Paper 32

Geological Interpretation of Airborne Magnetic Surveys - 40 Years On

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ABSTRACT

Regional airborne magnetic surveys have been a key start point for resource exploration and development programs since the 1960's. Growth in both the worldwide coverage and quality of such surveys has been enormous since then, and many mineral discoveries have been made as consequence of these often freely available data sets. The critical developments in the application of magnetic surveys have been image processing and satellite navigation. Great strides in data precision (particularly positioning) and diminished cost of coverage have lead to surveys with broader coverage, tighter line spacings and higher quality magnetometry. This in turn has enabled the more effective use of established numerical filters and transformations which, when coupled to imaging hardware and advanced data visualisation schemes, allow users to extract an extraordinary range of geological information from the magnetic data. Despite these developments and the consequent proliferation of high quality regional magnetic data in many countries, robust geological interpretation of these data is not commonly achieved, and the writers believe that establishing better links between the airborne data and the underlying geology requires more attention if full value is to be obtained from the surveys. This paper briefly restates the fundamentals of the application of magnetic surveys and highlights the developments which have fuelled the expanding use of such surveys in all facets of geological mapping. We comment on the interplay between advances in magnetics and those in the understanding of mineral deposit formation and localisation. We present recent examples where large scale surveys combined with incisive interpretation have lead to major exploration successes. We conclude by suggesting that future developments in this field should produce more sophisticated integration of magnetic data with other geoscientific data, particularly hard geological data, leading to more robust geological interpretations and more frequent economic discoveries. The notion that ready and inexpensive access to large, high resolution aeromagnetic data sets provides an accelerating mechanism for resource discovery is also actively promoted.

INTRODUCTION

Any strategist will tell you that a good start is essential for a successful campaign -- whether it is it business, or love, or in a mineral exploration program; you need to know where, how and when to start. The senior author (DMB), started in the airborne geophysical industry in the 1950's and presented the first substantial account of the geological mapping capabilities of airborne magnetics at the 1967 'Mining and Groundwater Geophysics' conference (Boyd, 1969). The purpose of this paper is not only to reflect on the developments and achievements in the ensuing 40 years, but also to promote the need for more persistent and 'profound' interpretations of the ever expanding global collection of high quality airborne magnetic surveys.

In resources development programs, whether it be for oil and gas, minerals or the management of water resources, ready access to a variety of informative data bases is essential. Airborne magnetic surveys in particular, have proven to be a most valuable start point to supplement geological and mineral mapping in countries all over the world.

Magnetic surveys have been found to be very effective at all stages of regional programs because of the widespread distribution of magnetic minerals through almost all geological terrains and the speed and cost effectiveness with which this 'magnetic mineral distribution' can be mapped. Magnetic surveys also have the advantage that they are now widely available on most continents.

Availability, or rapid and inexpensive acquisition of diagnostic data, is a central factor in implementing resource identification and development strategies. Time is a key element in national development, and even more so for mineral exploration companies, so timely availability of information is crucial to the decision making process. Early availability of regional magnetic data has proven to be the key to the success of a significant number of large scale resource projects. In developing countries, the need for not only the acquisition of such data, but also its effective interpretation and broad

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'utilisation' , continues to be a major consideration for international aid agencies (Reeves, 2005 and 2002)

It is not the place of this paper to dwell on the underlying physics of the magnetic method or the now highly sophisticated technology of data acquisition, processing and visualization. But it is important for interpreters to have a solid grounding in the basic science underlying the interpretation, and to be alert for problems which can arise from a misunderstanding of the principles of acquisition and processing. Our emphasis is on the end uses of magnetic data and the on-going need for comprehensive interpretations which integrate the best available geological data. The fundamentals of thorough interpretation are often overlooked in our haste to meet deadlines and budgets and custodians of these data sets need to be aware that full value from a regional magnetic survey may only be achieved after multiple interpretations which may span years or even decades.

MAJOR ADVANCES FROM 1967 TO 2007

An excellent account of the general practice in aeromagnetics prior to 1967 can be found in Reford and Sumner (1964). Outlined below in approximate chronological order are the advances which have had a major impact since that time.

Digital acquisition became established in airborne surveys by the early 1970's. This led to giant strides in data compilation and enabled the application of a wide range of numerical filters and transformations (Hood et al, 1979). The routine preparation of vertical gradient maps was a most important advance at this time. These developments greatly expanded our ability to recognise and map particular aspects of geology from magnetic data.

Cesium Vapour and Helium Vapour magnetometers provided the next major step forward bringing the smallest discernable airborne magnetic signal down from around 1nT to 0.05nT or less. While data compilation uncertainties and the general focus on 'strong' magnetic anomalies delayed the routine implementation of these magnetometers in airborne surveys, the high sensitivity data now proves its worth, particularly in sedimentary basin applications (Norman, 1993).

Image processing systems, developed initially for the analysis of satellite data, found favour with the airborne geophysics industry during the 1980's (Kowalik and Glenn, 1987). This heralded a new age in visualisation of the magnetic data itself, but more significantly, opened the door to rapid and effective integration of magnetic data with other geoscientific data such as radiometrics, satellite data and ultimately digital geological data (Spencer et al, 1989).

Real-time GPS navigation became a reality in the early 1990's and this has had a most profound effect on data quality and cost of acquisition. Where previously positioning had been one of the main sources of cost and data errors, GPS navigation essentially automated the process and made it remarkably reliable and inexpensive compared to all of the prior positioning techniques.

Steady developments and refinements in numerical transformations have also taken place over the past 40 years. While the methodologies of filtering (Bhattacharyya, 1972), transformation (Baranov and Naudy, 1964, Nabighian, 1972), inversion (McGrath and Hood, 1970) and automatic depth determination (Naudy, 1971, Spector and Grant, 1970) have been with us for many years, recent refinements in these methodologies combined with the huge explosion in desktop computing power have allowed previously 'difficult' or time consuming operations to become routine. Notable examples are the refinements in Reduction to Pole in equatorial regions by Campbell et al (1992), Li and Oldenburg (1993) and Keating and Zerbo (1996); in 3-D inversion (Li and Oldenburg, 2001); in enhancement of very small magnetic signals (Rajagopalan, 1987); and in automatic depth analysis, (Shi and Boyd, 1993). This has greatly expanded the interpreter's ability to clearly view and map particular geological features represented in the magnetic data.

In parallel with the above transformations, forward modelling has progressed from somewhat cumbersome schemes in the 1960's to highly sophisticated 3-D software which not only facilitates speed and versatility in the modelling process, but also incorporates effective visualisation of models in the context of other data sets (Pratt et al, 2001).

For a more complete discussion of the evolution of airborne geophysics in recent times, the interested reader is referred to Reeves et al (1997) and Thompson et al. (this volume).

Advances have also been made in the understanding of the magnetisation in rocks and how this impacts airborne magnetic interpretation. Papers by Grant (1984a and 1984b), Clark (1997) and McIntyre (1980) have significantly enhanced the geological 'credibility' in modern interpretation.

The style of regional magnetic interpretation has progressed substantially in the past 40 years, building on the fundamental principles outlined in Boyd (1967). Tucker (1983) consolidated a number of detailed aeromagnetic surveys to form a regional assessment of the Broken Hill District, which included a novel and very useful correlation between magnetic horizons and regional stratigraphy. Whiting(1986) used detailed aeromagnetic data to provide a comprehensive geological assessment of a base metal project area in a poorly exposed, complex metamorphic terrain and Corner and Wisher(1989) integrated aeromagnetic and gravity data with known geology to compile an enlightening solid geological interpretation of the Witwatersrand Basin. Jaques et al, (1997) present a government mapping perspective of geological interpretation in areas of limited outcrop based largely on aeromagnetics. Rankin and Newton (2002) used 400m and 200m spaced government data covering the Musgrave Block in South Australia to compile (at 1:100,000 scale) not only a detailed solid geological interpretation, but also a broad ranging synthesis of the tectonic history and the potential controls on mineralisation. Rankin and Newton's work covered the entire geological province (over 200,000 km²) and provides an excellent model for modern regional aeromagnetic interpretation.

A pertinent side issue in the progress of the utilisation of magnetic data is its interplay with the advances in understanding the controls on mineral deposit genesis and emplacement. On one hand, clearer concepts in ore deposit targeting have led to a clearer focus in magnetic interpretation. On the other hand, higher resolution in magnetic surveys has led geologists to 'see' features at a range of scales which have added significantly to ore genesis models. A good example of the former is the growth in the sophistication of targeting for Iron-Oxide-Copper-Gold deposits. Detailed studies of the behaviour of particularly magnetite and hematite in these environments (eg, Skirrow et al, 2002), now allow explorers to postulate specific alteration styles rather than simply, as previously, target magnetic 'anomalies'. In Archaean gold exploration, particularly in the arid, poorly-exposed regions of Australia and Africa, high resolution aeromagnetic data has provided key structural information allowing the construction of district and regional scale models for orebody genesis (Isles et al, 1990).

A final, often understated development in the utilisation of regional magnetic data has been the proliferation of large scale surveys worldwide. These have included proprietary surveys, non-exclusive commercial surveys and particularly government and aid-agency sponsored surveys. Not only has the worldwide coverage in high quality magnetic survey data spread enormously, but the ready availability of much of this data (often at negligible cost) has lead to a much more global perspective by mineral explorers in particular. This has been aided by a number of cooperative projects (eg, Fairhead et al, 1997) where disparate data sets have been 'stitched together' to provide coverage transcending geological and political boundaries and facilitating interpretation at continental scales.

THE (OFT-OVERLOOKED) FUNDAMENTALS OF REGIONAL MAGNETIC APPLICATIONS

Regional magnetic surveys come in various forms. Some regional surveys started as part of a long term plan, others just 'growed like Topsy' as a number of independent surveys were stitched together. Some regional surveys were flown high with wide spacing as part of studies of continent-scale structure, many were flown with the ground clearance of around 100m to provide information about the near surface geology: others were flown at heights of 10,000 m and the line spacing of the order of 10 or 20 km as part of the even more global scale studies of the physics of the earth.

Magnetic surveys of the oceans, which were regional surveys on a very broad scale, started as a matter of scientific curiosity, developed as a matter of national security in defense against submarines and provided the key evidence for the revolutionary theories of plate tectonics. While not the focus of this paper, these 'unusual' applications demonstrate just how important regional surveys can be in contrast to localized, detailed surveys carried out over specific target areas.

In discussing the fundamentals of regional magnetic application we take as given that survey design and data acquisition, processing and enhancement are appropriate and start by dealing with the stage which delivers the main outcome of the survey.

Interpretation

Interpretation is at the center of all geophysical surveys. Every time a geologist draws insight from an image he is carrying out an interpretation and hence presentation of magnetic data must be as meaningful for geologists as it is for their geophysical colleagues. We usually, however, think of interpretation as the systematic approach to deciding what the data can tell us about the geology.

A good interpreter is rarely a narrow specialist. The interpreter of a geophysical survey needs to understand many aspects of the project as well as his or her own geophysical discipline. The interpreter may be a member of team in which there are a number of specialists who focus on individual parts of the program but the interpreter must be able to communicate with all members of the team which will likely include geologists, mathematicians and physicists as well perhaps as economists and politicians. The interpreter should be able to take a long view of the work as well as be involved in the intimate detail of the many specialist aspects of interpretation.

Underlying the language and architecture of the magnetic data are of the laws of physics and potential field mathematics. To be useful to the geologist these data must be translated into the laws and concepts of geology and this process of translation is what we call interpretation. Figure 1 shows the location of magnetic data sets presented in this paper.

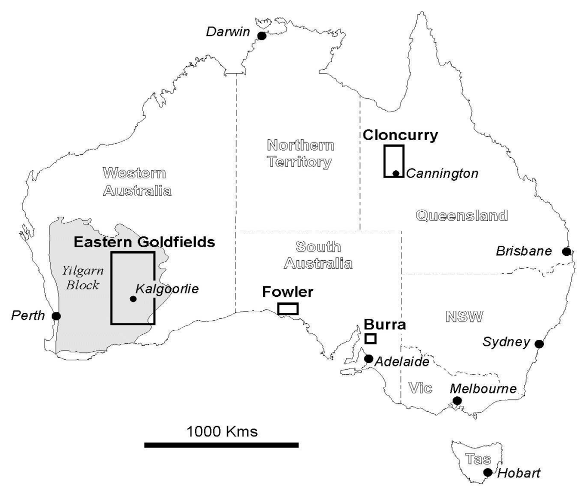

Figure 1: Localities of magnetic image areas

Thorough and meaningful interpretation of a regional airborne survey is a time-consuming and complex process which, like geological mapping, may take years or even decades before optimum value is realized from the data. Individual phases of the interpretation will often take months of continuous effort, and a useful rule of thumb for the allocation of time to the initial, dominantly qualitative phase of interpretation is that at least one (experienced) man-day is required per 1000 line kilometers of data. A plan or philosophy of interpretation is essential in order not to lose way or worse still, to prematurely consider the interpretation 'finished' or 'final'. Descartes (1937) prescribed four precepts or steps on the solution of complex problems provide an ideal basis for this plan:

i. Accept nothing that you have any occasion to doubt:
ii. Divide the total project into as many parts as seems appropriate:
iii. Solve the easiest problems first:

Review each step carefully to make sure you have missed nothing.

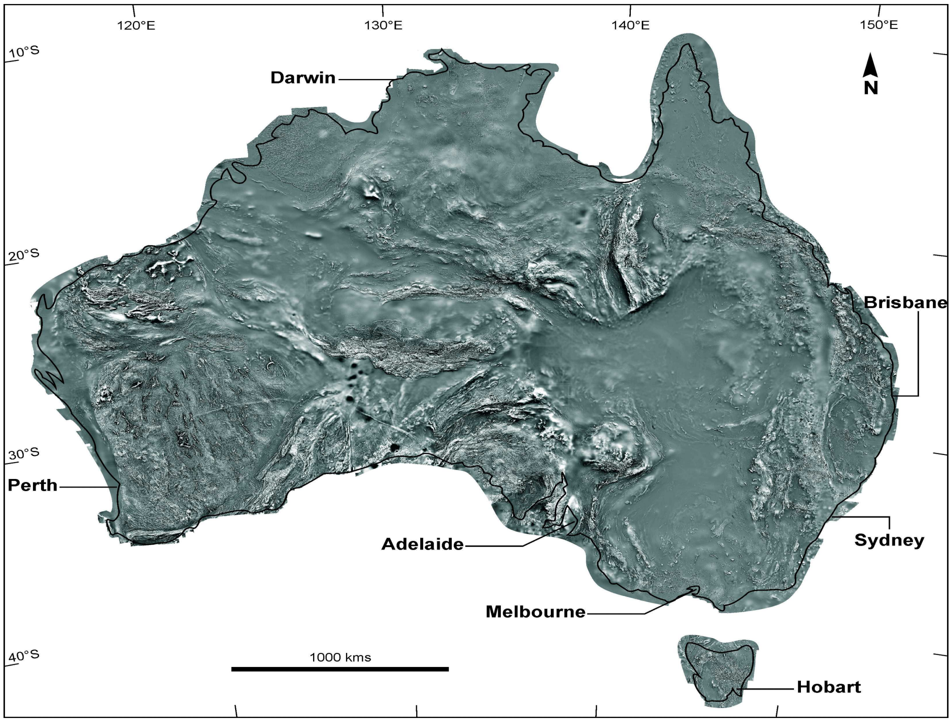

Figure 2: Aeromagnetic image of Australia comprising data entirely sourced from Geoscience Australia. The enhancement is a merge of TMI and 1st Vertical derivative grids.

These precepts apply to magnetic interpretation in the following way:

Step 1: Accept nothing that you have any occasion to doubt

There are four main types of data on which the interpretation will be based and each has its particular strengths and weaknesses which must be acknowledged and addressed. Our knowledge of each dataset is always incomplete, and in some cases misleading, because it is statistically unrepresentative or sometimes just plain wrong.

i. The magnetic data itself. Its main strength is its ability to provide a uniform and unbiased map of the distribution of magnetic minerals; minerals which are widespread in most geological terrains. For example, The Magnetic Anomaly Map of Australia (Tarlowski et al, 1997, Geoscience Australia, 2004) provides an incomparable overall picture of the Australian continent as illustrated in Figure 2. The '3-D' distribution of magnetic minerals which can be derived from magnetic data holds a wealth of information on lithology, structure and geological processes such as alteration and metamorphism. Weaknesses of magnetic data include situations where key geological contacts have no contrasts in magnetic mineral content, and also the limitations of survey specifications: surveys with wide line spacing or large terrain clearance will be limited in their resolution of 'finer scale' geological variations.

Errors in the magnetic map data may come about in many ways and can produce 'pseudo magnetic anomalies' which if taken at their face value by an inexperienced interpreter may be attributed to non-existent geological bodies or structures.

In older (pre 1990's) data the errors may be due to mis-location of the flight path, mistakes in transcribing the data, shortcomings in correction for diurnal variation, heading and parallax or to malfunctioning equipment. In modern surveys, as mentioned above, these errors are less likely to occur, but applications which use sophisticated analysis for deeply situated bodies in the upper or middle crust, may encounter long wave length errors introduced by drape flying and inappropriate corrections for diurnal variation of the Earth's field.

ii. Geological maps, sections and reports: Geological maps are based on the often subjective observations of one or more individual geologists; some geologists are very exact and reliable observers, others are not. Geological data sets are assembled from points where rocks have been studied in outcrop or have been recovered from drill holes, in addition to inferences drawn from features on the landscape or aerial photographs. Geological maps compiled from interpretation of a limited number of field observations can be very misleading. Geological data will, however, always form the basis of our interpretation. It is the fundamental means of limiting the choice of models in an interpretation.

iii. Other regional geoscientific data sets such as geochemistry, satellite imagery, radiometrics, gravity and electromagnetics. Each of these has the potential to add new and critical information to the interpretation and further constrain interpretative choices, but rarely do any have the range and degree of detail of geological information contained in magnetics.

iv. Rock properties. Measurements of magnetic susceptibility and remanence provide the hard link between rocks and the features observed in magnetic data. This crucial data is unfortunately very rarely available in sufficient quantity to significantly contribute to the interpretation. A particular limitation is that these measurements require fresh rock which may not be present in weathered or covered terrains. Rock property data from drill holes is most valuable, but in many regional programs, drill holes are rare. Indeed, drill holes are usually an outcome of any regional interpretation! As rock property data is accumulated, however, significant refinement can and should be made to interpretations, and this can be greatly enhanced where one central repository of petrophysical data is maintained. The Geological Survey of Finland provides a fine example of how this can be done effectively.

Conflicts between the above data sets will inevitably occur and it is the resolution of these conflicts that underpins the quality and value of the interpretation. Of particular note is the frequent situation where observations from magnetic data are at odds with well-established geological mapping. Where this occurs both data sets require critical review and it is wise to remember that the purpose of magnetic surveys is always to add to the geological picture, not simply to confirm what is already 'known'.

Step 2 Divide the total project into as many parts as seems appropriate

Regional interpretation is usually much too complicated to be accomplished in one sweep, and it is necessary to break the interpretation down into manageable tasks or stages which deal with particular aspects and problems. As Einstein said "make everything as simple as possible, but not simpler." This is good advice for the interpreter and there are various ways dealing with this simplification. While the initial purpose of the survey and the prescribed outcomes will dictate the emphasis given to each of the stages, a common template for interpretation involves the following stages.

i. Choice of data and presentation type. The very first step is to select and present the data in the most appropriate form for interpretation. The choices of data type are many. Measured (TMI) data may be complemented by numerous filters and transformations which highlight particular aspects or components of the data. The choice of data types will in part be dictated by geological terrain, in part by the application and in part by the personal preferences of the interpreters. An underlying principle is that most situations require multiple (at least 3) data and image types to reveal the full extent of the geological information contained in the measured magnetic data. A common mix in near surface mapping and exploration applications is TMI, RTP (the TMI data reduced to the pole) and 1VD (the first vertical derivative of TMI), which emphasizes structural detail.

In recent times, imaging systems with large, high resolution screens have tended to displace hardcopy maps. Pixel image format has also almost superseded the contour maps and stacked profiles which were the standard forms of presentation prior to the 1980's. While imaging systems undoubtedly have superior versatility in data presentation to the old pen and paper medium, we make two very important points.

- Pixel image displays are inferior to contour line displays at scales where data variations appear smooth. This situation is common where data is 'zoomed' to its maximum practical extent.
- The mechanics of drawing interpretive lines and subdivisions 'on screen' remain cumbersome, and limiting the size and physical location of the data display to a computer screen has certain drawbacks. A particular example is the large hardcopy image 'permanently' displayed on the geology department wall which continues to have exceptional value in stimulating discussion and debate.

We suggest that judicious use of 'new' and 'old' formats is needed in any comprehensive aeromagnetic interpretation.

ii. Mapping the 'geometric' aspects of the magnetic data. This stage involves the delineation of magnetic rock bodies, areas of differing magnetic mineral zonation and patterns of continuity and discontinuity. It may involve a component of quantitative analysis to constrain depths and dips, etc, but it is frequently a visual and qualitative process. This results in a 'structural skeleton' on which the geological 'flesh' can be built. An example of this process is presented in Figure 3.

iii. Assigning the most plausible rock units to subdivisions evident in magnetic data. This may be straightforward where ample, well mapped outcrop is present, but more commonly it involves a large degree of educated guesswork. The task becomes extremely interpretive when magnetic features are deep and have no exposed analogues. Combining this map of 'geological polygons' with the 'structural skeleton' yields a crude solid geology map which emphasises magnetic features.

iv. Integration of the above with all established geological information. This is the critical stage of interpretation. It is invariably a slow and challenging process requiring resolution of conflicts between data sets and a high degree of interpretive judgment. The task is made easier if the interpreter has a strong grasp of the local geological terrain as well as skills in understanding the magnetic data.

The map resulting from the completion of this stage is a solid geology which should be, as far as possible, true to the geological facts and include all key features of the magnetics expressed in geological terms. In some cases this will be close to the end result of the interpretation.

v. The further stages are the 'cream on the cake' and they may take many forms. Where 3-D information is important to the desired end result, a phase of focused quantitative processing may be essential and this will usually require specialist application of sophisticated software. Often the interpretation will be used to refine and extend the depositional and deformational history of the study area, again normally requiring specialist input. Many surveys are directly aimed at resource discovery, and the main 'output' required by the survey's commissioners is a 'target map'. In this case input from the ever-evolving specialist fields of structural and economic geology is extremely important. Once again, the interpretation process will always benefit from specialist knowledge of the attributes of the target resources, and the concept of breaking the process into small steps involving team members with a range of skills becomes plainly apparent.

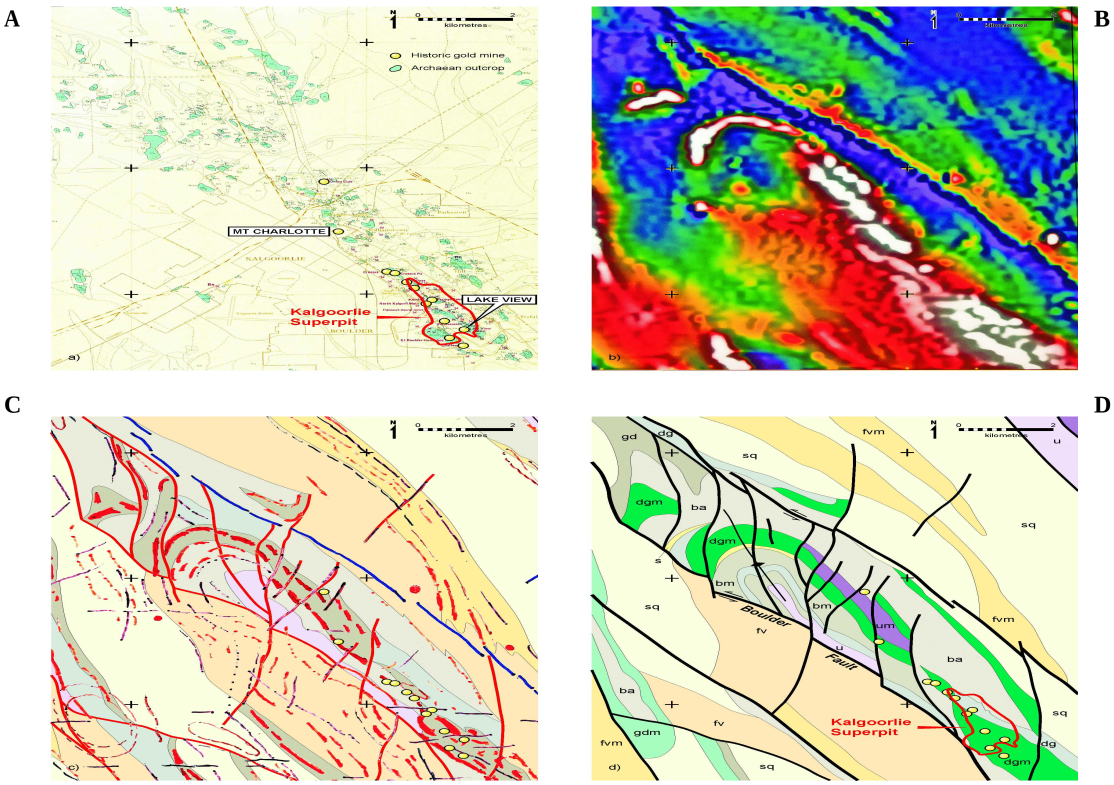

Figure 3: Kalgoorlie 'Golden Mile' district – detailed magnetic interpretation study. a- Distribution of outcop (after Keats, 1987), b- Image of merged TMI and 1st vertical derivative (after Isles,1989), c- Interpreter's 'structural skeleton'(Stage1) with Stage 2 'solid geology, d- Completed geological interpretation

Precept 3: Solve the simplest parts or problems first

This will apply in all of the stages listed above.

For example a very simple initial step in interpretation is to directly compare the magnetic map and the geological map. This should show at once which exposed geological units or parts of units are magnetic and which are not. Where ample exposure is present (and well mapped), this comparison may rapidly provide new information on changes in lithology, stratigraphy or alteration of geological units. This is a very simple but essential first step in interpretation.

It is relatively simple to visually estimate the approximate shape and orientation of a clearly defined magnetic rock body from a well presented image, but less straightforward (and more time consuming) to accurately determine depth, dip and edge positions; this more laborious analysis of anomalies is often more revealing when the interpretation questions have been asked and properly defined. The compilation of a 'structural skeleton' will rarely require precise quantitative detail, which may however be a critical element of 'stage iv'. It is also usually more productive to progress the interpretation to an advanced stage in local areas where the geology and magnetics 'make sense', rather than systematically work through the entire project area.

The solution of the simple problems frequently places the more difficult ones in a clearer context, and provides constraints which make the latter more manageable.

Step 4. Review each step carefully to make sure you have missed nothing

It is a normal procedure to go back continually over the work you have been doing to integrate the latest part into the earlier parts. Some of the evidence viewed earlier will only make sense when later information from interpretation becomes available. Isolated fragments of information at an early stage may, when reviewed, become important links in a chain of reasoning that underpins the interpretation. It is also very easy in the excitement of interpretation to lose sight of the main aim of the project and the review provides the opportunity to put the work back to proper perspective.

On-going Review

The concepts of staging and reviewing the interpretation process also apply at the broader level. Regional magnetic surveys in particular are designed to have a 'life span' of decades and this presents the opportunity for multiple interpretations, possibly for a range of purposes and employing multiple interpreters with diverse skills. The first interpretation of a new magnetic survey is usually done under pressure of time and budget, and will rarely include a comprehensive integration of all relevant peripheral data. It is therefore very unwise to take this work as being 'final'.

Very commonly the initial interpretation will lead to field investigation (such as drilling of 'targets') which immediately provides data to modify, upgrade and revise the interpretation. In this manner, magnetic interpretation should be regarded simply as a component of geological mapping, whereby as time passes, more and (hopefully) better data and ideas materialize, leading to more detailed, sophisticated and (hopefully) useful geological maps.

Of critical importance in mineral exploration is the review of data when new concepts in ore deposit genesis are formulated. An otherwise insignificant 'blip' in a magnetic image may become the key piece of information leading to discovery when the magnetic data is reviewed with new targeting concepts. Conversely, where new enhancements of magnetic data are developed, a new look at data in mineralized environments may be revealing and rewarding. Hence, periodic review and revision of the interpretation is an important aspect of obtaining full value from a regional magnetic survey

USES OF THE MAGNETIC SURVEY DATA

A good workman understands the capabilities of the product of his trade. Magnetic interpreters must be aware of the range of applications that their work may be 'used for', even if the initial purpose of the survey is broadly or vaguely defined. With very few exceptions, magnetic surveys are designed to 'map geology' (where bodies of minerals, oil and gas and groundwater are included as elements of the geological map). This may take the form of:

i. Driving solid geological mapping in poorly exposed areas ('interpolating between outcrops')
ii. Initiating mapping in totally covered areas (extrapolating from 'distant' exposed areas) or,
iii. Providing new geological insights in well exposed areas.

While the last of these uses is rarely given as much weight as the first two, the experience of both of the writers has been that surveys in well exposed areas frequently reveal critical features which change the perception of the geology and often result in important new leads in exploration.

Modern magnetic surveys have been shown to have valuable application in all geological terrains, and in recent times, expanded use of such surveys has occurred in sedimentary basins, mapping not only the conventional 'magnetic' sources (Gunn, 1997) but also extremely low order variations in magnetic mineral content which reflect changes in the 'non magnetic' sedimentary sequence (Norman, 1993).

Scale of Investigation

The scale and clarity with which this mapping is achieved is controlled by the flight line spacing, the flying height and the distribution of magnetic minerals. This can be quantified in terms of the scale to which data can be 'zoomed' without 'breaking up'. A reliable rule of thumb for the most detailed scale of presentation and analysis is that scale where one centimetre represents one flight line spacing (Isles et al, 1992). Magnetic images should always be examined at two different scales, differing by a factor of 4 or 5; this enables recognition of structures of widely differing magnitudes.

Regional magnetic surveys cover large areas and their purpose is usually to investigate the broadscale structures and major lithological units, whereas specific exploration surveys are usually tuned to a particular target style, in a geologically or tenure-controlled area. While regional surveys deal with the forest rather than the individual trees, and particularly allow the delineation of very deep and/or crustal scale geological features, a growing trend is for regional surveys to employ tighter line spacings which approach applicability to direct exploration. The 1950's to 1970's delivered regional surveys of typically around 1-2km line spacing where such surveys in the 200-500m range are now much more common. During the same period, line spacings in typical 'detailed' exploration surveys decreased from 200-300m to as little as 20m, and in many cases these 'ultra-detailed' surveys have been flown over considerable areas with fixed wing aircraft at terrain clearances of around 20m (ASEG,2000).

Hence in considering the uses of magnetic surveys and in particular, regional surveys, we find that modern practice yields an extraordinary range of possibilities from iron ore search to sedimentary facies mapping and from studies of surficial material to mapping the thickness of deep sedimentary cover.

EXAMPLES

We illustrate the three main uses of magnetic surveys with examples from surveys of considerable areal extent, each having a different commercial purpose. The location of all data examples presented in this paper are illustrated in Figure 1.

The Kalgoorlie ('Golden Mile') district in Western Australia

The area presented is a miniscule part of a 750,000 line kilometre, commercially available, non-exclusive data base of 200m-spaced magnetics and radiometrics covering much of the Archaean Yilgarn Block. The Yilgarn Block hosts world class nickel and gold provinces as well as significant occurrences of tantalum, platinum group metals, volcanogenic massive sulphides and uranium. The impact of this data base on exploration in the province is discussed later in this paper.

Figures 3a to 3d illustrate the 'interpolate between outcrops' capabilities of magnetic surveys. The +50 million ounce Kalgoorlie gold district (Ho et al, 1990) has limited outcrop and the magnetic data largely, but not exclusively, through the contribution of the mafic and ultramafic rocks, facilitates the construction of a solid geology map. This not only maps the distribution of key host rocks, but also provides an invaluable structural framework on which the various models of gold formation and distribution can be built. A fuller description of the application of these data in the Kalgoorlie district can be found in Isles et al (1990) and Keats (1987).

The Fowler 1:250,000 sheet area in South Australia.

Figures 4a to 4c illustrate 'mapping in covered areas' using a major part of the 'Fowler' 1:250,000 sheet area which lies in the southern part of South Australia's predominantly Proterozoic Gawler Craton. The area covers over 7,000 km² and features a relatively thin veneer of recent sediments with eight known Proterozoic outcrops totaling less than 20 km². The image of the magnetics shows a vast amount of contained geological information and, while the interpretation may appear far-fetched in the context of the exposed rock, it has been compiled by extrapolation from and with reference to neighboring areas where exposure is more abundant and magnetic data of equivalent quality exists (Fairclough et al, 2003). This data and interpretation formed a small part of the South Australian Exploration Initiative (O'Neil, 1994) whereby a state government committed to fund a huge program of 400m spaced magnetic coverage to stimulate exploration in this poorly exposed but thinly covered and highly prospective mineral terrain. The outcomes of the SAEI are discussed later in this paper. Gunn et al (1997) provide an expanded view of the methodologies of government mapping in poorly exposed terrains.

A

B

C

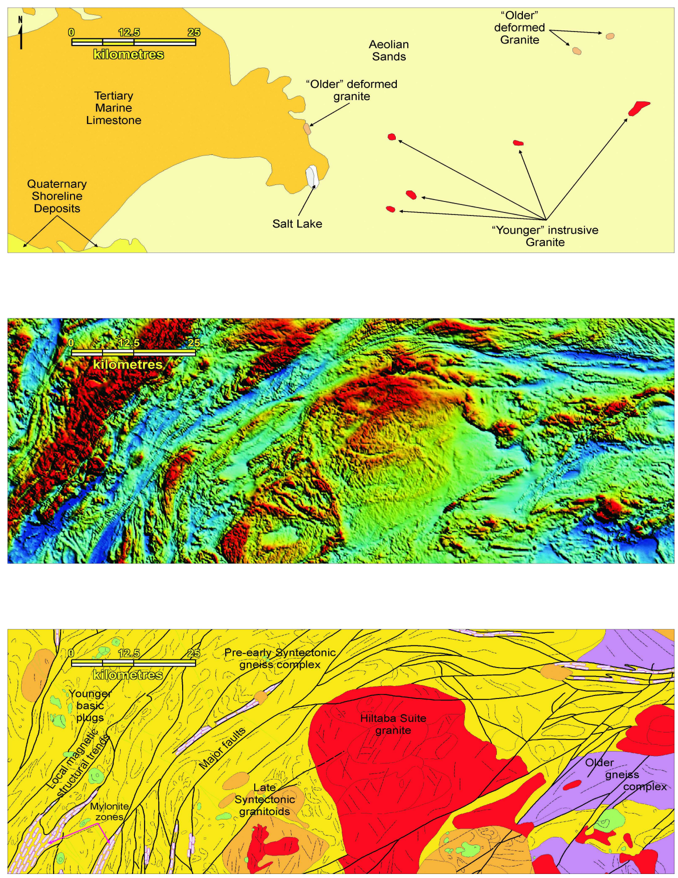

Figure 4: a) Surface geology from the 'Fowler' 1:250,000 sheet area, South Australia (PIRSA,2006). b) 400m-spaced 'SAEI' magnetic data (PIRSA,1992) covering the area in fig 4a. The image is a merge of shaded TMI with 1st Vertical Derivative. c) Interpretation map based on extrapolation from surrounding areas (after Fairclough et al 2002)

Kimberlite search data from the Flinders Ranges, South Australia.

The Flinders Ranges example illustrates the 'surprises' that frequently occur when high quality magnetic data is gathered over well exposed and well mapped geology. The area is part of a detailed proprietary survey flown in the Flinders Ranges of South Australia in the search for kimberlites. It is a scenic area with ample exposure of Adelaidean sediments which was mapped in some detail in the 1960's, as depicted in the published, now digital geological data shown in Figure 5a (PIRSA, 2006). While the regional aeromagnetic data produced in September 1996 showed clear evidence of NW trending dykes through this area, the existence and nature of the dykes was not recognised or seriously addressed until diamond exploration recommenced in the region in 2005 (Flinders Diamonds, 2005). A subsequent detailed magnetic survey (Figure 5b) revealed prominent dykes which form part of a major dyke swarm, previously unrecognized despite the fact that the dykes are often exposed (but may be very thin) as well as being clearly seen on the regional aeromagnetic map flown ten years earlier. The

A

B

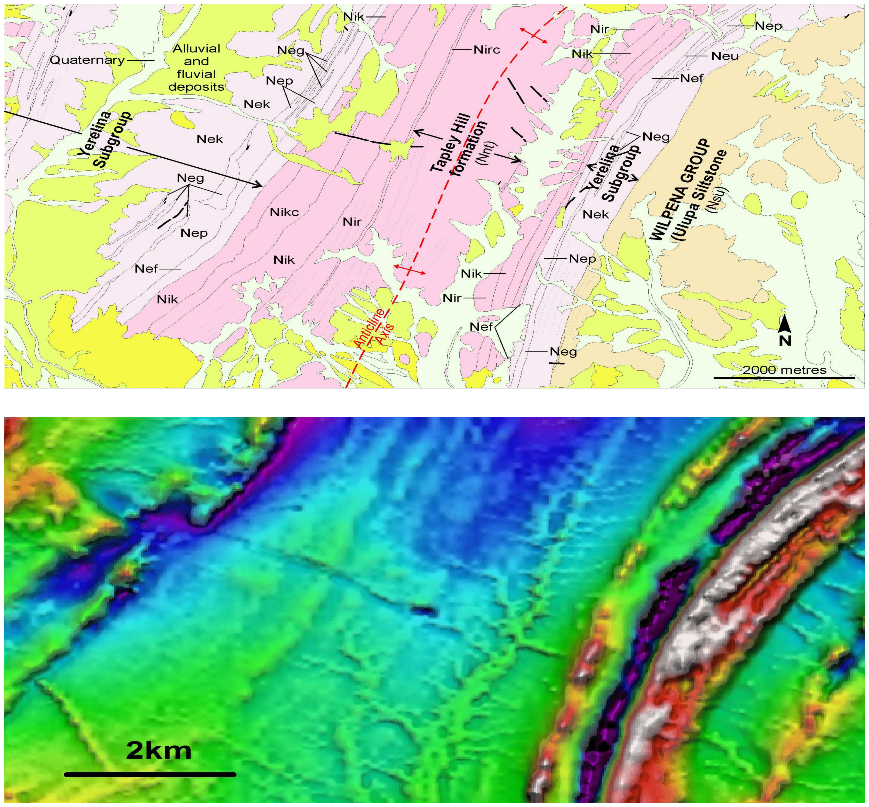

Figure 5: a) Mapped surface geology from the Burra 1:250,000 sheet area (PIRSA, 2006). All units apart from Neg(quartzite), Nep(tillite) and Neu(arkosic sandstone) are predominantly siltstone. b) Detailed 100m-spaced magnetics over the area in fig 5a (data courtesy of Flinders Diamonds Limited). The image is a merge of shaded TMI with 1st Vertical Derivative

distinctive magnetic low on the central part of the most prominent dyke is a kimberlite pipe discovered as a direct result of the magnetic survey. Both regional and detailed data also highlight the clear magnetic definition of lithological and structural patterns in a sedimentary package which in past times would have been regarded as unsuitable for the application of magnetic surveys.

Crustal Scale Features

One further illustration of the uses of magnetic surveys, and particularly those covering very large areas, deals with the recognition of crustal scale geological features which are not apparent from geological mapping either because they have no surface expression or because the nature of their surface expression is too diverse or too widely distributed to be recognizable in local scale mapping.

O'Driscoll (1990) observed striking correlations between patterns of distribution of mineral deposits and lineaments recognized in continental scale data sets such as gravity, aeromagnetics, satellite imagery and bathymetry. He described these linear zones containing mineral deposits as corridors and inferred that they are crustal discontinuities along which metallogenic processes have operated. While modern geoscientific data sets reiterate the existence of these lineaments, their specific nature remains poorly understood and the mechanisms by which they influence the localization of mineral, hydrocarbon and geothermal energy resources remain speculative. However, the importance of these lower crustal/upper mantle structures in exploration concept development should not be underestimated. The Olympic Dam discovery (Rutter and Esdale, 1985) is a prime example where such concepts played a key role.

Our example is drawn from the Yilgarn Block and the data is the 'one-mile spaced', federal government funded coverage of the Australian continent. The feature of interest is the 'Menzies Lineament', arrowed in Figure 6. It had been proposed on the basis of Landsat and pre-digital presentations of the magnetic data but largely discounted due to lack of 'outcrop support' until the magnetic data (gathered and compiled in the early 1960's in analogue form) was digitized and image processed. While debate on the nature of this feature continues, its existence is confirmed in modern, high resolution data and its relationships with the Keith Kilkenny Lineament (which does have substantial expression in exposed rocks) and a number of gold districts maintain its status as a 'feature of interest', particularly in the study of gold distribution in the region.

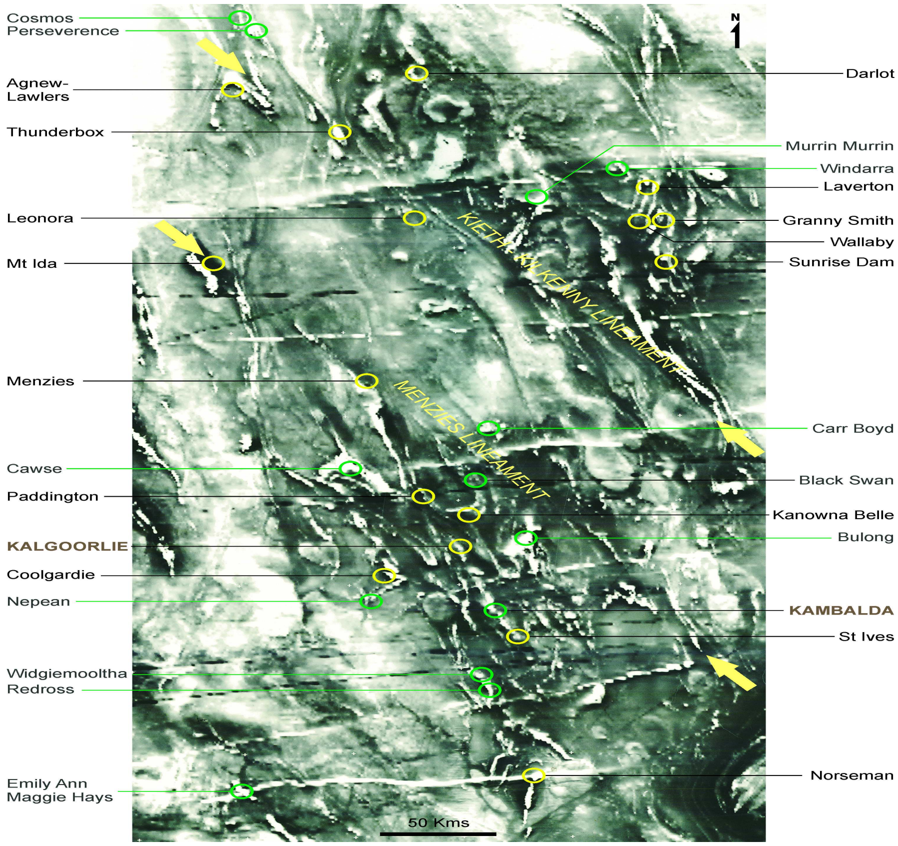

Figure 6: Lawlers-Kalgoorlie-Norseman BMR (now Geoscience Australia) 1960's vintage '1-mile-spaced' aeromagnetics illustrating regional scale features and the major nickel and gold districts. TMI image after Isles et al, (1989).

EXAMPLES OF 'SUCCESSES' FROM REGIONAL MAGNETIC SURVEYS

The undisputed pacemakers in the utilisation of regional airborne geophysical surveys have been Canada and Finland. Both nations have had a history of prosperity growth from mineral resource discovery and development, and both were quick to recognise the likelihood of accelerated exploration stemming from the open and inexpensive release of government-sponsored data sets. Summaries of aspects of these regional airborne programs conducted in Canada and Finland can be found in Hood et al (1982) and Peltoniemi (2005) respectively. In particular, the wonderful images of the regional, low level, detailed aeromagnetic surveys in Finland (Korhonen, 2005, Airo, 2005) have been an inspiration to other workers in the field and have proved their worth by playing an important role in discoveries (Ketola, 1987).

The writers have had close involvement with the evolution of such programs in Australia and regard the events in Australia as having benefited from prior lessons, particularly in Canada. We relate three Australian examples where ambitious, long term and 'expensive' regional airborne programs have not only borne fruit but clearly achieved their objectives, resulting in discovery, development and the generation of wealth (and healthy taxation and royalty revenue!).

Australian Bureau of Mineral Resources '1-Mile' Continental Coverage

The first is the federal government (Bureau of Mineral Resources, now Geoscience Australia) program of '1-mile' magnetic (and radiometric) coverage based on the 1:250,000 map sheet system (Denham, 1997). In its initial stages in the 1950's and early 1960's, it may have appeared somewhat 'flighty' and academic, but when the Kambalda nickel deposits were discovered by Western Mining Corporation in 1966 (Woodall and Travis,1969), the existence and ready availability of data which reliably mapped the distribution of the potentially nickel-bearing ultramafic rocks, rapidly focused the worldwide exploration community on the most prospective parts of a vast province of poorly exposed and unexplored Archaean rocks.

Many significant nickel discoveries were made and the value of airborne magnetic data was cemented in the minds of geologists, company directors and politicians alike. There is no doubt that the regional magnetic data was an important factor in the boom in nickel exploration which in turn led to a renaissance in mineral exploration in Australia during the last forty years. A modern representation of part of this 'vintage' data is presented in Figure 6, with the major nickel and gold districts marked.

This Australia-wide program had a role in a number of other exploration successes in the 1970's, the premier example being the discovery of the giant Olympic Dam copper-gold-uranium deposit in central South Australia. The pre-existing government data is given due credit for its role in the discovery (Esdale et al, 2003, Rutter and Esdale, 1985). The fact that regional magnetic (and gravity) maps covering a potentially prospective area of over 200,000 km² were already available allowed the Western Mining Corporation exploration team to focus on the extremely difficult task of defining targets and justifying to management a deep drilling program in a totally covered and untested area. This remains a remarkable case history in concept development and implementation by a skilled, multidisciplinary team having unwavering support from management during a period of subdued activity in the mining sector.

During the 1980's the program of airborne coverage maintained its momentum, supported by a program of 'converting' older analogue data to high quality digital data (Tucker et al, 1988). This enabled the ready use of integrated data sets on the evolving image processing facilities and spawned a feeding frenzy of regional exploration concepts, all anxious to match the Olympic Dam success. The '1-mile' program was completed in 1997 and the resulting, now freely available continent-wide data sets continue to form the foundation of broad-scale resource investigation in Australia. An important spin-off from this program was an increased appetite for detailed magnetic data (Isles et al, 1989).

The Aerodata (now Fugro Airborne Surveys) 'Multiclient' Yilgarn Data

Thus, the second Australian example stemmed directly from the first. During the early 1980's the 'value' of the government '1-mile' magnetic coverage was found to be limited in the blossoming gold exploration business and the impracticalities of a multitude of detailed, 'postage stamp', often overlapping proprietary surveys lead to the implementation of a novel and highly successful 'multiclient' approach to detailed airborne magnetic surveying (Sands and Cunneen, 1983, Bullock and Isles, 1994). This 200m spaced coverage of most of the prospective mineral belts in the Yilgarn Block now amounts to over 750,000 line kilometres available in very small or very large, client-selected blocks at a small fraction of the cost of proprietary surveys. It has not only been a commercial success for the initiating contractor, but has been a major contributing factor to the numerous and significant gold and nickel discoveries in the region in the past 20 years.

While it is difficult to quantify the contribution of this detailed but regional scale magnetic coverage in the Yilgarn Block to the many discoveries since the early 1980's , the development of sophisticated structural models for gold occurrence has unquestionably relied on interpretation of this data and there are few, if any, presentations on discovery and delineation of gold (and nickel) deposits in the region which do not include critical reference to the detailed airborne magnetics. Figures 3a to 3d, from the very first 'Aerodata Multicilent' survey, illustrate how the 200m spaced magnetic data transformed a poorly defined geological picture into one of considerable clarity and structural resolution.

The Cannington Discovery by BHP Minerals (now BHP Billiton)

The Cannington Ag-Pb-Zn discovery in northwest Queensland provides an example in the mould of Olympic Dam, but utilising proprietary regional survey data. In the early 1980's BHP Minerals (now BHP Billiton) formed a project aimed at discovery of a 'Broken Hill Type' lead-zinc-silver deposit. The project involved numerous specialists and considered potential 'BHT' terrains worldwide. After a thorough investigation of several such terrains, the Cloncurry region was selected as the most attractive, based mainly on some critical similarities between lithostratigraphic units in the eastern part of the Cloncurry region and the Broken Hill Block itself (Walters et al, 2002). The ensuing program was initiated by the flying of (proprietary) large scale detailed magnetic surveys and a commitment to systematic follow up which was maintained for 6 years before the discovery was made. Part of this commitment included 'in depth' geological interpretation of the magnetics, a challenging task considering the extensive cover and the complex magnetic patterns in the most prospective regions.

Many targets and particularly many magnetic anomalies were drilled prior to the discovery and a complicating factor was the generally highly magnetic terrain within which a number of magnetite-associated ore bodies such as Ernest Henry, Osborne and Starra had been discovered. None of these was a 'BHT' ore body but their presence created a potential distraction and 'undue' emphasis on very large magnetic anomalies. BHP's program achieved some early success in the discovery of the Altia Pb-Ag prospect and the Eloise Cu-Au deposit, but significantly the latter was not the target type sought and the systematic search continued.

Figures 7a and 7b illustrate the highly complex and magnetic terrain and the relatively 'unremarkable' nature of the magnetic anomaly related to the Cannington mineralisation (the target of the discovery drillhole). The telling factor in the discovery was the robustness of the exploration model and the skilful application of this model to the interpretation of the magnetics (Whiting, 1997). After drilling many such targets with limited success over a 6 year period the persistence and diligence was rewarded with a discovery which proved to comprise 43.8Mt grading 11.6% Pb, 4.4%Zn and 538ppm Ag (Walters et al, 2002). The key factors in the recognition of the Cannington magnetic anomaly as a top priority drill target were:

- the inference that it was located in the Soldiers Cap Group, a sequence of rocks with remarkable similarities to the Broken Hill Group.
- the observation that the anomaly occurred in an area where magnetic units displayed patterns suggestive of polydeformational folding, a characteristic of the Broken Hill district
- the assertion that the anomaly was likely to be due to magnetite-rich exhalite horizon, such horizons having a close association with the lode rocks at Broken Hill.

Significantly, the area of Figure 7b is totally covered, the nearest exposures of the prospective Proterozoic rocks being almost 20km away.

A **B**

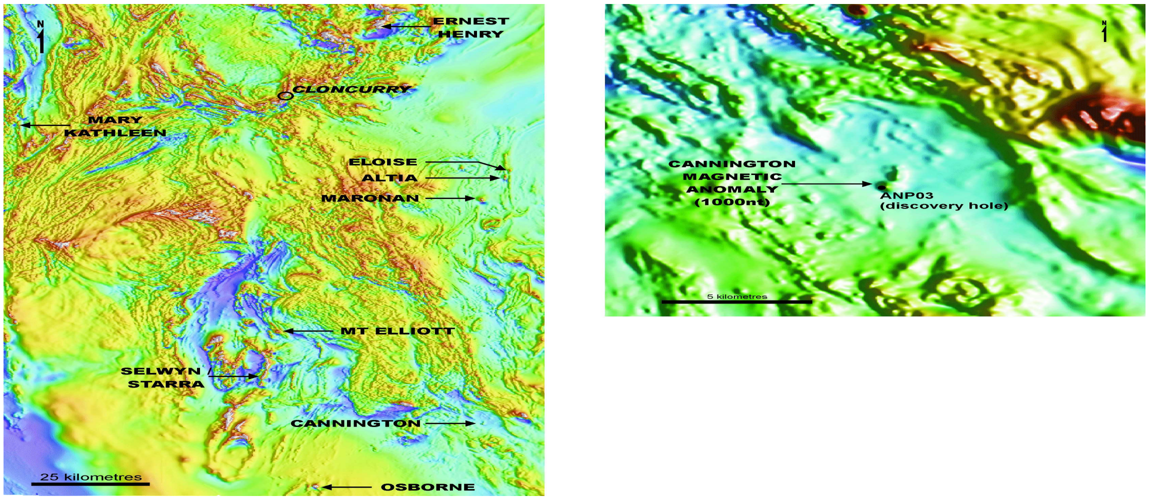

Figure 7: a) Regional 200m-spaced aeromagnetics over the Cloncurry Region, NW Queensland. Shaded TMI image, data courtesy Geoscience Australia. b) Section of the above data showing the Cannington magnetic anomaly.

Other noteworthy examples taken from further afield, include recent successes stemming from regional airborne geophysical programs have been in the Sultanate of Oman (Denham & Jacques,1994, Al Azry et al, 1993) and in Chile (Far West Mining Ltd, 2005). In both cases a large scale program was formulated to explore for a particular commodity and target type. The former program was government sponsored and conducted with foreign government technical guidance, while the latter was a joint venture between two mining companies. Common to both was a clear focus and a commitment to thorough interpretation and field follow up.

Remarks on Government-Sponsored Programs in General

The Canadian, Finnish and Australian examples in particular provide a model for developing countries. The abandonment of the concept of 'cost recovery' for high quality airborne geophysical data in favour of the notion that discoveries will flow more rapidly and frequently if many competing groups have ready access to the data, has paid dividends.

In the Australian example, state and federal geoscience agencies embraced the virtues of acquiring 'pre-competitive' airborne geophysical data during the 1980's but found that purchases, even at a fraction of the cost of acquisition, were limited largely to major companies. Smaller exploration groups perceived purchase of entire data sets as 'expensive' and 'unwarranted'. They tended to acquire data only over their immediate areas of interest thereby choosing to forego one of the major benefits of these broad-scale surveys, that is the ability see the 'big picture' and the fine scale detail in the same data set.

The State of South Australia was the first agency to change to a 'free' distribution policy as part of its South Australian Exploration Initiative (O'Neil, 1994). This paid immediate dividends in attracting greatly increased exploration expenditure, particularly by 'junior' companies. Discoveries have followed, the two most notable (Challenger, Au and Prominent Hill, Cu-Au) being ultimately made by junior companies. A further significant outcome of the SAEI was the pressure created on other states to follow suit in order to retain their share of company exploration expenditure. Hone (1997) summarises these developments in Australia and the writers are pleased to report that ready and essentially 'free' access to extensive, high quality digital data sets through government agencies is now established policy. We suggest that these programs of data acquisition and ready release have played a major role in the upsurge in exploration expenditure and consequent discovery in Australia.

Our message for countries which retain the policies of cost recovery is that resource discoveries require sustained and well-focused 'on-ground' expenditure. Where multiple explorers are competing for discovery in a region, expenditure rates increase as does the pressure to rapidly and effectively define exploration targets. Where high quality, regional data sets are freely available to all, this competitive pressure is heightened and the ability to develop and implement new and incisive exploration concepts is enhanced. We reiterate here the importance of such data sets in defining and finessing models for mineral deposit formation and localisation. Exploration expenditure can then become focused much more on testing targets and concepts rather than defining them, and this undoubtedly accelerates the rate of discovery. The benefits to any government of active and well-focused exploration as well as the prosperity that flows from discoveries far outweigh the potential revenue from cost recovery on regional airborne surveys.

CONCLUSIONS

The past 40 years have delivered a proliferation of regional magnetic surveys of increasing areal extent with tighter line spacings and more precise magnetometer data. The tools with which we manipulate and visualise the data have also become highly sophisticated and free availability of data has become 'government policy' in a number of countries. The implementation of exploration strategies founded largely on the interpretation of regional magnetic surveys has lead to numerous mineral discoveries and has, in numerous cases, 'paid back' the initial expenditure on surveys many times over. It is not uncommon, however to observe an absence of exploration action and initiative where access to the data is restricted by cost recovery policies.

The quality of acquisition and processing of magnetic data has progressed well ahead of our efforts to fully interpret and utilise the data. Despite some excellent examples of discovery linked to astute interpretation of magnetics, we perceive an overall shortfall in the return one would expect from a full and proper exploitation of the burgeoning worldwide magnetic data base.

While technological developments are certain to take place in future, there is a need to maintain perspective on the fundamentals of interpretation and the inseparable links required with 'hard' geological data. It is when these links with geology and ore body models are effectively maintained that new mineral discoveries are made.

ACKNOWLEDGEMENTS

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The previously published image in Figure 3b is part of a proprietary data base owned by Fugro Airborne Surveys. The data in Figure 7 was originally a proprietary survey subsequently acquired by the Queensland state government and is now part of the national aeromagnetic data base maintained and freely distributed by Geoscience Australia.

We finally pay tribute to the many colleagues in the Australian and international airborne geophysics industry who have contributed to a range of achievements in resource discovery and development and have made the writers' journeys in this exciting profession both memorable and rewarding.

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