Paper 45

Review of Geophysical Technology for Ni-Cu-PGE deposits

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ABSTRACT

As in the case of the geological models for Ni- CU-PGE deposits, a wide variety of geophysical signatures of Ni-Cu-PGE deposits can be generated by variations and combinations of the relatively few principal minerals that make up these deposits with a variety of host rocks. By studying the physical properties of the principal ore minerals and the common associated host rocks is possible to understand the geophysical signatures of most deposits of this type. It should be noted though, that nature has a way of complicating things and that unusual deposits should be expected. The sulphide ores of Ni-Cu-PGE sulphide deposits are strongly anomalous in virtually all physical properties including electrical conductivity, chargeability, density, magnetic susceptibility, natural radioactivity, and acoustic velocity. This combination of physical properties makes the detection of significant concentrations of NI-Cu- Sulphides fairly straightforward. Unfortunately, the common association with other conductive, dense, magnetic rocks and minerals such as pyrrhotite, mafic/ultramafics rocks, magnetite etc., makes the signatures non-unique. Recent developments in nuclear assaying outside the laboratory are opening the door to direct element identification, so far only at close range. A number of examples are presented that that illustrate the geophysical complexity of real deposits and some of the new or improved methods. Due the fundamental ambiguities in our process of geophysical methods based on physical properties it is essential that multidisciplinary methods be used, including geology, geochemistry, and geophysics in integrated models to maximize the efficiency of exploration programs.

INTRODUCTION

This review follows a previous summary of the geophysics in this field by an Inco geophysicist 40 years ago. The paper was titled “Geophysical Exploration methods for Nickel” and was presented by John Dowsett, Inco Chief Geophysicist, at Exploration 67 published by the GSC in 1970 (Dowsett, 1970). There was also an excellent review of the subject by Watts (1997) at the last decennial exploration meeting.

This paper is an attempt to capture the current state of the art by reviewing the fundamentals of geophysics for nickel sulphide (NiS) deposits and providing some examples that illustrate the complexity of real deposits and some of the new or improved methods.

Economic concentrations of nickel sulphides and associated metals are geologically rare but are quite distinctive geophysically as they are highly anomalous in almost all physical properties. Unfortunately none of the responses in themselves are unique due to interference from other geophysically anomalous materials. Hence good geology and integration of all methods are key to exploration.

As in the case of the geological models for NiS deposits discussed in this meeting (Lightfoot, 2007) where a wide variety of deposit types can be generated by variations and combinations of relatively few fundamental processes, variations and combinations of a few ore forming minerals and common ore source rocks (mafic/ultramafic or M/UM) with a wide variety of host rocks can produce an endless variety of geophysical signatures.

By studying the physical properties of the principal ore minerals and common associated host rocks rocks it is possible to understand and hopefully predict the geophysical signatures of most deposits of this type in various geological environments . It should be noted though, that nature has a way of complicating things and that unusual deposits should be expected.

PHYSICAL PROPERTIES

The ores of magmatic Nickel-Copper Sulphide deposits, which typically include (in order of abundance), pyrrhotite, pentlandite and chalcopyrite are anomalous in most physical properties including electrical conductivity, chargeability, density, magnetic susceptibility, natural radioactivity and acoustic velocity. This combination of physical properties makes the detection (as opposed to discrimination) of significant concentrations of Ni-Cu- sulphides fairly straightforward. Figure 1 (Killeen et al., 1995), which shows physical property logs for most available geophysical logging systems in a Sudbury area test site, illustrates the variety of physical properties measurements that are available to us. Note that the massive NiS ore, mainly pyrrhotite, highlighted in red, is anomalous in

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almost all the logs. This figure provides a menu of relevant physical properties which can be used to determine optimum survey methods. The best method or combination of methods in any particular environment will depend on many factors including depth penetration/range, resolution, interference from other geological features, cost etc.

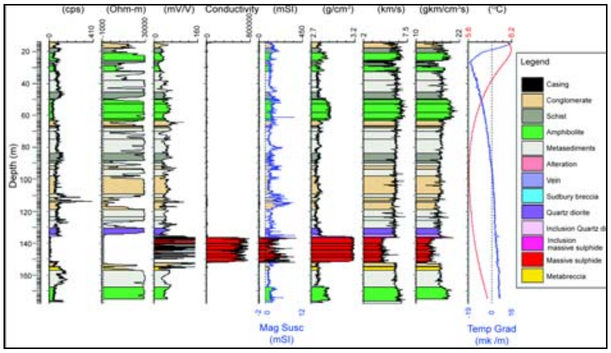

Figure 1: Physical Property Logs - McConnell Deposit BH 78930-0 (from Killeen et al., 1995)

Unfortunately the common association of the NiS ore minerals with other variously conductive, dense, magnetic mafic/ultramafics rocks as well as barren minerals such as pyrrhotite, magnetite and graphite makes the responses non-unique. In most cases pyrrhotite is the main sulphide mineral and usually dominates the physical properties of massive NiS ores. Because of this we are usually not able to directly detect the principal nickel sulphides such as pentlandite and millerite. To simplify terminology in the following discussions I will refer to the assemblage pyrrhotite, pentlandite, chalcopyrite and the associated minor sulphides as Ni-Cu-S's or just NiS's.

The principal physical properties of the principal Ni-Cu-S's are reviewed below with the object of assembling a toolbox of suitable geophysical methods. Then geophysical responses from a number of deposits including Thompson, Voisey's Bay and Sudbury (with locations shown in Figure 2) will be used to illustrate some of the applications with particular attention to complications and recent developments.

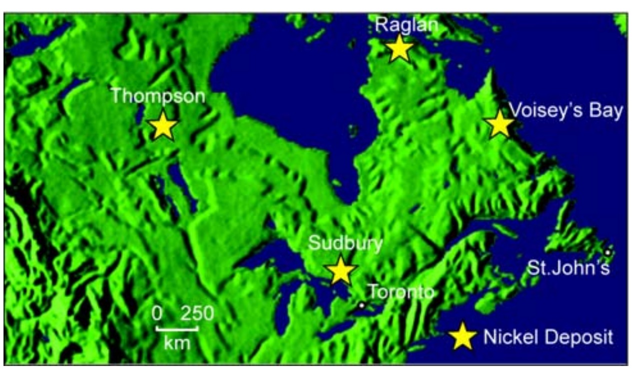

Figure 2: Site Location Map

Following these examples there is a general discussion of methods again with a focus on complications and recent developments. Because of their low concentrations, physical properties of PGE minerals are not usually apparent in bulk measurements, would be generally difficult to measure, and are not tabulated here.

Density

As can be seen in Table 1 density is a good indicator of sulphides and igneous rock type and as such can be used for direct detection of M/UM rocks and direct detection and quantitative measurement of NiS ore. Density can be measured directly on rock samples, in drill holes using gamma-gamma probes or inferred from airborne, ground, or borehole gravity measurements. It is also plays an equal part with acoustic velocity in the acoustic reflectivity coefficient, an important factor in hard rock seismic where velocity variations can be small and density values dominate the reflectivity.

Table 1: Ni-Cu -Sulphide Ore Mineral and Host rock Densities

Rock Type	Range (g/cc)	Average (g/cc)	Reference
Sulphides			
Pyrrhotite	4.5-4.8	4.65	Telford et al 1990
Pentlandite		4.8	Mateck 2007*
Chalcopyrite	4.1-4.3	4.2	Telford et al 1990
Host Rocks			
Felsic Igneous	2.3-3.11	2.61	Telford et al 1990
Mafic Igneous	2.09-3.17	2.79	Telford et al 1990
Ultramafic rocks (Peridotite)	2.78-3.37	3.15	Telford et al 1990

*Mateck Gmbh, 2007, http://www.mateck.de/MeSiCrys/e21e.asp

Until recently there were rarely regional or property scale gravity measurements available with good resolution. However this is changing quickly with the rapid deployment of airborne gravity gradiometer systems.

Higher densities are largely controlled by iron content in most rocks and minerals so the major minerals or rock types which can interfere with the direct detection of Ni-Cu-S orebodies are iron oxides and barren Fe sulphides and the dense M/UM rocks themselves. In general M/UM rocks and iron oxides are not highly electrically conductive on a large scale and electrical conductivity can usually be used to discriminate between base metal sulphides and Fe oxides and higher density rock units.

Magnetic Susceptibility

As shown in Table 2 Ni-Cu S's and their usual host/source rocks (M/UM rocks) are frequently magnetic but not always. As mentioned above, the physical properties of Ni-Cu-S ores are dominated by pyrrhotite (Po), which is moderately magnetic in its monoclinic form but is essentially nonmagnetic in its hexagonal form (as at Voisey's Bay). This magnetic variability in pyrrhotite's magnetic properties has important consequences for exploration but it also can be critical for mineral processing where magnetic separation is sometimes used to separate magnetic Po from the non-magnetic economic sulphides pentlandite and chalcopyrite.

Table 2: Ni-Cu-Sulphide Ore Mineral and Host rock Magnetic Susceptibilities in SI Units X10^3

Rock Type	Range	Average	Reference
Sulphides/Oxides			
Pyrrhotite	1-6000	15000	Telford et al 1990
Pyrrhotite (mono)		700	Emerson et al 2001
Pyrrhotite (hex)		2	Emerson et al 2001
Pentlandite		<1	Emerson et al 2001
Chalcopyrite		0.7	Telford et al 1990
Magnetite	1200-19200	6000	Telford et al 1990
Host Rocks			
Felsic Igneous	0-80	8	Telford et al 1990
Mafic Igneous	0.5-97	25	Telford et al 1990
Ultramafic rocks (Peridotite)	90-200	150	Telford et al 1990
Ultramafic rocks (Serp)	Mod-high	Mod-high	

The mafic and ultramafics host/source rocks are also usually magnetic but not always. For example the host rocks for the NiS's at Voisey's Bay, nonmagnetic troctolites and ultramafic rocks, can have highly variable magnetism depending on the degree of serpentinization. Adding to this problem is the large quantity of magnetic sedimentary and metamorphic host rocks and even some magnetic felsic intrusive rocks (ie. magnetic granites). As a result of these complications it is felt that density/gravity is often a better guide to NiS deposits and their host rocks than magnetics, However, due to the general lack of gravity data we are often forced to target on magnetic anomalies alone.

Note that remanent magnetism has to be taken into account as well and can cause great difficulties in modeling especially with automated methods. Po in particular can have Q values (ratio of remanence to induced magnetism) over 10 producing significant anomalies from disseminated Po with relatively low susceptibilities.

Electrical Properties: conductivity/resistivity

As shown in Tables 3 and 4 it is apparent that there is a very large contrast between the electrical properties of Ni-Cu-S's and their host rocks. This contrast is of the order of 8-9 orders of magnitude and makes measurement of electrical conductivity by far the most effective single tool in the identification of semi-massive to massive Ni-Cu-S's.

Table 3: NiCu-Sulphide Ore Minerals and Host rock Electrical Resistivities (ohm-m)

Rock Type	Range	Average	Reference
Sulphides			
Pyrrhotite	6-160x10^-6	10^-5	Carmichael 1989
Pyrrhotite (mono)		~3x10^-6	Emerson et al 2001
Pyrrhotite (hex)		~5x10^-6	Emerson et al 2001
Pentlandite	1-11x10^-6	5x10^-6	Carmichael 1989
Chalcopyrite	1.5-90x10^-4	5x10^-4	Carmichael 1989
Host Rocks			
Crystalline Host Rocks	10^3-10^-7	10^4	Telford et al 1990
Overburden	1-1000		

As mentioned previously the geophysical responses of massive Ni-Cu-S's are usually dominated by pyrrhotite which has one of the highest conductivities of any earth material. Only graphite is of the same order or higher but, in our experience, graphite rarely occurs in truly massive crystalline form over large thicknesses ie 10's of meter thick. This makes massive to semi massive pyrrhotite dominated bodies, with or without nickel sulphides, fairly unique in conductance (conductivity x thickness). The high conductivity contrast of massive NiS with their hosts make this physical property contrast the most valuable tool in the search for massive to semi massive Ni-Cu-S's but it requires EM or electrical geophysical systems that can detect and discriminate very high conductance's of the order of 10^3 - 10^7 Siemens and possibly higher.

Table 4: Ni-Cu Sulphide Ore Mineral, Host rock, Magnetite and Graphite Electrical Resistivities (ohm-m)

Rock Type	Range	Average	Reference
Sulphides/Oxides Graphite			
Pyrrhotite	6-160x10^-6	10^-5	Carmichael 1989
Pentlandite	1-11x10^-6	5x10^-6	Carmichael 1989
Chalcopyrite	1.5-90x10^-4	5x10-4	Carmichael 1989
Magnetite	5x10^-5 – 5.7x10^3		Telford et al 1990
Massive Graphitic rock	10^-4 – 5x10^-3		Telford et al 1990
Host Rocks			
Crystalline Host Rocks	10^3 – 10^-7	10^4	Telford et al 1990

Magnetite (Mt) also has intrinsically high conductivity but, due to its mineral habit, it is rarely well connected electrically in unaltered intrusive rock. Emerson and Yang (1994) have documented the conductivity of Mt and shown that even nearly massive Mt can be relatively resistive in spite of its high intrinsic conductivity. However variations in crystal habit (more common in hydrothermal Mt?) or small amounts of sulphides that connect Mt grains can produce high conductivity on large scales.

The electrical resistivity of crystalline rocks is of the order of 10^-4 making the contrast with massive sulphides in this physical property of the order 10^9 - by far the largest and hence the most diagnostic of any of the physical property contrasts.

For these reasons regional, near mine and in mine geophysics for semi massive to massive NiS's has been focused mainly on Electromagnetic (EM) methods that allow the detection of very high conductivities (up to 10^5 S/m and higher) and the discrimination of very high conductance's (10,000's of S. and higher). For example the Ovoid deposit at Voisey's Bay, with about 100m thickness of massive NiS ore, is estimated to have a conductance of about 10^7S and as such is a unique target in this or most other environments. Unfortunately there is not a reliable method for distinguishing between barren Po and Ni bearing Po. This is one of the biggest challenges for NiS geophysics.

In general for massive to semi - massive NiS's EM methods are used as opposed to grounded electrical methods as the EM methods do not require ground contact. As a result EM surveys can be done rapidly and relatively inexpensively from the air, on the ground and in boreholes.The value of EM is quite clear in concept but in practice can be quite complicated as there are a wide variety of EM systems available with quite different capabilities. This will be addressed further in the discussion section.

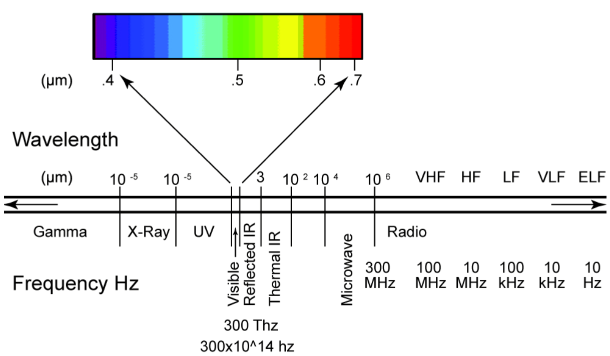

Figure 3: Electromagnetic Spectrum showing visible light range in relationship to more usual low frequency prospecting frequencies

Visual spectrum optical tools are utilized with borehole probes, and on rock samples or drill core. These high frequency EM methods are shown in Figure 3 and borehole images of the walls of the hole using down hole optical televiewers, borrowed from the geotechnical industry, are quite useful particularly in areas with complex structural control such as Thompson, Manitoba, or in footwall Ni – Cu –PGE vein systems at Sudbury. These tools provide detailed optical (figure 4) or acoustic images (not shown) of the drill hole and the images can be plotted on virtual core, that is 3D images of core that are oriented with respect to true north and to dip by accelerometers and dip sensors in the probe.

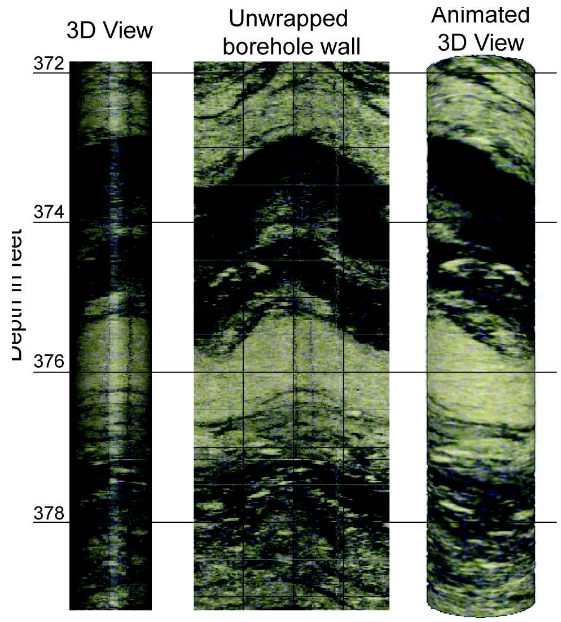

Figure 4: Optical Televiewer Images - Virtual Core - Thompson 1-D Mine

Interpretations of dip planes, lineaments and small folds are done semi automatically on the virtual core and provided to 3D visualization systems as digital data correctly oriented in space (Figure 5). These systems can provide virtual *oriented* core in any hole, old or new, cored or not cored with suitable borehole conditions. This may seem like pretty detailed work but it has been one of the most valuable tools for geologists in structurally complex environments.

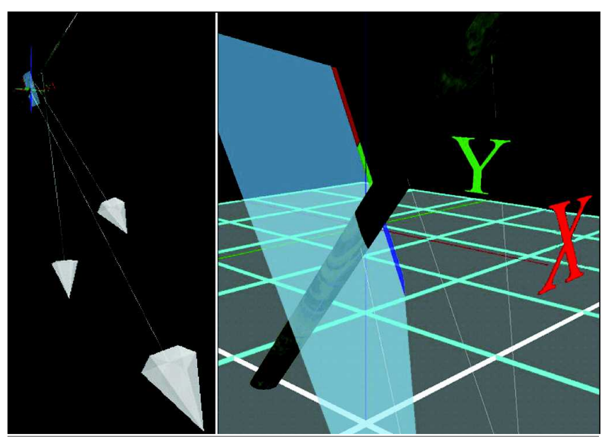

Figure 5: Oriented Virtual Core projected onto drill holewalls in 3D visualization software showing a fold in virtual core and interpreted fold axis surface.

Electrical chargeability

Vein type or disseminated Ni-Cu-S deposits can be very valuable economic resources at current prices if the sulphides have high Ni or Cu tenor or where high concentrations of PGEs add great value to the ore. This is particularly true for large open pittable resources. These factors make disseminated deposits like BHP Billiton's Mt Keith deposit in Australia and Mirabela's Santa Rita deposit in Brazil of considerable interest. Since the Ni-Cu-S minerals all have high metallic conductivity they have high electrical chargeability as shown in Tables 5 and good contrast with most host rocks and make good IP (Induced Polarization)targets.

Table 5: Relative IP Chargeability of common sulphide minerals in msec. for 1% by volume sulphides (measured using a 3 sec square 50% duty cycle wave with integration over 1sec)

Mineral	Chargeability	Reference
Sulphides		
Pyrrhotite	? ~10 ?	
Pentlandite	? ~10 ?	
Pyrite	13.4	Telford et al 1990
Chalcocite	13.2	Telford et al 1990
Copper	12.3	Telford et al 1990
Graphite	11.2	Telford et al 1990
Chalcopyrite	9.4	Telford et al 1990
Bornite	6.3	Telford et al 1990
Magnetite	2.2	Telford et al 1990
Galena	3.7	Telford et al 1990
Malachite	0.2	Telford et al 1990
Hematite	0.0	Telford et al 1990

One significant source of interference when using the IP method in Mafic/Ultramafic (M/UM) rocks is magnetite (Mt). The IP effects of Mt have not been well studied or documented with the exception of AMIRA project P 416 on the electrical properties of magnetite by Emerson and Yang (1994) It is clear though that disseminated Mt can cause chargeability anomalies and its ubiquitous nature in M/UM rocks is cause for concern when using the IP method for low levels of sulphides.

Natural radioactivity

In glaciated terrain, where many of the older large nickel deposits were located, natural radioactivity surveys have not been widely used for Ni-Cu-S's as the overburden is largely transported. With gamma ray penetration of the order of half a meter, measurement of the natural radioactivity due to K, U and Th (Figure 6) has not traditionally been very useful. Also, the natural radioactivity of M/UM rocks and Fe and base metal sulphides have little or no natural radioactivity as shown in Table 6. However, the anomalously low radioactivity of M/UM rocks makes radiometrics a very valuable tool in areas where surface soils have weathered in place as is the case in many low to mid latitude environments. Since radiometric data have been acquired on a regional basis comparable in scale to magnetics in many countries they can, in the absence of or in addition to detailed regional gravity, be one of the best tools to assist in locating M/UM host rocks.

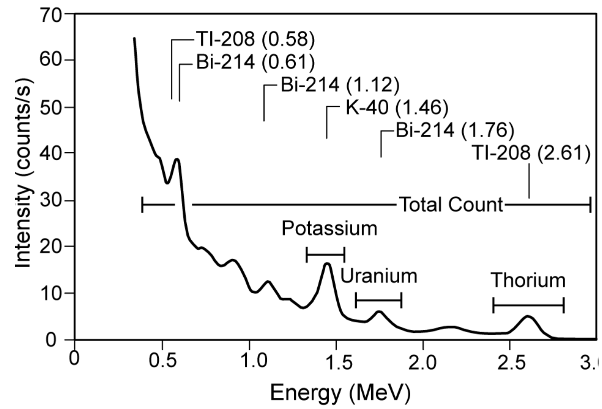

Figure 6: Natural Gamma Spectrum

The virtual absence of U,K and Th in massive NI-Cu- S as shown in Figure 1 also makes natural radiometrics a potentially useful passive radioactive method for identifying massive sulphides in boreholes, (through the absence of a response), as part of grade control programs in blast holes or other non cored drill holes.

Table 6: Radioelement concentrations in different classes of rocks

Rock Type	Potassium (%)		Uranium (ppm)		Thorium (ppm)	
	Mean	Range	Mean	Range	Mean	Range
Acid Extrusives	3.1	1.0-6.2	4.1	0.8-16.4	11.9	1.1-41.0
Acid Intrusives	3.4	0.1-7.6	4.5	0.1-30.0	25.7	0.1-253.1
Intermediate Extrusives	1.1	1.1-2.5	1.1	0.2-2.6	2.4	0.4-6.4
Intermediate Intrusives	2.1	0.1-6.2	3.2	0.1-23.4	12.2	0.4-106.0
Basic Extrusives	0.7	0.06-2.4	0.8	0.03-3.3	2.2	0.05-8.8
Basic Intrusives	0.8	0.01-2.6	0.8	0.01-5.7	2.3	0.03-15.0
Ultrabasic	0.3	0-0.8	0.3	0-1.6	1.4	0-7.5

Acoustic velocity

In conjunction with the Lithoprobe seismic work (Boerner et al., 1994 and Milkereit et al., 1996), done at Sudbury, Salisbury and others (Salisbury et al., 1996) provided acoustic velocity and density data on the principal base metal sulphides for the first time and the results, shown in Figure 7, were quite surprising. Most economically significant sulphides and pyrrhotite are all uniformly very low velocity. This makes them ideal targets for crosshole transmission seismic tomography that measures only velocity. They are also, as discussed previously, anomalous in density, and so they produce acoustic reflectivity anomalies.

However since acoustic reflectivity is proportional to the acoustic impedance (product of velocity x density) their high densities and lower velocities can result in reduced reflectivity.

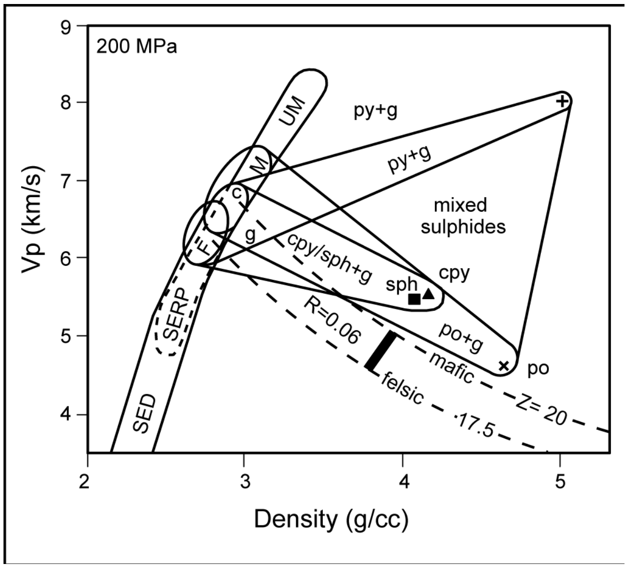

Figure 7: Seismic P wave Velocity versus Density for common rock types (Sed=Sedimenatry, Serp =Serpentinized UM, F=Felsic, M=Mafic, UM =Ultramafic) and common sulphide minerals with lines of constant acoustic impedance Z and typical Reflectivity value R (After Milkereit et al., 2000).

M/UM rocks, due to their high densities and velocities will in general be good reflectors in contrast to their host rocks and seismic reflection surveys from surface or in boreholes are an excellent tool for detailed mapping of mafic intrusive rocks in suitable environments.

The 2D Lithoprobe surveys at Sudbury demonstrated that reflection seismic could be used for mapping lithological contacts and major structures in a layered igneous complex and that discrete sulphide bodies could be detected (Milkereit et al., 2000). Further, 3D seismic surveys at Sudbury showed how seismic can be used in the 3D mapping of lithology, structure and detection (but not discrimination) of large semi massive to massive orebodies.

Active nuclear methods

Developments in active nuclear assay techniques are opening the door to direct element identification in the field and down boreholes but so far only at close range. Pulsed neutron generator technology is also being tested for on-line conveyor belt monitoring of grade and chemistry.

Borehole Neutron Activation

As a result of long term requests, from mine personnel, for improved grade estimates in production blast holes and other non cored holes the first borehole pulsed neutron borehole assay tool designed specifically for mining has been developed by CVRD Inco together with EADS Sodern and Mount Sopris Limited,. Previous tests of oilfield neutron activation tools at Sudbury (McDowell et al., 1998)) demonstrated the potential of these tools in a hardrock environment. The new tool analyzes for multiple elements down hole using a pulsed neutron generator source and BGO detector. (Fig. 8) Preliminary modeling and tests indicate that such systems can provide quantitative assays in a 0.8 m diameter cylinder centered on the hole for Ni, Cu, Fe, S, Cr, Mn, Cu, and Al with accuracy from about 1% for major elements down to about 0.1% for minor elements such as nickel and copper. Such systems can provide improved grade control in blastholes and have the potential to reduce delineation drilling cost through the use of non-coring drilling

Figure 8: Neutron Activation Multi-element Borehole Assay system – In-situ assay for Ni, Cu, S, Fe, Si , Mg, Al, Mn , Cr etc.

Case Histories

A number of examples are presented that illustrate some of the similarities and differences in the geophysical signatures of several major deposits and are used to highlight some new or improved methods.

Thompson Nickel Belt

The following examples from CVRD Inco’s Thompson nickel belt exploration programs are used to illustrate improvements in penetration with audiomagnetotellurics (AMT) and large loop EM as well as data integration with AMT, 3D magnetic inversions, deep drilling and borehole electromagnetics (BHEM). As well, at the other extreme of scale, an example of high resolution in-mine delineation work is presented with a cross hole seismic tomography example. .

EM and Magnetics - Thompson Mine was discovered in the mid 1950's by Inco using the first airborne EM (AEM) system (Dowsett 1970 and Zurbrigg, 1963). The company was brought into the area by favorable geology and a number of nickel sulphide showings but most of the belt was covered by thick moderately conductive glacial deposits and lacustrine clays. The discovery airborne EM and magnetic anomaly is shown in Figure 9 taken from Dowsett's original paper. Note that this was the first commercial scale AEM system but it was also a towed bird on time system operated at relatively low frequency. It was optimized to find NiS targets under cover and there was good reason for these design features as will be discussed in more detail below. In particular off time only (or out of phase only) EM systems can completely miss or at best misclassify the best massive NiS targets.

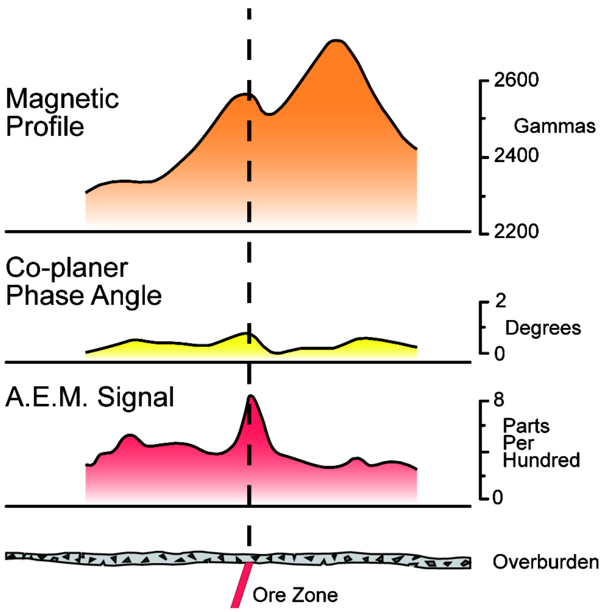

Figure 9: Inco AEM and Magnetics - Thompson Discovery Manitoba.

At the time, first priority was given to shorter strike length targets in close proximity to the large magnetic anomalies associated with large UM rock units. The main Thompson orebody has been structurally remobilized and is not in immediate proximity to large bodies of the UM host/source rocks. Because of this, the discovery anomaly was initially given a lower priority due to the lack of association with larger magnetic bodies and due to the length of the conductor (about 6km). Note the distinctive EM and smaller magnetic anomalies due to the massive pyrrhotite (Po) dominated sulphides and the larger magnetic anomaly on the right side due to a nearby large UM body. Due to the almost complete overburden cover in the Thompson area, geophysics has continued to be one of the primary tools in the exploration of the belt.

Following the initial discovery, the entire belt was covered in the late 1950's and1960's with ground EM surveying using vertical loop EM systems with targeting on the numerous AEM anomalies as well as fairly complete ground coverage. The combination of these airborne and ground systems had a depth penetration of about 100m.

In the last decade, Inco has undertaken to extend the EM coverage to a depth of at least one km for large (minimum 1000m by 1000m) sized deposits using the AMT method in combination with large loop EM, deep drilling and BHEM . This represents a 10 fold increase in depth penetration over the last full coverage of the belt.

AMT and BHEM - Full tensor AMT stations were recorded at 1000' intervals on 4000' spaced lines. Data were inverted on 2D sections with depth penetration in excess of 2km for very large conductive systems. These sections were then stacked in a 3D view as shown in Figure 10. This presentation laid out the large scale conductive stratigraphy of the Thompson belt, which is dominated by sulphidic metasedimentary rocks with some graphite, in 3D to a depth of a least 2 km. Three dimensional inversions of the AMT data were also done. Anomalous areas for followup were selected from the inversions and were apparent in the field resistivity and phase plots.. A single AMT station with only moderate bandwidth in one square kilometer can detect any large conductor (1-2 km in dimensions) to 1-2 km depth for a cost of several hundred dollars per station. This cost is considerably less than of airborne EM costs on a cubic kilometer basis.

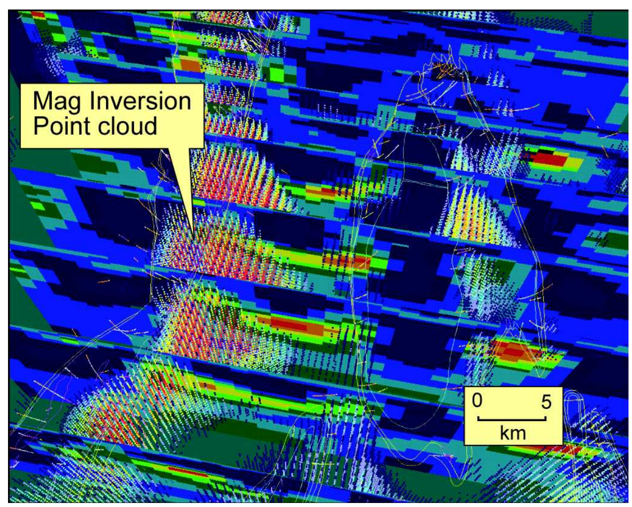

Figure 10: Thompson Nickel belt - AMT 2D stacked Vertical Sections and 3D magnetic inversions shown as point clouds (after Dowsett 1970).

The Thompson Nickel Belt was also resurveyed with helicopter magnetics in the early 1990's and the results have been inverted using the UBC MAG3D inversion code (Li and Oldenburg, 1996, 1997) and higher susceptibility values are shown as a colour coded point cloud in the same figure.

If conductive targets were within range of surface controlled source EM systems (in practice about 700m but potentially deeper) and magnetics and geology indicated a favorable environment the anomalous areas were surveyed with large loop surface UTEM systems with loops designed for optimum coupling with the target geometry derived from the AMT inversions.

In almost all cases significant conductors were located with a controlled source transient TEM (UTEM) systems at the anomalous AMT sites. The UTEM data was used to estimate conductance and detailed geometry and for targets in favorable geology, those with conductances greater than several thousand siemens, were selected for drill testing. As the holes drilled on these deep targets are often greater than 1km in length and there are numerous non-economic, weak to strong conductors in the metasedimentary package, discrimination by relative conductance is critical in targeting massive sulphides.

Figure 11 shows a conductor, interpreted from large loop surface UTEM data which was targeted on a deep AMT anomaly, with a top at about 600m and a bottom at a about 1200m. This target was drilled and intersected near it’s lower edge. Sulphide mineralization, as shown in red, was intersected at about 1500 meters down hole and the hole was surveyed with BHEM to provide more detail on conductor size, quality, and orientation.

Crosshole Seismic - In addition to ongoing surface exploration work there is also considerable work being done to assist the mining operations in mapping the very complex folded geology of the Thompson ore bodies. This is an ideal environment for crosshole seismic tomography as there is a very good acoustic contrast between all the host rocks and the low velocity sulphides. The only other significant low velocity zones are large shear zones but these can be identified in the drill holes or, potentially, by making tomograms of P wave amplitude attenuation.

Figures 12 and 13 show the survey layout for crosshole seismic tomography and a sample survey showing good correlation between low velocity zones shown in warm colours and sulphide intersections shown in red.

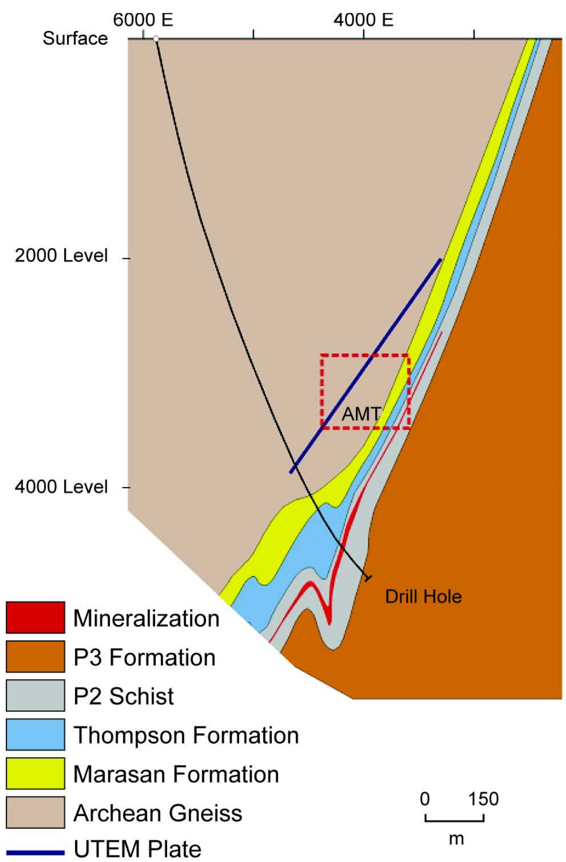

Figure 11: Drilling on a deep interpreted plate conductor which was targeted on a deep AMT target zone (red dashed line box). Depth levels are in feet.

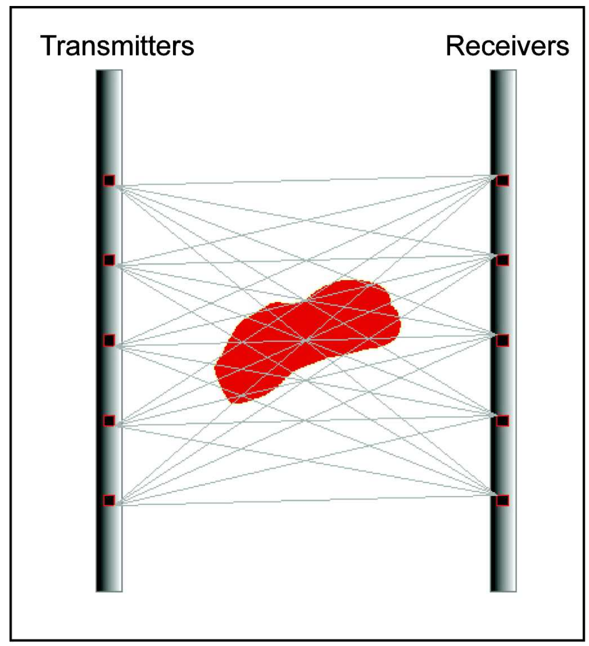

Figure 12: Seismic Crosshole Tomography – Schematic showing sample cross hole acoustic ray paths from transmitter locations in hole on the left to receivers in the hole on the right.

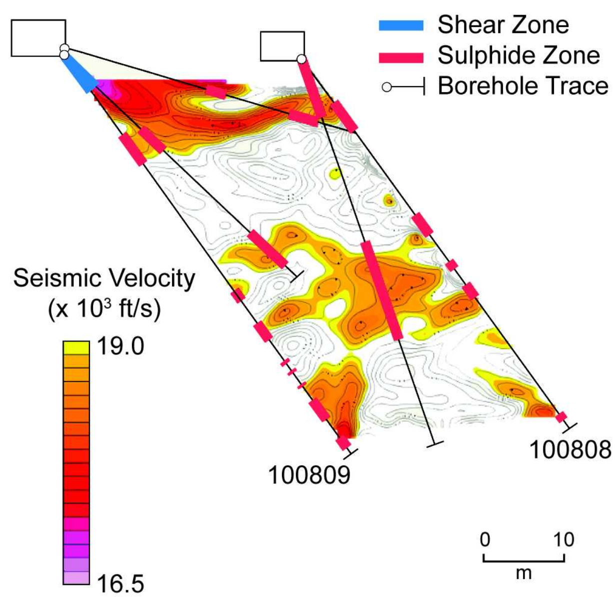

Figure 13: Seismic Tomography image - Thompson 1-D - low velocity zones shown in warm colours and sulphide intersections in drill holes shown as red bars.

Voisey's Bay

The Voisey's Bay deposit provides examples of extreme high conductivity-thickness, magnetic complications, and application of ground, and airborne gravity.

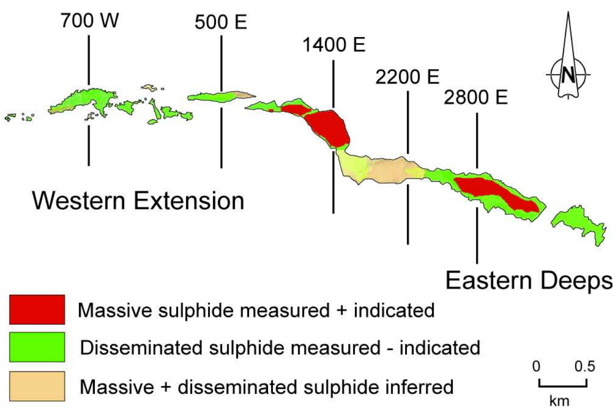

Figure 14: Voisey's Bay Plan Map of Deposits (from Balch 1999)

EM and BHEM - The Voiseys's Bay deposit was discovered by prospectors in 1994 (Crebs, 1996) Lower grade NiS mineralization outcropped on Discovery Hill resulting in a gossan with a significant visible-spectrum, high frequency natural source EM anomaly! Subsequent ground surveying with the MaxMin horizontal loop (HLEM) system and ground magnetics traced the conductive zone under cover into a wider, highly conductive zone. Drilling of this highly anomalous zone led to the discovery of the Ovoid deposit . Following the initial discovery, a DIGHEM frequency domain helicopter EM survey was flown and numerous surface and BHEM surveys were carried out to assist in exploration and to develop a geophysical signature for the deposit. Surveys have included ground and airborne magnetics and gravity, Geotem AEM , surface and borehole large loop EM, AMT, and IP/resistivity. (Balch et al 1998, Balch 1999)

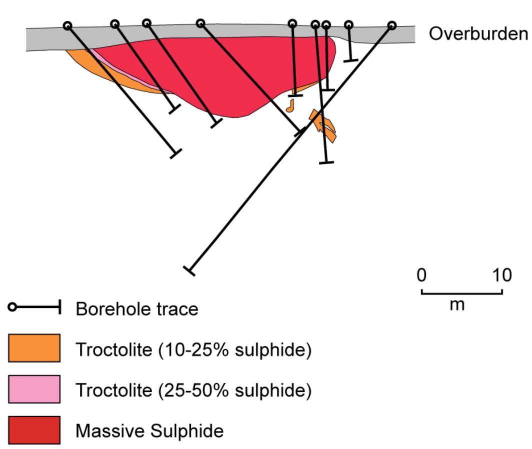

Figure 15: Voisey's Bay Ovoid Deposit 1400 E Section Looking West) (from Balch 1999).

Figure 14 shows a surface plan of the deposits and figure 15 shows a section through the middle of the massive, near surface, Ovoid deposit. Airborne and ground EM surveys on this section through the Ovoid are shown in Figure 16. The extreme conductance of the thick massive mineralization is evident in the high in-phase responses, almost complete absence of out of phase response in the HEM data, and the broad negative, high amplitude last channel UTEM channel 1 response, indicative of a large flat conductor that is nondecaying within the aperture of this 30 Hz survey, system. Decaying responses are evident in the 30 Hz Geotem data . These decaying responses are due to smaller/shorter time constant current systems flowing on the side or corners of the system and possibly in the very minimal disseminated material around the massive core.

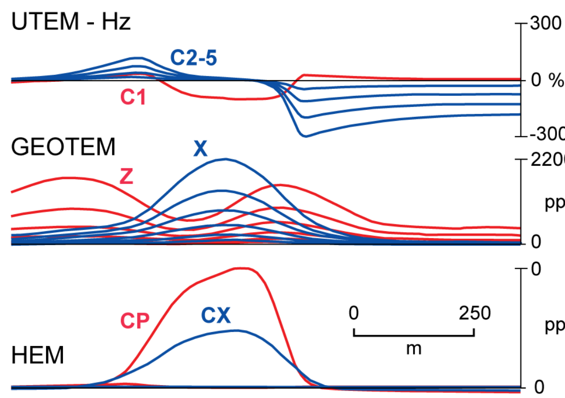

Figure 16: Geophysical Profiles 1400 E Section (from Balch 1999).

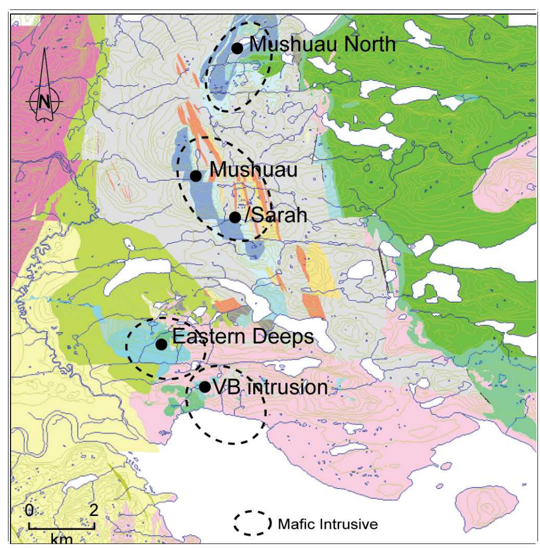

Figure 17: Voisey's Bay Main Block Geology showing main mafic intrusive bodies.

Gravity – The Ovoid itself is located in a widening of a narrow dike and shows a strong 4 milligal anomaly. This anomaly is due entirely to the massive sulphides as the sulphides constitute nearly 100% of the dyke at this location. The mafic host rock in the dike and nearby large chambers is troctolite , a hypersthene gabbro with abundant olivine but little magnetite. Hence it is dense but relatively nonmagnetic and can be distinguished from the other intrusive rocks of the Nain plutonic suite which are dense and magnetic (ferrodiorites), or nonmagnetic and less dense (anorthosites) by its low magnetic and high gravity response. Figure 17 shows the geology of the main property block with the main troctolitic intrusive bodies (labeled) shown in light and medium blue.

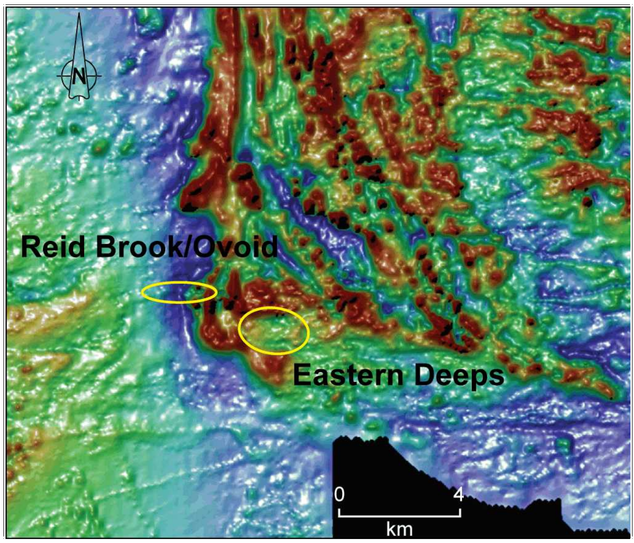

Figure 18: Voisey's Bay main Block airborne total field magnetics/

Magnetics - Figure 18 (after Balch 1999) shows a high quality recent magnetic image over the main block with, as expected no positive magnetic signatures for the troctolitic mafic intrusives, with local magnetism dominated by the Tasuiak gneisses.

To complicate the magnetic situation further the sulphides at Voisey's Bay are mainly hexagonal pyrrhotite and are nonmagnetic! However there is locally intense magnetism over the deposit but this is due largely to significant content of coarse-grained magnetite. So we have the rather surprising situation where neither the associated mafic host/source rock nor the sulphides themselves are magnetically anomalous.

The mineralized system extends to the east of the Ovoid into a large troctolite chamber and extends along the base with about a 20 degreee dip to the east. Geotem AEM responses pick up the mineralization to depth of about 400m and then AMT surveys are able to trace a core of massive and semi-massive mineralization easily to depths of greater than 1000m. The conductive AMT response at these depths comrises a significant halo of disseminated sulphides around semi-massive and massive sulphides .

Regional Gravity and Inversion Models - Figure 19 shows the extensive ground gravity coverage of the main block that clearly delineates the main mafic intrusives. Figure 20 shows the gravity in more detail around the ovoid and figure 21 shows the local gravity signature of the deposit and the results of a tightly constrained 3D gravity inversion using the UBC inversion codes (Li and Oldenburg, 1998), and (Ash et al., 2006).

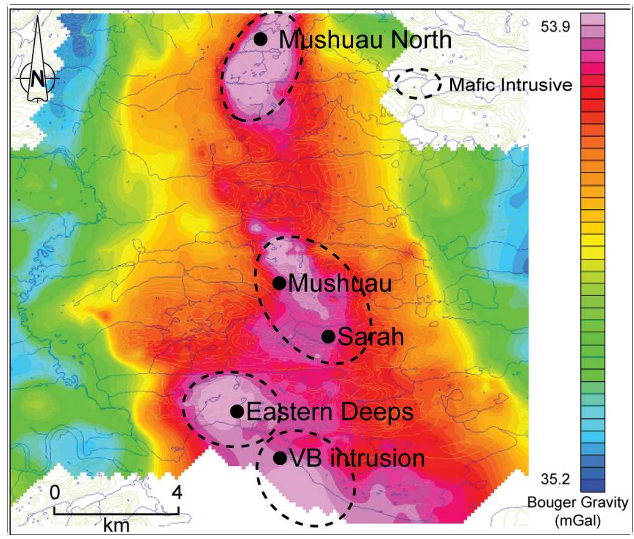

Figure 19: Voisey's Bay Main Block Ground Bouger Gravity

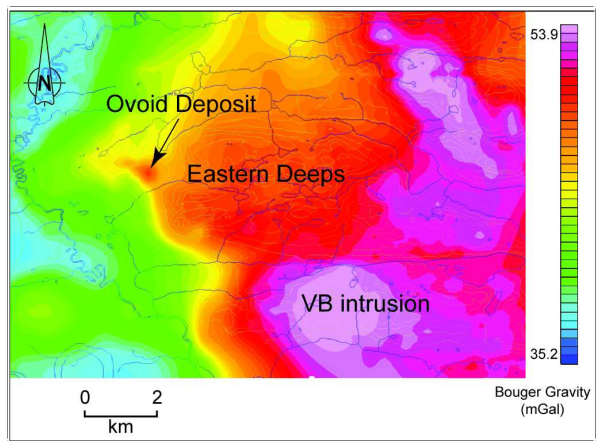

Figure 20: Ground Bouger Gravity over the Ovoid Deposit, and Eastern Deeps, and Voisey's Bay (VB) mafic intrusives.

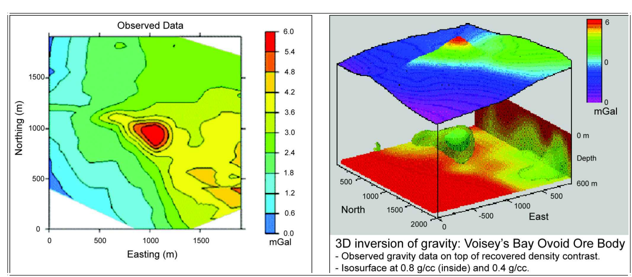

Figure 21: Local Bouger ground gravity response of the Ovoid deposit (left) and constrained 3D gravity inversion using the UBC inversion codes (right) (from UBC-GIF website and Ash et al, 2006).

Due to the success with ground gravity at Voisey's Bay an airborne gravity gradiometer system was flown over the parts of the main block and the surrounding area. This data is largely processed and interpreted and is in the process of being followed up. Airborne gravity is an exciting new tool for all commodities but especially NiS's due the good gravity signatures of the ore and typical host/source rocks

Sudbury

Examples for the Sudbury Igneous Complex (SIC) illustrate camp scale 3D inversions and modeling, 2 and 3D seismic , complex BHEM interpretations and crosshole Radio Imaging (RIM).

3D Modeling - 3D modeling is now playing an important role in exploration. Figure 22 shows a schematic map of the SIC geology. Since the mineralization at Sudbury is controlled by the footwall contact of the SIC there has always been great interest in the overall shape of the basin and any structures that might enhance or reduce exploration potential., As a result integrated modeling of multiple datasets into solid earth 3D geology maps has been done. Parts of this process are discussed here.

Figure 23 shows the traditional 2D colour image map of the regional Bouguer gravity response of the Sudbury Basin. Figure 24 shows the 3D gravity model of the whole basin (a volume approximately 40 by 80km by 5km deep) as determined using the UBC Grav3D inversion codes (Li and Oldenburg 1998). Note the untested denser body in the middle of the basin. This body was apparent in the surface data but 3D modeling and integration with other data sets has increased interest in this feature.

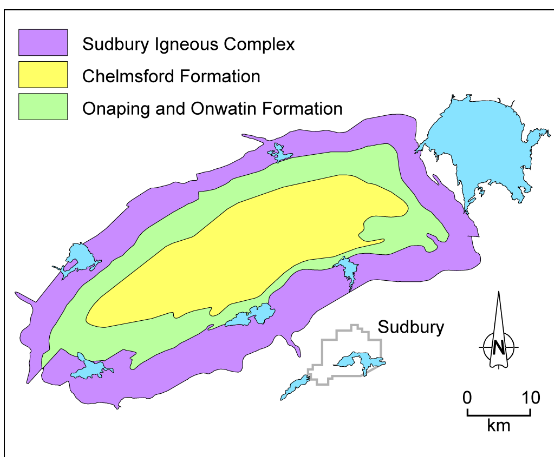

Figure 22: Sudbury Basin - Geological Schematic.

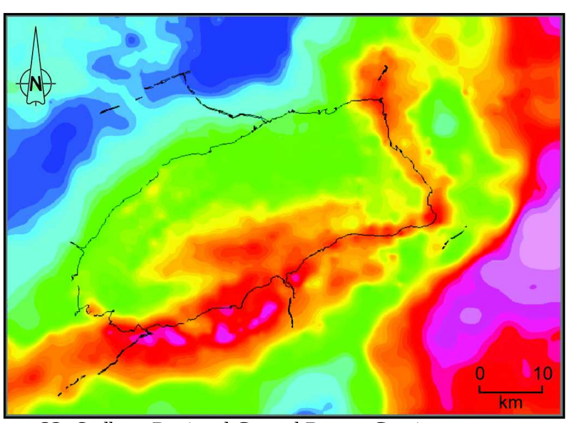

Figure 23: Sudbury Regional Ground Bouger Gravity.

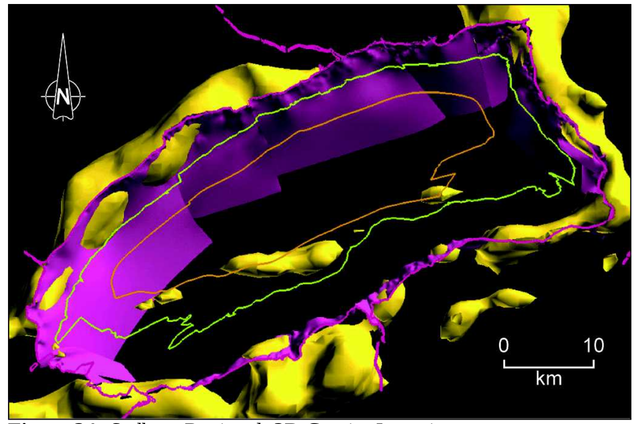

Figure 24: Sudbury Regional 3D Gravity Inversion.

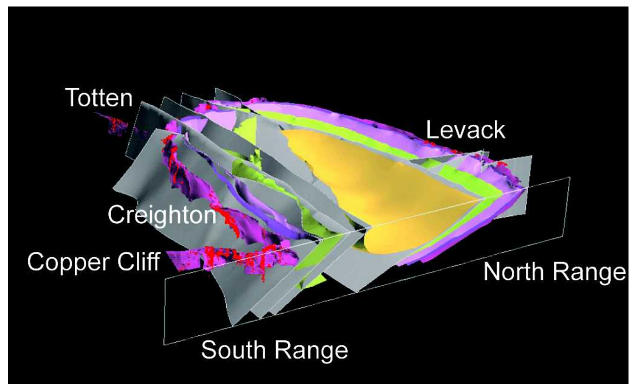

Figure 25: Sudbury 3D Model.

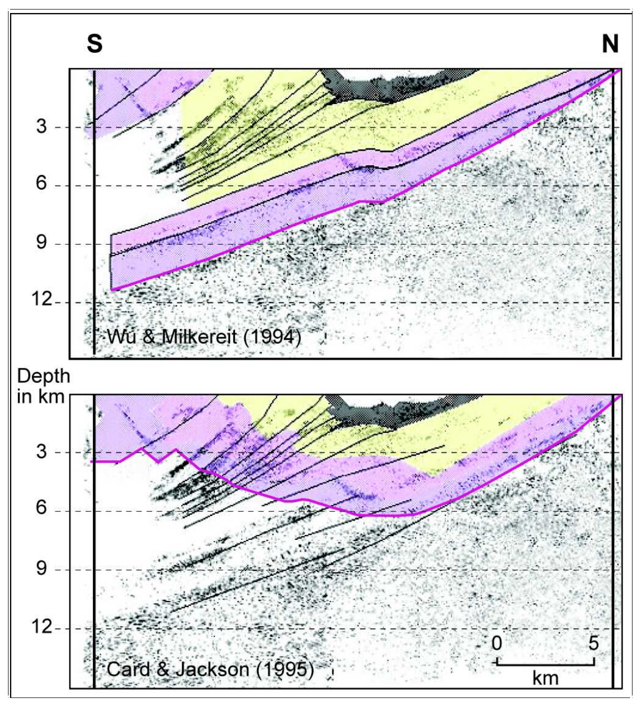

Figure 26: 2D Lithoprobe Seismic Reflection line across the Sudbury Basin showing two possible interpretations at depth.

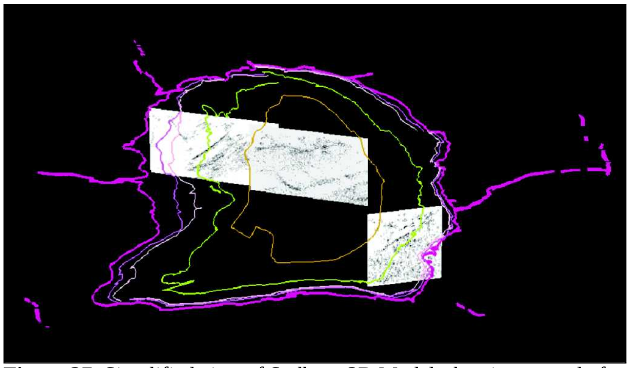

Figure 27: Simplified view of Sudbury 3D Model showing several of the Lithoprobe 2D seismic lines and surface traces of the main geological units.

A simplified view of the current 3D geological model developed in GOCAD is shown in Figure 25. Much of the detail beyond the surface geology and deep diamond drilling is derived from a series of 2D seismic lines surveyed over the Basin by the Lithoprobe seismic project as shown in Figures 26, and 27. (Milkereit et al., 1996)

Survey layout for a subsequent 3D seismic survey (Milkereit et al., 2000) over the relatively unexplored Trillabelle embayment on the west end of the Sudbury Basin is shown in Figure 28. Figure 29 shows some highlights from that survey: the base of the SIC as interpreted from the 3D survey, the known massive to semi-massive mineralization shown as a small black blob at 1800m depth, and a slice through the data cube at 612 msec. showing the expanding reflection from the mineralization.

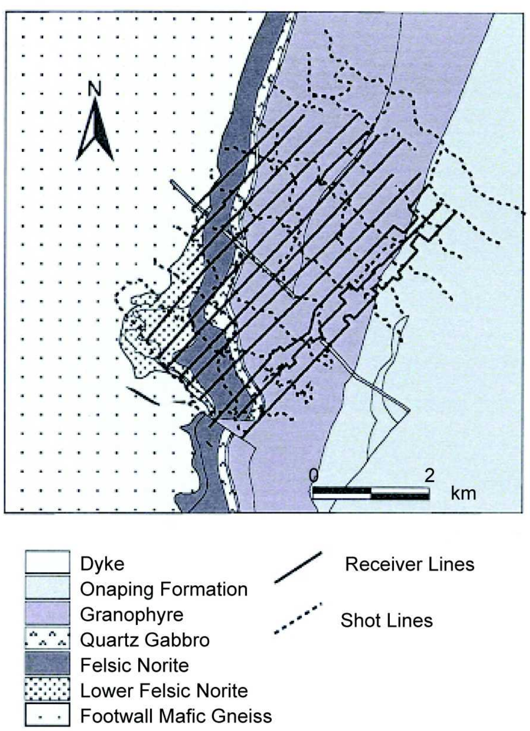

Figure 28: Survey layout for 3D Reflection Seismic survey, Trillablelle area, Sudbury Basin (from Milkereit et al , 2000).

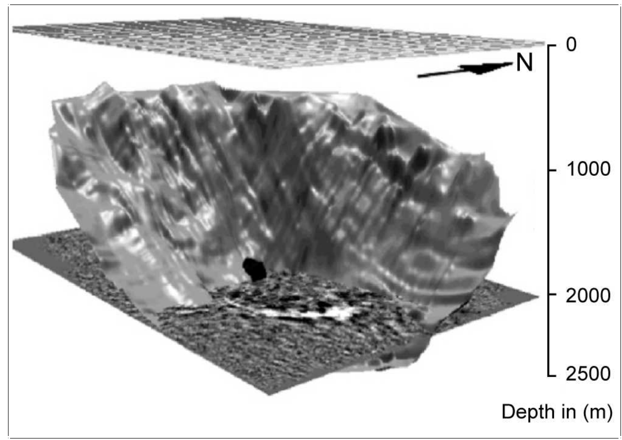

Figure 29: Trillablelle 3D Reflection Seismic survey highlights showing the base of the SIC as interpreted from the 3D survey, the known massive to semi massive mineralization (small black blob at 1800m depth) and a time slice through the data cube at 612 msec. showing the expanding reflection (white semicircle) from the mineralization (from Milkereit et al , 2000)

EM - Since most exploration at Sudbury is now at depths below 1km depth our primary tool for massive Ni-S sulphide orebodies is BHEM. At Sudbury there is an ongoing program, of surface drilling and BHEM logging of new and old surface holes as well as BHEM logging in the underground mines where the receiver and crew can be as deep as 7800' (2400 m) logging down holes that extend to depths of 10,000 ' (3050 m) and more using large surface EM loops. Due the complexity of the in and near mine environment this work is pushing the development of better BHEM interpretation tools such as curved sheets, blobs, multiple bodies, parametric and voxel based inversions, as well as integrated 3D viewing and modeling environments to handle the mass of geophysical and geological data.

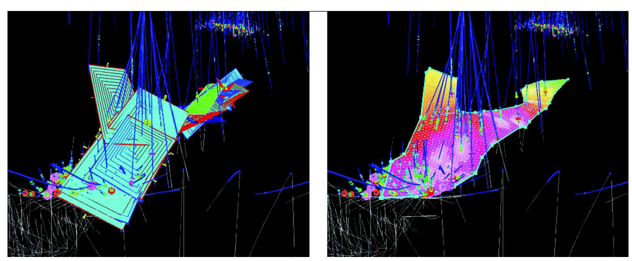

Figure 30: BHEM interpretation of multiple complex bodies: Left - current plate based iterative forward modeling and parametric inversion Right - new and future tools - automated iteration of surface facets on multiple curved sheets or solid bodies.

Figure 30 illustrates the evolution of BHEM interpretation in complex environments from the current iterative forward modeling and parametric inversion , using plate-based modeling software to the new and future tools which include automated iteration of facets multiple curved sheets, surfaces, and bodies. (Fig 30 right side) and in the next 2 figures (Figures 31 and 32) , voxel-based 3D inversion/imaging of EM and BHEM data using new software from the UBC GIF group (Phillips, 2006). These figures show samples of 3D inversion of BHEM data from Falconbridge's Nickel Rim South deposit.

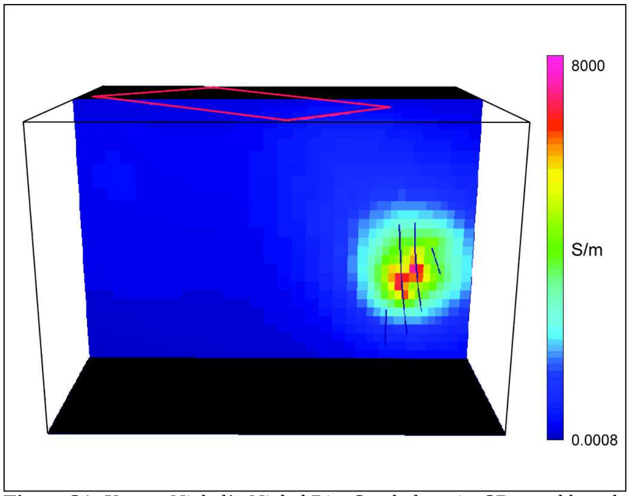

Figure 31: Xstrata Nickel's Nickel Rim South deposit : 3D voxel based inversion of borehole UTEM data for a high conductivity contrast body using new UBC TEM inversion software (from Phillips 2006).

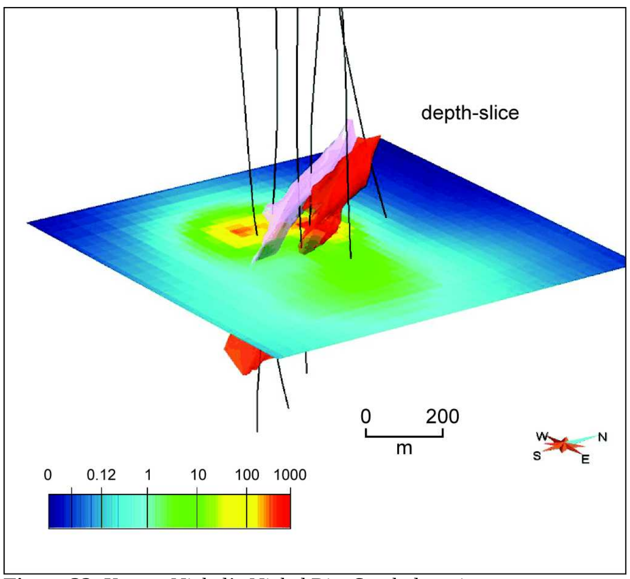

Figure 32: Xatrata Nickel's Nickel Rim South deposit - same conductivity inversion model showing mineralized zones (red and pink shapes) with depth slice through the inverted conductivity data cube (from Phillips 2006).

There is also an aggressive exploration program for PGE enriched footwall copper mineralization in disseminated, stringer and vein form. Due to the sometimes low bulk conductivity these are not always good targets for EM. However they are ideal for IP and for crosshole RIM surveys due to the high sensitivity of these methods to disseminated and vein type mineralization respectively. Figure 33 shows the mineral wire frame for a footwall copper PGE deposit and the RIM image. The correlation is excellent and the contrast with the various barren host rocks is very clear.

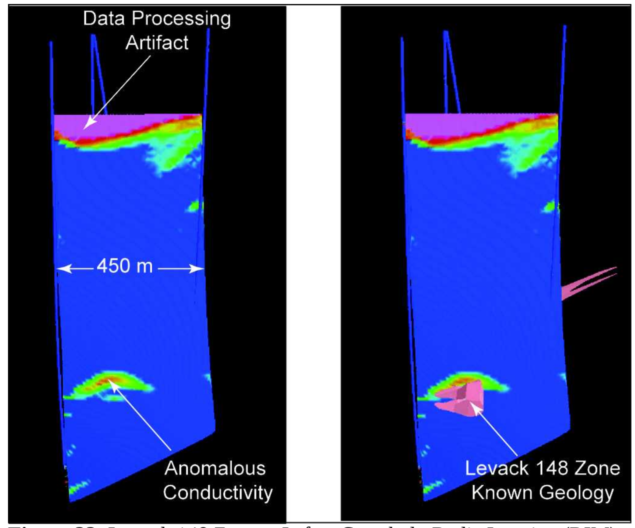

Figure 33: Levack 148 Zone - Left - Crosshole Radio Imaging (RIM) image – warm colours indicate higher radio wave attenuation and higher conductivity. Right – Known mineralization envelope (pink body) superimposed on RIM image.

DISCUSSION AND COMMENTS ON METHODS

Electromagnetics

The high conductance of massive Ni-Cu-S is both a problem and a benefit. The problem is that very high conductance targets are undetectable with the off-time dB/dt readings (time rate of change of magnetic field B) that TEM systems often used for ground and borehole TEM work and almost always used in airborne TEM. To detect a body of unlimited high conductance on-time B field TEM measurements are required. "On time" is equivalent to the "step response" capability discussed at length in a case history in Watts (1997).

The benefit of high conductance is, that once B field and ontime TEM systems are employed, the frequency can be reduced so the effect of even very conductive host rocks or overburden (as low as 10 to 1 ohm-meters) can be minimized. This allows extremely conductive bodies to be detected within geological "conductivity" noise. Note that frequency domain systems like ground horizontal loop EM (Maxmin), the old vertical loop EM systems as well as Inco's AEM system, the Geological Survey of Finland fixed wing system and DIGHEM HEM style systems are inherently "on time", however the operating frequencies of these systems are often not low enough to penetrate more than moderate to conductive overburden or host rocks.

Figure 34 (after West and Macnae, 1991) uses a single pulse to illustrate why B field measurements are required. If the conductance of a body is essentially infinite with respect to the time window of a TEM system, the current induced in a conductor does not decay over the time period of the measurement and dB/dt is effectively zero. There is no signal to measure in dB /dt. However while the secondary signal current is circulating in the body it is continually generating a constant and strong B field.

If only single pulses were measured B field measurements alone would be adequate but, by necessity, stacked alternating pulse sequences are used to see through ambient EM noise. If the decay of the secondary current in the target body is very long with respect to the pulse length subsequent measurements of the B field in the "off time" system exactly cancel leaving essentially zero signal again.

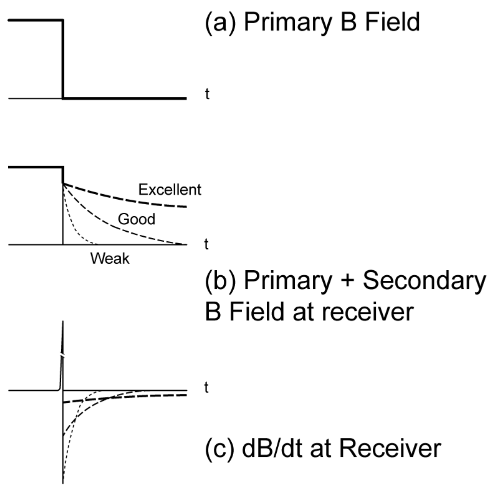

Figure 34: Schematic of an "off time" TEM system transmitted and received waveforms showing a) Primary B field from transmitter b) Primary plus secondary B field at receiver showing responses from weak, good, and excellent conductors c) dB/dt response at receiver for weak , good, and excellent conductors (after West et al 1991)

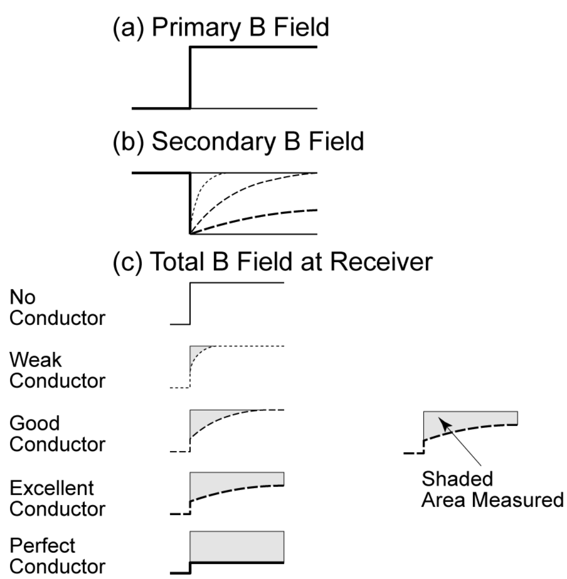

Figure 35: Schematic of an "on time" TEM system transmitted and received waveforms showing a) Primary B field from transmitter b) Secondary B field at receiver showing responses from weak, good, excellent and perfect (horizontal solid straight line) conductors c) Primary plus secondary B field =Total B field response at receiver for weak, good, excellent, and perfect conductors. Note that a perfect conductor has as strong and nondecaying response in the "on time" B field data (after West et al., 1991, Watts 1997, and Ravenhurst 1996)

In more fundamental terms – inside a perfect conductor the magnetic field has to be zero. In the "on time" in the presence of the primary field a perfect conductor prevents penetration of the field into the body by the formation of secondary currents that exactly cancel the primary field inside the body. In the "off time" the eddy currents are zero because the field has to be zero inside the conductor and there is no primary field to cancel.

Therefore for a very conductive target that has little or no decay on the scale of the measurement system both B field and "on time" measurements are necessary as shown in Figure 35 (after West et al., 1991,Watts 1997, and Ravenhurst, 1996)

It should be noted that on time measurements are much more difficult in practice because the primary field has be to accurately calculated and subtracted from the total field on time reading that includes both primary and secondary B fields. This requires geometric control of the primary field to the same

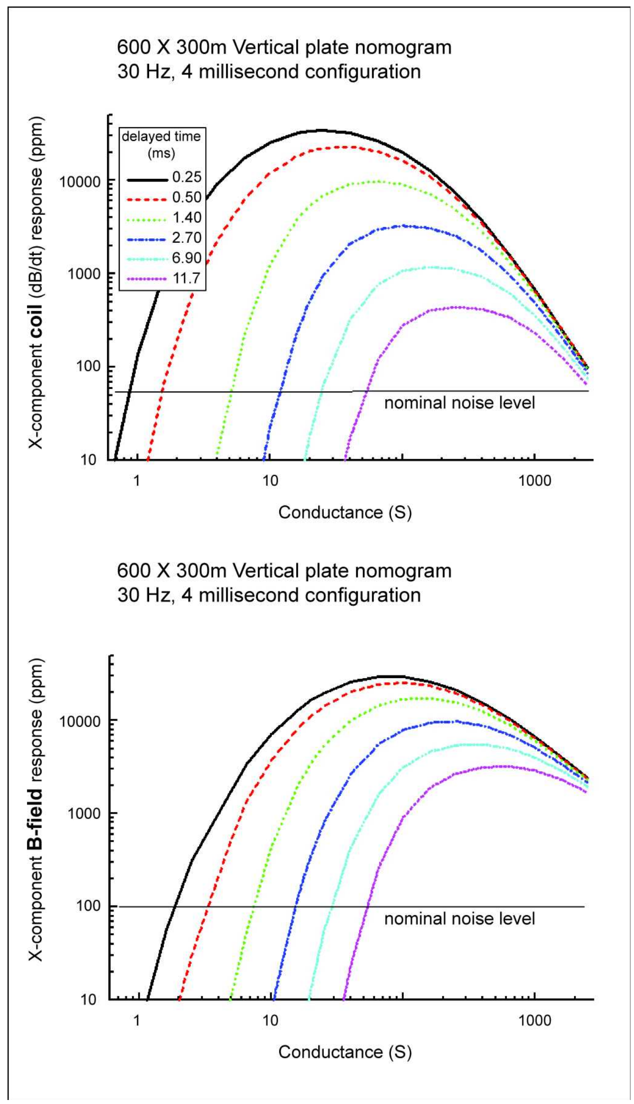

Figure 36: Left dB/dt versus Right B field calculated responses for a vertical 600m, by 300m plate for Fugro GEOTEM System (from Smith et al, 1998).

level that reading accuracy is desired. For this reason most Time Domain EM systems, particularly towed bird AEM systems (with the exception of the Inco AEM system) generally do not measure in the ontime. This problem has been addressed to some extent by the Aeroquest Helicopter TEM system. Because of the additional complications of full "on time" B field measurements many TEM surveys for massive Ni-Cu-S's are being done with B field only. As shown by the response curve diagrams for the Geotem AEM system in Figure 36 (Smith et al, 1998). B field measurements buy another decade or so of higher conductance aperture but as mentioned above full "on time" measurements are required for very high conductance targets.

Most nickel exploration for massive sulphide targets is done now with low frequency B field systems with typical operating frequencies as low as 1-3 hz. The CSIRO working together with Crone geophysics and Falconbridge (Osmond et al., 2002) put together the first commercial B field high temperature SQUID system (Figure 38) and more recently flux gate B field 3 component (3C) AC magnetometers have been widely deployed, first in Australia (Annison, 2004). These 3C B field sensors are small and are being used in borehole EM systems to get good B field 3C borehole EM measurements. Anglo American working with IPHT have a field system utilizing a Low temperature SQUID receiver (LeRoux, 2007) that is currently the most sensitive field B field sensor.

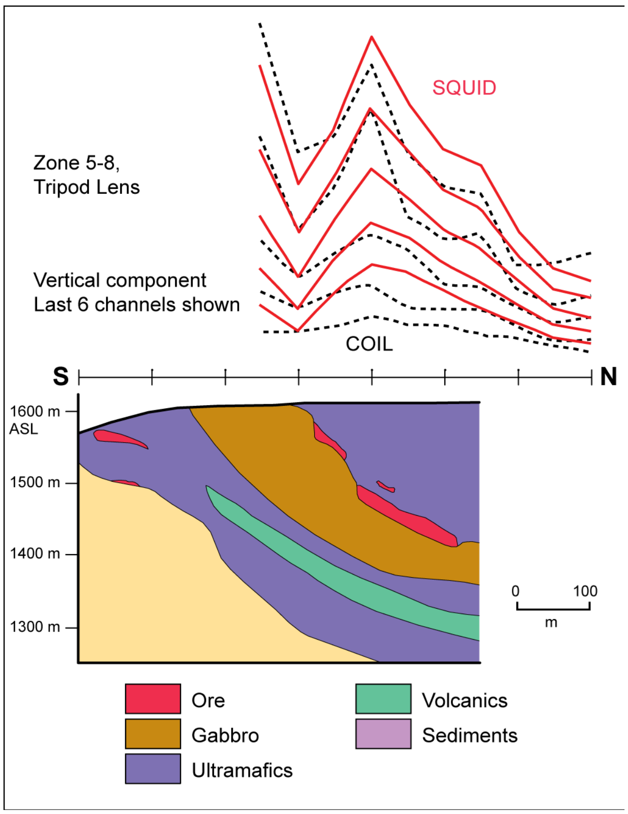

Figure 37: Ground Moving Loop 5 Hz TEM responses over small high conductance body at Raglan Quebec (Xtrata Nickel) - B field High Temperature SQUID receiver data vs Coil (dB/dT) Receiver data (from Osmond et al 2002).

AEM measurements continue to be a problem as they either have some or all of the following deficiencies: higher frequency dB/dt signal; or "off time". The Fugro Geotem systems are producing a good derived B field measurement as shown above and the Aeroquest systems have addressed the "on-time" issue to some extent. A fundamental problem with all current AEM systems is that there are practical limits to the lowest frequency that can be used, therefore penetration with AEM surveys in areas of very conductive overburden and high conductance discrimination remains a problem.

Helicopter TEM

A new generation of high power TEM systems are now available for situations that require deep exploration in rugged terrain and/or rapid deployment. The HeliGeotem, AeroTEM, and VTEM systems are pictured in Figure 38.These systems provide various combinations of capabilities to measure B field, partial "on time", low frequency and with high power and have greatly expanded the number and versatility of AEM systems available for surveys.

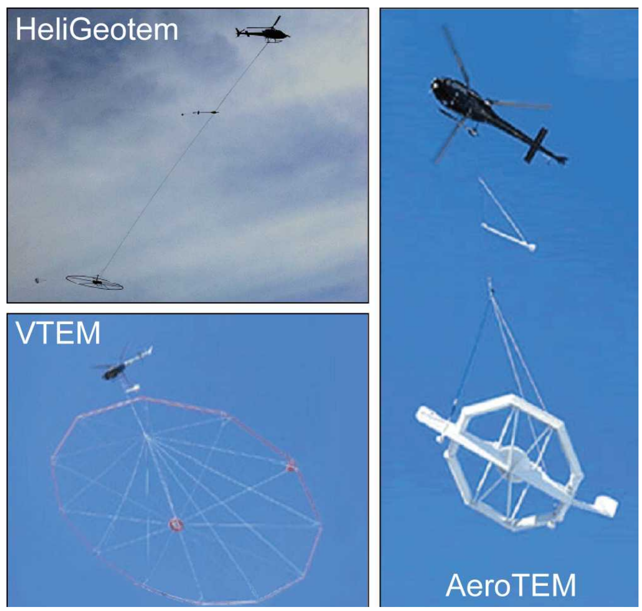

Figure 38: Helicopter time domain EM Systems.

Magnetics

Some of the uses and limitations and limitations of magnetics have been mentioned above. 3D inversions can rapidly produce 3D models of the subsurface on a large scale, but inversion algorithms that handle magnetic remanence are still apparently not widely used. (Shearer et al., 2004)

Gravity

As mentioned above detailed regional-scale gravity data has not been widely available, but this is changing rapidly with the advent of commercial airborne gravity gradiometry systems. It is proposed that regional airborne gravity and gravity gradiometer coverage, by companies and governments, at the global scale of the available airborne magnetic coverage would be one of the best ways to stimulate nickel sulphide (and other) exploration.

Borehole Gravity - With demonstrated value of surface gravity data and rapidly increasing use of airborne gravity surveys for mining applications the time is right to fill one of the major gaps in our borehole instrumentation. A new slim hole borehole gravity probe is being developed by Scintrex Ltd. and a group of sponsor companies under CAMIRO Project 05E01. This borehole gravity probe will fit inside NQ casing and will allow gravity surveying through the drill rods. This system will be useful for locating off hole mass, separating thin or graphitic good offhole EM conductors from thicker massive sulphides. It could also be used for estimating the total tonnage of orebodies from a few holes and for very accurate measurements of bulk density around drillholes. This latter capability should have valuable applications in laterite exploration as well.

The unmined Kelly Lake Ni-Cu deposit at Sudbury has been used as a template for synthetic modeling by Ecole Polytechnique as part of the development program. As shown in Figure 39 the calculated gravity response clearly shows intersected and off-hole mass. The data from this tool will be used to "hang" mass on the thin plates interpreted from BHEM that we usually use for interpretation of tabular conductors and should allow the estimation of total tonnage from a small number of drill holes. Other applications include location of off hole mass, separation of good conductors due to graphite or thin sulphidic bands from thick massive sulphides, and very accurate measurement of bulk density. This last capability should be particularly useful for laterite applications as well.

Seismic

Seismic reflection is the only method available to us where spatial resolution does not deteriorate rapidly with depth and has the capability to directly detect deposits at depths that are many multiples of their size, however, due to non-uniqueness in simple reflection images, these signatures are not yet definitive.

As well, seismic with its high spatial resolution, has an important role in structural and lithological mapping because it is the only method that can define sharp boundaries in the subsurface. These boundaries can be used as constraints in inversion of other methods such as magnetics and gravity that can be used to fill volumes with physical property values but have poor resolution at depth.

Complex geometries and steep dips can make hard rock seismic much more difficult but 2D surface Lithoprobe surveys at Thompson (White et al., 2000) have yielded interesting results and borehole VSP (vertical seismic profiling) work has been done at Sudbury (Snyder et al., 2002) and shown potential for detailed mapping around drillholes and imaging of steep dips.

Bushveld Seismic - The following is an example of some recent seismic work for PGE's in the Bushveld Complex and some of the most interesting recent work in mining geophysics. This data is from detailed 3D seismic work used to map thin PGE rich horizons in this large layered M/UM intrusive body (Larroque et al, 2002). As shown in Figure 40 the very thin horizons of economic interest, the UG2 and Merensky reefs, show strong local density anomalies which create good reflectivity contrasts and some quite remarkable seismic images. Figure 41 shows an image of the UG2 horizon with a horizontal resolution of the order of 10 meters or less at a depth of 800m. It should be noted that the Bushveld is a layered intrusive mafic complex and these results are an indication of the extremely high power of resolution by the seismic method in suitable environments with shallow to moderate dips.

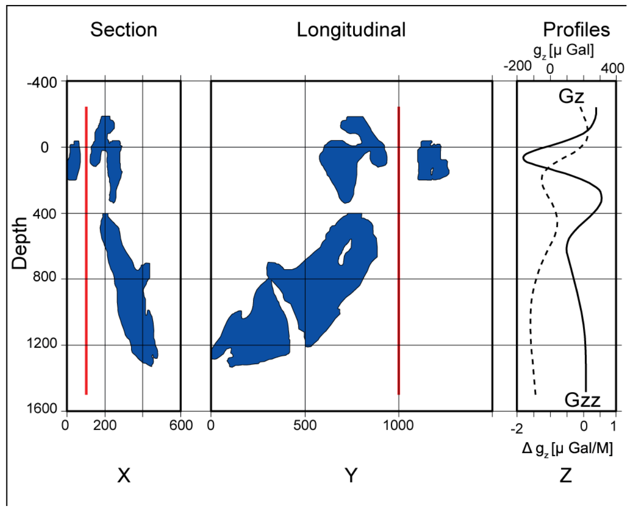

Figure 39: Borehole Gravity - Calculated responses Gz –dashed line and Gzz – solid line to known massive Ni-Cu-S orebodies (blue) at Kelly Lake, Sudbury from drillhole (red line) (After Nind et al., 2007)

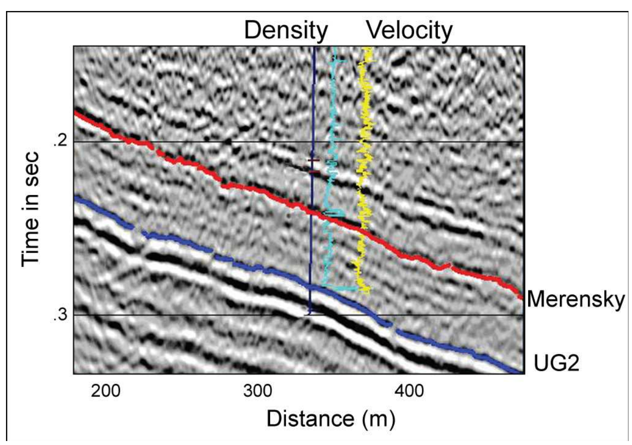

Figure 40: 3D Reflection Seismic Bushveld Complex – Vertical Section through 3D data volume showing reflections from the Merensky and UG2 horizons and Density and Velocity logs (from Larroque et al, 2002).

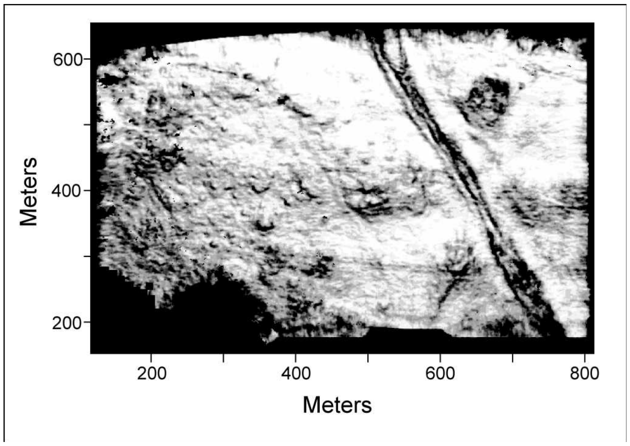

Figure 41: 3D Reflection Seismic Bushveld Complex – Plan view of Coherency Map along the UG2 horizon showing Potholes and Fault (from Larroque et al, 2002).

EM modeling

Modeling of discrete EM responses with thin sheets or plates has been a quick and easy method where the effects of host rocks and conductive overburden are not overwhelming. This includes resistive environments, deep borehole EM surveys where conductive overburden effects can be ignored or simplified, and high conductance targets at low frequencies where host rock/overburden effects are minimized. The University of Toronto PLATE modeling program (Dyck and West, 1984), Lamontagne's original Multiloop multifilament plate modeling (Polzer and Lamontagne, 1993) and EMIT's Maxwell (Duncan, 2007 – http://www.emit.iinet.net.au/) software provide fast forward iterative modeling of single and multiple conductors in free space or with simple flat overburden sheets. The Maxwell software also provides parametric inversion on plate models. EM modeling software from AMIRA project P223 has developed extensive modeling and inversion of layered earth's, plates and 3D volumes as well as combinations thereof. The UBC GIF group has also developed EM inversion codes for models ranging from layered earth to 3D volumes and is currently working on the holy grail of EM modeling - multisource full 3D TEM inversions (ie airborne TEM) that allows higher conductivity contrasts.

One of the fundamental problems of EM modeling for very high conductivities and conductivity contrasts is that skin depths can be very small, with currents concentrated on the surfaces of highly conductive bodies. This can require very small voxels near surfaces, especially for BHEM surveys where we are reading right through conductors, which can dramatically increase the size of a voxel based model . This problem favours solutions that operate on surfaces such as plates and sheets or methods that mix plates and volumes like some of the AMIRA P223 codes. The new MultiLoop 3 software (Northern Miner, 2005) provides forward models of curved surfaces and the surfaces of blobs and opens the door to parametric EM inversions of complex shapes.

Reduction of geophysical ambiguity: Need for full data integration in exploration models

Due the fundamental non-uniqueness in our process of geophysical methods based on physical properties it is essential that multidisciplinary methods be implemented to include all geological, geochemical and geophysical data and knowledge in integrated models to maximize the efficiency of exploration programs. The case histories described above demonstrate the essential role of geophysics to see below thick overburden and to locate targets at depths up to one or more kilometers. However, the various geophysical methods have a common shortcoming in the non-uniquess of solutions and interpretations. Therefore the continuing effectiveness of targeting under cover is dependent on constant improvement in the correlation between geophysical signals, physical rock properties, rock mineralogy and geochemistry and detailed variations in the target geology.

WHAT HAS CHANGED IN GEOPHYSICS IN 40 YEARS?

Most geophysical methods have experienced significant technical advances. In particular, the ability to integrate new and old data into 2D and 3D visualization platforms has taken exploration targeting to another level.

Airborne gravity and gravity gradiometry permits rapid acquisition of regional and target scale gravity data. This is a crucial new element in our knowledge base as gravity is often as good or better than magnetics for targeting M/UM rocks.

High power, low frequency on time TEM measurements are extending depth penetration for high conductance targets. EM systems have gone from depth penetrations of about 100m to 3km with surface AMT and BHEM.

Very low frequency EM systems that can penetrate almost any conductive overburden are available for ground surveys and there is a trend to arrays of multiple, multipurpose (EM, AMT, IP) receivers such as BHP Billiton's Geoferret systems (Golden, 2006) and the MIMDAS (Sheard et al., 2002) and TITAN IP/MT (Gordon, 2003) systems that is likely to continue.

IP remains an option for disseminated sulphides in resistive terrain and for distinguishing sulphides from the responses of conductive overburden and or saline groundwaters.

Getting to low enough frequencies for AEM systems to penetrate conductive overburden and to get high conductance discrimination with AEM systems remains a problem.

TEM measurements with B field data are widely available in airborne, ground and BHEM system and good, low frequency, B field, "on time" measurements are available in some surface and BHEM systems.

There are a number of good 3 component borehole EM systems and many other new exploration borehole methods including a wide variety of high resolution delineation tools.

Neutron activation tools can provide for the first time direct mulit-element detection and we should try to continue this trend and increase the range of direct element detection, possibly with other methods, to move beyond physical properties.

Seismic – Good quality surface seismic reflection data is being obtained in suitable hardrock environments as well as good borehole VSP and hole to hole transmission tomograms that directly image sulphides.

Computers – Computers are orders of magnitude better and improving steadily and rapidly.

Positioning – Accurate GPS positioning has become a standard part of all our work.

And finally as a result of the work by many groups including the AMIRA P223 project, UBC's GIF group, the CEMI group at the University if Utah and other's we have 3D inversion, or imaging, of all mining data sets together with a number of good 3D visualization and interpretation software environments.

THE FUTURE

There is tremendous value in integrating our multiple data sets qualitatively, through joint and cooperative inversions, as well as qualitatively as we are doing now in our 3D software environments. A number of good 3D software packages are available including: GOCAD, Geomodeller, VPMG, Profile Analyst, Target, Fracsys, Insight, etc, all with rapidly expanding capabilities.

The trend to multi sensor systems using multiple low cost sensors and receivers will continue and accelerate as cheap multi- channel, networked, recording systems become more widely available and used in other fields.

Autonomous systems such as UAV systems for airborne surveys will reduce costs, increase data volumes and increase safety.

Faster computers with better software and more memory will make detailed 3D imaging of most surveys possible as well as joint and cooperative inversions.

As well we need to work very hard to use physical properties more quantitatively to link geological and geophysical models and strive to move beyond physical properties if possible.

Our predecessors were very successful. They were adventurous, imaginative, worked closely with the fundamental physics and transferred technology from other fields. They invented and built new tools and found big ore bodies. Recently a lot of energy and money has returned to the mining business and we have a real challenge, in a very exciting exploration environment to equal the successes of our predecessors.

I expect that the next 10 (or 40 years) will be as exciting as the last, if so hang on - it's going to be a wild ride as the available technology is advancing at a accelerating rate. The only limitations are our imaginations and the fundamental laws of physics.

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