# Analyses and Preliminary Interpretation of Twin Lakes VLF data *for* Copper Reef

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# Analyses of Twin Lakes VLF data
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# Executive Summary

Forward:

Newer VLF equipment and software provides a more direct and easier means to interpret than historically allowed. A brief explanation of the principles behind VLF is given in Appendix A.

Survey:

A combined VLF and magnetic survey was carried out in December, 2012 by Jason Sigfrid using a combined VLF and magnetics instrument (GSM-19) manufactured by GEM systems of Ontario. The survey was carried out on a picketed grid of 25m station spacing and 50m line spacing on 27 lines and approximately 1100 stations. The data spacing is unusually sparse compared to accepted procedures particularly as it is understood that identification of narrow, linear features was the object of the survey. The data was collected in three days with the operator walking the lines in a general order of south to north on a line and north to south on the neighboring line as so forth. No repeats of any kind were taken as a quality control procedure and no instrument calibration tests are available. Data was collected at two frequencies originating from two VLF transmitters, one at Cutler, Maine and one at Seattle, Washington. Theoretically, the differences in the source field polarizations should provide good resolution of both EW and NS conductors.

Data Quality:

The data appears to be of good quality although this cannot be absolutely verified as no repeats were taken. It is observed, however, that there is a very close consistency between the data collected due to the Cutler transmissions and those of the Seattle transmissions. EW structures should show opposite polarity in the Inphase (IP) and Out-of-Phase (OP) measurements. We hypothesize that the instrument was not distinguishing the different frequencies as they are very close (24Khz vs. 24.8Khz). This issue could be clarified with particular calibration tests. From modeling, we suggest that both measurements are due primarily to the Seattle transmissions.

Data Interpretation:

We concluded from our examination of the provided GPS coordinates of the stations that GPS information was not correct. Therefore, we chose to perform the interpretation in the grid coordinates.

The broad aspects of the data agree well with the magnetics which should be expected helping to confirm the usefulness of the data. Standard techniques were used to identify the axes of the major conductors. One particular area was chosen for closer examination and modelling due to the nature of the responses and that several areas of mineralization have been observed according to the geological map

Conclusions:

While there is a great deal of information in the VLF data, careful examination of the anomalies with the input of the geologists should be made. Over interesting targets a more detailed survey should be carried out prior to drilling.

# Introduction

Forward:
VLF (Very Low Frequency) electromagnetic (EM) survey techniques date back to the 1960's and prior. This technique is an offshoot of the AFMAG technique which is in itself simply a modification of a standard magnetotelluric induction vector technique. For many years, this technique was very popular not only in mining exploration but also in groundwater applications. However, in the last two decades it has gone out of favor in mining exploration in favor of newer ground time-domain EM techniques. However, the technique has seen some return to favor particularly because of the success of airborne AFMAG techniques which are analogous to VLF.

Most textbooks and geophysics courses cover VLF to some extent but the ability to interpret this data has been lost to some extent within the geophysics community. This has occurred primarily because the data collected by the older equipment was extremely difficult to interpret and older interpretation techniques were convoluted requiring a lot of experience to use correctly. However, newer equipment and software provides a more direct and easier means to interpret. However, it should be noted that the explanation of the VLF response in textbooks and references should be taken with a grain of salt. A very useful reference is which is relatively correct from a theoretical perspective is a *VLF Interpretation Manual* written by James Wright in 1988. But for more complete theoretical explanation of the physics involved, the reader should turn to magnetotelluric references on *tipper vectors*. A brief explanation of the principles behind VLF is given in Appendix A.

Survey:
A combined VLF and magnetic survey was carried out in December, 2012 by Jason Sigfrid using a combined VLF and magnetics instrument (GSM-19) manufactured by GEM systems of Ontario. The survey was carried out on a picketed grid of 25m station spacing and 50m line spacing on 27 lines and approximately 1100 stations. The data was collected in three days with the operator walking the lines in a general order of south to north on a line and north to south on the neighboring line as so forth. Approximately two (2) minutes was taken to cover the distance between stations and collect both the magnetics and VLF data. No repeats of any kind were taken as a quality control procedure. Data was collected for two transmitters, one at Cutler, Maine and the other at Seattle. Both transmitters operated at approximately 25Khz.

# Introduction (cont)

Survey (cont):
The grid lines are at approximately 17 degrees west of  North and are approximately 1 km in length and the survey is about 1.2km wide. The survey begin in the south just north of Highway 10 and stops at the shoreline of the southern arm of Twin Lake as indicated in Figure 1.


Figure 1  - Survey Lines

The positions of the lines is only approximate in GPS as we were  not provided sufficient GPS data to position the stations and lines. The GPS positioning was provided to us was clearly incorrect. The data was thus analyzed in the grid coordinates.  A geology map was provided in a pdf format as shown in Figure 2.  However, there is some type of distortion in pdf presentation  and thus must be utilized with some care to its limitations.

# Introduction (cont)

Survey (cont):

The provided geological map with survey lines, claim boundaries and some geographic features is shown in Figure 2. When attempting to register the raster output from this map, a distortion is found and it cannot be registered as a flat uniform gird.

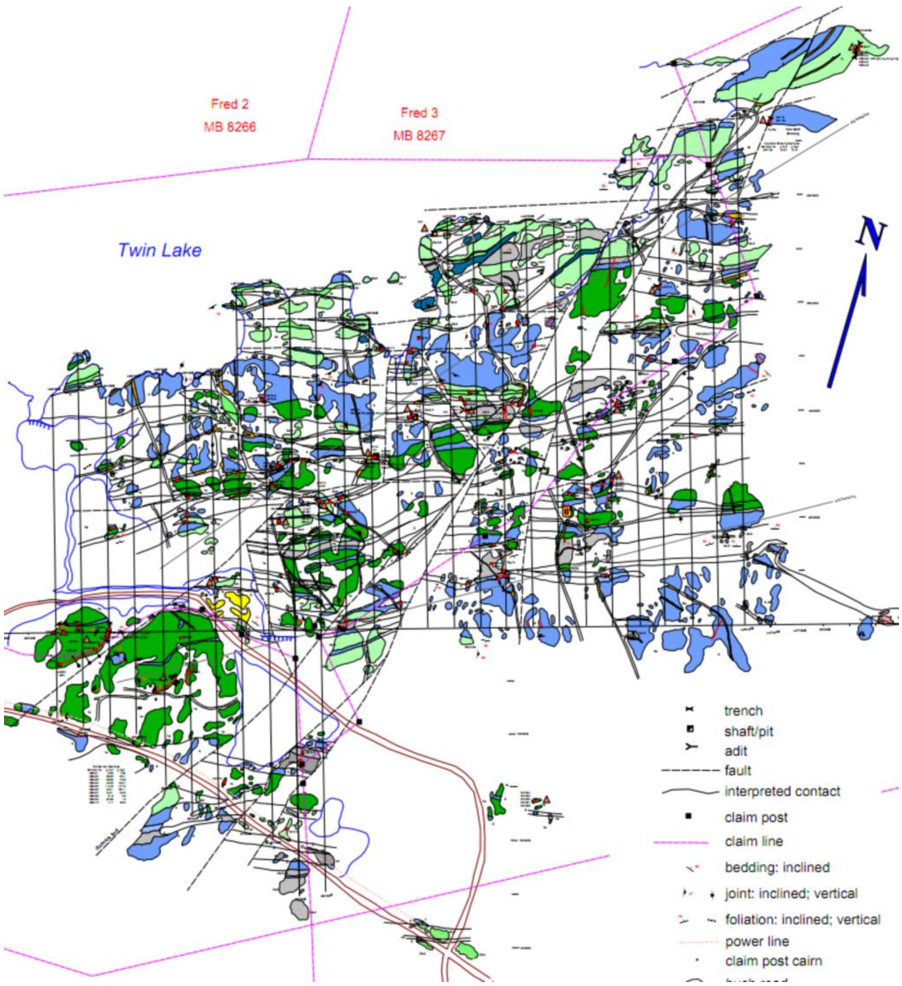



Figure 2 Geology Map

# Data Quality and Processing


**Figure 3:** IP (red) and OP(blue) VLF response along Line 33 50E.  Tx Cutler, Maine – azimuth 133 degrees

The difficulties involved in interpreting this data can easily be seen by plotting the responses along any of the lines. In Figure 3, the responses are shown along L3350E with stations close to the power line removed.  There is no anomalies with obvious shapes for interpretation but there are two rather large responses particularly at 2125N and 2300N. In the figure below, we see the response (IP and OP) for the next line east (3400E). There is some consistency in the response between lines.

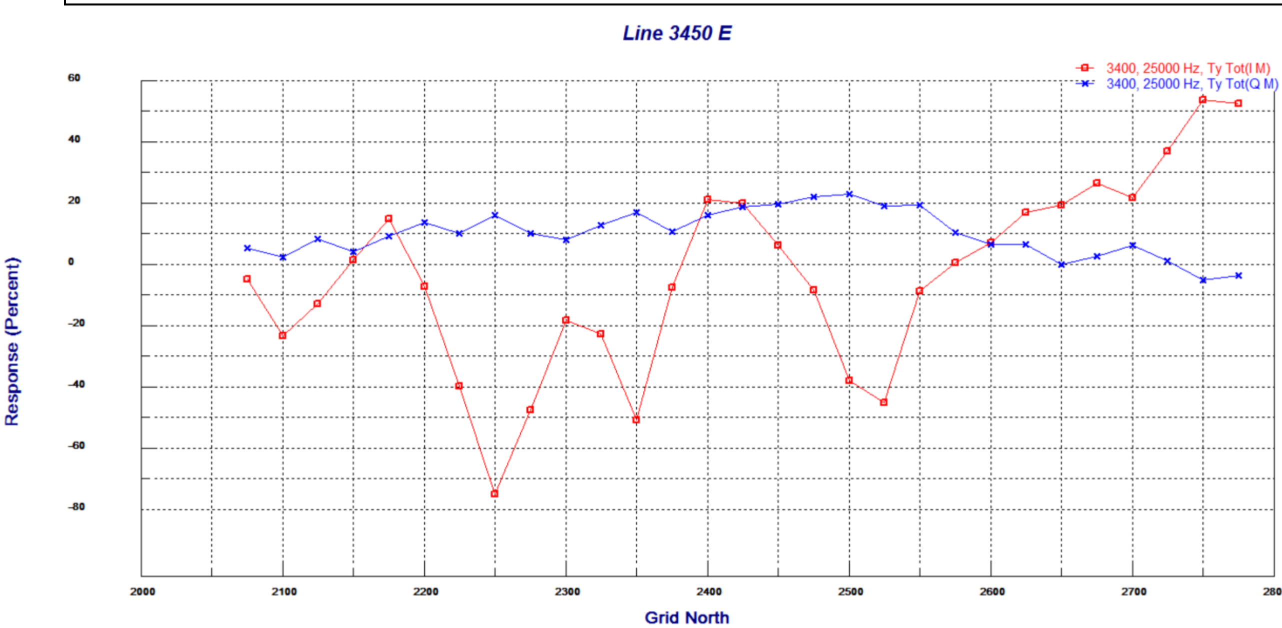



**Figure 4:** IP (red) and OP(blue) VLF response along Line 3400E.  Tx Cutler, Maine – azimuth 133 degrees

# Data Quality and Processing


**Figure 3:** IP (red) and OP(blue) VLF response along Line 33 50E.  Tx Cutler, Maine – azimuth 133 degrees

Figure 3 is repeated to indicated problems with regard to data collection and subsequent interpretation.  Important VLF responses tend to me narrow along the line and thus generally shorter station spacing is recommended . Stations in between pickets can be paced  for sufficient accuracy and thus data spacing at 12.5m spacings is not difficult to obtain. This would result in better magnetic resolution as well. Additionally, if a large negative or positive data outlier is observed such as seen at 2300N in the above line (3350E) then data spacing should be tightened to properly capture the shape of the anomaly.

Secondly, and of equal importance, is that no data repeats were collected. Thus, it can be difficult or impossible to distinguish between noise and the actual VLF signal to be measured.  As the data was collect at a rate of less than 2 minutes (on average) including walking, the addition of repeats would not impact  that significantly upon the time to collect the survey.  Walking the grid and walking into position would have taken the majority of the time for this survey. The addition of 2 repeats per station would have added approximately 1 minute or less to each station.

The resulting limitations on the data resolution and quality will significantly the quantifiable interpretation results.

# Data Quality and Processing

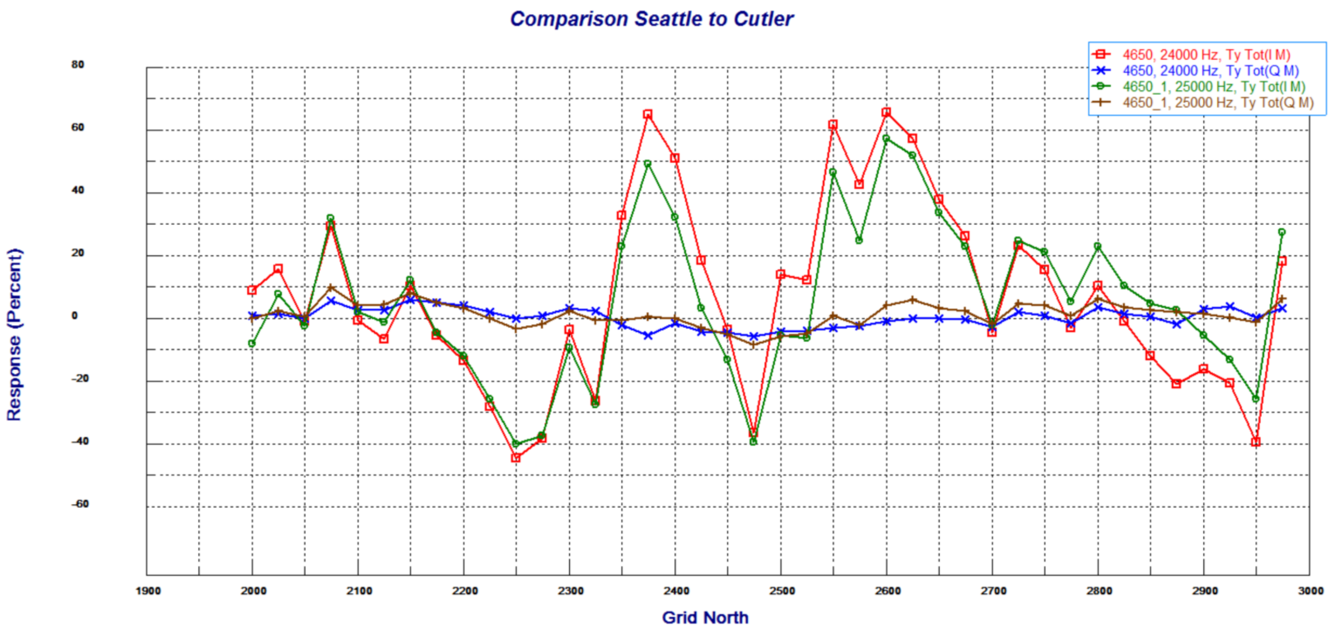



**Figure 4:** IP (red) and OP(blue) VLF response along Line 46 50E for Seattle and IP(green) and OP(brown) for Cutler,.

Figure 4 compares the data (IP and OP) resulting from the transmissions from Seattle and Maine. There is very close agreement which is not expected throughout the profile. In fact, the differences could be due merely to noise. Such agreement exists, generally, on all lines. It is suggested that there is either some fault in the instrument or there is internal processing which the manufacturer no longer understands and is not explained in the manual. Other experts which we have consulted also do understand this aspect of the data. Simple calibration experiments would clarify this issue.

# Data Evaluation

As we observe consistencies when plotting the response between neighboring lines, it is convenient to make a map or grid of the 4 data components ( IP, OP and for TX1 (Seattle) and TX2 (Cutler). The difference in the operating frequencies at the 2 transmitters is not geophysically significant. To the north, we observe a consistency with the magnetic response and in the central south, we also observe this consistency. The assists us in confirming the data results.

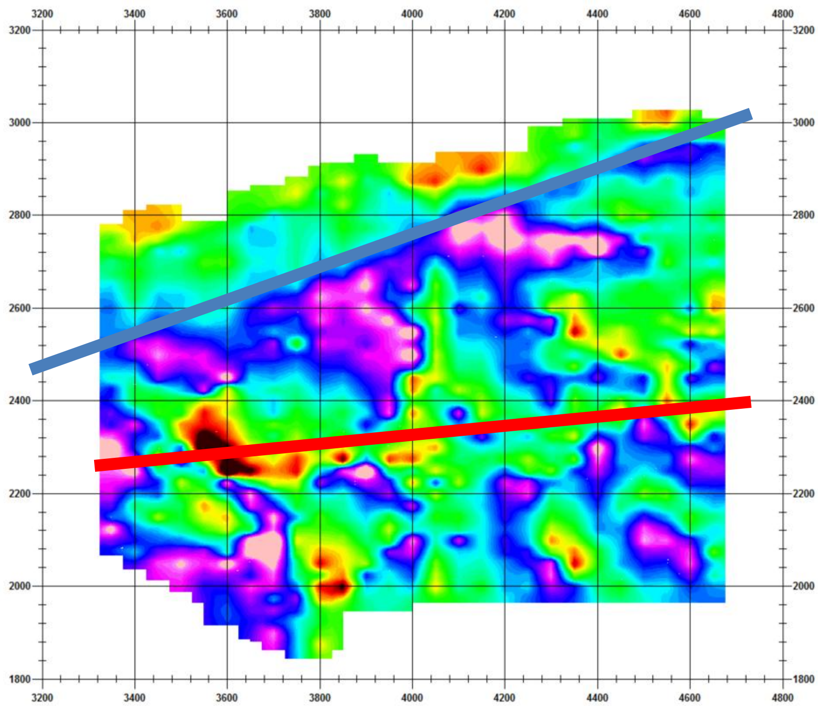
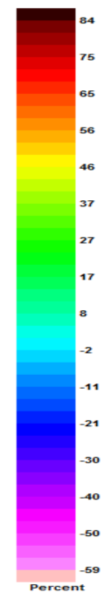



**Figure 5:** IP – Cutler Tx



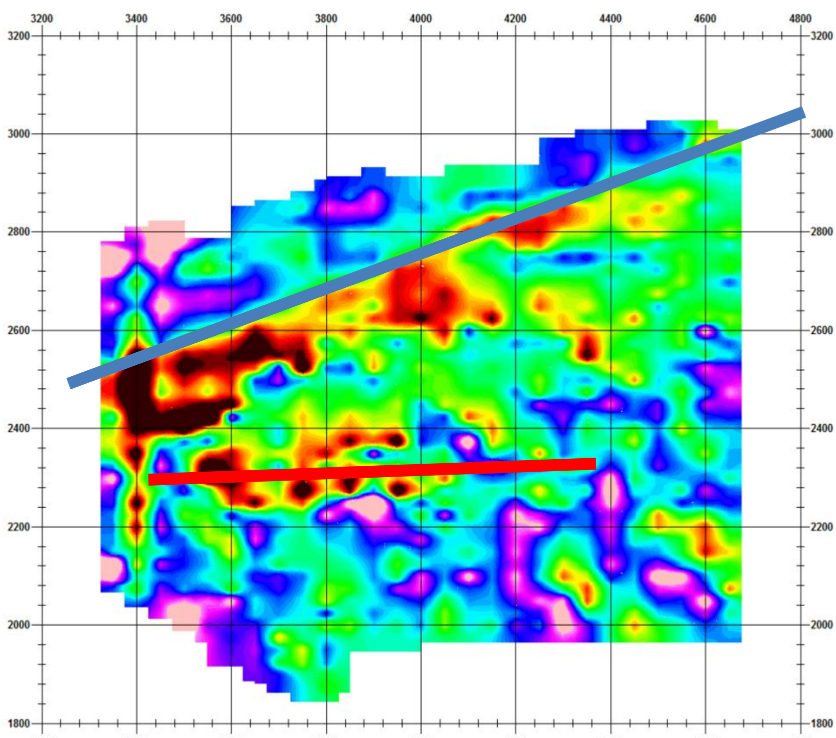
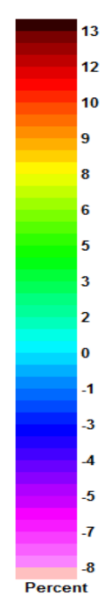




**Figure 6:** OP – Cutler Tx



# Data Evaluation

Fine details in the data are difficult to observe meaning fine features such as faults and contacts with mineralization are difficult to detect. This is possibly due to the wide station spacing but could be due to the lack of sharp linear features. However, two larger linear features are observed. One indicated by the blue line in Figures 7 and 8 follows the general strike in the North of the magnetic data but also appears coincident with the southern lake edge. The other linear feature, indicated by the red line, is more to the south and this is more EW which is consistent with a magnetic feature. The EW feature is the most interesting of these features particularly between 3500E and 4300E observed in both IP and OP. The NE to SW trending feature in the north will be examined later as a possible lake effect.

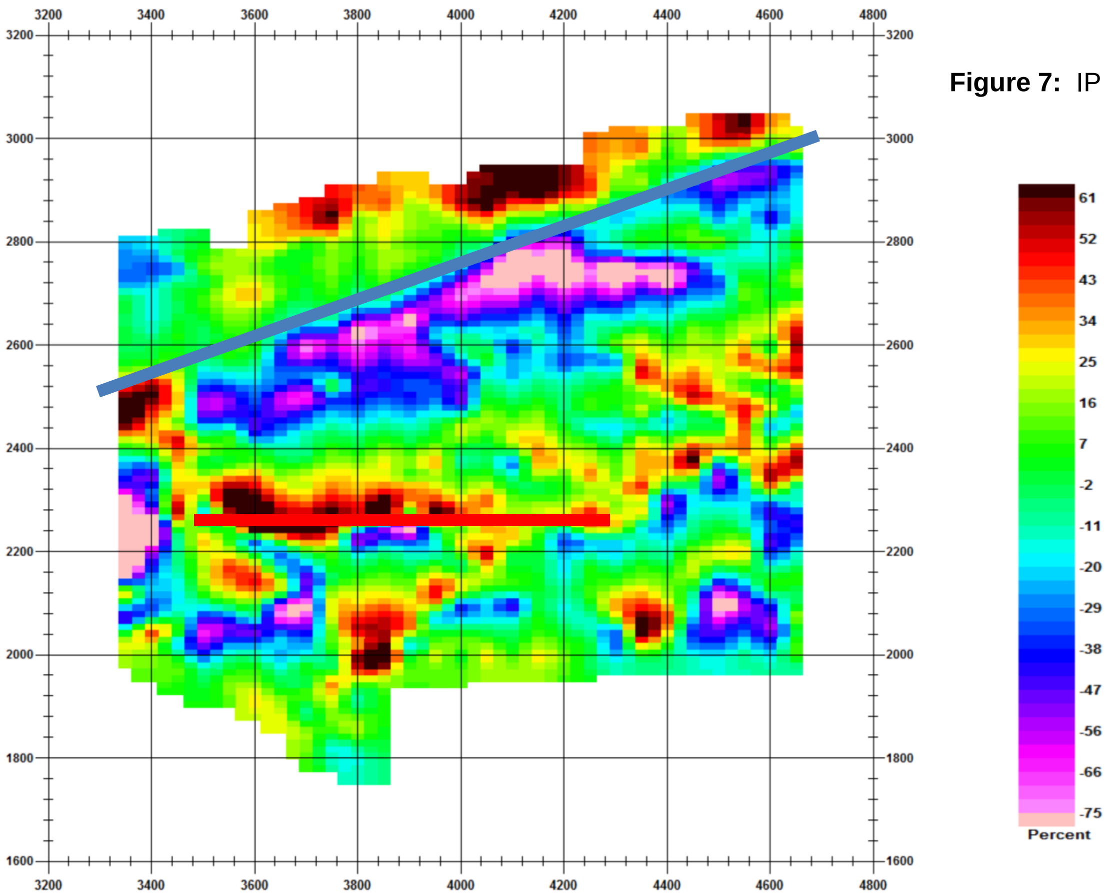



**Figure 7:** IP – Seattle Tx

The IP data due to the Seattle transmitter is shown in Figure7. The NE to SW structure (blue) to the north appears again as does the EW (red) at about 2300N as is indicated.

# Data Evaluation

The OP data due to the Seattle transmitter is strikingly different from the other data components. While the NE-SW trend remains , the EW trend appears to be the southern edge of a wide, NE-SW structure. In general, the OP data is considered to be less reliable that the IP data.

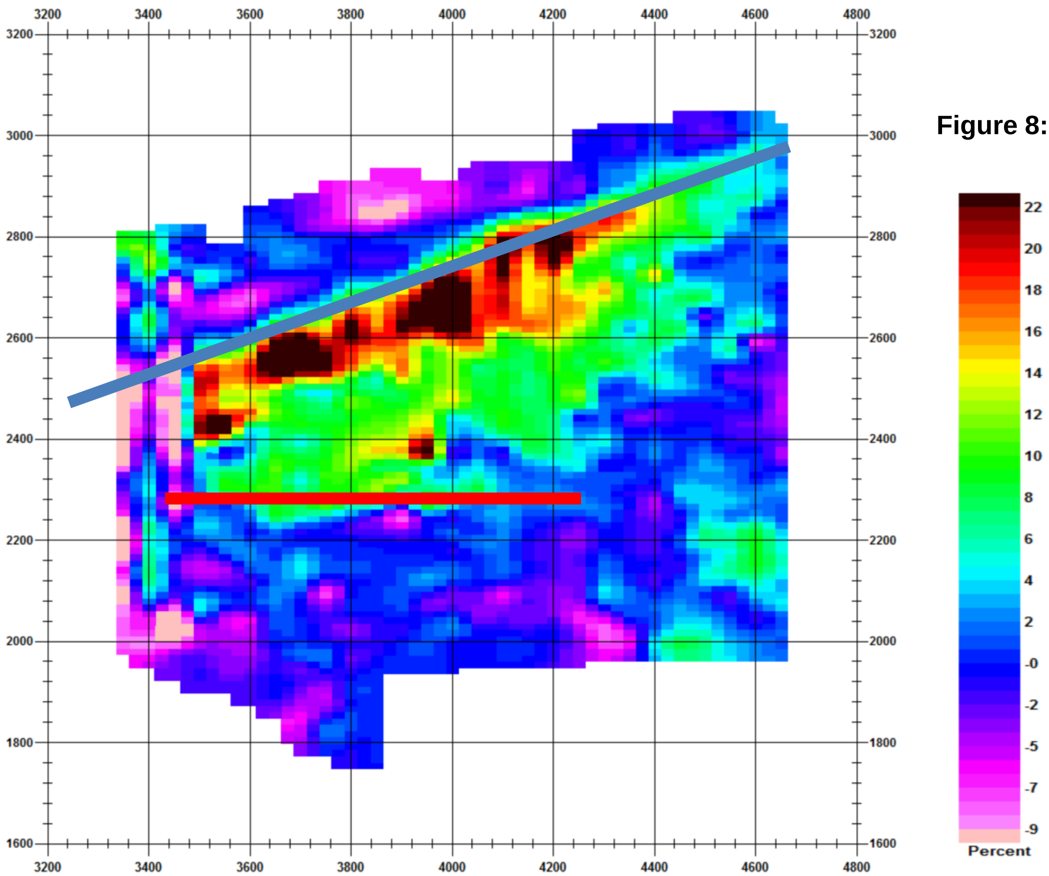



**Figure 8:** OP – Seattle Tx

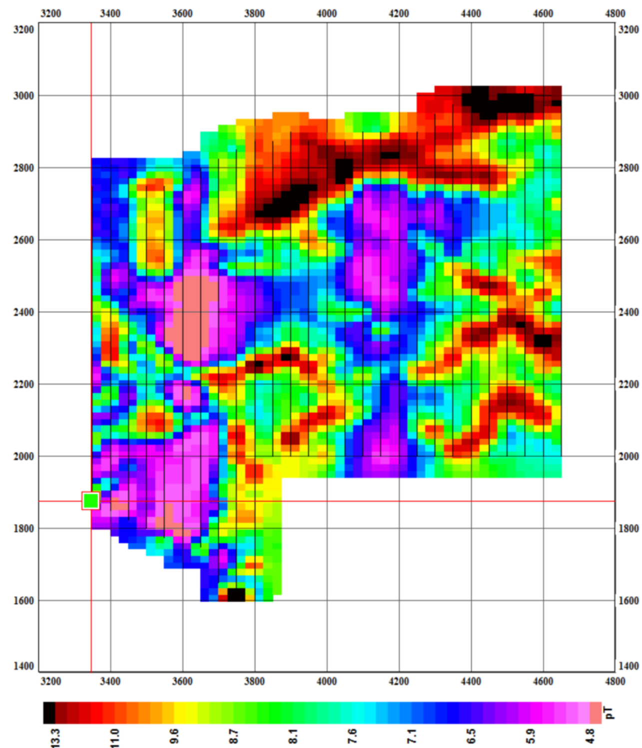
# Data Interpretation – Total VLF response

In most instances, there will be little response to a resistive structure and thus the general purpose is to detect conductive structures with a VLF survey.  A conventional understanding is that the total VLF amplitude will map the axes of any conductors. This data consists of the amplitude of the 3 components of the VLF signal – (Bx,By,Bz). The particular instrument (GSM-19) used for this survey is very convenient for obtaining this data as there are 3 coils in the instrument to measure these 3 data components and the standard output for the data contains a channel with this amplitude in units of picoTesla (pT). Thus, we will first examine this data for both the Cutler and Seattle stations.

## Total VLF - Seattle

**Figure 9:** Total – Seattle Tx Equal Weight (area)

*each colour range has the same number of cells*



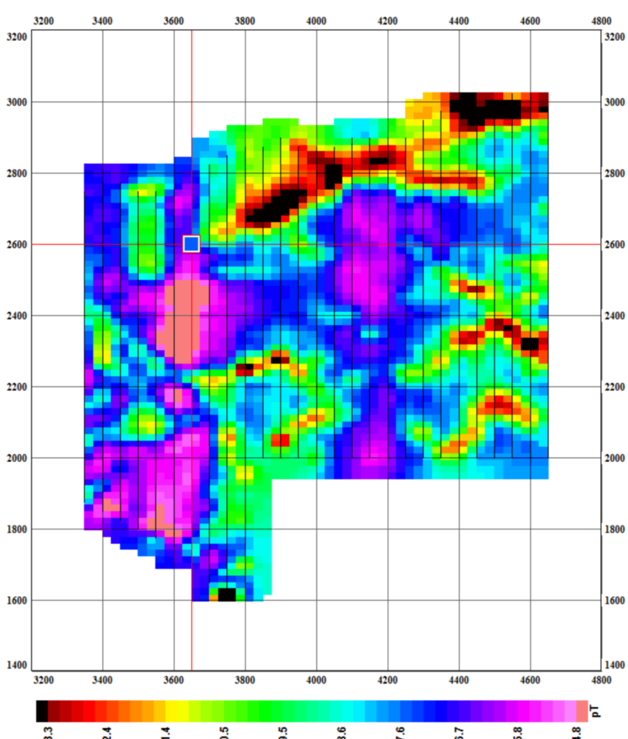




**Figure 10:** Total – Seattle Tx Equal Range)

Equal Range
- standard distribution

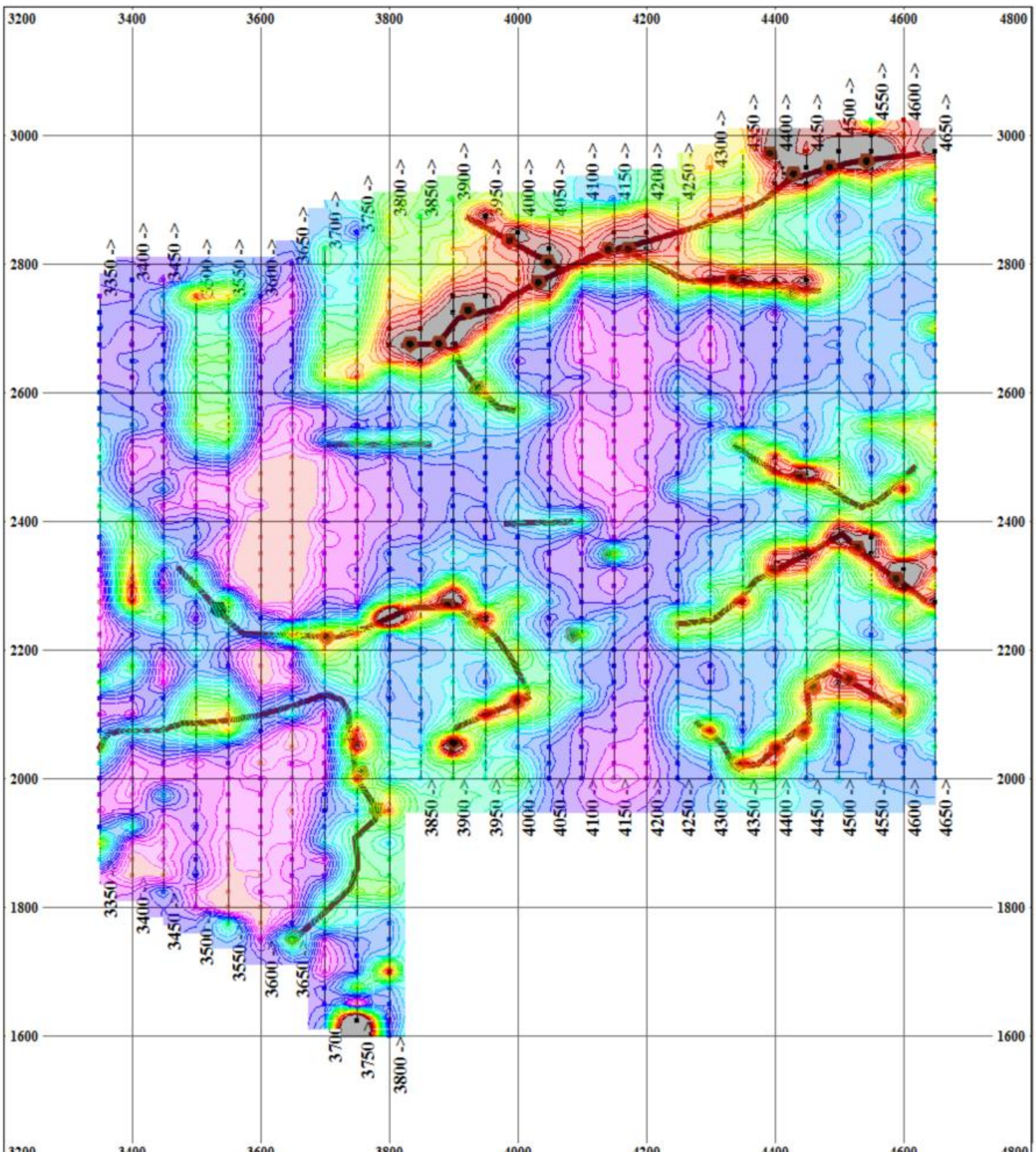
# Data Interpretation – Total VLF response

Here, we outline the main conductors as indicated by the total VLF response due to the Seattle transmission. The interpreted axes of the conductors are indicated by solid lines with specific stronger areas indicated with black dots. A large response is indicated by red to dark brown while a small response is indicated by purple to pink response.

## Total VLF - Seattle

Seattle Total VLF
*main conductors outlined*

**Figure 11:** Seattle Total VLF *main conductors outlined*



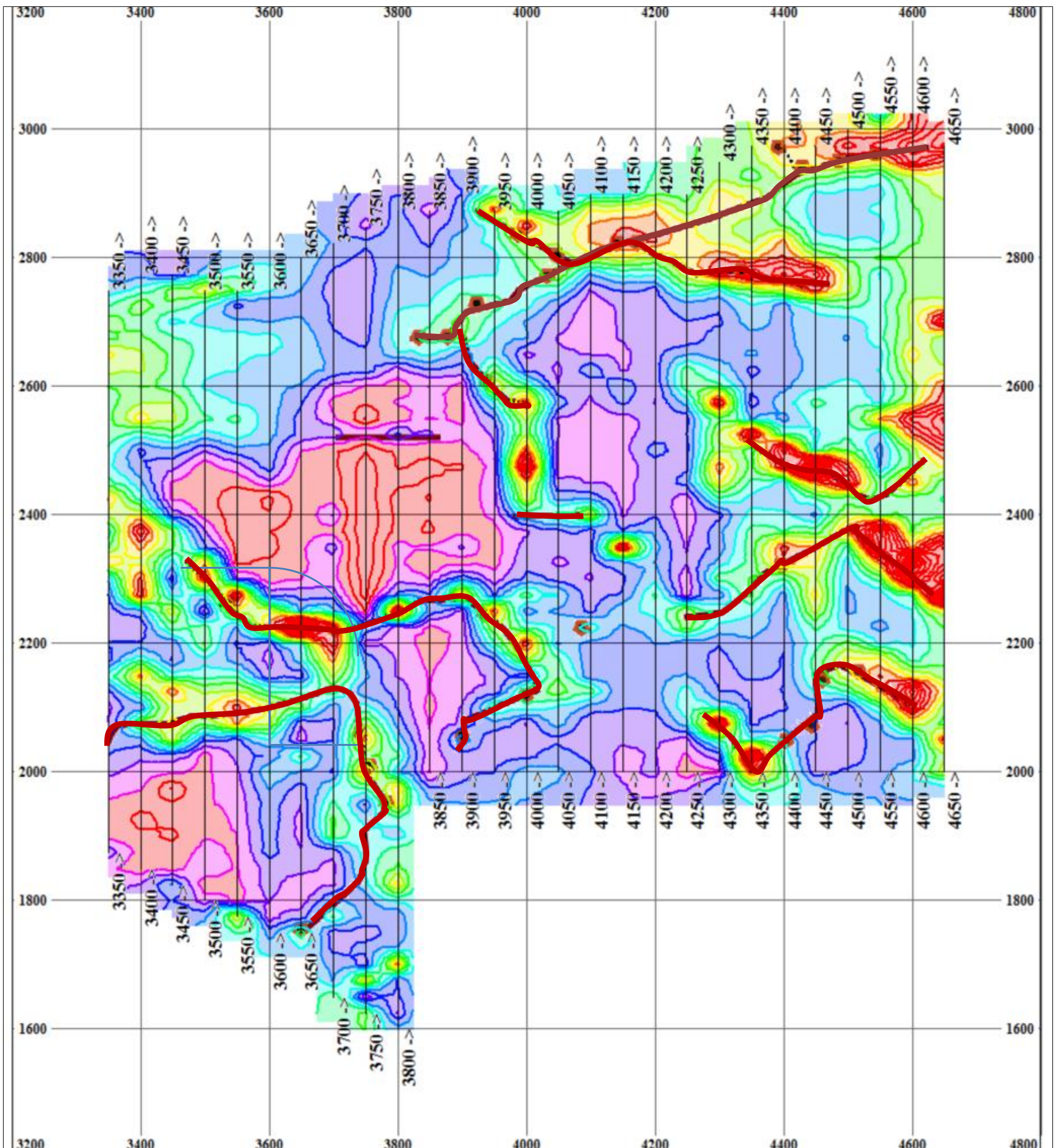
# Data Interpretation – Total VLF response

Here, we duplicate the total VLF response due to the Cutler transmission but outline the Seattle conductors for correlation between the two signals.. Correlation is quite good with some additional conductors indicated. These conductors may not be orientated to provide a response from the Seattle signal.

Cutler Total VLF
*main Seattle conductors outlined*

Total VLF - Cutler

**Figure 12:** Cutler Total VLF *main Seattle conductors outlined*



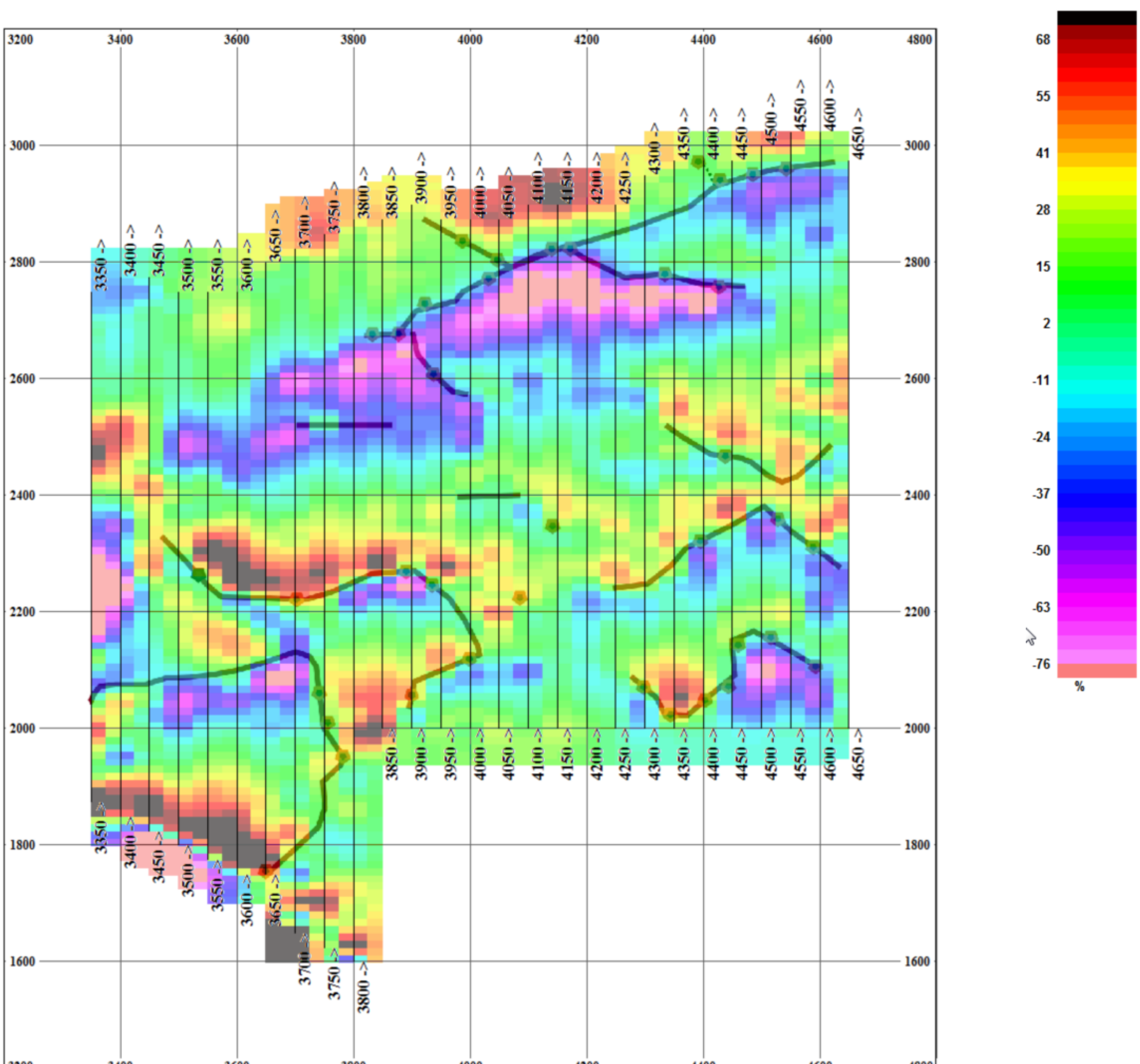
# Data Interpretation – Normal Vertical VLF IP

The standard VLF response is the vertical field (Hz) divided by the total horizontal response (Hx,Hy) and shown in percent. For a conductor, parallel to the primary electric field and perpendicular to the primary magnetic field, the response should show a cross-over as the survey progresses over the conductor. Thus, this normal response will change signs on either side of the conductor and be zero over the conductor.  To quantifiable interpret the strength, dip, depth, etc of the conductor this response is needed but mapping this response should show a correlation between the zeros of this response and the axes of the conductors as indicated by the total VLF field.

Generally, the IP zero response correlates with the axes of the conductors as indicated by the maxima of the total VLF response as shown in Figure 13. However, of concern, is the strong NE to SW trending structure which would appear to correlate with the boundary of the lake. As the lake bottom could contain sediments it could provide a VLF response. This will be examined in the following page.

Figure 13: Seattle Vertical  IP VLF
*main conductors outlined*

Vertical Hz Normalized

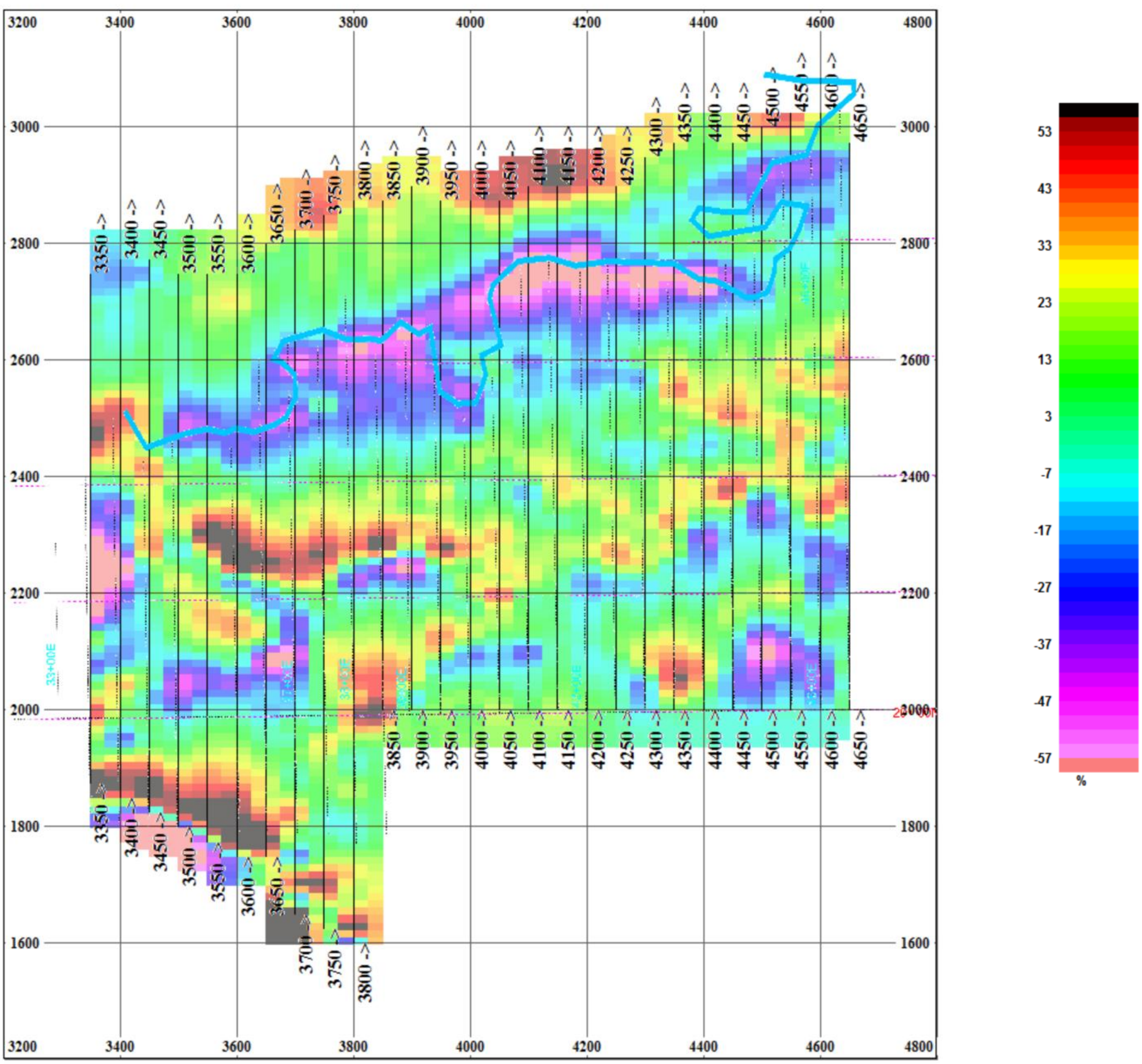


# Data Interpretation – Normal Vertical VLF IP

The correlation between the shoreline and the VLF data is made difficult as we do not have accurate GPS information for the VLF stations. However, GPS measurements for just a few stations would rectify this problem.

However, as indicated, below our guess as to the shoreline shows that the VLF response which trends SW to NE in the north could be due to the boundary between the lake and the shore.

Figure 14: Seattle Vertical IP VLF
*shoreline outlined (blue)*

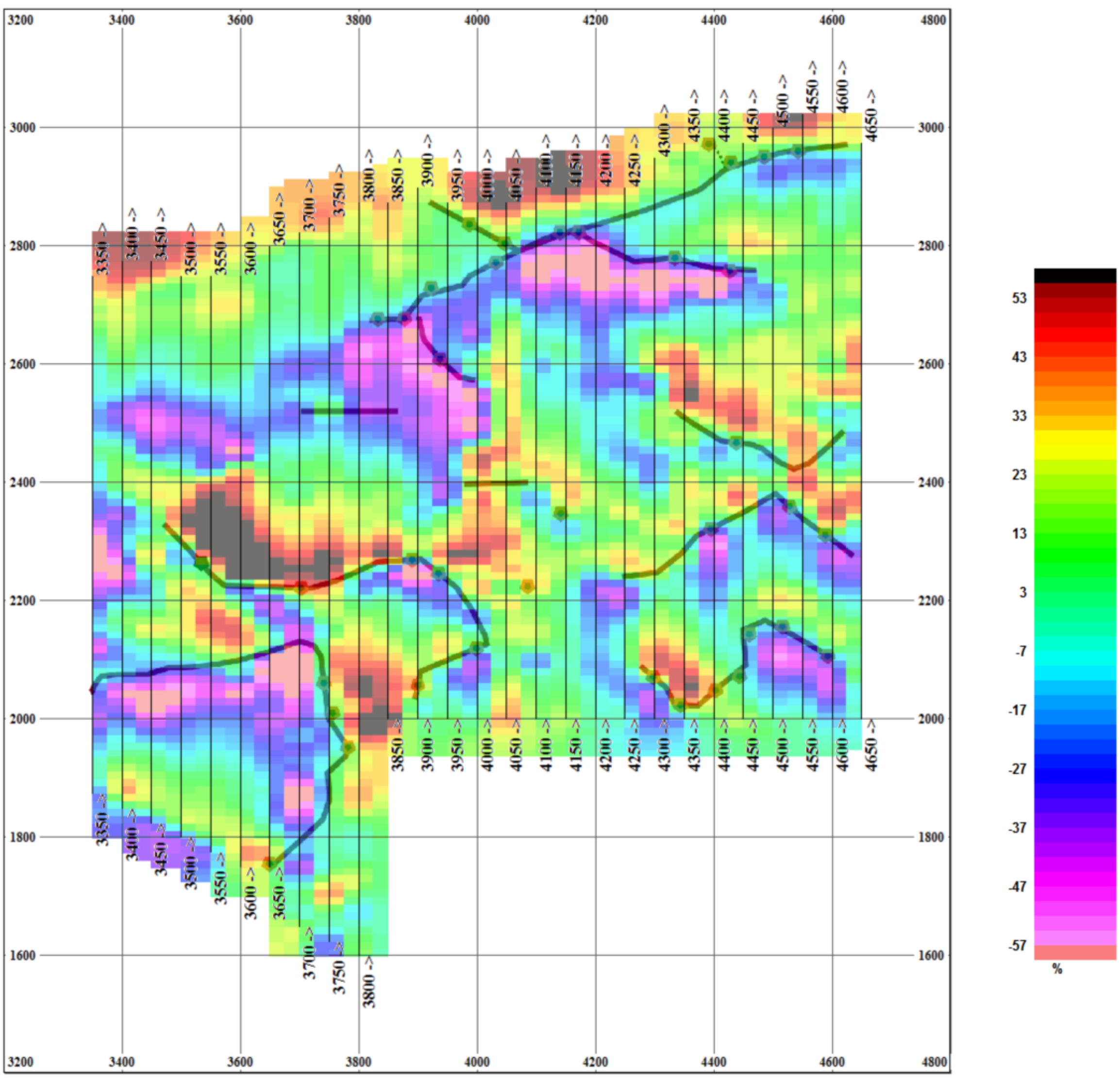


# Data Interpretation – Normal Vertical VLF IP

Finally, we show the Cutler standard vertical response (IP) with the Seattle conductor axes outlined. This appears to confirm the presence of the majority of conductors as indicated by the data due to the Seattle transmission.

Figure 15: Cutler Vertical IP VLF
*Seattle main conductors outlined*

Cutler Vertical IP Hz Normalized

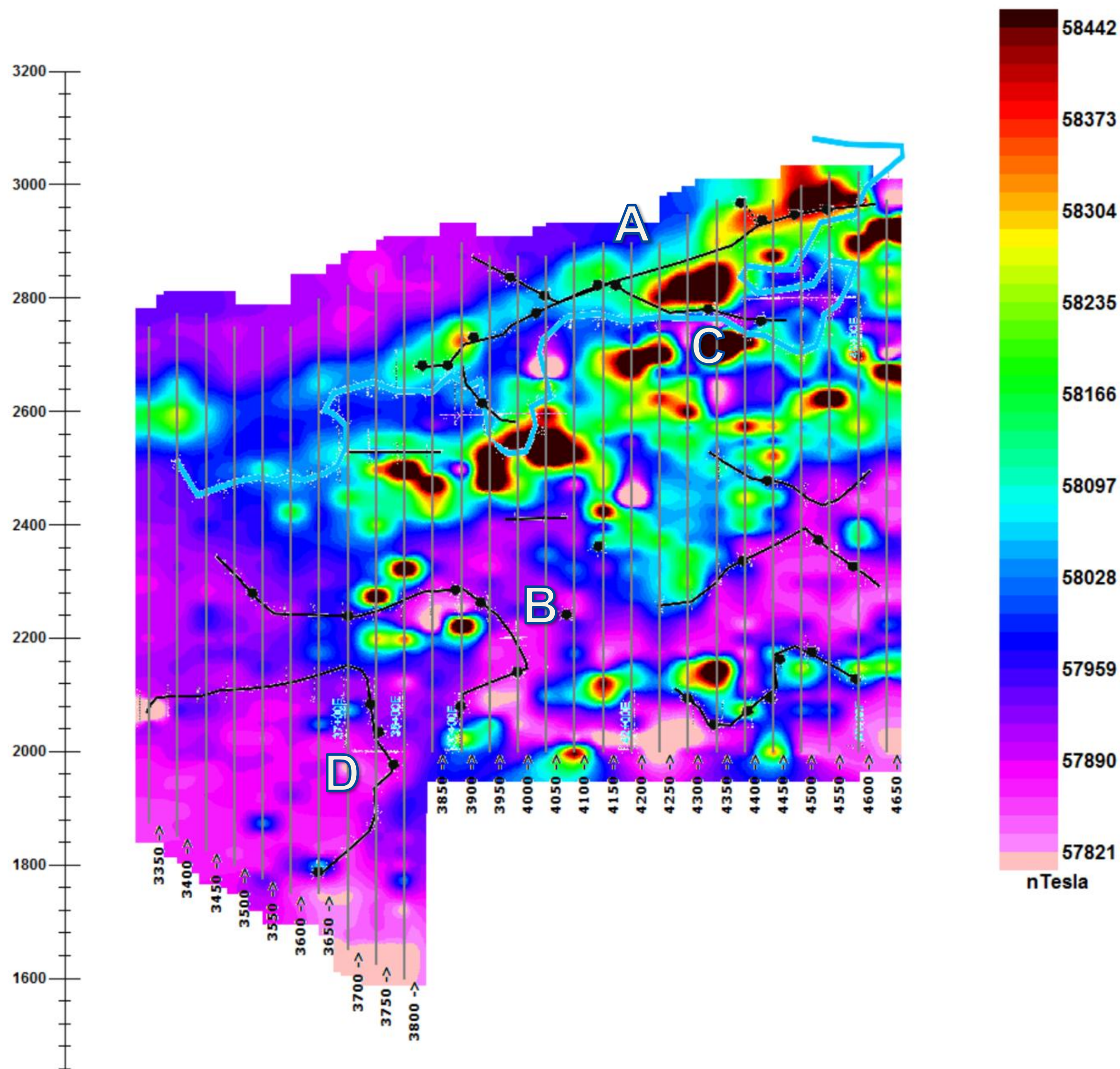


# Data Interpretation – Correlation with Magnetics

We first examined the relationship between the magnetics and the VLF anomalies. Figure 16 is a contoured display of the magnetic data with the VLF anomaly axes outlined in black and the shoreline estimate outlined in blue. Magnetic highs in red to dark red-brown, magnetic lows in pink with median values in green. Note that the average magnetics is a low compared to the world model implying a regional low.

For the NE-SW VLF anomaly in the north, it is clearly in the lake and an associated with a ridge of magnetic highs (A). But, there are several other interesting correlations with the magnetics and VLF. For example, B,C and D. The feature (C) partially corresponds to a fault as per the geology map. The feature, B, correlates with several features on the geology map including a small area of mineralization.

Figure 16: Magnetic Data

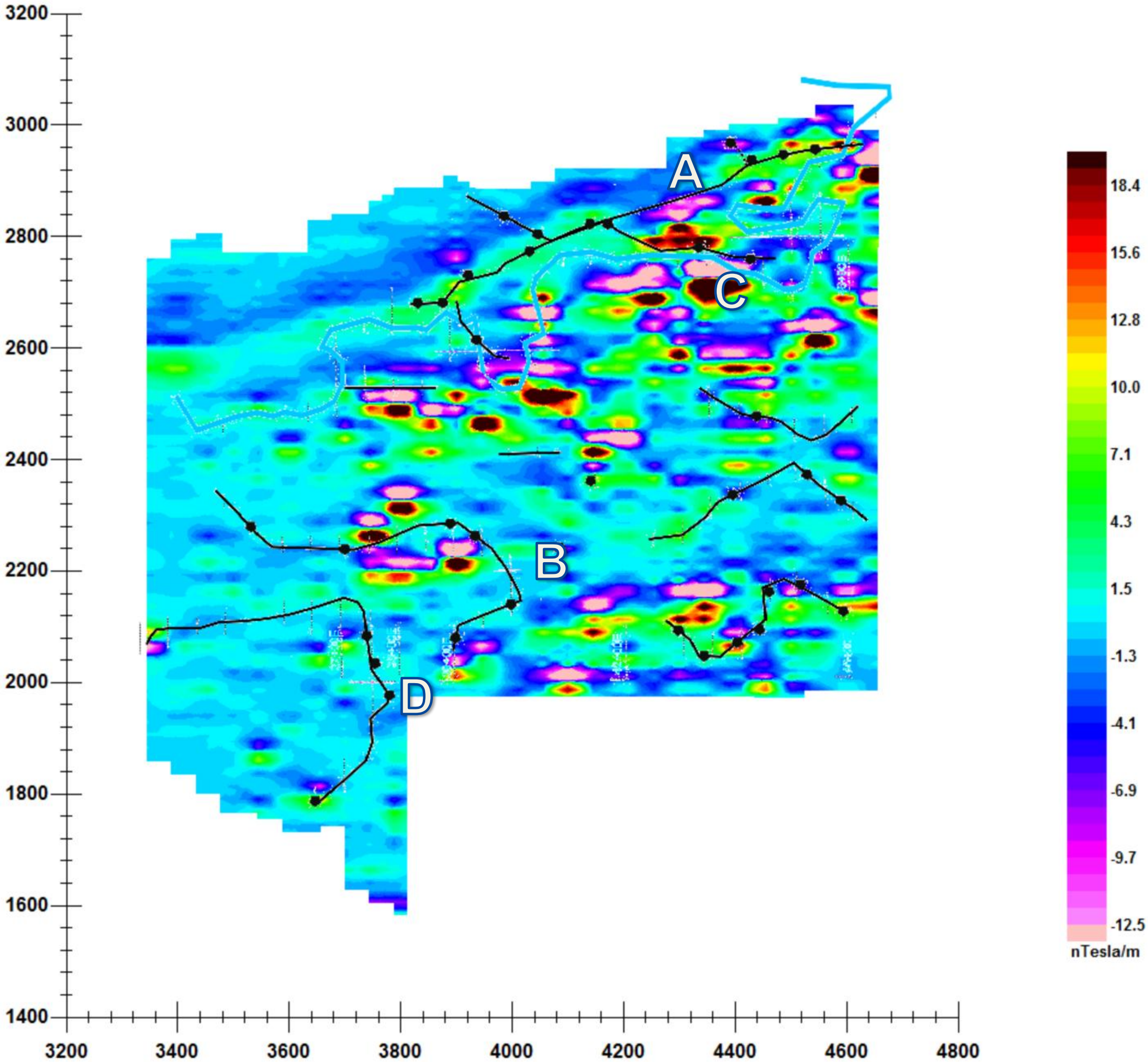


# Data Interpretation – Correlation with Magnetics

Another look at the magnetics is in regard to the change in the magnetic variation with position along the survey line. This is termed the NS gradient of the magnetic field. In this case, a zero is when light blue transitions to a darker blued and this maps either a boundary of magnetic material or a region of low magnetic variation.

Figure 17: Magnetic Data – NS gradient

*Seattle main conductors outlined (black) with shoreline (blue)*

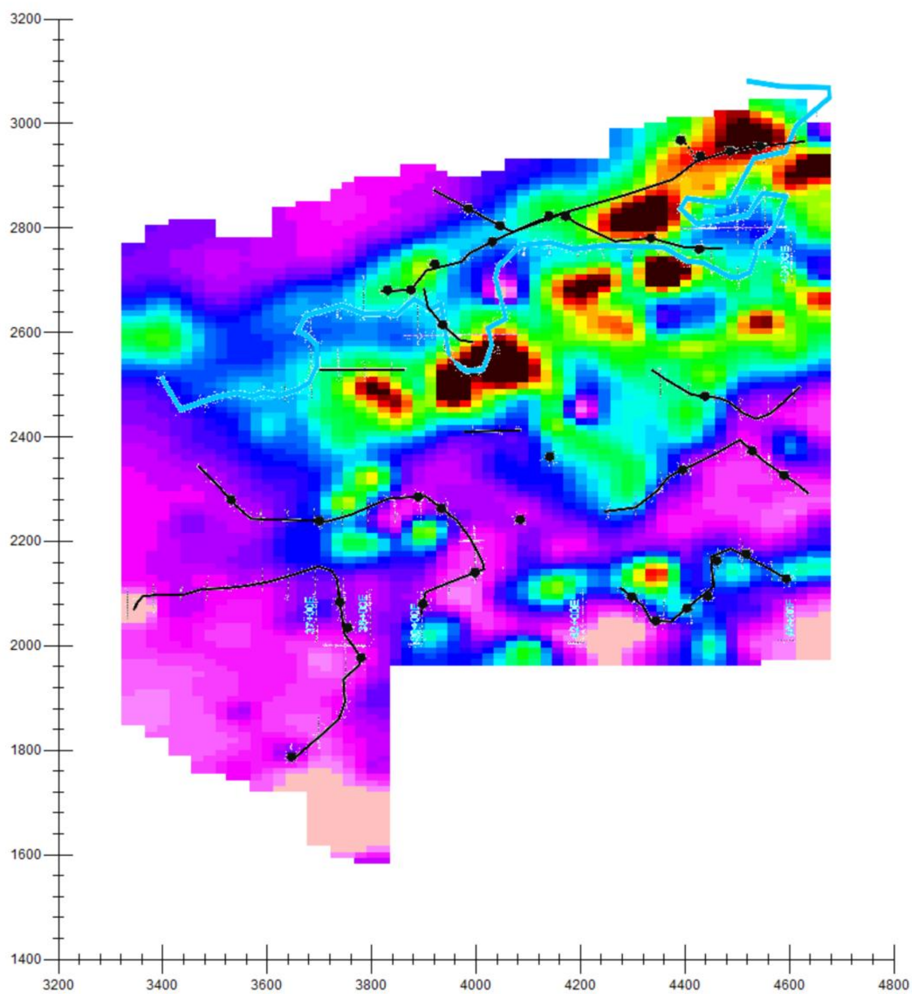


# Data Interpretation – Correlation with Magnetics

Of course, it is possible that the magnetic-VLF correlations are due merely to shallow materials. One means to try to answer this question is to upward continue the magnetic data. In this case, we upward continued the data to only 15m (about ½ the elevation of a helicopter borne magnetic survey. The results pose some interesting possibilities for the cause of the VLF anomalies.

Figure 18: Magnetic Data – Upward Continued 15m

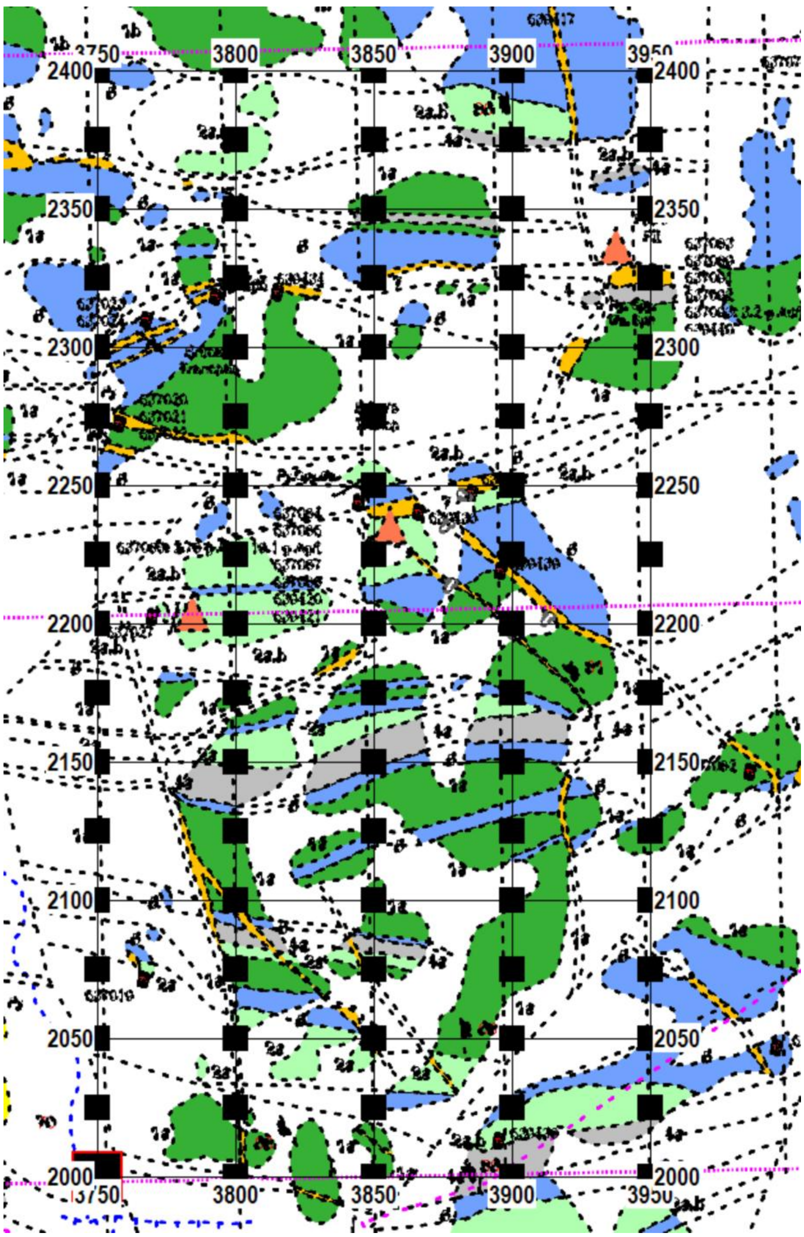
*Seattle main conductors outlined (black) with shoreline (blue)*



# Modeling Studies – Area B

We have chosen to look more closely at Area B referred to earlier. Figure 19 shows the data stations against the geological map. There is some rotation of about 1 degree in the geological map vs. the grid lines and some NS compression. Mineralization is indicated by orange and we can clearly see that the VLF station spacing is far too coarse to resolve the interpreted mineralized width.

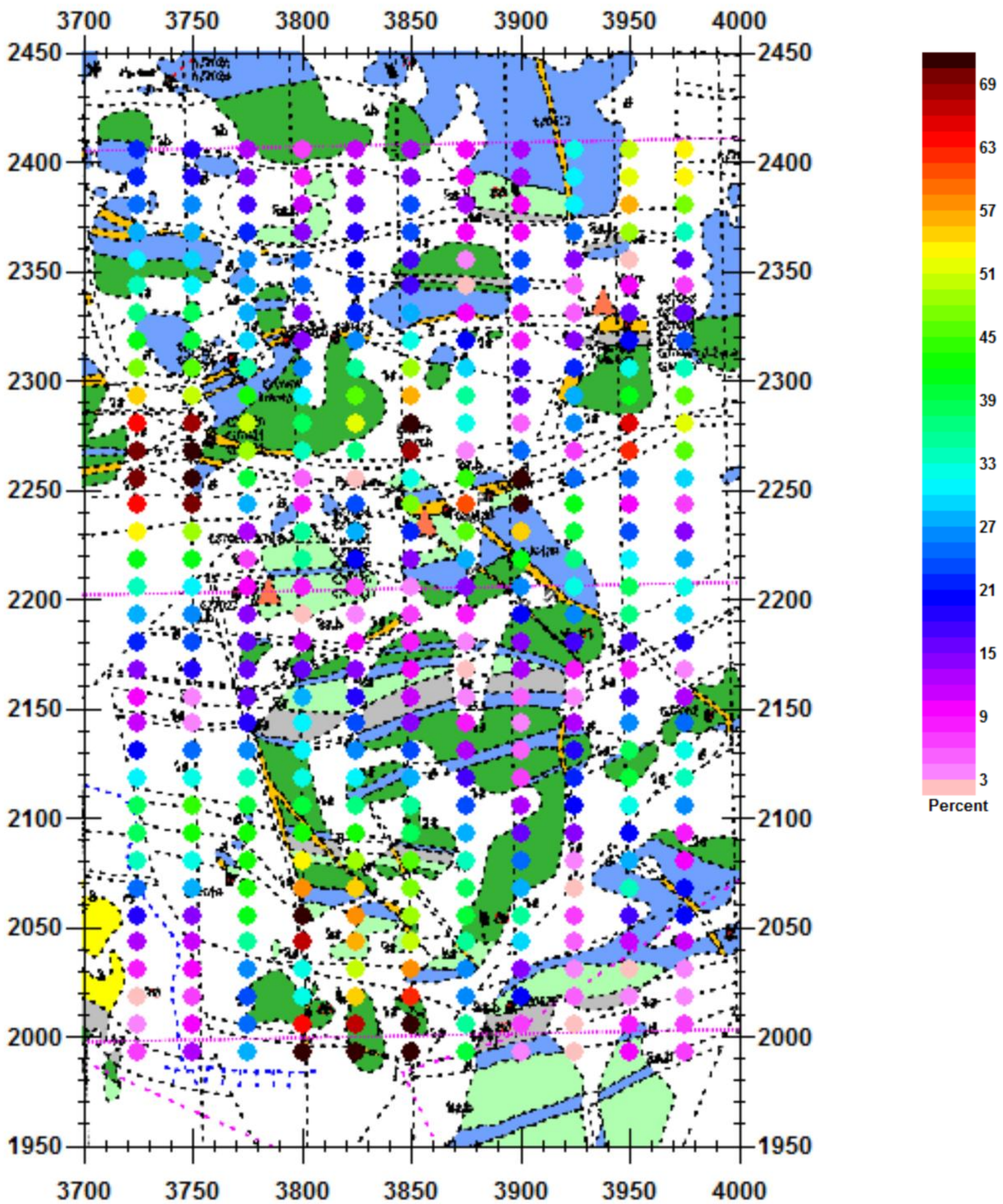
**Figure 19:** VLF Stations vs. Geological Mapping



# Modeling Studies – Area B

When creating a map of any data (e.g. VLF Hz amplitude), we first interpolate the data to a regular Cartesian grid. In this case, the grid is half the station spacing and half the line spacing. Any finer interpolation could create artifacts which do not represent the data. We can see here with the geology underlain that the grid is too coarse to resolve the identified mineralization.

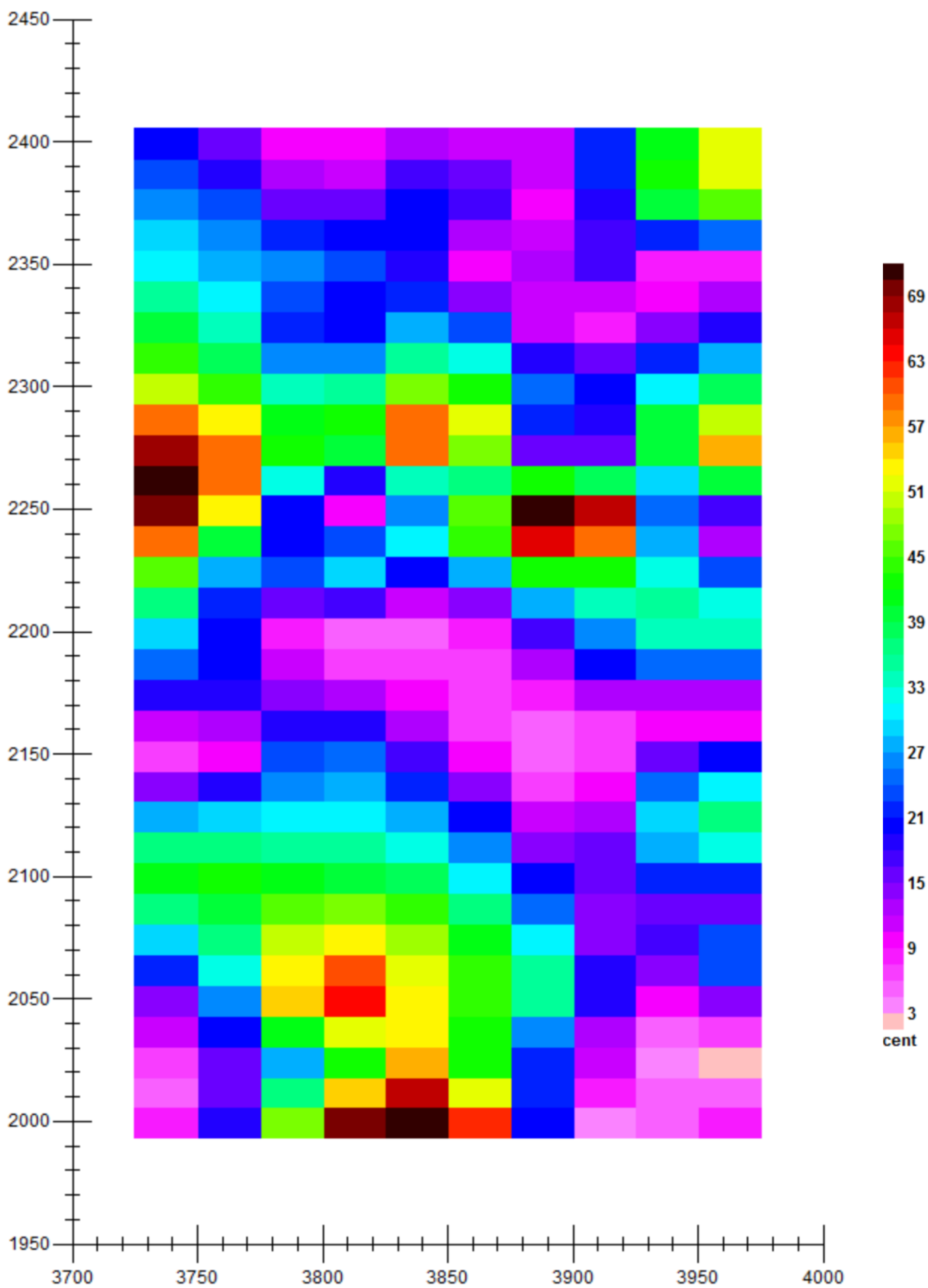
**Figure 20:** VLF Grid vs. Geological Mapping



# Modeling Studies – Area B – Cutler TX

Prior to contouring, we can see in Figure 21 that the interpolated map is very coarse compared to the interpreted geological structure. Nevertheless, we will attempt to geophysically model the VLF response.

**Figure 21:** VLF map Cutler TX



# Modeling Studies – Area B

In Figure 22, we contour the data and show the data points in the same color scheme. This shows that most of the fine features indicated in the contour are only supported by a single data point. This points again to the issue of coarse data sampling and lack of repeats to ensure that these data outliers are not noise.

However, there is considerable correlation between VLF highs and mapped mineralization. Some of these are indicated by the gold lines to represent approximately the mineralization as mapped. Otherwise, there are a quite interesting variations which correlate with mapping of other geological features. To understand these issues properly would require the geologist sitting down with the geophysicist to investigate some specifics.

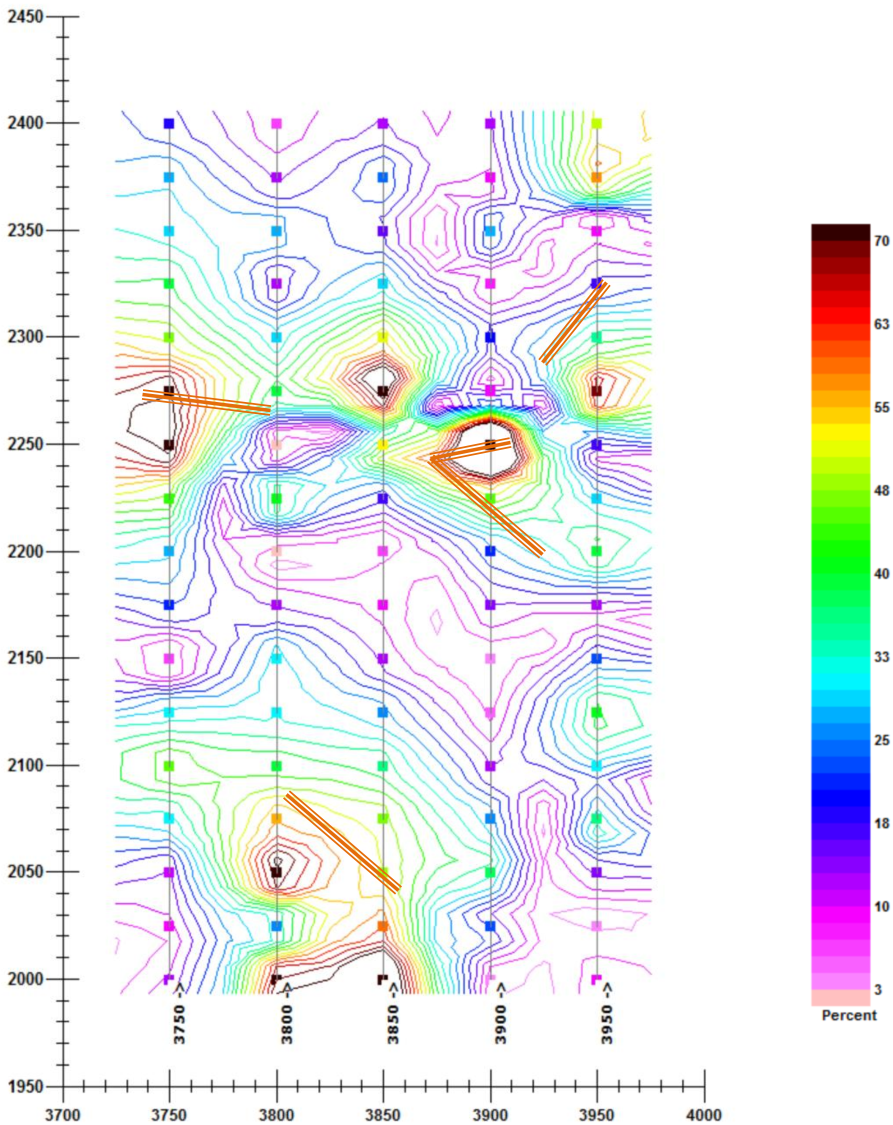



**Figure 22:** VLF contour with Data Points

# Modeling Studies – Area B

Figure 23 is the same representation of the data as Figure 22 However, we have underlain the geological map attempting to image the VLF w.r.t the geology.

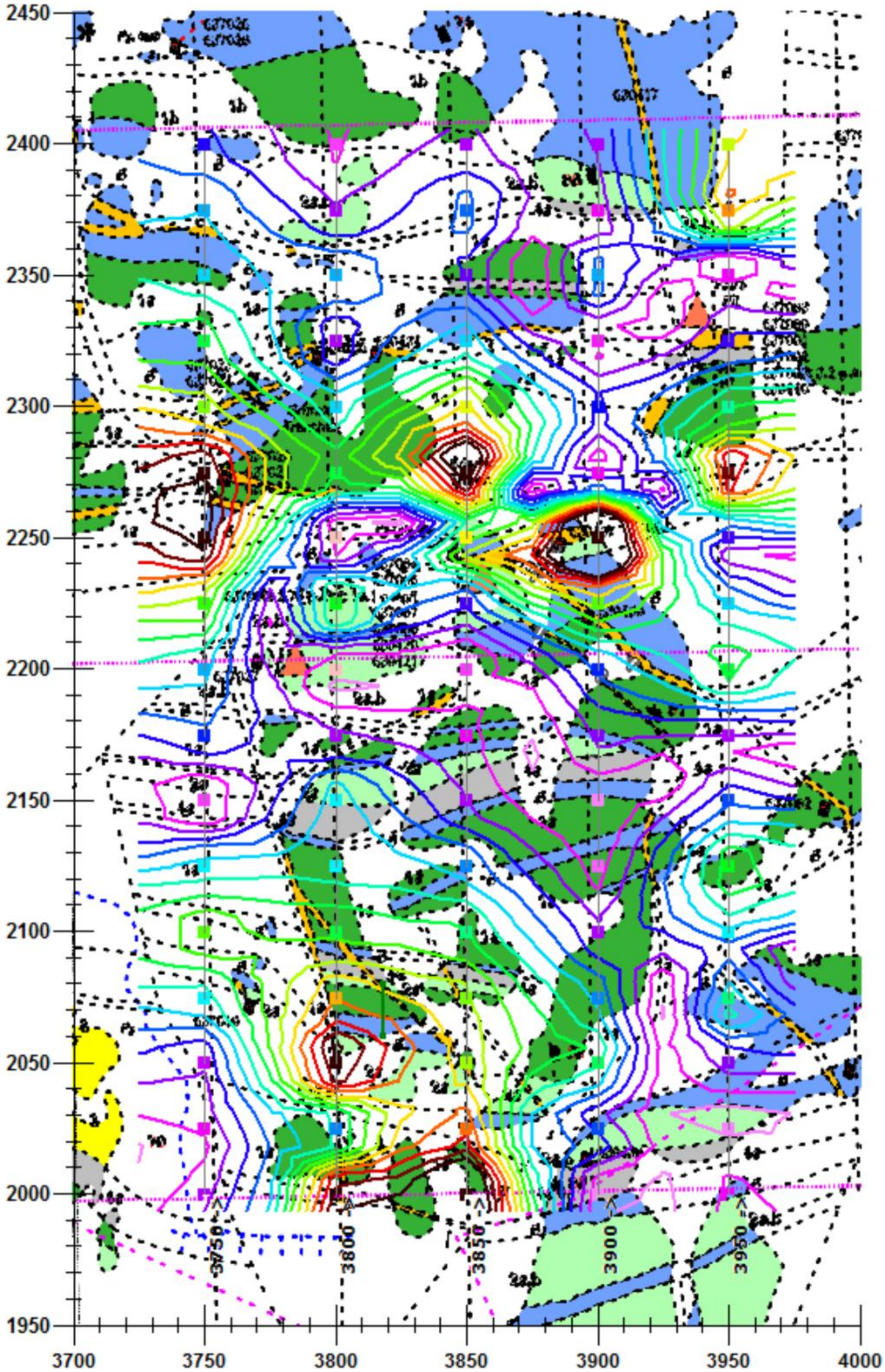



**Figure 23:** VLF contour with geological map

# Modeling Studies – Area B

Figure 24 is the IP VLF contoured and filled and made partially transparent over the geology map. Greens are a low response while reds are large positive and pinks large negative. All the areas of larger response appear to be over or near areas of mineralization. The interpreted axes of the principle E-W structure is shown by large black dots where it crosses each of the survey lines. The accuracy of interpreting this axes is , of course, limited by the data spacing. There is some correlation with this axes to two mapped faults, one EW and the other SW to NE connecting near Line 3800E.

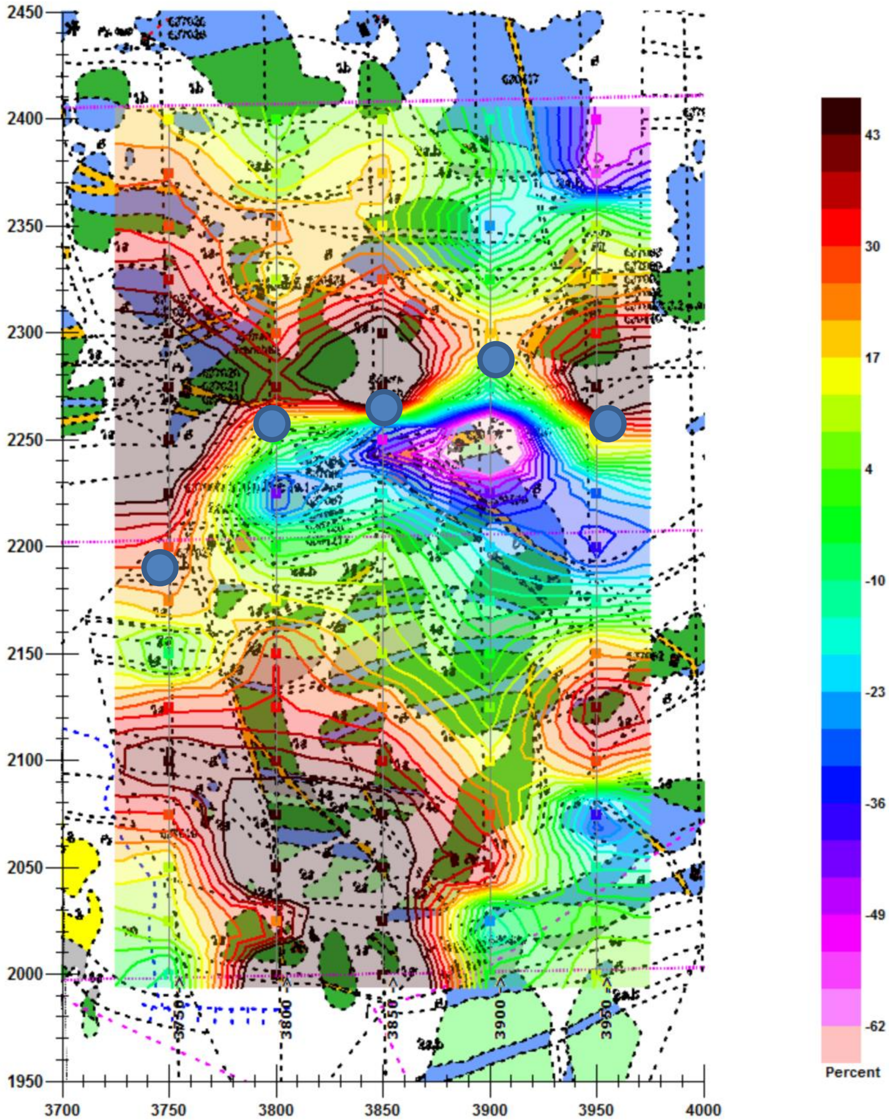



**Figure 24:** Cutler IP VLF contours with geological map

# Modeling Studies – Area B
# Quantitative Modeling – Cutler Tx

For the following work, we attempt to reproduce the signals or data values which were measured. This method requires mathematically representing the propagation of the source to the area and then to numerically simulating the response of a particular geological model to the source and then representing the resulting EM fields in the manner that the instrument outputs. Thus, these mathematical exercises requires mathematically representing the source of the fields, the nature of the instruments and finally the interaction of the geology with the EM fields which arrive at the local of the model of the geology.

The VLF signals will respond primarily to conductors which is why this system is used for exploring for mineralization. However, the response is due in part and in several different ways to the resistivity of the surrounding rocks. We do not know the resistivity of the surrounding rocks and in particular is there is a conductive cover and what are electric properties of this cover, is there a zone of weathering below the cover and what is the resistivity of this zone. Over the years, we have worked on other properties relatively close to this property with closest about 40km away. Thus, for the purposes of this modeling we are assuming a very resistive host rock of over 5000 Ohm_m with a very thin and not especially conductive cover.

Figure 25 is a series of plots of the IP response from south to north along the 5 lines in Zone B. One anomaly seems quite clear and covers the 5 lines and shows negative to positive crossovers on 4 of the 5 lines.

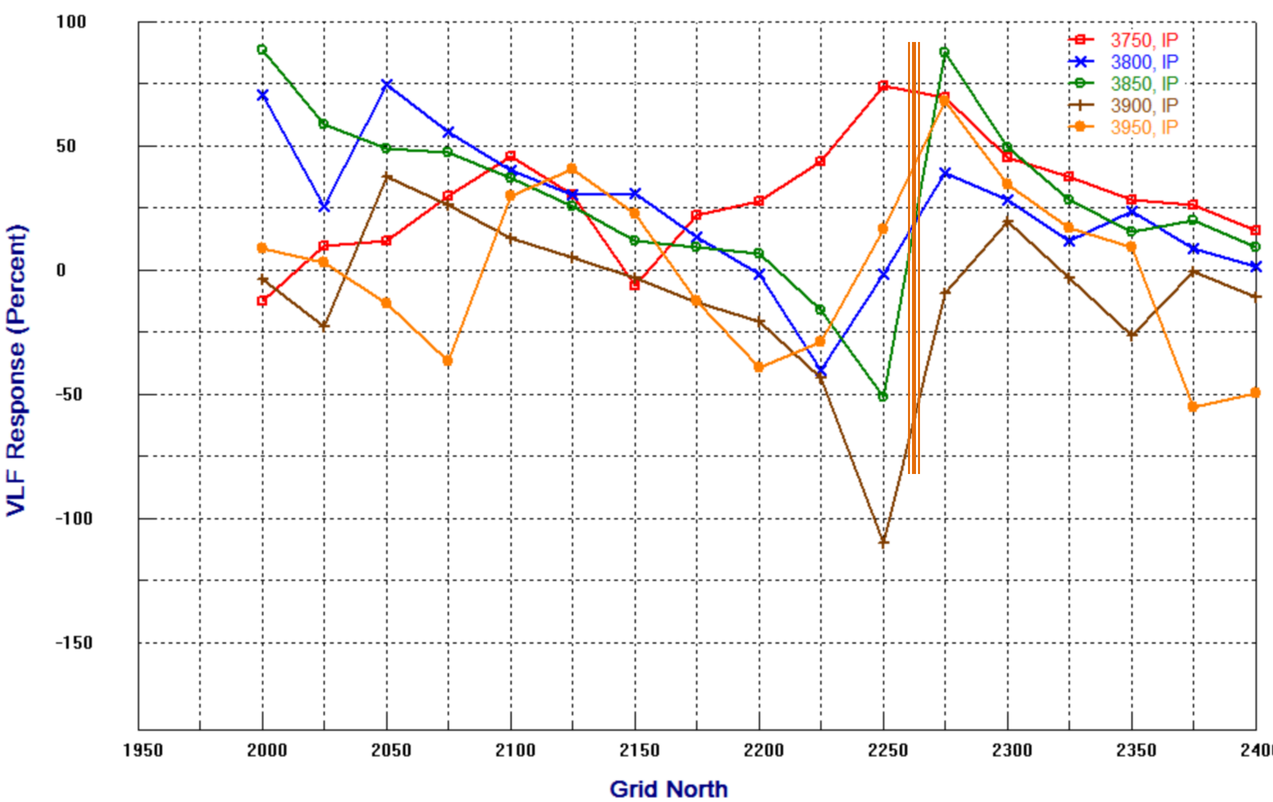



**Figure 25** IP VLF line plots for Area B

# Modeling Studies – Area B Quantitative Modeling

The response on Line 3800E in Zone B is quite representative of the response to the conductor in the north area. IP (red) and OP (blue) cross over from negative to positive close to station 2250N. The IP response peaks at 40% at 2275N which is quite strong but the IP is approximately 10% at this station. This indicates that the conductor is not very strong and the large inphase response indicates that the background is quite resistive. There is another large response to the south which has a long tail to the north but apparently not effecting the target centered on 2250N.

Given the sparse station spacing, it is difficult to be too precise with the depth to target or the dip of the target. However, the shape of the response would suggest it was quite shallow at least under some of the 5 lines.

It should be understood that the conductor may not be continuous along the indicated axis. However, the strength and shape of the response does help determine to what length the

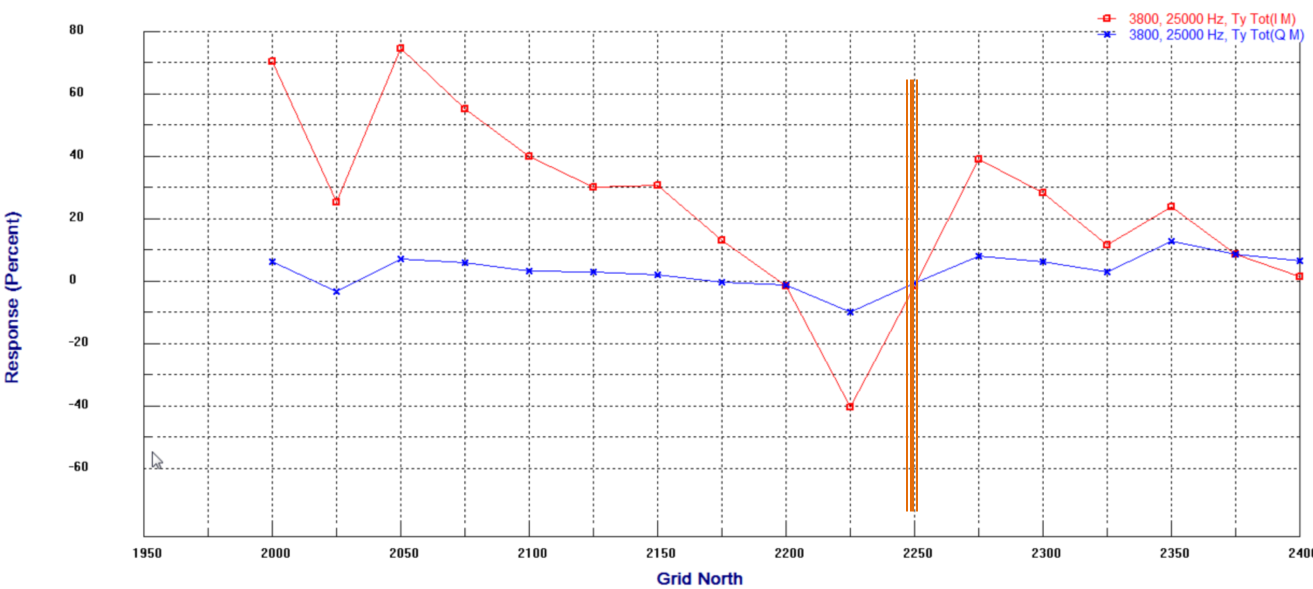



**Figure 26** IP and OP VLF line plots for Line 3800E.

# Modeling Studies – Area B
# Quantitative Modeling

Initial examination indicates that this conductor is generally EW but not exactly straight and has not exactly the same electric characteristics. However, a series of model simulations indicated that there was electrical connectivity of several hundred meters and that the conductor came quite close to surface. However, the modeling indicated that it had a depth extent of at least 150m but any greater depth extent could not be determined by the present data. Additionally, we were not able to determine dip of the target due to the lack of finer spaced data.

We will only present one of these here as the best model that we found with the time limitations that we had on this portion of the investigation.

**Model: 300m strike with 150m depth extent, vertical dip, 10 S conductor, background resistivity 5000 Ohm-m with a very thin low resistivity cover.**

We show first the comparison of the data with the model results on Line 3800E as we chose the northern position of the model to match this line. Red is IP data, Pink IP model, Blue OP data, and Purple, OP model. The electrical parameters provide a close enough match to the relation between IP an OP, the cross over is correct , the amplitudes of IP and OP quite close and the northerly tail on the model response matches the data quite well. Southerly tail of OP matches data reasonably as well.

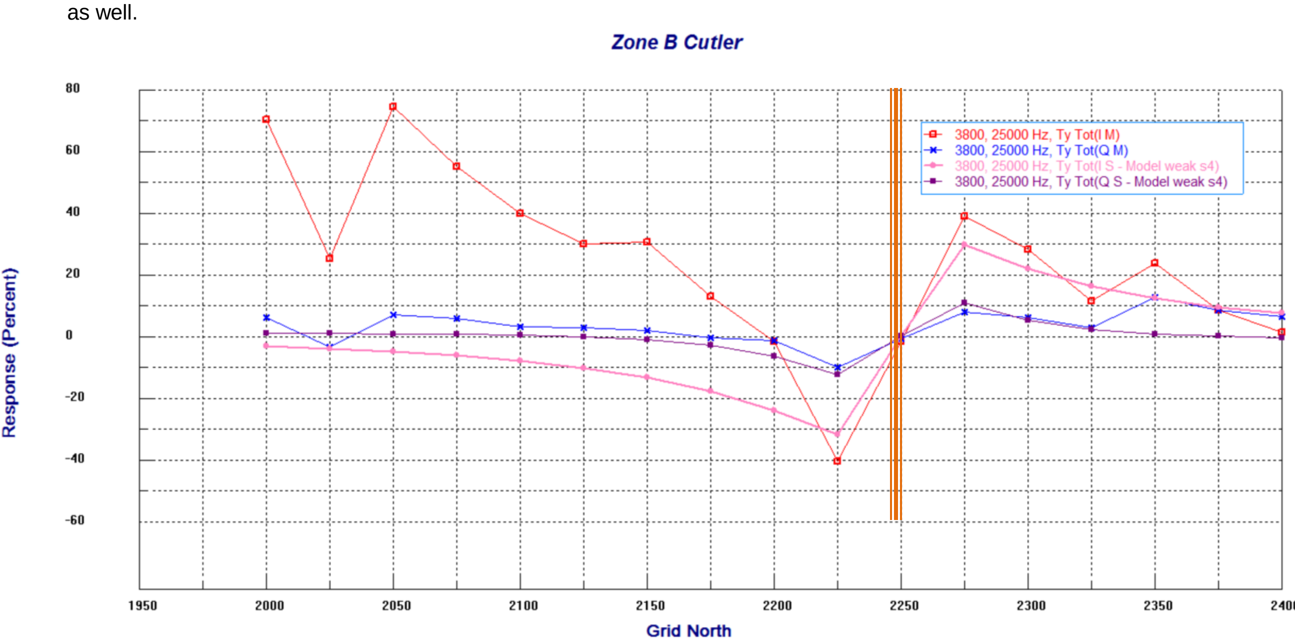



**Figure 27** IP and OP VLF line plots for Line 3800E vs. synthetic data from geophysical model

# Modeling Studies – Area B
# Quantitative Modeling

**Model: 300m strike with 150m depth extent, vertical dip, 10 S conductor, background resistivity 5000 Ohm-m with a very thin low resistivity cover.**

We show, below, the comparison of the data with the model results on Line 3850E. The position of the target (cross-over) is roughly 2865N or about 15m further north. This is not a consistent trend along the lines and thus EW is best average strike estimate. Of most particular note, is that the distance in the data from the peak negative to peak positive is 25m as opposed to the model's 50m. Additionally, the data response is significantly larger than the model particularly for the IP. The northern tail of IP is faster than the model implying shorter strike or less depth extent. But, in our opinion, given the limitations of the data, the model representation is good.

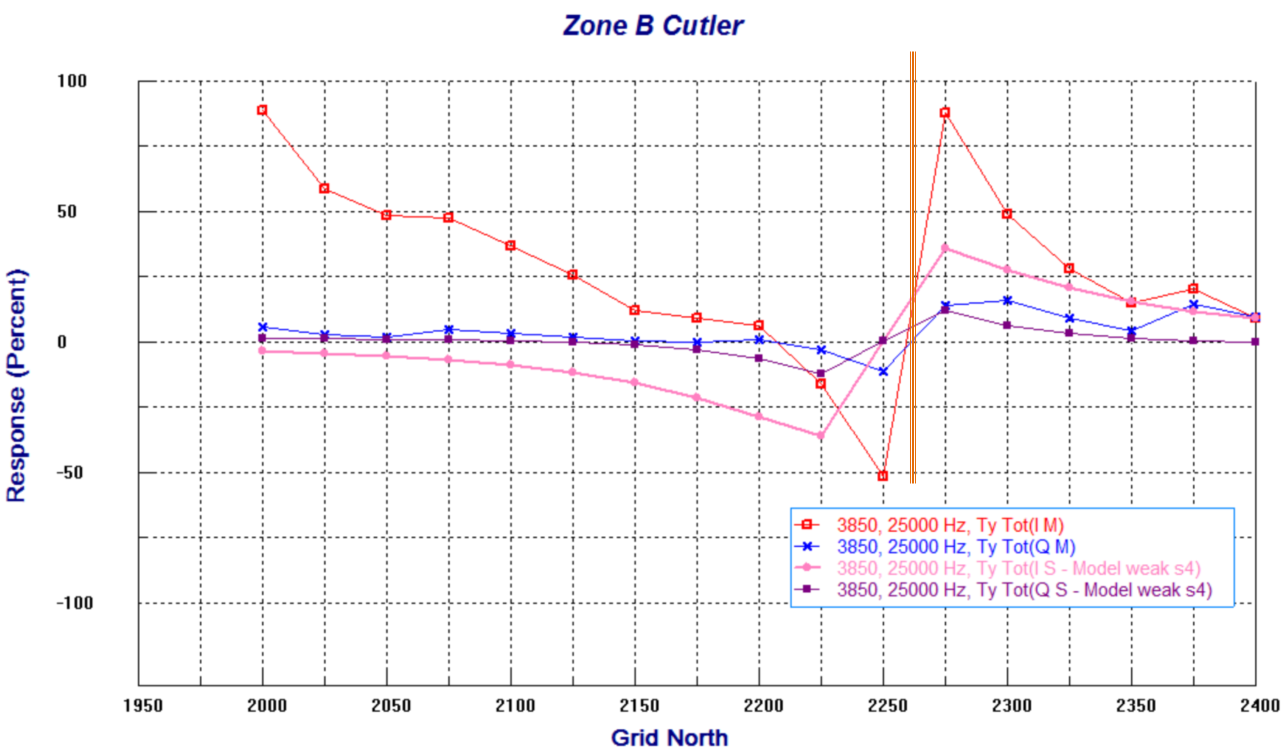



**Figure 28** IP and OP VLF line plots for Line 3850E vs. synthetic data from geophysical model

# Modeling Studies – Area B
# Quantitative Modeling

**Model: 300m strike with 150m depth extent, vertical dip, 10 S conductor, background resistivity 5000 Ohm-m with a very thin low resistivity cover.**

We show, below, the comparison of the data with the model results on Line 3900E. The shape of the data response appears quite different. However, this is most probably due to not having captured the conductor response on this line with the 25m sampling. The IP response on the south side indicates that the model response is too small in the IP. The remainder of the comparisons cannot be done due to data sampling and data quality.

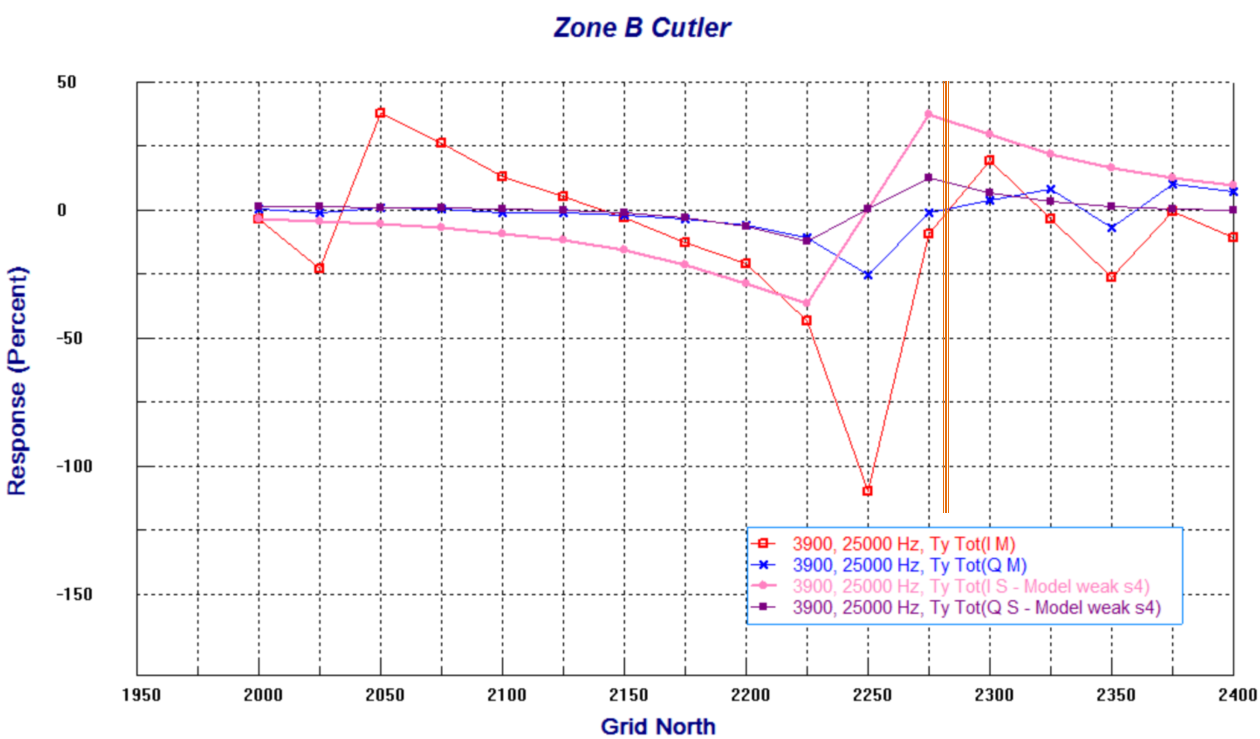



**Figure 29** IP and OP VLF line plots for Line 3900E vs. synthetic data from geophysical model

# Modeling Studies – Area B
# Quantitative Modeling

**Model: 300m strike with 150m depth extent, vertical dip, 10 S conductor, background resistivity 5000 Ohm-m with a very thin low resistivity cover.**

We show, below, the comparison of the data with the model results on Line 3950E. The northing location of the conductor may be a few meters south of 2250N. OP measured and synthetic agree quite well. IP strength of the model is a little to small and the crossover width of the model may be a somewhat smaller than the data. However, the data is obviously complicated by another anomaly to the south and a further one to the north.

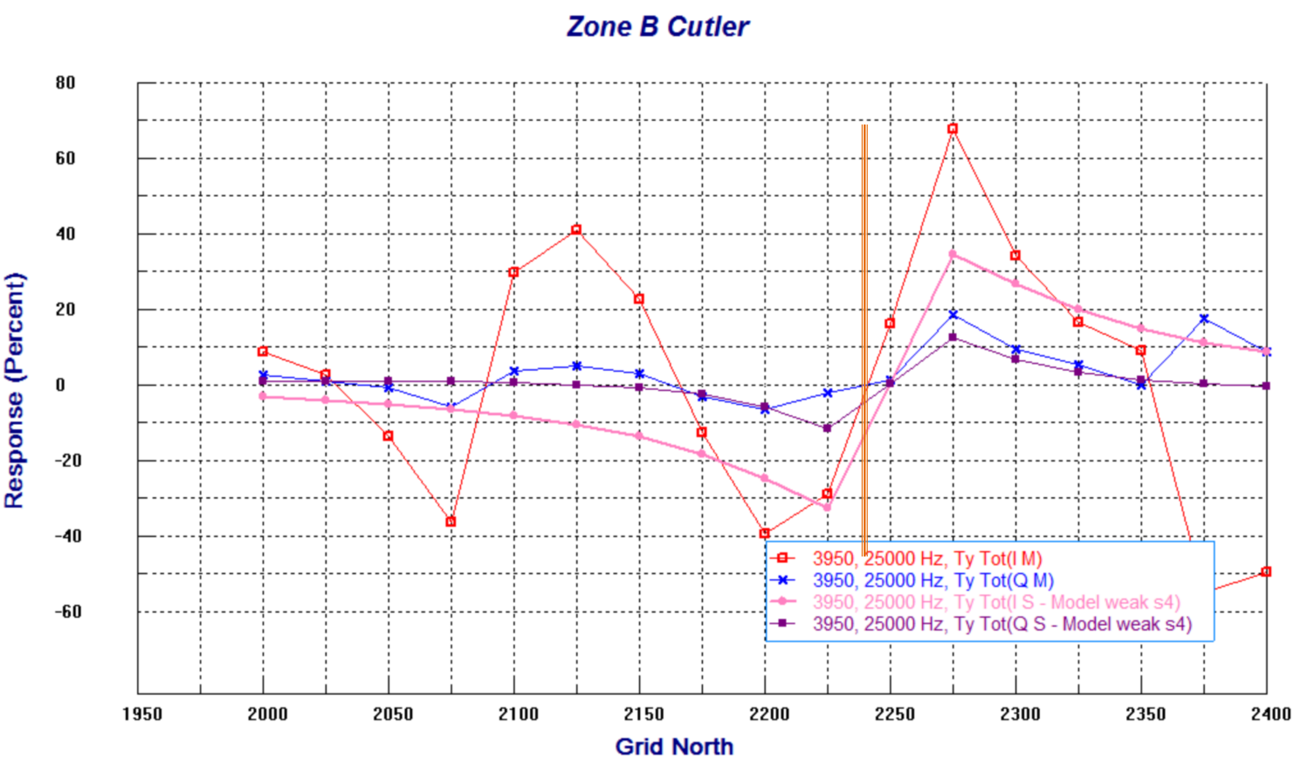



**Figure 30** IP and OP VLF line plots for Line 3950E vs. synthetic data from geophysical model

The data on Line 3750E is more complicated to explain and will not be shown here.

# VLF Data Comments and Recommendations

Recommendations for Further Work

Potential drill targets could be determined from this data. However, it would be more cost effective to engage in slightly more work prior to determining drill targets. We would recommend that a geophysicist discuss with the geologist the VLF anomalies and inferences both from a geological and geophysical perspective. From there, two to four small areas encompassing interesting VLF anomalies and geological features should be chosen. These areas should be approximately the size of Zone B in the report. On these areas, a finer spaced survey should be carried out utilizing pacing or simple chaining to establish stations between pickets. Magnetic data should also be carried out at the same data spacing. VLF and magnetic survey procedures should follow the recommendations provided.

From the data from these finer surveys and the calibration procedures provided, analyses should be able to determine if the VLF anomalies warrant drilling and if not, why not. From there, the VLF anomalies over the entire original survey can be reviewed with geological input to determine further drill placement.

It would be best for a properly skilled geophysicist accompany the operator for the calibration exercises and for at least one day of surveying. However, if this is not possible, then the geophysicist and the surveyor should be in phone contact during the calibration exercises which need not be in a remote location. Data should be delivered to the geophysicist on a daily basis to ensure quality control and to determine if any additional data need be taken.

# VLF Data Comments

Recommendations Survey Procedures

1. Collection of data repeats. The primary costs of the survey are the establishing of the grid, transporting personnel to the site and walking the survey. The time to take measurements is minimal and thus data repeats which are highly valuable to produce high quality results have minimal costs. This is particularly true for VLF data as this data is highly susceptible to signals from other sources than the distance transmitter.

2. A 25m data spacing is more coarse than accepted practice. Generally, 10-15m station spacings are recommended. However, the operator should be observing the IP data for the presence of crossovers (negative to positive or vice versa responses along the survey line). In these cases, the data sampling should be collected on a finer spacing near the conductor. Pacing of the data stations is sufficiently accurate for this purpose.

3. Instrument calibrations: A set of specific instrument calibrations should be carried out and kept on record to supply the geophysicist when interpretation is required. Calibration checks should be done prior to any new survey and a calibration site chosen near the survey and a small set of measurements taken at the beginning of each survey day to assure the instrument is working correctly and there are no drifts in the measured responses.

## Appendix A  - VLF Signals and Surveying Techniques

Very Low Frequency (VLF) electromagnetic signals are in the low end of the radio band thus generally from 10 Khz up to about 50 KHz.  A number of countries have operated transmitting stations using these frequencies for some decades primarily to aid in submarine navigation although now only a backup technique for such navigation.

Each of the VLF stations uses a unique frequency. For this data, the stations in Seattle and Cutler, Maine were utilized. In both cases, the frequencies used are approximately 25 Khz differing slightly but not significantly for geophysical purposes.

As these radio signals propagate, the electric field is rotated so that it is parallel (horizontal) to the earth's surface and the magnetic field remains horizontal. Thus, from a local perspective the wave is propagating down into the earth. The primary or source wave is polarized at the survey location so that the electric field is either directed away from or towards the transmitter and the source magnetic field is polarized in a direction perpendicular to the electric source field.

The instrument used to measure the signals consists of 3 induction coils which respond to the magnetic fields by inducing a voltage in the coils which is then converted by a calibration method to units of magnetic field. In this particular instrument, 2 of the coils are to be orientated so that there axes are parallel to the earth's surface and the third coil is orientated perpendicular (normal) to the earth's surface.  One of the outputs of the instrument is a ratio of the vertical (Hz) field to the amplitude of the horizontal fields ( Hx and Hy). In this way, it is only important to ensure that the instrument is orientated so that horizontal coils are in fact parallel to the regional surface (not the local surface) and that the vertical coil is still orthogonal to the horizontal coils.

There are a few critical operating procedures to ensure collection of useful data. It is important that the instrument be tested or calibrated in a standard location prior to any survey.  The location should be on flat ground, usually in a sedimentary environment away from faults, metal pipes, buried wires, metal or electric fences,  and away from any man-made (cultural) noise particularly certain types of power lines. Surveys should not be done in the rain or when there is fog as the moisture content in the air will heighten EM signals in this band from other sources.  As there is other sources of the fields at these frequencies other than the VLF transmitter  to which the system is tuned, it is critical to collect a minimum of 3 repeats at each stations. Finally, as the signal can be spatially very sharp (short) over a target of interest, it is important to collect data at a spatial density comparable to the target width. For example, if you were seeking a fault which you expect to have a thickness of 5m, then the station spacing should be approximately 5m. Additionally, the operator should be trained to recognize an interesting response and when such a response is thought to be observed then the station spacing should be decreased by a factor of two until good resolution of the response is caught.

While the survey costs of such a system are much less than those of other EM systems, the survey cannot be done without care and the practiced eye of the operator(s). These issues will be seen in this data set and we will examine these issues more closely in this report.

## VLF responses and the physics of VLF

Like any other EM system, there are source fields which excite the ground and produce secondary responses. In this case, there are 2 source fields, the electric field which provides currents in the ground depending on the resistivity of the ground and the magnetic field which will produce secondary fields from electrically conducting material in the ground. These two source fields cause anomalies in the data for two quite different physical reasons. Traditionally, it was thought that only the effect caused by the magnetic field hitting conducting material was important when surveying in resistive terrains.

However, the electric field from the source causes currents to be in the ground and the magnetic field from the source induces currents in any material that is not completely resistive. These currents when interacting with contrasts in resistivity in the ground produce magnetic fields which are measured by the instrument. It is almost impossible to interpret this type of anomaly without knowledge of the resistivity of the ground particularly the shallow material. Thus, if resistivity information is not available from other sources such as resistivity or other EM surveys, then it is necessary to do at least a few VLF-R measurements in the survey area.

## Illustrative Models of VLF responses

For these examples, the survey line is 2km in length running NS. Two models will be used. The first, is orientated perpendicular to the line and is a 300m in strike and 100m in depth extent with the top at 10m depth. It is a reasonably good conductor with a conductance of 10S, representative of a fault or vein containing sulphide mineralization. The second model is the same but now the model is orientated parallel to the survey line.

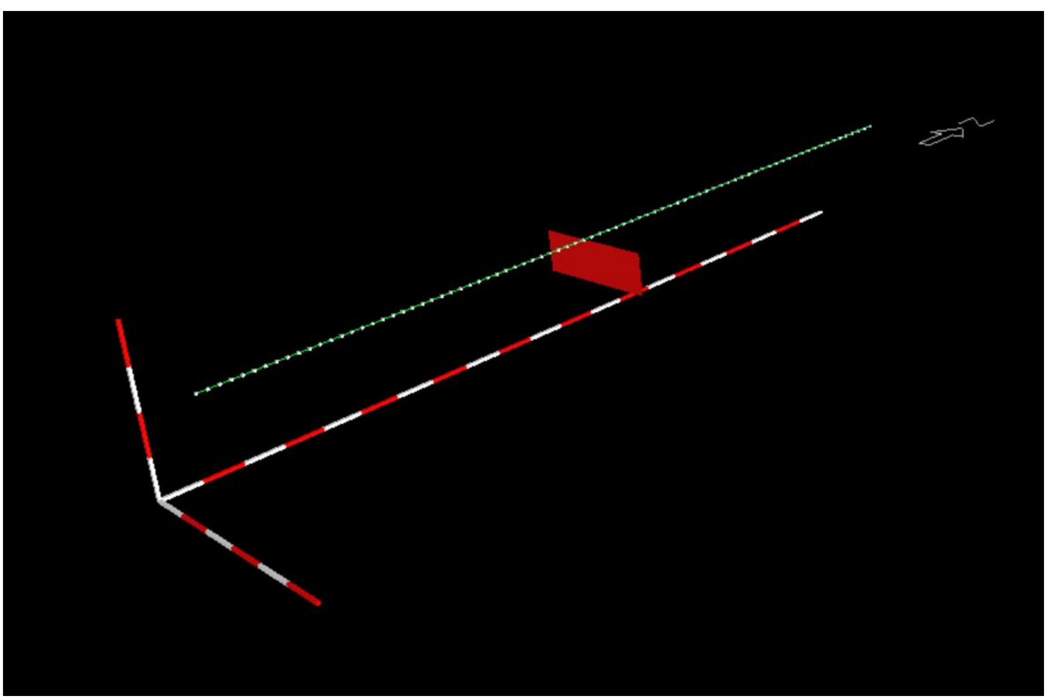


Figure A1. Example Model

# Illustrative Models of VLF responses

In addition to the orientation of the models, we must consider the location of the transmitter. In this case, we will consider one transmitter located to the west and one to the south. This is not exactly as in the survey case but suitable enough for understanding the issues as both transmitters used for the survey contained both an EW component and a NS component.  The resistivity of the ground also must be considered but for these first examples, we will consider only a very resistive ground with no effect from the covering material or weathered shallow structure.

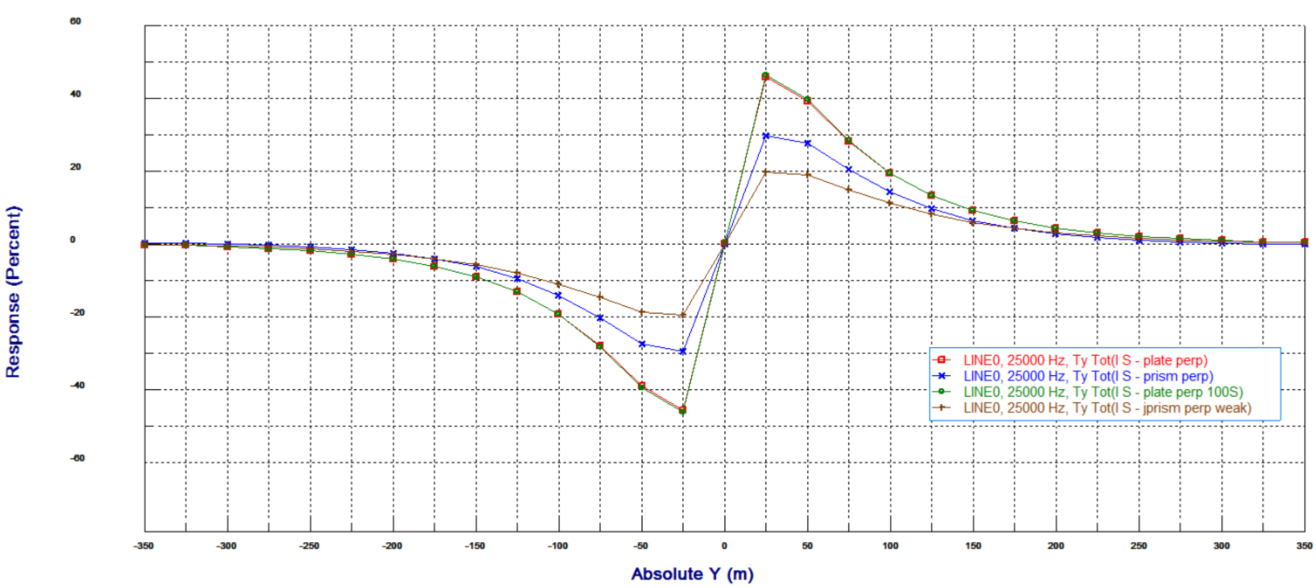
## Calculated VLF Response

What is output from the instrument is not what is actually measured but a processed response. First, the instrument detects the signal and synchronizes to the phase of the horizontal alternating sinusoidal signal. Then, the total voltage measured in the horizontal coils is computed and this is used to divide the vertical signal and then this ratio is multiplied by 100 to produce what is termed an InPhase and Out-of-Phase (quadrature) response in units percent.

## Case 1:  EW target strike, Tx to the West

In Figure A2, we present the IP response of 4 versions of our model. The IP response is most commonly interpreted and so we initially focus on this portion of the data.   The result of the model described above is given in red, while the response due only to the electric field from the source is given in blue. The result due to the electric field from the source due to a much weaker conductor is given in brown.  While the combined response due to electric field and magnetic field excitation for a conductor which is 10 times stronger than our model is given in green. We see from this that the excitation from the electric field in a resistive environment is quite significant and the strength of this response is not very sensitive to the conductive of the target. There is no noticeable change in the response of the strong conductor to the weak conductor in the IP. There is more noticeable effects in the quadrature.

Figure A2. EW strike, EW polarization



## Illustrative Models of VLF responses

### Effect of Dip

Figure A3, presents IP and OP (red,blue) of our model and that of the same model but dipping 45 degrees toward the north. – IP (pink) and OP (purple)/

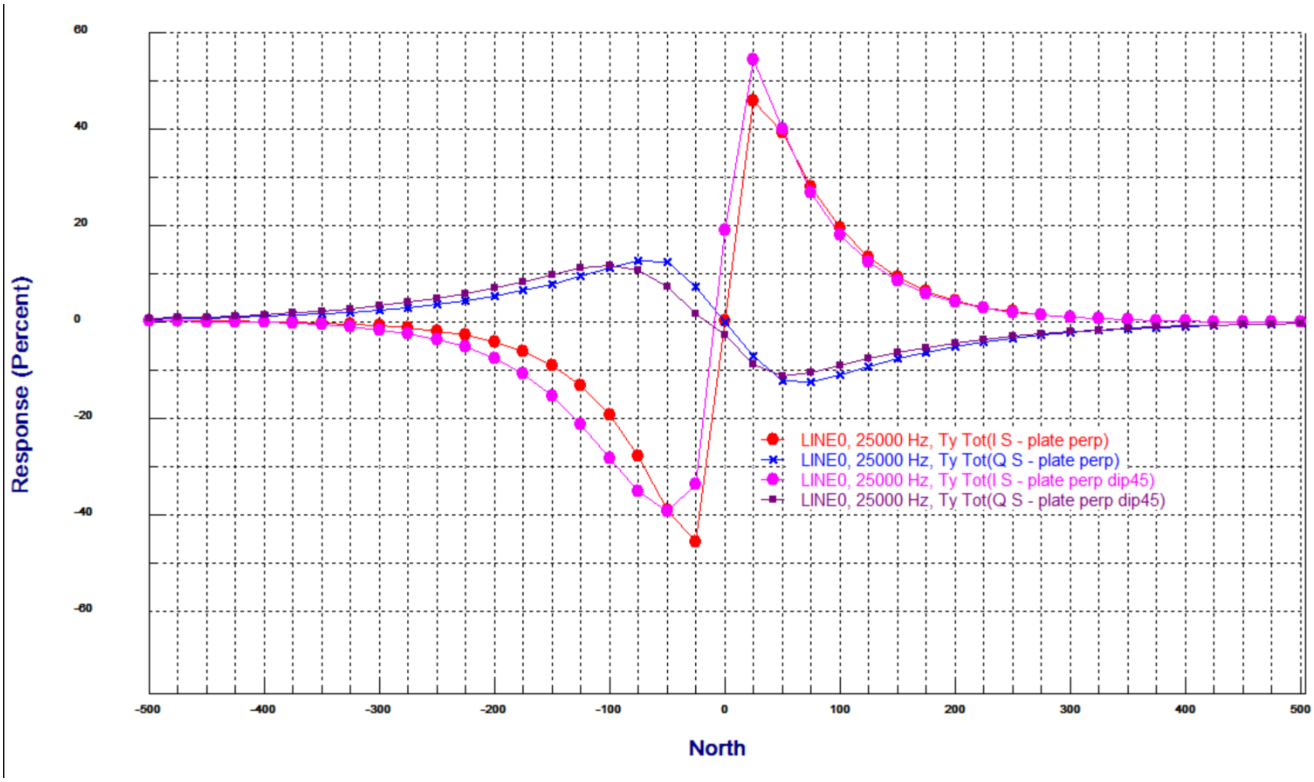



Figure A3. EW strike, EW polarization
Effect of Dip

**Comments on Data Sampling and Interpretation:** It is evident from this simple figure containing an isolated anomaly that a 25m spatial sampling is a maximum to detect placement but a 10m sampling is required to determine even a major dip difference. In a realistic geology, there are major and minor structures and thus a 25m data sampling may be far too coarse.

# Illustrative Models of VLF responses

## Case 2: NS target strike , Tx to the West

In this case, there will be almost no response at all. This is true if the target is off the line as well. If the target is at some other angle then NS or EW then it will have a reduced response from the EW target proportional to the strike angle.

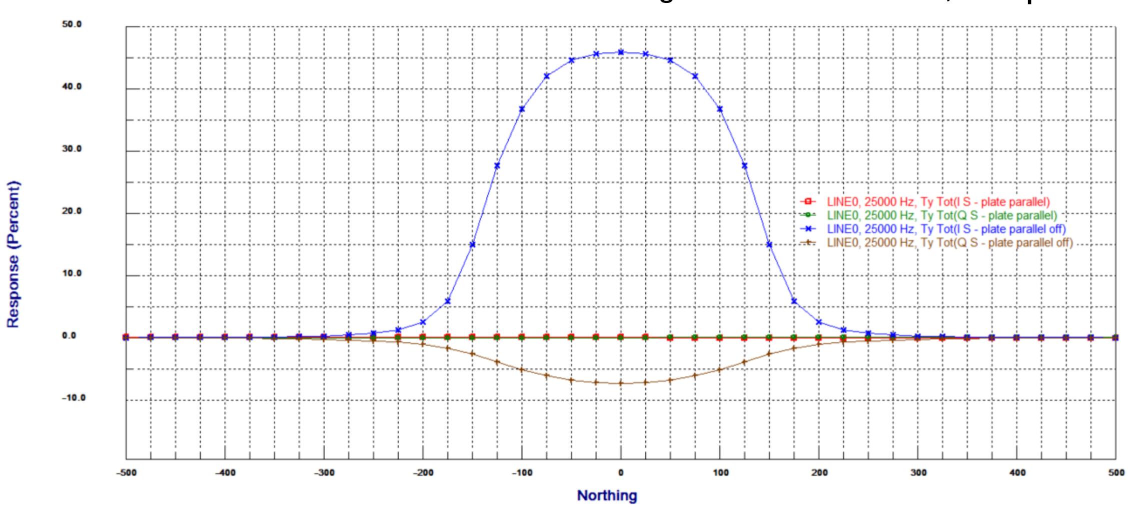
## Case 3: EW target strike , Tx to the South

In this case, the electric field source field is coming from the south and the source magnetic field is polarized EW. Thus, also in this case there will be only a very small response due to the electric field impinging on the target..

## Case 4: NS target strike , Tx to the South

In this case, the response will be dependent upon to what distance the target is off the NS survey line. In Figure A4, we show the response of the target immediately below the survey line as well as 25m to the east of the survey line. Both the IP (red) and OP (green) response of the target immediately below the line are essentially zero while the response of the target when 25m off the line reaches about 50% for the IP (blue) and the OP (purple) is small but significant. For a target dipping, the response increases if dipping east and decreases if dipping west but these changes are quite moderate.

Figure A4: NS strike, NS polarization




## Comments on Data Sampling and Interpretation:

For the case of the NS strike, data sampling is not critical as the response is broad and evenly symmetrical. However, line spacing is critical.

# Illustrative Models of VLF responses – Geological Noise

Other features which are of no exploration significance can also cause a VLF response. In these following illustrations, we will consider only 1 type of feature that must be considered. Features such as swamps, river and stream beds and in-filled eroded zones all have very similar VLF responses. The VLF responses of such features are in no way analogous to the responses for EM systems used in mining exploration but are rather much like magnetotelluric responses.

As such we will consider the response of a small swamp area abut 300m in length, 10m across and a few metres deep. The response of such a feature is, of course, governed by its size but very little by its resistivity. Here, we will assume that the fluids and sediments that comprise the swamp have a resistivity of 10 ohm-m.

## Case 5: EW strike parallel but off the survey line, Tx to the South

So as not to labour the points too much, we will only consider the case where the swamp runs perpendicular to the survey line and perpendicular to the electric field polarization. Case 5 and 6 should be sufficient for the reader to understand the responses for the 2 cases but with the electric polarization switched to EW.

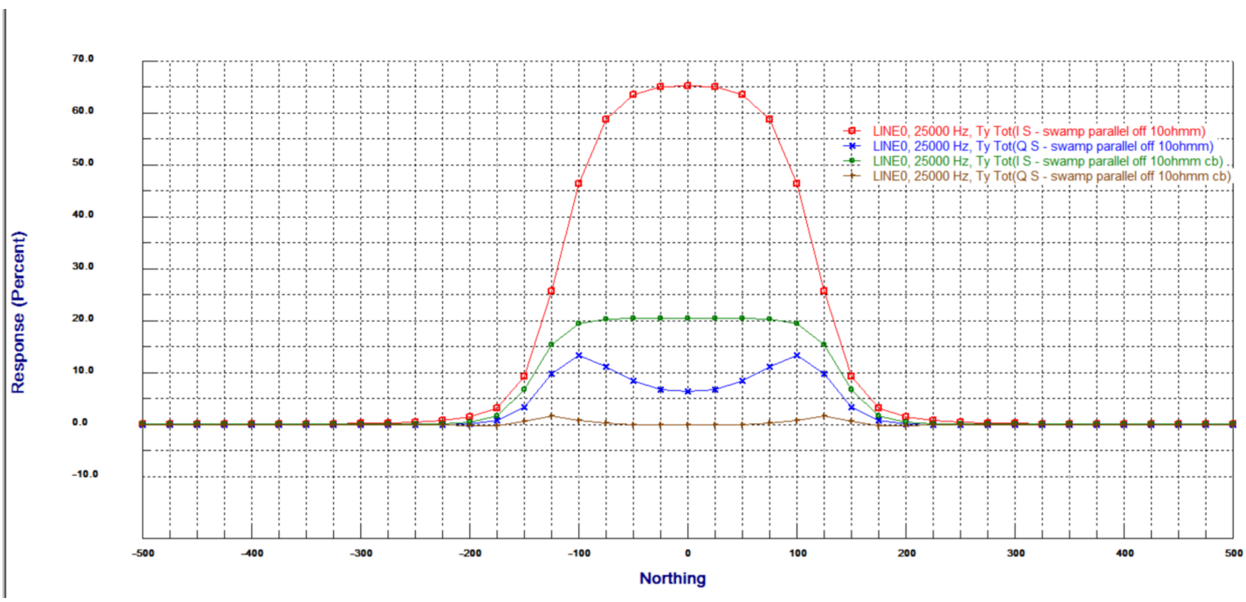



Figure A5: NS swamp, NS polarization of source

## Comments on Data Sampling and Interpretation:

Such natural and common features such as swamps and river and lake beds can have a significant response but it is critical to separating out these response for objects not of significant exploration interest to have some broad understanding of the resistivity of the shallow material, the resistivity and depth of weathering and the resistivity of the host rocks.

# Illustrative Models of VLF responses – Geological Noise

## Effects of EW structure:

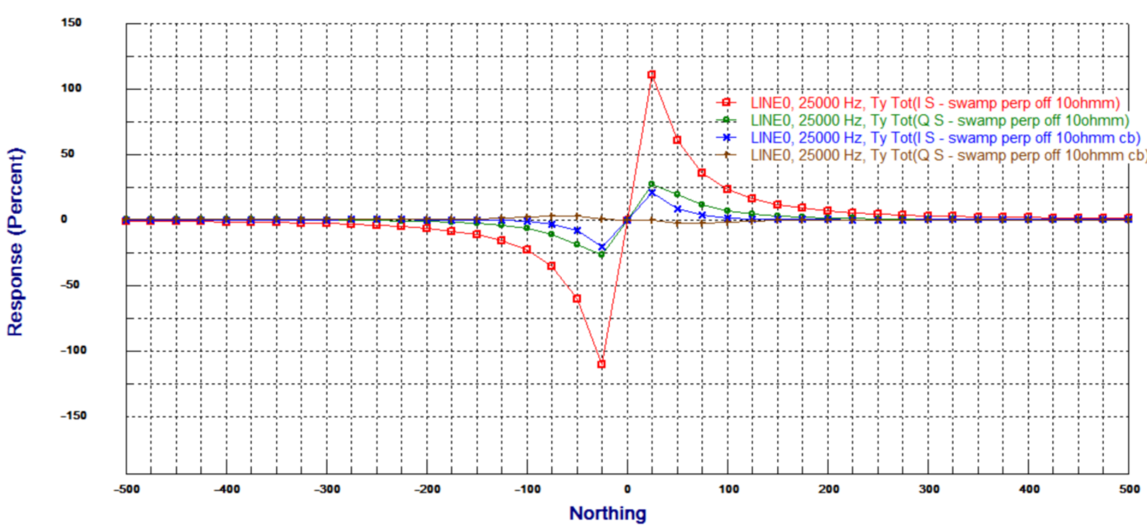
As the survey lines are oriented slightly west of NS, it is our assumption that the geological strike is generally approximately EW. We can observe that the lakes nearby are also generally EW and so we might assume that all geological noise such as swamps, river beds, weathering zones are also generally EW.

The two transmitters were at Seattle and Cutler and thus there will be a significant EW electric field polarization from both transmitters. Thus, we should examine somewhat the effect of these smaller scale, non-exploration features on the VLF signal.

To this end, we will consider the swamp model orientated EW with a resistivity of 10 ohm-m and consider the case where there is no conducting or weathered cover as well as the case where such cover does exist.

In the figure below, we show the VLF response as the survey line crosses the swamp model. In the case where the background rock is resistive, the IP response (red) is very large and the OP (green) still significant. When, the host rock has a weathered cover of 200 ohm-m, then the IP (blue) is much smaller and the OP very small and of reversed sign from when the host rock is resistive.

Figure A6: EW swamp, EW polarization of source




## Comments on Data Sampling and Interpretation:

These latter two figures, show that small features not of geological significance can be significant in the response. Additionally, identifying these response as not of geophysical importance can be difficult if we do not have knowledge of the resistivity in the host rocks and overlying material.