Transient Audio-Magnetotelluric imaging of a buried valley

D.K. Goldak *
EMpulse Geophysics Ltd., 26 Cartier Crescent, Saskatoon, SK, S7L 4L7.
empulse@sasktel.net

and

Shawn Goldak
Eagle Trading Systems, Princeton, N.J.

ABSTRACT

Thunderstorm activity produces large amounts of electromagnetic energy which is trapped within the earth-ionosphere waveguide. The random sum of energy from activity on a near global scale produces a low-level quasi-continuous source field. Very large, or equivalently, relatively nearby lightning discharges produce *individual* transient events whose amplitude are significantly larger than that of the low-level background field. Therefore, substantial increases in signal-to-noise ratio can be realized by recording exclusively sources of a transient nature. However, the transient events are strongly linearly polarized, the polarization diversity of which can affect the estimation of earth response curves.

It has been shown that an adaptive time domain averaging of the transient waveforms results in earth response curves whose bias converges to zero super-exponentially in stacked signal-to-noise ratio (Goldak et al., 2001).

The efficacy of the algorithm is shown in the results of a transient audio-magnetotelluric (TAMT) survey conducted over a buried valley system in southern Manitoba, Canada. Twenty-three sites at 200 m spacing were collected with the impedance tensor **Z** and the magnetic field tipper **T** estimated over the bandwidth 8 Hz – 32 kHz.

The results of the TAMT survey agree very well with those of a time domain electromagnetic (TEM) survey conducted by the Saskatchewan Research Council with a Geonics EM-47 over nearly the same profile.

Two dimensional OCCAM inversion of the TAMT data reveal the buried valley to be approximately 1 km wide, 70 m deep with a resistivity of approximately 12 Ohm-m, incised into conductive Cretaceous sediments of approximately 4 Ohm-m resistivity.

Introduction

The magnetotelluric (MT) method is a geophysical exploration technique in which the earth's electrical structure at depth may be determined from surface measurements of naturally occurring fluctuations in the earth's geomagnetic field along with electric field fluctuations induced within the earth by the former.

The chief source of naturally occurring energy in the ELF/VLF[1] bandwidth is due to lightning discharges (Pierce, 1977. Volland, 1982). Thunderstorm activity on a near global scale produces a low level, quasi-continuous component, superimposed on which, are *individual* transients which arise from either relatively nearby and/or very large current-moment lightning discharges (Tzanis and Beamish, 1987. Jones and Kemp, 1971). Note that nearby is defined relative to global waveguide attenuation. For example, nearby at 100 Hz may be 6 Mm[2] whereas at 5 kHz, perhaps 1.5 Mm.

Both energy sources can be used to estimate the impedance tensor or magnetic field tipper, but substantial increases in signal-to-noise ratio (SNR) are afforded by attempting to exclusively record transients.

Therefore, GEOTRAN-MT, designed and constructed by EMpulse Geophysics Ltd., captures only transient energy in the 8 Hz - 32 kHz bandwidth. Furthermore, all parameter estimation is carried out with EMpulse Geophysics' proprietary Adaptive Polarization Stacking (APS) algorithm (Goldak et al., 2001), designed to work exclusively with linearly polarized transient data.

In contrast with Remote-Reference (RR), our error analysis make no assumptions about the statistical distribution of the noise or the circularity of the source field. We have further shown that the APS method has a higher order bias convergence than RR given typical polarization characteristics of transient data (Goldak et al., 2001).

Theory

The fundamental quantity of interest for MT surveys is the impedance tensor **Z** which is the transfer function between mutually orthogonal, horizontal components of magnetic and electric fields as defined in equation (1). Implicit in the definition of the impedance tensor is that we work in the frequency domain, with a right handed co-ordinate system defined as +x North, +y East and +z down.

$$\begin{aligned} E_x &= Z_{xx} \cdot H_x + Z_{xy} \cdot H_y \\ E_y &= Z_{yx} \cdot H_x + Z_{yy} \cdot H_y \end{aligned} \qquad (1)$$

Also of interest is the magnetic field tipper **T** as defined below in equation (2),

[1] ELF: Extremely-Low Frequency, 3 Hz – 3 kHz, VLF: Very-Low Frequency, 3 kHz – 30 kHz.
[2] 1 Mm = 1000 km.

$$H_z = T_x \cdot H_x + T_y \cdot H_y \quad (2)$$

The magnetic field tipper is sensitive to lateral changes in earth resistivity structure and is therefore very useful for locating discrete features and for assessing the dimensionality of the data. Note that for a 1D earth there exists no vertical magnetic field of secondary origin and thus the tipper **T** vanishes.

If we consider **Z** only, the regression problem is then one of estimating the complex values thereof by minimizing the sum square error of the residual on the electric field channels.

However, we note that since we have four complex unknowns and only two equations, we need at least two independent measurements of equation (1) to solve for **Z**. If we consider this simplest case, we have

$$\begin{aligned} E_{xi} &= Z_{xx} \cdot H_{xi} + Z_{xy} \cdot H_{yi} \\ E_{yi} &= Z_{yx} \cdot H_{xi} + Z_{yy} \cdot H_{yi} \\ i &= 1,2 \end{aligned} \quad (3)$$

Solving this pair of 2 x 2 linear systems yields the two-point formulas for **Z**. The modifier two-point is used as although these are complex variables, the solution is analogous to passing a plane through the origin and two other points.

Until now, statistical analysis of the bias in estimates of **Z** has been done for the LS (Sims et al., 1971) and remote-reference (RR) (Gamble et al., 1979) solutions, but never for the two-point solution. Although it was claimed that RR is “unbiased"(Gamble et al., 1979), this is valid only in the limit of infinitely many independent measurements. Practically then, the solutions of **Z** just mentioned in fact display a finite *convergence* of bias as SNR becomes large. However, for RR and APS, there is also a bias convergence to some arbitrarily small level at fixed SNR, as the number of measurements N becomes large.

The LS solution has a bias that converges very slowly as inverse SNR squared. By contrast, the bias in the two-point formula is due only to nonlinearity in the complex quotient. Its bias is of infinitely smaller order, namely

$$\exp^{-0.5(ISNR \cdot \sin(\alpha))^2} \quad (4)$$

where α is the angle between the events, with 0 <= α <= 90 degrees.

However, the polarization diversity of received transients may be such that

α is much less than the optimal 90 degrees, but even for α =30 degrees, the reduction factor of $\sin(\alpha) = 0.5$ is quickly offset by the improvement in SNR gained by stacking. At only moderate improved SNR (ISNR) and angle α the stacking bias can already be less than $10^{-7}|Z|$ and hence negligible in single precision.

Results

In 1995 the Saskatchewan Research Council (SRC) was contracted by the Geological Survey of Canada (GSC) to conduct time domain electromagnetic soundings in locations deemed prospective for buried valley type aquifers.

The SRC used an EM-47 with a 40 m x 40 m single turn square loop, typically carrying on the order of 2 Amps current, employing two sweeps with 75 and 300 Hz repetition rates, with centrally located, in loop measurements only.

This study is concerned with one profile only, denoted 95V4, located in southern Manitoba approximately twenty kilometres south-east of the town of Melita.

Unfortunately, line 95V4 was collected in a ditch very close to a medium sized three-phase powerline. Therefore, the late time gates of the 75 Hz data are extremely noisy and thus provided very little additional depth information. The 300 Hz data are reasonable quality except for the two or three latest time gates.

A transient audio-magnetotelluric (TAMT) survey was conducted over the same buried valley system in late October, 2001, although displaced 500 m to the north of the powerline so as to minimize cultural noise effects.

Note that for a 1D isotropic earth the impedance tensor **Z** takes on a very simple form, namely,

$$Z_{xy} = \frac{E_x}{H_y} = -Z_{yx} = -\frac{E_y}{H_x}, Z_{xx} = Z_{yy} = 0 \qquad (5)$$

We see then that the modulus of the two non-zero components of **Z** (apparent resistivity) are equal and the argument of the two components are shifted by 180 degrees[3]. Of course in the 1D anisotropic case the modulus of **Z** is no longer single valued. Note that the only way to distinguish a 1D anisotropic earth from a 2D earth is by measurement of **T**.

[3] Although it is often seen that the yx phase is shifted to the first quadrant by a simple addition of 180 deg.

Although one is mainly concerned with the estimation of **Z**, for display purposes we usually present its modulus and argument. Similarly, for the tipper, the real and imaginary parts are plotted separately. The modulus and argument of the xy and yx components of **Z** are shown in Figures 1 and 2 respectively.

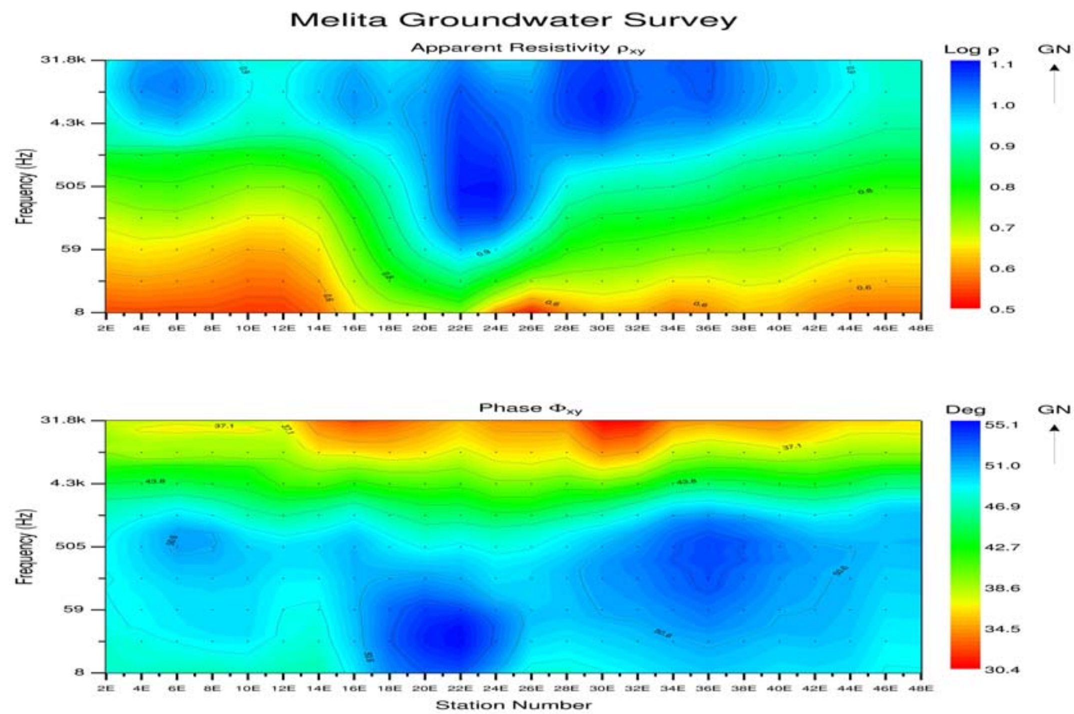

Fig. 1

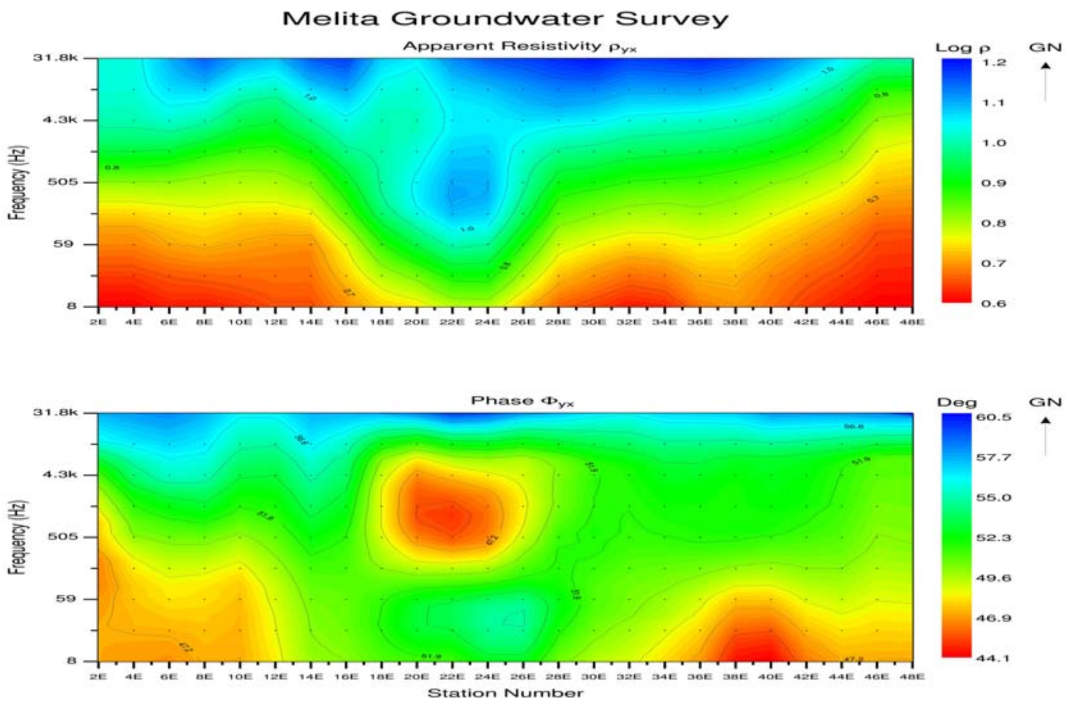

Fig. 2

Evidence of the paleochannel is clearly seen on both apparent resistivities and most especially the yx phase. Note that the data are extremely 1D, except over the edges of the paleochannel where the data are 2D. This is corroborated in the plot of the tipper data below in Figure 3. We see that the tipper is essentially zero except at two main locations which approximately define the edges of the paleochannel, although not strictly so as the tipper is sensitive to features *laterally displaced* from the measurement site. However, the relaxation distance is dictated partly by earth resistivity. For a very conductive earth as we have here, the relaxation distance is relatively small so the tipper anomalies in fact would quite closely outline the edges of the paleochannel.

Note that the tipper anomaly is quite small, as a percentage of the horizontal field approximately ten percent on the real component and five percent on the imaginary component [4].

---

[4] Extensive linear conductors as may be found in Northern Saskatchewan can produce tipper anomalies approaching 40 percent.

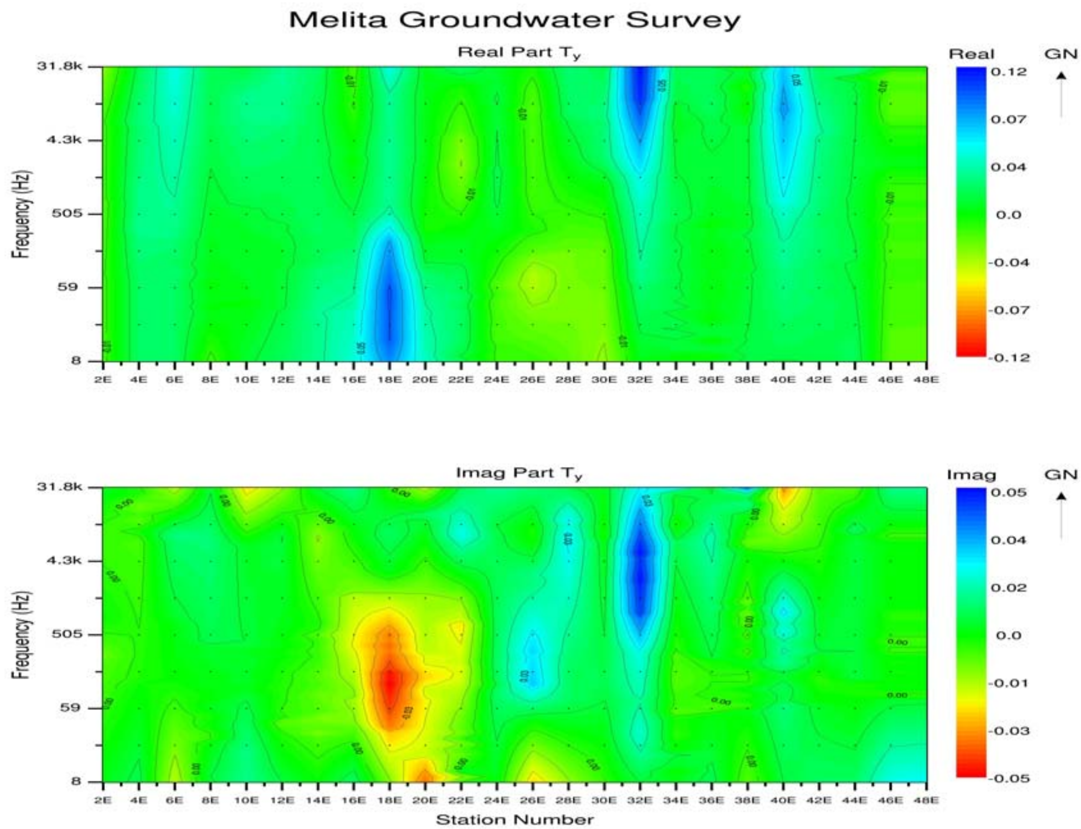

Fig. 3

Shown in Figure 4 are the results of 1D interpretation of the TAMT and EM-47 data. Note that the TAMT data have not been inverted in the truest sense but rather simply transformed. The Bostick transform (Bostick, 1977) is an approximate 1D inversion method for MT data that approximates a first-order image solution for the time-domain EM case (Nekut, 1982). This results in a smoothly varying resistivity profile as a function of (pseudo) depth which may not be the best approximation if the earth structure is truly layered as it appears to be for this data-set.

On the other hand, the EM-47 data have been inverted with a layered earth, iterative L.S. fitting process. However, note that neither of these 1D interpretive methods incorporate data errors in their analysis. Also, the Bostick transformed results of the TAMT data extend well past 275 m (pseudo) depth, for comparison with the EM-47 data though a reduced depth scale was used.

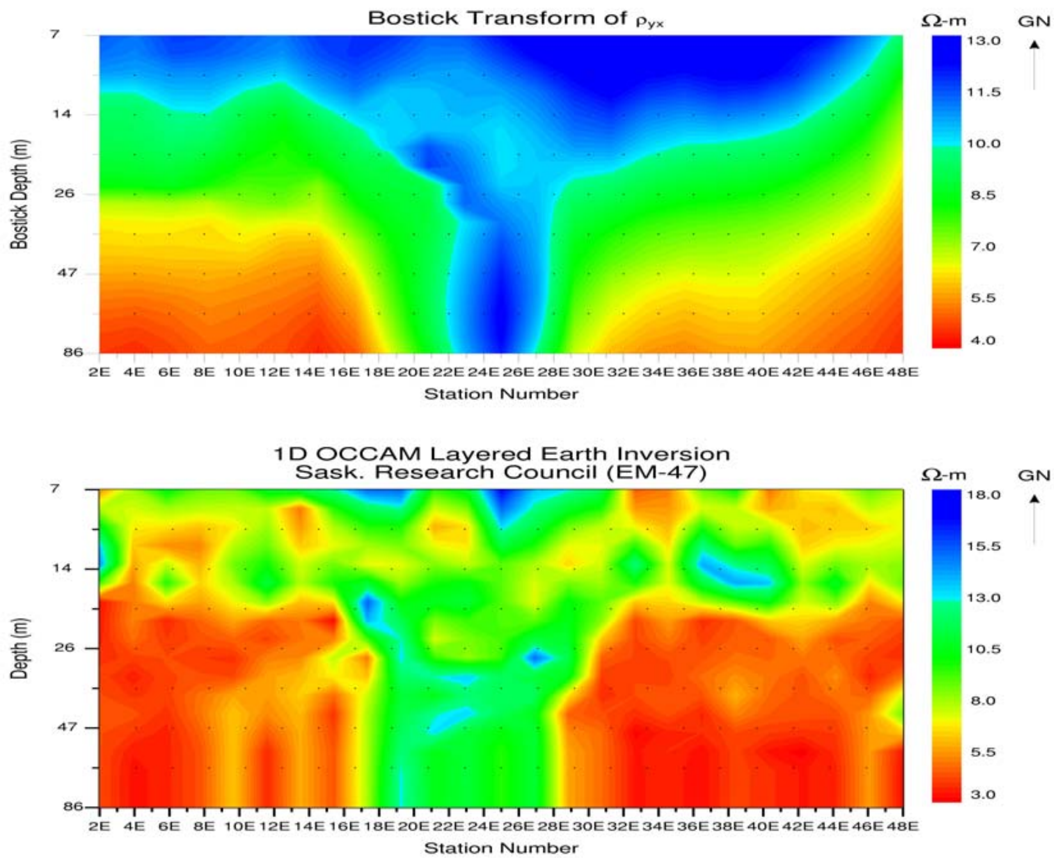

Fig. 4

We see that the TAMT data seems to be mapping the resistive drift in a superior fashion while the EM-47 data seems to be better mapping the depth to the marine Cretaceous shale. However, note the differences in the resistivity scale in the two plots above.

Shown in Figure 5 are the results of 2D OCCAM inversion (minimum structure) of the TAMT data. The 2D inversion is the most rigorous as the data around the edges of the paleochannel are 2D and data errors are properly utilized.

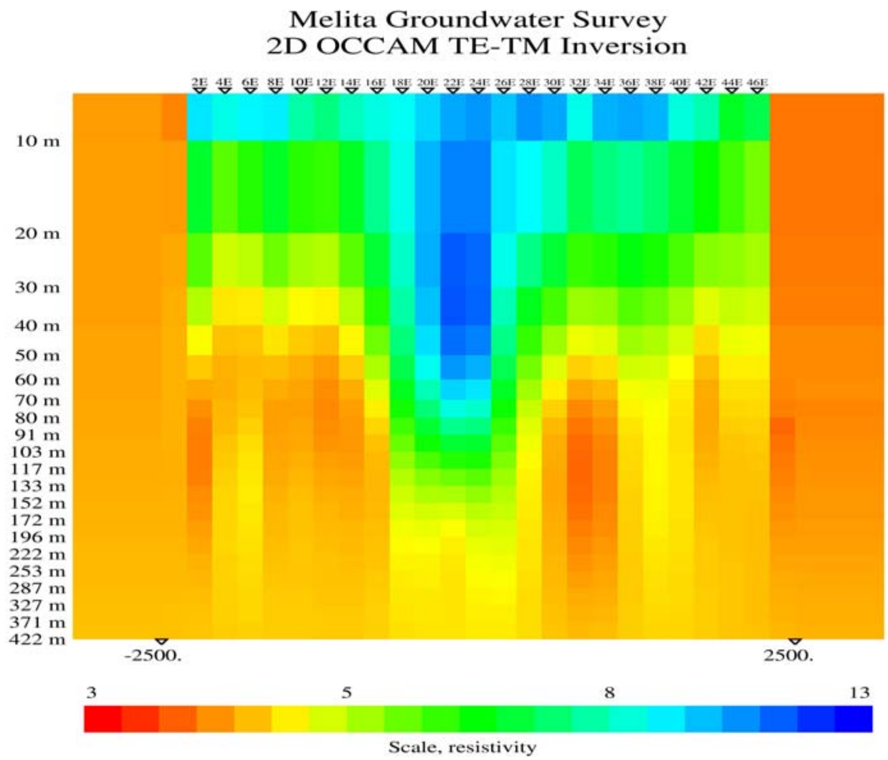

Fig. 5

We see the edges of the paleochannel at approximately 18E and 28E, the resistivity of the drift is approximately 12 Ohm-m while that of the Cretaceous marine shale, approximately 4 Ohm-m. The maximum thickness of the drift is approximately 70 m, occurring at stations 22E and 24E. The thickness of the drift outside the channel seems to vary from west to east, being approximately 10 m thick on the west end of the line and approximately 20 m thick on the east end of the line, although as we move past 38 E the drift appears to be thinning again.

This agrees with the study of Betcher (1983) who indicates approximately 20 m of drift over Cretaceous “bedrock” being typical and approximately 80 m of drift being observed within the channel.

The depth range 20 m to 40 m approximately covers the so called AMT dead-band where data errors are largest. Based on the EM-47 data, the conductive Cretaceous shales should extend up to 20 m depth or so on the 2D TAMT inversion. However, due to the larger data errors in this frequency range the inversion code is not required to put any structure here, it is not until about 40 m depth when the error bars tighten up that we clearly image the marine shales.

Conclusions

The largest naturally occurring signals in the ELF/VLF bandwidth are transients. In order to record transients most efficiently, a time localized recording technique is desired. In so doing, the best possible SNR in the raw data is obtained.

By performing an adaptive time domain averaging of the transient waveforms we obtain essentially unbiased estimates of the impedance tensor or magnetic field tipper while using only four or three channels of data respectively.

The effectiveness of the algorithm has been displayed with real data in the mapping of a buried valley system in southern Manitoba. Further verification is provided by the good agreement with EM-47 data collected by the Saskatchewan Research Council on nearly the same profile.

In agreement with Betcher (1983), we find the paleochannel to be approximately 1 km wide, 70 m deep with a resistivity of approximately 12 Ohm-m, incised into conductive Cretaceous shales of approximately 4 Ohm-m resistivity.

Acknowledgements

The assistance of the primary authors wife, Sheila Goldak, during the field work of this project was greatly appreciated. I would like to thank the Saskatchewan Research Council, Mark Simpson in particular, for releasing their data to me for this paper and for his abundant assistance in choosing a survey location. We would also like to thank Cameco Corporation for the use of their computing facilities and the assistance of Lawrence Bzdel and Garnet Wood in the use of TEMIX. Lastly, Michael Leppin of Cameco Corporation is thanked for the many interesting discussions concerning multi-dimensional electromagnetic inversion.

Bibliography

Betcher, R.N., 1983, Groundwater availability map series, Virden area (62F), Manitoba Natural Resources, Water Resources, Figure 3, 1:250,000 scale map.

Bostick, F.X., 1977, Workshop on electrical methods in geothermal exploration, U.S. Geological Survey contract number 14-08-001-G-359.

Gamble, T.D., Goubau, W.M. and Clarke, J., 1979, Error analysis for remote reference magnetotellurics: Geophysics, **44**, 959-968.

Goldak, D.K. and Goldak, S., 2001, Transient Magnetotellurics with Adaptive Polarization Stacking, presented at SEG International Exposition and 71'st Annual Meeting, 2001, San Antonio.

Jones, D.L. and Kemp, D.T., 1971, The nature and average magnitude of the sources of transient excitation of Schumann resonances: Journal of Atmospheric and Terrestrial Physics, **33**, 557-566.

Nekut, A.G., 1982, Direct inversion of time-domain electromagnetic data, Geophysics, **52**, 1431-1435

Pierce, E.T., 1977, Atmospherics and radio noise, in Golde, R.H., ed., Lightning, **1**, Academic Press.

Sims, W.E., Bostick, F.X. and Smith, H.W., 1971, The estimation of magnetotelluric impedance tensor elements from measured data: Geophysics, **36**, 938-942.

Tzanis, A. and Beamish, D., 1987, Audiomagnetotelluric sounding using the Schumann resonances: Journal of Geophysics, **61**, 97-109.

Volland, H., 1982, Low frequency radio noise: in Volland, H., ed., CRC Handbook of atmospherics, **1**, CRC Press Inc.