Burwash Area ELF Survey Technical Report – YTGS Burwash Geothermal Study

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AURORA GEOSCIENCES

TECHNICAL REPORT
Burwash Area ELF Survey Technical Report

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1 SUMMARY

An ELF survey consisting of 329 data points was conducted from June 12th to June 29th, 2019. The field report (YGS-20190703-Burwash_ELF_Survey_Field_Report), dated July 3rd 2019, contains logistical information, in-phase & quadrature maps for the N/E component profile lines, tipper vectors, & divergence plots for all measured frequencies (11, 22, 45, 90, 180, 360, 720, & 1440 Hz).

This report details results from 2D inversion to produce resistivity models. These models were created by using the program REBOCC (Reduced Basis Occam's Inversion) by Weerachai Siripunvaraporn, Ph.D., of Mahidol University (Siripunvaraporn and Egbert, 2000). A 2D inversion was chosen due to the large line separation relative to vertical cell sizes in the model. Resistivity varied from approximately 5 Ω·m to 5000 Ω·m, with structures that are not unreasonable for the local geology.

In addition, the ELF divergence plots produced previously as part of the field report were compared with the corrected first order trend removed Bouguer anomaly gravity data as well as known faults to identify similar trends.

Figures of the various inversions as well as comparisons made to the previous gravity study are appended to the end of this report.

2 ELF Instrument Background

2.1 General

The ELF (Extremely Low Frequency) instrument is not a common geophysical instrument. It shares design heritage with audio magnetotelluric surveys (AMT), except that it does not record the electric field. Rather, it only records the magnetic field on three orthogonal coils. AMT surveys also record the magnetic field thus. However, the advantage to not recording the electric field is a vast improvement in instrument simplicity, portability, and productivity. Two operators can obtain a larger data set than the equivalent AMT survey.

However, this configuration is relatively rare. Aurora operates the ground based ELF instrument, while Geotech's ZTEM airbone survey operates on the same principle, but incurs the cost of a helicopter.

Applied Geophysics (Telford, et al., 1990) calls this method AFMAG, or Audio Frequency Magnetic Fields (p. 366). Aurora calls this method ELF, although the terms are interchangeable. The method is infrequently used and detailed literature is sparse.

Rather than rewrite it, we quote relevant sections of Telford here:

> *AFMAG method. […] This is a natural-source dip-angle method, introduced by Ward (1959b). The main origin of the primary field is lighting discharge (sferics) associated with worldwide thunderstorm activity as in audiofrequency MT work. There are other minor sources of energy such as corpuscular radiation interaction with the earth's magnetic field and manmade noise. The EM energy is propagated between the earth surface and the lower ionosphere as in a waveguide. The frequencies associated with AFMAG are in the ELF range, from 1 to 1,000 Hz, with the best reception apparently between 100 and 500 Hz.*
>
> *Because the sferic sources are random, the signal is effectively noise with seasonal, diurnal, and short-period variations in intensity. Over the ELF range an AFMAG record is quite similar to the telluric current record […].*
>
> *Generally the vertical component is small compared to the horizontal, except in the vicinity of a good conductor. Hence the AFMAG field may be detected by a tilt-angle*

technique. The receiver, however, is modified from the conventional dip-angle detector because the random variations in primary field intensity make it impossible to locate the minimum with a single coil.

[…] The field procedure is otherwise quite similar to the fixed-transmitter [electromagnetic] method, with the transmitter considered to be at an infinite distance. Traverses are made at right angles to geologic strike where possible. […] The resultant crossover profiles may be plotted exactly as in the fixed-transmitter method, or they may be plotted as vectors if the minimum azimuth direction is distinctly different from that of the traverse line or if the azimuth varies appreciably over a short time interval. […]

AFMAG has several real and potential advantages over the artificial source methods. No transmitter is required. The frequency is comparatively and hence the depth of penetration is probably greater than for a local source. Because the primary field is uniform, at least instantaneously, over the survey area, all the conductors are energized uniformly. At times this may be a disadvantage, however, because it may emphasize large-scale, relatively poor conductors at the expense of smaller concentrated bodies.

There are two specific disadvantages with AFMAG. The first is the effect of large random changes in amplitude and direction of the inducing field, that produce corresponding variations in the signal strength as well as changes in anomaly shape and size. The second is that random fluctuations in direction may make it very difficult to locate the azimuth of the horizontal field.

Note that the ELF instrument Aurora used on this program does not have these problems as it uses three coils and a tilt sensor to automatically orient in the correct direction in software.

Recent work on more sophisticated equipment and controls (Labson et al, 1985) appears to have reduced or eliminated these limited in AFMAG. They constructed new field sensors (coils) sensitive enough to make year-round measurements (the AFMAG signal is weak in winter and at high latitudes) and incorporated digital acquisition and processing to provide results in the field, reducing noise by a remote reference source (Gamble, Goubau, and Clarke, 1979). These improvements produced relatively stable noise-free measurements of the ratio of vertical-to-horizontal H-field components (the "tipper" in MT work).

The ELF instrument used by Aurora owes its heritage to these previous designs. However, it has a wider array of frequency ranges to choose from, and is much faster to collect in the field. We do not, however, use a reference station to remove noise, so estimates for noise must be collected in the field by repeating measurements at the same location. This instrument also suffers from poor signal when operated in the Canadian arctic in winter.

The plotting of raw data is similar to that of a VLF (Very Low Frequency) survey when a single direction subset of the data are used, with profiles and cross-over points identified. Or the full dataset can be viewed as tipper vectors or divergence mapping. These data displays are fast and straightforward However, getting a model of terrain conductivity is the ultimate goal, and that requires inversion.

Because the data collected has so much in common with the MT method, namely collecting magnetic field (H-field) tipper data, the primary means of analyzing this data is with software designed for handling MT data. However, MT surveys also collect electric field (E-field) information and most MT modelling and inversion software assumes that this E-field data is present. The majority of MT inversion programs will completely refuse to function without the E-field data.

Aurora has acquired commercial access to software that can handle MT data without the E-field. This software is REBOCC (Reduced Basis Occam's Inversion) by Weerachai Siripunvaraporn, Ph.D., of Mahidol University (Siripunvaraporn and Egbert, 2000).

3 ELF 2D Inversion

What follows is a description of the parameters and process used to invert the data collected at Burwash.

3.1 Inversion Processing

REBOCC takes a reference model, the instrument response at each frequency (as projected into two dimensions), and a measure for error at each frequency as the inputs.

3.1.1 Data Preparation

Two channels of input data were rejected as too noisy for the whole survey: 11 Hz and 1440 Hz. These channels were not included in the inversions. The six remaining frequencies were included, with an estimate for the noise at each frequency being set as a constant for the entire grid based on repeated readings conducted throughout the survey.

Data from the ELF instrument was prepared from the database used in preparing the maps presented in the field report. Data was projected onto the line direction (40 degrees east of north). This data was indexed by station number, with station zero being on the south-west ends of the lines. All 12 lines were processed as 7000 m long lines with a station spacing of 250 m. Lines 10000 and 11000 had several points omitted at the start of the lines due to steep terrain, however these lines were treated identically. They begin at station 2000 and 2500, respectively.

3.1.2 Model Grid

This model grid was identical for all lines. The model grid was set at 20 m vertical and 125 m horizontal cell sizes near the surface. As depth increased, cell size increased telescopically. Padding was added on either end of the line, and air cells were added above the line by default.

Vertical cell thickness in descending order:

30x20 m + 8x50m+ 5x100m + 5x200m + 4x500m + 2x1000m + 2x2000m => 10.5 km total depth

Where there was data (including at the missing points on lines 10000 and 11000), cell widths were uniformly set at 125 m. Horizontal cell widths were padded at the start and end of each line. The padding cells had the following widths:

250m + 500m + 750m + 1000m + 2000m + 3000m + 4000m => 11.5 km total padding, on each end.

Finally, the default number of air cells above the model were used. These cells had the following thicknesses, in ascending order from the ground:

10m + 30m + 100m + 300m + 1000m + 3000m + 10000m + 30000m + 100000m + 300000m => 144.44 km

The cell coordinates in the output model is given as distance down line (station number), but do not correspond directly to the data acquisition locations as those locations ended up on a cell boundary. Cell coordinates are given for the centres of the cells, and depth below ground surface.

3.1.3 Topography

No topography was considered during the inversion process, as REBOCC does not support it. Topography was added to the models after the inversions were complete. As topography existed for the locations where data was collected, but not where the cells in the model ended up centred, linear interpolation was used to selected topographic points corresponding to the cell locations. Model depths were converted to elevation by subtraction.

3.1.4 Reference Model

The simplest reference model is a uniform half-space. To begin inversions, this was attempted for all 12 lines. Half-space resistivity values of 10, 100, and 1000 Ω·m were used as seed models. The most stable inversions occurred when using the 10 Ω·m half-space.

When the model results from these inversions were plotted, six of the twelve lines had very good line-to-line correlation (Lines 0, 1000, 2000, 3000, 8000, and 9000) and resistivity values between 5 and 5000 Ω·m. Another six lines had resistivity values that were not reasonable considering their neighbours and the results were discarded and another reference model was used.

In order to create congruous results, Lines 4000, 5000, 6000, and 7000 were rerun with the results from L3000 (inverted with 10 Ω·m half-space as starting model) as their reference model. Lines 10000 and 11000 were likewise rerun with the results from L9000 as their reference model. Once rerun, the model values converged to results within a similar acceptable range as their adjacent lines.

Using an adjacent line as a reference model risks biasing features, where features from the reference line are carried over onto the new line. This does not appear to have been a problem for these rerun lines, however it is a caution to be aware of when interpreting data for those lines.

3.1.5 Inversion Results

The modelled results have a resistivity range of 5 Ω·m to 5000 Ω·m, with little variation in range from line to line. L0 has a singularity on the south-west end that sent the resistivity climbing into the millions at that spot. For the purposes of plotting, we ignore that spot and set our ranges from 5 to 5000 Ω·m.

Resistivity is typically plotted on a logarithmic scale, so that was chosen for these plots. Aurora uses the Geosoft resistivity colour table to display resistivity results, in keeping with our practice when plotting resistivity results collected from other instruments. All figures are plotted with the same colour scheme and scale, and should be directly comparable to each other.

While there are cells in the model at depths of 10 km, this data is not considered reliable at this depth. These cells at depth serve as padding below the model area to prevent edge effects during the inversion process. When presenting the model results, after elevation was added, depths were cut off arbitrarily at -400 m elevation (approximately 800-1200 m depth below ground surface) – this was chosen as the model rarely varies below this elevation. However, the database of inversion results includes all cells to 10 km depth. It does not include the padding cells from the ends of the lines.

To obtain visual products, a voxel of all 12 lines was created. Due to the line separation, as compared to the cell sizes (in particular the vertical cell size), it was not reasonable to produce a single voxel which cleanly spanned all 12 lines. So each line was gridded without concern to neighbouring lines using inverse distance weighting. From the voxel, a number of slices were cut: one for each line to create section maps, one for each depth below ground surface from 0 to 500 m, and one for each constant elevation at 100 m intervals from 1200 m elevation to 0 m elevation, and also at -200 m and -400 m.

Inversion results are presented with minimal interpretation. It is Aurora's understanding that this data will be integrated with geology, drilling, and other results at a later date by the Yukon Geological Survey. Plan maps are delivered with elevation contours and mapped faults. Section maps include mapped locations of faults where they intersect the section at the surface.

4 Trend Comparison with FOTR Bouguer Anomaly Gravity Data, Known Faults

4.1 Divergence Plots and Mapped Faults

Twelve divergence maps were created using the data previously presented in the field report. These maps have had the mapped faults previously provided by the Yukon Geological Survey added.

The real ELF divergence anomalies are roughly in the same place as the known faults shown in black. One exception, the fault that crosses from L2000 station 2000 to L7000 station 4000, has no solid evidence in either the real or quadrature components. There is a feature not previously mapped that shows up in all the ELF data. Its location is in-between the two NW trending faults at roughly station 3000. This feature isn’t as prominent in the low frequency real ELF divergences plots but shows well in the imaginary & higher frequencies plots. This response indicates the feature is probably not as extensive or deep as the other linear anomalies identified by the ELF. The eastern side of the grid from L5000 to L11000 shows the northern most fault as breaking into 3 faults. This is not supported by the ELF divergence plots as no considerable thickening of the response is present compared to the NW portion. Perhaps it is a larger fault system instead of three distinct faults. In the south west corner the ELF divergence trend more to the north then the known fault. This could be a similar scenario indicating a larger fault system that was previously not mapped.

In the quadrature components there is a weaker feature northwest of the main Denali fault system. This feature is nearer to the surface then main Denali fault features because it is only seen in the higher 180, 360 and 720 Hz and only in the quadrature components. This is most likely a smaller fault with less displacement.

The additional ELF frequencies, 11 & 1440 Hz, were not used for this comparison. The 1440 Hz frequency showed some linear divergence highs in the real but was discontinuous throughout the grid. This was attributed to surficial features such as lake bodies & rivers. The 11 Hz frequency, in both the real and imaginary, suffered from low activity and as such could not be used for the comparison with the gravity data.

4.2 Divergence Plots and FOTR Bouguer Gravity

The First Order Trend Removed (FOTR) Bouguer gravity maps were created coincident with picked features from the ELF divergences maps. It shows a gravity high with a NW trend bound by two divergence highs clearly indicated in all frequencies from 22 Hz to 720 Hz in the real (In-Phase) and imaginary (Quadrature) components. This FOTR Bouguer gravity high is also located between two faults that have been previously mapped by the Yukon Geological Survey.

4.3 2D Section Maps

2D sections maps created from the results of the 2D inversion modelling were created for each of the 12 lines of data. The inset map shows the surface conductivity of each line, mapped faults, and the relative location of the current line. The section maps are plotted at 1:1 vertical exaggeration, with distance along line (station number) on the bottom axis, UTM coordinates on the top axis, and elevation on the vertical axis. The colour scales are from 5 to 5000 Ω·m. On the surface contour, inverted triangles are the locations where data was collected and squares are locations where the mapped faults intersect the cross section.

Several of the sections show good correlation between the mapped fault locations and features which could be interpreted as faults. L6000 is a good example, at station 3500. Other sections do not show such strong correlation. It is possible that the mapped faults were drawn too coarsely and the sections are more correct, or that the faults have varying contrast to the background materials. Some of these faults were inverted to have significant dip and may be in the correct locations at depth.

4.4 2D Depth Below Ground Surface Plots

Five maps with depth slices that follow surface topography were created for the near surface environment. The purpose of these maps is help show correlations between the inverted model and topography, or the model and surficial deposits.

Many of the section maps show near surface resistors, which are likely gravel or similar well drained material. The surface plots suggest that there is quite a thick sediment package in the top 300 m, but by 400 m below ground surface, there is more line to line correlation emerging, suggestive of underlying geology. There was no significant difference in the morphology of these features when varying the starting model. This information may be useful for correcting gravity data for overburden thickness.

There does not appear to be a strong correlation with topography.

4.5 2D Fixed Elevation Slices

A large number of model slices were created at fixed elevations. These slices are more useful when loading sections into 3D viewers. Model slives below 900 m elevation show strong linear features that may be detections of faults.

5 Recommendations, Suggestions, Future Work

The 2D models created in this dataset may form a viable input model for a 3D inversion. Aurora uses the 3D inversion software WSINV3DMT (Siripunvaraporn, 2009). The benefit of the 3D inversion is the production of a single model across the survey area, rather than relying on gridding algorithms to spread 2D models smoothly across large areas. Additionally, the full 3D components of the data are used, rather than a 2D projection onto a line. This is more complicated than producing 2D models, requires more data preparation time, and significant computing resources.

Additionally, the open source SimPEG project may be amenable to modification to handle ELF data natively. It is a framework for the inversion of many types of data. It may be possible to undertake joint inversions with ELF and other types of data, such as gravity, using the SimPEG framework. However, this will require a significant investment of programmer hours.

A VLF survey, a method that is related to ELF but operates at a higher frequency with a fixed transmitter location, may be a reasonable complimentary survey to refine the fault locations where they are near the surface, where the overburden thickness is not thicker than the VLF skin depth of approximately 100 m. A crew of two VLF receiver operators could acquire the same lines, with a station spacing of 12.5 m, in three to four days.

This ELF data was collected in June, an optimal time of year for data collection due to the large number of lighting events happening in North America. If the survey area is to be expanded, either by increasing line density, or expanding the grid, choosing to survey at an optimal time of year will yield similar results.

However, expanding the survey area in winter may require additional expense to create a fixed ground reference station, and corresponding processing time.

Creating an overburden thickness model from the ELF inversion models for the purposes of correcting gravity data may be a reasonable undertaking. The ELF data is very coarse, so the gravity corrections would be equally coarse. And until the ELF models are verified by other methods, they may serve to introduce anomalies into the gravity data.

6 Products

The following are attached to the digital version of this report

Folder	**File Name & Description of contents**
	YGS-20190723-Burwash_ELF_Survey_Technical_Report.*pdf* - A copy of this report in PDF format.
\Final Data	*YGS-20190702-ELF-Final.xyz, & .gdb*
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	YGS-20190703- FOTR_Grav_ALL.jpg

YGS-20190721-Burwash_Elf_Survey_Technical_Report_Figures.pdf

- *Includes all sections, depth slices, and elevation slices.*

7 References

Siripunvaraporn, W. and G. Egbert. WSINV3DMT: Vertical magnetic field transfer function inversion and parallel implementation. Physics of the Earth and Planetary Interiors 173 (2009) 317-329.

Siripunvaraporn, W. and G. Egbert. An efficient data-subspace inversion method for 2-D magnetotelluric data. Geophysics 65(3) (2000) 791-803.

Telford, W.M., L.P. Geldart, and R.E. Sheriff. Applied Geophysics, Second Edition (1990).

8 In Closing

ELF divergence maps show strong correlation to mapped faults, and gravity features, and also indicate at least one unmapped linear feature at higher frequencies. The collected data was successfully inverted. 2D models were presented in both cross section and depth slices. The data indicates strong line to line correlation generally, although not always coincident with the existing mapped faults as provided by the Yukon Geological Survey. It is consistent with gravity trends also mapped in the area.

Respectfully submitted,

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