Exploring for copper–gold deposits with electromagnetic surveys at Opemiska, Canada

by

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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, and the difficulty of relying on a definite EM signature to locate the economic sulfides. The Cu-Au zones showed a variety of EM responses with a maximum conductance of 100 Siemens and 2 ms time constant. The trends, sizes, shapes and conductances of the relatively strong conductors were identified with success and modeled using thin plates in full space. The vein direction in the weakly conductive zones were quantified from the x-component data. In only one instance was a TDEM response associated with mineralization interpreted to be chargeable. Petrophysical measurements and microscopic observations suggest complex interrelations between the amount of ore, the fabric of the rock, texture, porosity, 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 suggests that chalcopyrite might be a semiconductor at some locations at Opemiska.

The magnetic viscosity effects observed at time scales between 0.01 and 10 ms at Opemiska are associated with magnetic grains of variable size in rocks. Recent observations made during a ground time-domain electromagnetic (TDEM) survey at Opemiska are consistent with four aspects of the spatial and amplitude characteristics of a magnetic viscosity response: (1) the $\frac{\partial B_z}{\partial t}$ decay rate is roughly proportional to $1/t^{1+\alpha}$, where $-0.4 < \alpha < 0.4$; (2) the anomalies are mainly visible on the $z$-component when the EM receiver sensor is located inside or just outside the transmitter
loop; (3) there is no obvious x- or y-component response; (4) the sites where magnetic viscosity effect are seen in the TDEM data are coincident with an airborne magnetic anomaly. Previous studies have demonstrated that the magnetic viscosity could be caused by (i) fine-grained particles of maghemite or magnetite in the overburden, regolith or soil that were formed through lateritic weathering processes; (ii) volcanic glass shards from tuff containing ~1% by weight magnetite, which occurs as grains ~0.002 to 0.01 μm in size precipitated in a spatially uniform way, or (iii) from Gallionella bacterium that precipitates ferrihydrite that oxidizes to nanocrystalline maghemite aggregates. The sites investigated at Opemiska are outcropping and well exposed with relatively little or no overburden, and are unfavorable to the formation of maghemite; hence, it is assumed that the source of magnetic viscosity seen at Opemiska cannot be the maghemite, or the other aforementioned causes. Hand samples were collected from Opemiska to identify the minerals present. Polished thin sections observed under an optical reflecting microscope identified the accessory minerals magnetite, ilmenite and pyrrhotite, all known for their relatively high magnetic susceptibility. The use of the scanning electron microscope confirmed fine grained magnetite grains as small as 0.667 μm. An electromagnetic induction spectrometer confirmed the viscous nature of the susceptibility of the Opemiska samples. This suggests that magnetic viscosity could originate not only from fine-grained magnetite and maghemite particles located in the weathered regolith, but also from other iron oxides and magnetic minerals embedded in the rock itself.

KEYWORDS

electromagnetics, conductivity, anisotropy, chargeability, magnetic viscosity, superparamagnetic effects, magnetization, rock physics, time-domain, interpretation, petrophysics, mining exploration, chalcopyrite.
CO-AUTHORSHIP STATEMENT

This manuscript is composed of two main chapters:

1. (a) Some of the material from Chapter 1 has been published by the Society of Exploration Geophysicists (SEG), and is co-authored by Dr. Richard S. Smith:


   (b) Additional material from Chapter 1 has been submitted on April 11, 2017, to Exploration '17 - Integrating the geosciences: The challenge of discovery, and is co-authored by Dr. Richard S. Smith.

2. Chapter 2 has been accepted for publication in the Geophysics journal (Vol. 82, No.5), and is co-authored by Dr. Richard S. Smith.

The thesis was edited by Dr. Richard S. Smith, Bill Spicer, Alan King and revised following comments by the external examiner, Dr. Ian Ferguson.
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### GLOSSARY

**Abbreviations and chemical formulae of minerals**
( after Kretz, 1983; Lindsley, 1991; Whitney and Evans, 2010)

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Ideal Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>Gold</td>
<td>Au</td>
</tr>
<tr>
<td>Bt</td>
<td>Biotite</td>
<td>K(Mg,Fe)₃[AlSi₅O₁₀(OH,F)₂</td>
</tr>
<tr>
<td>Cpy</td>
<td>Chalcopyrite</td>
<td>CuFeS₂</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
<td>Cu</td>
</tr>
<tr>
<td>Hem</td>
<td>Hematite</td>
<td>α Fe₂O₃</td>
</tr>
<tr>
<td>Ilm</td>
<td>Ilmenite</td>
<td>FeTiO₃</td>
</tr>
<tr>
<td>Gr</td>
<td>Graphite</td>
<td>C</td>
</tr>
<tr>
<td>Gt</td>
<td>Goethite</td>
<td>α-Fe³⁺O(OH)</td>
</tr>
<tr>
<td>Mgh</td>
<td>Maghemite</td>
<td>γ–Fe₂O₃</td>
</tr>
<tr>
<td>Mlr</td>
<td>Millerite</td>
<td>NiS</td>
</tr>
<tr>
<td>Mrg</td>
<td>Margarite</td>
<td>CaAl₂(Al₂Si₂O₁₀)(OH)₂</td>
</tr>
<tr>
<td>Mt</td>
<td>Magnetite</td>
<td>Fe₃O₄</td>
</tr>
<tr>
<td>Or</td>
<td>Orthoclase</td>
<td>KAlSi₅O₈</td>
</tr>
<tr>
<td>Pn</td>
<td>Pentlandite</td>
<td>(Fe,Ni)₈S₈</td>
</tr>
<tr>
<td>Po</td>
<td>Pyrrhotite</td>
<td>Fe₁₋ₓS</td>
</tr>
<tr>
<td>Py</td>
<td>Pyrite</td>
<td>FeS</td>
</tr>
<tr>
<td>Qtz</td>
<td>Quartz</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Sp</td>
<td>Sphalerite</td>
<td>ZnS</td>
</tr>
<tr>
<td>Stp</td>
<td>Stilpnomelane</td>
<td>(K,Ca,Na)(Fe,Mg,Al)₁₂(Si,Al)₁₂(O,OH)₃₆ · nH₂O</td>
</tr>
<tr>
<td>Ttn</td>
<td>Titanite</td>
<td>CaTiSiO₅</td>
</tr>
<tr>
<td>Vio</td>
<td>Violarite</td>
<td>Fe²⁺Ni₂³⁺S₄</td>
</tr>
</tbody>
</table>
# Abbreviations and chemical formula of mineral groups

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>Amphibole</td>
</tr>
<tr>
<td>Px</td>
<td>Pyroxene</td>
</tr>
<tr>
<td>Cb</td>
<td>Carbonate mineral</td>
</tr>
<tr>
<td>Pl</td>
<td>Plagioclase</td>
</tr>
<tr>
<td>Ph</td>
<td>Phyllosilicates</td>
</tr>
<tr>
<td>Symbol</td>
<td>Term</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>A</td>
<td>Ampere</td>
</tr>
<tr>
<td>Å</td>
<td>Ångström ([10^{-10} \text{ m}])</td>
</tr>
<tr>
<td>a</td>
<td>horizontal spacing between two current or potential dipoles</td>
</tr>
<tr>
<td>α</td>
<td>alpha parameter</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>σ; σₐ</td>
<td>conductivity; apparent conductivity ([\text{S/m}])</td>
</tr>
<tr>
<td>I</td>
<td>electric current ([\text{A}])</td>
</tr>
<tr>
<td>∂</td>
<td>derivative ((∂B/∂t)) is the time rate of the variation of the magnetic field</td>
</tr>
<tr>
<td>E</td>
<td>electrical field</td>
</tr>
<tr>
<td>g</td>
<td>gram</td>
</tr>
<tr>
<td>G</td>
<td>conductance ([\text{S}])</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>k</td>
<td>kilo</td>
</tr>
<tr>
<td>l</td>
<td>liter</td>
</tr>
<tr>
<td>m</td>
<td>magnetance ((p_m / H)) ([\mu\text{l}])</td>
</tr>
<tr>
<td>B</td>
<td>magnetic flux density ([\text{weber/m}^2])</td>
</tr>
<tr>
<td>H</td>
<td>magnetic field intensity ([\text{A/m}])</td>
</tr>
<tr>
<td>p_m</td>
<td>magnetic dipole moment ([\text{Am}^2])</td>
</tr>
<tr>
<td>χ</td>
<td>Magnetic mass susceptibility ([\mu\text{l}/g = 10^{-6} \text{ m}^3/\text{kg}])</td>
</tr>
<tr>
<td>M; Ms</td>
<td>magnetization; spontaneous magnetization</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
</tr>
<tr>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>n</td>
<td>number of coil turns</td>
</tr>
<tr>
<td>n</td>
<td>pseudo-vertical dipole spacing</td>
</tr>
<tr>
<td>μ</td>
<td>micro ((10^6))</td>
</tr>
<tr>
<td>ml</td>
<td>milliliters</td>
</tr>
<tr>
<td>ms</td>
<td>milliseconds</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer ([10^{-9} \text{ m}])</td>
</tr>
<tr>
<td>ln</td>
<td>natural logarithm</td>
</tr>
<tr>
<td>%</td>
<td>percent</td>
</tr>
<tr>
<td>ρ; ρₐ</td>
<td>resistivity; apparent resistivity ([\Omega \cdot \text{m}])</td>
</tr>
<tr>
<td>S</td>
<td>Siemens</td>
</tr>
<tr>
<td>S/N</td>
<td>signal to noise ratio</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>τ</td>
<td>time constant Tau</td>
</tr>
<tr>
<td>μ₀</td>
<td>permeability of free space ([4\pi \times 10^{-7} \text{ weber/ampere meter}])</td>
</tr>
<tr>
<td>V</td>
<td>voltage</td>
</tr>
<tr>
<td>Term</td>
<td>Significance</td>
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<td>------</td>
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</tr>
<tr>
<td>AEM</td>
<td>Airborne electromagnetic</td>
</tr>
<tr>
<td>AUX</td>
<td>Back scattering electron image</td>
</tr>
<tr>
<td>DDH</td>
<td>Diamond drill hole</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>Emf</td>
<td>Electromagnetic field</td>
</tr>
<tr>
<td>Ex-In</td>
<td>Acronym for company name Explorateurs-Innovateurs de Québec Inc.</td>
</tr>
<tr>
<td>GDD</td>
<td>Acronym for company name Instrumentation GDD Inc.</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic information system</td>
</tr>
<tr>
<td>GSC</td>
<td>Geological Survey of Canada</td>
</tr>
<tr>
<td>L</td>
<td>Line</td>
</tr>
<tr>
<td>MPP</td>
<td>Multi-parameter probe</td>
</tr>
<tr>
<td>MV</td>
<td>Magnetic viscosity</td>
</tr>
<tr>
<td>NAD</td>
<td>North American Datum</td>
</tr>
<tr>
<td>NTS</td>
<td>National Topographic System</td>
</tr>
<tr>
<td>PTS</td>
<td>Polished thin section</td>
</tr>
<tr>
<td>Rx</td>
<td>Receiver</td>
</tr>
<tr>
<td>SCIP</td>
<td>Sample core induced polarization</td>
</tr>
<tr>
<td>SEI</td>
<td>Scanning electron image</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>N/S</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SIU, SI</td>
<td>International system of units</td>
</tr>
<tr>
<td>St.</td>
<td>Station</td>
</tr>
<tr>
<td>SPM</td>
<td>Superparamagnetic</td>
</tr>
<tr>
<td>TDEM</td>
<td>Time-domain electromagnetic</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UTEMIS</td>
<td>University of Toronto EM Induction Spectrometer</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Traverse Mercator</td>
</tr>
<tr>
<td>VLF</td>
<td>Very low frequency</td>
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Chapter 1

Exploring for copper–gold deposits exhibiting a wide range of conductivities with time–domain electromagnetics in the Chapais–Chibougamau mining camp
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 mine, lying within the camp, was discovered by Léo Springer and the Prospectors Airways group in 1929 (Derry and Folinsbee, 1957). 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 (Table 1) (Salmon and De l’Étoile, 2013).

Table 1.1: Historical mining production at Opemiska (Morin, 1994; Lacroix, 1998; Pilote 1998)

<table>
<thead>
<tr>
<th>Name</th>
<th>Production year</th>
<th>Production (metric tons)</th>
<th>Cu (%)</th>
<th>Au (g/t)</th>
<th>Ag (g/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springer</td>
<td>1954-1991</td>
<td>12 964 844</td>
<td>2.54</td>
<td>1.23</td>
<td>0.28</td>
</tr>
<tr>
<td>Perry</td>
<td>1965-1991</td>
<td>9 041 915</td>
<td>2.19</td>
<td>0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Cooke</td>
<td>1976-1989</td>
<td>1 973 188</td>
<td>0.66</td>
<td>5.04</td>
<td></td>
</tr>
<tr>
<td>Robitaille</td>
<td>1969-1972</td>
<td>188 000</td>
<td>2.04</td>
<td>0.53</td>
<td>11.21</td>
</tr>
</tbody>
</table>

The former underground Opemiska 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 operation and/or underground bulk mining operation in the former Springer and Perry shafts mine area. As further described in the compilation of the historical geophysical data section, there is no evident methodology which could effectively detect poorly conductive massive chalcopyrite veins and
disseminated copper-gold mineralization at the site. 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 methodology to discover economic copper-gold deposits close to the surface in the Chapais-Chibougamau mining district. An experimental ground electromagnetic (EM) survey was designed to map the conductivity, the chargeability, the anisotropy of the conductivity and the magnetic viscosity 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 electromagnetic survey to map the mineralization; and processing, modeling and interpreting all the data. As well, a detailed study of the impact of magnetic viscosity on TDEM data at Opemiska is presented in Chapter 2.

**GEOLOGY**

**Regional geology**

The Chapais-Chibougamau mining camp is part of the Abitibi-Chibougamau greenstone belt. The area of interest lies within the Archean Superior Province, which is bordered to the South by the Grenville Province (Figure 1.1). The Opemiska project is located next to the town of Chapais, in Lévy Township, NTS 32G15, in the province of Québec, Canada (Figure 1.2).

The geology of the Chapais-Chibougamau district consists of a greenstone assemblage with Archean volcanic and volcano-sedimentary rocks of the Roy and Opemiska groups, with various
sills of mafic to ultramafic composition (Figure 1.3). The sills have been folded and faulted with the volcanics. “The stratigraphy of the Roy Group in the area is characterized by three mafic to felsic volcanic cycles, represented by the Chrissie (first cycle), Obatogamau and Waconichi (second cycle), and Gilman and Blondeau (third cycle) formations. The Roy group is overlain by metasedimentary rocks of the Opemiska group” (Figure 1.4) (Leclerc et. al, 2009). The post-tectonic Opemiska granitic pluton intruded the Gilman and Blondeau formations (Figures 1.3 and 1.4) (Lavoie, 1972; Leclerc et. al, 2009).

Figure 1.1: Location of the Opemiska project within the simplified geological map of the Abitibi orogenic greenstone belt. Modified from Parsons et al. (2015).
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<table>
<thead>
<tr>
<th>Groupe</th>
<th>Mb / Affinité géochimique</th>
<th>Interprétation</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEMISCA</td>
<td></td>
<td>Conglomérat polygénique, grès feldspathique et grès lithique</td>
</tr>
<tr>
<td>Daubreé</td>
<td>calco-alcalin</td>
<td>DISCORDANCE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grès, wacke, siltstone, mudstone, claystone, tuf felsique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laminations, obliques et entrecroisées</td>
</tr>
<tr>
<td>Blondeau</td>
<td>calco-alcalin</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grès feldspathique, tuf felsique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laminations, obliques et entrecroisées</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roche volcanoclastique felsique, rhyoandesitique</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complex de Cummings (pyroxénite, gabbro, ferrodiorite, ferroagabro)</td>
</tr>
<tr>
<td>Mafique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gilman</td>
<td>Bruneau (batholitique)</td>
<td>Intrusion felsique à QZ-FF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalte et basalte andésitique, massifs, coussins ou bréchiques</td>
</tr>
<tr>
<td>Roy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felsique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wisconichi</td>
<td>Queylus/Allard (transition à calco-alcalin)</td>
<td>Roche volcanoclastique mafique à felsique, andésite, exhalite, turbidite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>et rhyolite à texture d'écoulement laminaire</td>
</tr>
<tr>
<td>Felsique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2730-2726 Ma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>David</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(batholitique)</td>
<td>Basalte et basalte andésitique porphyriques, massifs, coussins ou bréchiques</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moins de 1 % de glomérocrustaux</td>
</tr>
<tr>
<td>Mafique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obatogamau</td>
<td>médian (batholitique)</td>
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<tr>
<td></td>
<td></td>
<td>3-20 % de glomérocrustaux</td>
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</tr>
<tr>
<td>inférieur</td>
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<td>médian</td>
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<td></td>
<td></td>
<td>1-3 % de glomérocrustaux</td>
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<td>supérieur</td>
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<td></td>
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<tr>
<td>médian</td>
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<tr>
<td>inférieur</td>
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<tr>
<td>Felsique</td>
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<td>2791.4,2 Ma</td>
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</tr>
<tr>
<td>Mafique</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chrissie</td>
<td>supérieur (calco-alcalin)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite, roche volcanoclastique mafique à felsique, exhalite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalte et basalte andésitique, massifs, coussins ou bréchiques</td>
</tr>
</tbody>
</table>

Figure 1.4: Stratigraphy of the Chapais area (from Leclerc et al., 2009).
Local geology

A schematic diagram of the stratigraphic sequence in the area of study, including the different intrusions, is presented on figure 1.5. The third cycle of the Roy group comprises the Gilman and the Blondeau formations. 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, comprising five members, and sub-categorized in ascending stratigraphic order by the lower green pyroxenite, black pyroxenite, upper green pyroxenite, foliated gabbro, and Ventures gabbro. The Ventures sill is bordered by felsic volcanoclastic rocks with rhyolite capping its lower and upper stratigraphic sequences. 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 folded sills, volcanic and sedimentary rocks has a plunge of 45 to 65 degrees to the east (Watkins and Riverin, 1982; Coulombe, 1984). The synformal anticline is truncated by the east-west Gwillim fault, which has displaced the southern part 2 km to the east (Salmon, 1982; Daigneault, 1991; Morin, 1994). The Opemiska local surface geology is presented at Figure 1.6, with the structural features and mineralized veins illustrated. Note the multiple copper–gold vein orientations. A 3D geological model illustrating the lithologies from the Ventures sill, structural faults and veins is presented in Figure 1.7.

The Cu-Au veins have been interpreted to either be related to the regional folding events (Morin and Boisvert, 1991), considered contemporary with tectonic magmatism and hydrothermal fluid remobilization during movement along the Gwillim fault (Watkins and Riverin, 1982), or considered as a subtype of shear zone-hosted Au deposits (Leclerc et. al, 2012). The Opemiska deposit has been compared to porphyry copper deposits (Pilote, 1998), with Kirkham and Sinclair,
(1996) arguing that hydrothermal fluids extracting copper from the ascending magmas which was then deposited in cooler structurally favorable environments above the magma source.

**Alteration**

The above lithologies have been intruded by the Opemiska granitic pluton (Figures 1.4 and 1.5), 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). Watkins and Riverin (1982) note that alteration of igneous pyroxene into actinolite (uralitisation) with subordinate quartz and Fe-oxides is common, while a distinctive and heavy biotite alteration occurs within 3 m of vein margins. The alteration mineralogy is discussed in details in Watkins and Riverin (1982).

**Structure**

The majority of the Opemiska type copper–gold veins are found in structural faulting, fractures, shear zones and vein-breccia zones (Watkins and Riverin, 1982; Kirkham and Sinclair, 1996). The veins are preferentially located in fold hinges and appear to be syn-tectonic to post-tectonic in age (Coulombe, 1984; Robert, 1994). Brown (1970) proposed that the fractures developed in response to the folding. Robert (1994) also associates the Cu-Au mineralization with the presence of dykes, fractures, shear zones and faults which acted as a conduit for magma and hydrothermal fluids. In the former Springer-shaft area, most veins exhibit an east-west azimuth, dipping subvertically to the north (Figure 1.8). In the former Perry-shaft area, most veins show a north-south azimuth, with a 40- to 70-degree dip to the east (Coulombe, 1984). However, the azimuth of the veins are sometimes diverging from the main structural controls and can spread out in unpredictable directions.
**Texture**

The contacts between the massive-vein filling fractures and the host rock vary from sharp to (less frequently) diffuse and disseminated (Watkins and Riverin, 1982). The massive sulfides are sometimes surrounded by a halo of disseminated mineralization extending beyond the veins into the surrounding host rock (Stockwell, 1957). In addition, there are several conjugated fractures in which mineralization precipitated, taking the form of veinlets, stringers (stockwork) or breccias.

**Mineralogy**

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. Silver is found in variable quantities associated with the chalcopyrite, while gold can also be found independently. 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; Leclerc et al., 2012).

A correlation matrix (inset to Figure 1.9) constructed from 303,479 chemical assays demonstrates the statistical association between copper and silver and the absence of a correlation between gold and copper or between gold and silver (shown in Figure 1.9). The spatial distribution of gold in three dimensions (not shown) indicates that the grade and the quantity of gold intersected in the DDH increase going south from 0.5 g/t Au at Perry to 1.2 g/t Au at Springer, while the grades of copper are constant at 2.66% from Springer to Perry (Watkins and Riverin, 1982).
Figure 1.5: Stratigraphic sequence at Opemiska (from Lavoie, 1972). The copper-gold mineralization found at Opemiska is mostly hosted within the layered Venture sill.
Figure 1.6: 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.
Figure 1.7: Perspective view of the 3D geological model illustrating the lithological contacts between the members of the Ventures sill, structural faults and the approximate location of the copper-gold veins vertically projected to the surface.
Figure 1.8: North–south cross section 5000E of the Springer mine area, looking west. Distances are in the imperial historical mine system, in feet.

Figure 1.9: (a) Cross plot exhibiting a 0.74 correlation between copper and silver.

<table>
<thead>
<tr>
<th></th>
<th>Cu (%)</th>
<th>Au (g/t)</th>
<th>Ag (g/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Au (g/t)</td>
<td>1</td>
<td>0.29</td>
<td>0.19</td>
</tr>
<tr>
<td>Ag (g/t)</td>
<td>0.29</td>
<td>1</td>
<td>0.74</td>
</tr>
<tr>
<td>Cu (%)</td>
<td>0.19</td>
<td>0.74</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 1.9 (continuation): Cross-plots exhibiting the quasi-absence of relations between (b) gold and copper; correlation of 0.19 (c) gold and silver; correlation of 0.29.
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 Explorateurs-Innovateurs de Québec Inc. (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 interpretation of the results for the magnetic, EM and IP surveys are detailed in the following section.

**Magnetic**

The total magnetic intensity (TMI), the upward continuation, reduction to the pole, or analytical signal images from the ground survey do not show anomalies that could be related to mineralized zones. The same statement also applies to airborne data, with the magnetic field, the first and second vertical derivatives of the magnetic field, and the residual total magnetic field derived from the different historical airborne surveys not indicating mineralization directly. However, the interpretation of the data suggested a correlation between magnetic minerals such as magnetite, ilmenite and pyrrhotite, in the lower two members of the Ventures sill (the lower green pyroxenite and the black pyroxenite), but did not provide a direct vector to the mineralization itself (Figure 1.10). McMillan (1972), and Watkins and Riverin (1982) report that cumulus layers of primary chromite and magnetite were recognized in the different layers of pyroxenite, which explains the
strong magnetic anomaly (> 3,000 nT) seen in the Perry area. The magnetite observed in the thin sections has a cubic habit, suggesting a magmatic origin consistent with this interpretation.

Weaker magnetic anomalies were observed in the Springer area, in the upper Ventures sill (Ventures gabbro and foliated gabbro). This is consistent with the presence of titaniferous magnetite observed by McMillan (1972) at the base of the foliated gabbro and a 15 to 30 cm thick layer of clinopyroxene containing 30 to 40% magnetite observed by Watkins and Riverin (1982) in the foliated gabbro as well. Magnetic susceptibility measurements made with a handheld instrument on diamond drill cores and a polished thin section study confirmed the presence of a few percent magnetite in the Ventures gabbro, with enhanced concentrations of iron oxides in chalcopyrite veins.

This change in the amplitude of the magnetic anomalies from east to west (from Perry to Springer), seems to reflect the change in the content and nature of the magnetite. The secondary generation of magnetite was interpreted to be the result of alteration from hydrothermal fluids pulses interacting with the a priori existing 1st generation magmatic titaniferous magnetite. The alteration is stronger near the hinge of the syncline nose fold, and its amplitude diminishes going east.

**Induced polarization**

The dipole-dipole induced polarization (IP) survey showed low resistivity anomalies coinciding with mineralization, but also with swamps, streams, tailings and anthropogenic sources of noise (Figure 1.11). The chargeability anomalies were 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 (Figure 1.12). The results of the IP survey were unable to conclusively locate the Cu-Au ore since spurious cultural
anomalies (fences, pipes, infrastructures, DDH casings, former mine waste, powerlines, etc) (Figure 1.11), are also frequent in the vicinity of the former Springer and Perry shafts.

**Electromagnetic**

The *MaxMin* survey (Lavoie, 1980) appears to respond 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 (Figure 1.13). Finally, the survey only covers the Perry area of the property, and the readings were taken every 30 m, which it too broad to identify the narrow Opemiska veins known to be less than 6 m in width (Coulombe, 1984).

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 (Figure 1.14). This could be due to the fact that Input system has a lower relative dipole moment in comparison with modern systems, and will likely detect conductors at a shallower depth and will not detect orebodies that are in between flight lines that are spaced every 200m (Smith *et al.*, 2005). The more recent *Megatem* AEM survey detected four or five veins, but not all of them. In addition, it detected some conductors not known to be associated with mineralization (Figure 1.14) such as faults, powerlines, fences, or conductive geological horizons.

To better understand the link between the physical properties of the Opemiska rocks and the geology, petrophysical measurements were undertaken on diamond drill cores and rock samples.
Figure 1.10: Comparison between (a) the geological map and (b) a subset of the ground magnetic survey (TMI), for the Perry area, NE grid, with the geological horizons outlined in black. The magnetic horizon is folded and seems to be constrained to the black and lower green pyroxenite geological structures plunging to the east at 45 to 65 degrees.
Figure 1.11: Comparison between (a) the hydrography and (b) the IP resistivity map. The low resistivity anomalies mainly correspond to (i) swamps (ii) creeks (iii) tailings and (iv) cultural artifacts. However, some low resistivity anomalies correspond to (v) known mineralization.
Figure 1.12: Comparison between (a) the ground magnetic survey with upward continuation of 150 m and (b) the chargeability from the IP survey. The chargeability anomalies are interpreted to be either associated with (i) the presence of Cu-Au mineralization (ii) with magnetite (iii) pyrrhotite, pyrite and/or graphite hosted in barren rocks. Data shown for $a=10$ m and $n=2$ for the NS grid; $a=25$ m and $n=1$ for the NE grid.
Figure 1.13: Interpreted location of MaxMin conductors (dashed lines) superposed on the geological map. Except for the conductor #31, most of the conductors’ location do not coincide with the known mineralization shown in red.

Figure 1.14: Airborne Megatem (large black symbols) and Input (small blue symbols) anomalies superposed to the geological map and infrastructure. Several airborne anomalies are caused by (i) the power lines and (ii) cultural objects. (iii) Two strong Megatem anomalies detected the mineralization in the Springer area, but several veins south of these 2 anomalies were not located. In the Perry area, several weak to strong anomalies detected either (iv) the same mineralization detected by the MaxMin (v) faults, or conductive horizons.
PETROPHYSICAL STUDY

Conductivity

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 1.15), while other samples with grades less than 4.8% Cu would show unexpected conductivity values 10 to 40 times higher reaching 4000 S/m (Figure 1.16). From these observations, it was concluded there is not a simple relationship between conductivity and copper grades, a statement in agreement with the results of other studies such as Parasnis (1956).

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 1.17). 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 surrounding the sulfide grains and preventing conductive networks to be established (Figure 1.18), impurities (Figure 1.19), or phyllosilicates insulating the sulfide grains one from another (Figure 1.20).
Figure 1.15: 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 copper with grades up to 17.4% Cu (orange left). The vertical projection intersection shown from this diamond drill hole is located at the north-east end of line 100 of site #4.

Figure 1.16: Petrophysical measurements on core samples (DDH Op-2010-15) with the MPP handheld instrument (black right). High conductivity values of 500-4000 S/m (corresponding to semi-massive to massive mineralization) were obtained from samples with copper grades less than 4.8% Cu (orange left). The vertical projection intersection shown from this diamond drill hole is located 50 m north of the loop edge of site #3. Copper assays were done every 1.5 m.
Figure 1.17: A polished thin section from the highly conductive site presented on Figure 1.16. The pyrrhotite (Po) is organized in banded subdomains, intercalated with chalcopyrite (Cpy) and magnetite (Mt), with different crystallization orientations. The chalcopyrite and pyrrhotite are filling the interstices and form continuous conductive networks, reducing the bulk resistivity. Core sample R from the diamond drill hole OP-2010-15, from 20.27 to 20.31 m.

Figure 1.18: 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 feet. 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 1.19: A polished thin section from the weakly conductive site #4 (L0, St.0+00). The PTS made from rock sample H shows impurities such as the quartz (Qtz), the phyllosilicates (Ph) or the magnetite (Mt), which might to varying degrees decrease the bulk conductivity. The electrical current can still flow in the chalcopyrite (Cpy) but needs to find its way through the “maze” (Kirkby et al., 2016). A conductivity measurement of 0.36 S/m was obtained with the SCIP handheld instrument.

Figure 1.20: A polished thin section from the weakly conductive site #3 (L0, St.0+00). The PTS made from rock sample F illustrates acicular phyllosilicates (Ph) isolating chalcopyrite (Cpy) conductive network by segmenting it and preventing most of the electrical current to flow from one segment to another. A conductivity measurement of 0.01 S/m was obtained with the SCIP handheld instrument.
Measurements with the SCIP handheld instrument on hand samples bearing chalcopyrite established a lower conductivity limit of ~ 0.01 S/m (Figure 1.20). 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). He also indicates that the finer the grains are, the greater the amount of impurity that is required to form an insulating film around the grains. All other things being equal, the coarser the grain size in the rock, the lower the conductivity can be; it is however 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 graphite impurities in syenite or 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).

Petrophysical measurements and microscopic observations suggest complex interrelations between the amount of ore, the fabric of the rock, grain size and shape, texture, porosity, 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., 2006a).
Chargeability

The petrophysical study also confirmed the chargeability of the mineralization (Figure 1.21). A contrasting range of values was established with a lower chargeability limit of 1.95 mV/V for gabbroic host rock and a higher chargeability limit of 250 mV/V for massive chalcopyrite-pyrite-magnetite ore. The sources of the chargeability anomalies were not thoroughly investigated; however, it is assumed that pyrite, chalcopyrite, pyrrhotite, gold, silver and graphite could be responsible for the high chargeability observed (Telford et al., 1990). In addition, it is well known that magnetite can be chargeable (Pittard and Bourne, 2007).

Figure 1.21: Petrophysical measurements on core samples from DDH 142. Conductivity measured with the MPP handheld instrument; chargeability measured with the SCIP handheld instrument. The scale for the conductivity differs from that of Figures 1.15 and 1.16. The vertical projection intersection shown from this diamond drill hole is located 40 m south-west of the end of line 200 of site #1.
Density

Density was estimated by weighing each sample with an AV212 Adventurer Pro Ohaus scale (+/- 0.02g), and measuring its volume with a graduated cylinder (25 ml; 2 cm wide) or a beaker (F31; 4.5 cm wide). Figure 1.22 illustrates the average density of rock samples collected, showing a net contrast between the host rock (with a density below 3 g/ml) and the semi-massive to massive sulfides with a density range between 3.66 g/ml and 5.19 g/ml.

Figure 1.22: Box plot of density of hand samples collected at Opemiska. The median is represented by the horizontal lines. The whiskers extending above and below the boxes represent the values from the mean plus or minus one standard deviation. The outliers are shown as dots above and below. The samples studied are the same samples used for the polished thin section study and correspond to a wide variety of Cu-Au veins, mineralization type and host rocks. The density was calculated on rock cubes of approximately 1 inch diameter, and classified from visual observations as host rock, stringers, semi-massive or massive copper-gold mineralization. The density of pure chalcopyrite is 4.2 g/ml (Keller, 1987).
Anisotropy study

Mineral grains may be preferentially oriented with respect to their internal crystal structure, leading to anisotropy in resistivity at the crystallographic scale (Parkhomenko, 1967). At the scale of bedding, Dakhnov (1962) shows for sedimentary rocks that the resistivity along $\rho_\parallel$ and perpendicular $\rho_\perp$ to the bedding planes is given by:

$$\rho_\perp = \frac{(v+1)\rho_p\rho_s}{v\rho_s - \rho_p}, \quad (1.1)$$

and

$$\rho_\parallel = \frac{v\rho_p + \rho_s}{v+1}, \quad (1.2)$$

where $\rho_p$ is the resistivity of the poorly conducting interlayers, $\rho_s$ is the resistivity of the highly conducting layer, and $v$ is the ratio of the total thickness of layers with resistivity $\rho_p$ to the total thickness of layers with resistivity $\rho_s$. The coefficient of anisotropy in resistivity (Maillet, 1947), designated as $\lambda$ is defined as:

$$\lambda = \frac{\rho_\parallel}{\rho_\perp}, \quad (1.3)$$

Similarly, there could also be anisotropy so that the magnetic induction has values parallel and perpendicular to the tabular features (veins). Magnetic induction and eddy current induction anisotropy was thus investigated on the Opemiska rock samples, by taking 6 readings at 30 degrees intervals around a single axis with the *UTEMIS* instrument (see Chapter 2) (Bailey and West, 2007). The resistivity of an ore-bearing rock sample depends mainly on the shape of the ore-mineral grains and the way in which they are distributed through the host rocks (Parkhomenko, 1967). Unless the sample object is geometrically isotropic such as a sphere, the magnetance (see Chapter 2) of ferromagnetic or conductive rock samples is expected to be shape and direction
dependent (Bailey and West, 2007). With the UTEMIS, only the spatial component of the magnetic moment in the direction of the applied field is measured; since the sample can be rotated with respect to the field axis, spatial anisotropy of sample response can be determined (West and Holladay, 2014). Figure 1.23a shows anisotropy of the magnetization as a function of the primary excitation orientation on a 1-inch sample cube from Opemiska. The amplitude of the response reaches a maximum at 105 degrees and a minimum at 15 degrees (anticlockwise). This anisotropy might suggest that at a microscopic scale, the magnetic grains from a textural network that allows the magnetization to be amplified in one direction, the axial axis for instance, and minimal in the transverse axis. Optical microscope observations revealed the magnetite has a broad range of grain sizes, with grain widths as small as ~1 μm and as big as 1 mm. There is also a similar weak anisotropic quadrature component (labelled as Im or imaginary on the plot), suggesting the arrangement of the crystal lattices, the veinlets networks or the continuity of the mineralization texture is similarly favoring induction of eddy current in one of the orthogonal directions compared to the other. The Figure 1.23b shows the polar plot for a different sample exhibiting an isotropic response. Even though, the sample is made of massive chalcopyrite-pyrrhotite mineralization, there is no indication on the other frequencies of a frequency dependence in the in-phase or out-of-phase response that would imply conductive material.

The anisotropy of the conductivity and magnetic susceptibility was also evaluated on cubic rock samples using the **MPP handheld instrument**. Measurements were taken on the six faces of each of the cubes, rotating the probe at 0, 90, 180 and 270 degrees for each of the faces. Figure 1.24 shows the response from a massive chalcopyrite grab sample that was cut into a 5-centimeter diameter cube, from which similar grab samples returned assay values up to 20% Cu and 80 g/t Au. The magnetic susceptibility response varies from 20 to 175 x 10^{-3} SI, and the conductivity
varies from 2 to 39 S/m, depending on which face the measurements were taken. The angle with
which the sample was rotated about the normal to the face does not seem to affect the magnetic
susceptibility readings, since they remain relatively constant for one face. However, the
conductivity seems to be affected by the angle with which the MPP measurements were taken.
This can be observed, for example on the face 2, where at 0 degree, the conductivity is 23 S/m,
while for the 90-degree measurement, the conductivity is of 39 S/m. The variation in the
conductivity response could be explained by fabric orientation of the minerals encountered being
perpendicular to the exciting field and the currents flowing in preferential orientations. A parallel
could be established with sedimentary rocks where the resistivity transverse to the layering is
always larger than the resistivity along the bedding (Parkhomenko, 1967).

This historical compilation and petrophysical study identified the range of physical properties
present on the Opemiska property and provided data to evaluate how these zones correlate with
mineralization. The conductivity of the ore varies from weak to strong, it is chargeable, magnetic,
denser than the host rocks, and displays some anisotropy at hand-sample scale. However,
discriminating the host rock, from the ore by solely looking at the geophysical responses is
challenging since the ore sometimes has different characteristics and hence geophysical signatures
and some of these are not always significantly different from the host rock. An alternative
methodology is required to explore for copper-gold mineralization in the Chapais District. In the
remainder of this chapter, we discuss an experimental electromagnetic survey to see if any
characteristics of the EM response might be associated with ore.
Figure 1.23: UTEMIS polar plots a) Sample showing an anisotropic response as a function of the excitation orientation. b) Sample showing an isotropic in-phase response (labelled as Re or real on the plot). It is interesting to note that the massive chalcopyrite-pyrrhotite mineralization (b) does not even produce a quadrature (imaginary) response.
Figure 1.24: Anisotropy study of the (a) magnetic susceptibility and (b) the conductivity on (c) a rock cube measured with the MPP. The sample was taken on a massive chalcopyrite vein at site #3, near the mill foundations, in an area that was exposed in 2002.
METHODOLOGY OF THE TDEM SURVEY

Background, objectives and survey design

The information gathered during the petrophysical study, and the geological and geophysical data compilation indicated that the copper-gold mineralization is associated with variable weak to high conductivity, anisotropy, chargeability and that the ore is denser than the host rocks. The 2015 TDEM survey aimed to map and quantify (1) the conductivity (2) the anisotropy of the conductivity, and (3) the chargeability at larger scales at a number of locations on the property.

The electromagnetic survey was intended to characterize the geology in the top one hundred meters, for which a loop size of 50 m was determined to be adequate. Mineralization is concentrated in networks of veins of different orientations, stringers of veinlets and disseminated mineralization, hosted in variable contrasting geological environments. The site locations were selected to cover a variety of scenarios: both low-grade zones and rich massive veins, good conductors 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 Cu-Au 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.

Theory

The Faraday’s law of electromagnetic induction dictates that the magnitude of the induced electromagnetic field \( V \) is proportional to the rate of change of the magnetic field \( B \) measured in a coil with area \( A \). The induced emf is expressed by:

\[
V(t) = -A \frac{\partial B}{\partial t}.
\]  

(1.4)
The negative sign in Eq. (1.4) indicates that when the primary current flowing in an electromagnetic transmitter loop is switched off, secondary currents are induced in the ground so as to oppose the changing magnetic field associated with the transmitter current (Grant and West, 1965; West and Macnae, 1991) (Figure 1.25). If the current is flowing in such a direction that the magnetic field of the transmitter current is up inside the loop prior to the current switch off, then the currents induced in the ground immediately after switch off will result in the magnetic field inside the loop also being up (positive). At the same instant, the field outside the loop is generally down (negative).

Figure 1.23: Diagram of an EM system with (a) The time domain primary field emitted from the transmitter (Tx) loop before the turn-off; (b) Induced currents and their secondary field following turn-off. To oppose the changes in the primary field, the secondary field shown in green broken lines has the same direction as the primary. The receiver is a coil typically measuring the time derivative of the magnetic field. From Dentith and Mudge (2014) and adapted from Grant and West (1965).
If the rate of decay of the magnetic field inside the loop is estimated using the Maxwell software, (http://www.electromag.com.au/maxwell.php) then the conductivity of the ground can be estimated (Dyck, 1991). A rough estimate of the distance to the conductor can be obtained from the width of the EM anomaly on the profile; the dip can be estimated from the ratio of the positive and negative shoulder heights (King, 1996). The conductivity-thickness product or conductance \( G \) can then be estimated for a tabular body (Sheriff, 2002):

\[
G = \frac{\tau \pi^2}{\mu_0 2tl}
\]

(1.5)

where \( \tau \) is the time constant (sec), \( \mu_0 \) is the permeability of free space \( (4\pi \times 10^{-7} \text{ H/m}) \) and \( 2tl \) is the shape-dependant characteristic area of the body \( (\text{m}^2) \) for a 2D tabular plate with thickness \( t \) and depth \( l \). The apparent-conductivity as a function of depth can also be used with a coincident-loop TEM impulse-response configuration to approximate the conductivity along a section (Smith et al., 1994). As the first objective was to characterize the decay rate, the survey was designed to have receiver sensors measuring the decay at stations inside and outside the fixed transmitter loop.

The second objective was to evaluate the anisotropy of the conductivity. 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 \( \sigma_\| \) and also identify the direction perpendicular to the vein \( \sigma_\perp \) (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). If the conductivity is different in each direction, then the currents will diffuse asymmetrically (Dennis and Cull, 2012). Hoversten and Morrison (1982) demonstrated that the behavior of the induced electric fields is that of a single smoke ring, as described by Nabighian (1979).
The spatial location where the very early-time response changes from positive to negative is at the transmitter loop location as this is where the strongest currents are induced in a uniformly conductive ground. At subsequent delay times, these currents in the ground diffuse, moving outward and down into the ground (Nabighian, 1979) (Figure 1.26).

Figure 1.26: Section of the eddy current diffusion system in a conductive 0.1 S/m half-space at (a) early (b) mid and (c) late delay times. This is a cross section of a toroid diffusing outward and downward with time, referred as a smoke ring by Nabighian (1979). From Dentith and Mudge (2014); and adapted from Reid and Macnae (1998).
As the smoke ring diffuses, the largest currents are generally below the location where the z-component field transitions from positive to negative. This location is known as the z-component crossover. The rate of diffusion is a function of the conductivity of the ground. In conductive ground, the currents diffuse slowly and the magnetic fields remain large, while in resistive ground the currents diffuse quickly and the magnetic fields decay more quickly. Hence the z-component crossover will move slowly outward from the loop when the ground is conductive and quickly when it is resistive. The fact that the currents are getting deeper will be reflected in the crossover getting broader.

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. It was assumed that this process could give enough information to assess the azimuth of the weakly conductive veins at Opemiska (Figure 1.27). If asymmetry is identified, then one possible explanation for this asymmetry is the existence of weakly mineralized veins. For example, if the ground is more conductive in the east-west direction, then the east-west flowing currents will diffuse more slowly and the crossover will remain close to the north and south loop edges. If the conductivity is less in the north-south direction, then the crossover will move more quickly away from the east and west edges of the transmitter loop. In order to be able to monitor the rate of migration in two directions, the survey was designed to have lines running in at least two directions (east-west and north-south).
Figure 1.27:

(a) Perspective view of a TDEM transmitter loop current generating smoke rings. (i) Just after transmitter turn-off and (ii) – (iv) at progressively later times.

(b) Plan view of an isotropic diffusion of smoke rings (in blue) and anisotropic diffusion of smoke rings (in red). For an anisotropic subvertical geological set of layers, the outward diffusion rate when current is flowing in the relatively conductive direction is slower than in the orthogonal resistive direction. This diagram would indicate a vein system with a north-south orientation.
The third objective was to evaluate the chargeability of the mineralization using EM methods (Smith, 2016). In the case when the ground is chargeable, the flow of the secondary field induced in the ground will generate a tertiary polarization charge in the ground (Smith et al., 1988; Smith and West, 1988ab; Smith and West, 1989). When this polarization discharges it flows in the opposite direction to the secondary current. The field associated with this polarization current has a field that is down (negative) inside the loop and up (positive) outside the loop. Generally the fields associated with the polarization current are very small and only evident at late decay times when the secondary inductive current has decayed away. They manifest themselves as a relative negative inside the loop and a relative positive outside the loop. Modeling and field evidence shows that the polarization current is greatest where the induced currents are greatest; right below the transmitter loop. In order to identify these polarization currents confidently, the survey needed to measure the field with receiver sensors both inside and outside the loop to see if there was to be a relative suppression (negative) inside the loop and an enhancement of the field (positive) outside the loop. The criteria for identifying these polarization currents are satisfied and fulfill the design requirements for objective 2.

A fourth objective was added while the project was being undertaken when late-time power law decays with $V(t) \sim 1/t$ were observed during the off time inside the transmitter loop using a step source. This phenomenon observed at some of the surveyed sites was attributed to magnetic viscosity (MV) and is further discussed in Chapter 2.
**Survey location**

Fourteen different sites were investigated. Their locations are shown in Figure 1.28 and the variable field conditions are shown in Figure 1.29. The table 1.1 details their respective GPS location, geophysical characteristics, whether they might contain massive ore, sulfide stringers, or disseminated mineralization, and the different minerals observed from DDH cores while surveying in the field.

![Figure 1.28: Location of TDEM experiments. Thirteen sites were investigated in the vicinity of Chapais in NTS 32G15. A fourteenth site located 58 km South of Chapais in NTS 32G07 was also investigated. This additional site provided the EM response over an outcropping nickel copper occurrence, 20 km away from any power line or metallic structures that would be considered as a source of noise.](image-url)
Figure 1.29: Pictures of 4 different sites investigated with the impulse-response TEM system to evaluate contrasting environments.  
(a) Site #1: massive chalcopyrite – gold vein (within dashed red lines), hosted in resistive gabbro;  
(b) Site #3: stringers of sulfides (stockwork);  
(c) Site #9: altered felsic volcanics (tuffs) with sphalerite-pyrrhotite mineralization;  
(d) Site #8: tailing ponds (disseminated mineralization) with pyrrhotite vein near surface and graphite horizon at depth.
Table 1.2: GPS location for sites #1 to #14 in UTM, NAD 83, zone 18. Ore textures, minerals observed on site or from DDH cores that could have an impact on the geophysical response, and geophysical characteristics based on historical surveys are presented for each TEM site investigated.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>East</th>
<th>North</th>
<th>Minerals observed</th>
<th>Texture</th>
<th>Mag.susc.</th>
<th>Chargeability</th>
<th>Conductivity</th>
<th>Survey type for conductivity anomaly</th>
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<td>5514849</td>
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<td>XXX</td>
<td>X</td>
<td>Beep Mat</td>
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<td>5515497</td>
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<td>Massive</td>
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<td>XX</td>
<td>X</td>
<td>MaxMin, VLF, Megatem, Input</td>
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<td>XXX</td>
<td>X</td>
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<td>XXX</td>
<td>XX</td>
<td>Beep Mat</td>
</tr>
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<td>XX</td>
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<td>XX</td>
<td>XXX</td>
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<td>n/a</td>
<td>XXX</td>
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<td>n/a</td>
<td>XXX</td>
<td>Beep Mat, MaxMin</td>
</tr>
</tbody>
</table>

**Legend**

n/a = not applicable or unknown  
x = weak  
xx = moderate  
xxx = strong
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 stacking filter (at an appropriate base frequency) will remove noise associated with power-line signal. Electronic gain was adjusted for every station to ensure the signal was just below the saturation level. 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 degrees in every cardinal direction (Figure 1.30). 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;

- Receiver stations were spaced every 5 m, and measurements were taken inside and outside the transmitter loop;

- A square current waveform generated by a GDD 20 A – 50 V transmitter or by a Geonics TEM47 transmitter (Figure 1.30). When the environment was relatively quiet and noise-free, the TEM47 transmitter was used because of its fast turn-off time [Geonics (2011) reports 3.5 μs for a 50 x 50 m loop with 1 A current]. The TEM47 transmitter was powered by its internal battery with a maximum output of 3 A. The GDD transmitter was used in noisier and more conductive environments. The GDD transmitter had a fixed 50 V output and the current driven through the loop is determined by the resistance of the circuit. Thus
external resistances connected in series were sometimes used to control this current to approximately 6 A when powered by a portable 1000 W generator, and 10 A when powered by a larger 2000 W generator. Both transmitters used a bipolar (castle) waveform with 50% duty cycle (Figure 1.31);

- 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 $\partial B/\partial t$ coil sensor with an effective area of 200 m$^2$, and a bandwidth of 30 kHz (Geonics, 2013) was used. 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 $\partial B/\partial t$ response than in the B-field data (Smith and Annan, 1998);
- The synchronization between the transmitters and the receiver was done using the GPS pulse per second signals, or with an internal crystal clock embedded in the control box manufactured by Instrumentation GDD Inc.;
- The 3D sensor was aligned with the x-component pointing in the direction of increasing station coordinate along the line direction (Figure 1.30). Adjustment of the x and y-components were done visually looking at the profile stakes because of the presence of magnetite affecting the magnetic field compass direction. The z-component orientation was adjusted with a spirit level;
- A novel window scheme has been developed to filter the 25.2 kHz frequency using time windows with a width that is a multiple of 39.68 us (1/25.2 kHz). This re-windowing helped to reduce very low frequency (VLF) noise on the TDEM profiles (Appendix 1);
• In an effort to reduce the background noise level, stacking was adjusted and monitored in
the field by evaluating the regularity of the decay curve and examining the spectrum
(Appendix 1);

• To enhance the signal level, the transmitted magnetic dipole moment was increased by
passing more current through the loop, using a larger loop, or increasing the number of
turns (Appendix 1). After experimenting and comparing different geometries and arrays
at different sites, it was decided that the 50 x 50 m single-turn loop was the best choice to
achieve the required objectives;

• Lines sometimes had to be cut with a machete or chain saw to ease the path of the operators
carrying the instrumentation through the dense rejuvenating forest.

Table 1.2 summarizes all the details of the survey configuration and the minor variations used for
all the sites investigated.
Figure 1.30: Instrumentation set-up for the square fixed-loop transmitter of 50m side length with the GDD transmitter using external resistances and powered with generator or the Geonics transmitter. The line numbering convention is shown with survey lines radiating from its center at 45 degrees in eight cardinal directions. The x-coordinate is increasing to the north for L0, north-east for L100, east for L200 and south east for L300.
Figure 1.31: Bipolar transmitter waveform and the primary and the secondary response obtained from a coil sensor during one complete cycle. The polarity in this example indicates that the receiver coil is located inside the transmitting loop. (a) Current transmitted in the loop, with a linear build-up of the current reaching a plateau during the on time, and the turn-off with a linear ramp decaying to zero. (b) The voltage read at the receiver caused by the primary magnetic impulse excitation. (c) The secondary magnetic field measured at the receiver, which does also occur in the on-time, but is only shown in the off time. Measurements are normally taken during the off time, and the amount of time windows depends on the frequency used. These time windows are historically referred to as channels, and usually numbered in sequence, with “1” being the earliest. For a 30 Hz base frequency, a complete cycle lasts 33.33 ms; the measurements during each off-time will last 8.33 ms at maximum. Since the 1st window starts after the ramp has been completed, and the last window finishes just before the next transmitter pulse, these measurements last a few microseconds less than the theoretical time allowed.
<table>
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<th>Site</th>
<th>Loop dimensions</th>
<th>Loop Position</th>
<th>Frequency</th>
<th>Lines surveyed</th>
<th>Nb of turns</th>
<th>Wire gage</th>
<th>External resistance (Oms)</th>
<th>Loop resistance (Oms)</th>
<th>Total circuit resistance (Oms)</th>
<th>Current sent (A)</th>
<th>Transmitter</th>
<th>Generator</th>
<th>EM sensor</th>
<th>Ramp (ms)</th>
<th>Delay (ms)</th>
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<td>9.7</td>
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<td>L0, L100, L200, L300</td>
<td>2 18</td>
<td>N/A</td>
<td>4.8</td>
<td>4.8</td>
<td>1.00</td>
<td>N/A</td>
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<td>N/A</td>
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<td>7.2</td>
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<td>1.2</td>
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<td>6.4</td>
<td>1.2</td>
<td>7.2</td>
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<td>1 10</td>
<td>6.4</td>
<td>1.2</td>
<td>7.2</td>
<td>5.76-5.86</td>
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<td>6.4</td>
<td>1.2</td>
<td>7.2</td>
<td>5.81-5.86</td>
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<td>1.2</td>
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<td>6.4</td>
<td>1.2</td>
<td>7.2</td>
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<td>3 Hz</td>
<td>L0, L200</td>
<td>1 10</td>
<td>6.4</td>
<td>1.2</td>
<td>7.2</td>
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<td>0.190</td>
<td>0.035</td>
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</table>
PROCESSING

General methodology

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) (Figure 1.32); (iii) forward modeling of conductors was undertaken using plates in free space to evaluate the properties of some of the relatively strong conductors such as the dimensions, depth, orientation, conductivity–thickness, dip and plunge; (iv) grids of the observed total secondary magnetic field from the first window (early times) or 19th window (late times) were generated using the kriging interpolation technique.

Some experimentation was attempted with more specialized processing methods. These methods include: (v) continuous normalization by the total primary field measured or by the total primary field calculated in order to highlight weak conductors at the ends of lines; (vi) the calculation of the on-time in-phase and on-time quadrature responses to estimate the resistive and the inductive limits (Smith, 2000; Smith and Balch, 2000; Ravenhurst, 2001; Smith, 2001), (vii) plotting the secondary field vectors in 3D with Matlab to show the field vectors associated with current in the conductor(s) (viii) peak-to-peak analysis (ix) Hilbert transforms and total field on the Hilbert transform; (x) kriging of the decay constants on plan maps and rose diagrams for early and late time windows.

The results of these processing steps are shown and discussed in the sections below.
Figure 1.32: Time constant analysis on semi-log plots, for the site #2, station 0, at 15 Hz frequency. (a) Early times with $\tau = 0.34$ ms (time windows 1-16; 0.08 to 1.541 ms); (b) late times with $\tau = 1.60$ ms (time windows 19-24; 2.13 to 6.625 ms). The observed response is illustrated in black, and the modeled response fitting the observed is shown in red. The value on the horizontal axis is the center of the window, in milliseconds after the ramp time of 0.250 ms. Root mean square error $= 1.30\%$ for both fits.
RESULTS OF THE TDEM SURVEY

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 (http://www.electromag.com.au/maxwell.php) 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). Although 14 sites were surveyed, only two representative sites will be discussed in detail: #2 – the good conductor and #4 – the bad conductor.

Site #2 – the good conductor

Two main conductors were detected at this site. Figure 1.33 illustrates the conductive response (in black) from the first conductor located near the center of the grid, and the modeled response (in red), along profile L0, which is essentially perpendicular to the sub-vertical target. The conductor corresponds to an 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 modeling all lines in 3D with a plate in free space (red body in Figure 1.34a). The kriging technique, based on a variogram fitted to the observations, was used to interpolate in 2D the total component of the secondary magnetic field (SMF) in-between every station surveyed from TDEM window 1. The kriged data exhibited the same location and trend direction (277°) as the red body (Figure 1.34a) modeled in 3D. The SMF is expressed by:

\[
\text{SMF} = \sqrt{x^2 + y^2 + z^2}
\]  

(1.6)

where x, y and z represent the 3 components of the secondary magnetic field amplitude in μV/A.
Figure 1.33: Profiles of x, y and z-components, for site #2, L0, at 15 Hz, with time windows between 0.08 and 16.484 ms. The observed response is illustrated in black, and the modeled response in red.
Figure 1.27: Site #2 (a) Plan view of the 50 x 50m square-loop layout with surveyed lines radiating from its center. The surface projection of the conductive plate model is also shown in red. (b) Interpolation of the observed total secondary magnetic field response, using the kriging technique, from the first TDEM window (0.08 to 0.09 ms). GPS coordinates are in UTM NAD 83, zone 18.
The second conductor encountered at the extreme north of L0 while surveying site #2 was also modeled in a manner similar to that described above. The model location is illustrated in Figure 1.35, showing the modeled 2nd conductor plate (in blue), matching the geological model (in red) that was derived from diamond-drill-hole intersections where the copper grades are higher than 1%. The orange zone is the historical vertical projection to the surface of the vein derived by the mine geologists. 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) has a northwest-southeast azimuth.

Figure 1.35: N50° perspective view of site #2 and #7, showing the modeled plates (in blue), matching the geological model (in red). The historical vertical projection of the veins is shown in orange. The yellow dots represent the receiver station locations, and the blue pseudo-squares are the EM transmitter loops. Two conductors were identified while surveying L0 of site #2, corresponding to known mineralization. A similar conductor was also encountered while surveying site #7 and is illustrated as well. L0 is oriented north-south, with north being to the top left.
Another site surveyed (site #4), also had the north-south line (L0) perpendicular to what was known to be a massive chalcopryrite-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 1.36). 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 evident as an enhanced response inside the loop between -25 and +25 m are also evident. Even though regularly spaced channel and bulk sampling proved the existence of the vein (Figure 1.37), and surface mapping 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 was significantly above the noise level 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 1.38). Based on forward plate modeling, the western trend of the structure was established with a strike of 285 degrees, with a dip of 80 degrees. The interpreted trend is thus almost parallel to the surveyed L200, and dipping to the north. Following the discovery of this anomaly, Explorateurs-Innovateurs de Québec Inc drilled this target in December 2016 and intersected mineralization with an average grade of 3.36 % Cu over a length of 17.4 m, with more massive chalcopryrite intersections returning 21.2 % Cu over 1.2 m from 17.1 m to 18.3 m depth (Figure 1.39).
Figure 1.36: Site #4. (a) Profile of z-component for L0, at 30 Hz, showing windows 0.08 to 7.95 ms. The conductive anomaly of the known vein is only visible on windows 1 to 5, between -5 and 10 m. (b) Location of L0 and L200 with a plan view of the 50 x 50m square-loop layout (dark blue) with surveyed stations (yellow dots). The surface projection of the known vein is shown in red, with the projected modeled 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 modeled plate is shown in blue.
Figure 1.37: Channel and bulk sampling along the mapped vein of site #4, with copper and gold assays.
Figure 1.38: (a) Geological longitudinal section (bottom) with drill-hole traces and TDEM profiles (top) along L200 (which follows the vein) of site #4. The modeled 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. (b) Perspective view of site #4 with the chalcopyrite vein(s) shown in red modeled from the surface channel samples and from the 2016 DDH intersections over 0.5% Cu. The TDEM plates modeled from the ground survey are shown in blue behind the geological modeled veins. The receiver stations are shown in yellow and the squared transmitter loop is illustrated in blue. Only 3 DDH from 2016 are shown in black. The azimuth view is 10 degrees north-west different than in (a).
Figure 1.39: Section of the DDH Op-2016-08 which was planned to intersect the TDEM modeled plate. Mineralization was intersected from 7.6 to 25.0 m, with an average grade of 3.36% Cu, 1.22 g/ Au and 10.65 g/t Ag, with massive chalcopyrite intersections of 21.20%, accompanied by 8.69 g/t Au and 58 g/t Ag from 17.1 to 18.3 m. The modeled thin plate is an approximation of the more complex geology intersected in reality. Distances on the map are in feet, in the imperial coordinate system used at the mine during historical production. The copper assays over 1 % are represented with red color along the log of the DDH.
Anisotropy of the conductivity

Peak ratio of the x-component

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 S/N ratio. The idea can be drawn from diagram 1-27b, where it can be seen that when 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. 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 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.

Three sites examined with this method (#3, #4 and #10) are illustrated from Figures 1.40 to 1.42. Sites #3 and #4 exhibit an anisotropic response suggesting the presence of conductors, and the site #10 exhibits an isotropic response, suggesting the absence of anisotropy.
Figure 1.40: (a) 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 (270 degrees) exhibits the lowest ratio and correspond to the direction of the vein delineated by the black outline. (b) Cu-Au-Ag assays for surface dust sampling are shown along the vein delineated with a black contour.

Figure 1.41: (a) Rose diagram showing the inverse of the amplitude ratio of the x-component for the time windows 1 and 6 for site #4. L200 (290 degrees) exhibits the lowest ratio and correspond to the direction of the vein. The L0 (0 degrees), which is perpendicular to the vein exhibit the largest ratio. (b) The trend of the mapped vein is shown, with copper and gold assays.
Figure 1.42: (a) Rose diagram showing the inverse of the amplitude of the x-component for the time windows 1 and 6 for site #10. L0 (0 degrees) and L200 (90 degrees) have a similar decay ratio. The same observation applies to L100 (45 degrees) in comparison with L300 (135 degrees). Therefore, this site exhibits an isotropic response. (b) The plotted profile for L300 confirms the absence of any conductor. All lines exhibited the same kind of response as shown by the profile of L300.
**Block model**

A block model based on copper and gold assays from core extracted during diamond drilling was built to estimate the Cu-Au potential at various locations on the Opemiska property. This provided an estimate of the grades that were not yet mined and allowed a correlation of this geological model with the geophysical data described below. The block model approximately ignores the rock previously mined from historical veins and drifts. The data was interpolated from where there was grade data to where there was none onto a 15-foot cell size using inverse distance interpolation. As the grades are measured over very small volumes, they were aggregated into intervals of 5 feet. Intervals shorter than 2.5 feet, or intervals with no assays had no value and the value here was estimated by interpolation using ellipsoids. These ellipsoids were oriented according to the mineralization strike and dip with ellipsoid radii of 90, 90, and 20 feet, with the short axis being normal to the plane containing the vein. Other ways to calculate the copper grades were experimented with, such as using the grades from the channel sampling, grab samples, or bulk sampling, but since the sampling was not systematic at all sites, the block model was judged the most consistent way to estimate the copper grade with a regular cell size spacing.

**Peak to peak of the z-component**

The peak to peak z-component amplitude was calculated for every profile line of every site, and plotted versus the copper grades estimation from the block model at the same site (Figure 1.43). The copper values plotted were evaluated for every block cell which corresponds to a unique receiver station of the same size, for the cell near the topographic surface. All the copper values for one TDEM line were then averaged to a single value for that line. In theory, if a line was parallel to a vein, the copper grade obtained from the interpolation block model should be higher than the line perpendicular to the vein (Figure 1.44).
Two trends are evident on this plot:

1. A steep trend corresponding to a high ratio of peak-to-peak z-component when the copper grades are low;

2. A second flatter trend corresponding to a lower peak to peak ratio z-component with higher copper grades.

This bimodal distribution might suggest that the copper mineralization has a wide range of conductivity values, with the low-grade range having a different nature and behavior than the high grade range. This conclusion is consistent with the observations of the petrophysical study.

**Conductivity as a function of tau**

The decay rate tau was analyzed in an attempt to determine if the EM data could be used to estimate if the mineralization was conductive or not (Figure 1.45). The conductivity was estimated using the handheld SCIP and MPP instruments on rock and core samples, and the decay rate was determined at the exact XY location where these samples were collected in the field from the TDEM survey. The conductivities were also estimated using Maxwell software while modeling the data, by assuming a fixed thickness of the tabular features that represent the veins; this thickness was based on the diamond drill holes intersections. The conductivity estimations using the MPP differ from at least one order of magnitude with those obtained using the SCIP. The discrepancy between the two sets of measurements is interpreted to be attributed to the fact that the SCIP handheld instrument is measuring an average galvanic conductivity over the whole volume of the sample, while the MPP handheld instrument is measuring the EM conductivity using coils over a “surface” with a limited volume of investigation, which is function of the EM
frequency used. Additional data would be required to find a strong relationship between the conductivity and the decay rate. As above, there appears to be a bimodal distribution, with one cluster of points with conductivities of about 1 S/m or less (and low tau) and a second cluster with conductivities greater than 5 S/m and higher tau.

Figure 1.43: Plot of the peak to peak amplitude of the z-component of every profile line versus the copper grades (%) estimated from the block model (estimated every 5 meters cell and averaged for the whole line).
Figure 1.44: Perspective view of the block model (Cu %) for site #1. West (W) is facing the top of the figure and depth (Z) is facing the bottom of the figure. The block model was cut as a pseudosection along the north-south direction to better illustrate the modeled vein (shown in red) dipping subvertically to the north (N). The east-west line surveyed at surface with the TDEM system shown with receiver stations spaced every 5 m (in yellow) is pseudo-parallel to a copper vein (surface projection shown in red for values higher than 1% Cu). In theory, the averaged copper grade obtained from the interpolation block model should be higher for the line following the vein (east-west) than the line intersecting it (north-south).
Figure 1.45: Cross plot of the conductivity and the decay rate tau for the z-component.

(a) Measurements for the conductivity estimated using the SCIP handheld instrument.

(b) Measurements for the conductivity estimated using the MPP handheld instrument.
Chargeability

An estimation of the induced polarization effect has been calculated from shape reversal using the methodology described by Smith (2016), for some of the TDEM profile lines surveyed. Two examples are illustrated in Figures 1.46 (site #4) and 1.47 (site #10).

At site #4, the narrow anomaly has a strong positive response at 0 m and a weak relative negative at -5 m. The generally positive response is associated with an inductive current in the vein that charges the vein. After this response has decayed away, there is a mirror image anomaly evident that is associated with the polarization current (the small relative negative at 0 m and the even smaller relative positive at -5 m). The relative size of these responses indicates a chargeability of about 50% in the EM time range from 0.08 to 7.95 ms.

The reversals at site #10 are close to the loop, suggesting the chargeable zone is in the soil or overburden layer. In fact, the early-time data is negative, suggesting this is a polarization current charge by the currents induced in the ramp. However, it seems the flow of this polarization current has induced a second-order even smaller polarization current and the chargeability has been estimated from this. Site 10 is a tailings dump and the Cu grade is unknown and the environment is quite different from the active exploration areas. Hence this location is not really typical of the locations where we want to estimate the Cu grade from the TDEM data. There was only one location where chargeability can be estimated and the Cu grade is known. If there were more stations at Opemiska that are chargeable and the Cu grades is known, it might be possible to build up a plot of chargeability as a function of Cu grade and use this to estimate Cu grade from the measured chargeability.
Figure 1.46: (a) Estimation of the chargeability (a) for L0, site #4, from the TDEM data in the bandwidth from 0.08 to 7.95 ms. (b) The TDEM z-component profile of the same line. The shape reversal is visible on stations -5 and 0 m, which corresponds to the location of the chalcopyrite-pyrite-magnetite-gold vein. Petrophysical measurements on sample H collected from the site revealed a chargeability of 115 mV/V with windows between 240 ms and 1840 ms.
Figure 1.47: Estimation of the chargeability (a) for L0, site #10, from the TDEM data measurement with time windows between 240 ms and 1840 ms. (b) The IP effect was interpreted to be due to the very fine grains of magnetite in the tailings accumulated over several meters, after the historical milling process and dumped at this tailing site. (c) The TDEM z-component profile of the same line. The shape reversal is clearly visible from -50 to 50 m and peaks at -15 m. The time windows 1 to 3 were not plotted to enhance the contrast of the shape reversal.
DISCUSSION

The conductive Cu-Au 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 Cu-Au 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 modeling 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 degrees angles helped constrain the forward modeling 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.

The challenge arises in the detection of weak conductors associated with very high copper-gold grades, where the environmental and cultural ambient noise often dominates the signal. Anthropogenic sources of noise such as proximal 60 Hz power lines, VLF, 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 show low amplitude signals. Since there is always a trade-off between quality and productivity, the stacking in noisy environment was at most 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; a smaller loop was used as the 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 centered over the vein. The fact that the profile shape remains the same implies that the veins are thin. Knowledge of the conductor location is thus beneficial when planning the loop locations.

The continuous normalization of the secondary field aimed to amplify the very poor responses attributed to weak conductors far from the loop (West et al., 1984; Polzer et al., 1990; Lamontagne, 1999). However, the result of this processing technique is not conclusive in the Opemiska case, because it attenuated the strong conductor located near the loop, and amplified the cultural noise without making significant progress to the delineation of the weak conductors.
Modeling the weak conductors using the peak ratio of the x-component is an alternative to the plate modeling. Even though this methodology is not yet perfected, it helps to get a sense of whether there might be veins present and if so, what the direction of the vein system might be. Knowing this will help when planning subsequent exploration effort. The plotted direction of the inverse of the normalized ratio of the x-component amplitude for the time windows 1 and 6 on the rose diagram seems to correlate well with the direction of the Cu-Au veins. This is particularly true for the sites where the conductivity was relatively low and plate modeling is more difficult. As this procedure has only been undertaken at two sites, more work is required to build confidence in the results.

The decay rate could be used to estimate if the mineralization is conductive or not. If it is conductive, the flat trend from figure 1.41 could be used to estimate the Cu grade from the peak to peak amplitude of the z-component. If it is resistive ore, the steep trend could be used instead. These results are very approximate as the copper percentages illustrated in Figure 1.41 were based on an approximation from a three-dimensional interpolation and averaged for a complete line near surface using 5 m block cells from the copper grade block model. For more accurate results, a detailed study of core samples is suggested to correlate conductivities from SCIP measurements and X-ray fluorescence measurements to determine the elemental composition of the cores at regular interval, and at a lower cost. Assays from the laboratory could be used to monitor the results from the X-ray fluorescence handheld instrument. Similar correlations between the nickel grade and the conductivity have been successfully established by Vale in Sudbury (McDowell et al., 1998; 2004; 2007), but the relationship is easier to establish due to the quasi-constant presence of the highly conductive pyrrhotite that is proportional to the nickel grade. The conductivity from different chalcopyrite ores is variable and depends on the texture, impurities and host rock; hence
it is difficult to establish a direct link between the Cu grade and the conductivity of the chalcopyrite samples. 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.

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 (Pridmore and 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 (Pearce *et al.*, 2006b). 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. 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. 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.

CONCLUSION

The compilation and processing of the historical galvanic resistivity/IP chargeability method did not reveal identifiable differences between magnetite, pyrite, pyrrhotite or graphite and the economic chalcopyrite mineralization. However, even though they can be ambiguous, high resistivity anomalies thought to be due to anthropogenic sources or water retentive areas, should be investigated as some Cu-Au mineralization can be resistive. Conversely, isolated low resistivity anomalies should also be thoroughly investigated since they can be associated with conductive Cu-Au mineralization. The total magnetic intensity map did not show anomalies that could be interpreted as mineralized zones.

The TDEM survey conducted on the Opemiska property also 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, 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 some indication from the literature that 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 modeling 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.

Conductivity could be estimated using the decay rate, and then using the peak-to-peak z-component curves to estimate the Cu grade as one would know whether to use the steep or flat curves. More data is required to confirm the validity of such a methodology.

The chargeability was estimated from EM shape reversal. However, the TDEM chargeability anomalies can sometimes be caused by other minerals than the ore itself such as magnetite, graphite, pyrrhotite or pyrite. The correlation cross-plots demonstrated that gold is statistically not always associated with chalcopyrite, suggesting different episodes of mineralization in the history of the deposit. Thus, the chargeability estimation from EM data could be employed to target gold horizons as these are associated with pyrite in resistive host rocks, however, more sites that display TDEM chargeability are required to establish a correlation between TDEM chargeability and Cu grade or Au grade.

From an exploration perspective, prospecting for massive vein-type and disseminated chalcopyrite in the area should also be targeting weakly conductive anomalies, since the Cu-Au 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.
RECOMMENDATIONS FOR FURTHER EXPLORATION

Potential of sulfide discovery to the East of the historical Perry mine seems promising: the density of diamond drill holes is less than at Perry or Springer, and the TDEM experiments showed that good conductors that correspond to mineralization could be detected. Examples of these types of mineralized zones can be found at sites #2 and #7. Further exploration using the same approach is suggested in this sector of the Opemiska property. This area has lower background noise and the conductive and massive mineralization more strongly responds to the TDEM excitation. In addition, it is recommended to explore along the northern geological contact between the Ventures gabbro and the rhyolite. Prospecting should prioritize the areas where the faults, fractures and shear zones intersect the lithologies since these structural controls are spatially associated with the formation of veins and related mineralization.

The use of a transmitter with a faster turn off time would be beneficial to locate weak conductors. A fast transmitter current shut off produces a primary EM field containing more high frequency harmonics. Such a waveform will generate early off-time responses in weakly conductive zones allowing near-surface conductivity mapping. As an alternative, borehole EM could be performed in some of the open or newly drilled holes as this could potentially improve the S/N ratio by decreasing the influence of cultural EM noise coming from the surface.

A three-dimensional integration of the geology and geophysics could also be done to produce an exploration model. The combination of different surveys and layers of information would allow identification of target areas of high mineralization potential. The model could incorporate the inverted galvanic IP data, the structural geology, the block model, inverted magnetic data, EM modeled plates, DDH and surface assays. The model would synthesize 3D data, determine relationships between different layers using a knowledge or data driven approach, and combine
evidences to identify high potential targets. This 3D predictive model would be simpler to look at and could optimize the exploration by integrating all the data collected in such a way that unexplored areas favorable for copper-gold mineralization could be investigated.

The petrophysical gravity measurements exhibited a net contrast between the host rock and the semi-massive to massive mineralization. A microgravity survey experiment on the property could be used to evaluate the response of the mineralization and the possibility of locating the veins with this method.
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Chapter 2

The impact of magnetic viscosity on time-domain electromagnetic data from iron oxide minerals embedded in rocks at Opemiska, Québec, Canada
INTRODUCTION

Magnetic viscosity

Magnetic viscosity (MV) is an effect exhibited by fine-grained magnetic minerals that gradually align atomic spins to develop an induced magnetic field oriented with an external magnetic field. The same effect can be observed when there is a change of the exciting field, or there can be a decay in the induced field when the external magnetic field is removed (Dunlop and Özdemir, 2001; Barsukov and Fainberg, 2001; Pasion et al., 2002). The phenomenon is also called superparamagnetic (SPM) effects, frequency-dependent or time-dependent magnetic susceptibility.

Rock magnetism researchers (Néel, 1949; Stacey, 1962; Stacey and Banerjee, 1974; Hodych, 1977; Halgedahl and Fuller, 1980; Boyd et al., 1984; Williams and Dunlop, 1989; Worm et al., 1991; Xu and Dunlop, 1993; Dunlop, 1995) have found that magnetism in minerals can occur in domains where the spins are aligned in parallel or antiparallel directions and magnetic minerals can either contain multiple domains (MD) or single domains (SD). Extremely fine-grained magnetic minerals (slightly < 1 μm) tend to have a single domain and realign their atomic spin with a relaxation time on the order of milliseconds, so they behave viscously (Dunlop and Özdemir, 2001). In a multi-domain grain, the individual domains may reorient the grain’s magnetic direction (Bogdanov and Vlasov, 1966), or even enlarge some of the domains at the expense of others (Stacey and Banerjee, 1974; Dunlop, 1995). These multi-domain grains tend to hold their magnetization for much longer periods, but they can exhibit some SD-like properties when the grains are up to ~ 20 μm (Clark, 1983). So, rather than exhibiting a sudden transition between SD and MD, there seems to be a smooth transition between the two behaviors (Stacey,
1962; Fabian and Hubert, 1999). It is however unclear if MD grains can produce MV at the time-scales observable in previous TDEM studies.

Our research aimed to explain the magnetic viscosity seen at Opemiska with a timescale of observation between 0.01 and 10 ms, corresponding to the time windows of the 15 Hz or 30 Hz base frequency used during the TDEM survey. In this paper, we briefly review the influence of size and shape of magnetite grains on magnetic viscosity, and the environments in which magnetic viscosity has been detected. In the case of Opemiska, we characterize the magnetic viscosity decay using a decay rate for predictive mapping. We also investigate hand samples using petrophysical, optical and scanning electron microscopic studies. Finally, we use an electromagnetic induction spectrometer to investigate the frequency dependence of the susceptibility to see if this is consistent with magnetic viscosity.

**Size and shape of magnetite grains**

Depending on the time of exposure to a magnetic field, magnetic viscosity is more pronounced in the single-domain range (0.1 to 5 μm), even though it can be substantial in the multi-domain range (10 to 15 μm) (Parry, 1965; Dunlop, 1983). Mullins and Tite (1973) also report that the multi-domain grains do display magnetic viscosity, with a response 2 orders of magnitude less that the single domain grains. Dunlop and Schutts (1979) demonstrated that viscous magnetization is strongest in single-domain grains of the order of 0.5 μm in size, but in the time scales of interest, it can also be appreciable in larger grains (10 to 15 μm) if they are elongated, a result consistent with the theoretical model developed by Butler and Banerjee (1975).

Buselli (1982) reports that the presence of fine-grained particles of magnetite with radii of the order of 0.025 μm or less, will cause these materials to exhibit magnetization and to behave
viscously. Strangway et al. (1968), came to a similar conclusion for spherical magnetite or maghemite with grains of 0.02 μm for a 1 ms measurement at room temperature. Dunlop (1973) measured MV on equant grains ranging from 0.01 to 0.065 μm in size. Magnetic SD structures were observed on perfect octahedral crystal of magnetite by Özdemir and Dunlop (1993). However, Dunlop (1995) showed that magnetite grains as large as 10–100 μm in size can also have intermediate or pseudo-single-domain properties. Fabian and Hubert (1999) suggest that an imbalance in asymmetrical particles contributes substantially to the SD-like fraction of the overall remanence. Finally, Macnae (2016) suggests that the magnetic viscosity will be favored with grain sizes in the 0.1 to 0.9 μm range, and emphasizes that a preferred magnetization will be developed along the longest direction of the single-domains grains, aligned with the direction of the applied field, and that it is those grains that are causing detectable magnetic viscosity. Although there is some debate about the exact grain size and nature of the magnetic material causing the magnetic viscosity, it also appears that grain shape, the mineralogy, the intensity of the field used to induce the remanence, and the direction of the external field applied in regard to the axis of the grains is influencing the amplitude of the response obtained (Levi and Merrill, 1978).

**Detection of magnetic viscosity**

Magnetic viscosity has been previously observed by different authors in (i) weathered oxidic soils of tropical and subtropical climates such as regolith in Australia (Buselli, 1982; Barsukov and Fainberg, 2001) and Africa (Macnae, 2016), (ii) microcrystals of iron oxides in quenched volcanic glass shards from tuff where ~1% by weight magnetite occurs as grains ~0.002 to 0.01 μm in size precipitated in a spatially uniform way (Schlinger and Smith, 1986a; Schlinger et. al, 1986b; Julian et al., 1988; Dunlop, 1995), (iii) airborne EM data from Greenland (Taylor, 2016; Legault et al., 2016), (iv) attributed to fine-grained volcanic materials (Macnae, 2016), (v) associated with glacial
tills in Finland (Montonen, 2015) and (vi) from biogenic origin when Gallionella bacterium precipitates ferrihydrite that oxidizes to nanocrystalline maghemite aggregates (Moskowitz et al., 1988; Tabbagh and Dabbas, 1996; Konishi et al., 2012).

Magnetic viscosity can be detected with decay constants in the millisecond range (Kratzer et al., 2013) using ground or airborne TDEM methods with a coincident loop TDEM configuration (Kozhevnikov and Antonov, 2011). In ground measurements, magnetic viscosity is mostly seen inside the loop, or a few meters outside (Buselli, 1982). In airborne measurements, magnetic viscosity signals decrease rapidly with height (Lee, 1978; Raiche, 1978; Buselli, 1982) and disappear in modern systems (where the receiver is inside the transmitter) if terrain clearances of approximately 50 m are reached (Taylor, 2016). This is intuitively reasonable, since effects are most likely to be observed in cases where the applied field from the transmitter magnetizes material in close vicinity and the receiver is also nearby to sense these fields. The low-amplitude, slow decays caused by magnetic viscosity have a similar signature to good conductors, such as massive sulphides, and many anomalies have been previously mis-interpreted as first priority targets to be drilled (Mutton, 2012; Taylor, 2016; Legault et al., 2016). Magnetically viscous minerals exhibit late-time power law decays with $V(t) \sim 1/t$ during the off time for an impulse response (Billings et al., 2003), and on a double logarithmic scale, the graph of $V(t)$ is a straight line with a slope of -1 (Buselli, 1982). This temporal behavior has also been observed by Nagata (1961), Barsukov and Fainberg (2001), Montonen (2015), Taylor (2016), and explained mathematically by Chikazumi and Charap (1978), as cited in Lee (1984b).
METHODS AND RESULTS

Magnetic viscosity in TDEM field survey, at Opemiska

During summer 2015, fourteen different sites were investigated on the Opemiska property with ground fixed loop TDEM system using a square waveform. Out of the fourteen sites investigated, five of them (sites #1, 4, 5, 10 and 12) were presumed to be exhibiting MV that shared the following characteristics:

1. The $\partial B_z/\partial t$ decay curve exhibits a negative slope with an approximate $1/t$ time dependence during the off-time, consistent with work from Buselli (1982), Lee (1984a) and Billings et al. (2003). However, the MV decay rate is sometimes slightly different from the $1/t$ time dependence. Observations show that the electromagnetic field transient response $V$ in the receiver sensor is proportional to $1/t^{1+\alpha}$, where $-0.4 < \alpha < 0.4$ (Figure 2.1). This observation is comparable with data collected by Barsukov and Fainberg (1997), and Sattel and Mutton (2014), where they observed $-0.2 < \alpha < 0.2$, and with data collected by Dabas and Skinner (1993) who observed a power law with exponent $-1.4$ between 56 and 417 μs.

2. The stations where the relation of $V(t) = 1/ t^{1+\alpha}$ is observed, are located inside the fixed ground loop transmitter and less than 10 m outside the edge of it (Figure 2.2). This observation is in agreement with Buselli (1982).
3. The TDEM anomalies attributed to be caused by magnetic viscosity are visible on the z-component, with no corresponding x or y-component response (Figure 2.2). This observation is consistent with Taylor (2016).

4. All z-component profiles along the lines surveyed exhibit a similar shape. This profile shape is similar to the one also observed by Mutton (2012). There is a characteristic reversal of sign when crossing the loop edge, from inside the loop to outside the loop. The shape of the magnetic viscosity profile is similar to the monitored primary field at the receiver, but the amplitude of the MV response is several orders of magnitude smaller.

5. All the sites where MV was observed coincide with strong airborne magnetic field anomalies (Keating et al., 2010). This confirms the existence of magnetic material in the study area.

6. The overburden thickness is different at each site, ranging from zero to several meters of till, or tailings. Out of the five sites where the possible MV was observed, two of them had the survey equipment lying directly on the outcrop (site #1 and #4). On the other three sites (#5, #10, and #12), drilling confirmed three to ten meters of overburden above the bedrock. The decay regression analysis for the sites with the presence of overburden, confirmed negative slopes with systematic time dependence close to $1/t$. 
Figure 2.1: Linear regression analysis of the TDEM $\frac{\partial B_z}{\partial t}$ decay for the site #1, line 0, station $-5$ m. The TDEM $\frac{\partial B_z}{\partial t}$ decay linear regression line in red fitting the observed response in black exhibits a negative straight slope of $-1.332$ on a log-log scale.
Figure 2.2: Profile response of x-, y- and z-components for site #5, line 0, at a base frequency of 30 Hz. The TDEM anomalies attributed to be caused by magnetic viscosity are visible on the z-component, with no corresponding x- or y-component response.
Predictive mapping of mineralization using the $\alpha$ parameter

Barsukov and Fainberg (2001) showed that in some cases, a magnetic viscosity effect can be used as a powerful exploration tool for certain types of mineral deposits. Their results showed that for deep intrusive nickel orebodies, the parameter $\alpha > 0$ from $V(t) = 1/t^{1+\alpha}$ would indicate the location where ore deposits associated with magnetite exist, and $\alpha < 0$ indicates where there aren’t any orebodies.

At Opemiska, the $\alpha$ parameter from $V(t) = 1/t^{1+\alpha}$ was plotted for every TDEM station surveyed where magnetic viscosity was observed. Kriging interpolation of the $1+\alpha$ parameter suggests a correlation between a large positive $\alpha$ and the chalcopyrite ore associated with magnetic minerals (shown with the black outline on Figure 2.3). The trend direction of the red zone corresponds roughly with the direction of the vein, but the sampling is poor, hence the trend direction is not estimated with confidence. Further petrographic work and denser sampling is required to correlate $\alpha$ with chalcopyrite percentages and the distribution of the mineralization.

Figure 2.3: Kriging interpolation of the $1+\alpha$ parameter, from the z-component, at site #1.
**Petrophysical measurements on hand samples from Opemiska**

At sites #1 and #4 where magnetic viscosity was observed in the TDEM data, outcropping bedrock allowed for rock samples to be collected for petrophysical and microscopic observations (Figure 2.4). Magnetic susceptibility measurements were done using the handheld multi-parameter probe (MPP) manufactured by Instrumentation GDD Inc. The magnetic susceptibility measured from the 10 samples collected at sites #1 and #4, ranges from 1.47 to 493 x 10^-3 SI and are presented in Figure 2.4. The measurements were collected from rock biscuits, from which the polished thin sections were also prepared. Since the coil of the handheld instrument is bigger than the rock samples, the measurements are considered only as semi-quantitative, and roughly indicate the range of magnetic susceptibility values. Microscopic observations confirmed the presence of magnetite grains in all the samples. The magnetite modal percentage was approximated by doing visual observations on polished thin sections, with a content ranging from 1 to 15%. A Rietveld analysis would be needed to determine quantitatively the modal abundance of the ilmenite, magnetite and pyrrhotite. This X-ray diffraction method would allow us to establish a correlation between the MV amplitude and the modal abundance of the observed minerals, the grain sizes volume fractions, and a magnetic-content versus the magnetic susceptibility such as in Clark and Emerson (1991).
Figure 2.4: Location of rock samples used to prepare the polished thin sections and conduct the UTEMIS measurements on sites #1 and #4. Magnetic susceptibility measurements on the samples collected at sites #1 and #4 are also shown on the inset. The colors of the different stars represent the amplitude of the magnetic susceptibility measurements.


Scanning electron microscope study

Objectives and methodology

Optical microscope examination of polished thin sections coming from Opemiska outcrops, where MV was observed with the TDEM survey, shows obvious magnetite grains with diameters of less than 5 μm (Figure 2.5). These observations are at the lower limit of the optical microscope used with a 40X lens. Ilmenite and pyrrhotite were also observed in these samples, and these minerals might possibly be contributing to the magnetic viscosity. Ilmenite lamellae were observed in the \{111\} planes of the host magnetite and chalcopyrite (Figure 2.6), and this oxyexsolved process (Tucker and O’Reilly, 1980; Lindsley, 1991) is known for subdividing the large grains into a number of magnetically independent smaller grains (Graham, 1953). Strangway et al. (1968) point out that the trellis texture of ilmenite lamellae may result in SD grains, with a grain diameter much larger than the SPM critical size calculated by the Néel theory. To confirm the finer grain structure of the magnetic grains, the scanning electron microscope (SEM) was used to determine the accurate dimension (width) of the smallest iron oxide grains that could be observed. Four polished thin sections (PTS) have been selected for SEM observations: PTS B and C from site #1, and PTS J and M from site #4.

The PTS were first coated with carbon (0.015 μm thickness) prior to the observations under the JSM-6400 scanning microscope in the central analytic facility at Laurentian University in Sudbury. The voltage applied was 20 kV, with a current of 1 nA. Work conducted on the PTS mainly used the back scattering electron images (AUX) to locate and identify different minerals and obtain their respective chemistry by looking at their reference peaks. Mapping analysis has also been conducted for some areas of interest to evaluate all the elements that were present. Since the beam
of the SEM used has a diameter of ~ 1 μm, the chemistry of the grains observed smaller than that dimension will encompass an average of the minerals surrounding them.

Results and interpretation from the scanning electron microscope work

A magnetite grain with a grain width of 0.667 μm (Figure 2.7) was observed on polished thin section J. All of the four polished thin sections examined under the SEM showed magnetite with grain widths as small as ~ 1 μm. The smaller magnetite grains are inferred to be the result of bigger grains that were broken. This grain fragmentation is interpreted to have developed during regional compression which created folds and fractures, controlling the emplacement of the Cu-Au mineralization (Lavoie, 1972; Watkins and Riverin, 1982; Leclerc et. al, 2009). Hence, one possible factor contributing to magnetic viscosity observed at Opemiska is the deformational history, which is partly responsible for the various sizes and orientations of the domains of the magnetite grains found in the rock samples. The exsolution is a second factor that may also have produced smaller magnetic grains than the original grains (O’Reilly, 1984), and these intergrowths could also be contributing to the MV observed.
Figure 2.5: Optical microscope observation of polished thin section J (site #4). The magnetite grains are broken into smaller pieces. Some of the magnetite grains have a diameter of less than 5 to 10 μm.
Figure 2.6: Optical microscope observation of polished thin section C (site #1). The ilmenite trellis texture presents broken edges with micro-cavities. It is interpreted that the ilmenite developed along the \{111\} planes of the magnetite and has subsequently been replaced by chalcopyrite.
Figure 2.7: Scanning electron microscope observation of PTS J (site #4).

The magnetite grain width in (i) is 1.17 μm; and in (ii) is 0.667 μm.
**EM induction spectrometer study**

To confirm the possibility that magnetic viscosity was originating from the fine particles of iron oxides embedded in the Opemiska rock formations, an additional experiment was designed to observe induced magnetic moment in laboratory-scale samples.

**Principles of operation**

The instrument used was the University of Toronto EM Induction Spectrometer (UTEMIS), a transportable tabletop instrument for measuring the ratio of the time-varying magnetic moment induced in small, laboratory-scale samples by a time varying, spatially uniform, alternating magnetic field. Static magnetic induction and eddy current induction are measured and expressed as the magnetance, \(m\), of the form

\[ m = \frac{p_m}{H} \quad (2.1) \]

where \(p_m\) (Am\(^2\)) is the induced magnetic moment, and \(H\) (A/m) the exciting magnetic field intensity. The ratio \(m\) has units of cubic meters, indicating the measurement is proportional to sample volume (Bailey and West, 2007). However, the results of this study are normalized by the mass \(m\), to give the magnetic mass susceptibility \(\chi = m/m\), as a way to account for the different shape and sample sizes. The mass susceptibility is thus expressed in units of \(\mu l/g\) (= 10\(^{-6}\) m\(^3\)/kg). Volume could have been used as an alternative to mass normalization, but the relative effort and error in measuring mass was judged to be less than estimating volume. The UTEMIS reports its measurements of magnetance as a complex number, with the measurements given directly as real and imaginary components at a prescribed set of frequencies between 140 Hz to 63 kHz (West and Holladay, 2014).
To speed up the measurements, the applied field is not a single pure harmonic. The current that excites the Helmholtz configuration source coils of the system is generated from a prerecorded digital sequence 3 seconds long, consisting of six quasi-square-wave signals. Individual odd harmonics are extracted from the recorded signals by Fourier analysis. The prerecorded sequence can be transmitted several times, and stacked sequentially. Averages and standard deviations of the readings are calculated and results tabulated (Bailey and West, 2007). The figure 2.8 shows a picture of the mark II version of the UTEMIS and a close up of a sample.

Figure 2.8: (a) Picture of the UTEMIS II with a pseudo-cubic 2.5 cm width specimen from Opemiska on the sample pedestal inside the instrument. (b) Close-up of cubic specimen from which UTEMIS measurements were made.
Methodology

Surface grab samples or diamond drill cores from Opemiska sites where TDEM surveys were done during the summer of 2015 were cut into rock cubes with dimensions of 1 inch or smaller to fit the vial of the UTEMIS. The 22 samples studied with the UTEMIS are the same samples used for the polished thin section study and correspond to a wide variety of Cu-Au veins, mineralization type and host rocks. For statistical purposes, several rocks cube specimens coming from each site were prepared. The dimension of 2.5 cm or less ensures the magnetic field induced on the samples is as uniform as possible. We acquired four repeat measurements with the UTEMIS, except when the size of the sample was smaller than 2.5 cm, then 16 repeats were performed. This is because smaller sample volumes yield less signal, increasing the effects of noise and drift, particularly for weakly responsive samples (West and Holladay, 2014).

To ensure the UTEMIS instrument was working properly, a calibration reading over a ferrite bead, and a copper loop were taken at the beginning and the end of the day. Figure 2.9a shows the pure inductive response from a copper loop wire with a zero in-phase response at low frequency and a quadrature response that peaks at the same frequency that the in-phase shows an inflection. The measurements from a non-conductive non-viscous but susceptible ferrite bead sample (Figure 2.9b) show a zero quadrature response and an in-phase measurement that does not vary from the low-frequency value.

Samples which show viscous magnetization (Figure 2.9c) are expected to have a declining in-phase magnetization that varies as a function of frequency increase, with a nearly constant out-of-phase component (Das, 2005; Bailey and West, 2007).
Figure 2.9: Plots of UTEMIS responses for the frequency spectrum of magnetance obtained for known samples. The magnetance was not normalized by the mass for (a) and (b), and normalized by volume for (c).

(a) Conductive sample with no magnetic susceptibility (copper ring sample).
(b) Magnetic susceptible sample with no conductivity and no magnetic viscosity (ferrite bead sample).
Figure 2.9: (c) Soil sample from Australia (AzC-2, 12.5 ml), exhibiting magnetic viscosity. The in-phase component varies as a function of frequency, and declines as the frequency increases, while the out-of-phase component is negative and approximately constant (modified from Bailey and West, 2007).

**Electromagnetic induction measurements results**

Opemiska ore consists of semi-massive to massive chalcopyrite, silver and gold with erratic distributions of pyrite–pyrrhotite–magnetite. The veins and veinlets are hosted in a gabbro with quartz, calcite, carbonate and stilpnomelane (McMillan, 1972). Opemiska rocks exhibit a wide range of physical properties, chemical composition, mineralogical assemblages and textures. The responses obtained with the UTEMIS reflect this variety and are presented in Figure 2.10. The type of responses obtained from Opemiska rock samples can be summarized into 4 main categories:

1. A response exhibiting a constant relatively small magnetization for the in-phase component, with an obvious out-of-phase response displaying a negative slope (Figure 2.10a). The highest frequency response shows no appreciable in-phase component, and
the largest observed out-of-phase response was measured at \(-3.55 \, \mu l/g\) for the 63 kHz frequency. The inductive limit is not reached, taking into account that higher frequencies are not measured. This spectrum, with variation in the out-of-phase component only, suggests the presence of a weak to moderate conductor. The small but invariant in-phase component suggests a small amount of ferromagnetic material with frequency-independent susceptibility.

2. A moderate to strong magnetization response visible on the in-phase component, with no out-of-phase component (Figure 2.10b). The susceptibility spectrum for the in-phase component shows almost no dispersion and is constant. This suggests the presence of ferromagnetic material with coarse grains, with multi-domain boundaries and no frequency dependence or magnetic viscosity.

3. A stronger negative slope in the in-phase component in comparison with the other samples, with a corresponding peak in the out-of-phase component (Figure 2.10c). One interpretation is that this frequency-dependent magnetization response suggests the presence of a conductor, with the in-phase component representing the induction of conduction currents (eddy currents) superposed on a frequency-independent induced magnetization. In this case, the sample would contain material that is both conductive and multi-domain ferromagnetic. The mineralogical microscopic observations confirm the presence of pyrrhotite, chalcopyrite and magnetite, which explains the UTEMIS response. On the other hand, there is ambiguity and the spectrum might indicate a strong change in
the susceptibility as a function of frequency which will distort the in-phase component and
the out-of-phase components as a consequence of the Kramers-Kronig relation.

4. A negative slope in the in-phase component, with a constant negative out-of-phase
component (Figures 2.10d). This type of response where the spectrum exhibits dispersion
infers magnetic viscosity: the in-phase component declines with a proportional increase in
frequency with a steady negative out-of-phase. A Kramers-Kronig relationship between
the in-phase and quadrature was expected to be visible (Van Kampen and Lurçat, 1961).
However, the expected decline in the out-of-phase response predicted from the changes in
the in-phase is not seen. The standard deviation error is 0.05 μl/g, 10 times less than the
decreasing interval 0.5 μl/g observed for the in-phase component.
Figure 2.10: Plots of UTEMIS responses for the frequency spectrum of mass susceptibility obtained from Opemiska rock samples.
(a) Weak conductive material with very weak magnetic susceptibility (sample B4)
(b) High magnetic induction material with no conductivity (sample F1)
Figure 2.10 (con’t): Plots for: (c) A frequency-dependent magnetization response showing a strong negative slope in the real component, with a corresponding quadrature component (sample R1-repeat, 1.9 g). (d) A frequency-dependent magnetization showing a negative slope in the real component, with a nearly constant negative imaginary component (sample J4-ii, 16.5 g). The in-phase decline over a 0.5 μl/g interval is proportional with the increase in frequency, and shows a dispersive spectrum typical of magnetic viscosity. The anomalous measurements values at low and high frequencies may be affected by extraneous sources.
DISCUSSION

The magnetic response of coarse-grained magnetite is typically non-dispersive (Bailey and West, 2007). Measurements with the UTEMIS on Opemiska rock samples show a wide range of magnetization amplitudes, sometimes with a weak frequency-dependent response superposed. This suggests that magnetic material embedded in the rock is comprised of both coarse and fine grains. The coarse multi-domain grains will amplify the magnetization response, while the fine single-domain grains will be time dependent and decay with time.

The observations made with the spectrometer are consistent with the polished thin-section studies. For example, the PTS J for which magnetic viscosity seems to be observed with the UTEMIS, has been described with a modal composition consisting of 65% chalcopyrite, 15% magnetite, 15% quartz, 5% pyrite, and traces of biotite. Looking at this specific PTS under the microscope, one can clearly see that some of the largest magnetite grains appear to have been crushed as a consequence of the physical strain, resulting in smaller very fine broken grains. Qualitatively, the grain size is not uniform and spreads over at least 4 orders of magnitude. The scanning electron microscope study on PTS J confirmed the size of magnetite grains to be as small as 0.667 μm. Thus, it is possible that very fine magnetic grains (< 1 μm) would induce a response different from large ones (> 100 μm) as suggested by previous workers, and that these two responses would be superimposed. Even though the modal abundance could be determined quantitatively, it is interpreted that this wide range of grain sizes lead to an induced magnetization superimposed with a magnetic viscosity. The volume fraction of coarse ferromagnetic grains in the rock will enhance the strength of the magnetization, and exhibit a susceptibility that is frequency-independent, while the fine magnetic grains show a viscous magnetization, and exhibit a frequency dependence.
These induction measurements, done independently from the PTS and SEM studies, support the a priori hypothesis that magnetic viscosity could be seen in the z-component response from the Geonics coil sensor used during the 2015 field TDEM survey at Opemiska. The slow $\partial B_z/\partial t$ decay amplitude measured inside the TDEM loop for the vertical component exhibited a $1/t$ dependence, and was seen between 0.2 and 7 ms at 30 Hz. The polished thin section J comes from the TDEM site #4 investigated during the 2015 summer where MV is hypothesized to be observed. The UTEMIS measurements done on PTS J, showed a frequency-dependence visible from 140 Hz to 63 kHz. This frequency spectrum range corresponds to the equivalent of the time range that the TDEM instrument is sensitive to.

Other hypotheses were examined to attempt to explain the slow z-component decay, which could originate from another source than the magnetic minerals embedded in the rock itself:

- A slow leakage of the TDEM transmitter after the turn-off, potentially resulting in a residual current flowing in the ground after the non-ideal termination. However, two different transmitters were used, manufactured by two different companies, GDD and Geonics, and the results were similar. It is unlikely that both instruments are at fault in an identical way. Also, similar effects were not seen at other resistive sites, suggesting a geological explanation, not an instrument problem. If the shape of the late-time EM response is identical to the primary field, this would mean that the source of the signal is geometrically the same as the source of the primary field. The differences in shape between the primary field from both transmitters and their respective secondary response for late-time were examined closely by superimposing them at the same scale. The result shows they are similar but don’t fit perfectly. This would suggest that the signal seen is modified
in some way by the magnetic field of currents induced at early time, or by some other current flowing in the ground.

- Another explanation could be magnetically viscous fine-grained particles of maghemite or magnetite in the overburden. However, some of the sites where the phenomenon was observed were surveyed with the TDEM sensor lying directly on the bedrock. There is bedrock alteration associated with mineralization at Opemiska, but this is limited to no more than twice the width of the associated mineralized veins (Watkins and Riverin, 1982), meaning a maximum of 3 to 5 meters in total. The observed MV phenomenon was seen over an area of 50 x 50 meters while surveying inside the loop. In addition, the climatic conditions in Quebec for the last few thousands of years do not favor the formation of regolith as seen in tropical or subtropical soil environments. Even though oxidation of magnetite to maghemite is common but not abundant in North America, it has been observed in Canadian iron formations as a rim, sharp linear features or masses within the magnetite grains (McLeod, 1970). Maghemite is also observed in Canada in the oxidized zone of surface geological deposits and is attributed to biochemical oxidation of pyrite (Pawluk, 1971). It is also sometimes inherited from the transformation of goethite during bush fires (Schwertmann and Fechter, 1984; Anand and Gilkes, 1987; Stanjek, 1987) or attributed to pedogenic processes (Van der Marel, 1951; Oades and Townsend, 1963; Taylor and Schwertmann, 1974). However, the Opemiska vein copper – gold deposit is interpreted to have been formed by hydrothermal process crosscutting a mafic to ultramafic sill (McMillan, 1972; Salmon, 1982; Hutchinson, 1982; Robert, 1994), and maghemite was not recognized in the PTS nor the SEM studies done on Opemiska rocks. Although further
research is required to confirm the absence of maghemite in the soil at Opemiska, it is unlikely that altered magnetite present in the overburden at Opemiska could be the main source for the MV.

Finally, it should be emphasized that the UTEMIS response obtained from representative rock samples is difficult to interpret as it can be comprised of induced magnetization and a conductive response. For example, Figure 2.11 shows frequency dependence of the in-phase component which is superposed on a strong frequency-independent induced magnetization; and the out-of-phase component shows a very weak response. This type of response infers that magnetic viscosity could be interpreted to be present. However, since there is known massive chalcopyrite in the studied sample J, the response could also be explained by its conductive nature. Discriminating between the dispersive rock susceptibility response and very weak conductive mineralization is not obvious on these samples. The same ambiguity exists in the time domain, which is why the MV responses can be misinterpreted as due to conductive bodies. In the time domain, the MV is characterized by a $1/t$ time dependence. In the frequency domain, there might be a comparable characteristic that can be used to identify MV, likely one or more changes in the in-phase component over a broad range of frequencies.

Data at more sites is required to establish a link between mineralization and magnetic viscosity. If more work is done at Opemiska and magnetic viscosity is observed in areas where the Cu grade is known, it might be possible to estimate grade from magnetic viscosity.
Figure 2.11: UTEMIS plot of the mass susceptibility for the M1-M2 sample (7.73 g). The negative slope in the real component between 300 Hz and 10 kHz with a nearly constant out-of-phase component suggests a frequency-dependent magnetization. The out-of-phase negative peak at 1.4 kHz indicates a very weak conductive component, suggesting the overall response is complicated and encompasses induced magnetization and a conductive response. The measurements values over 20 kHz may be affected by extraneous sources.
CONCLUSION

Ground TDEM measurements at some stations at Opemiska, Québec, show a slow positive decay inside the loop and a negative decay outside the loop. We have concluded that this is due to magnetic viscosity because the time decay exhibits a power law decay with the exponent being close to $-1$, which is consistent with other cases where there is magnetically viscous material in the subsurface, and is also consistent with theoretical predictions for MV material.

In other locations in the world, the MV material is believed to be mainly due to maghemite in the weathered regolith or soil. Although further research would be needed to confirm the absence of maghemite in the Opemiska overburden, maghemite is unlikely at Opemiska where there is no regolith; furthermore in some cases the MV at Opemiska is measured where there is exposed bedrock. A source of MV is therefore directly required from material in the bedrock.

The amplitude of the MV response is more likely exhibited by the presence of extremely fine-grained magnetic material, but is also a function of the grain shape, the mineralogy, and the time scale, intensity and direction of the external field applied to induce the remanence. Samples collected from the Opemiska area where MV is measured show magnetic minerals with grain sizes less than 1 μm, with variable orientations, shapes and textures.

Material that is magnetically viscous typically shows a magnetic susceptibility that varies as a function of frequency. The UTEMIS measurements of the magnetization as a function of frequency on Opemiska rock samples display a noticeable frequency dependence of the in-phase component with a near zero out-of-phase component. The frequency dependence could be explained by conductive effects, but a relatively large non-zero frequency independent magnetization implies the material is magnetic and hence the dispersion is more likely due to MV
associated with fine-grained magnetic grains. The magnetic nature is consistent with a certain fraction of coarse grained magnetic grains, which are also seen in the microscopy.

We therefore conclude that at Opemiska, the fine fraction of the ferromagnetic grains (such as magnetite, ilmenite and pyrrhotite) in the bedrock could cause magnetic viscosity and be responsible for the late-time $1/t$ decay observed in the $z$-component of the TDEM survey carried out in 2015. This conclusion at this site might be applicable at other sites in Canada and Greenland where MV effects have been observed in airborne EM data and where maghemite in regolith, soils or clays is unlikely.
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Chapter 3

Final conclusion
The project was originally intended to determine the best ways to use electromagnetic methods to explore for Cu-Au deposits at Opemiska, and the conclusions are:

- The time-domain electromagnetic (TDEM) survey conducted allowed us to define the location, size, trend and conductance of conductors (potentially striking in multiple directions) that are present in the area of interest, by taking measurements along 4 different receiver-traverse orientations with a 50 x 50 m transmitter loop. Strong conductors were modeled using thin plates in free space, whereas weak conductor’s trends were estimated using the peak ratio of the x-component time windows 1 and 6 by plotting the results on rose diagrams;
- The hand-held physical properties measurements confirmed the variability of the conductivity of the mineralization (0.01 – 4000 S/m), which was consistent with the highly variable responses observed during the ground TDEM survey, with high copper grades not guaranteeing a strong TDEM response. A polished thin section (PTS) study showed resistive silicates isolating the chalcopyrite grains from each other, and preventing most of the electrical current flowing from one segment to another. The variable nature of the fabric of the rock, variable mineralogy and impurities are other factors altering the physical properties of chalcopyrite at Opemiska.

In the process of collecting and interpreting the TDEM data, unusual effects inside the loop were observed. These were not a benefit to the primary objective of the project (Cu-Au exploration); however, others have observed similar effects in airborne TDEM data, which appear very similar to the response of highly conductive bodies and could be mistaken for ore deposits. The data collected and the field samples collected therefore provided an opportunity to attempt to explain these responses. Their explanation is likely magnetic viscosity (MV) in fine grained magnetic
minerals embedded in the rocks in the near-surface (unweathered) material. This was concluded on the basis of the following evidence:

- The $\partial B_z/\partial t$ decay rate inside the loop at some stations from the ground TDEM survey exhibits a power law decay with the exponent being close to $-1$;
- The sites investigated where the magnetic viscosity effect is seen in the TDEM data are coincident with an airborne magnetic anomaly;
- Maghemite is unlikely at Opemiska where there is no regolith; furthermore in some cases the MV at Opemiska is measured where there is exposed bedrock;
- High magnetic susceptible minerals such as magnetite, ilmenite and pyrrhotite were identified using polished thin sections under an optical reflecting microscope;
- The use of the scanning electron microscope confirmed fine magnetite grains as small as 0.667 μm, and the presence of fine-grained ilmenite lamellae exsolutions.
- The UTEMIS measurements of the magnetization as a function of frequency on Opemiska rock samples display a noticeable frequency dependence of the in-phase component with a near zero out-of-phase component. The frequency dependence could be explained by conductive effects, but a non-zero frequency independent magnetization implies the material is magnetic and hence the dispersion is more likely due to MV associated with fine-grained magnetic grains.

The fine-grained (< 20 μm) fraction of magnetite, ilmenite and pyrrhotite in the bedrock could cause MV and be responsible for the late-time $1/t$ decay that is observed between 0.01 and 10 ms in the z-component of the TDEM survey at Opemiska. Further studies are required to provide evidence of what exact minerals, or combination of minerals are necessary to cause the observed responses.
APPENDIX 1
PROCESSING TDEM DATA

Electrical and electromagnetic noise

Sources of noise

Anthropogenic sources of noise is an important issue at Opemiska: power lines, antennas, cultural objects and waste from the former mine, pipes, fences, infrastructure, buildings, DDH casings, underground galleries, were encountered at most sites investigated. Processing of the data was necessary to manually edit and remove the interpreted meaningless stations where cultural sources of noise and distorted signals would be present. Other sources of noise include thunderstorms which produced random spherics. The local humid climate favored rapid changes in the daily weather conditions. In stormy circumstances, the crew halted acquisition for safety reasons and data quality.

Stacking

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. Stacking data is a very effective means to improve signal quality (Macnae et al., 1984; Allard, 2007). By repeating the measurement, the noise is decreased and the signal enhanced (Christiansen et al., 2009). Increasing the number of measurements in the stack by a factor of about ten resulted in three times less noise. While surveying one of the sites located 1 km NE of Chapais at a frequency of 30 Hz, the noise would be < 0.3 μV/A with 128 stacks, < 0.1 μV/A with 1024 stacks, and < 0.03 μV/A with 8192 stacks. In theory stacking reduces Gaussien noise by a factor proportional to $\sqrt{N}$ where N is the number of measurements in the stack (Christiansen et al., 2009). Increasing the stacking time meant spending more time at each receiver location. A trade-
off had to be established between data quality and productivity to ensure a reasonable rate of daily production. In low-noise conditions, three distinct readings were acquired and averaged for every receiver station to control the quality and ensure the repeatability of the measurements. In noisy conditions, up to nine readings were performed at each location. Weaker conductors yield less signal, so increasing the relative effects of man-made noise, so in these cases nine readings were also acquired. The stacking algorithm of the Nordic EM24 receiver was designed to reject the 60 Hz power lines noise while acquiring the data.

**Very low-frequency radio transmitters**

The TDEM systems are adversely impacted by what is considered noise from the very low frequency (VLF) radio transmitters, which has the greatest impact on the off-time horizontal components. Spectral analysis of the EM signal acquired during the survey identified unwanted signal from a number of stations (Table A.1.1). The NML station emitting at a frequency of 25.2 kHz and the NAA station emitting at 24.05 kHz were found to be most prevalent (Figure A.1.1). A specially designed window scheme has been developed to filter 25.2 kHz using time windows with a width that is a multiple of 39.68 us (1/25.2 kHz). A comparison of decay curves using the default window widths and the modified window scheme is presented at Figure A.1.2 and Table A.1.2. This method considerably improved the smoothness of the decays. However, the VLF noise was mainly an issue when the conductors to be detected were weak and the amplitude of the response was near the noise level. Overall, when looking at the profiles (not shown), a significant improvement was not observed, since this procedure mostly benefited the late times windows, but did not improve the early-time windows where lower noise levels are most required to identify the location of weak rapidly decaying conductors.
Table A.1.1: Identification of the radio transmitters (VLF) stations affecting the TDEM data at Opemiska. Identification of the location name and call sign from Lorent (2012), Loudet (2013) and Martek (2017).

<table>
<thead>
<tr>
<th>Call sign</th>
<th>Frequency (Hz)</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
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<td>Unknown</td>
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<td>ICV</td>
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<td>Isola di Tavolara, Italy</td>
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<td>E 009° 43' 51.64&quot;</td>
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<td>HWU</td>
<td>22600</td>
<td>Rosnay, France</td>
<td>N 46° 42' 47.26&quot;</td>
<td>E 001° 14' 42.89&quot;</td>
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<tr>
<td>NAA</td>
<td>24000</td>
<td>Cutler, Maine, USA</td>
<td>N 44° 38' 41.77&quot;</td>
<td>W 067° 16' 53.90&quot;</td>
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<tr>
<td>NLK</td>
<td>24800</td>
<td>Oso Wash, Jim Creek, USA</td>
<td>N 48° 12' 12.55&quot;</td>
<td>W 121° 55' 0.58&quot;</td>
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<tr>
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<td>W 098° 20' 8.30&quot;</td>
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Figure A.1.1: Spectral analysis of the EM response acquired during the off time at 30 Hz, for a specific station on site #4. The 24.05 kHz and 25.2 kHz peaks that are originating from VLF radio stations act as a source of noise. The horizontal components are the most affected.
Figure A.1.2: Decay curves comparison between (a) the default response with VLF noise and (b) the rewindowed data showing a reduction in the noise.
Table A.1.2: Window scheme specifically designed to reduce VLF noise for a 30 Hz base frequency.

<table>
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Magnetic dipole moment

Other means of enhancing the signal-to-noise (S/N) ratio is to increase the transmitted magnetic dipole moment $p_m$:

$$p_m = n I A,$$  \hspace{1cm} (A1.1)

where $n$ is the number of coil turns, $I$ is the effective electric current and $A$ is the effective loop area. The direction of the dipole moment is orthogonal to the plane of the current loop, with the sense given by the right-handed rule, where the palm of the right hand facing in the current direction and the thumb indicates the direction (Sheriff, 2002). The number of coil turns, with gage wire #10, was increased from a single turn to four turns using gauge wire #18, the area of the loop was increased from 20 to 50 m, and the transmitting current rose from 1 to 10 A. Using a loop larger than 50 m width would increase the dipole moment, but also energized deeper structures, with a greater volume of influence. We wanted to avoid galvanic and capacitive coupling by minimizing the extent to which we would energize buried pipes, metallic infrastructure and metallic objects in the former mine galleries. In addition, a larger loop would result in a larger loop inductance, resulting in a longer ramp or switch off time and this could contaminate the early time data and mask the weak conductors. Using large loops, for example 1 km x 1 km loops, is challenging at Opemiska from a safety perspective as curious local people could get injured by picking up the live wire.

After experimenting and comparing different geometries and arrays at different sites, it was decided that the 50 x 50m loop was the best choice to achieve the objectives targeted.