Exploring for copper-gold deposits with time-domain electromagnetics in the Chapais-Chibougamau mining camp: case history of a challenging variable environment.

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Summary

Following petrophysical studies, geological and geophysical data compilation, the former Opemiska underground mine of the Chibougamau District was selected for conducting an experimental TDEM ground survey. Fourteen different sites confirmed the variability of the EM response associated with chalcopyrite veins, and the difficulty in relying on an equivocal signature to locate the massive sulfides. Surveys away from the veins showed a variety of responses. Petrophysical measurements and microscopic observations suggest complex interrelations between the amount of ore in the rock, fabric, texture, porosity, mineralogy and impurities, leading to a wide range of bulk conductivity values that suggest chalcopyrite might be a semiconductor at this site.

Introduction

The Chapais-Chibougamau mining camp is the second-largest mining district in the Quebec part of the Abitibi greenstone belt (Leclerc and al., 2012). The Opemiska mine (fig.1), lying within the camp, produced 600,000 short tons of copper, 216,000 ounces of silver, and 529,000 ounces of gold from 1953 until its closure in 1991. The underground mine used shafts and galleries to extract narrow but high-grade syn-magmatic copper-gold veins formed through hydrothermal processes (Salmon, 1982). The ore consists of semi-massive to massive chalcopyrite-quartz-carbonate ± pyrite-pyrrhotite-magnetite-gold veins and veinlets in a subophitic gabbro (Leclerc and al, 2012), with minor amounts of sphalerite gersdorffite and galena (Salmon, 1984). Traces of molybdenite, cobaltite, scheelite, bornite, and malachite are present in the mineralization (McMillan, 1972). Since 1993, a junior company has been assessing the possibility of exploiting lower grade ore as a high tonnage open pit operation. The exploration problem consists in finding new ore zones close to the surface that can be mined economically.

Since the closure of the mine, geophysical work on the property has focused on outlining the limits of the chalcopyrite ore. The surveys acquired include MaxMin, magnetic and resistivity/IP surveys, which were compiled as part of this study. The interpretation of the total-field magnetic survey suggested a correlation between magnetite and pyrrhotite or pyroxenite, but didn't provide a direct vector to the mineralization itself. The dipole-dipole induced polarization survey showed resistivity anomalies coinciding with swamps and streams. The chargeability anomalies were interpreted to be either associated with the presence of copper-gold mineralization or with magnetite, pyrrhotite or pyrite hosted in barren rocks. This information gathered during the geological and geophysical data compilation provided a better understanding of the property. Mineralization is concentrated in networks of veins and veinlets of different orientations with dips generally sub-vertical. The objective of the TDEM survey was to understand the response characteristics in the different areas so we could develop a procedure to explore and map near-surface copper-gold ore, both low-grade zones and rich massive veins, with varying strike, dip, plunge and length.

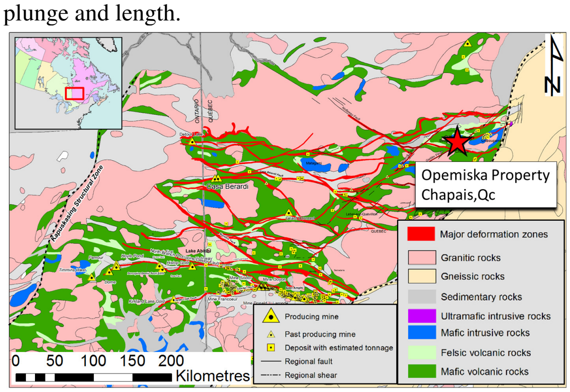


Fig. 1. Location of TDEM experiments within the Abitibi greenstone belt (modified from Parsons et al., 2015).

Methodology

The configuration of the 2015 transient EM investigation consisted in a square fixed-loop transmitter of 50m side length with survey lines radiating from its center at 45 degrees in every cardinal direction (fig.3a). Such configuration was employed to establish the varying direction of narrow veins with massive mineralization. Receiver stations were spaced every 5m, and measurements from an impulse-response TEM system were taken inside and outside the loop. A squared waveform 1A battery powered transmitter was used in quiet noise-free environment, while a 20A-50V transmitter powered by a 1000W portable generator was used in noisy and conductive environments. Electronic gain was adjusted for every station to ensure the signal was just below the saturation level. Fourteen different sites were investigated to evaluate different environments with varying conductivity, chargeability, magnetic response, sulfide content, rock type and texture. The base frequency used ranged from 3 to 30 Hz and was adjusted depending on the decay rate of the conductor so as to ensure the late-time decay drops below the noise level. In an effort to reduce the background noise level and enhance the signal, stacking was adjusted and monitored in the field by evaluating the regularity of the decay curve and examining the spectrum. Three distinct readings were acquired and averaged for every receiver station to control the quality and ensure the repeatability of the measurements. A Geonics three-component dB/dt coil sensor with an effective area of 200 m^2 and a bandwidth of 29 kHz was connected to a GDD NordicEM digital 24-bit EM receiver using a sampling rate of 120,000 Hz and a digital stacking algorithm. Synchronization between the transmitter was achieved using GPS signals, or with an internal crystal clock. The 3D sensor was aligned with the X component pointing in the direction of increasing station coordinate along the line direction. Adjustment of the X and Y components was done visually looking at the profile stakes because of the presence of magnetite affecting the magnetic field direction and the Z component orientation was adjusted with a levelled bubble. Lines sometimes had to be cut with a machete or chain saw to ease the path of the operators with instrumentation through the dense forest.

Processing

The full-wave was recorded so as to allow reprocessing of the data after the survey by adjusting the gate positions depending on the ramp length. Stations with saturation or interpreted anthropogenic sources of noise were eliminated to get rid of distorted signals and removed from the profiles. A power-line-noise rejection filter was applied as part of the stacking process.

Off time profiles were drawn for every line surveyed. Quality of the conductors was estimated with a time constant analysis for early times (windows 1-15; 0.08 to 1.284 msec) and late times (windows 19-24; 2.13 to 6.625 msec). Forward modelling of conductors was undertaken using plates in free space to evaluate some of the conductor's dimensions, depth, orientation, conductivity, thickness, dip and plunge. Grid interpolation of the observed total secondary magnetic field from the first window was also done using the kriging technique.

Results

Although 14 sites were surveyed, in this abstract, we only discuss two sites in detail (site #2 and #4). Figure 2 illustrates the conductive response (in black), and the modeled response (in red), from site #2, with a 100 m NS line profile (L0), essentially perpendicular to the sub-vertical target. The conductor corresponds to a known horizon of pyrrhotite and chalcopyrite, corroborated with historical diamond drill holes and observations on trenched outcrops. The EW trend of the conductor was defined by modelling all lines in 3D with a plate in free space (red body in fig.3a). Interpolating in 2D the Z component secondary magnetic field from TDEM window 1 data exhibited the same location and trend direction (277°) as the red body (fig.3b) modelled in 3D.

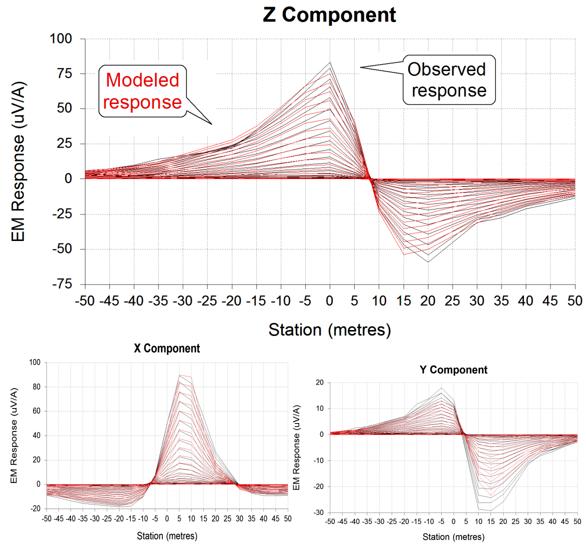


Fig. 2. Site #2, L0. Profiles of X, Y and Z components, at 15 Hz, with channels 1 to 29 (0.08 to 16.484 msec).

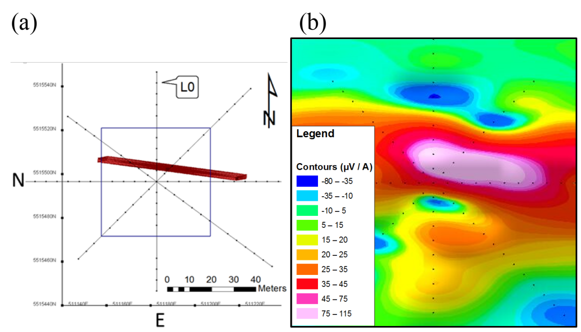


Fig. 3. Site #2 (a) Plan view of the 50 x 50m square-loop layout with surveyed lines radiating from its centre. The surface projection conductive plate model is also shown in red. (b) Observed secondary field, from the first TDEM window (0.08 msec) for the Z component.

Another site surveyed (site #4), with a NS line (L0) perpendicular to what was known to be a massive chalcopyrite-pyrite vein proved to be more challenging: the EM response was weak and decayed quickly (Nabighian, 1991), only being evident on the first five early-time windows (up to 0.207 msec) (fig.4). The amplitude of the anomaly is reduced by a factor of about 10. Even though regularly spaced trenching and bulk sampling proved the existence of the vein, and surface mapping implied an extension along a 130 m strike length, another TDEM line (L200) placed along the vein strike did not reveal any anomaly above the noise level and that would be interpreted to correspond to the vein. However, an unknown extension of the vein was surprisingly discovered at the western end of line 200 (fig.5). Based on forward plate modelling, the western trend of the structure was established as 285 degrees, with a dip of 80 degrees (fig 5). Following the 2015 geophysical investigation, the current owner of the property, drilled this last identified target and hit 0.98% Cu over a length of 52.9 m, with massive chalcopyrite intersections returning 22.78% Cu over 0.75 m (fig.5). Even though the property has been explored for more than 50 years by previous companies, this TDEM survey discovered three new anomalies in the area.

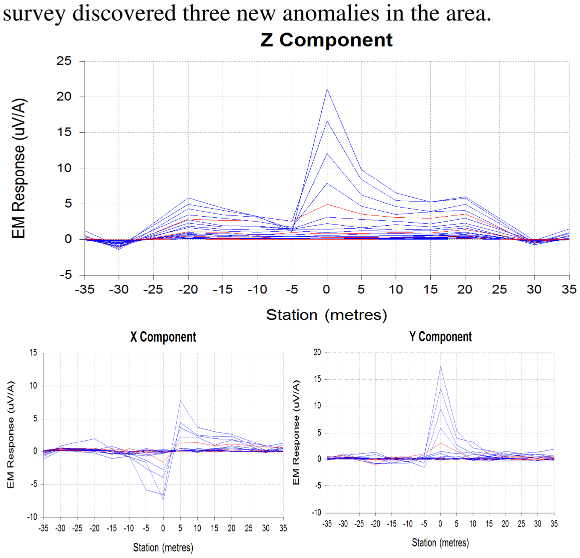


Fig. 4. Profiles of X, Y and Z components, at 30 Hz, with channels 1 to 25 (0.08 to 7.95 msec), with a ramp of 0.16 msec. The anomaly of the vein is only visible on windows 1 to 5, between -5 and 5m. L0 (North-South), site #4.

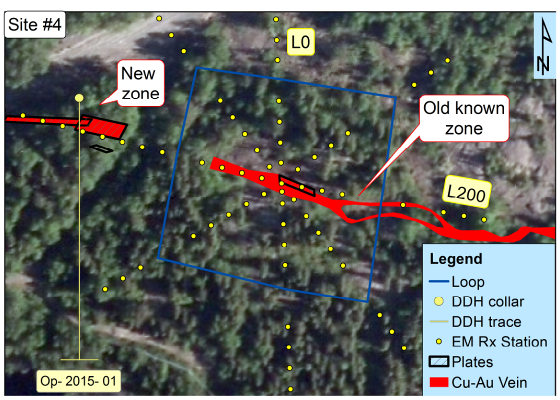
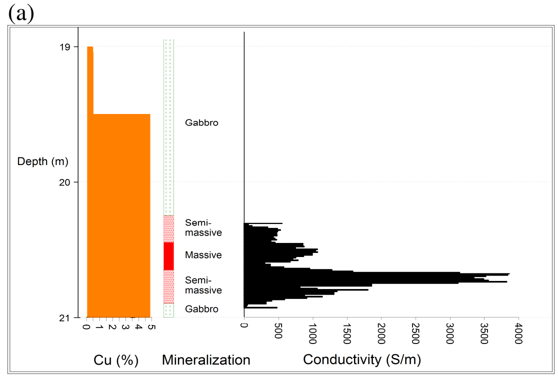


Fig.5 Plan view of the 50 x 50m square-loop layout with surveyed stations. The surface projection of the vein is also shown in red, with the plate models for the new western extension.

Petrophysical measurements on core samples with MPP and SCIP hand-held instruments allowed us to establish a conductivity and magnetic susceptibility range for different chalcopyrite veins. Moderate conductivities of 10-100 S/m were obtained from samples with copper grades with up to 17.4% Cu (fig.6b), while other samples would show conductivities 10-40 times higher with lower grades up to 4.8% Cu (fig.6a). From these observations, we conclude there is not a direct relationship between conductivity and copper grades. Microscopic observations on polished thin sections lead to the interpretation that high conductivity was caused by pyrrhotite (fig.7a), while chalcopyrite rich sulfides had a weaker conductivity (fig.7b), or would not respond at all.

(a)



(b)

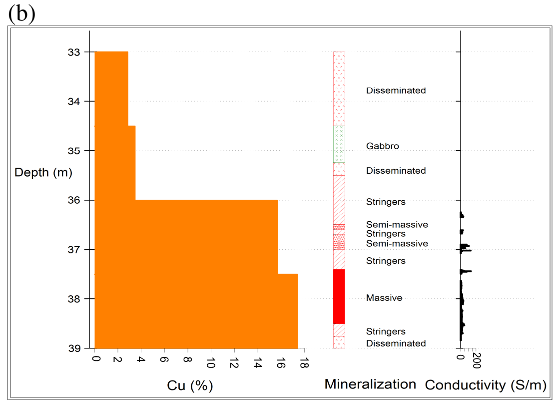


Fig. 6. (a) Moderate Cu grades with high conductivity.
(b) High Cu grades, with moderate conductivity.

(a) (b)

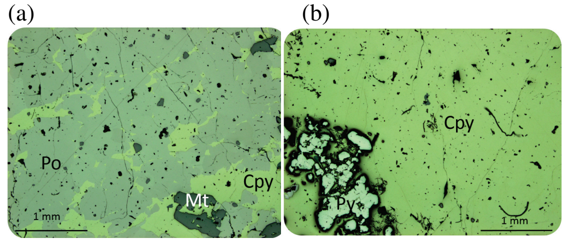


Fig. 7 (a) Pyrrhotite (Po) intercalated with chalcopyrite (Cpy) and grains of magnetite (Mt). (b) Uniform distribution of chalcopyrite, with grains of pyrite (Py).

Exploring for copper-gold deposits with time-domain electromagnetics

Discussion

Anthropogenic sources of noise such as proximal 60 Hz power lines, metallic infrastructure (buried pipes, metal fences, excavated underground galleries) and former mine waste are present almost everywhere on the property. Identifying the responses associated with these features can be challenging: particularly when they are superimposed on the mineralized zones of interest and the latter showed low amplitude signal. Since the time spent in the field is a trade-off between quality and productivity, the stacking in noisy environment was no greater than 2048 transients at 30 Hz. Increasing the transmitted magnetic dipole moment by using a larger loop or more current, would enable more distal structures and anthropogenic features to be excited; we used a smaller loop as our goal was mapping near surface mineralization. A small loop also results in a shorter ramp time, allowing measurements at the early times associated with weak conductors. In areas where the less conductive veins showed a weak EM response, the Geonics TEM 47 with a fast turn-off ramp resulted in higher amplitude responses evident on the profiles; while in noisier and more conductive environments, the GDD EM transmitter was able to drive 10 times more current and improved the quality and efficiency of the survey by providing data with a better signal to noise ratio.

Different layouts were tested to enhance the response of the known veins reaching surface. When the loop was in a position to maximize primary field coupling with the target, the signal amplitude was 500% greater than when the loop was centred over the vein. The fact that the profile shape remains the same implies that the veins are thin. A knowledge of the conductor location is thus beneficial when planning the loop locations.

The fact that chalcopyrite ($CuFeS_2$) might be considered as a semiconductor rather than a conductor (Shuey, 1975) could partly explain why the measured conductivity on core samples and in the field is varying: 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, 1976). It has been demonstrated that increasing the content of chalcopyrite above 70% does not significantly increase the conductivity (Parkhomenko, 1967). In addition, the copper oxidation state varies in chalcopyrite, with oxidized copper either being monovalent or divalent, and this variability can play an important role by affecting the crystal chemical properties and thus its electrical properties (Pattrick et. al, 2006). Looking at polished thin sections under the microscope from samples collected over the veins surveyed with the TDEM survey, it is clear that chalcopyrite has sometimes been tarnished and oxidized (fig.8a). Finally, it should be noted that the texture of the chalcopyrite also plays a role in the conductivity variations observed at Opemiska (Semenov, 1948): 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 (fig.8b).

(a) (b)

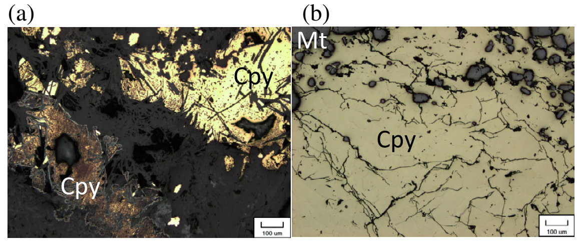


Fig. 8. (a) Tarnished and oxidized chalcopyrite (Cpy). grains. (b) Polished thin sections (10X) from the weakly conductive site presented at fig.4, where assay returned 9.1% Cu over 1.98 m. Resistive gangue minerals are isolating the chalcopyrite by filling the fractures.

Conclusion

Taking measurements in different line directions with a relative small loop, allowed a rapid assessment of whether a conductor was present in the area of interest. In the data from the two sites we presented here, we were able to identify the conductor's trend. However, we found that the conductivity showed greater variability than expected.

Bulk conductivity of targeted ores helps a geophysicist determine which geophysical method should be employed, and the expected response. Impurities, fabric, interrelation between the ore minerals and the rock matrix are some of the factors altering the physical properties of chalcopyrite. The TDEM survey conducted on the Opemiska property demonstrated considerable conductivity variability, with high copper grades not guaranteeing a strong response. Our thin section work implies that the lower conductivities are due to the conductive grains being surrounded by resistive material and not electrically connected. There is also some indication from the literature that in some cases chalcopyrite can be a semi-conductor. From an exploration perspective, prospecting for massive and disseminated chalcopyrite in the area should also be targeting weak conductive anomalies, since the Cu-Au ore did not show a direct correlation with high bulk conductivity.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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