Appendix 1 – Reprocessed Data

Image Atlas
Proto Resources and Investments Ltd

Lindeman’s Bore Regional Project
September 2010
PROTO RESOURCES and INVESTMENTS LTD
LINDEMANN'S BORE REGIONAL PROJECT

Image Atlas Index

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Abbreviations: TMI - Total Magnetic Intensity, RTP - Reduced to Pole, AGC - Automatic Gain Control, 1VD - First vertical derivative, 2VD - Second vertical derivative, TC - Total Count, K - Potassium, U - Uranium, Th - Thorium, U/Th - Uranium/Thorium Ratio, K/Th - Potassium/Thorium Ratio.
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PROTO RESOURCES AND INVESTMENTS LTD
LINDEMAN'S BORE REGIONAL, WESTERN AUSTRALIA
AIRBORNE GEOPHYSICAL SURVEY
TOTAL MAGNETIC INTENSITY
REDUCED TO POLE (NL)
NORTH AGC SHADOWING

DATE:
BY: D. Mackay
PLAN NO.
SCALE: 1:1,350,000
REF: R. Mortimer
SOUTHERN GEOSCIENCE CONSULTANTS PTY. LTD.
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AIRBORNE GEOPHYSICAL SURVEY
TOTAL MAGNETIC INTENSITY
REDUCED TO POLE (NL)
NORTH EAST AGC SHADOWING

DATE:______________________BY: D. Mackay PLAN NO.:______________________
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TOTAL MAGNETIC INTENSITY
REDUCED TO POLE (LIN)
NORTH EAST AGC SHADOWING

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AIRBORNE GEOPHYSICAL SURVEY
TOTAL MAGNETIC INTENSITY
REDUCED TO POLE (LIN)
75% FVD AGC SHADOWING

DATE:                    BY: D. Mackay                    PLAN NO.
SCALE: 1:1,350,000       REG: R. Sumner
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AIRBORNE GEOPHYSICAL SURVEY
TOTAL MAGNETIC INTENSITY (RTP)
FIRST VERTICAL DERIVATIVE (NL)
EAST AGC SHADOWING

DATE: 
BY: D. Mackay
PLAN NO.
SCALE: 1:1,350,000
REF: R. Mortimer

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Kilometers
DATUM: GDA94
GRID: MGA82
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TOTAL MAGNETIC INTENSITY (RTP)
FIRST VERTICAL DERIVATIVE (LIN)
EAST AWC SHADOWING

DATE: [Blank]  BY: D. Mackay  PLAN NO. [Blank]
SCALE: 1:1,350,000  REF. R. Mortimer
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AIRBORNE GEOPHYSICAL SURVEY
TOTAL MAGNETIC INTENSITY (RTP)
FIRST VERTICAL DERIVATIVE (LIN)
SOUTH EAST AGC SHADOWING

DATE: [Missing]
BY: D. Mackay
PLAN NO: [Missing]
SCALE: 1:1 350 000
REF: R. Mortimer
INTRODUCTION:
These notes were put together initially for the use of clients of SGC. They are, however, sufficiently generalised to be of use to explorationists using other imaging services.

Image Processing generally consists of taking a set of ‘located X,Y,Z’ data, converting it to pixel format (gridding), carrying out computations to enhance the data and then presenting it in some form of ‘hard copy’. SGC uses a wide variety of software, some commercial and much written in-house, which is all PC based.

THE RAW DATA:
Airborne geophysical data are generally measurements of one or several of the following:
- Total magnetic field
- Total count radiation (TC)
- Potassium radiation (K)
- Uranium radiation (U)
- Thorium radiation (Th)
- Electromagnetic parameters (QUESTEM, GEOTEM)
- Elevation (DTM)

These measurements are usually gathered from a height above ground level of about 50m using a line spacing of say 200m and sampling along line about every 5m. These data are all recorded digitally together with real time positional information from differentially corrected GPS.

LOCATED DATA:
The raw data and the positional information are processed and merged. The geophysical data are corrected for PARALLAX and HEADING which are due to recording system lag and aircraft magnetic effects respectively. Radiometric data are calibrated and STRIPPED to convert the readings into pure element responses. The theoretical earth’s (IGRF) magnetic field may be removed from the magnetic data. The resulting data, now deemed to be free of errors, corrected, calibrated and accurately located are written out as the LOCATED DATA (LD). This is usually in the form of one-line ASCII records containing various fields such as:
- Flight line
- Fiducial
- Northing
- Easting
- Raw magnetic value
- Corrected magnetic value
- Total count
- Potassium
- Uranium
- Thorium
- Elevation

A typical 10000 line km survey would thus have about 2 million records and create an LD file of 200 Mb.

**GRIDDING:**
This is the first step whereby the X,Y,Z data are interpolated onto a regular square mesh using an appropriate pixel size. If the data are in a poorly processed state they may require ‘leveling’. Often the contractor will supply the client with both X,Y,Z data and gridded data as Located Data and Gridded Data respectively.

The LD file is subset on the computer to extract:
- Line Number
- Easting
- Northing
- Value (eg Magnetic reading)

This data is essentially in the form of an approximate 200m (line spacing) by 5m (sample interval) grid. The gridding process uses this data to estimate the data value on a regular square grid or mesh. The spacing of this mesh is usually set at about 1/3 to 1/4 of the line spacing (eg 50m x 50m for 200m line spacing).

Gridding is achieved by using one of several means including:
- Bicubic splines
- Akima
- Minimum curvature
- Inverse Distance
The gridded data are then recorded as the GRIDDED DATA (GD). This file normally contains a header describing:
- Origin of the grid (E, N)
- Rotation angle of the grid
- Mesh size
- Number of lines (rows)
- Number of pixels (columns)
- Data type

The actual readings follow the header or are in a separate file and are often in BINARY format to save space. They can be 1 byte, 2 byte or more commonly 4 byte integers. For the theoretical 10000 km survey on a 50m x 50m mesh this would be 800 000 grid points or 3.2 Mb in 4 byte format.

**STATISTICS AND HISTOGRAMS:**
The gridded data file is scanned by a program to determine the MINIMUM, MAXIMUM and MEAN of the data. Using these numbers another program produces a HISTOGRAM of the data showing its distribution. A CUMULATIVE FREQUENCY table is also generated.

**SCALING:**
In order to produce an image of raw data it is necessary to convert the data from 4 byte numbers to 1 byte numbers (0 to 255). This is because most imaging systems have a display and processing capability of 256 levels of grey or colour.

LINEAR scaling is done by setting the 1% value of the data (from the cumulative frequency plot) to 0 and the 99% value to 255 and proportionally scaling the data in between. The data below 1% and above 99% is clipped and set to 0 and 255 values respectively. Linear scaling can also be done using the minimum and maximum values rather than 1% and 99% but this usually gives an image with little information other than the very high and very low anomalies.

NON-LINEAR scaling usually uses the cumulative frequency histogram to scale the data so that the data range containing the bulk of the data is expanded over a wide 1 byte range and the upper and lower (less common) values are compressed into a smaller 1 byte range. This is also known as HISTOGRAM EQUALISATION and has the effect of extracting more detail in lower amplitude background areas. The resulting 1 byte files are SINGLE CHANNEL (BAND) files that can be displayed.

**PSEUDOCOLOURING:**
A displayed single channel image is in GREYSCALE initially. By using a LOOKUP TABLE (LUT) it can be coloured according to any colour scheme stored as a LUT file on the computer. A LUT is simply a list of 255 rows of 4 columns containing:
- Greyscale
- Blue
- Green
- Red
The grey scale value is read and the blue, green and red colour guns are set to the corresponding values in the table to create the desired colour. The most commonly used LUT is the rainbow spectrum with purple/blue values being low and red/white values being high.

MULTI-CHANNEL IMAGES:
Imaging systems can usually display the three primary colours, blue, green and red (BGR) as separate channels. This means that say uranium could be displayed in blue, thorium in green and potassium in red. This gives a multicoloured image with the different colour hues representing element ratios and the colour intensities the concentrations. This can be extended to displaying various combinations of magnetic, radiometric and other data types.

ENHANCEMENTS (FILTERING):
The raw gridded data is processed in many different ways to produce a wide variety of enhancements, each of which is stored as new grid files. These enhancements commonly include:

- Four greyscale directional gradients (horizontal derivatives)
- First and second vertical derivatives
- Automatic Gain enhancements on the above
- Pseudocoloured magnetic intensity - linear and non-linear scaling
- Coloured magnetic intensity shadowed with any of the first three enhancements
- Combinations of gradients

Radiometric and elevation data if available can be treated in the same manner.

The 1 byte image files or the 4 byte grid files can be mathematically processed to produce ENHANCED or FILTERED files. In geophysical work it is preferable to process the 4 byte files to maintain precision. This of course means that the resulting intermediate files go through the STATISTICS, HISTOGRAM and SCALING steps. Filtering is done in either the SPATIAL or FREQUENCY domains:-

SPATIAL DOMAIN FILTERING:
Spatial filtering generally involves the convolution (multiplication) of the data grid (an R x C array where R= number of rows and C = number of columns) by a filter array (operator) (usually 3 x 3). A simple horizontal gradient filter would look like:

```
1 1 1
-1 0 1
1 1 1
```

This would create an image with an apparent illumination from the west. More complicated algorithms can be used to produce filter arrays that will simulate illumination from any elevation and azimuth. Other filters can be designed and applied to generate vertical derivatives, edge enhancements, etc.
FREQUENCY DOMAIN FILTERING:
This is usually done by SGC on 2 byte grid files using two-dimensional fourier transform software. It allows the computation of first and second derivatives, reduction to the pole, upward and downward continuation and spectral filtering (commonly referred to as “depth slicing” by some contractors).

- The first vertical derivative is theoretically the rate of change of the magnetic field with increasing height. In practice it has two desirable effects. Firstly it tends to sharpen and separate magnetic anomalies. Secondly it makes the mean background level of the data equal to zero.
- The second vertical derivative is the rate of change of the rate of change of the magnetic field with increasing height. It sharpens and separates anomalies even further and is also symmetric about zero. SGC tends to use spatial filtering to obtain this parameter.
- Reduction to the pole is the correcting of the magnetic field for the inclination of the earth’s magnetising field in the survey area. It theoretically removes dipolar lows and places the positive highs directly over the magnetic bodies. In practice it can result in artefacts, particularly if remanence is present.
- Upward or downward continuation is the calculation of what the magnetic field would look like if measured at a height different to that actually used. Upward continuation is relatively straightforward and results in a smoother data set with less detail. Downward continuation is more complicated and initially sharpens up anomalies. It can, however, rapidly break down and give numerous artefacts.
- Spectral filtering is the practice of separating out the data into different spectral populations. Calculating the spectral profile of the data, measuring the various breaks in the profile, and then calculating the specific populations can do this. These populations are clustered around different wavelengths of anomalies and are related to depth. If say three populations of spectral wavelengths can be separated, they can be crudely equated to three “depth slices”.

AUTOMATIC GAIN CONTROL:
Automatic gain control (AGC) is a process whereby anomalies or features in an image are all reduced to similar amplitudes. This is very useful for extracting fine detail from images that are otherwise dominated by one or two high amplitude features. There are several steps to the procedure, which is done in the space domain.

Firstly a WINDOW size is selected appropriate to the data (it is often 11 to 19 cells (pixels) across). This square window is moved over the gridded data one pixel at a time. All of the pixel values within the window are squared, added together and then averaged. The square root of this average gives the mean absolute amplitude of the data within the window. The inverse of this value becomes the amplification factor, which is multiplied by the central pixel in the window to give a new pixel value in the output file. The effect is to amplify pixels in low relief areas and depress pixels in high relief areas.

One common artefact of AGC is the creation of an artificially quiet area adjacent to formerly high amplitude features. This boundary of this zone can look like a contact. The width of the zone is related to the window size.
SHADOWED IMAGES:
A common operation is to ‘shadow’ a pseudocoloured ELEVATION channel with a shading channel. Typically this is the pseudocoloured magnetic intensity shadowed or illuminated with a horizontal gradient or illumination (e.g. North gradient). This creates the ‘sun angle illuminated’ coloured images that are in common use.

The operation is very simple. The elevation data channel (typically magnetic intensity) is firstly pseudocoloured but then the resulting three colour (blue, red, green) pixel values are combined with the shading band value one at a time. The simplest operation is to add 50% of the colour pixel value to 50% of the shading pixel value to give the output pixel value. These percentages can be varied depending on whether the shadowing or the colouring should be dominant. The output is a three band (BGR) file.

Many combinations are possible. The elevation data can be magnetic intensity (linear or non-linear scaling), digital terrain, total count, etc. The shadowing channel can be a magnetic gradient, a vertical derivative, with AGC or without, etc.

The method can also be applied to existing three band images such as a K, U, Th combination. In this case shadowing with say a magnetic derivative or gradient can be useful in relating the magnetics to the radiometrics. The colour information of the multispectral data is retained.

Another technique is to shadow magnetic data with a Landsat Band or scanned aerial photography to give positional information in the image. Alternatively three Landsat bands can be shadowed with a magnetic gradient or derivative to give a colour Landsat image with magnetic trends.

ANALYTIC SIGNAL:
This is a method technique, which utilises a combination of three orthogonal spatial derivatives of the magnetic field to produce anomalous values over areas of maximum combined gradient. For narrow bodies it produces high values directly over the body and for wide bodies, the high values are over the edges. It has the advantage of positioning the anomalous values correctly regardless of magnetic inclination or remanent magnetisation and is thus useful in equatorial areas.

IMAGE ATLASES:
SGC records all enhancements as A4 or A3 colour inkjet plots and binds them into a volume together with an explanation of the enhancements. This allows a complete visual record of all of the enhancements at an accurate scale. The scale is selected to maximise the image size rather than to conform to standard scales.

A0 INK JET PRINTS:
This is now the most commonly used method of making large prints. The quality is slightly lower than photographic prints but costs are lower, particularly for large maps. This output is from ERMapper or RTICAD at SGC and allows full annotation, contour overlays, vector overlays and many other features. Multiple copies are considerably cheaper than photographic prints. Presentation or gloss paper can be used.

PHOTOGRAPHIC HARD COPY:
An uncommon procedure now. This involves the production of an undistorted transparency (usually 10” x 8”) using a bureau to convert the digital data directly to an image. Several enhancements can be combined on one transparency to save costs if resolution is not compromised. The resulting transparency is used to produce large accurately scale photographic prints using commercial laboratories. SGC can annotate these images with AMG grid lines, scale bar and title block but the numbering of the grid lines has to be done manually later.

**IMAGE SLIDES:**
An uncommon procedure now. SGC can record all enhancements in full resolution as fully annotated 35mm slides taken directly of the screen. These suffer from some minor distortion and are not ideal to make later maps from but have the advantage of being low cost and offering the client every enhancement available for his data. It is useful to project these slides onto a wall or through a projection table during interpretation. More accurate slides can be made using digital files but at higher cost.

**REAL TIME IMAGING:**
The RTICAD and ERMapper software used by SGC allows the various enhancements to be viewed and manipulated interactively using a ‘sun illumination’ that can be moved in real time - this is very useful during interactive interpretation.

**DIGITAL IMAGE FILES:**
SGC can provide any enhancements as digital image files on CD, typically as TIF files with or without Mapinfo or Arcview registration.
Appendix 2 – QUT Report

QUT Report
Executive Summary

Kalkarindji Flood Basalt Province of Australia: comparisons with the Siberian Traps CFBP and associated Norilsk Ni-Cu-PGE mineralization

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The Kalkarindji CFBP (c. 505 - 510 Ma) represents the most ancient example of an LIP for which significant thicknesses of the lava succession remain preserved. Due to erosion it remnants now consist of a scattered series of basaltic suites occurring across northern and central Australia; its eruptive volume is estimated as exceeding 5 x 10^5 km^3 but, by analogy with other better preserved CFBPs elsewhere, its original volume may have been significantly greater than 1 x 10^6 km^3.

Although scattered basaltic suites (e.g. Antrim Lavas) have long been documented across northern and central Australia, the Kalkarindji CFBP has only recently been recognized (i.e. c.10 years) as a "bone fide" example of a once continuous CFBP. This lack of recognition is largely due to the inaccessibility of the region, a grave paucity of previous documentation and, hitherto, a lack of a commercial or academic motivation to invest the resource for detailed investigation.

By comparison with the Siberian, Karoo, Deccan and Columbia River CFBPs, The Kalkarindji CFBP still remains largely unknown. For instance, during the past 25 years the body of peer-reviewed research published detailing the Deccan Traps exceeds 500 papers (similar comparisons may be made for Karoo and Siberian Trap literature); by contrast the body of research detailing the Kalkarindji (or Antrim lavas) over the same period is likely less than 20 research papers in total. Accordingly, due to its obscurity, the Kalkarindji CFBP potentially provides a highly fertile area for research investigation and investment both commercially and academically. Many regions within the postulated extent of this huge CFBP effectively represent 'virgin territory'.

CFBPs are characterised by basaltic lavas which are derived from the partial melting of Earth’s mantle; the mantle is the layer which exists beneath the continental (or oceanic) crust. Once the melt is generated it migrates surface-ward as a magma, usually via conduits (lower-crustal dykes) or else becomes stored in 'high level' chambers within the crust (>1 – 10 km depth); these are, in turn, then tapped by shallow conduits (higher-crustal dykes), and the magma is erupted at the surface as lavas.

During ascent from the mantle, CFBP lavas pass through, or are stored and then tapped within, the continental crust. This 'plumbing system' allows the hot magma to interact with the continental crust, and scavenge elements from it. Those lavas which contain significant amounts of scavenged contaminants are termed ‘contaminated lavas’; they are often characterised by elevated K, Sr and Rb concentrations (as well as a suite of rarer, but petrogenetically significant elements such as Cu, Ba, and some rare earth elements (REEs)). However, although some degree of contamination is not unusual, as a rule highly contaminated lavas are a rarity in most CFBP successions. Accordingly, CFBP lava successions do not represent commercially extractable resources. However, the Norilsk-type deposits of the Siberian Traps represent a notable exception to this rule.

The Norilsk -Talnakh is associated with the Siberian Traps CFBP. This nickel-copper deposit was formed 250 million years ago during the eruption of the Siberian Traps igneous province. Here lavas were erupted through tapping of a series of flat-lying lava conduits (sills). The ore bodies were was formed when the erupting magma encountered significant thicknesses of organic-rich sediment during its ascent and eruption; the magma became contaminated and saturated in sulphur which formed sulphides. These molten sulphides sequestered trace elements (i.e. chalophile elements) from the erupting basaltic magmas during their passage through the crustal conduits. These sulphide phases became highly enriched in a range of commercially important elements. The sub-surface sill bodies are now host to commercially important ore bodies.
The presence of organic-rich sediments in the Proterozoic basement through which the Kalkarindgi lavas were erupted provide a geological setting directly analogous to that which gave rise to the Norilsk-type mineralization associated with the Siberian Traps CFBP.

Trace element enrichments in the Kalkarindgi basalts indicate they are highly ‘contaminated’; that is, they interacted with crustal materials during their ascent through the continental lithosphere. Current geochemical data reveal that the Kalkarindgi lavas commonly display significant crustal contamination (at enrichment levels which place them among the highest of all CFBP analyses). The only other CFB which displays this degree and frequency of contamination are the basalts of the Siberian Traps CFBP.

Analysis reveals that both the Kalkarindgi and Siberian Traps basalts are relatively depleted in sulphur. This indicates that sulphur (both that derived from the primary magma, and from crustal contamination with organic-rich sediments) has itself effectively been sequestered prior to eruption. In the case of the Siberian Traps, the host bodies of this sulphur sequestration are the magmas frozen in the high-level sills and conduits which originally fed the surface eruptions. The assumption is that the same process operated during the eruption of the Kalkarindgi lavas, and that these sub-surface magma bodies await discovery.

Of key importance to locating potential sulphide-hosted commercially significant element concentrations is the identification the high-level dyke conduits which fed the surface lava flows; a suite of these will typically indicate proximity to sill bodies in which the sulphide minerals have precipitated.

The emplacement, distribution and orientation of feeder dykes (conduits to lava flows) are normally associated with crustal heterogeneities and or/weaknesses that are exploited during the surfaceward migration of magma. These weaknesses become particularly prone to exploitation when the crust is under stress (i.e. subject to extensional tectonic forces). Since many CFBPs are associated with episodes of crustal extension and/or continental rifting, those regions of the CFBP which were proximal or adjacent to the extension/ rift axis will offer the greatest potential for hosting the CFBP magma plumbing system (i.e. dykes and sills).

The tectonic setting of the wider Kalkarindgi CFBP is very poorly known. Based on state of the art Cambrian (500 – 550 Ma) palaeogreographic reconstructions for Australia and Antarctica, the most likely position of any extension/riifting likely to have been associated with the genesis of this CFBP would have been located along the NW Australian margin. This interpretation is broadly supported by geochemical modelling (Glass, 2002) which indicates significant crustal thinning in the NW prior to the eruption of the Kalkarindgi basalts, and the fact that typically thicker lava successions are preserved in the north compared with the south (i.e. Central Australia).

Through detailed mapping and reconnaissance (October 2010), considerable advancement has been achieved in broadening our understanding of the volcanology and regional setting of the Waterloo and Wave Hill areas of the Kalkarindgi volcanics (for further detail, see report by Murphy et al. 2010). A relatively modest investment in field-based studies, and associated laboratory-based geochemical analyses, provides a cost effective method of targeting and/or verifying regional geophysical surveys. The paucity of geological information concerning the evolution and structure of the Kalkarindgi CFBP demands further investigation of this type if the apparently promising commercial prospects (described above, and in the detailed report; Murphy et al., 2010) are to be identified and realised.

Since Norilsk-type deposits are so intimately associated with the emplacement Siberian Traps CFBP, there is a clear commercial potential for CFBPs exhibiting a similar geological setting and geochemistry. Since a considerable body of information on CFBP genesis resides in the academic realm, a programme combining commercial interest and academic expertise would provide the opportunity to develop a unique synergy of industrially- and research-based investigation for the Kalkarindgi CFBP.

Further investigation using field-based programmes to inform sophisticated geophysical surveys is clearly warranted. Such linked investigative programmes should be considered for support over a 2 to 3 year period in order to provide the necessary context and detail. An identification of key areas for exploration is required in order to achieve a more thorough assessment of whether the Kalkarindgi CFBP indeed represents a Norilsk-type analogue with all its attendant associated commercial prospects.
Appendix 3 – ZTEM Data

SEE ATTACHED FILES
ZTEM HELICOPTER ELECTROMAGNETIC APPLICATIONS
FOR MINERAL EXPLORATION

The ZTEM helicopter-borne electromagnetic method is a passive natural field (tipper AF-MAG) system that has been primarily designed for deep penetration mineral exploration applications. The ZTEM system uses worldwide sferic thunderstorm activity as its primary EM source field and, like other ground natural source EM methods, such as AMT, is capable of depths of investigation ranging from tens to thousands of meters. Coupling this with its sensitivity to weak lateral resistivity contrasts and the benefits of rapid 2D-3D inversion make it a powerful subsurface rapid reconnaissance geologic mapping tool.

Airborne electromagnetic methods have long been highly effective detection tools for most base-metals and nickel deposits, as well as certain precious metal and kimberlite deposits, involving high conductivity contrast with the surrounding bedrock. Helicopter time-domain EM (HTEM) systems in particular have significantly improved penetration, sensitivity and positional accuracy that easily rival ground systems. Geotech Ltd. was established over 25 years ago, building advanced airborne electromagnetic equipment for the exploration industry. The company’s instrumentation development has included VTEM (versatile time-domain electromagnetic system, Figure 1a) in 2002 that is the Geotech award winning and industry leading airborne EM technology. Winner of the 2005 Exploration Equipment award, VTEM is the most innovative and successful airborne EM system to be introduced in more than 30 years. More recently, Geotech introduced ZTEM (z-axis tipper electromagnetic) natural field airborne EM system (Figure 1b), the only commercially available AFMAG (audio frequency magneto-variational) system of its kind worldwide, airborne or ground, that is capable of penetration depths in excess of 2km in most mineral exploration environments and features a unique resistivity mapping capability that rivals ground electrical surveys.

**Figure 1:** a) VTEM Time-domain EM system (left) and b) ZTEM Natural-field AFMAG system (right).
ZTEM System

The development of the ZTEM (z-axis tipper electromagnetic) system shown in Figure 1b, represents the first airborne application capable of deeply penetrating EM (>1-2km) that permits the mapping of geologic units, structure and alteration based on lateral resistivity contrasts. It therefore represents a unique airborne deep resistivity mapping tool that is capable of exceeding the 300-500m depth penetration limits of traditional AEM systems in mining exploration environments.

The ZTEM airborne AFMAG uses naturally occurring audio frequency magnetic fields as the source of the primary field signal, and therefore requires no transmitter. The primary fields resemble those from VLF except that they are lower frequency (tens & hundreds of Hz versus tens of kHz). These EM fields used in AFMAG are derived from world wide atmospheric thunderstorm activity, have the unique characteristic of being uniform, planar and horizontal, and also propagate vertically into the earth – to great depth, up to several km, as determined by the magnetotelluric (MT) skin depth, which is directly proportional to the ratio of bedrock resistivity to the frequency. At the frequencies used for ZTEM, the investigation depths likely range between approx. 100m to 1000m in sedimentary regions (approximately for 10-100 ohm-m average resistivity assumed) and significantly greater then 1000m in more resistive environments, as shown in Figure 2a.

![Figure 2: a) Magnetotelluric skin depth chart (left) showing the calculated ZTEM AFMAG minimum to maximum depth investigation versus earth resistivity; b) ZTEM Hx-Hy base station coils (center), c) ZTEM Hz receiver (right).](image)

The ZTEM system comprises airborne tipper AFMAG as well as aeromagnetics using a caesium magnetometer (Figure 1b). The vertical (Z) component data are obtained using the Geotech ZTEM aircoil receiver system, suspended at approximately 85m elevation above ground level (Figure 2c). The vertical component data (Hz) are then ratioed to fixed horizontal field measurements (Hx-Hy) obtained using identical reference coils (Figure 2b). The ZTEM In-Phase and Quadrature tipper transfer functions are obtained using Fourier-based, digital signal processing analyses, at 6 frequencies, between 30Hz and 720Hz.
Examples of successful ZTEM mining applications include the *Lone Star* porphyry copper deposit in Arizona unconformity uranium deposits of the *Athabasca* region of Saskatchewan, Canada, magmatic nickel deposit at *Axis Lake*, Saskatchewan and carbonate replacement deposits (CRD) at *Cinco de Mayo* over the *Jose Manto* Ag-Pb-Zn zone and the *Pozo-Seco* moly-gold zones in Chihuahua, northern Mexico. They also include the 5.1 billion tonne *Pebble Porphyry* cu-mo-au deposit in Alaska where ZTEM survey results defined the *Pebble West* and deeper *Pebble East* deposits to below 1.5km, shown in Figure 3 (Legault et al., 2010). Recent ZTEM results over the deeply buried (550-1200m) 12.3 M tonne *Lalor Lake* gold-copper-zinc VMS orebody compare favourably with the known 900m x 700m deposit geology that has escaped detection in previous airborne geophysical surveys, shown in Figure 4.

![ZTEM Helicopter Electromagnetic applications for Mineral Exploration](image)

**Figure 3:** A) ZTEM total phase rotated 30Hz In-Phase results and Right 2D inversion results over Pebble cu-mo-au porphyry deposit (after Legault et al., 2010)

![ZTEM Helicopter Electromagnetic applications for Mineral Exploration](image)

**Figure 4:** A) ZTEM phase rotated 30Hz In-Phase Z/X (in-line) results and B) 2D inversion results over Lalor Lake cu-zn-au deposit (courtesy Hudbay Minerals Ltd.).