Investigation of gold-bearing veins in Charters Towers, Australia using magnetics and TEM

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Summary

Gold-bearing fractures have been mined near Charters Towers, Queensland, Australia (CT) for over a century. Sulfides and high concentrations of gold are precipitated from fluids in very small lenses that are difficult to find by drilling and standard geophysical techniques. While ground time-domain electromagnetic (TEM) is normally used in mining for exploring for strong conductors, this paper demonstrates that precise knowledge of the equipment characteristics and accurate 3D modeling can allow accurate exploration for weak conductors.

Ground TEM data were collected at a site at which there are two known gold-bearing structures. Airborne magnetic data at the site are also available. The purpose our studies was to determine if these geophysical methods could locate the known structures and to better understand their geometry. Such knowledge would assist in detecting the small lode structures.

Modeling of the TEM data indicates that the structures which include the mineralized veins are weakly conductive and are actually composed of multiple structures in close proximity. The TEM structural interpretation has a close correlation to linear anomalies in the magnetic data caused by low-susceptibility material. These anomaly types correlate not only at the known gold-bearing structures, but also at new structures. These new structures are to be studied in future exploration plans.

Introduction

The CT goldfield is located in northwest Queensland, Australia. It has a long history of gold mining, dating back to the late nineteenth century. The gold ore occurs in quartz-sulfide veins, which are hosted in granitoids of the Ravenswood batholith. The veins formed in the late Silurian to early Devonian along faults and fractures (Kreuzer, 2007).

The gold-bearing veins are 70-90% quartz and 10-20% sulfides which are mainly pyrite, galena, and sphaelerite (Kreuzer, 2007). The gold is predominantly found in micro-fractures in the pyrite. The veins are surrounded by an inner sericite-ankerite alteration zone and an outer epidote-hematite-chlorite alteration zone. The fractures also contain highly-weathered materials which are often wet to several hundred meters.

Within the veins, the distribution of gold is sparse. This is the challenge of exploration. Here we focus on the detection and resolution of the faults/fractures in which the veins are hosted with the intent to reduce drilling costs, as well as to assist in other geophysical techniques to specifically isolate the lenses.

This study concerns the area around the Warrior Mine immediately south of Charters Towers, operated by Citigold Corporation. Two structures are being mined at 100-300 m depth: Warrior and Sons of Freedom. The tops of these structures are within several meters of the surface, and both structures generally dip to the north. The Warrior structure is associated with a pre-mineralization basalt dyke whereas the association with a dyke is not clear at Sons of Freedom.

The initial purpose of this project was to determine if geophysical methods could be used to identify these structures and more clearly delineate them, as well as to find other targets of interest. Induced polarization (IP) is commonly used to locate disseminated sulfides associated with gold ore in such fracture zones. A different approach was used here due to the small size of the lode lenses and their depth. We integrated aeromagnetic data with new ground TEM.

With TEM, we aimed to identify the fracture/fault structures in which the ore is found, rather than attempting to specifically locate sulfides. TEM is advantageous because it does not involve injection of current into the ground with the uncertainty of where it will flow in such resistive, fractured rocks. Fixed loop TEM surveying was utilized as this approach is also much faster to perform than IP arrays.

Methods

Magnetics

There has been some qualitative study of the aeromagnetic data in the Charter Towers goldfield in (Kreuzer, 2007), including mapping of linear structures with the RTP vertical derivative. Kreuzer examined the data on a regional scale, whereas we present a more in-depth study of the magnetic response near the mine. This includes modeling work, a new RTP algorithm, as well as discussions on the relationship between the magnetic and EM responses and the known structures.

1) Datasets

Airborne data were collected in 1999 by UTS Geophysics (Perth) over a large area along north-south lines with a 50 m line spacing and 5 m station spacing. The elevation of the sensor was roughly 50 m.

A high-resolution ground magnetic survey was completed in 2008 and 2010 in the Warrior area. The ground data were upward continued to a height of 50 m and compared with the airborne data. Following this adjustment, it was found that the airborne data and upward continued ground data agreed quite closely, giving us confidence in using the airborne data for detailed imaging and modeling. The 2008 data did not have sufficiently low noise levels to augment the airborne data.

2) Processing

Our interpretation focuses on the vertical derivative following reduction to pole (RTP) using specialized low latitude procedures. The purpose is to:

1. Better determine the position of magnetic structures
2. Improve discrimination

a) Reduction to pole

The site is at a latitude of 20^0 S, and the inclination is -50^0. As a result of the direction of the background field, the structures are south of the peaks of the anomalies. We used reduction to the pole so that the anomalies were coincident with the structures causing them. The reduction to pole was performed in using an enhanced FFT (Fast Fourier Transform) technique for low latitudes (Keating and Zerbo, 1996).

b) Vertical Derivative

The vertical derivative enhances boundaries between structures with different susceptibilities, thus providing better discrimination for the relatively thin linear features.

The basic geometry of the structures is a thin dipping sheet. This is confirmed with forward modelling. The sign of the vertical derivative determines either a negative susceptibility or a reduced susceptibility from the background granites.

TEM

1) Surveying

TEM surveying at the Warrior site presents challenges as there is an operating mine and other man-made features. The TEM surveys were carefully planned to minimize the impact of such features on the response. In the initial surveys, detailed data sampling was made near the man-made structures to determine the nature, wavelength and strength of their signals in order to design our surveys.

Several surveys were performed in 2010 and 2011. Early surveys were performed with the following loops:

1. Loop I: This loop was about 700 m x 600 m and was south of Warrior. Several lines were surveyed from the centre of the loop north to cross over Warrior.
2. Loop II: This loop was 200 m x 530 m and located over the southern portion of Sons of Freedom. Data were collected over ten lines.
3. Loop III: This loop was 350 m x 500 m and was located just north of the western extension of Warrior.

In a later 2011 survey, eight 100 m x 100 m loops were utilized to examine the details of the structures, particularly the central section of the Warrior structure. These loops were located close to or over the structure.

In all cases, both vertical (Hz) and in-line (Hx) components were collected using Crone Pulse equipment at a base frequency of 25 Hz. Station spacing was 10-25 m.

Although some borehole data was collected, it is of questionable value and not discussed here.

2) Modeling

Forward modeling was performed in EMIGMA, using an inductive plate algorithm based on the formulation of Annan (1974). Unlike some other plate algorithms, the induced current distribution is not restricted to a single ring current. While a single ring current may be appropriate when there is a uniform source over a structure, our targets are close to the surface and are quite large. Thus, the current distribution is more complex.

An inductive algorithm is appropriate in this environment as the host granitoids have a very high resistivity. The data show a resistive background with a very thin conductive overburden. Our adaption of the original algorithm by Annan allows for an inductive response in an arbitrary background, allowing us to model both the inductive effect of the targets and the effect of the relatively conductive overburden caused by weathering of the granitoids.

We consider the response at the receiver to be a convolution of the response of the ground with the current input function, and the system response of both the transmitter and the receiver. Simulations are performed in the frequency domain, and time-domain convolution is frequency-domain multiplication. Careful use of high-resolution waveform sampling allows for accurate simulation of early time responses, which is extremely important for our application.

Results

Magnetics

Upon mapping the vertical derivative of the RTP data, many linear anomalies were noted (Figure 1). These anomalies all indicate negative susceptibility with respect to the background. RTP anomalies are observed over both the mined structures. Modeling of both the RTP total field and derivatives confirms a negative susceptibility.

TEM

a) Initial data for Warrior

An EM response over Warrior was clearly observed in Hz and Hx using Loop I (Oct. 2010).

A 3D model of Warrior based on drill log intersections was constructed, and then used to design a starting point for plate modeling of the EM data. The simulated data were iteratively compared with the measured data. Adjustments were made to the depth extent, depth to top, conductance, and position of the plate until the synthetic data fit the measured data sufficiently with respect to the both the profile and the decay responses. Hx was particularly useful for finding the strike and position of the structure, and Hz was useful for study of the decays.

Charters Towers case study

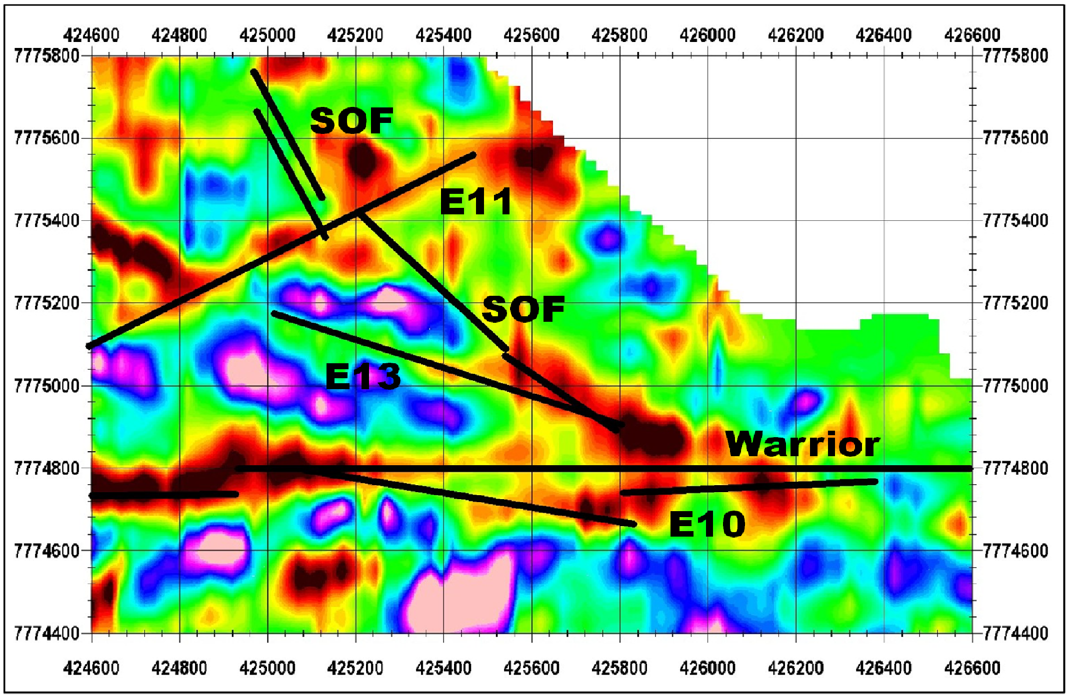

Figure 1: Map of the contoured RTP vertical derivative, with interpreted structures from the TEM shown in black. Warrior and Sons of Freedom (SOF) are the known gold-bearing structures; E10, E11, and E13 are interpreted from the data.

The fracture model we produced has a conductance of only 4.5S. As the structure is weakly conductive, good data quality is particularly important and as such the survey specifications required long stacking, duplicate measurements and numerous repeats between survey days.

Based on drilling results, the dip of Warrior is approximately 50^0 north, and a plate with this approximate dip is required to fit the EM data. However, the design of this initial survey could not resolve the dip of the target with high accuracy.

The dip extent of our model is 400 m, but the geologists' understanding is that the structure continues to much greater depths. If the dip extent is increased significantly beyond 400m then the synthetic response at late time is too large, and the shape of the response along the profile is not consistent with the data. This would therefore imply that although the structure might continue deeper, the electrical connectivity of the structure does not.

We identified another structure about 75 m south of Warrior (E10), roughly parallel to Warrior (Figure 1). Due to the proximity of these structures and the survey design, we were unable to resolve the details of this structure.

b*) Further data*

Data were collected using Loops I, II, and III later in 2010, and our models of Warrior and E10 were adjusted based on these data. As one example, see Figure 2.

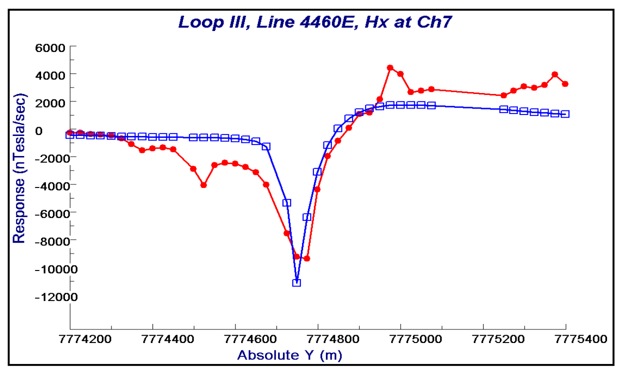

Figure 2: Measured data (red) vs. Model of Warrior West (blue) on Line 4460E for Loop III. Channel 7 (0.088 ms after end of pulse), in-line component.

Using the new Loop I data, E10 was split into three structures (east, central, and west) with slightly different strikes and conductances. Earlier data did not enable us to determine its strike and extent. But with the addition of seven lines from of Loop I, we could track the changes in strike direction across its length.

Modeling of Sons of Freedom was also performed, primarily using the data collected from Loop II, but a few lines from the other two loops were utilized.

In addition to E10, two other anomalies were identified in this data (E11 and E13). These anomalies do not correspond with known structures but are consistent with magnetic anomalies. Modeling indicates the structures causing these anomalies have similar properties to Warrior and Sons of Freedom.

c) Small-loop data
From the small-loop surveys performed in 2011, we were able to refine our models of Warrior and E10. These data also assisted us in understanding the response in previous surveys.

The small loops were more sensitive to the dip, and the greater station density allowed us to more precisely locate the structures. We also found that Warrior is more complex than initially thought: the data indicate that it is comprised of several structures. However, it is not possible from the data to determine if the structures converge at depth.

d) Decay comparison for different coils
From the magnetic and ground TEM results, the obvious next step is borehole TEM surveying. More than ten holes were read with TEM; however, the data were inconclusive. As a result, some tests were performed near Warrior at surface utilizing both surface and borehole coils. It was found that there were significant discrepancies in the nature of the decay (Figure 3). The borehole sensors show a much slower late-time decay, which is inconsistent with surface probe, drilling and mining results. Our conclusions were that the borehole data could not be used, but we intend to utilize other borehole TEM equipment in the future to explain this issue.

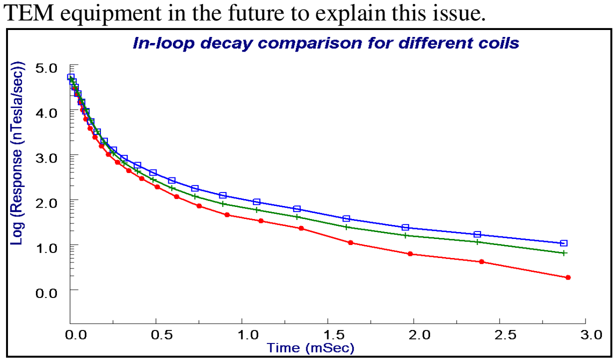

Figure 3: The decays at an in-loop station for three different coils, up to 3 ms after the end of the pulse. Hz.

<u>Integration of TEM and Magnetics</u>
The tops of the structures interpreted from the TEM are mapped in Figure 1 with the magnetic data. The RTP data indicate the approximate dip but provide limited depth interpretation. There is a strong correlation between the TEM structures and the magnetic highs, not only at the mined structures, but also over the three new structures.

The EM models were converted to magnetic models with thicknesses of 5 m and susceptibilities between -0.1 and -0.05 (SI). The simulated magnetic response was found to be in good agreement with the measured data. The rather large negative susceptibilities indicate a larger volume than can be explained by the veins alone. However, we can conclude that the weak conductors causing the EM anomalies are associated with low magnetic susceptibility. Note that in the Warrior area, we do not observe any magnetic anomalies that are not associated with an EM anomaly.

Discussion

We believe that the source of the weak conductivity is the clays in the alteration zone around the veins, and the sulfides.

Kreuzer (2007) suggests that the negative susceptibility is due to pyrite and other secondary minerals replacing the magnetite in the granitoids. While this may be a partial explanation, we believe it is insufficient to explain the strong anomalies observed. We would expect an upper limit on the susceptibility of the granitoids to be 0.003 (SI). Using this as an upper limit for the susceptibility of the structures requires a much larger volume than can be explained by the veins.

One possibility is that, if the altered and weathered granite is included, the thickness of the structure could be of sufficient volume to provide a more reasonable susceptibility contrast. We would expect the alteration and weathering processes to remove the susceptibility from the granite. Another possibility is that there are multiple non-magnetic structures. In the modeling of the small-loop TEM data, we found that Warrior was composed of several proximate structures. Perhaps the combined volume of the multiple structures would add sufficient volume, but still be observed as a single anomaly in the airborne data. Further, more accurate ground data would be required to answer this question.

Conclusions

Two known lode structures at Charters Towers are associated with both magnetic and EM anomalies. These structures were found to be weakly conductive, and the magnetic response over these structures indicates a negative susceptibility contrast with the host rock.

The structural interpretation of the EM data also resolves three similar anomalies in the immediate vicinity, which correlate with magnetic anomalies. Due to their favorable geophysical response in comparison with the known gold-bearing structures, these are of interest for further exploration.

It is expected that this approach will be used to find potential lode-bearing structures in the Charters Towers goldfield. Areas of interest can be first identified in the magnetic data based on the RTP vertical derivative, and then TEM will be performed at these sites. We have demonstrated that, through careful modeling, TEM can be used to understand the geometry of weak conductors.

We expect to use direct electrical excitation of the fracture zones accompanied by measurements with a magnetometer in boreholes to directly detect the highly conductive sulfide lenses.