east of NRD-8. At present underground exploratory drilling suggests that the mineralization in NRD-11 has an east-northeast trend, and will likely pass within 40 m of NRD-8, as predicted by the original interpretation of the UTEM off-hole anomaly.

At the time these surveys were carried out the lack of off-time and "primary-pulse" response from the Crone system in NRD-8 was puzzling. Previous experience from Victor Depth had indicated that even though impulse off-time response was dramatically attenuated in the vicinity of perfect conductivity off-hole targets, significant response was always observed in the "primary-pulse" channel. The major difference between the two project areas is that at Victor Depth, the ore body occurs at least 100 m below the base of the SIC in the Sudbury Footwall gneisses, while on the North Range Project ore lies in contact with the Sub-layer at the base of the SIC. As the NRD-8 results from both systems show, weakly mineralized (<5% sulphides) Sub-layer itself can be moderately to strongly conductive. After much debate amongst the participants in the NRD-8 BHEM test program, it was concluded that the conductive Sub-layer host was in effect blanking, or screening, the 'primary-pulse' off-hole response which would presumably be present in the absence of the Sub-layer response.

In mid-1996, W. Ravenhurst of Crone Geophysics derived a relatively simple procedure to produce a parameter that would be analagous to a Channel 1 step (UTEM) response by summing the measured 'primary-pulse' with selected off-time channels. The resultant Last Step

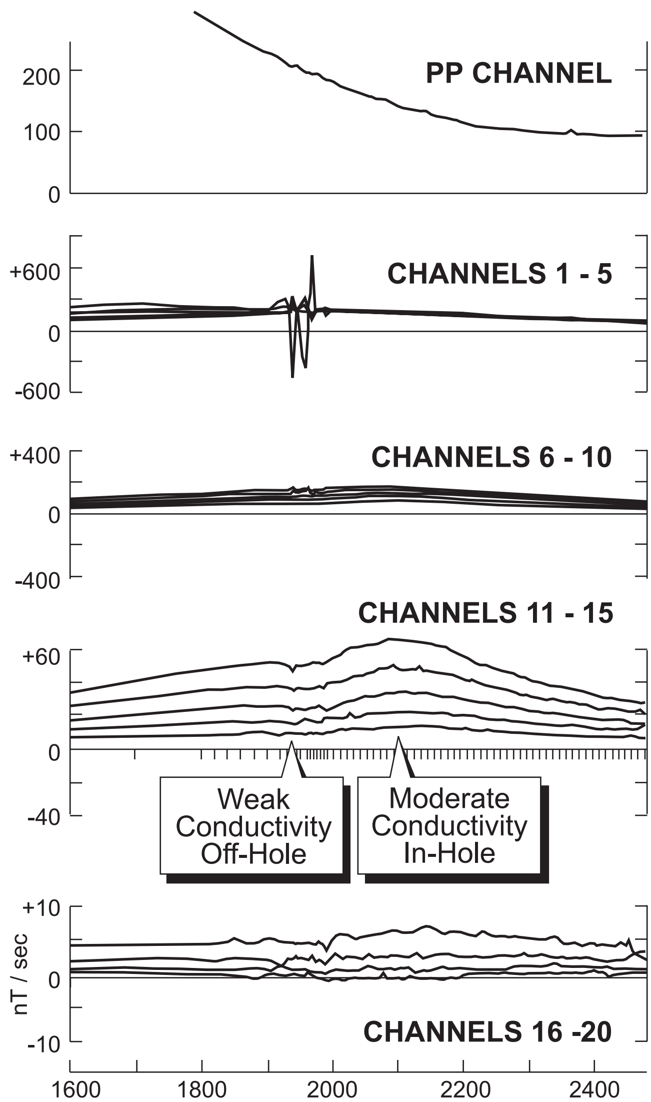

Figure 4: *Crone PEM survey, NRD-8, axial component, September, 1993.*

(cleaned primary-pulse) parameter is then subtracted from the theoretical primary pulse value and expressed as a percentage (pers. comm):

$$\text{LS(Last Step)} = \text{PP} + \text{Ch11} + \text{Ch14} + \text{Ch16} + \text{Ch17} + \text{Ch18} + 2(\text{Ch19}) + 2(\text{Ch20}) \quad [1]$$

The result of this procedure for NRD-8 is presented in Figure 5. Note the similarity of the LS Crone parameter to the UTEM Ch 1 off-hole response at 2100 m, and the corresponding lack of response from the Residual 'primary-pulse' parameter at the same depth. The usefulness of the 'Last Step' derivation on other Falconbridge projects in the SIC since the NRD-8 test work has proven itself several times over. This derivation of course implies the same precise knowledge of transmitter to receiver probe geometry that is necessary for the processing of UTEM data.

In conclusion it can be stated that, in the SIC, the traditional approach of presenting impulse-type time-domain EM data in off-time and raw 'primary-pulse' profile format only, has proven to be ineffective in the detection of nearby highly conductive massive-sulphide ore. After much debate, controversy, and collaboration between Falconbridge geophysical staff and the various contractors involved, a processing sequence is now in place to ensure these conductors are not missed. It can also be stated that detection of an inductive-limit off-hole UTEM response in NRD-8 provided substantial impetus for continued drilling in the NRD-8 area, which eventually led to the discovery of the Craig Depth ore body.

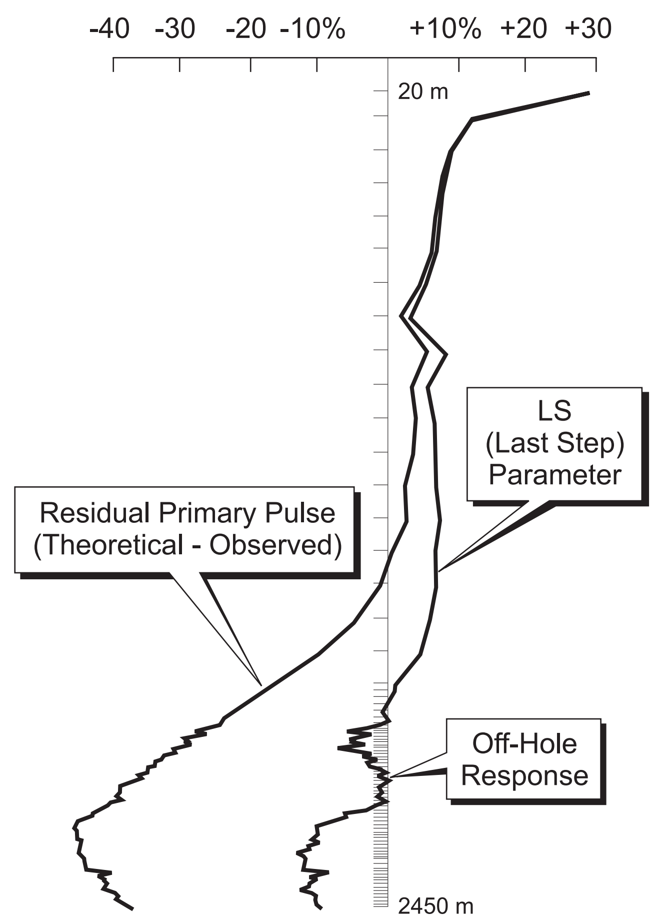

Figure 5: *Re-processed Crone PEM survey, last step and residual 'primary-pulse' profiles, NRD-8, October, 1996.*

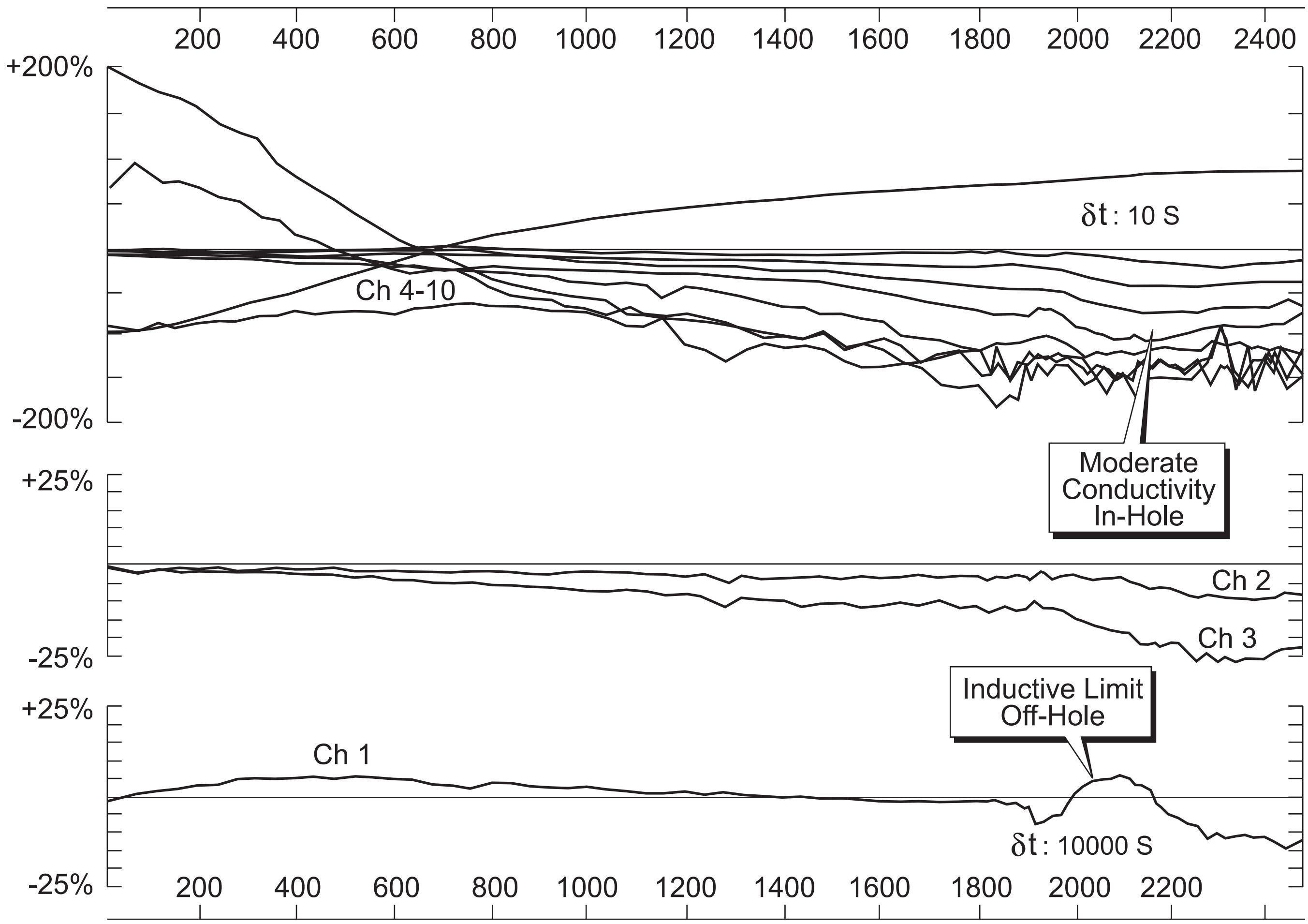

Figure 6: *UTEM survey, NRD-8, axial component, September, 1993.*

JOE LAKE ZONE (WISNER TOWNSHIP—SUDBURY)

An example of 400 m+ depth penetration for a discrete massive-sulphide target using fixed-loop time-domain EM

Falconbridge's Joe Lake Property (Figure 1) is located on the North Range of the Sudbury Igneous Complex (SIC), 30 km east of the Onaping/Levack cluster of Inco and Falconbridge Ni mines. Falconbridge obtained mineral rights to approximately 11 km of SIC contact between the period 1940–1973. Until 1993 very little exploration had been carried out on the property, ostensibly due to lack of easy access. Inco had defined a small deposit, ie., 205 000 tonnes at 2.22% Ni and Cu, at surface immediately northwest of Falconbridge's property. Other favourable indicators on the property are the shallow dip, < 40° S, apparent thickening of the prospective Sub-layer unit, and evidence for the presence of an embayment structure in the SIC footwall.

In March 1993, Falconbridge contracted out a program of 31 km of deep-penetrating surface UTEM coverage to Lamontagne Geophysics. This survey covers 3 km of strike length and 1.5 km of dip length of favorable SIC footwall contact stratigraphy. The in-loop configuration is not the standard mode of operation for the UTEM system because geometric inaccuracies are more difficult to correct for, but was specified for this survey because of the excellent primary field coupling this configuration would provide to a shallow-dipping Sub-layer–hosted target. Two 1.9 km × 2.5 km loops were surveyed, with measurements of the vertical component of the magnetic field (H_z) taken at a nominal 50 m spacing. Ten channels of data were acquired using a base repetition rate of 31Hz.

The results from this survey are summarized in Figures 7 and 8. The former is a plan profile map of UTEM Channel 3. Note the broad positive peak-type response centered on approximately 1300N. The shape of anomaly is typical of a shallow-dipping conductor for the Z-component. A vertical conductor would produce a crossover-type profile. Though this conductor appears open to the west, a barren hole drilled by Inco at approximately 3750E/1400N provides the apparent western limit to the conductor. Line 3900E is provided as a typical of the full ten-channel response profile over the Joe Lake UTEM anomaly. This set of profiles clearly shows the response from the lake between 1300N to 1600N predominates at early times, after which a more conductive deeply buried target starts to emerge between 1100N->1500N. Computer modeling (Figure 9) using the Multiloop program indicated a conductor varying in depth to top of 375 m to 425 m in the conductance range of 50 s–400 s, and a consistent dip of 30°S. It should be noted that, even at a target depth of 400 m, the UTEM anomaly of between 2–4% on Channels

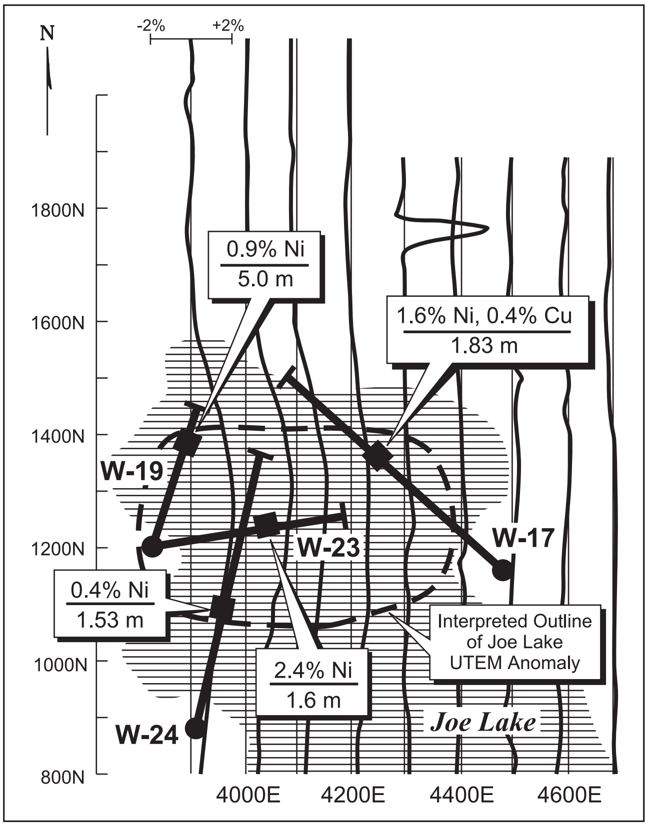

Figure 7: *Joe Lake surface UTEM survey—Channel 3 profiles and follow-up drilling.*

2 to 6 is still well above the noise level of the system, and it is estimated that this conductor would still have been detected at a depth of 600 m.

The first drill-hole into the Joe Lake UTEM anomaly, W-17, intersected stringer to semi-massive sulphide at vertical depth of 420 m, and assayed 1.59% Ni, .39% Cu over 1.83 m. The borehole UTEM results produced an edge-type anomaly, i.e., in-hole polarity at early times, off-hole signature at late times, and the conductor was subsequently tested from the west shore of the lake with holes W-19, 23 and 24. Holes W-19 and 24 obtained sub-economic mineralization at the target horizon, while W-23 intersected 2.43% Ni, 0.16% Cu over 1.59 m. Holes W-19 and W-24 were surveyed with both the UTEM single-component and Boliden three-component systems, the latter a proprietary frequency-domain system. The Boliden 3-D vector-based filament inversion interpretation system (Pantze *et al.*, 1986) was used to interpret the two holes. The results confirm that W-19 and -24 (Figures 10 and 11) intersected the north and south edges of the Joe Lake UTEM target respectively.

W-23 could not be logged due to hole blockage, but it is interpreted from surface and other borehole EM data to have passed through the middle of the mineralized zone. A comparison of the axial component data in W-24, for the Boliden and UTEM systems, is shown in Figure 12. A close match between UTEM Ch4 and the Boliden 238 Hz in-phase component is evident.

Subsequent drilling to the south and west of the UTEM target did not intersect any mineralization. Though this prospect proved ultimately to be non-economic, the depth at which it was intersected doubled Falconbridge's previous record for discrete massive sulphide target detection for a surface EM survey. Informal discussions with geophysicists from other mining companies confirm the relative scarcity of successful testing of surface TEM targets at depths greater than 200 m. No doubt the shallow geologic dip and the choice of an in-loop survey configuration were critical factors in this technically successful exploration program.

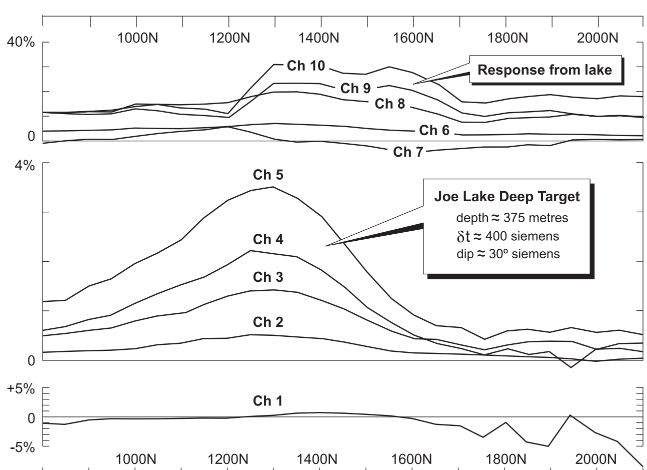

Figure 8: *UTEM survey, Joe Lake, L3900E.*

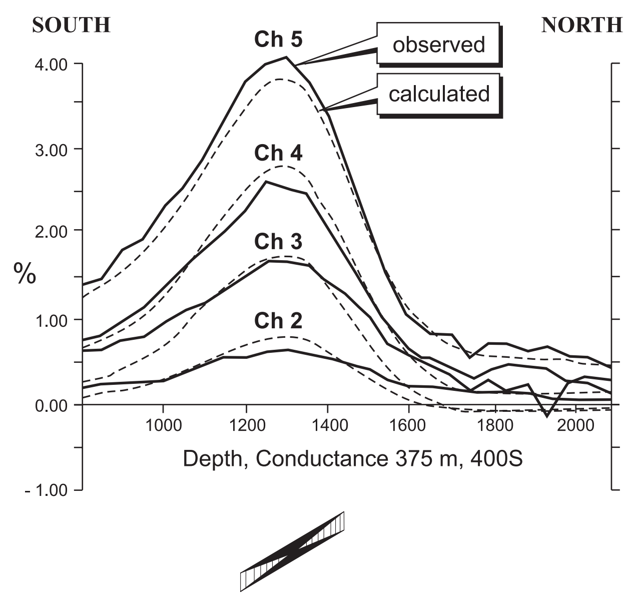

Figure 9: *Line 3900E multiloop model, Joe Lake.*

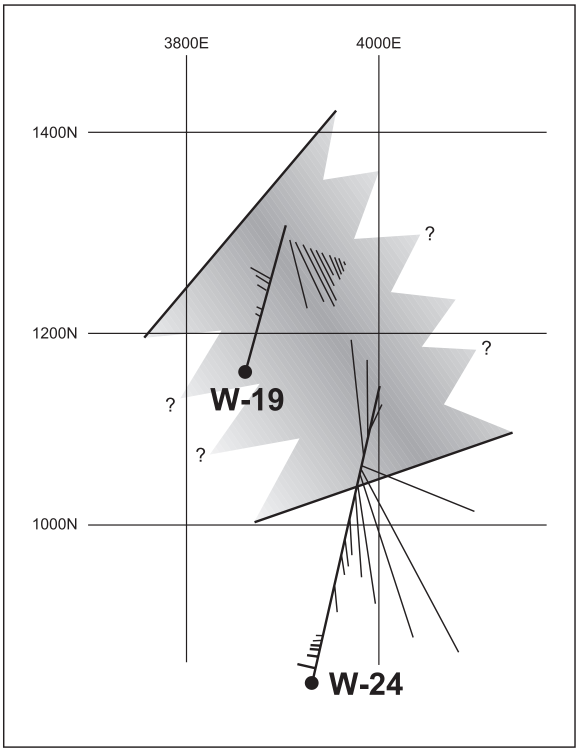

Figure 10: *Joe Lake, Boliden three-component EM, 238 Hz, plan view. Secondary field vectors and interpreted conductor.*

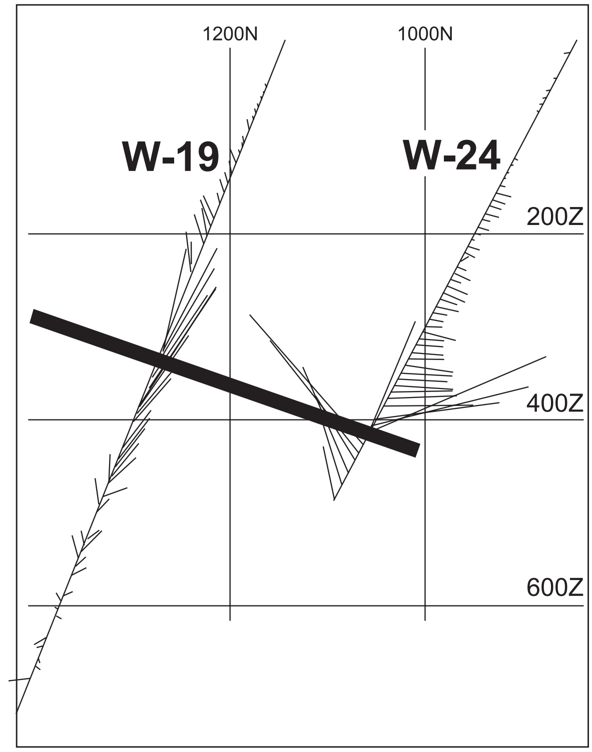

Figure 11: *Joe Lake, Boliden three-component EM, 238 Hz, cross-section looking east. Secondary field vectors and interpreted conductor.*

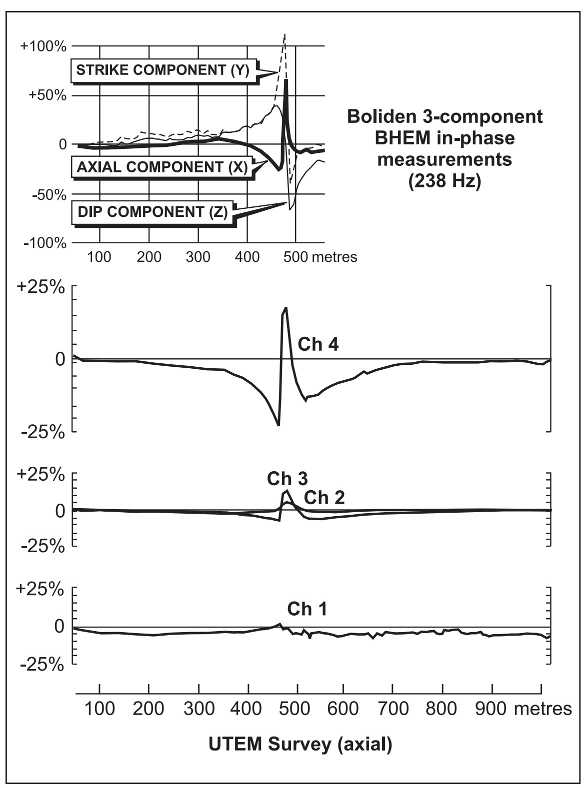

Figure 12: *W-24 Boliden/UTEM comparison, Joe Lake.*

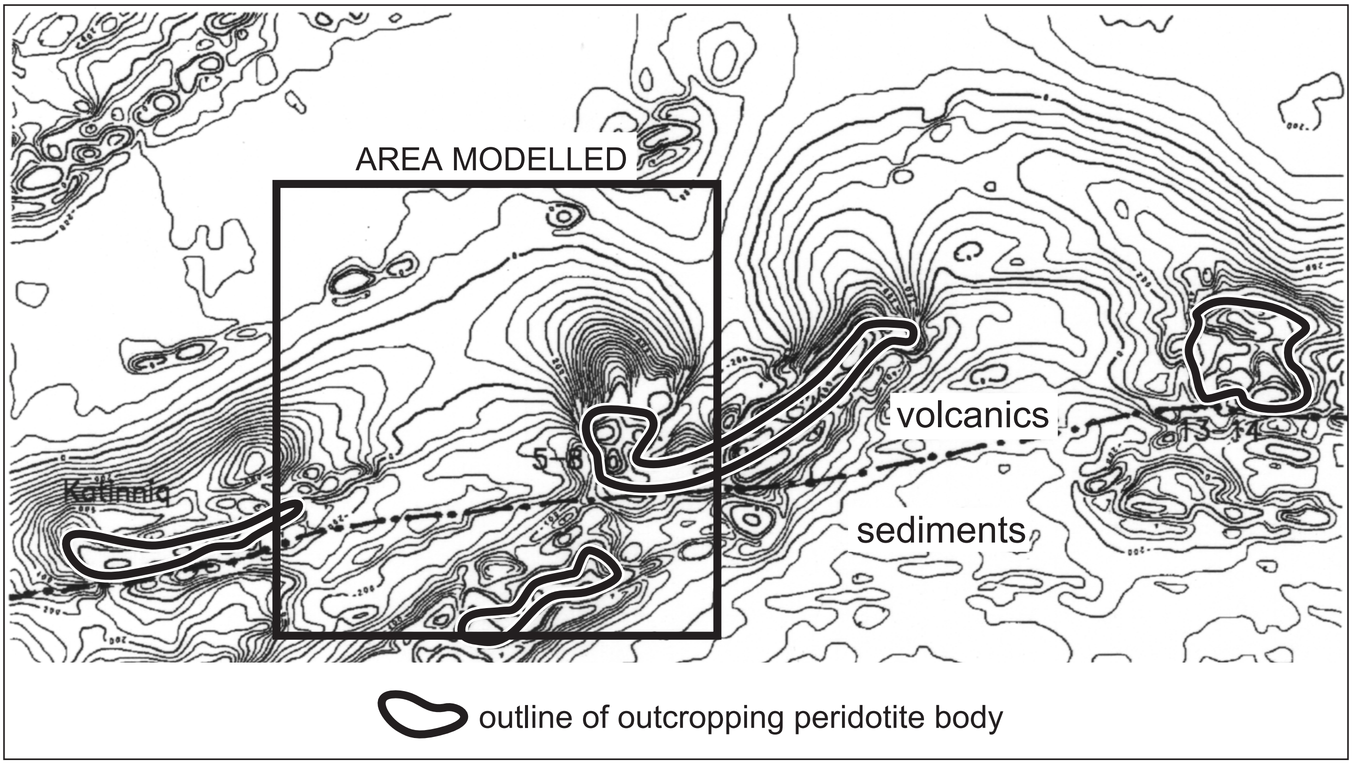

Figure 13: *Total field aeromagnetics, general geology, and area modelled with MAG3D, Katinniq Area, Raglan Project.*

KATINNIQ-EAST DEEP PROJECT

Example of the application of 3-D magnetic modeling and visualization to the mapping of at depth of prospective ore-bearing stratigraphy.

The Katinniq deposit (Figure 13) consists of 8 mt of 3%Ni, .8%Cu and will be Falconbridge's first production site when the Raglan Project comes on stream in late-1997. The deposit is located in the Cape Smith Belt, Ungava Peninsula, Québec. The Raglan nickel ore bodies are dotted along the entire length of a 50 km belt of ultramafic rocks, that belong to the Chukotat Group and the Katinniq deposit is the largest of those discovered to date.

This belt of ultramafic rocks consists of a complex assemblage of peridotite, gabbro, pyroxenite, with a footwall of Povungnituk sediments, and a hanging wall of basaltic lavas. Ore bodies discovered to date are hosted by what have appeared to be discrete 2–3 km-long bodies of strongly magnetic peridotite, which frequently are associated with a non-magnetic and barren basal gabbro unit. Magnetic susceptibilities of the peridotite unit fall in the range of $30\text{-}70 \times 10^{-3}$ SI units. The peridotite bodies were originally thought to be intrusive in nature, and were identified as such by individual names such as the Katinniq Sill, 5-8 Sill. Recent work by Lesher *et al.* (1995) suggest that they are in fact extrusive in nature, the product of channelized lava-flow systems.

In 1988, Falconbridge flew a detailed, radio-navigation controlled, helicopter EM and magnetic survey of the entire Raglan belt, at a line-spacing of 100 m. The aeromagnetic results of this survey are depicted in Figure 13, and show the excellent correlation between the numerous known "sill bodies" and high-intensity magnetic features. Note, however, the unusual "fan-like" contour pattern emanating from either end of the known, outcropping peridotite bodies, especially in the eastern half of the belt. At the time the survey was flown, the preferred explanation for this peculiar pattern was that it was the result of a shallow northward plunge to an outcropping peridotite sill whose extremity would invariably exhibit a pronounced change in strike direction. This explanation might have been valid for that area immediately north of a particular sill extremity, but the apparent continuity clearly outlined by the magnetic contours between outcropping sills required further explanation. In all cases, these less intense and broader intervening magnetic trends lie several hundreds of metres north of the mapped Raglan ultramafic belt and ostensibly fall within belt of well-mapped basaltic lavas which are persistently non-magnetic in hand specimen.

In 1989, a proposal that the aeromagnetic data was in fact suggesting that the various Raglan ore-bearing "sill" bodies that lie between the Donaldson and Katinniq deposits—a distance of 20 km—could in fact be linked at depth and were likely to be continuous over this distance, was met with some skepticism. One of the major stumbling blocks to making a convincing argument at the time for this hypothesis was the inability of the geophysicist to model and represent accurately the magnetic data in three dimensions.

In 1994, Falconbridge, as part of a consortium supporting development of 3-D geophysical modeling code at the University of British Columbia, obtained MAG3D, a program that allows the geophysicist to take the total field values from an airborne or ground magnetic survey and calculate a 3-D earth model which would produce the observed

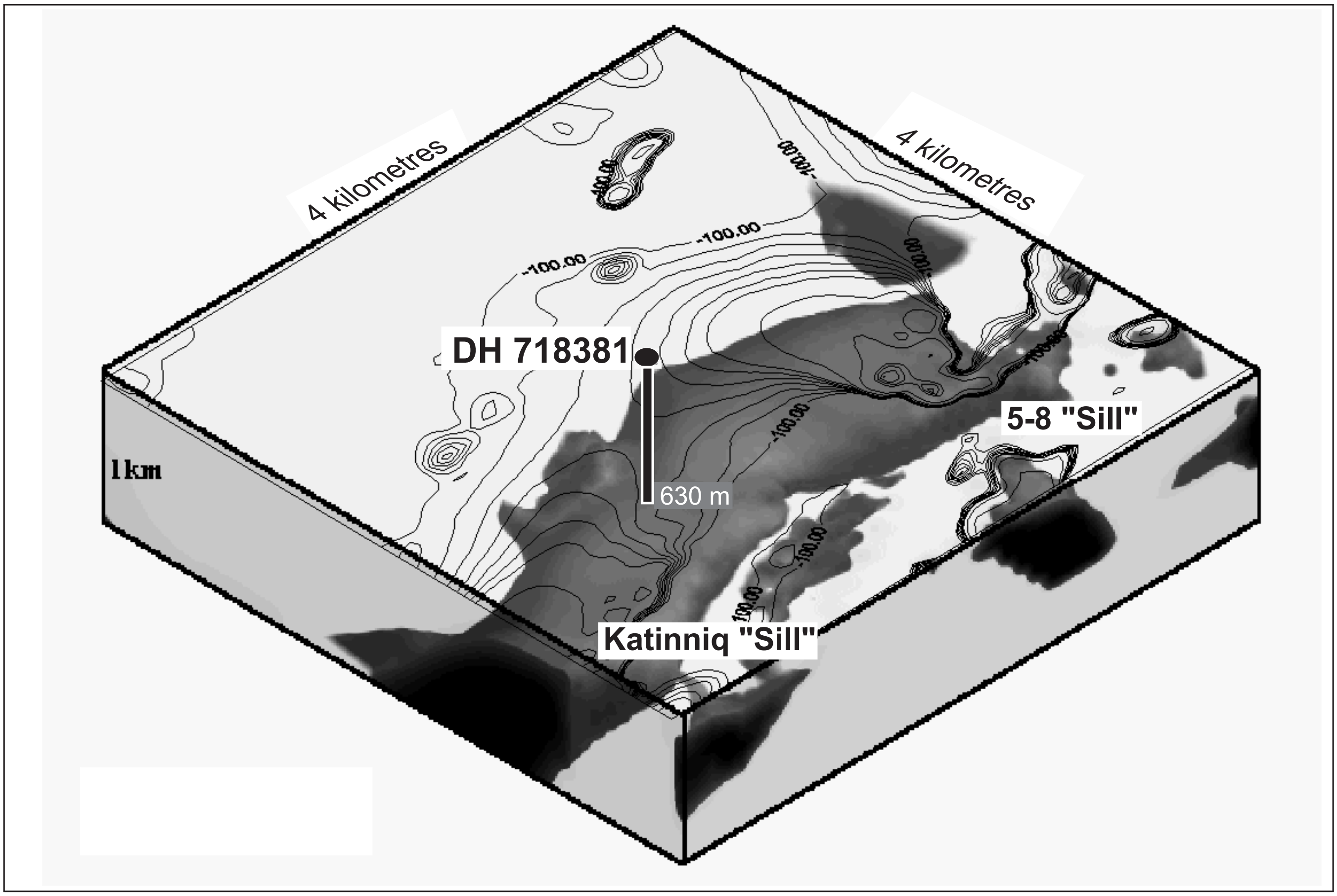

Figure 14: *Rendered 3-D isometric view of MAG3D inversion results, BH 718381 and superimposed aeromagnetics, Katinniq/ 5-8 Area.*

data. The area between the Katinniq and 5-8 "sills" was used as the guinea pig for this new program whose output is a 3-D mesh of rectangular or cubic blocks of susceptibilty values which would best fit the observed total field data set.

The results from this 3-D magnetic modelling are shown in Figure 14. Because MAG3D solves for the entire data volume, in representing the results in 3-D a lower limit to the susceptibilities portrayed is usually set. This figure represents all susceptibilities 40×10^{-3} SI and above. It quite clearly shows that the Katinniq and 5-8 "sills" are linked at depth. Project geologists were significantly more receptive to drill-testing the area between Katinniq and 5-8 after being presented with the 3-D model.

As a result, DH 718381 was collared in June, 1995, and ultimately drilled to a depth of 1050 m. This drillhole intersected a highly magnetic peridotite unit from 650 m to 980 m. This depth and thickness (330 m) agrees within 10% of that predicted by MAG3D and also more traditional 2-D magnetic modeling of profiles in the area. Of added importance was the intersection of a 10 m thick intersection averaging 0.85% nickel in the middle of the peridotite body. The success of this deep "wild-cat" hole suggests that many of the Raglan Ni-bearing peridotite bodies east of the Katinniq Deposit, instead of being isolated pods, could in fact be connected at depth. A program to systematically test for these buried extensions has been initiated.

This case-history illustrates how powerful modelling and visualization tools, available on the desktop computer only since the early 1990s, can provide the geologist and/or exploration manager with an easily understood representation of a geophysicist's oftimes esoteric ramblings.

LOMA CARIBE NICKEL LATERITE DEPOSIT, DOMINICAN REPUBLIC

An example of the usage of ground-penetrating radar to measure thickness of the limonite layer in a laterite profile

The Falcondo nickel laterite mine is located in the interior of the Dominican Republic, 80 km north of Santo Domingo (Figure 15). It has been owned and operated by Falconbridge since the late 1960s. It produces approximately 30 million tonnes of Ni ore per year, at an average grade of 1.6%.

Nickel laterite deposits are produced by tropical weathering of ultramafic source rock. The source rock is usually dunite or peridotite containing 0.25->0.4% Ni that has substituted for magnesium in olivine. Weathering causes the nickel to be leached out of the bedrock, resulting in a nickel-rich (as much as 2-3% Ni) overburden profile. This

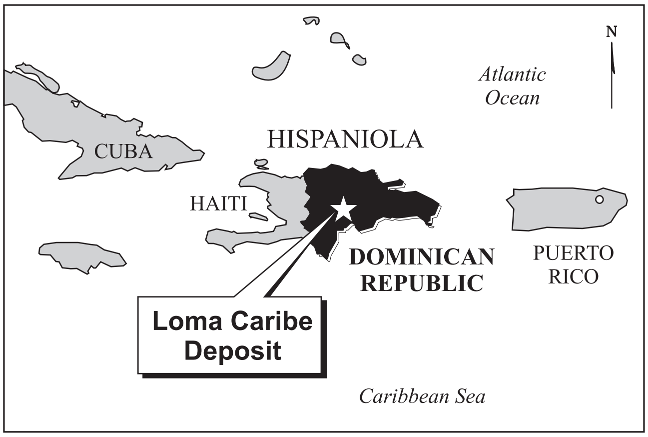

Figure 15: *Location of Loma Caribe nickel laterite deposit, Dominican Republic.*

overburden profile can generally be divided into two major components, an upper soft sediment-like limonitic layer and a lower saprolitic (serpentinite) layer which is made up of blocks of Ni-rich serpentinitic boulders encased in a limonite matrix. A typical Ni laterite profile can be extremely variable in thickness and composition, and at Falcondo the normal routine is to drill percussion holes at least every 10 m for mine planning purposes.

In August, 1995 it was decided to test the GPR method at Falcondo to ascertain how effective it might be in mapping a typical laterite profile. Several case histories at the time detailed the use of the technique in measuring overburden thickness for placer gold deposits, environmental, and engineering purposes, providing a reasonable degree of hope that the technique would work for laterites. The Loma Caribe laterite deposit was chosen as the primary test site as it had been drilled off at close intervals was not being actively mined at the time of the survey.

The GPR method

The GPR method detects changes in permittivity and conductivity. A portable transmitter emits high frequency (25 MHz to 1000 MHz) pulses which propagate as wave fronts, not too dissimilar from seismic waves, into the underlying overburden and bedrock. When the radar wave front encounters a conductivity/permittivity boundary, part of the wave energy is reflected and part refracted. The reflected signal is detected by a receiving antenna located from 0.5 m to 3 m away, depending on the frequency employed, from the transmitter antenna. Depth to the reflecting boundary can be determined, as it is in conventional seismics, by taking the product of the two-way travel time and average velocity through the propagating medium.

For this test survey, a Pulse Ekko IV system, manufactured by Software and Sensors of Mississauga, Ontario, was used. Data were collected with transmitting and receiving antennae in direct contact with the surface to provide maximum antennae-to-overburden coupling. Reading interval for the 150 m long Loma Caribe traverse was 0.5 m, and the frequency employed was 25 MHz. Initial tests with the higher resolution, and logistically more convenient 100 MHz antennae indicated that this frequency was not capable of much more than 10 m penetration, insufficient for the purposes of the test.

GPR test results

Figure 16 shows the GPR results with interpreted major regime boundaries and actual drill hole results superimposed. It is immediately evident that the GPR wiggle-trace section can be divided into three

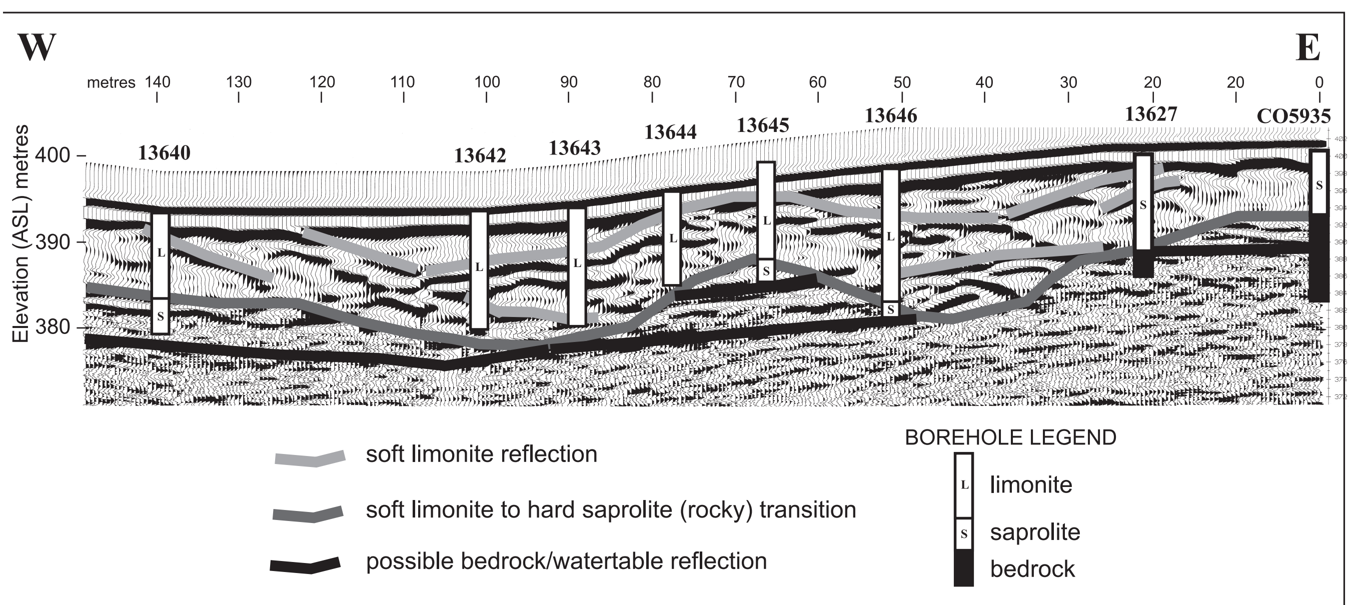

Figure 16: *Loma Caribe 25 MHz GPR section, with geophysical interpretation and drill results.*

major regimes vertically. The uppermost regime, a set of two high energy continous reflectors, correlates to the direct arrival wave, below which is a regime of low velocity, relatively coherent reflections, which in turn is underlain by a much "noisier" discontinuous, short wavelength regime. The boundary between the latter two regimes has been interpreted as representing the limonite/saprolite interface and is demarcated with a red line. Drill holes, with the actual depth to the base of the limonite indicated, i.e., the L/S boundary, in general show an excellent correlation with the interpreted depths. An exception is noted at the right side of the section, where significant departures in two drill holes are evident. These two drill holes were in fact located 5-10 m off the survey traverse and it is suggested that they are not in fact representative of the laterite profile immediately below the traverse. It was hoped that the GPR method might also be able to map saprolite/unweathered bedrock boundary. A semicontinuous reflector within the lowermost, "noisy", regime has been interpreted as representing this interface, but unfortunately no holes are available to corroborate this interpretation, but it is felt that this correlation is a much more suspect than the well-defined limonite/saprolite transition.

From the GPR test at Loma Caribe it was concluded that the method is capable of providing accurate and timely information on the thickness of the limonite portion of a typical laterite profile and the possibility of using the technique in the exploration of new laterite deposits in the Ivory Coast and New Caledonia is being considered.

CONCLUSIONS

The four case histories presented above showcase but a small cross-section of the plethora of new and exciting geophysical tools available to the mineral exploration geophysicist in the 1990s. The BHEM case history presented highlights the need to be continuously questioning traditional ways of processing and interpreting geophysical data. The search for nickel deposits remains a challenging one, especially when considering that any new ore found in the existing major nickel mining camps of the world will likely be at depths greater than a kilometre. It is predicted that recently refined deep-search techniques such as three-component BHEM, audio-magnetellurics, and 3-D seismics will become much more commonplace in future nickel exploration programs.

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