3D Modelling of TEM Data
from Rajapalot Gold-Cobalt prospect, northern Finland

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ABSTRACT

The Rajapalot gold-cobalt project in northern Finland is an exciting, relatively new discovery, still being explored with hopes to start mining in the future. The area was found by a IP/Resistivity survey in 2013. Extensive geophysical follow-up surveys have delineated several electromagnetic targets, one of which, named Raja, is the target anomaly this master thesis is built upon. A TEM survey was carried out during late August to early September 2018. The data collected was analyzed, processed and later modelled in Maxwell using Leroi, a CSIRO module. Three separate models are produced with one, two, and three plates respectively. The result is compared to existing VTEM and resistivity models.
# TABLE OF CONTENTS

**INTRODUCTION** ........................................................................................................... 2
  Aim and method ............................................................................................................... 2
  Rajapalot ......................................................................................................................... 2
  Regional geology ............................................................................................................ 3
  Local Geology ................................................................................................................ 4

**THEORY** ....................................................................................................................... 5
  Electromagnetism ........................................................................................................... 5
    Maxwell’s equations ....................................................................................................... 6
    Physical properties ....................................................................................................... 7
  Transient Electromagnetism .......................................................................................... 8
    Receiver sensors ......................................................................................................... 9
    Transmitter waveforms .............................................................................................. 10
    Diffusion depth .......................................................................................................... 10
    Smoke ring .................................................................................................................. 14
    Conductive overburden .............................................................................................. 15
    Current channelling ................................................................................................. 15
    IP effect ...................................................................................................................... 15
    Heterogeneity ............................................................................................................ 15
    System geometry ....................................................................................................... 17

**METHOD** ..................................................................................................................... 18
  Field measurements ..................................................................................................... 18
  Data processing and modelling .................................................................................... 19

**RESULT/ANALYSIS** .................................................................................................... 24

**REFERENCES** ............................................................................................................. 28

**Appendices** ................................................................................................................. 1
  Main model .................................................................................................................. 1
1-plate model ............................................................................................................. 4
2-plate model ............................................................................................................. 7
Matching decay-rate .................................................................................................. 10
Instruments .................................................................................................................. 11
INTRODUCTION

Aim and method

The aim of this master thesis is to produce a 3D model of the gold-cobalt mineralization known as Raja, at Rajapalot in northern Finland. This is achieved by collecting data with transient electromagnetic field-measurements. The data are analyzed, and a model is created with the software Maxwell (EMIT).

Rajapalot

In 2013 Mawson Resources Ltd had a helicopter based VTEMplus survey performed over the Rajapalot area. The survey produced several interesting electromagnetic anomalies, later named Palokas, South Palokas, The Hut, Terry’s Hammer, Rumajärvi, and Raja. Follow-up ground magnetic, and IP/Resistivity surveys were performed to further delineate the targets (Mawson Resources Ltd, 2019).

In this master thesis the focus will be on the Raja prospect, part of the Rajapalot Gold-Cobalt project.

Figure 1: Map of Norway, Sweden, and Finland with a red star showing the location of Rajapalot.
Regional geology

The Rajapalot Gold-Cobalt project is placed in Lapland, northern Finland, roughly on the municipality border between Ylitornio and Rovaniemi. The prospective area is located in the northern part of the Peräpohja Belt (PB), bordered by the Central Lapland Granitoid Belt to the north, the Pajala shear zone to the west, and the Archean Pudasjärvi gneiss complex to the south (Ranta, Molnár, Hanski, & Cook, May 2018).

Figure 2: Bedrock map (Geological survey of Finland) of the region, showing the location of Rajapalot and the closest major cities. The Peräpohja belt roughly outlined in red.

According to (Vanhanen, et al., 2015) the PB is a “Paleoproterozoic supracrustal sequence of quartzites, mafic volcanics and volcaniclastics, carbonate rocks, black shales, mica schists, and graywackes”.

The Peräpohja belt includes the older Kivalo group followed by the Paakkola group. The formation of the Kivalo group started by uplift and erosion of the 2.44 Ga layered mafic-ultramafic intrusions, creating a basal layer of sedimentary rocks interlaced with volcanic rocks, dikes and sills followed by evaporitic- and coarse glacimarine sedimentary rocks.

The Paakkola group is made up of four different formations. Pillow lava at the bottom, formed around 2.05 Ga ago, followed by felsic and mafic tuff, mica and black schist, and more mica and black schist together with greywackes. The youngest formation, dated to around 1.92 Ga, has undergone five deformation event and the metamorphic grade varies from greenschist facies in the south, to amphibolite facies in the north. (Ranta et al., May 2018).
The Peräpohja belt has three different Paleoproterozoic granitoid intrusions, the Kierovaara-type, the Haaparanta series, and a tourmaline-rich pegmatitic granitoid. Multiple hydrothermal events have been identified and dated to correspond with the “major tectonic, metamorphic, and magmatic events in the area” (Ranta, Molnár, Hanski, & Cook, May 2018).

Local Geology

The Raja prospect (Raja) is part of the 4 km long trend that makes up the Rajapalot Gold-Cobalt project (Rajapalot Gold-Cobalt Project, 2019). Due to a sparse number of outcrops, together with a thick glaciogenic till cover in the area, the local geological information is mostly from drill cores. A complete geological map has therefore yet to be produced (Ranta, Molnár, Hanski, & Cook, May 2018).

Cook and Hudson (2018) divides the local geology into two isoclinally folded sequences. Sequence one is a largely oxidized “siliciclastic, dolomitic carbonate and albite-altered metasedimentary sequence … interpreted as forming in a platformal to continental margin setting”.

Unconformably placed on top of sequence one is “a second metasedimentary sequence … of pelitic turbidites, arkosic sands, carbonates, impure and pure quartzitic sandstones and sulphidic bituminous rocks”. Up to 20 % of both sequences is made up of mafic rocks, such as lava flows, volcaniclastic sediments, dykes, and sills. Exposed tourmaline-bearing granitoids have been found three kilometers to the north, and nearby drilling has revealed albitized granitoids and diorites.

Raja is a “disseminated, sulphide-associated structurally-controlled gold-cobalt” mineralization (Cook & Hudson, 2018). It is of “potassic-iron type characterized by muscovite-biotite-chlorite quartz pyrrhotite-rich schist with subordinate albite, iron-magnesium amphiboles and tourmaline” (Rajapalot Gold-Cobalt Project, 2019).

The Raja mineralization is interpreted to be stratabound with linear and sub-vertical structural control (Mawson Resources Ltd, 2019).
THEORY

In this chapter the basic theory for electromagnetism along with the theory for transient electromagnetism together with some common field measurement-methods is presented.

Electromagnetism

Whenever an electric current is flowing, a magnetic field is formed around it. For a current running through a wire, the magnetic field is formed as concentric circles around the wire and the intensity of the magnetic field is proportional to the level of the current. If a right hand closes around said conductor with the thumb in the direction of the electric current (conventional), the magnetic field will flow in the direction of the fingers wrapped around the conductor. This is called the right-hand rule and can be seen in the figure below (Dentith & Mudge, 2015).

Figure 3: Illustration of the right-hand rule. The magnetic field as green concentric circles around a grey conductor. The blue arrow shows electric-current direction and the red arrow shows the direction of magnetic field.
Maxwell’s equations
Maxwell’s equations describe all electromagnetic phenomena on a larger than subatomic scale. In time domain their differential form are:

**Gauss’s law for electric field:**

\[ \nabla \cdot \mathbf{D} = \rho, \]  
\[ (1) \]

**Gauss’s law for magnetic field:**

\[ \nabla \cdot \mathbf{B} = 0, \]  
\[ (2) \]

**Faraday’s law:**

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \]  
\[ (3) \]

**Ampere-Maxwell:**

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \]  
\[ (4) \]

where
- \( \mathbf{D} \) is the electric displacement \([\text{C/m}^2]\).
- \( \rho \) is the electric charge density in \([\text{C/m}^3]\).
- \( \mathbf{B} \) is the magnetic flux density in \([\text{Wb/m}^2]\) or \([\text{T}]\).
- \( \mathbf{E} \) is electric field intensity in \([\text{V/m}]\).
- \( \mathbf{H} \) is the magnetic field intensity \([\text{A/m}]\).
- \( \mathbf{J} \) is electric current density \([\text{A/m}^2]\).

Eq. (1) states that the total electric flux out of a closed surface is equal to the total charge inside that surface. Eq. (2) states that the sum of magnetic flux passing through a closed surface is always equal to zero, and therefore prohibits the existence of magnetic monopoles. Eq. (3) states that a time varying magnetic field induces an electric field. Vice versa eq. (4) states that a time varying electric field induces a magnetic field (Ward & Hohmann, 1988).
Physical properties

The physical properties relevant to electromagnetism are (EM GeoSci, 2019):

**Electrical conductivity** $\sigma$

is measured in siemens per meter [$\text{S/m}$] and quantifies how easily electrical charges moves through a material when subjected to an electric field. The electrical conductivity defines the ratio between an electric field $E$ and the resulting current density $J$ within a material as

$$ J = \sigma E. $$

Eq. (5) is commonly known as Ohm’s law. The reciprocal of conductivity is resistivity

$$ \rho = \frac{1}{\sigma}. $$

Resistivity is measured in ohm per meter [$\Omega\text{m}$] not to be confused with the electric charge density in eq (1).

**Magnetic permeability** $\mu$

is measured in henry per meter [$\text{H/m}$] quantifies the amount of induced magnetic flux in a material when subject to an external magnetic field. It defines the ratio between a magnetic field $H$ and the resulting magnetic flux $B$ in a material as

$$ B = \mu H. $$

**Dielectric permittivity** $\varepsilon$

is measured in farad per meter [$\text{F/m}$] quantifies the level of electric polarization, i.e. the induced polarization (IP), in a material when subject to an external electric field. It defines the relation between an electric field $E$ and the resulting electric displacement $D$ in a material as

$$ D = \varepsilon E. $$

Maxwell’s equations are true for all homogenous, isotropic and non-dispersive materials and eq. (5)-(7) makes up the constitutive relationships of their vector functions $\textbf{D}, \textbf{B}, \textbf{E}, \textbf{H}, \textbf{J}$ (Ward & Hohmann, 1988).

For further reading on electromagnetism see (Ward & Hohmann, 1988).
Transient Electromagnetism

When an electric current is transmitted through a loop or a coil, a primary magnetic field is created with the direction governed by the right-hand rule. The intensity of the magnetic field is directly proportional to the magnitude of the electric current and quantified by the magnetic dipole moment as

\[ m = nIA, \]

where \( m \) is the magnetic dipole moment in ampere per square meter \([A/m^2]\), \( n \) is the number of turns in the loop/coil, \( I \) the electric current in ampere, and \( A \) the area of the loop in square meters.

By Faraday’s law (eq. (5)), a conductive medium will be induced by an electromotive force (emf) causing electric currents called, eddy currents (EC) to circulate. The EC will, upon turning on the transmitter (Tx), try to preserve the previously static state, by going in the opposite direction of the current in the loop, thus creating a secondary magnetic field, opposing the primary field. The EC will dissipate over time, and the secondary magnetic field will decay.

By turning off Tx, the sequence of events will be reversed, and the induced EC will now flow in the same direction as the transmitted current in the loop, thus creating a secondary magnetic field in the same direction as the primary field. Initially, the magnitude of the secondary field will be equal to that of the primary field. As the EC dissipates, the secondary magnetic field will decay, or attenuate.

A larger area, a stronger current, and more turns in the loop/coil all increases the dipole moment, and thus increasing the strength of the primary field and the induced EC. For coils and small loops, the intensity of the primary field decreases by \( 1/\text{distance}^3 \), but for large loops the intensity decreases by \( 1/\text{distance}^2 \) allowing response from deeper targets. However, a larger loop (or number of turns) increases the inductance in the loop. Turning on or off the transmitter, the inductance delay changes to the electric current. The effect is known as back emf and prevents instantaneous turn-on/off, forcing a slower rate of turn-on/off known as ramp time. If a longer ramp time is used, response from the fastest diffusing eddy currents will be missed.
In a layered earth a separate EC system is created for each layer. In the case of a confined conductor, one EC system is induced in the conductor and a separate EC system is induced in the surrounding medium. In the confined conductor, the induced currents will initially flow in the outermost part of the body. If the conductor is very large in comparison to the transmitter loop, the currents will at first be induced in the part closest to the transmitter. The EC will then spread out, enclosing the conductor before they diffuse inwards, towards the centre, until the currents are evenly distributed throughout the body. The secondary magnetic field, induced by the currents in the confined conductor, will then have reached a steady state (Dentith & Mudge, 2015). See illustration below.

![Diagram showing primary and secondary magnetic fields](image)

*Figure 4: Showing the primary magnetic field in red and the eddy currents induced at turn-off in green. Top: The eddy current systems for a confined conductor with contrasting conductivity to its surrounding homogenous half-space. Bottom: A two-layer model with separate eddy current systems.*

**Receiver sensors**

In transient (or time domain) electromagnetic measurements the decay of secondary field is measured by abruptly changing the primary field, i.e. by turning on/off the transmitter. There are two types of EM receiver (Rx) sensors, called **B-field sensor** and **dB/dt sensor**. The B-field sensor measures the intensity of the secondary magnetic field (commonly known as the **B-field**) directly with a magnetometer.
The dB/dt sensor is a coil or loop that measures the voltage induced by the decaying secondary magnetic field, i.e. the time derivative of the B-field (Dentith & Mudge, 2015). Both types of sensors measure the direction of the secondary field in three components. One vertical component and two horizontal components. Most receivers measure after turn-off to avoid interference from the primary magnetic field.

Transmitter waveforms
There are several different transmitter waveforms, where the triangle, the impulse, and especially the step waveform are most common. The step waveform transmits a rectangular signal, varying the polarity, with off-time in between. Measurements are most commonly done during off-time. The triangular waveform transmits a triangular wave, continuously varying the primary field. The impulse waveform transmits short pulses.

In the absence of ground response, the B-field sensor approximately reproduces the transmitted waveform. The dB/dt sensor instead gives an impulse response to a transmitted step wave and a step response to a transmitted triangular wave. See illustration below.

![Illustration of different transmitter waveforms](image)

Figure 5: Illustration of different transmitter waveforms. The step wave (A) and its impulse response from a dB/dt-sensor, triangular wave (B) with its step response from a dB/dt-sensor, and the impulse wave (C).

Diffusion depth
In a confined conductor EC dissipate inwards, towards the center. The dissipation is controlled by the physical properties of the medium and moves slower in good conductors. The B-field’s coupled attenuation is called the skin effect. When the effect of the electrical conductivity is very large compared to the dielectric permittivity, the skin effect is quantified by the skin depth, in metres, as
\[ \delta = \frac{1}{\sqrt{\pi \sigma f}} \]  

(9)

where \( f \) represents the frequency of the primary magnetic field in hertz. The skin depth is a measure of distance to where the amplitude of the electromagnetic field has attenuated to \( 1/e \approx 36.8\% \) of its initial value. The magnetic permeability of most rocks is almost identical to that of vacuum \( (\mu \approx \mu_0 = 4\pi \times 10^{-7} \text{ henry/m}) \) giving

\[ \delta = \frac{503.8}{\sqrt{\sigma f}}. \]  

(10)

In the time domain, the corresponding equation is

\[ d = \frac{\sqrt{2t}}{\mu \sigma}. \]  

(11)

where \( d \) is the depth in meters to the maximum current density at a particular delay time \( t \), i.e. how far, or deep, the eddy currents have diffused. When \( \mu \approx \mu_0 \) eq. (11) can be rewritten as

\[ d = 1261.6 \frac{\sqrt{t}}{\sigma}. \]  

(12)

The measurements are made in time-windows (or channels). The response from poor conductors are registered in early channels and the response from good conductors are registered in late channels. (Dentith & Mudge, 2015).
The amplitude $A$ of the decaying (or transient) secondary magnetic field is given by

$$A(t) = A_0 e^{-t/\tau},$$

(13)

where $A_0$ is the apparent initial amplitude of the exponential decay, depending on the conductor’s depth, size and shape. $t$ is the time, usually in milliseconds (ms) and $\tau$ is the time constant, the time taken for the signal to decay to $1/e$ of its initial value. The time constant has the same units as $t$ and is characteristic for the specific conductivity and effective cross-section of the conductor. $\tau$ is given by

$$\tau = \frac{\mu \sigma S}{\pi^2},$$

(14)

where $S$ is the shape-dependant size of the conductor in square meter. The time constant for typical mineralizations ranges from around 200 microseconds ($\mu$s) up to several seconds for very good conductors (Dentith & Mudge, 2015).

For the step response of confined conductors, large time constant gives large amplitude, continuously decreasing with smaller $\tau$ for all delay times. The amplitude is predominantly controlled by the size and shape of the conductor, where a large body gives a large response and vice versa, and less controlled by the conductance. The amplitude of the impulse response is larger for bodies with low $\tau$ at early-stage and reversely the amplitude is larger for bodies with higher $\tau$ at late-stage response. The impulse response is complexly controlled by both the size and shape, and the conductance of the conductor making it harder to interpret than the step response data (Dentith & Mudge, 2015).

For a homogenous half-space, the secondary field decays as a power-law where the signal varies with delay time as $t^k$ where $k$ is the power-law constant. On a logarithmic scale the decay plots as a straight line where the slope is equal to the negative of the decay constant. For a conductive overburden, the secondary field decays similarly as for a homogenous half-space, but with a larger decay constant, and therefore a faster decay. See illustration below.
Both the homogenous half-space and the conductive overburden are also known as unconfined conductors. In the case of a confined conductor in a more resistive medium, the secondary field decays exponentially, as per eq. (13), during the late stage. The illustration below shows the decay for different quality conductors in a perfect scenario.

\[ T = \frac{t_2 - t_1}{2.3 (\log A_2 - \log A_1)} \]
For the previous example where a confined conductor sits in a less conductive bedrock, the initial response of the host rock will dominate the early channels. However, due to the faster decay of poorer conductors, the later channels will be dominated by the confined conductor. Plotted in a semi-log diagram the late-stage exponential response of the confined conductor will plot as a straight line with the slope equal to $-\frac{1}{2.3\tau}$, as seen in the illustration above.

Smoke ring

If the transmitter loop is placed upon a homogenous conductive medium, known as a *half-space*, the eddy currents will dissipate downwards and outwards, continuously creating a new replica of the transmitter loop, growing larger and weaker as it propagates downwards, all the while slowing down. This phenomenon is known as a *smoke ring*. In a more resistive medium the movement is more vertical and in a more conductive medium the movement is more lateral. See illustration below.

*Figure 8: Illustration of the propagation of smoke rings.*
Conductive overburden
In the case of a conductive overburden, the primary field strongly couples and the response from its EC system initially takes over and obscure the response from potential deeper targets. The decay is faster than that of a half-space or a confined conductor resulting in their response taking over in later channels, as seen in figure 6 above.

Current channelling
When trying to locate conductors in a conductive host rock the targets are often electrically connected to the surroundings. This allows electrical currents to flow between target and host rock causing their individual EC systems to interact, creating a phenomenon called current channelling. Current channelling amplifies and broadens the anomalous response from a confined conductor (Dentith & Mudge, 2015).

IP effect
When a confined conductor is electrically polarizable, as is the case for a disseminated sulphide, the induced current system generates a polarization. The polarization results in a second current system flowing in the opposite direction. This creates a separate secondary magnetic field opposing that of the normal eddy currents, effectively dampening the surface response from the confined conductor. The effect is usually of negligible amplitude, but in some cases, it must be taken into consideration (Macnae & Nabighian, 1991).

Heterogeneity
According to (Thunehed, 1997) a cluster of conductors, a conductor fractured by faults or dikes, or an inhomogeneous conductor with varying conductance, can all give the same EM response as a larger homogeneous body with the same time constant, but for a smaller amplitude. This makes the interpretation of EM data harder.

If a confined conductor has local areas of different conductivity, i.e. a heterogenous conductor, separate eddy current systems will be induced in the larger body, and each of the local areas of different conductivity. All decaying with separate time-constants. If the different parts are seen as different conductors, the magnetic flux created from the EC system of each conductor will affect the others by mutual inductance. If one of those conductors has a much greater conductivity then the rest, there would be slowly decaying currents in the other conductors as well, even if their original EC has decayed completely. The magnitude of the secondary currents would depend on the mutual inductance between the conductors.
Imagine measurements are performed above two identically shaped conductors, one heterogeneous, with areas of higher conductivity, and one homogeneous, with lower conductivity. The shape of an anomaly curve along a profile would then be almost identical for the two conductors, unless the measurements are made very close to the conductor or the transmitter loop is small in comparison to the conductors. However, the decay curve of the model response for a heterogeneous conductor would not match the decay curve of the field data. If one were to match the amplitude for a given channel, the model response would decay too fast. Consequently, if one instead were to match the decay rate, the amplitude would not match. The difference in amplitude is a qualitative measure of the degree of heterogeneity (Thunehed, Seminarium tolkning av TEM-data, 2019). Example given in the figure below.

![Diagram](image.png)

*Figure 9: Decay curves of field data in black and model response in red. The lower diagram shows the decay from station 200 of line 23 from the main model. The upper diagram shows the same station with the conductance raised to match the time-rate of decay of the field data.*
System geometry

There are numerous methods of arranging the transmitter and receiver when measuring TEM, but they can be divided into fixed loop and moving loop. Their names are quite self-explanatory. Moving loop measurements can be performed both on the ground and in the air and the receiver location is fixed in relation to the transmitter loop, normally in the centre of the loop. In early stage exploration, when the location, size and attitude of a target conductor is unknown, a moving loop configuration is preferable, since the transmitter location changes between each measurement. This means the coupling to a potential target conductor varies between measurements, allowing the transmitted magnetic field to hit a target conductor from different angles, thus increasing the chance for a strong response. When measuring over a known target a fixed loop could be preferable, since the transmitter loop can be placed so optimal coupling to the target conductor is achieved. The measurements are then carried out by moving the receiver along profiles over the target. The illustration below shows a transmitter loop centred over a horizontal conductor (a) and displaced to the side of a vertical conductor (b), allowing for optimal coupling where the primary field intersects the conductors at an almost perpendicular angle.

![Diagram of transmitted primary field and conductors](image)

*Figure 10: The transmitted primary field and a horizontal (a) and vertical (b) conductor.*
METHOD

Field measurements

The field survey was carried out during late August to early September 2018. A fixed-loop setup was used where a total of eight profiles were measured across two separate transmitter-loops, 500x375 and 550x375 meters respectively. The target area was located roughly 700 meters into a Natura 2000 zone where no vehicles were allowed that time of the season. The transmitter was powered by eight large batteries, making the system large and heavy to carry in and out of the area each day. The solution was to place the transmitter outside the protected area, connected to the loop via extended loop-cables. The receiver was attached to a carrying frame together with an external battery-pack. A large external, three coil dB/dt sensor was used, one coil for each component of the secondary magnetic field. Data collecting was made by two people, one handling the receiver and navigation, and the other handling the antenna. Pictures of the instruments can be found in the appendix. Previous geophysical surveys have shown a shallow, elongated conductor dipping towards NNW. The survey layout can be seen in the figure below, where the profiles are 650 meters long. The lines were named 11-14 for loop 1 and 21-24 for loop 2. Line 22 and 23 were extended by 150 m during the survey.

Figure 11: Map showing transmitter loops (black) and measurement profiles with receiver locations marked as dots. Red dots for Rx locations for loop 1 (right) and green dots for Rx locations of loop 2 (left). The transmitter is marked with a red star, placed outside the Natura 2000 border (dashed purple line).
To avoid extensive coupling to the shallow tip of the conductor, the transmitter loops were placed more towards the deeper parts so that the primary magnetic-field flux would intersect the deeper parts almost perpendicular while running more parallel to the tip. As illustrated below.

![Illustration of the transmitter loop dislocation from the tip of the Raja conductor.](image)

Measurements were made every 25 meters, where the antenna was placed, in level, along the profiles, attenuated so that the coils were directed along, across, and vertically perpendicular to the profile.

The loops were laid out from cable drums, attached to carrying-frames carried on the back. Once measurements over the first loop were finished, the loop was cut in segments and wound up on the drums using a modified ice-drill engine, before laying it out in the second loop position.

**Data processing and modelling**

All data processing and modelling were performed in Maxwell (EMIT). During the field survey the data were stored as lines, one file per line. However, since some days were ended in the middle of a line, and two of the lines were extended afterwards, some lines were divided into separate files. The data was stored as TEM-files (.tem), a text file with a header describing the instrument parameters. The first step was to merge data so as each line had a separate file. This was done in MS Excel. The receiver and Maxwell have different defined directions for the components. To get a correct model, the Y-component was renamed to X-component and the X-component became the new Y-component with reversed sign, as seen in the figure below. During the survey, some stations had to be moved due to bogs and boulders etc. affected coordinates were corrected. All data were loaded into Maxwell.
Decay curves and amplitude from each station was evaluated and obviously erroneous datapoints were removed. Once satisfied with the remaining data, a 3-point averaging filter was applied to both profiles and decays to reduce noise. The profile for Z-component and the decay curves for station 200m of line 23, before and after filtering, can be seen in the figure below.

A 3-point averaging filter takes the mean average of three consecutive points. For any given point along the profile, the previous and following values are used to calculate a mean. The process is called smoothing and is used to remove spikes in the data (Dentith & Mudge, 2015). Since the anomalous response has a large, wider shape, a 3-point averaging filter is safe to use without risk losing small anomalies. In this case, filtering has the same effect as using longer time windows (i.e. wider channels).
The receiver records the response between 8 µs up to 8.333 ms divided into 36 channels with channel one representing the shortest delay-time. The anomaly-curve shape does not change with time after channel 19, indicating that the secondary field has reached a steady state. The model was produced from the response of channel 22 to 30.

A multiple plates model project was created, and a plate was added to the model. Location for the plate was concluded by studying the EM-response sign for each component along every profile. In the figure below the EM response for channel 22-26 from line 24 can be seen together with an illustration of a conductor and axes showing the component direction. By studying the negative Y-component response, together with the sign-change of the X-component and the peak of the Z-component at around 250 meters one can deduce that the center of conductor should be to the left of the line at around the 250-meter mark.

Maxwell model thin plates in free space by simulating eddy currents with so called ribbons. Each ribbon represents a closed circuit with no interchange occurring between them. The idea of modelling thin plates is that there is no variation in current flow across the thickness of the sheet. An assumption is made that the conductivity is high enough that the conductivity-thickness product (i.e. conductance) \( \sigma d \), where \( d \) is the thickness, remain unchanged as \( d \) approaches zero (Macnae & Nabighian, 1991).
The size and shape, attenuation and location, and conductivity-thickness (C-T) product were altered to better match the model response to the field data. Another, and later a third, plate was added to better match the data. However, the vertical component of the model response for the peripheral profiles remained too weak compared to the field data. To overcome this, the CSIRO (AMIRA) Leroi algorithm was used. Leroi allows for modelling thin plates in a layered earth model. A half-space with 2.4 kohm-meter (kΩm) resistivity was introduced around the model-plates, increasing the amplitude of the vertical component all over. The resistivity of the area varies extensively, but due to limitations of Leroi, one common resistivity was set for the surrounding half-space. By further tweaking the plate-parameters, a decent match to the field data was reached. No inversion was used, only forward modelling. The model response and field data from line 23 can be seen below. All other profiles can be seen in the appendix.

Figure 16: Field data (black, blue, green) and the model response (red) for channels 22-26 from line 23.
The modelling was performed so as to match the amplitude of channel 22, resulting in the decay curve of the model response not matching the decay rate of the field data. The decay rates of the model response were later matched by raising the C-T of the modeled-plates. This resulted in the model-response amplitude, greatly surpassing that of the field data, as discussed in the Heterogeneity section above. The decay curves can be seen in figure 9 above. A profile showing the model response of the raise C-T, of line 23, can be seen in the appendix.

Separate models with one, and two plates were also made to show that a decent match to the field lines can be made with an even simpler model. Both models can be seen, together with their profiles, in the appendix.

No published information on the forward modelling algorithm was found for either Maxwell thin plates or Leroi.
RESULT/ANALYSIS

The main 3-plate model can be seen in the first two figures below. For comparison, a VTEM-model and a resistivity model is presented.

Figure 17: Birds-eye view of the main 3-plate model showing the plates horizontal location in relation to the loops.

Figure 18: TEM model showing the three modeled plates together with the transmitter loops, measuring-profiles of loop two and drill holes.
Figure 19: Resistivity model

The resistivity model is produced by Dr Hans Thunehed at GeoVista AB and is based on data from IP/Resistivity, Mise a la masse (Applied potential), and 3D Resistivity surveys performed during 2018.
The VTEM model is produced by Dr Hans Thunehed at GeoVista AB and is based on data from a helicopter based VTEM-survey performed during 2013.
All plates in the TEM model dip 25 degrees with a 330 degrees strike. The two shallower plates have a conductivity-thickness product of 30 siemens and the deeper plate has a C-T of 20 siemens. All plates are 80 meters wide with a depth extent of 200, 400, and 600 meters respectively, with a total strike length of roughly a kilometre.

Generally, the TEM model correlates well to the other models, where the location, dip and dip-direction follows the other models well. However, upon closer inspection, the resistivity model and the VTEM model, both have a steeper dip than the TEM model, resulting in a lateral mismatch in the deeper parts. This is likely due to the small, shallower, conducting bodies, seen in the shallow part of the resistivity model. They increase the gradient of the anomalous response, making the larger body appear more shallow.

After recent drilling the gold-bearing body appears to continue straight down, in continuation of the central body (Mawson Resources Ltd, 2019). However, to fit the TEM model to the data, the downwards continuation needs to be horizontally displaced from the central body. This indicates a non-gold-bearing conductive volume present to the west of the mineralization. Further TEM-surveys have been performed over the deeper parts, during the winter 2018/2019. Data from these more recent surveys are not handled in this thesis.

Results found in the appendix are:

- Selected profiles and decay curves demonstrating the amplitude difference before and after raising the conductivity-thickness product of the main model.
- Results from the alternate 1-plate and 2-plate models, that show a similar, but slightly impaired match to the data.
REFERENCES


Appendix

Main model

All profiles for the main 3-plates model. To reduce clutter, only channel 22-26 are displayed. Model response in red.
A surface grid of EM-response for channel 22 (upper left) to channel 30 (lower right). The crosses mark the receiver locations. The EM response ranges varies from 0.4-2.2 µV/A for channel 22 to 0.03-0.04 for channel 30. Red is high, and blue is low.
1-plate model

The alternative 1-plate model.
All profiles for the alternative 1-plate model. To reduce clutter, only channel 22-26 are displayed. Model response in red.
2-plate model

The alternate 2-plate model.
All profiles for the alternative 2-plate model. To reduce clutter, only channel 22-26 are displayed. Model response in red.
Matching decay-rate

The profiles for line 23 over the anomaly are presented to the left, and shows the amplitude difference, when matching the model-response decay-rate to the data of a heterogeneous conductor. The decay-curves for station 200m of the same line is presented to the right, before and after the C-T has been raised. The C-T was raised to 115 S for the two shallower plates and to 95 S for the deeper plate. Model response in red.
Instruments

Pictures of the instruments from Monex GeoScope. To the left: The terraTEM receiver mounted on a carrying-frame together with its battery-pack (yellow). Upper right: The terraTX-50-transmitter with one of the batteries. Lower right: The receiver antenna. Fold ruler for scale.