On the Use of High-Resolution Airborne Magnetics (HRAM) to Map and Characterize Major Faults

Hernan A. Ugalde

Department of Physics, University of Toronto, ugalde@physics.utoronto.ca

INTRODUCTION

Due to its cost-benefit ratio and since results can be obtained promptly; airborne magnetics are of great use for regional and detailed reconnaissance. One of its main uses is structural geological mapping. However, misconceptions on the magnetic petrology of the geological features to be mapped can yield undesired results. The present work attempts to address the main constraints to be considered in the design, acquisition and interpretation of high-resolution airborne magnetic surveys (HRAM) for fault mapping.

HIGH-RESOLUTION AIRBORNE MAGNETICS (HRAM) – DEFINITIONS

There is no consensus on exactly what flight specifications constitute a high-resolution survey. However, data are generally collected as close to the ground as allowed by aircraft safety and regulations, giving nominal terrain clearances of about 80-150 m (Murray & Tracey, 2004). Line spacing is more variable, ranging from 100 to 500 m. In order to have an appropriate resolution of 3D magnetic sources, the ratio of line spacing to height above sources should be

less than 1 (Grauch & Millegan, 1998). Line spacing wider than flying height produces aliasing that can make interpretation difficult.

FAULTS AND FAULT ZONES - DEFINITIONS

In the classical sense, a "fault" can be defined as "a surface or narrow zone along which one side has moved relative to the other in a direction parallel to the surface or zone" (Twiss & Moores, 1998)

Though most faults are brittle shear fractures (Figure 1A) or zones or closely spaced shear fractures (Figure 1B), some of them are shear zones of ductile deformation where movement took place without loss of cohesion at the outcrop scale (Figure 1C; Twiss & Moores, 1998; Ramsay, 1980).

The term "fault" is generally used indiscriminately for all the above cases, and no matter if the scale is on the order of meters or kilometres. For geophysical data interpretation, this leads to some confusion, since "fault" in the precise definition (narrow zone) involves different geological effects compared to a fault zone. Furthermore, step blocks are commonly used for geophysical data modelling, no matter the scale of the problem, or the width of the deformation zone (Chowdary, 1978; Bhattacharyya, 1978; Blakely et. al., 2000; Grauch et. al., 2001).

MAGNETIC PETROLOGY OF FAULT ZONES

Magnetite can be either created or destroyed during metamorphic processes (Figure 2; Reeves, 1987). The two factors that determine how much secondary magnetite can form during metamorphism are (Grant, 1985):

- total Fe content: determines the upper limit for potential production of magnetite.
- oxidation state*:* controls partitioning of iron between oxides and silicates.

Therefore, iron-poor rocks can never form significant quantities of magnetite, no matter what their oxidation state. Among sedimentary and metasedimentary rocks, this fact imposes a clear distinction between carbonates and sandstones and their metamorphic derivatives on one side, and argillaceous sediments (shales) and their metamorphic derivatives on the other. This is because shales generally contain more iron than sandstones or carbonate rocks due to the tendency of iron to attach to clay particles during sedimentation. This division persists up to the higher metamorphic levels (Grant, 1985).

Higher temperatures favour the breakdown of hydrous (Fe, Mg) silicates into progressively less hydrous and chemically simpler compounds. Secondary magnetite is produced from these reactions. Thus, there is a general tendency for iron-bearing rocks to become more magnetic with increasing metamorphic grade.

On the other hand, migmatization and granitization decrease magnetization, and in general extreme metamorphism will be accompanied by a decrease in magnetic strength (Grant, 1985).

As a summary, the conditions that increase rock magnetization (either increasing magnetic susceptibility or creating new magnetite) are (Grant, 1985):

1. mechanical deformation
2. repeated metamorphism
3. high temperature hydrous alteration (serpentinization)

On the other hand, conditions that destroy magnetite are (Grant, 1985):

1. low temperature alteration (carbonatization, chloritization, sericitization)
2. extreme oxidation (including chemical weathering, leaching)
3. granitization / metasomatism

The geology of the area of study and the geological history of the rocks must be considered when interpreting a HRAM survey. Faulting creates space for fluids to migrate and therefore alter the hosting rocks. The temperature of the hydrothermal system and its oxygen fugacity will determine the amount of magnetite present on the fault zone, and therefore, its magnetic response.

HRAM - DATA PROCESSING AND ENHANCING TECHNIQUES

The following is a summary of the most common and some new techniques and procedures that could be used to enhance the magnetic signature of faults and related structures.

(i) 2-D Frequency-domain filtering

These filters are the most commonly used for preparation of final grid and map products (Blakely, 1995). In the frequency-domain, one can prepare and analyze the power spectrum of the data, which shows the distribution across all measured low to high frequencies (i.e. long to short wavelengths). The shortest wavelength anomalies represent magnetic or gravity sources at or close to the Earth's surface (as well as noise). The longer wavelengths generally reflect deeper sources, although they also contain contributions due to the shallow responses. The power spectrum allows isolation of specific wavelengths within a grid as part of the filtering process, and estimation of source depths associated with these wavelengths. Filtering in the frequency-domain is fast, and allows several filters to be easily combined.

ii) Wavelet transform

Processing and preparation of geophysical data for interpretation has historically been performed by using Fast Fourier transform (FFT) algorithms. However, this transform does not provide time-frequency resolution. Wavelet

transforms give the ability to simultaneous time and frequency resolution, which turns into a powerful tool for denoising and data processing (LeBlanc and Morris, 2001; Martelet et. al., 2001; Gibert and Pessel, 2001; Sailhac et. al., 2000).

On the other hand, interpretation of potential field data can be improved, like inversion algorithms based on wavelets (Li and Oldenburg, 2000; Sailhac et. al., 2000) and depth to source estimations through the definition of a scaling parameter (depth) via analytic continuation (Archibald et. al., 1999; Holden et. al., 2000).

iii) Airborne vector magnetometry and full magnetic tensor measurements

Modern airborne magnetic surveys only focus on the magnitude of the total magnetic field without regard to its vector direction. Magnetic vector data gives additional information regarding the directional variations of the total magnetic field (Christensen & Dransfield, 2002; Nelson, 1988). Extracting this information would be beneficial for magnetic data interpretation on areas of strong magnetic remanence and in low magnetic latitudes.

According to Hogg (2004), the use of horizontal gradients can provide higher resolution and greater accuracy at wider line spacing (Figure 3). This feature becomes critical when trying to map linear features such as fault zones and/or dikes from magnetic data.

APPLICATIONS OF AEROMAGNETICS FOR STRUCTURAL MAPPING

When using magnetic data for structural mapping, specifically for major faults, it is essential to keep in mind: a) In the case of major faults, the problem will be to map a fault zone rather than a fault in the classical sense, that is the change in magnetic pattern will not necessarily be just a line, but a linear zone of changes; b) a major fault may have different segments with distinct reactivation and kinematic patterns, i.e. it would not be unusual to find changes in dip or direction of vertical movement along the trace of the fault zone.

To assist in determining fault displacement, some ancillary structural elements can be mapped through HRAM.

1. Dip of the structure.

Some information about the dip of a structure can be obtained from the following processes applied to HRAM data:

(i) *Wavelet analysis*: the larger the wavelet scale, the deeper the sources that are being mapped. Therefore, by comparing the location of the edges of the sources with different scales, it is possible to get an idea of the dip of the structure.

(ii) *Combination of band-pass filtering*: according to Spector & Grant (1970), different parts of the energy spectrum of the data resemble distinct scales of sources. That is, high frequencies are associated with shallow sources

and low frequencies with deeper sources. Some pitfalls of the method are: a) there is always contamination of higher frequencies to the low frequency parts of the spectrum ("backscattering"); b) the Spector & Grant method assumes that geology is made up of many blocks of constant magnetic properties, which is not normally the case. Despite these drawbacks, the method gives a good approximation of the depth distribution v/s frequency of the anomalies. Similarly to wavelet analysis, by comparing the source location given by a high pass filter (shallow sources) to the one given by a low-pass (deep sources), same idea can be gathered about the direction of structural dip (Figure 4).

(iii) *Wavelength analysis within anomalies*: as magnetic sources get deeper, they will produce longer wavelength (lower frequencies) anomalies. Therefore, the direction of increase of wavelength within an area of common magnetic sources (lithology) will indicate the dip direction.

2. Sense of movement.

The use of other linear features to determine the sense of movement of a fault must be applied with care. Nevertheless, qualitative analysis of the anomalies gives further indication of the sense of movement on a fault.

(i) *Use of first vertical derivative intensity*: as magnetic sources get deeper, the magnetic anomalies associated with them become broader and less

intense. A decrease in the intensity of magnetic anomalies will indicate that source depth increases vertically, or that they were uplifted and then eroded (Figure 5).

(ii) *Bending of aeromagnetic anomalies*: Henderson & Broome (1989) investigated the bending of aeromagnetic anomalies that characterize a shear zone. Aeromagnetic anomalies trended NE and bent south as they merged with EW trending anomalies, suggesting dextral net shear. This information, as well as geological mapping of asymmetrical structural fabric elements within the shear zone where it was exposed, allowed them to infer the geometry and kinematics of the shear zone.

SUMMARY AND CONCLUSIONS

Historically, a disproportionate effort has gone into collecting survey data, compared with rock property studies which could be used to help in the interpretation of variations seen in the geophysical anomaly fields (Clark, 1997). Therefore, studies of the magnetic properties of rocks in the area of study are indispensable to carry out a good interpretation of any dataset.

In addition, smaller scale geological mapping is critical, to pick up any lithologic changes that are not seen on the regional map. Airborne radiometrics has proven to be a useful tool to recognize lithologic changes that are not seen by ground mapping (Ugalde, 2000; Milligan & Gunn, 1997). It can be therefore

included in the data collection plan, since cost will not increase more than 30% and the added value to data will be much higher.

Two critical issues concerning magnetic anomalies interpreted as faults are (Grauch et. al., 2001):

1) distinguishing anomalies related to faults from those associated with a paleochannel filled with detrital magnetite;
2) distinguishing anomalies produced by the juxtaposition of sediments having different magnetic properties at faults from anomalies related to secondary geochemical processes that have either destroyed or introduced magnetic minerals along the fault zone.

The first issue can be addressed by providing independent evidence for faulting in another dataset, such as seismic reflection profiles (Gunn et. al., 1997) or gravity. The second issue is difficult to address because the interpreted faults are buried.

An integrated approach that includes HRAM, radiometrics, detailed geological and magnetic rock property mapping whenever possible is desirable. With that resolution, shear indicators should be mapped by the magnetic data (Henderson & Broome, 1990; Schetselaar & McDonough, 1996).

To aid in the interpretation, high resolution techniques such as wavelet analysis and 2D FFT filtering should be applied to the data. Then again, the interpreter must recognize that fault zones can exhibit distinct behaviour on different segments, simply tracing a line should be avoided.

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FIGURE CAPTIONS

Figure 1

Styles of faulting: A) single fault consisting of a single shear fracture; B) a set of associated shear fractures; C) a zone of ductile shear. (From Twiss & Moores, 1992)

Figure 2

Scenario for basic rock metamorphism, indicating the possible repeated destruction and re-creation of magnetite in a simple basalt during increasing degrees of metamorphism (From Reeves, 1987).

Figure 3

Left: conventional total magnetic field response measured over an offset linear structure. Right: the same structure mapped with horizontal gradients. From Hogg & Associates, www.shageophysics.com

Figure 4

Scheme of the proposed dip estimation algorithm by using high-low pass filtering. At least in relative terms, it will be known that Z1<Z2, then the direction of d can be determined. Otherwise, if we can trust on the numerical estimations of Z1 and Z2 ("depth slicing"), $d = \arctan\left(\frac{Hdist}{Z2 - Z1}\right)$.

Figure 5

Left: total magnetic intensity on one area of northern Chile. Right: First vertical derivative of the magnetic field on the same area. Note the decrease in intensity on the 1VD where some structures were outlined. The same approach was used to mark the lineaments on the left, which could be related with subsequent normal faulting.

Figure 1

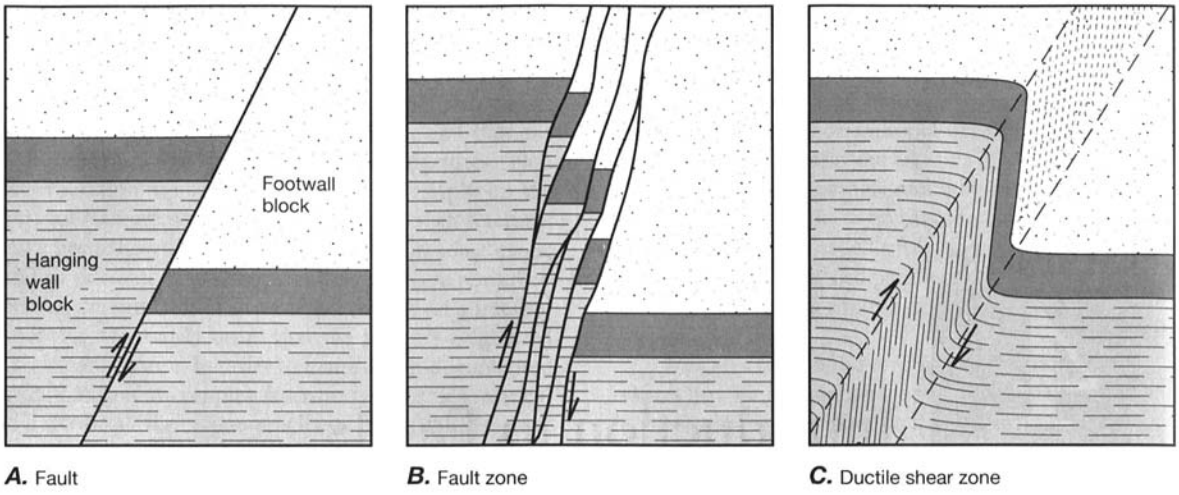

Figure 2

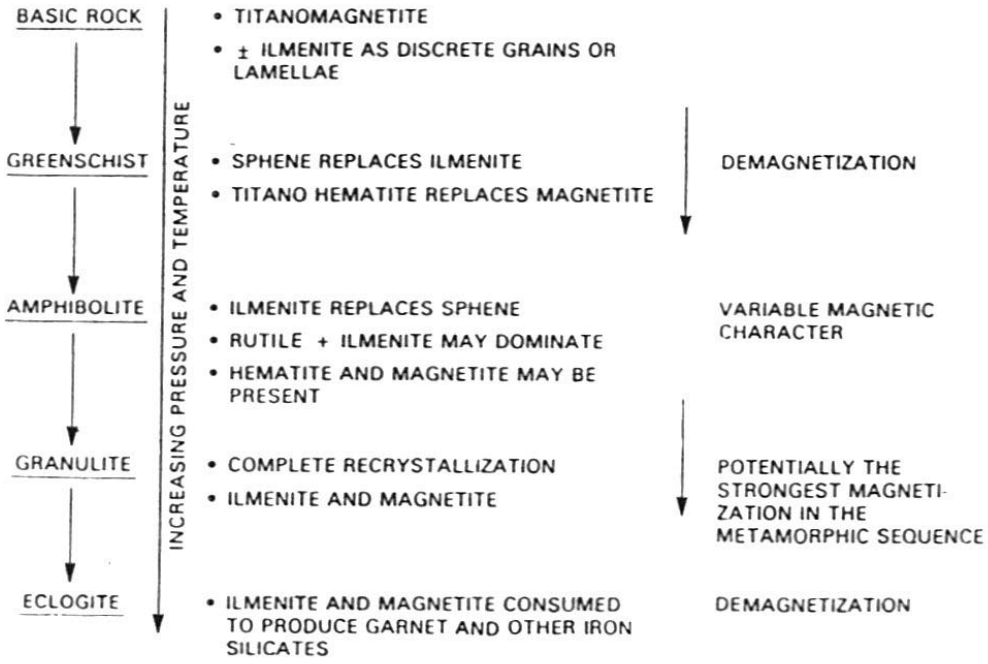

Figure 3

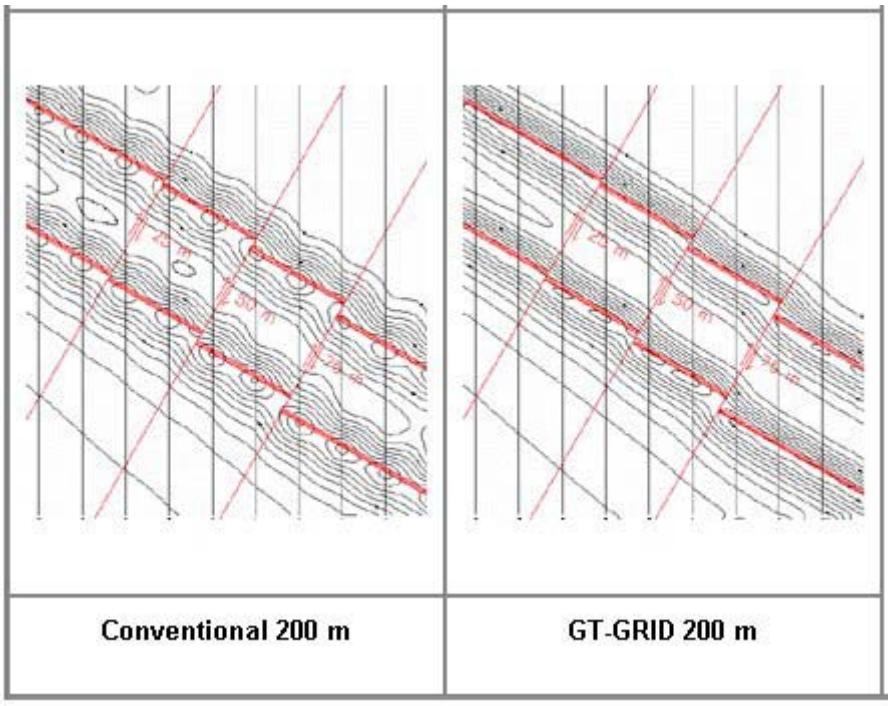

Figure 4

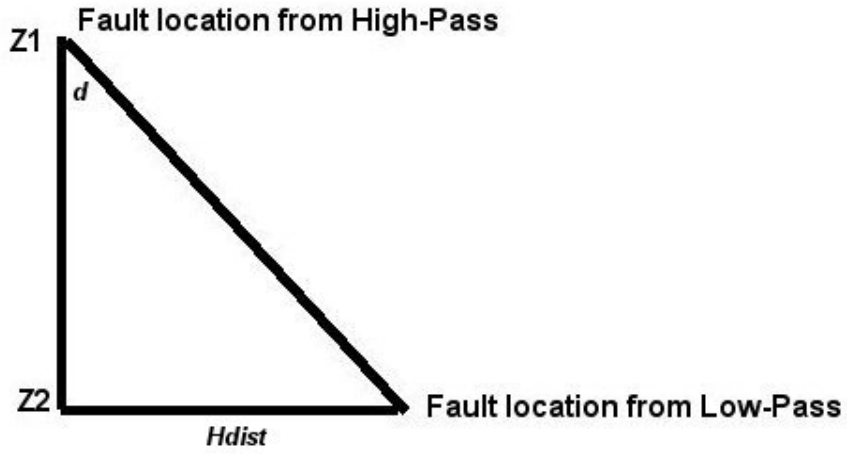
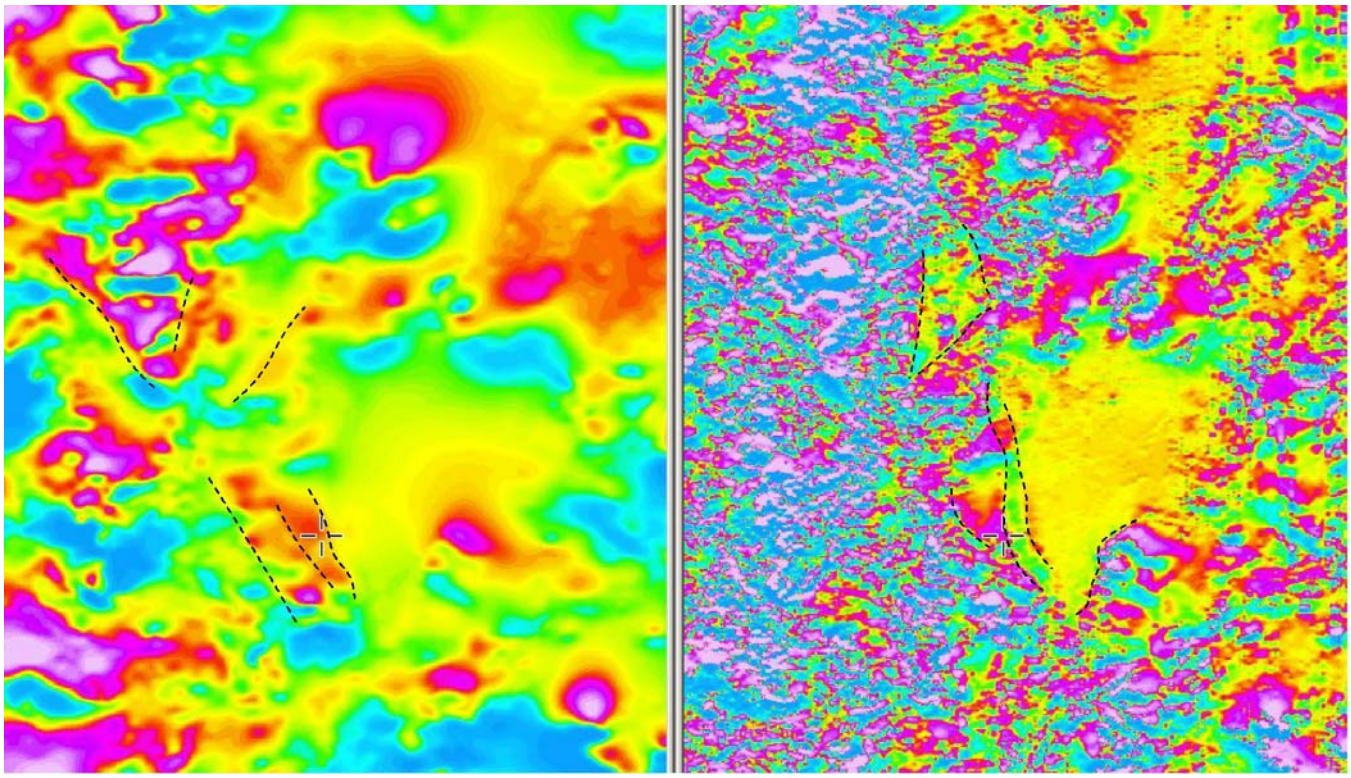
Figure 5