

RESOLVING THE AERO ELECTROMAGNETIC (AEM) AND AEROMAGNETIC SIGNATURE OF THE BRUNSWICK NO 12 SULPHIDE DEPOSIT FROM ADJACENT FORMATIONAL ANOMALIES

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RESUMO

A região de Bathurst Mining Camp (BMC), no Canadá, possui 46 depósitos de sulfato maciço vulcanogênico sedimentar, incluindo o depósito Brunswick No. 12. Entretanto, a assinatura magnética deste depósito é mascarada pela resposta de uma formação basáltica próxima. Um modelo 3D confiável pode contribuir significativamente para uma melhor compreensão da natureza do depósito de Brunswick No. 12 em profundidade e fornecer um vetor importante para sua exploração. A abundância de pirrotita no depósito gera uma forte anomalia magnética. A modelagem 3D dos dados magnéticos integrado com as informações sobre a geologia e dados de perfuração disponíveis na literatura como vínculos para inversão produziram um modelo mais confiável do comportamento em subsuperfície. A comparação dessa inversão com o modelo geológico apontou para uma boa correlação do comportamento vertical do modelo 3D com uma seção geológica previamente derivada. Embora contínuo em profundidade, o modelo exibe diferenças entre as porções norte e sul do corpo. Este aspecto "bifurcado" é consistente com a presença de duas anomalias magnéticas associadas ao depósito. O modelo magnético foi então comparado com a assinatura aero eletromagnética (AEM) da área, a qual também indicou uma bifurcação entre as porções norte e sul. A correlação da interpretação de dois métodos geofísicos baseados em propriedades físicas diferentes ajuda a confirmar a confiabilidade do modelo 3D obtido. Os resultados deste estudo contribuem para uma melhor caracterização das assinaturas geofísicas associadas ao depósito No. 12 de Brunswick e ajudam a entender sua composição petrofísica. As características geofísicas fornecem uma referência para comparação com outras anomalias (parcialmente) mascaradas observadas tanto na área do BMC como em outros lugares do planeta.

Palavras chave: inversão 3D; magnetometria; eletromagnetometria, estimativa de parâmetros; métodos potenciais.

ABSTRACT

The Bathurst Mining Camp (BMC), Canada, hosts 46 volcanogenic-sedimentary massive sulphide deposits (VHMS), including the world-class Brunswick No. 12 deposit. The magnetic signature of this deposit is masked by the magnetic response of a nearby basaltic formation. A reliable 3D model may contribute significantly to a better understanding of the nature of the Brunswick No. 12 deposit at depth and provide an important vector for exploration. Locally abundant pyrrhotite in the deposit generates a strong magnetic anomaly. 3D modeling of the magnetic data using the geological and drill hole data available in the literature as constraints produced a model that could be compared with previously established geological models. This comparison pointed to a very good correlation of the vertical

behavior of the 3D model with a previously derived geological section. Although continuous at depth, the model displays differences between the northern and southern portions of the upper region of the body. This “bifurcate” aspect is consistent with the presence of two magnetic anomalies associated with the deposit. Independent geological interpretations of the sulphide body indicate a greater discontinuity of the body in the E-W direction compared to N-S discontinuities in the magnetic model. The magnetic model was then compared with the deposit aero electromagnetic (AEM) signature, which also indicated a bifurcation between the northern and southern portions. The correlation of the interpretation of two geophysical methods based on very different physical properties helps to confirm the reliability of the 3D model obtained. The results of this study contribute to a better characterization of the geophysical signatures associated with the Brunswick No. 12 deposit and help understanding its petrophysical composition. The geophysical characteristics provide a benchmark for comparison with other (partially) masked anomalies in BMC area or elsewhere.

Keywords: Inversion 3D; Magnetics; Electromagnetics, Parameter estimation; Potential field.

INTRODUCTION

The Bathurst Mining Camp (BMC) is a world-class base metal mining district located in northern New Brunswick, Canada. It hosts over forty five Zn-Pb-Cu-Ag type massive sulphide (VMS) deposits and occurrences, as well as dozens of lesser occurrences (Luff *et al.*, 1992, McCutcheon, 1992). Goodfellow and McCutcheon (2003) and Goodfellow *et al.* (2003) highlight that approximately 70% of BMC deposits were discovered using geophysical methods; primarily airborne magnetic and electromagnetic methods. The release of airborne geophysical maps of the BMC led to the discovery of the Camelback massive sulphide deposit (Goodfellow *et al.* 2003) and to the identification of several new anomalies with high mineral potential that were evaluated (Chung, 2003; Keating *et al.*, 2003), thus highlighting the importance of geophysics in the discovery of deposits even in a mining camp that has seen locally intense exploration over several decades.

Keating *et al.* (2003) state that magnetic data are essential for mineral exploration, especially in the BMC, where many sulphide deposits have a significant magnetic signature. The magnetic response

of many of the BMC deposits is a function of the magnetite and pyrrhotite content of the massive sulfide lenses and the magnetite content of overlying, chemical exhalite, stratiform oxide-facies, i.e. Fe formation (Goodfellow *et al.*, 2003). Along the Brunswick Belt located on the eastern part of the BMC, horizons of volcanogenic massive sulfide (VMS) deposits are overlain by highly magnetic alkali basalts. The proximity of such highly magnetic basalts to VMS deposits presents an exploration challenge when trying to discern VMS related anomalies adjacent to or below larger host-sequence related anomalies. A better understanding of the geophysical signature of the BMC deposits and the comprehension of how their geophysical signatures can be enhanced provide an important reference to identify similar masked deposits and how to optimize their study and exploration.

The study herein is focused on reinterpretation of magnetic data of Brunswick No. 12 deposit. The isolated and 3D modeling of the magnetic signature of the basalt, and the removal of this anomaly, enhance the VMS signal favoring to a better interpretation of Brunswick No. 12 deposit. Geological and borehole information available in literature were

used to constrain the inversion and improve the reliability of its results.

Electromagnetic anomalies may not be directly associated with exploration targets themselves, but can delineate horizons in which massive sulphides bodies may exist. Aero electromagnetic (AEM) data was used to analyze the subsurface behavior of the deposit. Both magnetic model and electromagnetic results pointed to a bifurcated format of the deposit in depth along the NS direction. AEM data relies on the conductivity properties of the substrate which are very different from the magnetic susceptibility. The magnetic and AEM methods measure different physical properties; hence comparison of results obtained by both methods provides means for independent assess of the relative results. In this case, AEM data and their analysis provide a very useful tool to evaluate the 3D magnetic model obtained.

REGIONAL GEOLOGY

The BMC is composed of several tectonic blocks and slivers juxtaposed during the closure of the Tetagouche-Exploits Back-arc Basin (Van Staal *et al.* 2003) initiated by continent-continent collision in the late Ordovician and Early Silurian (450–440 Ma; Malehmir *et al.* 2013). The same authors divide the rocks of the BMC into five main groups, which from stratigraphically oldest to youngest are the Miramichi, Sheephouse Brook, Tetagouche, California Lake and Fournier Groups. These groups range in age from Cambrian to Silurian (Fig. 01).

The first three groups, were deposited during the initial opening of the Tetagouche- Exploits Back Arc basin, they are more or less coeval, and are dominated

by felsic volcanic rocks which host VMS deposits. These groups are characterized by felsic volcanic rocks that give way up section to tholeiitic mafic volcanic and related sedimentary rocks.

The Cambrian-Lower Ordovician Miramichi Group consists of a thick sequence of quartzose turbidites capped by Lower Ordovician volcanogenic wackes and slates of the Patrick Brook Formation. The overlying groups are Middle Ordovician to Lower Silurian. The Sheephouse Brook, Tetagouche and California Lake Groups are composed mostly of metamorphosed volcanic and sedimentary rocks, whereas the Fournier Group consists of tholeiitic and alkali basalts with lithic wacke-shale rhythmities, limestones and black shale (Van Staal *et al.* 1992).

The northeastern portion of the BMC is affected by two major northeast-trending folds, the Tetagouche antiform (TA) and the Nine Mile synform (NMS in Fig. 1), with the Brunswick No. 12 deposit located on the eastern flank of the synform. Felsic volcanic rocks of the Flat Landing Brook Formation (Tetagouche Group) dominate the central core area of the BMC and the Tetagouche antiform. The Nine Mile synform is built mainly by the formations of the two uppermost groups (the California Lake and Fournier Groups).

Goodfellow and McCutcheon (2003) highlight that the BMC deposits have been intensely deformed and metamorphosed during multiple collisional events related to northwest subduction of the Tetagouche-Exploits back-arc basin. Peak metamorphic conditions vary from 325° to 400°C and 6 to 7 kbars (Currie *et al.*, 2003).

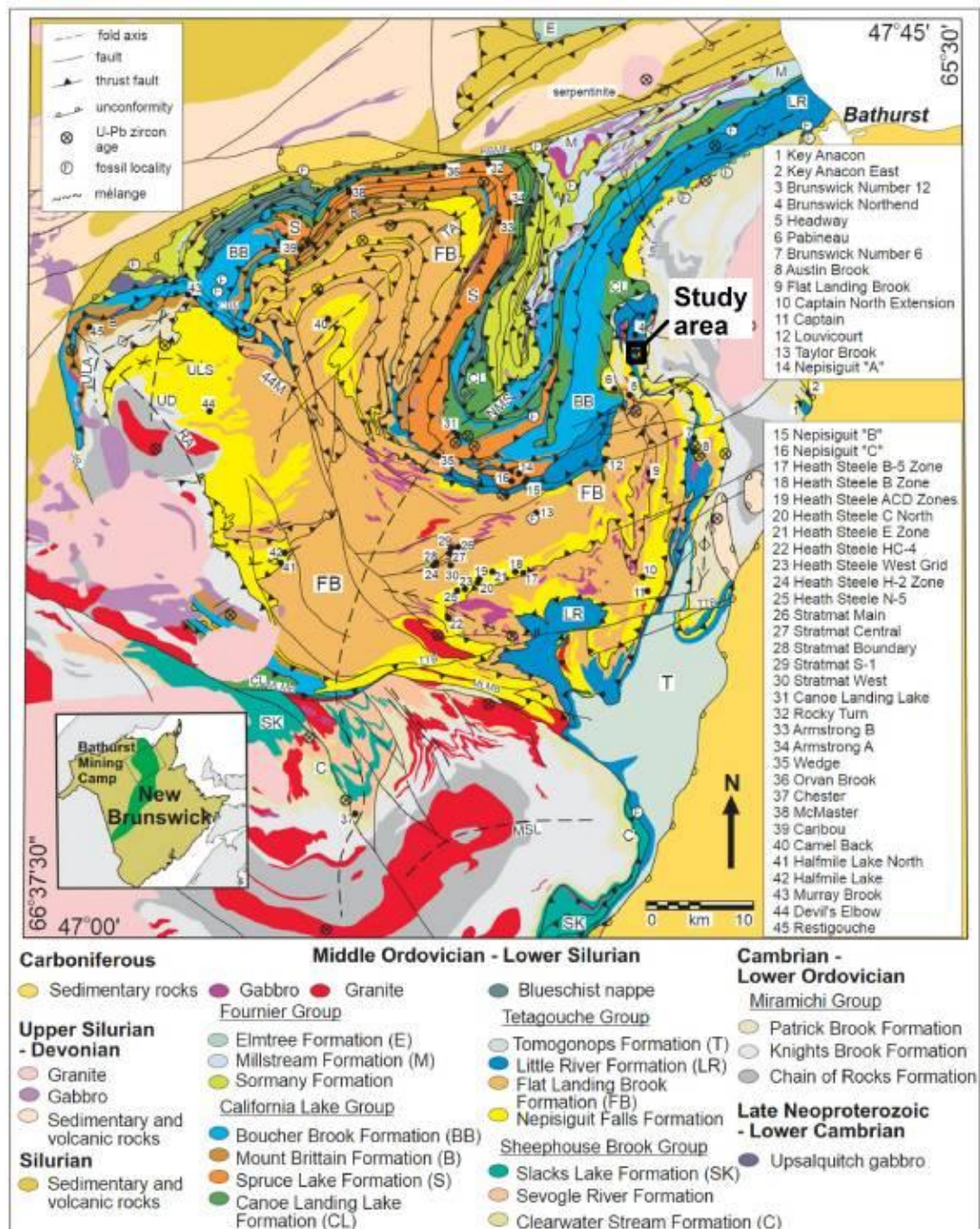


Figure 1. Tectonic map of the Bathurst Mining Camp (BMC) displaying the distribution of the major blocks, slivers, major nappes and sulphide deposits (after Van Staal *et al.* 1992, Van Staal *et al.* 2003, and Goodfellow *et al.* 2003). Black polygon limits the study area shown in Figure 2.

Most sulphide deposits in the BMC are closely associated with tuffites and silicic volcanic rocks of the Nepisiguit Falls and Flat Landing Brook Formations (van Staal *et al.* 1992). Others are hosted by the Boucher Brook Formation generally close to contacts with silicic volcanics of

the Flat Landing Brook Formation or Nepisiguit Falls Formation, and some are hosted by sedimentary rocks of the Patrick Brook Formation (van Staal *et al.* 1992).

Geological setting and characteristics of Brunswick No. 12 deposit

The stratigraphic column in the Brunswick No. 12 area is composed from base to top of: Miramichi Group, Nepisiguit Falls Formation, Flat Landing Brook and Little River Formations (Scott and Goodfellow 2003). The Miramichi Group consists of a thick sequence of quartzose turbidites capped by Lower Ordovician volcanogenic wackes and slates of the Patrick Brook Formation. The Nepisiguit Falls Formation consists of (only quartz; is that correct?) quartz-feldspar porphyry, rhyolite flows and tuffs, aphyric rhyolitic tuffs, and fine-grained tuffaceous sedimentary rocks. The felsic volcanic rocks of the Flat Landing Brook Formation are dominantly dacite and rhyolite lavas with lesser amounts of pyroclastic and volcanosedimentary rocks,

while the sedimentary rocks of Little River Formations are dominantly dark blue-gray to black, pyritiferous shales, with occasional siltstone horizons (Scott and Goodfellow 2003).

According to Malehmir *et al.* (2013), the Nepisiguit Falls Formation (Fig. 1 and 2) dominated by felsic volcanic and volcanoclastic rocks is the base of the Tetagouche Group. The Austin Brook member of the Nepisiguit Falls Formation (AKA the Brunswick horizon) occurs at the top of the Nepisiguit Falls Formation and includes all chemical exhalative rocks including sulphide, carbonate, oxide, and silicate facies. This horizon is a key target for geophysical and geochemical exploration in the camp as it contains the Brunswick #12 and, #6 deposits as well as the Austin Brook deposit (Peter and Goodfellow 1996).

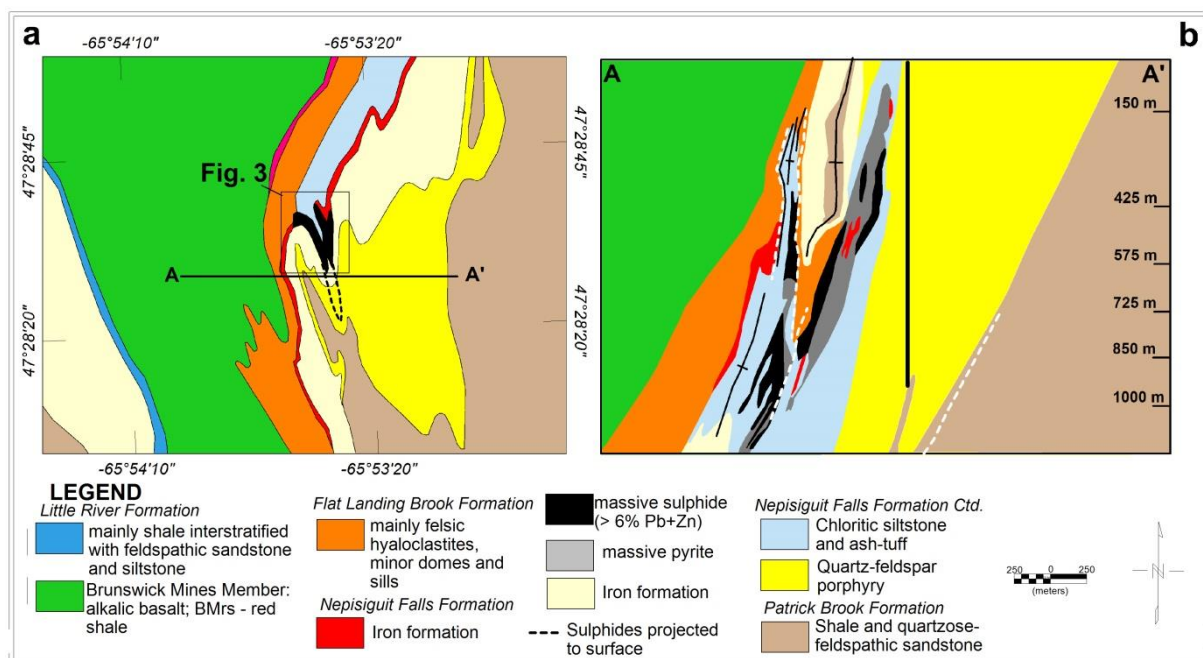


Figure 2 – Geological map (a) and cross section (b) of the Brunswick No. 12 deposit area (after Thomas *et al.* 2000). The dotted line indicates the projected area of the sulphide deposit in to surface. The black polygon locates the map shown in Fig. 03. The AA' line locates the profile section proposed by these authors presented in (b).

The alkali basalt flows and related sedimentary rocks of the Little River Formation form of the youngest sequences of this group. The Flat Landing Brook Formation (FLBF) rocks contain rhyolite flows and rhyolitic volcanic/hyaloclastic rocks (Fig. 1 and 2).

The term “horizon” used in this work refers to a stratiform hydrothermal chemical exhalative horizon including all related sulphide, oxide silicate and carbonate facies. Note that it may include shallow subsurface stratabound replacement type massive sulphide bodies spawned from the same hydrothermal system.

The Brunswick No. 12 deposit lies below the contact between the Nepisiguit Falls Formation and overlying FLBF (Fig. 1 and 2). Goodfellow and McCutcheon (2003) highlight the fact that the present morphology, sulfide textures, mineralogy, and chemical zonation of BMC massive sulfide deposits reflect the combined effects of sea-floor hydrothermal processes and a subsequent polyphase deformation.

According with Thomas *et al.* (2000), a footwall feeder zone has been recognized by Luff *et al.* (1992), but intense deformation has transposed the stringer zone sub-parallel to the massive sulphide lens.

Van Staal and Williams (1984) report that the massive sulfide deposits such as the Brunswick No. 6 and No. 12 deposits were folded by D2 structures and thickened in the hinges of the folds. Thomas *et al.* (2000) note that a result of the fold interference in Brunswick No. 12 orebody is the reversal of its plunge direction at depth.

Goodfellow and McCutcheon (2003) claim that the intense deformation of sulfide stringer zones is expected considering the susceptibility of the phyllosilicate-dominant mineralogy of hydrothermally altered footwall rocks to high strain. Luff *et al.* (1992) identify a possible reactivated and transposed

extensional fault that separates the main and west ore zones of the Brunswick 12 deposit (Fig. 3). These authors have identified several types of hydrothermal alteration processes that can be active during sulfide deposition, i.e. chloritization, sericitization and silification. According to Lydon (1984), these processes depend on one or more different parameters such as fluid temperature, water/rock ratio, host-rock composition, pH, among others. During hydrothermal alteration of the sub-seafloor rocks at the site of hydrothermal sulphide deposition alkali feldspars are typically replaced by chlorite or quartz (Large, 1977).

Brunswick No. 12 hydrothermal alteration has been documented in detail by several authors (Goodfellow, 1975; Juras, 1981; Luff *et al.*, 1992; Lentz and Goodfellow, 1994, 1996).

Luff *et al.* (1992), Lentz and Goodfellow (1993b), and Shives *et al.* (2003), among others, document the occurrence of alkali feldspar-destructive hydrothermal alteration in the BMC. Luff *et al.* (1992) showed that K-feldspars are progressively replaced in the original rock by albite that is subsequently replaced by quartz (silicification), sericite (sericitization) or chlorite (chloritization) with increasing intensity as a function of the proximity to the feeder pipe. According to Shives *et al.* (2003), this replacement generally results in a decrease in K (and Na) counts with increasing alteration intensity with closer proximity to the feeder pipe.

Lentz and Goodfellow (1994) and Goodfellow and McCutcheon (2003) remark that hydrothermal alteration in BMC deposits is widespread (1–5 km laterally and hundreds of meters vertically) and comprises the following assemblages from the core to the margins of the feeder zone: zone 1—quartz + Fe-rich chlorite + pyrrhotite + chalcopyrite; zone 2—Fe-rich chlorite + sericite ± pyrite; zone 3—Fe-Mg

chlorite + sericite + albite; zone 4—albite + Mg-rich chlorite. Still, according to these authors, the enrichment in Mg, Mn, CO₂, S and base metals and depletion in Na, Ca, Ba, and Rb in zone 3 reflects the widespread hydrothermal destruction of K feldspar and plagioclase and the formation of chlorite and sericite. Zone 4, in turn, is enriched in Mg and Na and depleted in Ca, reflecting the chloritization and albitization

of plagioclase (Goodfellow and McCutcheon, 2003; Yang *et al.*, 2003).

The intensity of hydrothermal alteration as defined by increasing Mg/Ca and increases systematically with increasing proximity to the core of the hydrothermal vent in the footwall zone (Fig. 4).

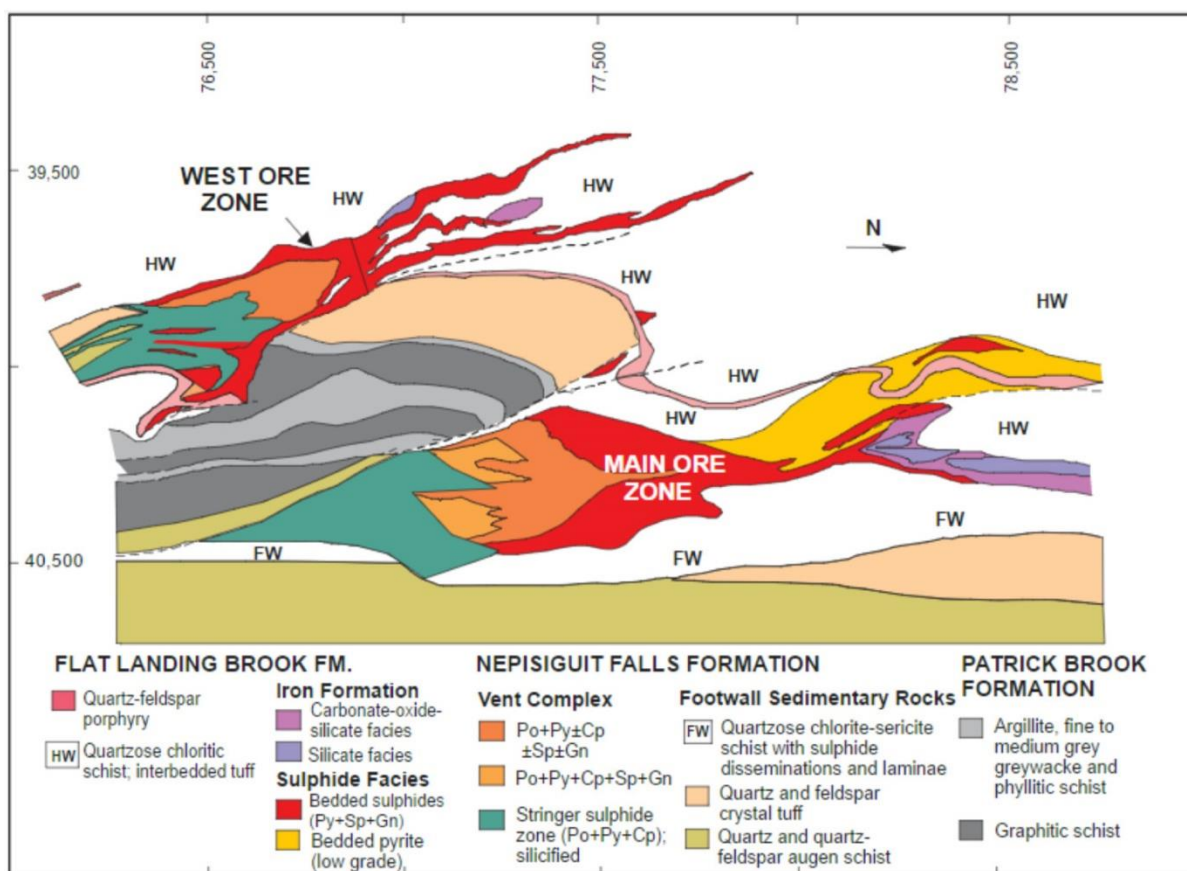


Figure 3. Geological cross-section of the Brunswick No. 12 deposit, showing highly deformed and distorted massive sulfide facies and underlying sulfide stringer zone (Luff *et al.* 1992).

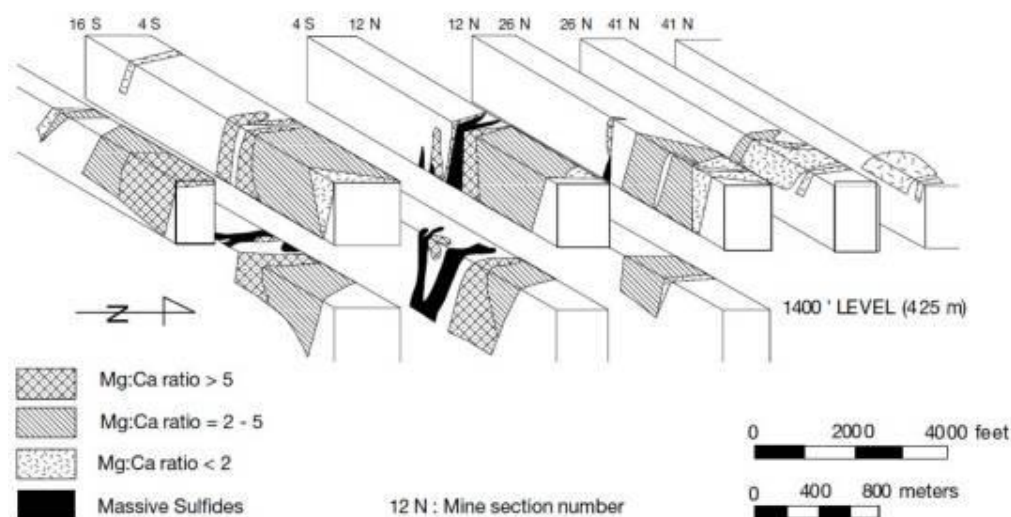


Figure 4. Three-dimensional distribution of Mg/Ca ratios in felsic volcanic rocks of the Nepisiguit Falls Formation that host the Brunswick No. 12 deposit (Goodfellow 1975).

MAGNETIC DATA

Residual total magnetic field data from the vicinity of the Brunswick No. 12 deposit was obtained from the Geological Survey of Canada (GSC) (Geoscience Data Repository for Geophysical Data: <http://gdr.aggr.nrcan.gc.ca/gdrdap/dap/search-eng.php>) and was interpolated to a grid using the minimum curvature technique with an interpolation window of 40 m (a fifth of the 200 m line-spacing specified for the survey, Fig. 5). The residual total magnetic field component was derived from the magnetic data provided by Natural Resources Canada (NRCAN, <http://www.nrcan.gc.ca>) by subtracting the average International Geomagnetic Reference Field (IGRF) for the period of the survey.

The aero survey was completed along lines spaced 200 m apart and at a

survey height above the ground surface of 120 m, under the project Bathurst MEGATEM in 2004. The data used is contained in survey Block 3, and was measured along lines oriented with 110° - 290°, i.e. running E20°S to W20°N. The magnetic sensor system was a Cesium magnetometer manufactured by Scintrex, with sensitivity of 0.01 nT. The nominal height of the sensor was 73 m above the terrain.

The major anomaly observed in Fig. 5 is interpreted to be associated with the large body of alkali basalt flows, i.e. the Brunswick Mines Member of the Little River Formation lying just west of the Brunswick No. 12 deposit (LR_{BM}, Fig. 1 and 2). This anomaly has a strong intensity, over 2252 nT in amplitude, and interferes with the magnetic response that we infer to be associated with the sulphide ore body (black polygon in Fig. 5).

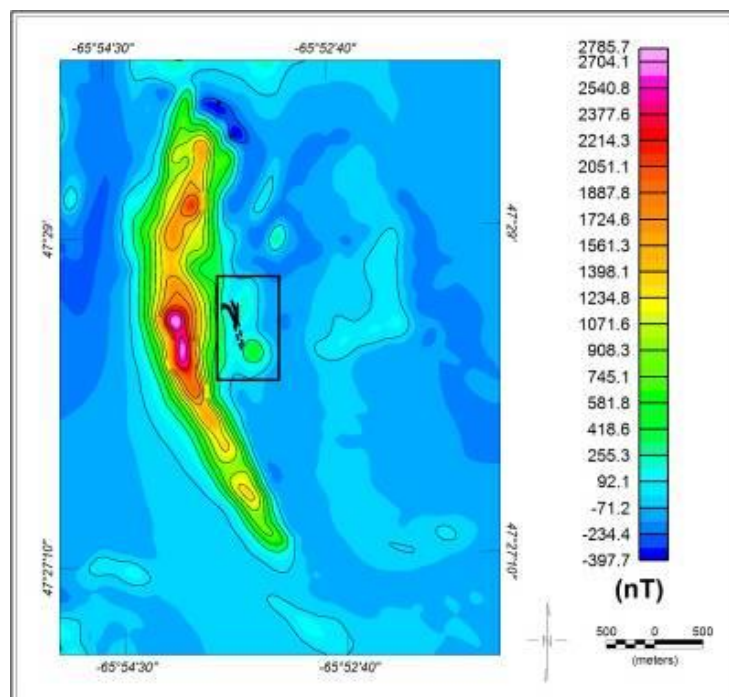


Figure 5 - Residual magnetic field of the region of Brunswick No. 12 deposit provided by GSC. The black rectangle locates the area of the interpreted sulphide magnetic anomaly (Figures 6-8 and 12). Black irregular shape massive sulphides. The black dotted line indicates the limits of the south-plunging deposit projected vertically to surface (see location in Fig. 2, Thomas *et al.*, 2000).

The sulphide limits were projected to surface, as proposed by Thomas *et al.* (2000), on the geophysical maps in order to determine the degree of correlation between the sulphide body and any geophysical anomalies (Fig. 2). Two roughly oval-shaped positive magnetic anomalies occur to the east of the Brunswick No. 12 sulphide deposit (Fig. 5), which lies east of the magnetic anomaly generated by the nearby body of alkali basalt flows.

Although the residual magnetic map (Fig. 5) indicates the presence of two small anomalies on the eastern flank of the sulphide deposit, the difference in their intensity make difficult a reliable interpretation, once most processing techniques and 3D inversion algorithms focus on the greatest magnetic contrast source over smaller anomalies. Since the large magnetic anomaly of the basalt overshadows that of the Brunswick No 12

deposit, it is essential to use a procedure to isolate and enhance the target signal without generating any distortion. Li and Oldenburg (1998) proposed a procedure to isolate the residual component of the regional magnetic fields using a 3D inversion. The separation is achieved by inverting the observed magnetic data from a large area aiming to construct a regional susceptibility distribution. The magnetic field produced by the resulting model is then removed from the original data by a simple subtraction. We adapted this methodology to isolate the magnetic contribution of the basalt formation, enhancing the sulphide magnetic anomaly. For that, the area corresponding to the sulphide anomaly (the area outlined by the black rectangle on Fig. 5) was isolated and subtracted from the original grid (Fig. 6-A) and the resulting data were re-interpolated to produce a new grid of values that is displayed in Figure 6-B. The original

magnetic map used in this process is that shown in Figure 5, which includes the entire interfering anomaly due to the basaltic LR_{BM} unit west of the sulphide body. It is important to mention that the area considered includes the entire anomaly to be modeled to avoid its misinterpretation due to a misguided inversion of its source in depth. The gridded magnetic data displayed in Fig. 6-B was then inverted using the MAG3D algorithm (Li and Oldenburg, 1996). The inversion parameters are presented in Table 1 and 2.

The MAG3D inversion algorithm (UBC-GIF 2005) considers a mesh of rectangular cell and seeks to adjust a constant magnetic susceptibility inside each cell without altering mesh dimensions during the inversion. The magnetic data do not contain depth information, so a depth weighting function is applied to the sensitivity matrix values. The depth weighting function balances the natural decay of the resolution of the signal with depth. This procedure prevents the inversion from concentrating the anomalous distribution of magnetic susceptibility in the top of the model.

The addition of constraints independent of the data used in the inversion reduces the ambiguity of the final model. In this case, information on the geology of the Brunswick No. 12 deposit and the expected magnetic susceptibility of these units was obtained

from previously published sources (Luff *et al.*, 1992; and Langton, 1992; Telford *et al.*, 1990, Thomas *et al.*, 2000). Table 1 presents the magnetic susceptibilities obtained by Thomas *et al.* (2000) on core samples for the Brunswick No. 12 and its host rock. The first inversion (Fig. 6) was intended to provide a rough approximation of the regional magnetic field around the ore body, i.e., the source of the magnetic anomaly related to the LR_{BM} (Fig. 2). The parameters for inversion were defined considering the aero survey characteristics (space between lines surveyed and flight height – Table 2) and available geologic information for the area and the Brunswick No. 12 massive sulphide body (ore body depth and magnetic susceptibility expected for the lithology).

The 3D inverted model (Fig. 6) showed a high apparent contrast of magnetic susceptibility (ranging from 0.07 SI to 0.30 SI) located in the west of the mesh. Its location and the apparent susceptibility contrast are consistent with the alkali basalt) of the LR_{BM} (Figs. 1 and 2).

After the inversion, the predicted field of the 3D magnetic model (Fig. 6b) was subtracted from the original residual magnetic field (Fig. 6a). This procedure removes the influence of the magnetic signal of the LR_{BM} basalt, thereby enhancing and separating the magnetic response of the Brunswick No. 12 sulphide body (Fig. 7).

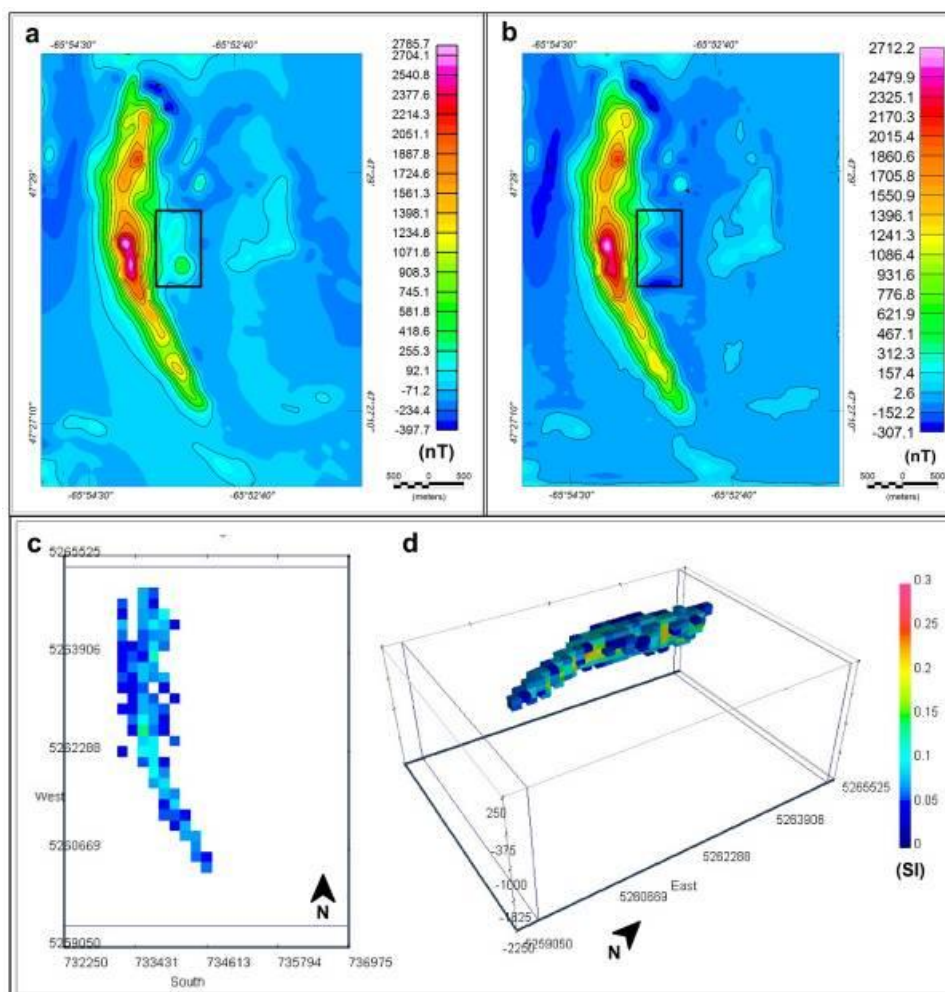


Figure 6 – (a) Map of the regional magnetic field outlining the area of the ore body in the black rectangle within which the anomaly related to the body was subtracted from the original magnetic field; and (b) predicted field generated by the 3D regional inverted model shown in c. (c) Plan view of the 3D model obtained by the inversion of the detailed area of the magnetic map in (a) and (d) perspective view of the inverted model. The contours interval in (a) and (b) is 250 nT. Magnetic susceptibilities of model cells are colour-coded and in units of SI.

Table 1 – Magnetic susceptibilities obtained in core samples of the Brunswick No. 12 deposit and its host rock (Thomas *et al.* 2000).

Rock Type	Magnetic Susceptibility (SI x 10 ⁻³)	
	Range	Mean and S.D.
Sulphide		
Massive sulphide	0.20 – 962	51 ± 124
Semi-massive sulphide	0.30 – 14	5.1 ± 3.76
Host and Adjacent Rocks		
Iron formation	15.4 – 3700	990 ± 967
Crystal tuff	0.02 – 0.40	0.01 ± 0.01
Quartz eye schist	0.05 – 2.70	0.39 ± 0.82
Massive basalt	0.72 – 41.6	10 ± 13.4

Table 2 - Inversion parameters and performance of the regional inverted model.

Mesh Parameters			
Axis	X (East)	Y (North)	Z (Vertical)
Mesh Size	4725 m	6475 m	4375 m
Number of Cells	27	37	25
Size of Cells	175	175	175
Upper south-west corner coordinates	732250 m	5259050 m	250 m above sea level
Inversion Constraints			
Upper Susceptibility Bound (SI)	0.3		
Lower Susceptibility Bound (SI)	0.0001		
Initial Model	0.001		
Reference Model	Null		
Length Scales (L_x, L_y, L_z)	1	1	1
Inversion Performance and Performance			
IGRF direction and magnitude	Inclination: 71.40	Declination: -20.40	Amplitude: 54888.0 nT
MAG3D parameters (incl, decl, geomag)	71.40°, 20.40°, 54888 nT		
MAG3D parameters (aincl, adecl, dir)	71.40°, 20.40°, 1		
Number of data values	5704		
Data Error	5nT floor plus 2% magnitude of the data		
Achieved Data Misfit	156.7		

Brunswick No. 12 3D model

The residual map (Fig. 7) obtained by removing the magnetic signature associated with the LR_{BM} basalts (Fig. 6) shows two oval anomalies with maximum amplitudes of 589 nT (southern anomaly) and 389.7 nT (northern peak). This dual signature is likely related to the separation of north and south portions of the magnetic source associated with the vent complex deposits deposit (Figs. 2 and 3).

Inversion of the magnetic map obtained by the residual-predicted field subtraction of the basalt magnetic anomaly (Fig. 7) was completed in order to define the geometry of the magnetic source in the subsurface (Figs. 2 and 3).

The reference model used in the 3D inversion was based on the vertical geologic cross-sections (Figs. 2b and 4) using the parameters in Table 3. The magnetic susceptibility contrast attributed to the reference model was 0.05 SI based

on the average value for core samples measured by Thomas *et al.* (2000; Table 1).

Figure 8b shows a map of the difference between the residual magnetic field for Brunswick No. 12 area (Fig. 7) and the magnetic field predicted by the inversion (Fig. 8a). The residual analysis of this inversion (Fig. 8b) indicated a maximum difference less than 10% of the maximum value of the residual magnetic field map intensity (589.6 nT in Fig. 7) with a small concentration over the central part of the map.

The magnetic map calculated from the inverted model had amplitudes that range from -278 to 589 nT (Table 3; Fig. 8a). The maximum residual value was 10.2 nT (Fig. 8b), representing 1.73% of the maximum amplitude of the magnetic anomaly we associated with the sulphide deposit (589.6 nT; Fig. 7). This map presents a strong anomaly with oval shape

associated with the southern part of the sulphide body (with 589.6 nT; Fig. 8a).

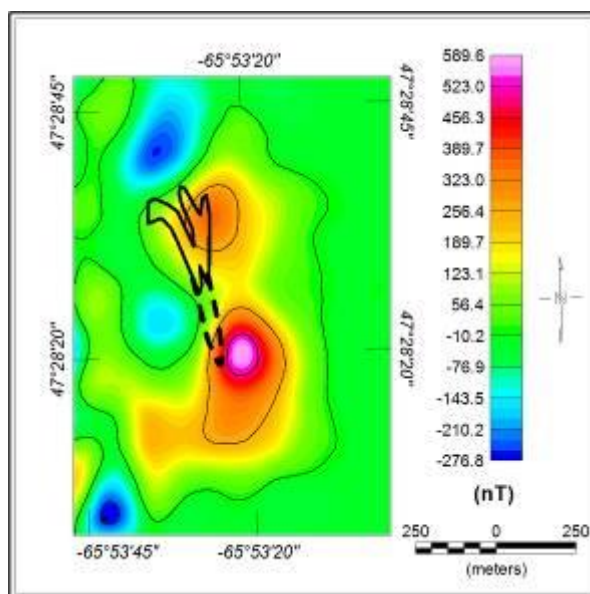


Figure 7 – Map of the regional magnetic field of Brunswick No. 12 massive sulphide body enhanced by removing the effect of the magnetic signature of the hanging wall basaltic formation (LRBM). The contours interval is 250 nT. Black irregular shape outlines the massive sulphides. The black dotted line indicates the limits of the south-plunging deposit projected vertically to surface. Area of map is outlined in Fig. 5.

Table 3 - Inversion parameters and performance of the Brunswick No. 12 3D inverted model.

Mesh Parameters			
Axis	X (East)	Y (North)	Z (Vertical)
Mesh Size	1160	1520	1670
Number of Cells	36	48	53
Size of Cells	1*50, 2*40, 30*30, 2*40, 1*50	1*50, 2*40, 42*30, 2*40, 1*50	40*30, 10*35, 3*40
Upper south-west corner coordinates	733818 m	5261730 m	250 m above sea level
Inversion Constraints			
Upper Susceptibility Bound (SI)	0.065		
Lower Susceptibility Bound (SI)	0.0001		
Initial Model	0.001		
Reference Model	0.050		
Length Scales (L_x, L_y, L_z)	0.1	0.1	1
Inversion Performance and Performance			
IGRF direction and magnitude	Inclination : 71.40	Declination: - 20.40	Amplitude: 54888.0 nT
MAG3D parameters (incl, decl, geomag)	71.40°, 20.40°, 54888 nT		
MAG3D parameters (aincl, adecl, dir)	71.40°, 20.40°, 1		
Number of data values	9280		
Data Error	5nT floor plus 2% magnitude of the data		
Achieved Data Misfit	10.2 nT		

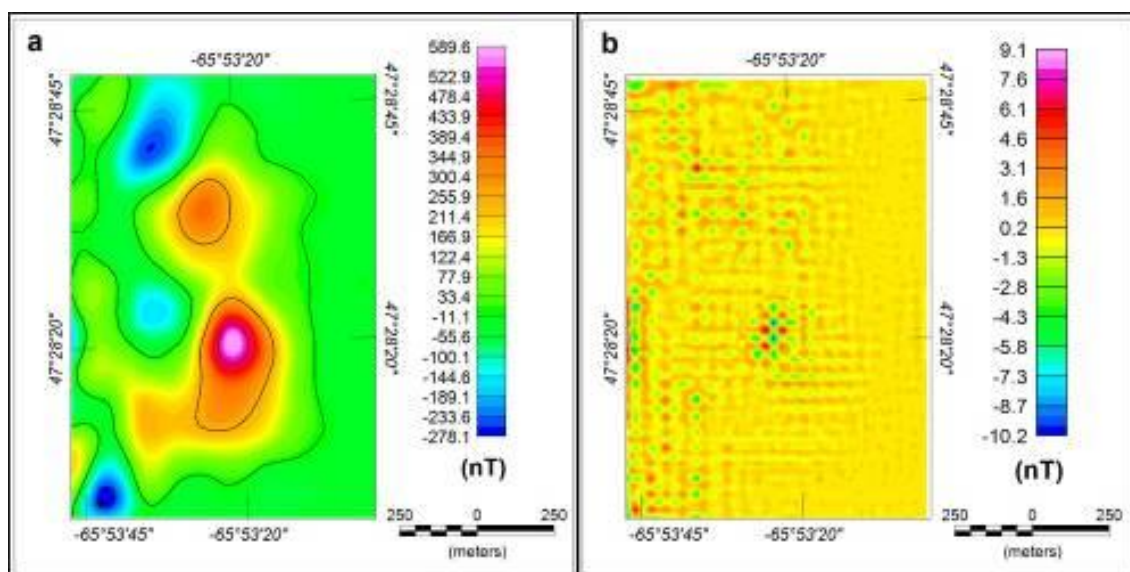


Figure 8 – (a) Magnetic field map produced by the inverted sulphide model and (b) residual map generated by the subtraction between the regional magnetic field (Fig. 07) and the 3D model magnetic field in (a). The contours intervals in (a) is 250 nT.

The 3D inverted model obtained for Brunswick No. 12 sulphide deposit (Figs. 9 and 10) shows a positive apparent magnetic contrast with the host rock. The anomaly is elongated vertically in the north-south direction, but is more restricted in the east-west direction (Fig. 10). The 3D modeling displays a continuous distribution of magnetic susceptibility in subsurface. The apparent contrast generated by the magnetic inverted model, from 22.10^{-3} to 63.10^{-3} SI (Table 3), is consistent with the value obtained by Thomas et al. (2000) for Brunswick No. 12 deposit core samples (Table 1).

AERO ELECTROMAGNETIC DATA

Aero electromagnetic method (AEM) is one of the most commonly used tools in mineral exploration. AEM allows the direct detection of conductive base metal deposits due to the large conductivity contrast between these ore bodies and the resistive host rocks or thin overburden cover.

Keating *et al.* (2003) noted that electromagnetic maps of the Bathurst

Mining Camp AEM data outline areas of high conductivities having various circular-elliptical shapes also distributed in linear belts, typically 1 to 3 km wide, and from 10 to 60 km in length along the strike. These authors interpreted that some linear conductive zones occurred within mapped antiforms and synforms that commonly included conductive geological formations such as graphitic shales.

Between January and April 2004, Fugro Aero Surveys conducted a MEGATEM electromagnetic and magnetic survey (Blocks 1 to 5) in New Brunswick, vicinity of Bathurst, Canada. The flight lines have a 035° - 215° direction and their spacing was 200 m, while the perpendicular tie-lines were spaced 2,000 m apart.

GEOTEM® (GEOterrex Transient ElectroMagnetic system) is a time-domain towed-bird electromagnetic system incorporating a high-speed digital EM receiver. The system uses a large transmitter loop surrounding the aircraft maintaining an average altitude of 120 m at 200 km/h. The nominal height above ground of the receiver is ~ 70 m, placed

~130 m behind the center of the transmitter loop.

The loop is wound around the aircraft, anchored to the wing tips and on extended booms located off the nose and tail. The receiver has three orthogonal receiver coils: two oriented in the horizontal plane (X and Y) and one in the vertical plane (Z). The receiver coils measure the change in total field produced by both transmitter and conductors.

The primary electromagnetic pulses are created by a series of discontinuous sinusoidal current pulses transmitted through a vertical axis loop of 406 m² with 6 turns. The base frequency rate used was 90 Hz and the pulse width is 2330 μ s. The off-time was 3126 μ s. The transmitted current was 605 A and the dipole moment is $1.47 \cdot 10^6$ Am². The pulse delay is 100 μ s. The survey data were processed and compiled by the Fugro Aero Surveys' Ottawa office. The x, y and z-coil data were processed from the 20 raw channels recorded at 4 samples per second.

The AEM data provided was already corrected by Fugro Aero Surveys for drift in flight form (prior to cutting the recorded data back to the correct line limits) by passing a low order polynomial function. The data were edited for residual spherical spikes by examining the decay pattern of each individual EM transient. Fugro also made corrections were applied to the x- and z-coil data for low frequency, incoherent noise elements in the data (OMEGA process) and noise filtering.

Figure 11 shows the off time channels 8 to 17 in in the X and Z-coils sampled over the profile AB in Figure 12. These channels were chosen because they are off-time channels not too late in time, showing or having less influence of noise.

Scrivens (2005) presented the modeled responses of several synthetic conductors with varying shapes, sizes, depths and orientations. Figure 11 evidences the presence of two peaks on both X-coil and Z-coil channels profiles.

By comparing these peaks with synthetic models from Scrivens (2005), it is possible to associate Brunswick No. 12 signature with two vertical conductor materials close together in subsurface. The difference between the maximum values of each peak observed for the X-coil response in Fig. 11 can be explained by a difference in their depths

Figure 12 presents the total energy envelope (TEE) calculated by Fugro for the studied area. This process aims to combine the information provided by both X and Z coil data and reduce the asymmetry in the signature of the anomalies. The TEE is computed through a Hilbert Transform and is given by the square root of the sum of the squares of each component. For the studied area, Fugro used the channel 08 in X and Z components (mid-time position of 359 μ s after turnoff) to calculate the TEE variation map presented in Figure 12.

Thomas *et al.* (2000) indicated that the Brunswick No. 12 HEM response is influenced by the tailings ponds, to the east of the deposit, and the mine installations. Even with the influence of the mine installation and the noise due to 60Hz contamination from the neighbor power lines, these authors identified a sharp conductivity response directly over the orebody. In fact, the TEE map clearly presents a high anomaly over the limits of the VMS deposit (Fig. 12).

Thomas *et al.* (2000) highlight that “the offset between the conductive maxima calculate from the coaxial and coplanar coils are diagnostic of a “dipping orebody”. The dip of the orebody possibly indicates the presence of a difference in the depth of the electromagnetic source top. This interpretation agrees with the difference between the northern and southern portions depth indicated by the profile in Figure 11.

DISCUSSION

Keating *et al.* (2003) suggest that most of the massive sulphide deposits in the BMC have positive magnetic and conductivity responses. According to these authors, these anomalies are in general discrete and easy to identify. However, in the case of Brunswick No. 12, the anomaly is partially masked by a larger and more intense anomaly associated with basalts of the Brunswick Mines Member of the Little River Formation (LR_{BM}). Thomas *et al.* (2000) outline of the Brunswick No. 12 sulphide body where it intersects surface under the overburden coincides with the south area of the northern oval anomaly, of intensity of about 350 nT (Fig. 7). These authors also suggest that the buried extension of the deposit towards the south-southeast (dotted line in Fig. 2) is generally associated with smaller amplitudes of the magnetic field, though it does touch on the southern oval anomaly.

After removing the magnetic anomaly associated with the alkali basalt of the LR_{BM} (Figs. 1 and 2), the residual Brunswick No. 12 magnetic anomaly is seen to have a strong signal near the southern part of the deposit (Fig. 7).

King (2007) states that pyrrhotite in particular can have high Koenigsberger ratios (Q), with values over 10. Therefore, bodies with relatively low magnetic susceptibility related to disseminate pyrrhotite can have the potential to produce significant anomalies if they process a strong remnant magnetization component (Clark and Tonkin, 1994; King, 2007). In the case of Brunswick No. 12, a remnant component associated with the pyrrhotite-rich keel at the base of the deposit (Fig 3) may be responsible for the strong positive magnetic anomaly in the southern part of the sulphide body (Fig. 7). If the presence of this remnant component is confirmed by further studies, it may establish an important vector to pyrrhotite-rich massive sulphide mineralization since it can be used to differentiate the magnetic anomaly generated by VMS deposits of

other anomalous sources, such as banded iron formations.

The presence of a significant remnant component can affect drastically the magnetic signature of a source, even changing its polarization (e.g. Ribeiro *et al.* 2013; Louro *et al.* 2014). Significant remnant component can also influence the application of several classic processing techniques such as the reduction to the magnetic pole (RTP), and can generate instable results as observed by Ribeiro and Mantovani (2010) and Conego Junior *et al.* (2013) for anomalies with different directions and intensity of magnetization. Since the remnant magnetization is directly associated with the presence of ferromagnetic minerals such pyrrhotite, this component may be used to differentiate the magnetic signature of VMS deposits (with high concentration of pyrrhotite) from formational magnetic anomalies, i.e. those due to induced magnetization, such as oxide facies iron formation (rich in magnetite).

The 3D model (Figs. 9 and 10) generated by the inversion of the residual magnetic field is a vertical body having a greater extension in the north-south direction. The apparent susceptibility contrast and body subsurface distribution recovered by the 3D model are also consistent with geological and boreholes results available in literature (Goodfellow, 1975; Luff *et al.*, 1992, Langton, 1992; Thomas *et al.*, 2000).

The maximum depth obtained by the model was 850 m (Figs. 9a and 10), which is about 250 m shallower than the geological model in Fig. 2b. This model is a mathematical solution for the magnetic field inverted, but does not necessarily represent the distribution of specific lithological units (in this case massive sulphides) in the subsurface. Additionally, the potential field method is effective for determining lateral extent of the sources, but is less suitable for accurate depth determination. For this reason, it is

expected that will occur some divergences between the synthetic model and the geology cross-sections related to its vertical extension. The geological section (Fig. 2b) presents a discontinuity of the massive sulphide body in the E-W direction. However, this feature is quite small compared with the line survey spacing, and for this reason the magnetic data do not have enough resolution to recover such relatively small-scale features in a derived model.

The residual magnetic map for the immediate area of the sulphide deposit (Fig. 7) was obtained removing the field related to alkali basalts and clearly outlines two magnetic anomalies. The 3D model generated through the inversion of this map (Fig. 7) is bifurcated, with a discontinuity between the northern and southern portions of the body. This feature, proposed in this work, is not represented in any geological map of the deposit.

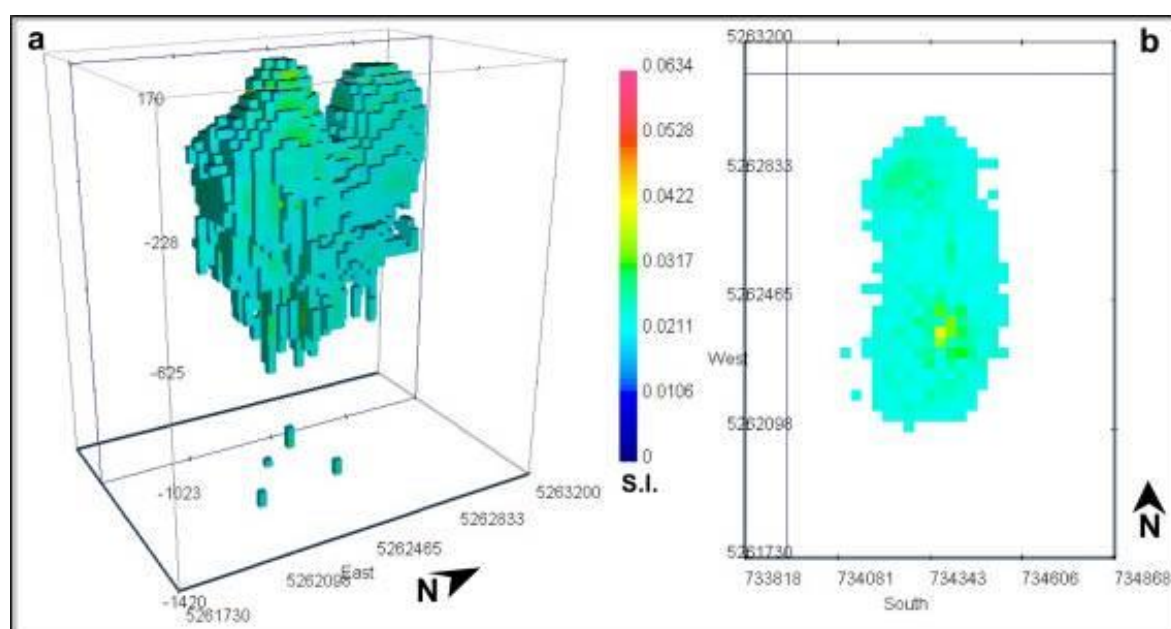


Figure 9 – (a) 3D inverted model and the (b) plan view of the 3D inverted model derived from the enhanced magnetic signal of Brunswick No. 12 deposit. The units in axes are given in meters. Magnetic susceptibilities of model cells are colour-coded and in units of SI.

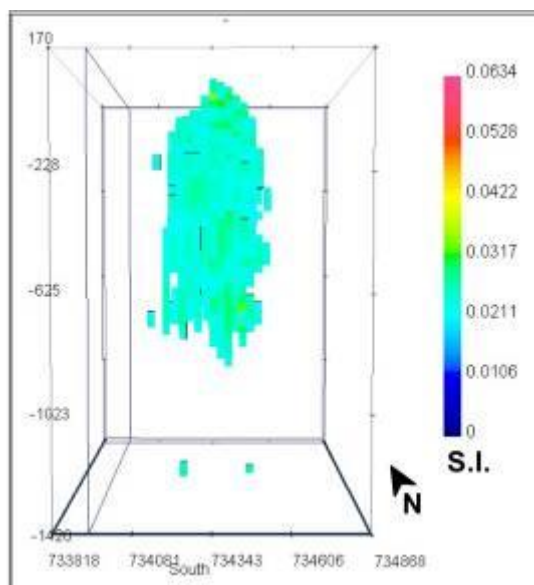


Figure 10 – View looking north of the 3D inverted model Brunswick No. 12 deposit area. Magnetic susceptibilities of model cells are colour-coded and in units of SI. The units in all axes are given in meters.

The 3D magnetic model was compared with AEM data of the area analyzed to determine if there were elements of the AEM data that were compatible with the model. Since the electromagnetic and magnetic methods are based on two different physical properties, interpretations of respective data sets are independent of one another, and commonalities in results are mutually supportive.

The comparison of the X and Z-coils profiles with the synthetic results obtained by Scrivens (2005) indicates that

the electromagnetic signal (Fig. 11) is probably associated, at least at shallow depths, with two bodies with small distance between them, and with the southern body being a little deeper. The AEM survey configuration presents a more limited signal penetration than the magnetic method, and for this reason, it is not possible to confirm that there is a connection between the two interpreted electromagnetic sources in subsurface. In contrast the magnetic 3D model displays continuity across the area containing two separate electromagnetic sources.

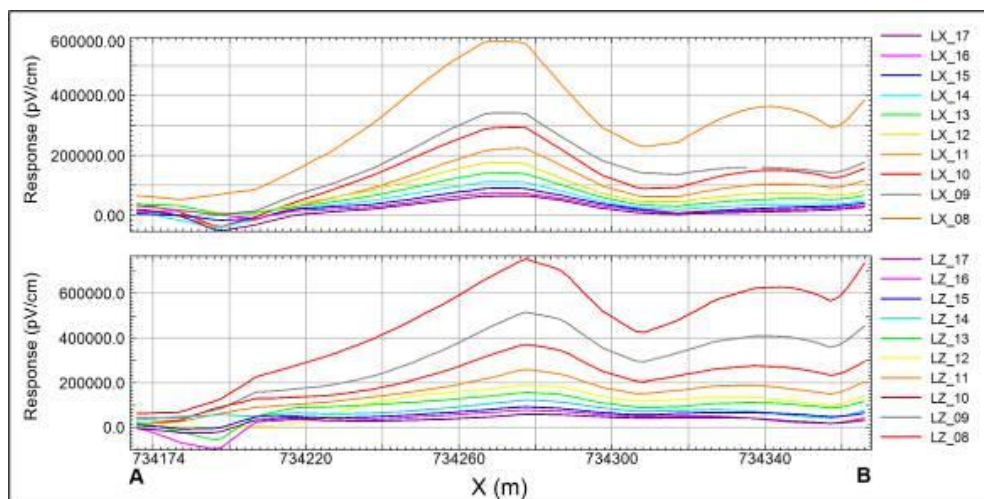


Figure 11. Response obtained for X-coil (A) and Z-coil (B) for the profile AB (Fig. 12) considering the off channels 08 to 17.

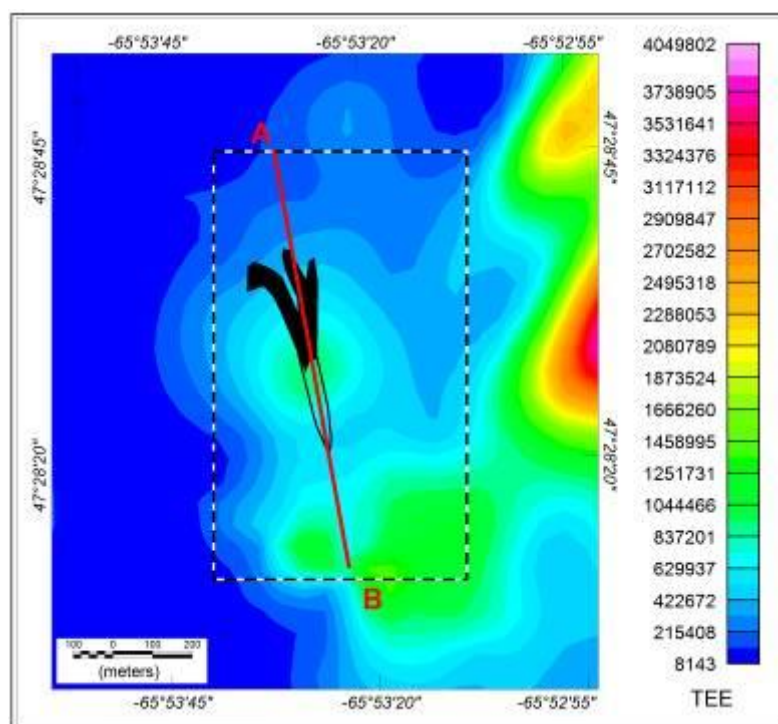


Figure 12. Total Energy Envelope (TEE) calculated for the channel 8. The red line locates the profile AB used to compose the Fig. 11 across the VMS deposit (black polygon).

CONCLUSIONS

The Camel Back deposit, in BMC, was first identified by a combined aeromagnetic and electromagnetic survey (Walker and Carroll, 2006). Although this small deposit is non-economic, it proves that modern surveys can delineate new

targets for exploration, even in a region explored for over 40 years. A better knowledge of the geophysical signature expected for a deposit, using the state-of-art strategies to enhance and interpret it, can provide an important tool to identify and to explore new potential targets,

especially if it is overshadowed by regional anomalies.

Many orebodies in the BMC are associated with small magnetic anomalies and a minority of these (Brunswick 12, Austin Brook and Canoe Landing Lake) may be camouflaged and/or overshadowed by larger formational magnetic anomalies. The procedure to isolate and enhance the magnetic anomaly of the Brunswick No. 12 sulphide deposit described herein is an important step to better interpret this kind of anomaly. The 3D magnetic model produced using this procedure had an apparent magnetic susceptibility contrast and depths consistent with results from several previously published studies (Thomas *et al.* 2000, Goodfellow 1975). This work has shown that the magnetic anomaly associated with the Brunswick No. 12 deposit is strongest at depth in the south end of the body and is probably associated with a pyrrhotite-rich keel of the deposit. Further studies are necessary to determine if there is any relationship between a potential presence of pyrrhotite and any strong remnant magnetization component.

If confirmed the relation between the remnant component and the presence of pyrrhotite in VMS deposits, this signature will allow to better differentiating aero magnetic anomalies generated by sulphide deposits from the ones related to oxide-facies chemical exhalite, i.e. Fe formation (linked mostly to induced anomaly). The procedure implemented in the Brunswick No. 12 deposit allowed us to isolate and obtain the 3D model of a ferromagnetic body in depth, independently of the presence of strongest anomalies nearby. Both magnetic and electromagnetic data indicated a heterogeneity discontinuity between the north and south top portions of the deposit. Since these methods rely on different physical properties, and the analysis of magnetic and AEM data sets was performed totally independently, any

correlation between their results provides important supporting evidenceto help confirm the reliability of the 3D magnetic inversion. Hence, the combination of the remnant study and the processing procedure presented here can establish an important vector to identify new potential exploration targets in BMC as well as assists to reduce ambiguity in the differentiation between VMS anomalies and other magnetic sources, such as banded iron formations.

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