THE FEASIBILITY OF THE AIRBORNE FLUXGATE MAGNETOMETER AS AN EXPLORATION TOOL – RESULTS FROM THREE DIMENSIONAL NUMERICAL MODELLING

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INTRODUCTION

The earliest geophysical exploration strategies relied on measurements of variations in the Earth's magnetic field. Even today, magnetic methods are the most commonly used geophysical exploration techniques because magnetic observations can be made relatively easily and cheaply. Although compasses are the most common type of mechanical device used to measure the horizontal attitude of the magnetic field, other devices have been developed to measure various components of the magnetic field. Magnetometers are instruments, usually operating non-mechanically, that are capable of measuring the strength of the magnetic field. Various types of magnetometers are available; for example, torsion magnetometers, proton precession magnetometers, alkali-vapour magnetometers and fluxgate magnetometers.

Fluxgate magnetometers were originally designed and developed during World War II for detecting submarines, and are based on what is referred to as the magnetic saturation circuit. Two parallel bars of a ferromagnetic material are placed closely together. The susceptibility of these two bars should be large enough so that even the Earth's relatively weak magnetic field can produce magnetic saturation. Each bar is wound with a primary coil, but the direction in which the coil is wrapped around the bars is reversed. An alternating current (AC) is passed through the primary coils causing a large, inducing magnetic field that produces induced magnetic fields in the two cores that have the same strengths but opposite directions. A secondary coil surrounds the two ferromagnetic cores and the primary coil. The magnetic fields induced in the cores by the primary coil produce a voltage potential in the secondary coil. In the absence of an external field (*i.e.* if the earth had no magnetic field), the voltage detected in the secondary coil would be zero because the magnetic fields generated in the two cores have the same strength but are in opposite directions (their effects on the secondary coil exactly cancel). If the cores are aligned parallel to a component of a weak, external magnetic field, one core will produce a magnetic field in the same direction as the external field, and reinforce it. The other will be in opposition to the field and produce an induced field that is smaller. This difference is sufficient to induce a measurable voltage in the secondary coil that is proportional to the strength of the magnetic field in the direction of the cores. Thus, the fluxgate magnetometer is capable of measuring the strength of any component of Earth's magnetic field by simply re-orienting the instrument so that the cores are parallel to the desired component. Fluxgate magnetometers are capable of measuring the strength of the magnetic field of the order of 0.1 nano Tesla (nT). In this paper we shall be dealing with the responses from a modified version of fluxgate magnetometer, which can be mounted on airborne platforms, and the potential of this airborne instrument as a tool for mineral exploration.

METHODOLOGY

As explained in the previous section, the magnetometer measures the magnetic field component along the axis of its core and must be oriented with the field if the total intensity is to be measured. Fluxgate magnetometer sensors oriented in mutually perpendicular direction can measure three components of the geomagnetic field (*i.e.* two horizontal and one vertical components). Among the most difficult problems associated with aeromagnetic surveys is fixing the position of the aircraft at any time and orientation of the fluxgate sensors. With the recent advancement in high precision real-time differential GPS systems, gimbal-mounted sensors and fast sampling devices, this difficulty is rapidly disappearing.

In the scientific literature there are very few articles related to airborne fluxgate magnetometer (AFMAG) measurements (*e.g.* Ward, 1959). The approach is quite different from usual airborne EM and aeromagnetic surveys. It has more similarity with ground based magnetovariational (MV) or geomagnetic depth sounding (GDS) where we look at wide frequency range of (or time varying) signals within the natural field. The only difference between the methods is that instead of an array of stations simultaneously measuring the variations in the natural field for a long period of time, AFMAG is flown over an area of interest and measures a range of high frequency signals at a pre-defined interval. The 3-component magnetic data could be processed in a similar fashion to that of GDS method to calculate the induction arrows (e.g. Parkinson, 1964, Everett and Hyndman, 1967), which in turn provides information about lateral conductivity variations in the subsurface. The depth from which the information is returned depends on the frequency (or periodicity) selected. High frequency signals provide information on shallow structures while lower frequencies provide information on the deeper structures. Recently Lo et al. (2006) made significant advancement towards developing AFMAG system, but it still needs a lot of improvements before it can be implemented as a mineral exploration tool. Figure 1 shows the prototype AFMAG system developed by Geotech Ltd. This method could be successful applied to exploration in cratonic areas where there are lots of fresh rock exposures, however it is uncertain how successfully the method could be applied in areas of thick regolith cover such as occur over much of Australia. Numerical modeling can test the likely success of the method under these conditions.

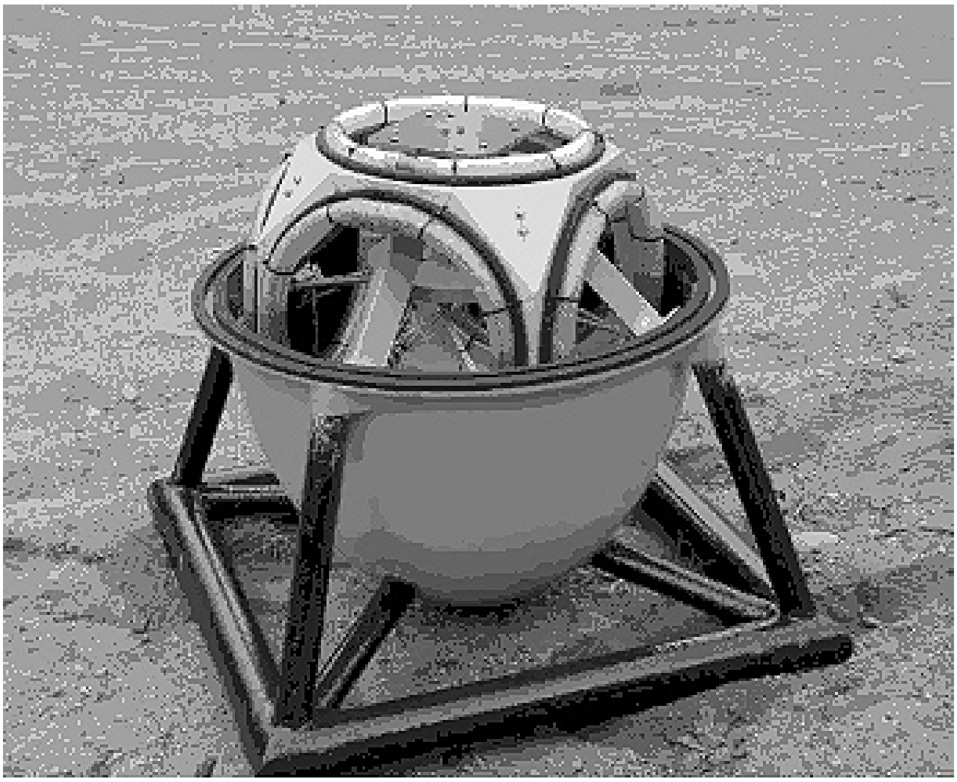

Figure 1, Prototype AFMAG system showing orthogonal fluxgate coils, damping mechanism and suspension developed by Geotech Ltd (after, Lo et al. 2006).

NUMERICAL MODELLING

In the last three decades, there has been a tremendous amount of progress made in three-dimensional (3-D) electromagnetic modelling. Much of this work has been devoted to the integral equation technique (*e.g.* Hohmann, 1975; Wannamaker, 1984). Solutions derived from this approach are quite accurate and have been used to understand the effect of simple 3-D models. They become computationally inefficient as the complexity of the model increases. In order to model arbitrarily complex geometries, we must use finite difference (FD) or finite element method (FEM). Examples of such approaches can be seen as early as in Jones and Pascoe (1972) and Reddy et al. (1977). Although these algorithms result in a large system of equations to be solved, advances in iterative solutions techniques (*e.g.* Sarkar, 1991) can make them very efficient and robust. The finite element method is more accurate but the finite difference method is simpler and quicker. Mackie et al. (1993) have developed a difference equation algorithm based on the integral form of Maxwell's equations. This direct solution is similar to a numerical propagator matrix technique and essentially breaks the problem down in doing several smaller matrix inversions instead of single large matrix inversion. Figure 2 shows the detailed difference equation geometry. Later in 1994, Mackie et al. modified the algorithm using the minimum residual relaxation method so that the results are more accurate and robust.

The above algorithm has been developed especially to carryout forward modelling of ground based GDS and magnetotelluric (MT) responses. In this model calculation we can assign the tangential H-field on the boundaries of the model for appropriate polarisation. These boundary values come from a two dimensional (2-D) transverse magnetic TM-mode calculations where each vertical plane of the 3-D model is treated as the inner part of a large scale 2-D model. The values obtained at the positions corresponding to the boundaries of the 3-D model are then used as the boundary values for the 3-D problem. TM-mode values are used because they are appropriate for a current that crosses resistive boundaries. This approach has been successfully used for computing land based and seafloor EM responses (*e.g.* Mackie et al. 1996; Joseph et al. 2000). I have modified the above algorithm so that we can compute the AFMAG type of responses of various 3-D earth situations at arbitrary height above the ground.

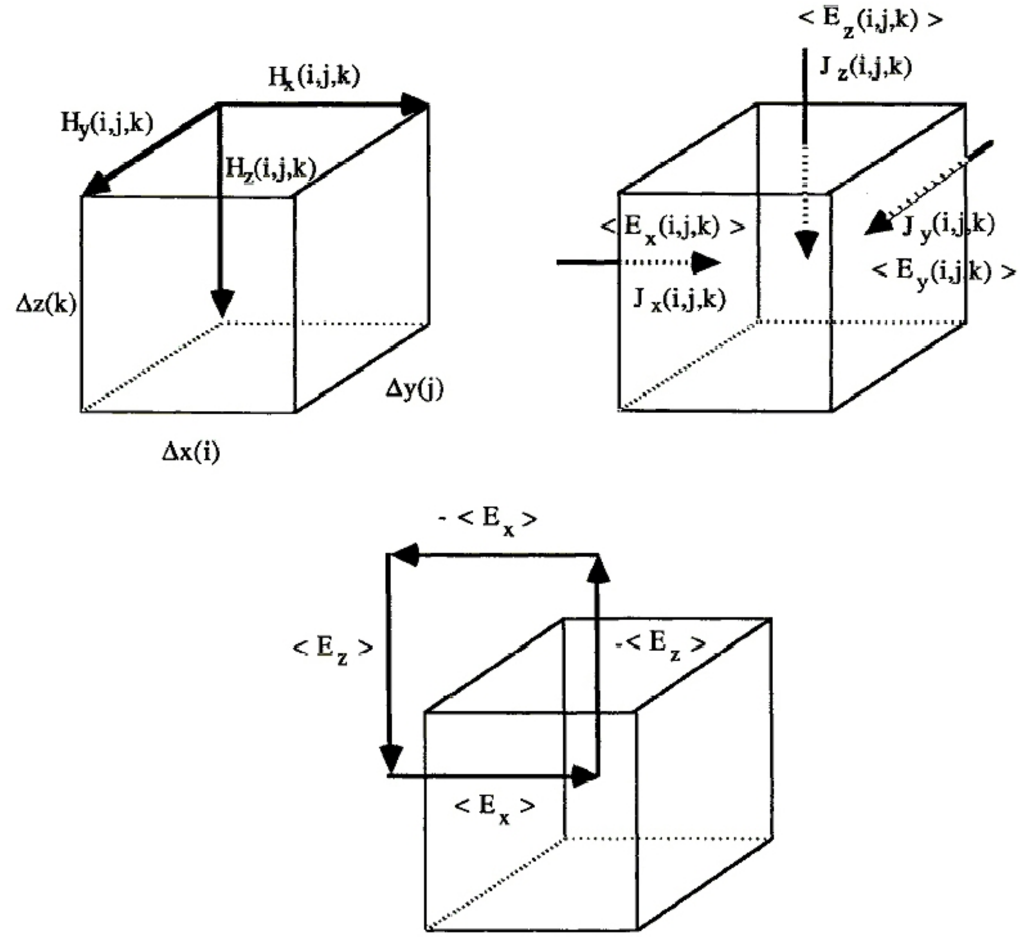

Figure 2. The detailed difference equation geometry based on the integral forms of Maxwell's equations. Each block has resistivity $\rho(i,j,k)$ and magnetic permeability μ_0(after Mackie et al., 1993).

A 3-D model was created by 50 X 50 X 16 blocks totalling 40,000 model parameters. Here the horizontal spacing of each block was taken as 100 m making the survey area a total of 25 sq.km. The source field was a uniform current sheet that was put right above the flight (or sensor platform) altitude. At the top of the air layers, a 1-D plane wave impedance for the outgoing field was used. Likewise, a 1-D plane wave impedance for a layered media was used at the bottom of the Earth model. The thickness of each block varies for each layer, with the top earth surface block corresponding to 20m followed by 50m, 100m and so on to a total thickness of 250 km. Responses were calculated for various altitudes (e.g. 30 m, 50 etc) and for various frequencies (1.0 Hz, 10.0 Hz, 20.0 Hz, 50.0 Hz and 100.0 Hz). Initially a 1-d layered earth model was considered and responses were calculated. Then geological structures such as dykes (both vertical and inclined) were incorporated into the model and the responses computed as seen on Figure 3. We then computed the amplitude of GDS responses for a vertical and inclined but low resistive dyke. Figure 4 shows the attitude (*magnitude and direction*) of GDS induction vectors over vertical and inclined dykes. It is evident that the modelled responses are distinctly different for different geological structures. This exercise has been repeated for different surface and subsurface resistivity situations. The preliminary results seem to be encouraging however it is still necessary to carry out a detailed numerical study and field test.

CONCLUSIONS

AFMAG system is potentially a useful tool in exploration geophysics. It is quite effective in cratonic regions, which are dominated by fresh rock exposures, i.e. there is a greater resistivity contrast between the host rock and intrusive bodies such as dykes. When the system is deployed over regolith dominated terrains the flight altitude, frequency ranges for the EM response and the sensitivity of the system as a whole become critically important. The sensitivity level should be improved from nano tesla (nT) to pico tesla (pT). As the sensitivity increases care needs to be taken to account for cultural noise. It is highly desirable to carry out 3-D forward model calculations prior to carrying out an expensive airborne survey.

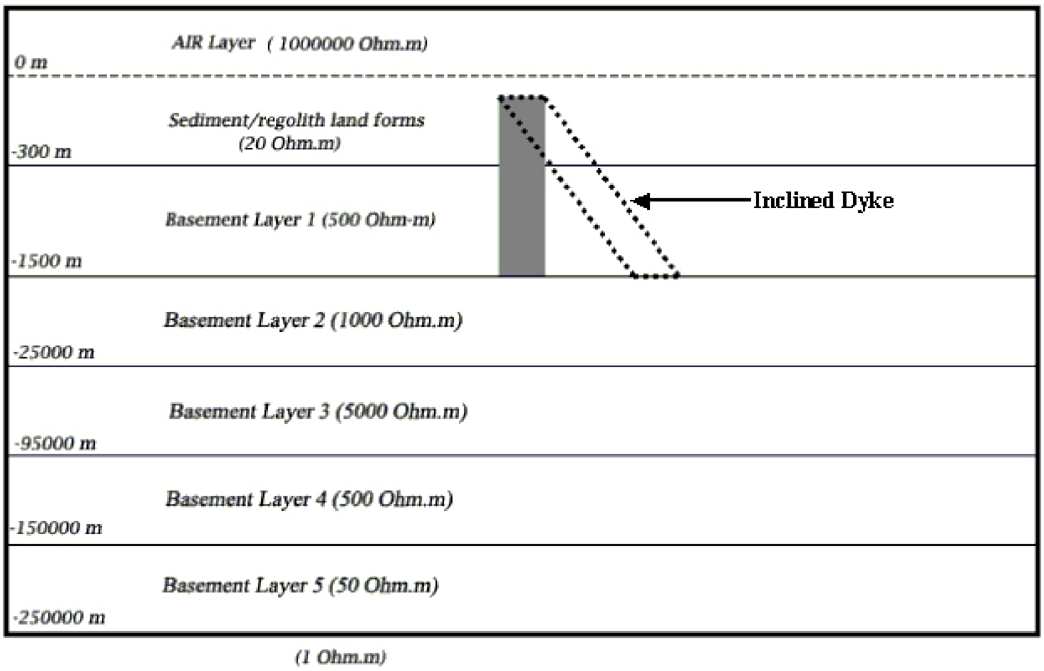

Figure 3. A schematic representation of the 3-D model cross-section with vertical and inclined dyke.

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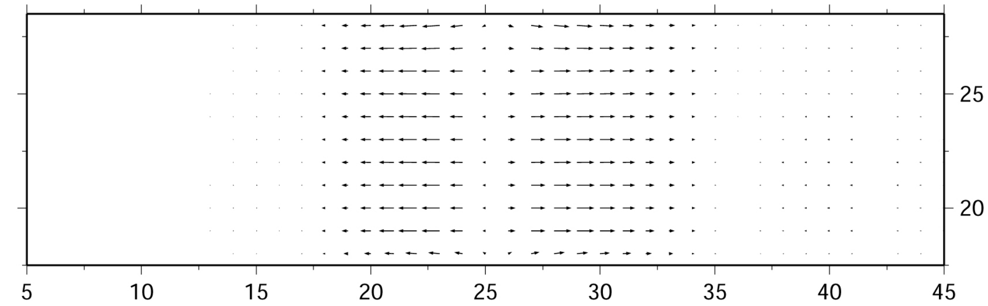
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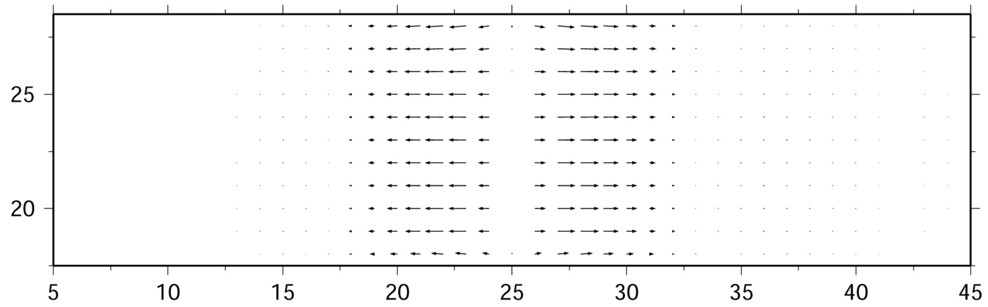
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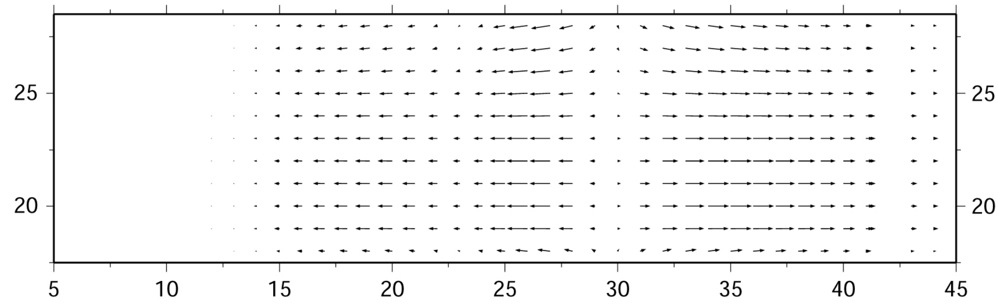
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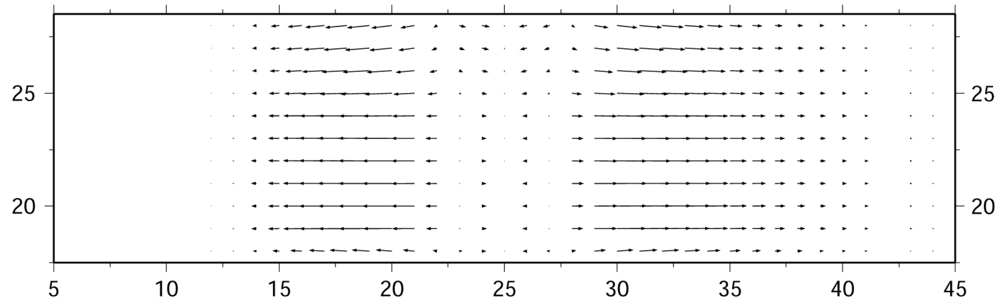
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Figure 4, Comparison of GDS induction arrows computed (100 Hz) for a 3-D model with (a) vertical dyke and (b) inclined dyke corresponding to a fluxgate sensor at ground level and at an altitude of 30m.