Artificial intelligence techniques to the interpretation of geophysical measurements

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SUMMARY

Integration of geology and geophysics thinking requires a common earth model, that accommodates, with errors, all the features from the geophysics interpretation products, topological rules from geology, field mapping and drill logs, and the link between the two via physical rock property estimates. Automation of intelligent search, inference engines to this problem involves 200+ individual processes, to yield a family of plausible models. The true limiting factor is managing technical complexity and communicating to the geoscience team, not compute power.

All models are wrong and are destined to be replaced as further data or insights are gleaned. So, taking too much time trying to create the ultimate "correct" interpretation is wasteful, hence the need for automation.

An example of a simple pattern recognition technique to locate kimberlite pipes that have a magnetic and/or gravity response is given. This uses a range of pipe diameters, depths, topography, density and susceptibility, and variable directions of remanent magnetization vectors, in an automated manner.

Key words: artificial intelligence, airborne geophysics, feature extraction, structural geology.

INTRODUCTION

There have been the repeated efforts to use artificial intelligence (AI) methods to deduce the geology form airborne geophysics for many years. Smith (1991), only considered aeromagnetics in this context. He identified three stages. The first concentrated on the signal processing aspects of the task, the second on the local model building, and the third on the global modelling and the incorporation of ancillary data into the interpretation process. At each stage, aspects of AI were used.

At first, the features of the data, viewed as a contour map or an image, are identified. Of course, only certain features of the data are important. Some features are indicative of the general geology while others are mineral specific. An important aspect of these features is that they are characteristics of the signal alone and do not require geological knowledge to recognize.

Clearly, the selection of features to be recognized is based on an understanding of geology and mineral formation processes, but the actual recognition itself only involves signal processing.

The second step in interpreting aeromagnetic data is one of associating the features detected in the signal with features of the geology. This requires the geophysicist's expertise. His ability is based on his understanding of the effect geological lithology and structure has on geophysical data. In addition, the geophysicist's knowledge of geology limits the type of geological framework he will propose. In other words, the process is not simply one of inverting the geophysical data to recover the geology. It is one of proposing an acceptable geological structure that is consistent with the geophysical features. At first, the geophysicist makes the association between features of the data and geological features on a local basis. Often there may be more than one possible interpretation. As the picture is built up he is more cognizant of the overall global structure and begins to select local interpretations that are consistent with the global picture. On occasion, the picture painted by the airborne geophysical data is insufficient to allow a unique interpretation of an area.

The third interpretation step is somewhat a mixture of the previous two. The essential difference is that extra information is sought in building a final map for the area. Generally, this information comes from a geologist. Multiple interpretations are resolved on the basis of an understanding of the geology. This understanding may come from the geologist's field work or from experience with similar areas or structures.

Example From 2000s

Airborne geophysics methods have a long and successful track record at finding diamond prospects (kimberlite + lamproite). In parts of Canada, where there is often little cover, standard magnetic surveys, and Falcon AGG have worked quite well. Exploring for kimberlite typically calls for high resolution geophysical surveys owing to the small scale of pipes and their signatures. Keating et. al (2004) pointed out many of the difficulties of using the measured TMI in a search. He articulated a top 5 list of issues a search method needs to cope with - influence of magnetic field orientation, reverse magnetization (i.e. remanence), shape factors such as radius, depth to top, square instead of round, and measurement noise. He advocated for transformation to the analytic signal, prior to any search to help alleviate many of the above factors. He used differing cross-section shapes, square and cylinder vertical bodies to explore the sensitivities. The amplitude of the analytic signal A of M(x,y,z) is calculated by taking the square root of the sum of the squares of each of the calculated directional first derivatives of the magnetic field.

$$|A(x,y)|=\sqrt{(\partial M/\partial x)^2+(\partial M/\partial y)^2+(\partial M/\partial z)^2}$$

From 2005, direct measurement of gravity gradients has become routine. In this case, the measured gravity tensor gradients provide something similar but richer, to the "analytic

signal". Thus, a breakthrough in the resolution and reduced noise levels has occurred, e.g. airborne gravity gradiometry. So, measured gradients have proven to be always superior to any calculated derivatives. Hatch (2004) also recognised this, when he demonstrated the need to create a 1Eotvos resolution vertical gravity component instrument, via his "Kimberlite farm" sensitivity study. Magnetic gradient measures have a chequered history, and it is only recently that a fully commercial service to gather magnetic tensor gradients has become available. DeBeers uses SPECTREM and the IPHT instrument. While the quality of measurements from all airborne geophysics systems has markedly improved, there remains similar problems to the past, especially to do with survey design and large aliases along the line, versus across the line. The cross-line gradient, or lack of it, has a major influence on detecting, or not detecting small 3D bodies that mostly lie between flight lines. For this reason, AEM systems, while offering superior ability to indicate deeper geology under the flight line, remain unable to reliably define the detail of 3D bodies, like a kimberlite, between lines. There is no information off-line.

More Recent Times

Meyer (2015) termed signal induced by terrain, nominal subsurface geologic variations, and instrument noise an unwanted clutter subspace in the signal domain. He proposed amplifying signal induced by kimberlite pipes while suppressing the unwanted clutter. Meyer argued that overlap of these two subspaces (unwanted clutter, and signal induced by kimberlite pipes) encapsulates the difficulty of the detection problem. A novel addition was to add a third False Target (FT) class of structured non-pipe features that cause gradient anomalies mimicking those of pipes, comprising shallow depressions filled with low density sediment. This is then used to propose an improved pattern matching framework, by adding in datasets that can be trained to be rejected for not having sufficient depth. Given that over 80% of the measured gravity gradient data is due to the terrain, techniques for removing the terrain effects should be applied, prior to any attempt at convolution operations. Of course, a terrain correction also amplifies the signal to noise ratio of what remains. In some locations, fresh water lakes also mark the top of a pipe. In this case, the terrain correction is more complex and requires bathymetry.

METHOD AND RESULTS

The prior practise, based largely on "feature extraction" and the emerging AI direction, and are the two streams in the Methods discussion. The following three steps in the interpretation of airborne geophysical survey data have counterparts in computer-based processing of that data.

Signal Processing

The emphasis is on extracting linear features (that have predetermined shapes), and on extracting texture features.

Airborne geophysical data can be thought of as defining a surface in 3-D space where two of the axes represent the spatial aspects of the data while the third, say the elevation, represents the signal strength. Surface analysis techniques for finding ridge lines, valleys, fall lines, etc. allow the data to be characterized by aspects of its 'surface' shape. An example of this is 2.5DAEM inversion on flight lines, leading to geoelectric sections that show near surface layer features, and also show steeply dipping conductive marker features and their thicknesses.

Alternatively, airborne geophysical data may be viewed as an image where the signal strength is the image's intensity. Image analysis techniques for finding linear structures, patches of similar texture, etc., can be used to further characterize the data. This is the method developed for kimberlite detection in the second part of this paper. However, knowledge of the underlying domain is needed to identify which features are important.

The important aspect of this processing is that it deals with the signal only. No knowledge of the underlying domain, namely, the geology, is needed. This interpretation process is based on known image processing techniques. The software tools codify (1) the identification of the features to be found, and (2) the implementation of procedures for finding these features in the data.

Geological Features

This step associates geological characteristics with signal features. The relationship between data features and geological features must be defined by a set of 'rules'. These rules embody part of a geophysicist's knowledge about the effect, of geological structure on airborne geophysical data. As well, they restrict the allowed geological outcomes to those that are feasible. While the initial phase of processing associates local geology with local data features, the subsequent phases incorporate constraints imposed by the global picture that is being built up from local features. Technology for storing and reasoning about the spatial relationships between features is needed. The reasoning process has a flexible control structure that allows strong features to influence the interpretation of weaker features.

The reasoning is driven by the data that is available rather than from some predetermined prescribed chain of associations. When multiple interpretations of the data are possible, they are all kept. This step in the interpretation process is based on techniques for handling spatial data and for controlling the reasoning when there are multiple opinions about aspects of the data. In addition, this step requires the rules relating signal features and geological features to be encoded. The software tools undertake (1) the encoding of the geological rules, and (2) the adaptation of spatial data techniques to support the application of the geological rules.

There are many well established examples of Geology Feature extraction techniques:

- Multi-scale edge detection methods or "WORMING" is an example of this style of thinking. Extensions from 2D to 3D, including estimating the strike and dip of contacts or fault planes, are now available - see FitzGerald et al. (2013)
- Naudy auto-model for extracting dyke swam starting geology models from aeromagnetic line data. See FitzGerald et al. (2011)
- Eigenvector analysis and anisotropic clustering for defining linear features in Gravity Gradiometry, leading to local fault planes, with strike/dip and tilt estimates. FitzGerald et al. (2014)
- Keating (2004) and vertical pipe identification, discussed further below.

Geological Structure

This final step integrates the multiple local geological interpretations into a consistent global interpretation. Three aspects of this step should be noted.

1. Further topological/ geological rules are necessary. These describe the relationship between global structure and local structure. They encode the knowledge a geologist adds to the interpretation. The big leap forward in this endeavour, occurred with Calcagno et al. (2008). Since that breakthrough, a formal high-level API, that uses the Google messaging technology, encodes these rules.
2. Reasoning techniques must be employed that draw conclusions based on the weight of evidence for, and the lack of substantial evidence against those conclusions. Such evidential reasoning techniques allow substantive conclusions to be drawn even when the available evidence is incomplete and even incompatible. Of course, strong conclusions can only be drawn when the evidence supports a consistent set of hypotheses.

Geological Uncertainty – Leading Edge Practise

There are many aspects that remain uncertain, especially the fault network, and detail rock relationships, rock properties etc. This uncertainty leads to the conclusion that there is no one "true" 3D geology model. A family of plausible models that derive from all observations of geology and the features derived from geophysics, is the consequence. Elements of Bayesian Theory, or Experimental design provide the basis for generating this family of models. To complete the loop, geophysics surveys have a place to validate and provide bounds on each proposed geological model. Inversions of the geophysics data, constrained by the geology "rules", drive changes to the 3D geology model so that the family of equally plausible models, remain consistent with the geophysical survey data. see Guillen et al. (2008) and Pakyuz-Charrier et al. (2017).

The jump to more systematic implementations, as seen in TensorFlow, from Google, has lagged, as the geoscience toolkits have until now, not adopted the language of the AI community. That has changed with Intrepid V6, and a new API that is comprehensive and covers all the common geophysics needs, while using the Google syntax. covering the geophysics convolution filters, terrain correction, forward models etc. More than 200 high level function points encapsulate the techniques and "rules", that either human or machine intelligence can wield to achieve a high level of automation. The real constraint has been the lack of engineering for complexity in the geosciences. Discrimination methods and a move to more holistic 3D context with proper respect for the appropriate basis functions also aids in the rejection of "false positives".

Feature Extraction using Image Processing Techniques

The closest point of reference to what is often termed AI, for the geophysicists, has historically been to do with image processing methods. The methods proposed by Keating (2004) and Meyer (2015) are precursors to a branch of the emerging universal problem-solving mechanism in artificial intelligence. In particular, Convolutional Neural Networks (CNN) take a series of input grids, multiplies each input by a weight and passes the data through a series of layers. They use rectangular filters and pool layers to reduce dimensionality.

<u>Example Training Location</u>

Figure 1 prepared by Lynton Jacques in 2005, shows the known occurrences in Australia of all diamond pipes, kimberlites, lamprophyre, lamproite, carbonatite and alkali basalts. The gravity and magnetic datasets did not play a big role in this compilation, once the field moved to being intensively explored. Stream sampling (geochemical information) and field geology mapping (context) and topography followed by drilling became more dominant. This then is the basis for using, real independent data as a training set control.

Ellendale Diamond Mine is located approximately 100km northwest of Fitzroy Crossing and 120 km east of Derby in the West Kimberley region of Western Australia.

The immediate diamond field contains around 100 known pipes. As exploration has been on-going in this field for many years, it is assumed all pipes have already been mapped. Ellendale includes the E4 and E9 pits, waste rock landforms and tailings storage facilities.

There are indications of rift boundary faulting cutting right through the field, northeast to southwest, with more recent cover rocks. Small plugs, <100 m to 1.8 km across; several, known as the Ellendale Vents, are diamondiferous. There is a small difference in age between the northernmost intrusions of the Ellendale area (20-22 Ma) and those further south in the Noonkanbah area (18-20 Ma).

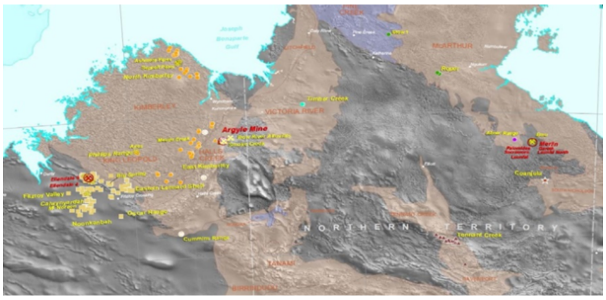

Figure 1. The magnetic image was derived from the Magnetic Anomaly Map of Australia grid. It is a grey-scale total magnetic intensity image of Australia enhanced using a sun angle illumination from the northeast. The image has been overlain by major geological regions, labelled in brown text, to assist with positional context of deposit localities. Insets show individual locations overlain on a colour image of the total magnetic intensity. Locational and other information for the diamond deposits and kimberlites, lamproites, ultramafic lamprophyres and garnet-peridotite facies alkali basalts.

The mean depth of overburden is approximately 200 metres. The cover is lateritic soils with a significant weathering horizon. The known locations are available in a points dataset with attributes.

Geophysical data

In 2008, reconnaissance TMI data at 400 m line spacing was flown in a north-south direction. A Falcon survey has been conducted in the Fitzroy trough area as well. This has not been considered yet, for the task of finding diamond occurrences. In 2018/2019, Sander Geophysics has completed 2.5 km spaced airborne gravity. So, in practical terms, the training dataset is confined to be the regional mapping standard, conventional, 400 m+ wavelengths.

The initial depth of exploration is about 100 metres below the aircraft. Given the original TMI survey data acquisition, it is unlikely that any feature in a 500 x 500 m window would be detected.

Table 1. Ellendale TMI survey – principal facts.

Bounding Coordinates	**124.75,125.00**	**-18.00, -17.25**
Coordinate System	Geodetic	GDA53
Survey Year	2008	
Line spacing	400 m	
Mean Clearance	50 m	
Mag Intensity	49881 nT	
Mag Inclination	-48.08 degrees	
Mag Declination	2.82 degrees	

Forward Model

The ability to predict the response of a range of reasonable compact geology models of a kimberlite, covering scale, variable physical properties, and all the possible ways that a geophysical signal may be measured is critical. Forward modelling capability should cover many combinations of simple geometries, property distributions and an ability to calculate predicted responses for any gravity and magnetic magnitude, component or gradient, and combinations such as analytic signal.

Convolutional Neural Networks Simplified Workflow

A diamond pipe can be approximated by a vertical cylinder, with a radius and length. An improvement, to a more carrot-like shape can follow.

The physical property contrast of the material in the pip, vs the host rock creates a detectable anomaly. This is improved enhancing the geophysical signal using any or all:

- reduction to pole for magnetics, possibility of a magnetic vector reversal for remanence;
- terrain correction for gravity or its gradients;
- vertical and horizontal derivatives leading to the Analytic Signal for scalar measures, to transform to gradients; These are all close friends of each other.
- using combinations of the tensor gradient measures, such as the invariants; so that one or more semi-radial anomalies, with sharpened edges emerge.
- development of a third class, to cope with false positives

One or more geophysical grids of potential field data (gravity/magnetics or any/all of the measured gradients) can also be scanned, using a "convolution" algorithm, to assign a "fit coefficient" to every feature in the appropriately enhanced grid. This can be just one dataset, or a combination of disparate, or the Full tensor gradient, as realised by a 6-band grid.

Figure 2 shows the extended workflow with three classes of solutions, and not just one coefficient of "fit". The aim must also be to minimize the known physical factors in the frame that can be modelled out, e.g. terrain corrections, labelled as geological clutter above. False targets are shallow depressions with nowhere near the required buried extent or geometry characteristics for a valid target of interest. A terrain correction ends up modelling out all expressions from the terrain and reduces the topography to a horizontal plane.

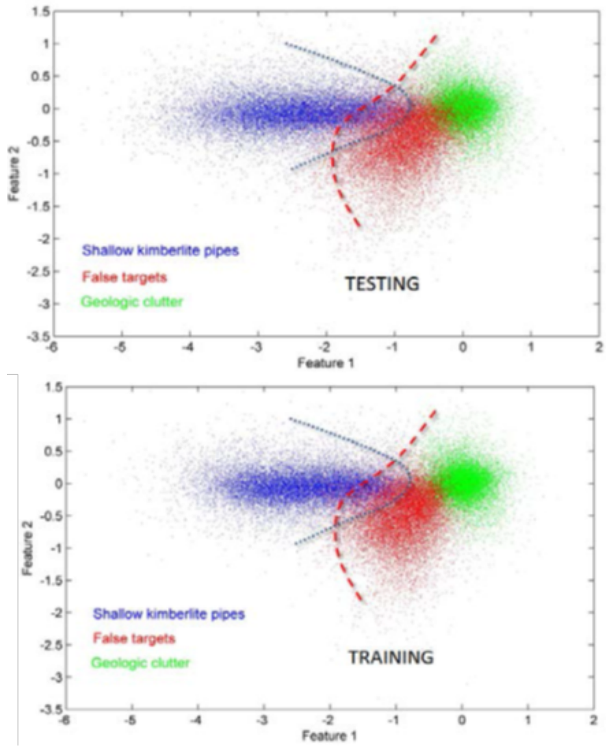

Figure 2. Feature populations for the three-class problem with shallow burial of small and medium-sized pipes, after Meyer, 2015. Feature 1 is depth of body, feature 2 is radius.

Feature Extraction Example

The Ellendale magnetic data comes from two surveys. The magnetic grid was reprocessed and gridded, then merged. The magnetic residual signal for both surveys was adjusted at the join, which mostly coincides with the northern flank of the Fitzroy trough. Levelling was necessary to reduce survey acquisition artefacts. The majority of the mapped/known pipes occur in the bounding fault region on the northern flank. However, by inspection, there are several interesting features in the magnetically quieter basin. The convolution process on the analytic signal finds many more candidate bodies than the known bodies and picks out some elongated features. This indicates the early stage training process must be improved some more.

CONCLUSIONS

In some cases, simple pattern recognition technique can be used to locate kimberlite pipes that have a magnetic and/or gravity response. Some pre-processing of the geophysics data, beyond careful preparation of gridded data is required. Removing the terrain effects, prior to any attempt at convolution operations is a prerequisite.

The use of intelligent search, inference engines to the problem of detecting diamond pipes, present many exciting new opportunities, considerably extending what has been achieved to date. This makes use of expected pipe diameters, depths, topography, density and susceptibility, and variable directions of remanent magnetization vectors, in an automated manner.

The use of the analytic signal for scalar measurements, or manipulations of the gravity and magnetic tensor gradients is recommended as the causative body anomaly shape is less dependent on factors such as the direction of the magnetic field and remanent magnetization of the kimberlite. In practice, pipes are at the surface or are located beneath the overburden, and it is easy to search for various pipe diameters.

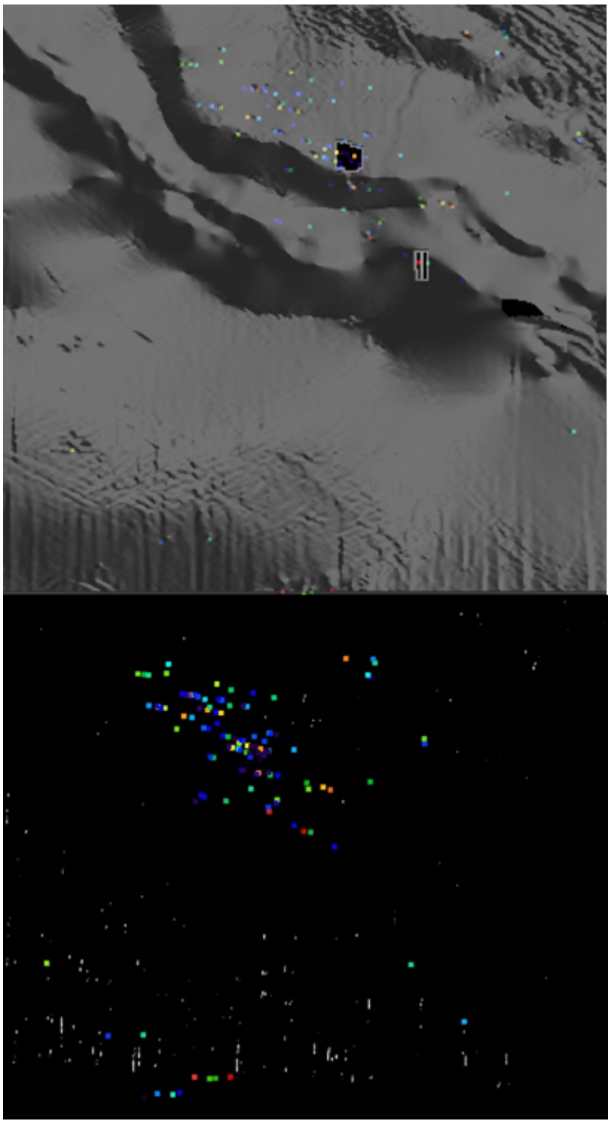

Figure 1. Preliminary training on the Ellendale TMI residual data. Left hand side shows a sun angle drape, with the known occurrences as coloured dots. Right hand shows the same known occurrences, and a greyscale of the "hits" using the analytic signal and the convolution solutions where the correlation is above a threshold.

True integration of geology and geophysics thinking requires a common earth model, that accommodates, with errors, all the features from the geophysics interpretation products, topological rules from geology, field mapping and drill logs, and the link between the two via physical rock property estimates. Automation of these steps involves 200+ individual processes, to yield a family of plausible models. The true limiting factor is managing technical complexity and communicating to the geoscience team, not compute power. All models are wrong and are destined to be replaced as further data or insights are gleaned. So, taking too much time trying to create the ultimate "correct" interpretation is wasteful.

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