Interpreting Aeromagnetic Data In Areas Of Limited Outcrop, An Update From 1997

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SUMMARY

Being critical about magnetic survey practise and how to revisit older surveys, and uplift the information content to modern standards, is an on-going challenge. Many data repositories have 20 + year old surveys that remain the only alternatives, for mounting a fresh campaign to explore under cover. With 50 years of continuous improvements in automation in geophysics, a solid case can be put that ML and AI is applicable. However, the older surveys and their limitations, present some complex requirements for decision making that are not yet automatable.
The geology side is still emerging from being a descriptive science. Structural geology rules and an implicit engine based upon geostatistical methods has emerged as the front runner for ML in geology.
In the case reported here, creating the Intrepid database, levelling, choosing Trend Gridding to improve the ability to honour underlying gradients and resolution, decorrugation, Reduction to the Pole, Worming, Cauchy Integration, Down wards continuation for depth constraints and plunge, and then looking at a first 3D model, all repeatable, semi-automatic, processes. What used to take months can be done in less than a day. However, the sequence and the checking remain a human only activity. Managing expectations about the role of Artificial Intelligence in exploration geoscience, is tough.

Key words: magnetics, machine learning, Cauchy integration, feature extraction, geology under cover.

INTRODUCTION

In 1997, P.J. Gunn, D. Maidment & P.R. Milligan authored “Interpreting aeromagnetic data in areas of limited outcrop”. The authors defined a clearly articulated audit of the methods and thinking required to infer solid geology.

Interpretation of aeromagnetic data in areas of limited outcrop use data enhancement to support accurate positioning of geological boundaries and magnetic sources. Where no outcrop calibration exists, magnetic sources must be characterised by physical parameters relating to their form, depth and relative magnetisation. The final stage of the interpretation process is to apply geological reasoning, in the context of the area being interpreted, to deduce the rock types causing the magnetic responses and the structural relationships of the lithological units. The methodology used in 1997 was driven by experienced geophysical interpreters and was reported as:

Inspection of computer screen and hard-copy images,
maps of the aeromagnetic data, and other relevant data to define:

. boundaries of magnetic units.
. structures dislocating or affecting the morphology of magnetic units.
. depth and attitude of magnetic units.
. any superposition of magnetic units.
. lithological units.
. chemical changes.
. a structural synthesis relating distribution of inferred lithologies and structure.

The first large scale regional aeromagnetic surveying in the Northern Territory was being undertaken in the mid 1990’s. The Highland Rocks case study in the Northern Territory was used as the case study, to illustrate the proposed workflows, as it was also under active consideration at that time.

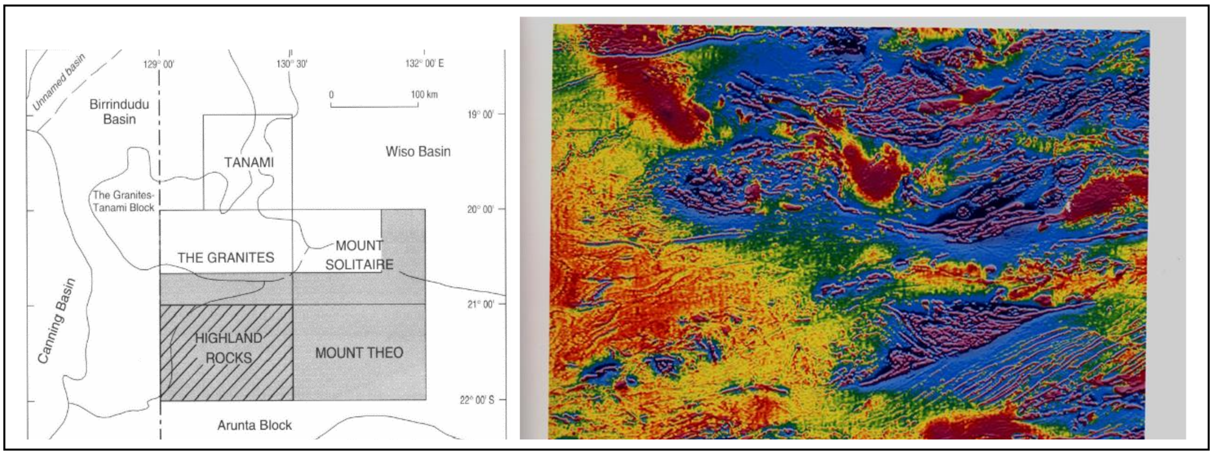

Figure 1. a. Locality map of the area used to illustrate the interpretation methodology showing Tanami, Granite, Highland, Solitaire and Theo sheets.
b. Highland Rocks sheet, colour image of the vertical gradient of the total magnetic intensity reduced to the pole, illuminated from the north (red high- blue low), units nT/m.

REPORT ON MAGNETIC SURVEYING

A feature of the last decade has been the realization that regional solid geology mapping depends upon better quality multi-geophysics datasets. This is in contrast, to the imperative to use every magnetic survey, no matter if it was good bad or indifferent, to achieve the first continent coverage. For the Northern Territory, in the period following 1997, regional airborne geophysics only had one or two new contributions. From this 1997 perspective, the GA portion of this coverage (Brodie 1994) comprised 111 710 line-km of data with 90 m nominal terrain clearance along north-south flight-lines spaced 500 m apart. East-west tielines were at 5000 m intervals. Navigation was by global positioning satellite (GPS). Magnetic data were recorded at 0.1 s intervals (approximately 7 m). This is an older proton precession magnetometer survey, with no continuous record of flying height, no record of base-station magnetics, and it is delivered with around 20 spikes of +5 nT to 50 nT single point spikes.

The sin of omission here, for the million-scale map, was to ignore the fact that more than half the surveying derived from prior GPS controlled data, collected by BHP in 1988. Granites/ Tanami was reflown by NTGS and made open file in 2018. As seen in figure 2, the highlands rocks portion of this map, has had no new data acquired in the last 20 years.

Figure 2. Granite, Highland, Solitaire and Theo sheets, magnetic line datasets, as at 2022. The Northern Tanami desert surveys, shown in RED, are the main differences since the 1997 compilation. Note, the surveys lines are primarily flown North-South, giving a better opportunity to deduce shallow sources at depth.

It is only in 2022 that there is a growing realization that the archive of National Magnetic surveys, includes many sub-standard surveys, with little ability to report on their status, nor make a plan to redress the issue.

Not only in the Northern Territory, but in fact, in every state of Australia, there is a legacy of what is now considered sub-standard magnetic surveys. By this we mean, a patchwork of 400m+ line spacing or more, non-GPS controlled navigation, with sub-standard sampling and poor signal/to noise standards, compared to today's standards.

Exhibit A for this argument, is the Gawler Craton survey in South Australia. This is arguably, the best regional coverage of magnetics, anywhere in Australia, on that scale. Now all geophysical grid merged compilations are published (2021), and then transformed into GIS images, all the prior solid geology maps are shown to need significant revision, as there are serious inconsistencies with this higher quality. The first third order TMI Cauchy derivative TMI grid in the world, was included in this compilation.

Once the goal posts are moved, this leaves the pack wondering how to catch up.
How can you make a "silk purse from a sow's ear?". The recognition of these issues has led to a comprehensive review of all the Northern Territory geophysical surveys, and recommendations for those remaining areas that deserve an upgrade, see Morse, 2022.
The "clip, zip and ship" mentality, ignores this underlying mess. Creating State-wide magnetic maps with 20-meter cell size, also contributes to the out of sight, out of mind, problems. Is it any wonder that mindless application of machine learning convolution algorithms, has contributed to the growing sense that geophysics is failing to identify new exploration targets?

GEOLOGY

The Gunn et al, 1997 paper is the first use of geophysics in this area, to help with understanding the geology. The resulting solid geology maps were published in 2006 (see Figure 3). It is clear there is very limited outcrop in this 1:1000000 scale map.

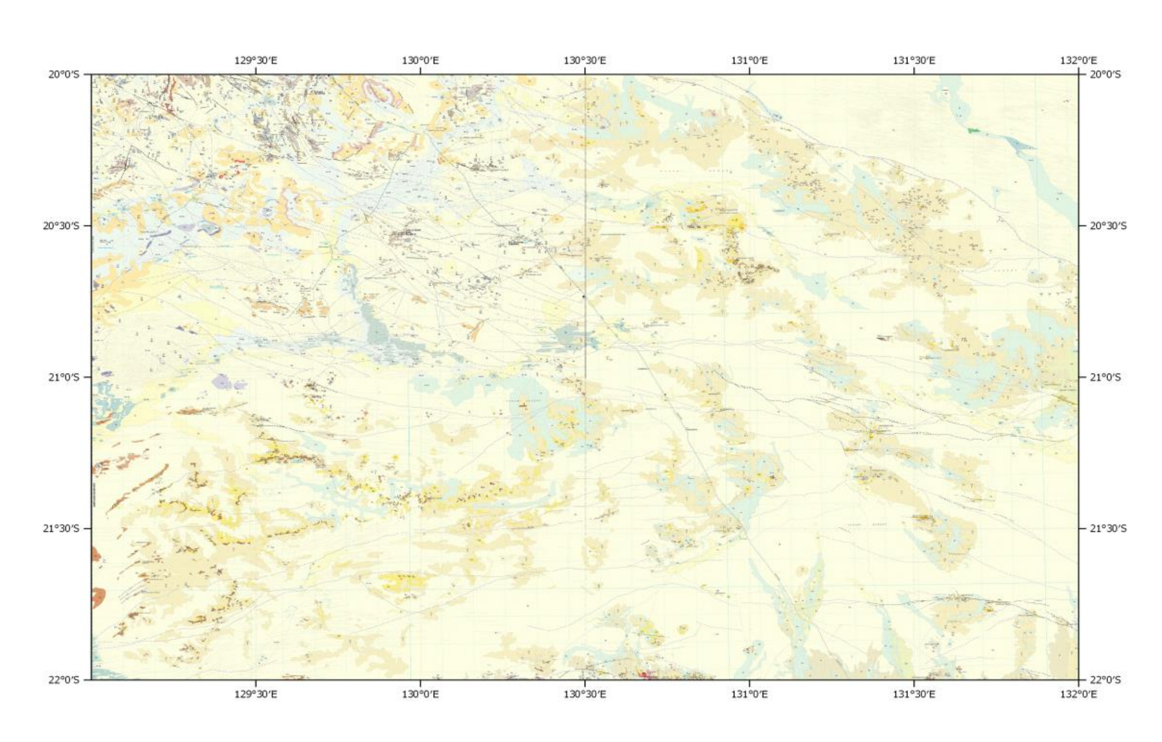

Figure 3. 1:1000000 scale map solid geology, 2006. Granite, Highland, Solitaire and Theo

Prior regional exploration focussed where there is outcrop, then gradually spread from there. Gold was first discovered in the Tanami Desert in 1898 and small-scale mining dates back to the early 1900's. Operations in the region were sporadic until the 1980's when the underground Tanami Gold Mine was developed by Normandy Mining (now Newmont), with first gold production in 1983.

The most recent significant interpretation work, Maidment, 2020, concentrates on the geochronology.
The Granites – Tanami Orogen (Top left-hand corner) has had the most geology mapping done on it. The geology pile, and main structural trends were published in 2006.
- Component of the North Australian Craton. This is best delimited by the regional TMI grid.
- Comprises of Paleoproterozoic volcano-sedimentary sequence overlying Archean crystalline basement
- Terrane is host to orogenic gold deposits with historic production + current MI&I endowment of ~20 Moz

SIGNIFICANT TECHNOLOGY DEVELOPMENTS

In 1997, limitations of digital computing, and languages restricted many developments. Whilst technology has advanced in the intervening 25 years, cutting corners remains rampant in the industry. A complacency factor has emerged that what was good enough then remains good enough today. This is despite the Moore's law effect of now having unlimited computational capacity, and much better digital sensing instrument systems. The hope that somehow the technology majors (i.e. Google, Amazon, etc.) developing and deploying on the cloud, will magically overcome the deficiencies and rigour in the application of the correct physics, material science, mineralogy, and structural geology, is exposed. Aspects of the 1997 methods are still elusive to ML and AI.

On the positive side, there is now for all intents and purposes, unlimited computational capability. Full waveform inversions, use of complex number theory for stabilizing potential field datasets via the Cauchy integration theorem, rigorous identification of measurement errors and tracking these through modelling to produce uncertainty estimates, so all can contribute to understanding "hidden" geology. However, there are few capable thought leaders, and the pool of experienced practitioners is dwindling alarmingly.

Also, in the intervening years, the aspiration of creating a 3D geology model, not just the surface solid geology map, has become more common. This is a much more demanding objective, as it opens the need to make the interpretation work in 3D, and allows for the introduction of physical properties into the model. Forward geophysical models and inversions can be undertaken, to test the coherence between the geology and the geophysics. More recently, the geological uncertainty is being embraced and quantified. This uncertainty, including all measurement errors, provides much-needed "quality indications".

The pathway to a sensible use of machine learning in the geosciences requires careful codification of the practise of physics, and geology. In effect, new lexicons for a language evolves, that is extensible. Usually, the definition should be independent of any coding language as well. None of these tools, or methods existed in 1997. GOOGLE deserves a big thank you, for open sourcing their message passing methodology, plus all the tools to expose any developer properly and reliably, using whatever coding language he chooses, to use these tools for systematising each function point.
The potential for automation has thus been greatly enhanced, with the burden of fundamental, low-level, technology development, removed from the geoscientist.
Given that automation is now more commonplace, each required interpretation method is discussed, following the topics from 1997.

FUNCTION POINTS, AUTOMATION ACHIEVEMENTS

The current paper identifies improvements in computational geophysics methods, including progress on Machine Learning and Artificial Intelligence developments and provides a score card evaluation of current "best practice" against the original paper's definitions. Current rating:

- 1 means nothing much has improved.
- 2 means functions available in ML language,
- 3 means an ability to link tools in a chain, without human intervention.
- 4 means deriving field geology observations from the geophysics.
- 5 means common earth model can explain the geophysics

Uplifting original TMI survey line data

The 1993 AGSO survey data, as archived, requires line levelling, gridding, decorrugation, before any grid filtering. Levelling of the line data cannot attempt an altitude adjustment, as there is no recorded altitude field, other than the survey was flown at 90m clearance. The altitude information may be recoverable from the Gamma Ray version of the survey data, in its navigation archive. The "Residual" and "TMI" magnetic field has a mean of 5107 nT. So, this is the residual anomaly derived from an IGRF subtraction and a "Diurnal" adjustments of sorts. There is no actual TMI recorded. Because of the line spacing, and age of the survey, trend gridding was also used to try and get more value from this survey (Smith and O'Connell, 2005).

Total magnetic intensity reduced to the pole

Basic interpretation of the aeromagnetic data set was performed on various images of the data set reduced to the pole. Where magnetisation of the rocks in an area is by induction, and no significant permanent magnetisation occurs in a direction other than that of the Earth's field, anomalies in reduced to the pole maps and images occur vertically above their sources. Such maps and images are thus significantly easier to interpret than original data sets in areas of significant magnetic inclination. Experience has shown that the assumption of induced magnetisation holds for most areas. When it does not, anomalies with a significant component of remanence manifest themselves after the reduction to the pole process with a smeared 'comet tail'. No such smearing is obvious in the reduced to the pole images of Highland Rocks, so it is probable that no significant remanence is present.
The reduced to the pole representations of the total magnetic intensity produced for this interpretation were:
• reduced to the pole line contours. This map shows representations of field gradients, which are essential for determining magnetic source boundaries and for qualitative estimates of source geometry and depth. CR1
• reduced to the pole colour image with illumination from the north (Fig.1b). This image, which uses a rainbow colour scheme (blue low to magenta high), proved most useful for subdivision of the area into units of different magnetic intensity and character. It is most useful when overlain on the line contour reduced to the pole map. The northerly illumination enhances subtle magnetic features not obvious in the simple non-illuminated representations of the data.
• greyscale reduced to the pole image with northerly illumination. Many interpreters prefer greyscale images to colour images because they perceive that subtle magnetic features are more obvious in greyscale images. This appears to be so and greyscale images have a definite use in extracting fine detail in magnetically 'flat' areas. CR2 (Figure 6)

TakeAWAY: Contours have dropped out of practise, as have stacked profiles.

Boundaries of magnetic units (AI version)

Individual anomaly axes and outlines of the internal magnetic rock units are the 'skeleton', and the boundary of the assemblage of anomaly axes and internal magnetic rock units is a geological 'unit'. CR2
Multi-scale edge detection (WORMing) is one the obvious automated workflow to do this job. CR3 (Figure 7)

    - It is geared to elongated anomalies
    - large discrete isolated magnetic anomaly
    - boundary is traced where the edge of the source is estimated to be. Eg granite dome structure
- Concentrations of organised, semi-organised or random anomalies will occur which cover specific areas.
- Irregular weathering of magnetic units, (CR3 Cauchy Downwards continuation!)
- volcanic flows, dykes (CR3 Naudy in particular for this)

TakeAWAY: Gradients of potential fields are critical, so improved methods to minimize errors, and denoise the data should be a prerequisite. Value adds, by stacking several algorithms together, can aid the 3D structural data automatic harvesting.

Structure recognition

- Faulting can be recognised by:
    - offsets of apparently similar magnetic units,
    - sudden discontinuities of magnetic units,
    - an abrupt change in depth to magnetic sources,
    - a linear narrow magnetic low caused by weathering along a fault plane oxidising magnetic minerals to non-magnetic minerals (joints can have a similar magnetic expression),
    - Half-Graben recognition and basic geometry characterization. Note, this requires Full Tensor gradient data.
    - a linear magnetic high, which may be discontinuous in nature, due to magnetic minerals precipitated in the fault plane.
- Folding can be recognised
    - by patterns of linear magnetic anomalies
    - and the geometry of the larger magnetic sources in much the same way that folds can be recognised in outcropping geology.

TakeAWAY: Partial solutions that are automated are emerging.

Depth and Attitude determination

- Depth and attitude (dips) can be estimated qualitatively by experienced interpreters familiar with typical anomalous responses of magnetic bodies.
- The depth of a magnetic source manifests itself as the sharpness of the resultant anomaly, with deeper sources causing broader anomalies.
- Depth can also be calculated by computer modelling. (Poor man’s inversion)
- Attitude of magnetic sources can be qualitatively estimated through a familiarity with anomaly forms and how they vary with dip.
- It is important to be able to distinguish between magnetic sources of effectively infinite depth
- and depth-limited sources such as horizontal lava flows or sills.
- Horizontal magnetic sources are generally surrounded by magnetic lows. Again, a familiarity with standard anomaly forms facilitates recognition of such bodies.

TakeAWAY: Many algorithms have been proposed and discussed. In this case study, there is a demonstration of the downwards continuation methods. CR3 (Figure 8)

Recognizing superposition of magnetic units

- It is possible for surveys to detect the magnetic effects of superimposed magnetic sources.
- It is important not to ascribe these responses to a single source. Depth estimates or the recognition of markedly different contour gradients should allow the identification of such situations.

TakeAWAY: almost no algorithmic progress has been made on this subject

Recognition of Lithological units

Finally, methods close to the Convolution Neural Network philosophy were articulated in 1997.

- correlations with outcrop geology and drill hole data.
- correlation with radiometric data—different radioelement concentrations can indicate particular lithologies (Dickson & Scott 1997).
- correlation with gravity—gravity results indicate density.
  - amplitude of response can indicate possible lithology—
  - for example, amplitudes of several thousand nanoteslas can indicate magnetite-rich ironstone.
  - A basic knowledge of the different relative responses likely to arise from different rock units is required to be able to make plausible identifications. Such knowledge comes from experience; however, Clark (1997) provides a basis for this knowledge.
- The outlines of magnetic units can suggest their lithology.
  - For example, round or ovoid anomalies several kilometres across and which obviously crosscut the local geology would suggest an intrusion.
  - A magnetic high on all or part of the boundary of such a feature would suggest a magnetic aureole.
  - Imagination, backed by a comprehensive geological training, is required to cover all possibilities.
- The texture or character of magnetic units can also give clues to their origin.
  - For example, lava flows generally exhibit a semi-random internal anomaly character, owing to the inhomogeneity of the magnetic properties of the flow.

Chemical change/Alteration

- Discordant changes in magnetic intensity within a magnetic unit
  - can indicate modification of magnetic properties by contact
  - or regional metamorphism, alteration and weathering.
- Mapping in 3D, of each formation is first required.
  - The variation in the magnetic properties along this formation, can then be assessed (eg Brockman Syncline)

Structural synthesis

This is the process of relating inferred lithology and geology structures. Mathematical geology has made great strides since 1997, towards transforming geology mapping from a descriptive science only, into a set of workflows and processes that ensure similar interpretations in 3D will derive from the same set of principal facts. Approximately 200 functions points can be coded based upon treating geology as the "signal" and using Geostatistical algorithms to codify an implicit Structural Geology engine. GeoModeller, (Calcagno et al. 2008 and Guillen et al. 2008), is the leading example of this ability to create 3D from sparse data observations, and then using multi-physics datasets, such as Magnetics and gravity, to form a common-earth model that starts to explain all the principal **facts**. What has also emerged here, is the realization that errors and uncertainties, can be directly used in this process, to obtain not just one model, but potentially thousands of equally likely models.

Figure 4 illustrates the use of a Radial Basis Function/Cokriging, to drive the volumetric implicit interpolator. Critically, observations of the Geology gradient (strike/dip) are separately observed to the geology contacts.

TakeAWAY: Very significant move to mathematical 3D geology has occurred, and automation of these rules-based methods are in good shape. For the Highlands Rocks sheet, work on gravity is needed first, to help. CR5

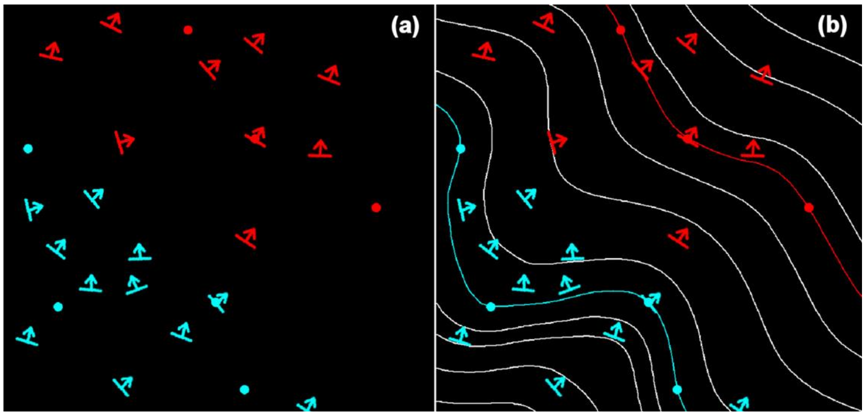

Figure 4. Principle of the potential-field interpolation method (illustrated in 2D).
(a) A geological formation mapped by the position of its interfaces with two other formations (red points and blue points) and dip measurements (dip symbols).
(b) The geological formation modelled by the potential-field method. Red and blue curves represent the reference isovalues of the modelled geology contact interfaces. White curves are selected isovalues of the potential field; in geological terms these may be 'trends' or foliations trajectories.
The geological interfaces honour both contact points and orientation vectors.

Dating

One of the elusive aspects of the magnetic method, remains the recognition of remanence in the survey data. This is something of a holy grail, as if remanence is recognised, it starts a process of deriving dates from the geophysics, to rocks that are buried. Thus, geophysics can contribute to the understanding of the geological pile.

Caveats from 1997

It must be stressed again that a good understanding of fundamental geological concepts is required for an interpreter to be able to produce plausible interpretations.

The interpretation process is always iterative as no one image of data will show all relevant information. Different images and different data sets will contain relevant, albeit different, presentations of the total story.

CUTTING CORNERS AND ERRORS IN GEOPHYSICAL PRACTISE

Exploration geophysics is an evolutionary technology that has many markers in time, to indicate significant breakthroughs, where talented individuals have had insights, they have used to explain in simple terms and then demonstrate these ways of processing and visualization. Aeromagnetic surveying has evolved with many approximations at its heart. To name a few:

- Space weather, or diurnal, micro-bursts etc. variations of the field
- Alias sampling along lines
- Measuring a magnitude, not its gradients or components (ignoring angles)
- Transient EM interference with the measurement system.
- Mostly ignoring topographic influences

In conjunction, software processing methods evolved to compensate, drawing on theoretical/mathematical basis functions, to guide creating representations of the magnetic field anomalies, digestible in GIS.
The volume edited by the author, Peter Gunn, created such a benchmark with the Vol 17 journal, that captured the recommended practise at that time marker, 1997.
This leads us to the state of things we have today. It is far from a static situation, as the economic imperative churns up efforts to improve. The ML & AI efforts to this end, are not clearly helping at present.
Historically, it is usually the pure mathematicians, followed by theoretical physicists, and then experimentalists who have laid the groundwork for this discipline. Geologists tend to be fast followers, rather than the leaders.
The inability to communicate the meaning and interpretation of geophysics signals to geologists, still plagues exploration.

GIS and use of images of geophysics is a blight to interpretation, as significance is often put on colours.
The historic use of contours and stacked profiles for interpretation has fallen out of favour because this is not the linga-franca of GIS. However, they are very useful for indicating maximum and minimum gradients, and the physics tells us, these extrema, are where the edges are.

Fast Fourier Transforms and the spectral methods that are commonly used in exploration geophysics, derive from the original digital filters derived by Bell Laboratories (Hamming, 1998) for cleaning up analogue telephony. At the time of initial use, there was a restriction on size and speed of memory and CPU computational capacity. These Conventional methods are only capable of producing derivative orders up to 2.

These computational restrictions no longer apply, and the known better physics (i.e. the Laplace second order sum of the XX+YY+ZZ tensor components is zero, and the property of holomorphism), can now be universally deployed. In particular, the Cauchy derivates by integration methods, detailed over 100 years ago, do not suffer from band limiting the signal and are quite capable of producing 7th order derivatives of potential field data that remains coherent. It requires an upgrade from simple scalar mathematics to 2d and better 3d complex number space.

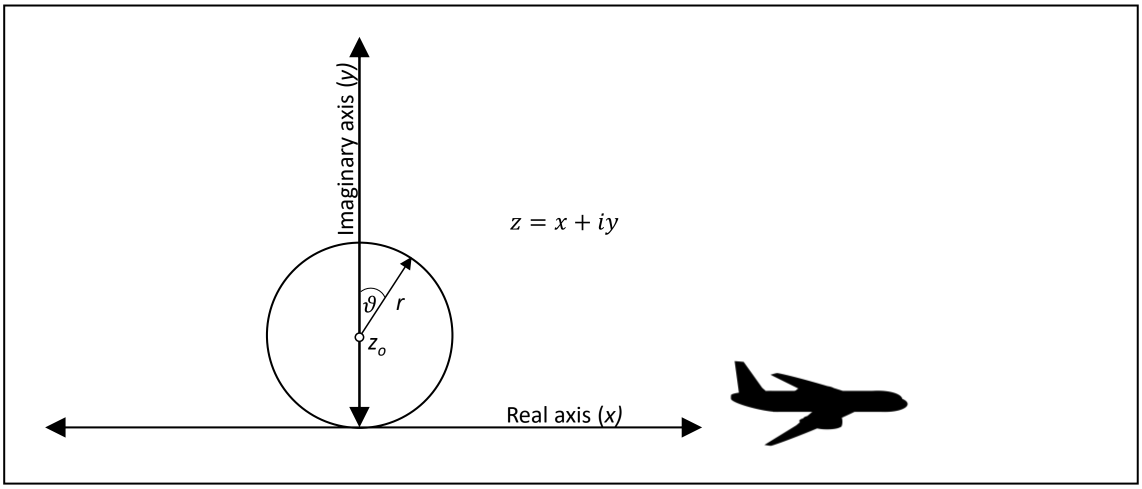

Figure 5. Differentiation by Integration with Cauchy's Integral Formula.

Cauchy Implementation

```
For each processed flight-line profile:
   Continue upwards at several discrete levels
At each sample:
   interpolate around a circle of radius r
   Fourier transform the interpolated data
   Multiply the nth-order Fourier coefficient by the factor n!/r^n
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To date, measuring geophysics signal gradients, is almost always able to produce better representations of the Earth's potential fields, see the discussion above! These instrumentation systems are well developed and able to produce high resolution, cost effective gradient maps directly. Examples include Falcon AGG, Bell FTG, IPHT Mag tensors. Just as medical science imaging has taken great steps forward by employing tensor measures, exploration geophysics can achieve the same benefits. What is lacking, is the commitment to actual treat the tensor measures as the signal to be processed and used directly for interpretation purposes, instead of immediately degrading back to the familiar scalar quantities. The mathematics is well understood, but the concept of all measures having errors and noise, is often overlooked. The Cauchy-style improvements should roll out into Euler deconvolution and worming in the next year. The benefits of better stabilised signals already inherent in existing surveys, should prove an irresistible driver.

2022 HIGHLANDS REPROCESSED/REINTERPRETED

Significantly better and uplifted working grids of the magnetic data for the Highlands Rock sheet, are demonstrated in Figures 6 & 7. Application of the Cauchy derivatives being used to estimate the downwards continuation of the magnetic field around the granite intrusion, is shown in Figure 8. As the signal is recast as the TMI plus its Hilbert transform, it has both phase and magnitude attributes. The phase is mostly tightly constrained, after the RTP operation except for the unit just to North of the granite intrusion.

Continuing to then create a common earth 3D model, constrained by features extracted from the gravity as well as the magnetic geophysics is possible, but not shown here.

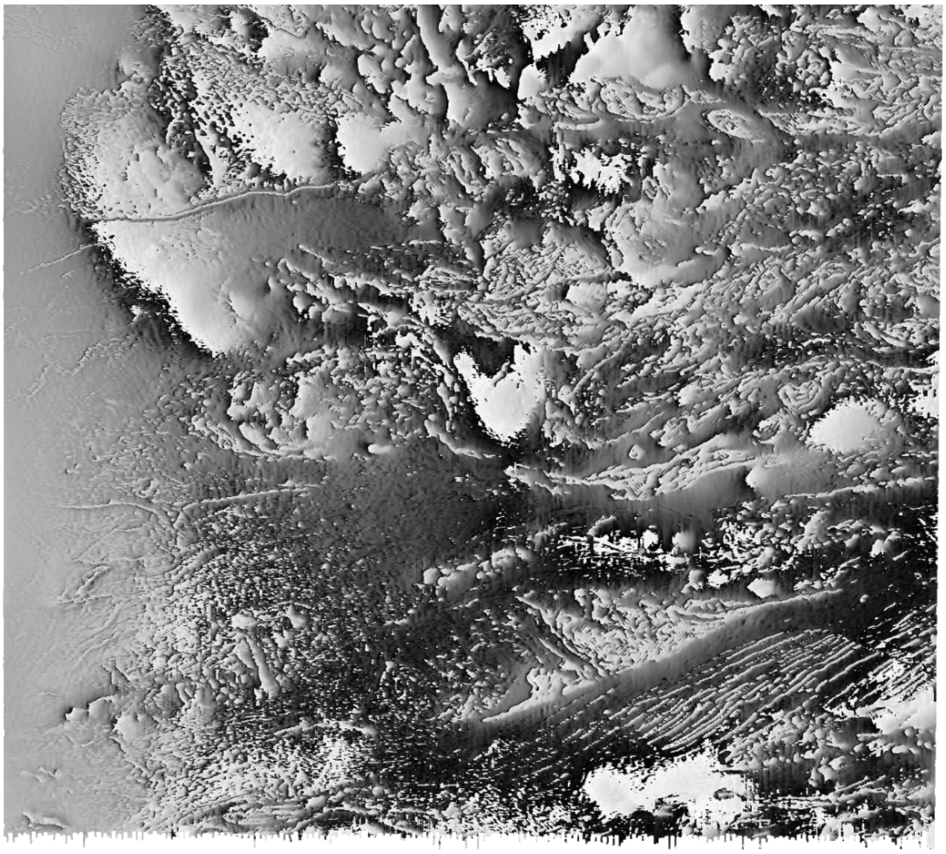

Figure 6. Cauchy Third order vertical gradient, after trend gridding, decorrugation & RTP, Units nT/m^3.

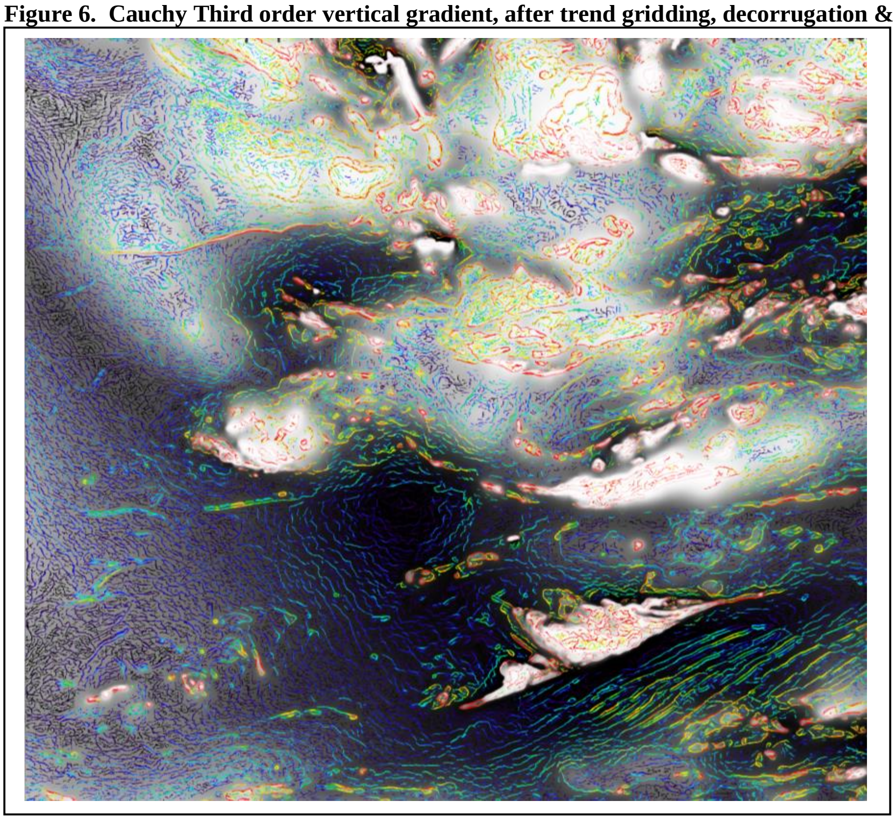

Figure 7. Worming, to delineate major structural lineament. Dyke swarm at bottom, synclines, and major faults.

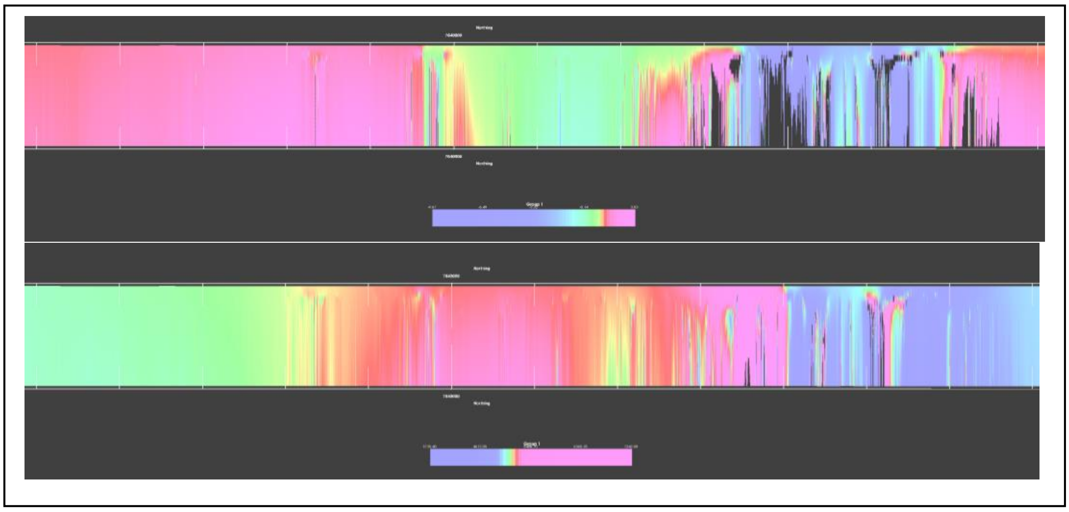

Figure 8. Downwards continuation North-South across the center of the granite intrusion, to a depth of 1000m. Top is the phase, -9 degrees to 3 degrees, bottom is the magnitude.

CONCLUSIONS

Managing expectations about the role of Artificial Intelligence in exploration geoscience, is tough. With 50 years of continuous improvements in automation in geophysics, a solid case can be put that ML and AI is applicable. The geology side is still emerging from being a descriptive science. Structural geology rules and an implicit engine based upon geostatistical methods has emerged as the front runner for ML in geology.

In the case reported here, some human intelligence was needed to assess the state of the starting survey data. Creating the Intrepid database, levelling, choosing Trend Gridding to improve the ability to honour underlying gradients, and resolution, decorrugation (not available in 1994), Reduction to the Pole, Worming, Cauchy Integration, Down Wards continuation for depth constraints, and then looking at a first 3D model, all are semi-automatic. Default parameters were mostly used. Stringing the workflow together using the Python scripting language is also easily achieved. This means all of the reported work can be reproduced in less than 2 hours elapsed. The approximation of ignoring the topography, cannot really be sustained in 3D. Full automation, without human supervision, is not achievable yet.

The geological pile of the more important lithology units, and the tectonic history cannot be deduced purely from the magnetics.

ACKNOWLEDGMENTS

Peter Milligan’s legacy cannot be overstated. He took over generating the national TMI compilation (Version 5). He spearheaded the AWAGS survey which allows the national TMI to be levelled well as required for the variable RTP.

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