Advances in aspects of the application of magnetotellurics for mineral exploration

Garcia, Xavier and Jones, Alan G. Geological Survey of Canada, 615 Booth St., Room 208, Ottawa, Ontario, Canada. K1A 0E9.*

Summary

The high-frequency magnetotelluric method, audio-MT (AMT), is currently being widely used for mining exploration, especially in Canada. However, there are still some aspects regarding its implementation that need to be considered. These range from signal detection and processing to response function analysis to appreciation of three-dimensional effects.

The main natural electromagnetic source at the range of frequencies covered by mining scale MT, audio- frequencies of 10 Hz - 20 kHz, is the global system of lightning. Due to the physical characteristics of the Earth's ionosphere and atmosphere, there is a minimum in the electromagnetic spectrum around 1,000-3,000 Hz, which is exactly the frequency range that is first sensitive to the presence of a typical conducting body.

Some ore deposit exploration is being carried out in areas where there is existing mining activity, thus the data can be seriously affected by noise. The classical processing schemes are based on either the Fourier or the windowed Fourier transforms, and these methods do not readily separate noise from signal. The application of the wavelet transform offers an analysis of the time series at the frequency and time domains simultaneously.

One of the main problems during the interpretation stage of MT data is the detection and removal of galvanic distortion effects caused by near-surface inhomogeneities. In mining exploration there is the additional problem that the targets are complicated 3D structures, and thus the classical 3D/2D decomposition schemes fail. For this reason a new 3D/3D algorithm has been designed.

Target bodies are usually complex in geometry and are strongly conductive, requiring full 3D interpretation of the data. Different structures can be inductively coupled adding a new difficulty to this geophysical method. We have undertaken analyses to check the validity of 2D interpretations over 3D regional structures.

In this paper we describe our efforts in these four aspects of MT exploration.

Source field structure

The main source for AMT sounding is the system of electric currents generated by lightning activity that radiate around the world in the Earth-ionosphere waveguide. The physical properties of the ionosphere and the atmosphere change dramatically both diurnally and seasonally, and with solar activity. The ionospheric layers are formed of particles that are electrically charged and that attenuate EM waves. The diurnal variation in attenuation is due the lower conductivity of the atmosphere at night because of the smaller aerosol content (no sun activity). This results in higher penetration of EM waves to higher latitudes. Using AMT data recorded in Sudbury (northern Ontario) and in northern Germany, we have studied this diurnal variation of the magnetic field amplitude at audio frequencies (Figure 1). The daytime and nighttime amplitudes can vary by 2 to 3 orders of magnitude, which explains reports from several studies of an increase in signal-to-noise ratio during nighttime AMT acquisition.

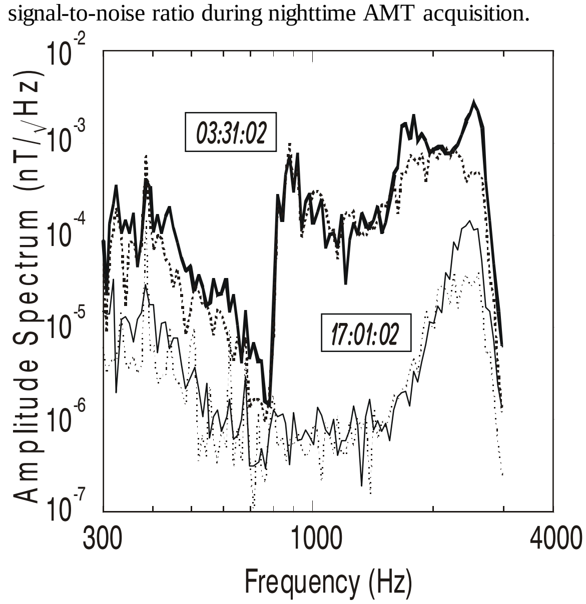

Figure 1. Power spectra of two time series recorded at different times in the Sudbury area (Canada). Evident is the increase in the amplitude for the nighttime hours (bold lines) compared to the daytime hours (light lines). The continuous lines denote real part and the dashed linesimaginary parts of the spectra.

Secondly, we have verified a seasonal variation in amplitude. The analysis of the Canadian data, recorded from May until October, suggests that there is an increase of the activity covering the summer months with a low amplitude of the magnetic fields at the end of the spring and early fall. This permits to extend the annual variation observed in Ionospheric studies to the audiofrequencies (Figure 2).

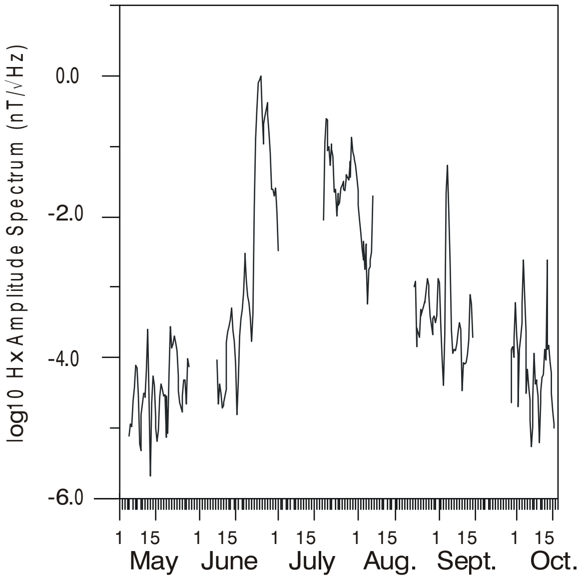

Figure 2. Power spectra at 1000 Hz of the Hx magnetic component recorded at local midnight in the Sudbury area. The increase of the amplitude of the magnetic field is evident during the summer months.

Application of Wavelets to MT data processing

Subsequent to data acquisition, the time series must be processed. Conventional MT processing schemes are based on Fourier transformation, which is suitable for signals and noise content obeying certain properties (ergodicity, stationarity, Gaussian distributed, etc.). Normally, neither the MT signals nor the noise components strictly obey these requirements, and conventional schemes often do not result in reliable and high quality response function estimates (see Jones et al., 1989, for a comparison).

Chave et al (1987) and Chave and Thomson (1989) have applied robust windowed Fourier transformation to MT processing. The windowed Fourier transform is a time-frequency transform, suitable for quasi-stationary signals (stationary at the scale of the window). The smaller the window the better time information one has, at the cost of losing information about low frequencies. Large windows give superior frequency information but less precision about time. Another problem with the windowed Fourier transform is that it requires large amounts of data, which are not usually available in mining studies.

We are approaching this problem by using wavelet transformation. The use of the S-transform permits us to obtain a time-frequency representation of the data. The main advantage of this transform is that it uses analytical wavelets which can be specifically designed for the signal and noise characteristics of the particular data. Furthermore, these analytical wavelets permit us to derive the continuous wavelet transform (CWT), where the scale factor is a linear relation with the frequency. Another advantage is that one can use Fourier transformation to calculate the CWT, from which there is an analytical expression for the impedance matrix as a function of the wavelet transform of the EM fields (Zhang and Paulson, 1997).

Our current research is centered on the detection of outliers using the high sensitivity of the CWT. The detection is realized at different scales in the time-frequency space.

3D/3D decomposition

Decomposition of MT data into local galvanic 3D distortion matrix and a regional 2D Earth (3D/2D) has caused a quantum leap in our ability to interpret and model data from complex environments. The Groom-Bailey (Groom and Bailey, 1989) method is the most appropriate decomposition to use given its physical basis and its separation of distortion parameters into determinable and indeterminable parts. However, often this decomposition fails in that the misfit of the model to the data is far greater than the data errors permit. Thus, the 3D/2D model is inappropriate.

Here we describe our attempts to increase the utility of the decomposition approach by considering 3D distortion of regional 3D data (3D/3D). There are insufficient data to accomplish this uniquely for a single site, so some assumption must be made. The approach we use is to assume that two neighboring sites are sensing the same regional structure if they are sufficiently close compared to the skin depth to the structure, but that the two sites have differing distortion matrices.

The basic scheme describing the physical effects observed in a mining environment is shown in Figure 3. At high frequencies the response of the regional 3D structures may be 2D-like, and a Groom-Bailey 3D/2D decomposition could be validly applied to obtain a distortion matrix, C_L, describing near-surface effects. At lower frequencies, the effects of the body will be both 3D inductive and galvanic, the galvanic part being described by a distortion matrix C_B. Thus for the frequencies of interest the impedance tensor will be decomposed in the following way:

$$Z = C_L \cdot C_B \cdot Z' \qquad \textbf{(1)}$$

where Z' describes the 3D regional responses.

Our solution of this formulation is based on the Groom-Bailey approach to the decomposition of the distortion tensor in terms of separable (*twist* and *shear*)and inseparable (*anisotropy* and *site gain*) parts. We assume that two adjacent sites have the same regional 3D response but will be affected in a different manner by galvanic effects. The decomposition becomes:

$$Z^i = g_i T_i S_i A_i Z$$
$$= \begin{pmatrix} 1 & -t_i \\ t_i & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & s_i \\ s_i & 1 \end{pmatrix} \cdot \begin{pmatrix} g_i(1+a_i) & 0 \\ 0 & g_i(1-a_i) \end{pmatrix} \cdot \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \quad \textbf{(2)}$$
$$= \begin{pmatrix} 1 & -t_i \\ t_i & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & s_i \\ s_i & 1 \end{pmatrix} \cdot \begin{pmatrix} g_i & 0 \\ 0 & g_i \end{pmatrix} \cdot \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$
$$i = 1,2$$

To solve this problem we currently use a Newton algorithm to find the minimum of the square of the norm between the estimated and the measured impedances. We find the algorithm to be strongly dependent on the initial model and very unstable, and are evaluating other approaches.

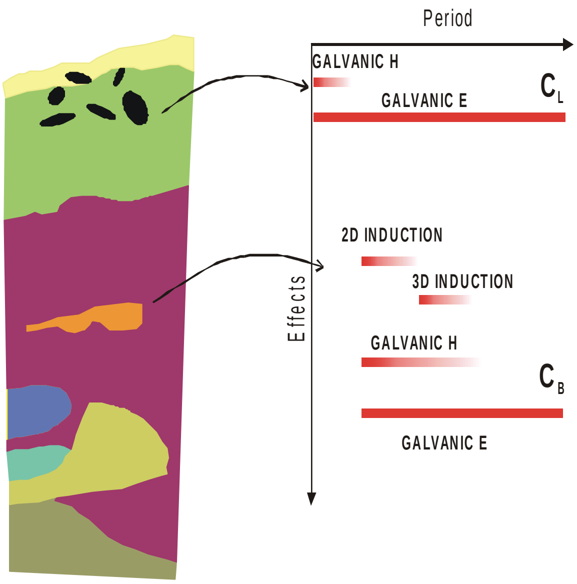

Figure 3. Cartoon of the different inductive and galvanic effects that appear in a MT mining scale survey.

3D model responses

Three-dimensional electromagnetic induction by natural sources takes place in our three dimensional world, but the question to address is whether a 2D interpretation is sufficient or not, and under what circumstances may one be led astray. Here we analyze theoretical 3D AMT responses over a numerical representation of the generic Canadian mineralized body found using EM methods. We demonstrate that a 2D interpretation is sufficient for exploration purposes for those sites over the middle of the body if the body is isolated electrically. However, when there is a large regional conducting structure nearby, such as an ocean or a sedimentary basin, then one must consider the effects of the interaction between the mineralized body and the regional body.

A 3D model was constructed of a small-scale 2 Siemens mineralized body plus the very large scale Atlantic Ocean. The forward calculations were performed using the LN approximation with PetrosEikon's EMIGMA code. Models were run of the body-alone, the ocean-alone, and the body+ocean in the frequency range 10,000 - 1 Hz.

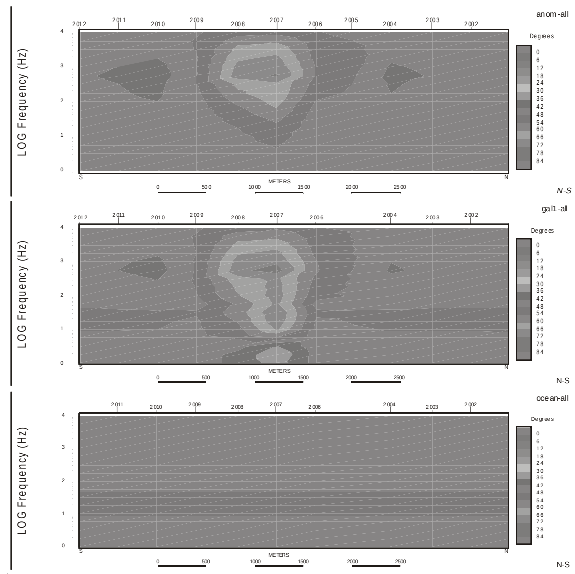

Figure 4. Phase pseudosections for the regional quasi-TM mode for the *body* (top), *body+ocean* (middle) and *ocean-alone* (bottom).

Figure 4 is a plot of the three phase pseudosections for a profile crossing the body for the mode in which the currents are crossing the shoreline (regional TM mode, local TE mode). The top pseudosection is for the *body-alone*, the middle one is for the *body+ocean*, and the bottom one is for the *ocean-alone*. As would be expected, the *ocean-alone* is spatially monotonous showing a spatially-uniform phase response over the whole survey region with increasing phase with decreasing frequency. The *body-only* phase pseudosection shows that the EM response of the body has decayed by approximately 30 Hz, which is coincidentally the frequency at which the distant ocean is first sensed by sites located over the body. However, when both the local mineralized body and the regional ocean are included together, there is an interaction between the two such that the phases at the sites sensing the anomaly increase dramatically with decreasing frequency. Clearly, the body is influenced by the relatively close proximity of the ocean currents.

Application of MT for mineral exploration

Conclusions

We are investigating methods for advancing the application of MT in mineral exploration, and have considered four aspects. These are:

1. AMT sources
2. Wavelet transformation of the time series
3. Separation of galvanic distortion parts from a "regional" 3D structure response, and
4. Appropriateness of 2D models of 3D structures and the Interaction between local 3D structures and distant large-scale 3D structures.

For (1), we have demonstrated that there are diurnal and seasonal variations of AMT sources. Generally, nighttime signal levels are sufficiently intense to provide good estimates of the AMT transfer functions.

Impedance estimates derived using wavelet transformation of the time series are sensitive to the presence of outliers. The next step will be to use a robust approach and obtain a reliable processing algorithm.

We developed a 3D/3D decomposition algorithm to remove 3D galvanic distortion and recover the 3D regional responses. For this purpose we use two nearby stations and assume that the distance between them is smaller than the skin depth to the target 3D body. Further work is required to stabilize the algorithm. This may require a different parametrization than the Groom-Bailey one adopted.

We have shown that for mining scale problems of 2D interpretations, especially with regional-scale structures, should be used carefully. The coupling between bodies can introduce false structures in the data that can be interpreted as drilling targets.

Acknowledgements

We wish to thank Phoenix Geophysics, Geosystem Canada and Gallery Resources for providing the data and responses analysed herein. XG is supported by an industry-GSC research fellowship, and thanks GSC, Geosystem, Phoenix and Inco for his support.

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