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Exploring for Copper–Gold Deposits Exhibiting a Wide Range of Conductivities with Time–Domain Electromagnetics at Opemiska, Canada

Gaucher, F.E.S. [1], Smith, R.S. [1]

1. Laurentian University, Harquail School of Earth Sciences, Sudbury, Ontario, Canada.

ABSTRACT

Finding and delineating new economic Cu-Au ore zones corresponding to poorly conductive disseminated mineralization and narrow massive chalcopyrite veins in the Chapais-Chibougamau mining district of Québec is a challenging exploration problem. The site of the former Opemiska underground mine was the location for conducting an experimental ground time-domain electromagnetics (EM) survey for mapping the conductivity, the anisotropy of the conductivity, and the chargeability estimated from shape reversals. Measurements at fourteen different sites confirmed the variability of the EM response. The trends, sizes, shapes and conductances of the relatively strong conductors were identified with success and modelled using thin plates in full space. The vein direction in the weakly conductive zones was quantified from the x-component data. Petrophysical measurements and microscopic observations suggest complex interrelations between the amount of ore, the fabric of the rock, texture, mineralogical associations and impurities. This explains a wide range of bulk conductivity values from ~0.01 S/m to 4000 S/m measured on rock samples and also suggests that chalcopyrite might be a semiconductor at some locations at Opemiska.

INTRODUCTION

The Chapais-Chibougamau mining camp is the second-largest mining district in the Québec part of the Abitibi greenstone belt (Leclerc et al., 2012). The Opemiska project is located next to the town of Chapais. The Opemiska mine (Springer, Perry, Cooke and Robitaille shafts) produced 600,000 short tons of copper, 216,000 ounces of silver, and 529,000 ounces of gold from 1954 until its closure in 1991 (Salmon and De l'Étoile, 2013). The former underground mine operated by Falconbridge Copper Ltd, used shafts and galleries to extract narrow but high-grade copper-gold ore (Salmon, 1982). Since 1993, a junior company under the name of Explorateurs-Innovateurs de Québec Inc. (Ex-In) has been assessing the possibility of exploiting lower grade ore as a high tonnage open pit and/or underground bulk mining operation. The exploration problem consists of finding tools that can delineate new high- and low-grade ore zones close to the surface that can be mined economically. Diamond drilling and assaying the rock is a proven technique to achieve this goal, but pattern drilling is very expensive. A geophysical method that could guide the drilling is desirable.

This project aimed to develop an electromagnetic (EM) methodology to discover economic copper-gold deposits in the Chapais-Chibougamau mining district. An experimental ground EM survey was designed to map the conductivity, the chargeability, and the anisotropy of the conductivity related to the Opemiska mineralization. The phases of the project involved: compiling pre-existing geophysical and geological data; taking petrophysical measurements on rock samples from diamond drill core and outcrop; execution of an innovative ground time-domain EM survey; and processing, modelling and interpreting all the data.

GEOLOGY

The copper-gold mineralization found at Opemiska is mostly hosted within the layered Ventures sill, which is composed of 800 m of different episodes of gabbros and pyroxenites (Figure 1; McMillan, 1972; Lavoie, 1972). The Ventures sill was deformed and folded along with the host rock into an antiform-synform pair, and appears at surface in the form of a Z. The axis of the sills, volcanic and sedimentary rocks that have been folded have a plunge of 45° to 65° toward the east (Watkins and Riverin, 1982; Coulombe, 1984). The above lithologies have been intruded by the Opemiska granitic pluton, compressed and metamorphosed to greenschist facies (chlorite-epidote-tremolite) (Salmon, 1982). The alteration of the host rock associated with mineralization at Opemiska is limited to a width about twice the width of the mineralized veins (McMillan, 1972). The Opemiska local surface geology is presented in Figure 1, with the structural features and mineralized veins illustrated. Note the multiple copper–gold vein orientations.

The Opemiska ore, referred in the literature as Opemiska-type Cu-Au veins (Pilote, 1998; Leclerc et al. 2012) consists of semi-massive to massive chalcopyrite associated with ± pyrite–pyrrhotite–magnetite. The veins are narrow but are high-grade (Salmon, 1982). Silver is found in variable quantities associated with the chalcopyrite, while gold can also be found independently (Gaucher, 2017). Veins and veinlets of sulfides are found with quartz, calcite, carbonate and stilpnomelane, and are hosted in a subophitic gabbro. Minor amounts of sphalerite, gersdorffite, galena, and traces of molybdenite, cobaltite, millerite, scheelite, bornite, malachite, linnaeïte, uraninite and monazite are also present in the mineralization (McMillan, 1972; Coulombe, 1984; Salmon and Ouellet, 1984). The majority of the copper–gold veins are found in structural faulting, fractures, shear zones and vein-breccia zones (Watkins and Riverin, 1982; Kirkham and Sinclair, 1996). In the former

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Springer-shaft area, most veins exhibit an east-west azimuth (Figure 1), dipping subvertically to the north. In the former Perry-shaft area, most veins show a north-south azimuth (Figure 1), with a 40° to 70° dip to the east (Coulombe, 1984). However, the azimuth of veins are sometimes diverging from the main structural controls and can spread out in unpredictable directions.

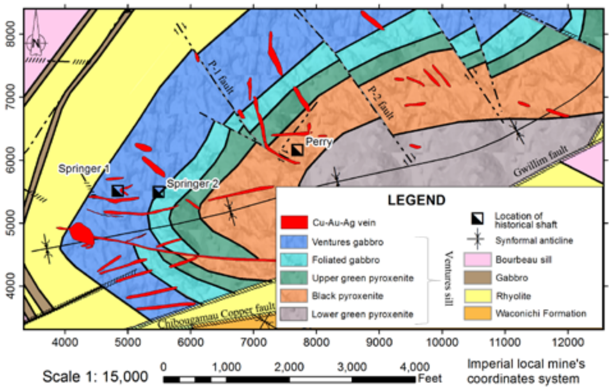

Figure 1: Surface geology of the Opemiska area. The location of the historical Springer and Perry shafts are shown. The locations of the Cu-Au veins (in red) are shown at their vertical projection to the surface.

COMPILATION AND PROCESSING OF THE HISTORICAL GEOPHYSICAL DATA

Since the closure of the mine, geophysical work on the property has focused on outlining the limits of the chalcopyrite ore. The geophysical surveys acquired by Ex-In include ground magnetic, resistivity/chargeability from an induced polarization (IP) survey, and Beep Mat data which were compiled as part of this study. In addition, other historical data were examined and compiled such as an airborne Input MK VI survey (Questor Surveys, 1978; Sial Geosciences, 1989), a Megatem survey (Dumont and Potvin, 2006; Dion and Loncol-Daigneault, 2006; Kiss and Oneschuk, 2007), airborne magnetics surveys (Reford et al., 1990; Keating et al., 2010), a partial MaxMin survey (Lavoie, 1980) and a partial Turam survey (Falconbridge Copper Ltd, 1968).

The total magnetic intensity (TMI) map does not show anomalies that could be related to mineralized zones (Gaucher, 2017). The dipole-dipole IP survey shows low resistivity anomalies coinciding with mineralization, but also with swamps, streams, tailings and anthropogenic sources of noise. The chargeability anomalies are interpreted to be either associated with the presence of copper-gold mineralization or they could be associated with magnetite (Pittard and Bourne, 2007), pyrrhotite, pyrite and/or graphite hosted in barren rocks. The results of the IP survey were unable to conclusively locate the Cu-Au ore since spurious cultural anomalies (fences, pipes, infrastructure, former mine waste) are also frequent in the vicinity of the former Springer and Perry shafts. The MaxMin survey (Lavoie, 1980) appears to react weakly at high frequency (3555 Hz) to Cu-Au veins under shallow overburden, but does not map deeper zones. In addition, several MaxMin anomalies were interpreted to be caused by geological formations rather than the mineralization of interest. The historical Turam survey performed by Falconbridge showed conductive anomalies associated either with pyrrhotite, graphitic tuff horizons or copper mineralization. This survey is partially covering the zone of interest, but large portions of the Opemiska property were not investigated. The Input airborne electromagnetic (AEM) survey detected six weak to intermediate conductive anomalies on the Opemiska property; however, only two of them coincide with known mineralization. The more recent Megatem AEM survey detected four or five veins, but not all of them (Gaucher, 2017).

PETROPHYSICAL STUDY

Measurements on hundreds of meters of diamond drill core samples and rock samples were done with the handheld multi-parameters probe (MPP) to measure the magnetic susceptibility and the EM conductivity, and the sample core induced polarization (SCIP) tester to measure the galvanic resistivity and the chargeability, both instruments being manufactured by Instrumentation GDD Inc. The conductivity of different chalcopyrite veins covered a range of values, with moderate conductivities in the range 10-100 S/m being obtained from samples with copper grades with up to 17.4% Cu (Figure 2a), while other samples with grades less than 4.8% Cu would surprisingly show conductivity values 10 to 40 times higher (Figure 3a). From these observations, it was concluded there is not a simple relationship between conductivity and copper grades.

Although chalcopyrite can have a large conductivity (Parkhomenko, 1967), microscopic observations on polished thin sections lead to the interpretation that higher conductivity could also be caused by pyrrhotite (Figure 3b). According to Parasnis (1956) and Parkhomenko (1967), the conductivity of pyrrhotite ranges from 10^{+3} to 10^{+5} S/m, which is higher than the conductivity of chalcopyrite, from 20 to 10^{+4} S/m. Murashov et al. (1929) even reports a relatively low conductivity of 1.5 S/m for a 90% chalcopyrite ore with 9% quartz and 2% pyrite.

The Opemiska copper rich sulfides are interpreted to sometimes have a relatively weaker conductivity caused by a molecular film of resistive silicates (such as quartz or phyllosilicates) surrounding the sulfide grains and preventing conductive networks from being established (Figure 2b). Measurements with the SCIP handheld instrument on hand samples bearing chalcopyrite established a lower conductivity limit of ~ 0.01 S/m. Kazer demonstrated that for a 0.01 mm grain diameter, only 0.01% of an impurity is necessary to form a resistive film around the grains (Semenov, 1948). It is believed that the major factor influencing the electrical conductivity of semiconductors is the presence of impurities and imperfections rather than the bulk composition of the rock (Keller, 1982). Impurities within the chalcopyrite might increase the conductivity of ionic dielectrics and electronic semiconductors by contributing electrons acting as charge carriers for conduction with low activation energy (such as chalcocite emulsions in sphalerite), but impurities tend as well to decrease the conductivity of metals if they are distributed uniformly through the material (such as silicates, carbonates, phyllosilicates and other impurities in chalcopyrite ore at Opemiska) (Parkhomenko, 1967; Keller, 1987).

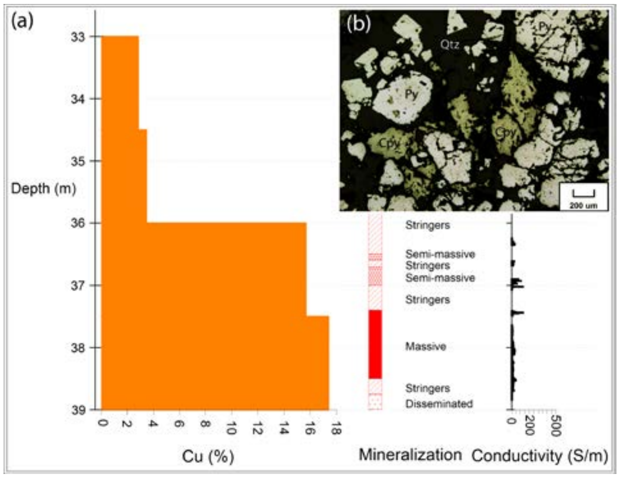

Figure 2: (a) Petrophysical measurements on core samples (DDH Op-2010-19) with the MPP handheld instrument (black right). Moderate conductivity values of 10-100 S/m (corresponding to stringers, and semi-massive to massive mineralization) were obtained from samples with Cu grades with up to 17.4% Cu (orange left). (b) A polished thin section from a rock sample I (from site #4, L200, station 0+10 E), which was measured with the SCIP instrument to be weakly conductive (0.03 S/m). Assay returned 9.52% Cu over 3.5 ft. Resistive gangue minerals (such as the quartz shown in black) are isolating the chalcopyrite grains from one another by filling the fractures, markedly increasing the bulk resistivity.

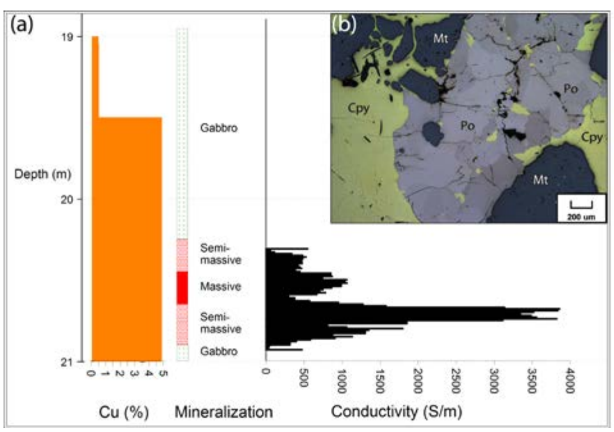

Figure 3: (a) Petrophysical measurements on core samples (DDH Op-2010-15) with the MPP hand-held instrument (black, right). High conductivity values of 500-4000 S/m (corresponding to semi-massive to massive mineralization) were obtained from samples with Cu grades less than 4.8% Cu (orange, left). (b) A polished thin section from the same site presented in (a). The pyrrhotite (Po) is organized in banded subdomains, intercalated with chalcopyrite (Cpy) and magnetite (Mt). The chalcopyrite and pyrrhotite are filling the interstices and form continuous conductive networks, reducing the bulk resistivity.

Petrophysical measurements and microscopic observations suggest complex interrelations between the amount of ore, the fabric of the rock, grain size and shape, texture, mineralogy and impurities, leading to a wide range of bulk conductivity values. This suggests that chalcopyrite might be a semiconductor at this site, and that its conductivity is mainly controlled by the concentration of minor impurities constituents and the geometric relation of the component mineral grains (Shuey, 1975; Pridmore and Shuey, 1976; Keller, 1987; Pearce et al., 2006).

TDEM SURVEY

Objectives and Survey Design

The information gathered during the petrophysical study and the geological and geophysical data compilation indicated that the copper-gold mineralization at hand-sample scale is associated with variable weak to high conductivity and chargeability. The 2015 TDEM survey aimed to map and quantifying at a number of locations on the property (1) the conductivity (2) the anisotropy of the conductivity, and (3) the chargeability. In the remainder of this paper, we only present the results for the first and second objectives with a view to determining if any characteristics of the EM response might be associated with copper-gold mineralization.

The electromagnetic survey intended to characterize the geology in the top one hundred metres, for which a loop size of 50 m was judged adequate. The site locations were selected to cover a variety of scenarios: both low-grade zones, stockwork and rich massive veins, good and weak conductors with varying strike, dip, plunge and length. The survey aimed to examine the variability of the EM response for different types of copper-gold veins, but also the impact of the host rocks on the response in different environments where chargeable, conductive and magnetic anomalies were observed in the previous geophysical surveys.

Instrumentation and Survey Parameters

The survey configuration for the 2015 campaign comprised:

- A GDD Nordic EM24 digital 24-bit receiver, with a sampling rate of 120,000 Hz. Stacking was adjusted and monitored in the field by evaluating the regularity of the decay curve and examining the spectrum. The Nordic EM24 measured the full (on and off) waveform so as to allow reprocessing of the data after the survey, e.g. adjusting the window positions depending on the ramp length, or looking at the on-time data;

- A square fixed-loop transmitter of 50 m side length with survey lines radiating from its center at 45° in every cardinal direction (Figure 4). Most of the sites have 4 lines: L0 (N-S), L100 (NE-SW), L200 (E-W) and L300 (NW-SE). Multiple directions were employed to allow for the varying direction of narrow veins with massive mineralization and to measure the anisotropy of the conductivity;

- A square current waveform generated by a GDD 20 A – 50 V transmitter or by a Geonics TEM47 transmitter

(Figure 4). When the environment was relatively quiet and noise-free, the TEM47 transmitter was used because of its fast turn-off time (Geonics, 2011). The GDD transmitter was used in noisier and more conductive environments. Both transmitters used a bipolar (castle) waveform with 50% duty cycle. The base frequency of the current waveform varied between 3 to 30 Hz, depending on the decay rate of the conductor so as to ensure the late-time decay drops below the noise level;

- A Geonics three-component ∂B/∂t coil sensor with an effective area of 200 m^2, and a bandwidth of 30 kHz (Geonics, 2013). The amplitudes of the early-time coil responses are relatively large, but rapidly decay to zero (Le Roux and Macnae, 1997). This means that the response from weak conductivity targets (such as can be seen at Opemiska) is measured at early times. In addition, the S/N ratio of poor conductors is greater in the ∂B/∂t response than the B-field data (Smith and Annan, 1998);
- Receiver stations were spaced every 5 m, and measurements were taken inside and outside the transmitter loop. The 3D sensor was aligned with the x-component pointing in the direction of increasing station coordinate along the line direction (Figure 4).

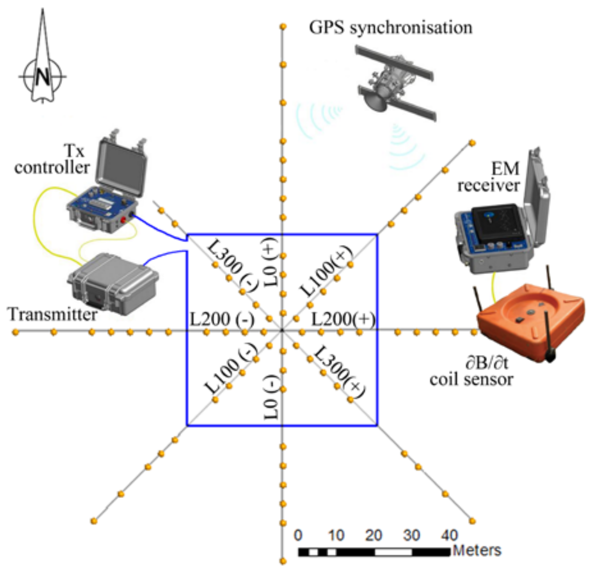

Figure 4: Instrumentation set-up for the square fixed-loop transmitter of 50 m side length with the GDD 20 A – 50 V transmitter or with the Geonics TEM 47 transmitter. The line numbering convention is shown in with survey lines radiating from its center at 45° in eight cardinal directions. The x-coordinate is increasing to the north for L0, northeast for L100, east for L200 and southeast for L300.

RESULTS OF THE TDEM SURVEY

Processing

Stations with saturation or interpreted anthropogenic sources of noise were removed from the profiles to get rid of distorted signals. The steps in the processing comprise: (i) Off time profiles were drawn for every line surveyed; (ii) the quality of the conductors was estimated with a decay-time-constant analysis for early times (windows 1-16; 0.08 to 1.541 ms) and late times (windows 19-24; 2.13 to 6.625 ms); (iii) forward modelling of conductors was undertaken using plates in free space to evaluate some of the relatively strong conductor's dimensions, depth, orientation, conductivity–thickness, dip and plunge. Some of the results of these processing steps are shown and discussed in the sections below. Although 14 sites were surveyed, only three representative sites will be discussed in detail: #2 – the good conductor, #4 – the bad conductor, and #3, – the weak conductor.

Conductivity

Out of the fourteen sites investigated with the TDEM method, six of them exhibited relatively strong anomalies. Hence, the measured responses of sites #2, 4, 7, 8, 9, and 14 were forward modeled using Maxwell software by approximating the discrete zone of conductivity with thin plates in free space (Dyck, 1991). The estimated plate conductance is as large as 100 S for the zones dominated by chalcopyrite ore (sites #2, 4, and 7), while the conductance can reach 1000 S at sites dominated by pyrrhotite (sites #8, 9 and 14).

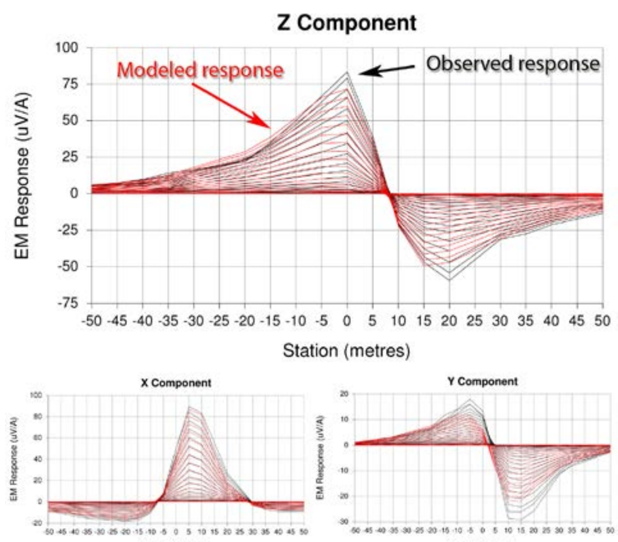

Figure 5: Profiles of x, y and z-components, for site #2, L0 from -50 m to +50 m, at 15 Hz, with time windows between 0.08 and 16.484 ms. The observed response is illustrated in black, and the modeled response is illustrated in red.

Site #2 – The Good Conductor

Two main conductors were detected at this site. Figure 5 illustrates the conductive response (in black) from the first conductor located near the center of the grid, and the modelled response (in red), along profile L0, which is essentially perpendicular to the sub-vertical target. The conductor corresponds to a horizon of chalcopyrite, known from historical diamond drill holes and observations on the trenched outcrop. The east-west trend of the conductor was defined by modelling all lines in 3D with a plate in free space. The models based on TDEM data are consistent with the geological models and exhibit a similar azimuth. The TDEM succeeded in identifying the different orientations of the conductors, the 1st (near the grid center) being east-west, while the second conductor located near the end of L0 (not shown) has a northwest-southeast azimuth.

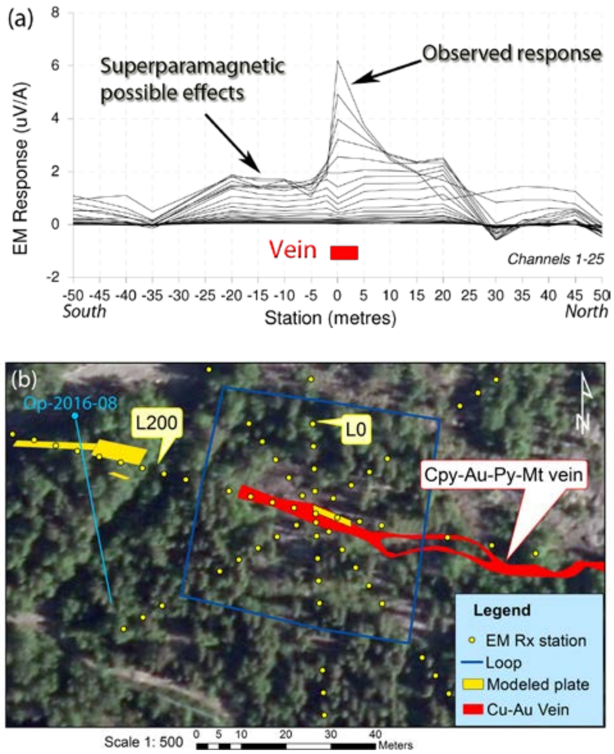

Figure 6: (a) Profile of z-component for L0, at 30 Hz, showing time windows 0.08 to 7.95 ms. (b) Location of L0 and L200 with a plan view of the 50 x 50 m square-loop layout (dark blue) with surveyed stations (yellow dots). The surface projection of the known vein is shown in red, with the projected modelled plates in yellow near the center of the loop on L0 and further west on L200. The vertical projection of the follow-up drill-hole Op-2016-08 that subsequently intersected a newly discovered vein extension in the rough location of the modelled plate is shown in blue.

Site #4 – The Bad Conductor

Another site surveyed (site #4), also had the north-south line (L0) perpendicular to what was known to be a massive chalcopyrite-pyrite vein. This site proved to be more challenging to interpret as the EM response was weak and decayed quickly so an isolated response was only evident on the first five windows (as late as 0.207 ms) (Figure 6). The anomaly is evident between locations -5 and +10 m on the profile and the amplitude is reduced by a factor of about 10 in comparison with the anomaly at site #2. Possible superparamagnetic effects are also evident as an enhanced response inside the loop (Gaucher and Smith, 2017). Even though regularly spaced channel sampling proved the existence of the vein, and implied an eastern extension along a 130 m strike length, another TDEM line (L200) placed along the vein strike did not reveal any anomaly inside the loop that could be interpreted as corresponding to the vein. However, an unknown extension of the vein was surprisingly discovered (with a slow decay) outside the loop at the western end of L200 (Figure 7). Based on forward plate modelling, the western trend of the structure was established with a strike of 285°, with a dip of 80° (almost parallel to the surveyed L200). Following the discovery of this anomaly, Ex-In drilled this target and intersected mineralization with an average grade of 3.4 % Cu and 1.2 g/t Au over a length of 17.4 m.

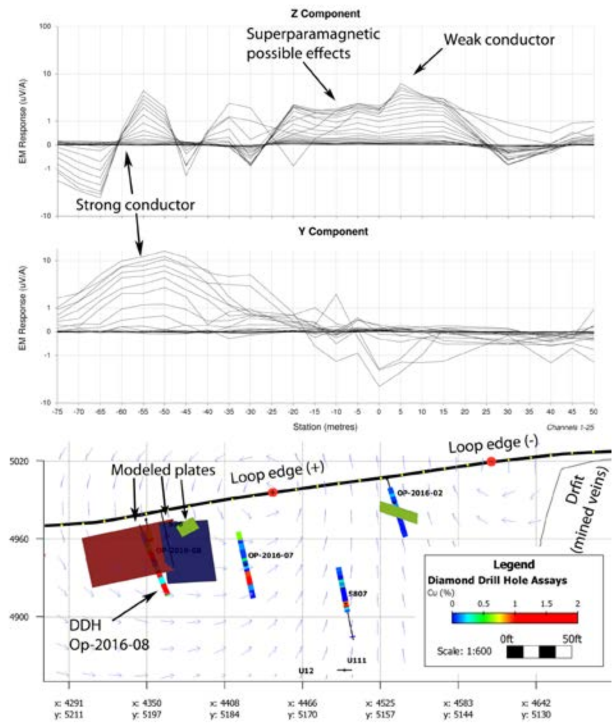

Figure 7: Geological longitudinal section (bottom) with drill-hole traces and TDEM profiles (top) along L200 (which follows the vein) of site #4. The modelled plates are shown on the section in red and blue (strong conductance) and green (weak conductance). The primary magnetic field is represented on the section with pale blue arrows, and its polarity is positive inside the loop, with edges at +/- 25 m.

Anisotropy of the Conductivity

In the more weakly conductive zones, the vein direction was quantified using rose diagrams. A method that looked at the peak ratio for the x-component was developed to map the direction of greater conductivity for sites presenting a weak conductivity with a low singe-to-noise (S/N) ratio. The smoke rings will travel through the different geological layers and be distorted from their original half-space pattern by the different diffusion velocities and attenuation rates of each layer. The diffusive currents will have a tendency to stay in the conductive medium; thus, their diffusion velocity will be slower than when flowing in resistive material (Gaucher, 2017). The TDEM survey aimed to assess if the eddy currents induced in the subsurface would gather preferentially in one direction, and whether it would be possible to identify an orientation parallel to the mineralized veins that is more conductive $\boldsymbol{\sigma}_{\parallel}$ and also identify the direction perpendicular to the vein $\boldsymbol{\sigma}_{\perp}$ (Sandberg and Jagel, 1996; Al-Garni and Everett, 2003; Al-Garni, 2004; Katsube et al., 2003; Wannamaker, 2005; Collins et al., 2006; Steelman et al., 2015). It was assumed that this process could give enough information to assess the azimuth of the weakly conductive veins at Opemiska. If asymmetry is identified, then one possible explanation for this asymmetry is the existence of weakly mineralized veins. The idea is based on the concept that if the current flow is in the more conductive direction, the slowest decay (or more closely gathered current lines) is observed on the profile lines that are perpendicular to this direction.

Peak Ratio of the X-Component – The Weak Conductor – Site #3

The largest positive or negative response amplitude on the x-component was estimated for every profile line of every site for which a conductive response was detected. The ratio of the largest amplitude measured in the first x-component time window divided by the largest amplitude measured in the sixth x-component time window was then calculated. The lowest ratio obtained by comparing the results for the four lines computed would indicate the slowest decay rate, and thus greater conductivity in a perpendicular direction. This lower ratio was taken as a common denominator to normalize with other ratios from other lines. The result is plotted on a rose diagrams for every line direction and multiplied by 1000 to give a ratio as a part per thousand or ‰. Hence, the smallest ratio is attributed a ratio of 1000‰ since it is divided by itself. To make the smallest ratio largest in the direction of greatest conductivity, the inverse is taken. The rose diagrams are then compared with the mapped chalcopyrite veins outcropping to evaluate if the most conductive direction can be estimated (Figure 8).

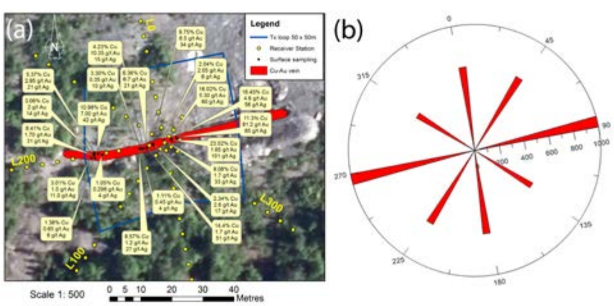

Figure 8: (a) Cu-Au-Ag assays for surface dust sampling at site #3 are shown along the vein delineated with a red contour. (b) Rose diagram showing the inverse of the amplitude ratio of the x-component for the time windows 1 and 6 for site #3. Line L200 exhibits the lowest ratio and correspond to the direction of the vein delineated by the red outline.

DISCUSSION

The conductive copper-gold ore at Opemiska near the historical Springer and Perry shafts area have been modelled with plates with a maximum conductance of 100 S and time constants $\tau < 2$ ms. These values are much less than the nickel copper-pyrrhotite sulfides found in the Sudbury Igneous Complex, where conductors with conductance of 10,000 S and time constants of several hundred milliseconds are used to fit the observed TDEM data (King, 1996). Nevertheless, mapping the near-surface copper-gold mineralization at Opemiska using thin plates works very well for the most conductive ore. The various orientations of the veins can be defined from the modelling and they correspond to known mineralization proven with diamond drilling. Surveying the sites using a star configuration with lines radiating from the center of the loop spaced at 45° angles helped constrain the forward modelling done in Maxwell. Anomaly shapes are simplest when the plane of a tabular conductor is normal to the surveyed line (Lamontagne, 2007). However, dipping and plunging conductors with lateral variations in their conductivity can exhibit complex shapes with little symmetry. The configuration used helped to define the vein's orientation, dip, plunge and conductance. Even though the property has been explored for more than 50 years by previous companies, this TDEM survey discovered at least one new anomaly in the area along an unknown extension of a massive chalcopyrite vein.

Modelling the weak conductors using the peak ratio of the x-component is an alternative to the plate modelling and seems to correlate well with the direction of the copper-gold veins. Even though this methodology is not yet perfected, it helps to get a sense of whether there might be veins and if so, what the direction of the vein system might be. Knowing this will help when planning subsequent exploration effort. This is particularly true for the sites where the conductivity was relatively low and plate modelling is more difficult. As this procedure has only been undertaken at two sites, more work is required to build confidence in the results.

The fact that chalcopyrite ($CuFeS_2$) can in some cases act as a semiconductor rather than a conductor (Shuey, 1975) could partly explain why the measured conductivity on core samples and in the field is highly variable: the conductivity of a semiconductor is highly sensitive to minor variations in chemical composition, and impurities serve as sources of charge carriers (Parkhomenko, 1967). The conductivity will be controlled by deviations from stoichiometry and the copper/iron ratio will also play a critical role (Shuey, 1975). It has been demonstrated that increasing the content of chalcopyrite above 70% does not significantly increase the conductivity (Parkhomenko, 1967). Finally, it should be noted that the texture of the chalcopyrite also plays a role (Semenov, 1948) in the conductivity variations observed at Opemiska: in some of the polished thin sections, the conducting mineral formed continuous filaments whereas in others, its distribution shows a habit of small grains surrounded by resistive molecular film of impurities insulating them from each other. The weak EM response observed while surveying orthogonally to some outcropping massive chalcopyrite veins is mainly attributed to the impurities and texture altering the physical properties of the mineralization. Hence, it is difficult to establish a direct link between the Cu grade and the conductivity of the chalcopyrite. Fullagar et al. (1996) and Venn (1995) showed a non-linear positive correlation between conductivity and copper grade; and Fallon et al. (2000) demonstrated that the use of geophysical logs at Mount Isa copper is rather indicative of an ore to waste boundary than a specific estimator, achieving 80% reliability with 2.5% Cu cut-off grade.

CONCLUSION

The TDEM survey conducted on the Opemiska property demonstrated considerable variability in the conductivity of the mineralization (0.01 – 4000 S/m), with high copper grades not guaranteeing a strong response. The thin section work implies that the lower conductivity is due to the conductive grains being surrounded by resistive material and not electrically connected. Impurities, fabric, the copper/iron ratio, and the relation between the ore minerals and the rock matrix are some of the other factors possibly altering the physical properties of chalcopyrite at Opemiska. There is also some indication from the literature that in some cases chalcopyrite can be a semiconductor.

Taking measurements along lines with different orientations with a relative small transmitter loop, allowed a rapid assessment of whether a conductor was present in the area of interest. In the data from the sites presented here, the strong conductor's trends, sizes, shapes and conductances were identified with success by modelling the data using thin conductive plates in free space. In the case of weaker conductors, the vein's trends were approximated using the peak ratio of the x-component time windows 1 and 6 and plotting the results on rose diagrams. This methodology allowed the identification of sites with isotropic conductivity and also those exhibiting anisotropic conductivity, while at the same time determining the weak conductor's azimuths.

From an exploration perspective, prospecting for massive vein-type and disseminated chalcopyrite in the area should also be targeting weakly conductive anomalies, since the copper-gold ore did not always show a direct correlation with high bulk conductivity. Every TDEM anomaly, whether it is strongly or weakly conductive, should not be discredited, but should be followed up and investigated with a diamond drill hole or channel sampling if conditions allow it.

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REFERENCES

Al-Garni, M. A., and M. E. Everett, 2003, The paradox of anisotropy in electromagnetic loop-loop responses over a uniaxial half-space, Geophysics, 68, 892–899.

Al-Garni, M. A., 2004, Electromagnetic smoke rings diffusion in a horizontally anisotropic conducting half-space: Symposium on the Application of Geophysics to Engineering and Environmental Problems, 654–667.

Collins, J. L., M. E. Everett, and B. Johnson, 2006, Detection of near-surface horizontal anisotropy in a weathered metamorphic schist at Llano Uplift (Texas) by transient electromagnetic induction: Physics of the Earth and Planetary Interiors, 158, 159–173.

Coulombe, A., 1984, La mine Cooke, la mine Springer, et la mine Perry, Chapais (Corporation Falconbridge copper, division Opémiska). In : Chibougamau–Stratigraphie et minéralisation « Une ceinture Archéenne unique » : Canadian Institute of Mining and Metallurgy Bulletin. Livret guide pour le symposium tenu à Chibougamau, 89–93.

Dion, D. J., and D. Loncol-Daigneault, 2006, Données numériques des levés géophysiques aéroportés versés aux travaux statutaires, région de l'Abitibi : publication du MRNF, DP-2006-02.

Dumont R., and J. Potvin, 2006, Block A, MEGATEM II survey Chibougamau 2006, Parts of NTS 32 G/10 – 32 G/15, Québec: Geological Survey of Canada, Open Files 5242-5254.

Dyck, A. V., 1991, Drill-hole electromagnetic methods, in M. Nabighian ed., Electromagnetic methods in applied geophysics – Volume 2, Application, Parts A and B.

Falconbridge Copper Ltd – Opemiska Copper Mines Ltd (Québec), 1968, Turam EM survey, Map sheet 1 of the mine area with surveyed lines and interpretation, unpublished.

Fallon, G.N., P.K. Fullagar, and B. Zhou, 2000, Towards grade estimation via automated interpretation of geophysical boreholelogs: Exploration Geophysics, 31, 236–242.

Fullagar, P. K., G. N. Fallon, and B. Zhou, B., 1996, In-mine geophysical trials at Mount Isa Mine: Centre for Mining Technology and Equipment, Brisbane, Report MM1-96/7.

Gaucher, F. E. S., 2017, Exploring for copper–gold deposits with electromagnetic surveys at Opemiska, Canada: MSc thesis, Laurentian University.

Gaucher, F. E. S and R.S. Smith, 2017, The impact of magnetic viscosity on time-domain electromagnetic data from iron oxide minerals embedded in rocks at Opemiska, Québec, Canada: Geophysics, in press.

Geonics Limited, 2011, TEM47 HP – Battery-powered high power – TDEM transmitter – Operating notes, http://geonics.com, accessed March 1st, 2015.

Geonics Limited, 2013, Induction coils, http://geonics.com, accessed 27 March 2017.

Katsube, T.J., P.B. Keating, S. Connell, M.E. Best, and C.J. Mwenifubo, 2003, Electrical anisotropy characteristics of mineralized and nonmineralized rocks in the Bathurst mining camp: implications for airborne conductivity interpretation: Economic Geology, Monograph, 11, 861–877.

Keating, P., D. Lefebvre, D. Rainsford, and D. Oneschuk, 2010, Geophysical series, parts of NTS 31, 32, 41 and 42, Abitibi greenstone belt, Québec and Ontario: Geological Survey of Canada, Open File 6563.

Keller, G. V., 1982, Electrical properties of rocks and minerals, in R.S. ed., Carmichael Handbook of physical properties of rocks – Volume I.

Keller, G. V., 1987, Rock and mineral properties, in M. Nabighian ed., Electromagnetic methods in applied geophysics – Volume 1, Theory.

King, A., 1996, Deep drillhole electromagnetic surveys for nickel/copper sulphides at Sudbury, Canada: Exploration Geophysics, 27, 105–118.

Kirkham, R. V. and W. D. Sinclair, 1996, Vein copper, in O.R. Eckstrand, W. D. Sinclair, and R. I. Thorpe eds., Geology of Canadian mineral deposit types: Geological Survey of Canada, Geology of Canada, 8, 399–408.

Kiss, F., and D. Oneschuk, 2007, Levé magnétique et électromagnétique MEGATEM II dans la région de Chibougamau-Lac aux Dorés, Québec: Ministère des Ressources naturelles et de la Faune du Québec, DP2007-02.

Lamontagne, Y., 2007, Deep exploration with EM in boreholes, in B. Milkereit, ed., Proceedings of Exploration 07, 401–415.

Lavoie, C., 1980, Levés électromagnétiques et magnétiques, EMH, VLF et MAG, propriété Opémiska et Test PP sur le gisement Cook : MRNF, GM 38025.

Lavoie, J. S., 1972, Geology of Opemiska mines, Falconbridge Copper Limited, Opemiska Division: Internal report.

Leclerc, F., L. B. Harris, J. H. Bédard, O. Van Breemen, and N. Goulet, 2012, Structural and stratigraphic controls on magmatic, volcanogenic, and shear zone-hosted mineralization in the Chapais–Chibougamau mining camp, northeastern Abitibi, Canada: Economic Geology, 107, 963–989.

Le Roux, C., and J. Macnae, 1997, SQUID sensors for EM systems, advances in ground and borehole geophysics, in B. Milereit, ed., Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, 417–423.

McMillan, R.H., 1972, Petrology, geochemistry and wallrock alteration at Opemiska – a vein copper deposit crosscutting a layered Archean ultramafic-mafic sill: PhD thesis, University of Western Ontario.

Murashov, D.F., E.V. Berengarten, A.V. Echeistova, and L.D. Khudyakova, 1929, Electrical conductivity of ore and rock: Goelkom.

Parkhomenko, E.I., 1967, Electrical properties of rocks: Springer.

Parasnis, D. S., 1956, The electrical resistivity of some sulphide and oxide minerals and their ores: Geophysical Prospecting, 4, 249–278.

Pearce, C.I., R.A.D. Pattrick, and D.J. Vaughan, 2006, Electrical and magnetic properties of sulfides: Reviews in Mineralogy and Geochemistry, 61, 127–180.

Pilote, P., 1998, Géologie et métallogénie du district minier de Chapais-Chibougamau: nouvelle vision du potentiel de découverte : Ministère des Ressources naturelles du Québec, DV 98-03.

Pittard, K., and B. Bourne, 2007, The contribution of magnetite to the induced polarization response of the Centenary orebody: Exploration Geophysics, 38, 200–207.

Pridmore, D. F, and R. T. Shuey, 1976, The electrical resistivity of galena, pyrite and chalcopyrite: American Mineralogist, 61, 248–259.

Questor Surveys LTD, 1978, Levé EM aérien par INPUT MK VI, région d'Opémiska, publication du MRNF, DP 587.

Reford, S. W., V.K, Gupta, N.R. Paterson, K.C.H. Kwan, and I.N. MacLeod, 1990, The Ontario master aeromagnetic grid: a blueprint for detailed magnetic compilation on a regional scale, 60th Annual International Meeting, SEG, Expanded Abstracts, 617–619.

Salmon, B., 1982, Distribution de la minéralisation d'une veine cuprifère sur la propriété de Falconbridge Copper Ltée à Chapais, P.Q.: B.Sc.A thesis report, École Polytechnique de Montréal.

Salmon, B., and A.J. Ouellet, 1984, Structure, mineral distribution and wallrock alteration of the no. 7 vein, Opemiska copper mine, in J. Guha and E. H.Chown eds., Chibougamau – Stratigraphy and mineralization, CIM Special Volume, 34, 357–369.

Salmon, B., and R. de l'Étoile, 2013, Determination of exploration potential at the Springer mine – Opemiska property: Roscoe Postle Associates Inc.

Sandberg, S.K., and D.L. Jagel, 1996, The electromagnetic azimuthal resistivity method: Proceedings of the symposium on the application of geophysics to engineering and environmental problems, 31–40.

Semenov, A.S., 1948, Resistivity of minerals with high conductivities: Geofizika, 13, VSEGEI, Gosgeolizdat.

Shuey, R.T., 1975, Semiconducting ore minerals, Developments in Economic Geology, 242.

Sial Geosciences Inc., 1989, traitement des données géophysiques (aéromagnétiques) – Chapais, publication du MRNF, DV 89–11.

Smith, R.S., and A.P. Annan, 1998, The use of B field measurements in an airborne time-domain system: Part 1. Benefits of B field versus dB/dt data: Exploration Geophysics, 9, 24–29.

Smith, R.S., D. Fountain, and M. Allard, 2005, The MEGATEM fixed-wing transient EM system applied to mineral exploration: a discovery case history: CSEG recorder, 30, 27–30.

Steelman, C.M., B.L. Parker, and C.S. Kennedy, 2015, Evaluating local-scale anisotropy and heterogeneity along a fractured sedimentary bedrock river using EM azimuthal resistivity and ground-penetrating radar: Journal of Applied Geophysics, 116**,** 156–166.

Venn, M.J., 1995, The electrical rock properties of the 1100 copper ore system, Mount Isa, Australia: A detailed field and petrophysical based study, exploring the reasons for variation in the electrical conductivity of the 1100 copper orebody: MSc thesis, Monash University.

Wannamaker, P.E., 2005, Anisotropy versus heterogeneity in continental solid earth electromagnetic studies: fundamental response characteristics and implications for physicochemical state: Surveys in Geophysics, 26, 733–765.

Watkins, D.H., and G. Riverin, 1982, Geology of the Opemiska copper–gold deposits at Chapais, Québec, in R.W. Hutchinson, C.D. Spence, and J.M. Franklin eds., Precambrian Sulphide Deposits, H. S. Robinson Memorial Volume: Geological Association of Canada, Special Paper 25, 427–446.