An iterative approach to optimising depth to magnetic source using the spectral method

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SUMMARY

Knowledge of the depth of cover is poor across large areas of Australia. The spectral method is an efficient method of producing reliable depth to magnetic basement estimates across large regions of the continent.

A semi-automated work-flow has been created that enables the generation of depth to magnetic source estimates from windowed magnetic data using the Spector and Grant method. The work-flow allows for the correction of the power spectra, prior to the picking of straight-line segments, to account for the fractal distribution of magnetic sources. The fractal parameter (β) varies with depth and was determined by picking multiple depth estimates in regions of outcropping magnetic basement which have been upward continued to different levels in order to simulate different amounts of burial beneath non-magnetic sediments. A power law function best approximates the decay of β with depth.

An iterative schema used to determine the optimum β where the depths of magnetic sources are unknown, has been incorporated into the workflow. Preliminary testing in a region of known magnetic basement depth has produced encouraging results, although further testing is required. The decrease of β with increasing depth suggests that the fractal distribution of magnetisation becomes less correlated, or fractal, over larger volumes of observation.

Key words: depth to magnetic basement, spectral method, fractal, magnetisation.

INTRODUCTION

Large regions of Australia are blanketed by cover material, ranging from shallow surficial sediments to sedimentary basins containing 10 km or more of sediments. While the cover may only be tens of metres thick, this may be enough to obscure potentially prospective basement. Knowledge of the depth extent of this cover is therefore vital for a number of disciplines. For the mineral explorer, the depth of cover influences the economic viability for mineral extraction from basement. For both the hydrocarbon and geothermal explorer, the thickness of sediments also influences prospectivity.

The knowledge of the depth of cover, however, is poor across large areas of Australia. This lack of knowledge has recently been recognised as an impediment by the 2010 Theo Murphy High Flyers Think Tank (http://www.science.org.au/events/thinktank/thinktank2010/documents/thinktankproceedings.pdf). The think tank was convened by the Australian Academy of Science in order to provide a road map to address the fundamental needs of the exploration industry. Six initiatives were proposed, one of which was to create a national map of the depth and character of the cover.

This paper describes the ongoing development within Geoscience Australia of the spectral slope method to produce depth to magnetic source estimations. The spectral method, although one of a number of depth to magnetic source methods, is considered by Geoscience Australia as an efficient means of producing reliable estimates of the depth to magnetic basement across large regions of the continent.

THE SPECTRAL METHOD

The original work in estimating the depth to a single rectangular prismatic body using Fourier analysis was by Bhattacharyya (1966). Spector and Grant (1970) expanded this approach to incorporate an ensemble of rectangular vertical sided prismatic bodies of various geometries. An ensemble average depth to the top of the bodies may be determined by analysing the azimuthally averaged power spectrum of a magnetic grid for straight-line segments. The gradient of the straight-line segment is proportional to the top of the ensemble magnetic sources. This relationship holds where a minimum of approximately five bodies are present within the magnetic grid, so long as the differences in the depth to top of each of the bodies making up the ensemble are no greater than the ensemble average depth to top (Spector and Grant, 1970).

Pilkington and Todoeshuck (1993) proposed that the decay of the power spectrum at high wavenumbers as described by Spector and Grant (1970) infer exponential decay due to uncorrelated crustal magnetisation. Pilkington and Todoeshuck (1993; 1995) show that power spectrum decay follows a power-law function and is the result of the fractal nature of magnetisation distribution in the crust. Fedi *et al.* (1997) also recognise the power law decay and state that this decay characteristic occurs for both a uniformly distributed ensemble of magnetised blocks as well as a fractal distribution of magnetisation. To account for this power-law decay

Fedi *et al.* (1997) propose that the power spectra must be divided by a correction factor $\rho^{-\beta}$, where ρ is the wavenumber and β is the fractal parameter. The higher the value of β the more self-similar, or fractal, is the distribution of magnetisation in the crust. Using uncorrected spectra is the equivalent of applying a β value of zero, and simulates uncorrelated crustal magnetisation. Fedi *et al.* (1997) determined through use of synthetic modelling of an ensemble of uniformly distributed magnetised blocks that a β value of 2.9 adequately corrects power spectra for fractal magnetisation. From observed magnetic data in North America they generated depth estimates from straight-line segments of corrected power spectra, which were shallower than for uncorrected spectra. In addition, the corrected power spectra were less ambiguous to interpret than the equivalent uncorrected power spectra due to the reduction of multiple straight-line segments (and hence, multiple depth estimates) in the latter to a single straight-line segment.

A semi automated workflow has been produced by Geoscience Australia using the Python Programming Language (http://www.python.org) and Intrepid software batch processing (http://www.intrepid-geophysics.com) to rapidly generate depth estimates from windowed magnetic grids. The workflow sub-sections grids based on a moving, overlapping window and power spectrums are generated for each window. The workflow then allows the picking of straight-line segments of the displayed power spectrum by interactively choosing the start and end points of the segment. The program applies a least squares fit to the selected data and returns an estimated depth to source. The user has a choice of correcting the spectrums, and hence the calculated depth estimate, by a user specified β value.

DEPTH vs β

Initial testing to locate the depth to known magnetic basement from drill-hole data using a β value of 2.9 (Fedi *et al.*, 1997), produced mixed results. The spectral method overestimated magnetic basement in regions of relatively shallow cover, and underestimated basement depths in regions of thick cover. It appeared that the β was dependant on the depth to the top of the magnetic source and thus to produce reliable depth estimates the value of β must vary with depth. To determine the relationship between β and depth a systematic approach was devised. Three regions of outcropping magnetic basement were identified that coincided with good quality airborne magnetic surveys acquired at 400 m or less flight-line spacing. The 80 m cell size gridded data for these regions were downloaded from Geoscience Australia's GADDS database (http://www.ga.gov.au/gadds) and then reduced to pole. The grids were then upward continued to a series of higher levels, thereby simulating the burial of the magnetic basement beneath increasing thicknesses of non-magnetic cover.

Two of these regions, the Mount Isa Inlier (Figure 1) in north Queensland and the Yilgarn Craton in Western Australia, were selected for their markedly different nature of the observed magnetic field. The study area in the Proterozoic Mount Isa Inlier has a strong north-south orientated structural fabric of strongly magnetised volcanic rocks and non-magnetic sediments (Kositcin *et al.*, 2009). The observed magnetic field is dominated by strong elongated magnetic anomalies (Figure 1). The study area in the Archean Yilgarn Craton consists mainly of granites and minor greenstones (Myers, 1995). The magnetic field in this region is mostly subdued with the granites coinciding with subtle massive magnetic anomalies and the greenstones with mostly low amplitude elongate anomalies and minor higher amplitude anomalies. These regions, with their contrasting geology and hence magnetic source distributions, were selected to also test the relationship between magnetic source distribution and β. A third region in the Mesoproterozoic Musgrave Complex in the Northern Territory (Wade *et al.,* 2008) consists of high-grade metamorphic rocks which exhibit high frequency, relatively high amplitude elongate to massive textured magnetic anomalies. The Musgrave Complex was selected as the nature of the observed magnetic field in the study area lies between the strongly elongate anomalies of the Mt Isa and the mostly subtle massive texture with minor elongate anomalies of the Yilgarn study areas.

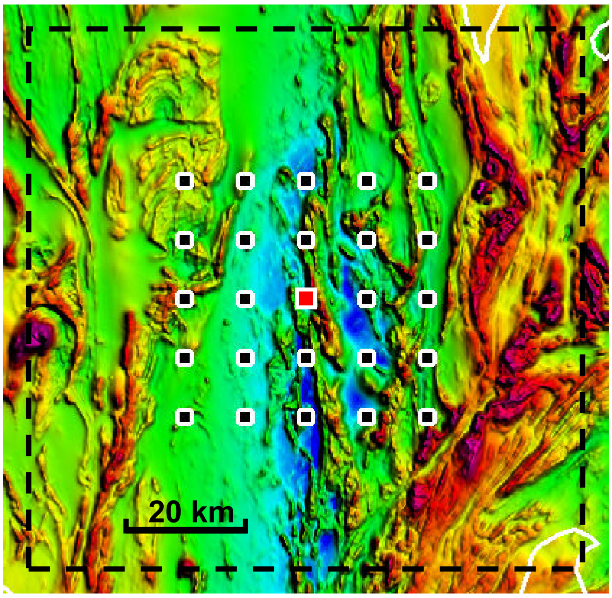

Figure 1. Reduced to pole magnetic image of the Mt Isa study area, upward continued 250 m. The area beyond the dashed line consists of data padding. The study area consists mostly of outcropping basement except beyond the white lines where basement is under cover. The locations of the window centres are shown (black boxes). Red box is the location of windowed power spectra in Figure 2.

The study area for each geological region was large enough to enclose multiple windows (25 for Mt Isa; 16 for Yilgarn and Musgrave) spaced 10 km apart using the largest window size (50 by 50 km), as well as data padding. The data padding ensured that the upward continuation process was not negatively influenced by edge effects. The window sizes were determined by trial and error (evaluated to 5 km intervals) for each upward continuation level (Table 1). The smaller a window for a given upward continuation level the noisier the spectrum, resulting in a larger ambiguity when picking straight-line segments. Larger windows produce smoother spectrums and are less ambiguous; however, larger windows in real world applications will enclose larger areas of potentially varying basement topography. Variations in basement depth greater than the average depth to top (Spector and Grant, 1970) will result in ambiguous spectra and potentially misleading depths. The optimum window size was defined to be the smallest size that produced relatively smooth spectra and, therefore, easily determined straight-line segments resulting in reliable depth picks.

Table 1. Optimum β value and window size for each level of upward continuation (UC) for the Mt Isa study area. The median depths calculated and standard deviation are also shown.

UC (m)	Window Size (km)	β	Median depth (m)	Standard deviation (m)
50	10	5.8	49	41
100	10	5.0	101	38
150	10	3.9	152	26
250	15	2.7	250	23
350	20	2.1	354	26
500	25	1.8	505	27
600	30	1.7	605	38
750	30	1.6	758	48
1000	35	1.6	1002	117
1250	35	1.6	1248	143
1500	40	1.5	1516	135
2000	50	1.3	1981	211
2500	50	1.4	2532	270

For each study area, and for each upward continuation level, depths were generated from straight-line segments using an initial β value. Trial and error was employed to determine a reasonable initial β value that returned depths close to the corresponding upward continuation levels. These initial picks provided the corresponding wavenumbers at the start and end points of the straight-line segments. Multiple depths were generated for each window at each upward continuation level for each study area. This was achieved by least squares fitting between the start and end point wavenumbers which have been corrected using a range of β values. This approach is valid as the start and end wavenumber values, for a straight-line segment, do not change for corrected power spectra of varying β. Median depths were then calculated for the multiple windows at each upward continuation level. This process allowed for the identification of the optimal β value for each upward continuation level and, hence, the depth to the top of magnetic sources.

Figure 2 shows examples of straight-line segment picks for a single window using the optimum β value for a number of upward continuation levels. The straight-line segments progress to lower wavenumbers as the depths increase. The length, and therefore, the reliability of picking straight-line segments decreases as depths increase. Beyond ~2500 m, straight-line segments could not be reliably picked. Figure 3 shows plots of optimum β value for each upward continuation for each study area. The plot shows a strong relationship between β and depth. The general trends for the three study areas are similar, indicating that β is more strongly correlated with depth to top of magnetic sources compared to source geometry. The Yilgarn trend shows higher β values for shallower depth levels and lower β values for deeper depth levels when compared to the Mt Isa trend. The Musgrave trend tracks more closely to the Mt Isa trend. The grey polygon (Figure 3) encloses β values generated for the Mt Isa study area that produced depths that are within +/-20% the upward continuation levels. This depth range provides an indication of the sensitivity of depth with varying β. A line of best fit has been applied to the data using a power law function and is shown as the dashed line in Figure 3.

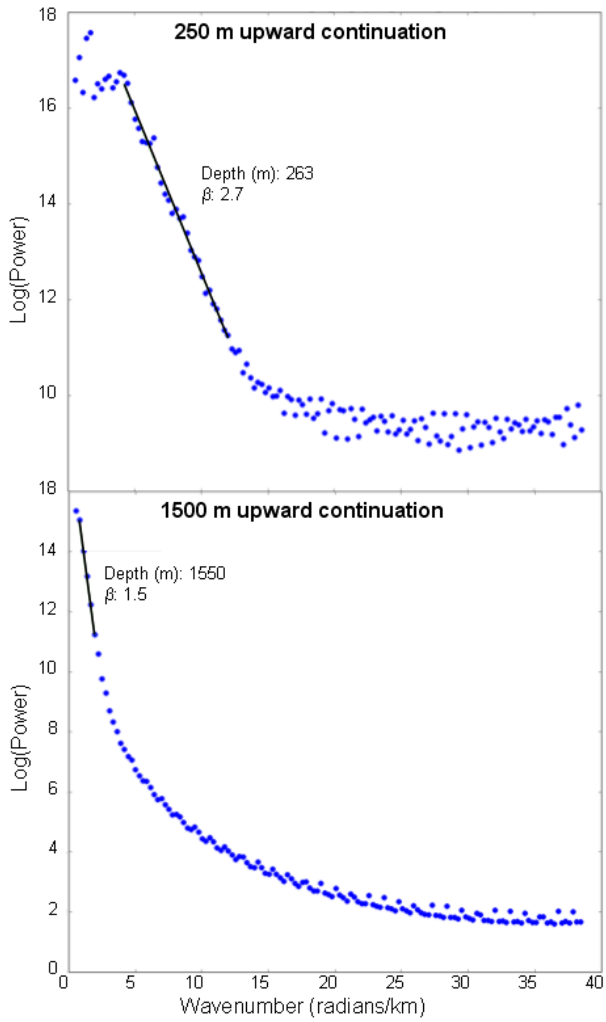

Figure 2. Spectra showing straight-line picks for the optimum β value for two upward continuation levels. The window location is shown in Figure 1.

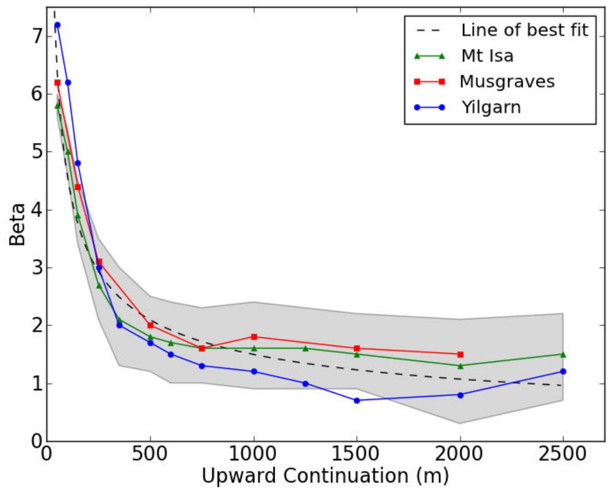

Figure 3. Plot of depth versus β for the three study areas. The grey polygon encloses β values generated for the Mt Isa study area that produced depths that are within +/- 20% of the upward continuation level.

ITERATIVE APPROACH TO OPTIMISING β

Depth to magnetic basement estimation requires depth estimation where depths, and therefore, β are unknown. To determine both β and depth an iterative schema has been added to the workflow, which uses the line of best fit (Figure 3) to map the β value to depth. For a given window the user specifies an initial β value and the user is shown a display of the corrected power spectra. The user then picks, if present, a straight-line segment and a depth is computed. This initial depth is fed into the power law function line of best fit which produces an updated value for β. The above process is iteratively looped, with each iteration producing a new depth estimate that converges towards an optimum value. Once the residual from one depth iteration to the next falls below a user defined value, the process ends.

Testing of the iterative schema is preliminary at this stage and involved generating depth estimates from 20 km windowed data, with window centres located within ~8 km of drill-holes. The depths to magnetic basement identified in the drill-holes ranged from 225 to 1067 m. The median percent difference (depth estimate minus drill-hole) was -1.6% with a standard deviation of 11.1% based on 22 depth picks. Although these results are encouraging, further testing is required.

DISCUSSION

The results of the upward continuation testing shows that β changes with depth, ranging from high values (~5.5 to 7.5) and decreasing with increasing depth to low values (~1 to 1.5). This finding agrees with Fedi *et al.* (1997) who state that the rate of decay of the power spectrum is determined by the exponent of the power law ($-\beta$) and the depth. Where our method differs from Fedi *et al.* (1997) is in the application of the correction factor. Where Fedi *et al.* (1997) use a single value of 2.9 for β, we recognise that β must vary with depth to produce more reliable depth estimates.

The decrease of β with depth suggests that the deeper the magnetic source the less correlated, or fractal, the magnetisation distribution appears as observed in the magnetic data. We suggest that this changing appearance is due to imaging of larger volumes of crust with increasing upward continuation levels. By increasing the height of observation the amplitude of anomalies due to shallower magnetic bodies falls off at a faster rate than deeper sourced magnetic bodies. Increased burial is, therefore, the equivalent to observing deeper into the crust. The increasing window sizes, a requirement to interpret spectra for larger upward continuation levels, capture larger wavelengths, also results in deeper observation within the crust. The larger window sizes also enclose larger areas which when combined with the larger depths of observation, results in a larger volume of geology, and hence, magnetisation distribution which is being observed. The change in β with increasing volume of observation suggests that the fractal nature of magnetisation distribution varies at different volume scales with smaller volumes more highly correlated than larger volumes.

CONCLUSION

A workflow has been successfully implemented for determining depth to magnetic sources from a power law corrected power spectra. The process recognises that the correction, or applied β value, changes with depth of burial of the source and an iterative schema has been introduced that allows for the optimisation of β with changing depth. Initial testing against drill-hole data is encouraging, but more testing is required. Different geological regions appear to produce different rates of decay of β with depth (Figure 3). Additional geological regions should be evaluated to determine the decay rate of β for different magnetic source geometries. This additional data could be used to update the β to depth function for subsequent depth to magnetic basement mapping.

ACKNOWLEDGMENTS

We thank Peter Milligan and Richard Chopping for their review and comments, Richard Lane for some good advice, and Indrajit Roy for the initial application of the spectral method to depth to basement mapping in Geoscience Australia. Geoscience Australia authors publish with permission of the Chief Executive Officer, Geoscience Australia.

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