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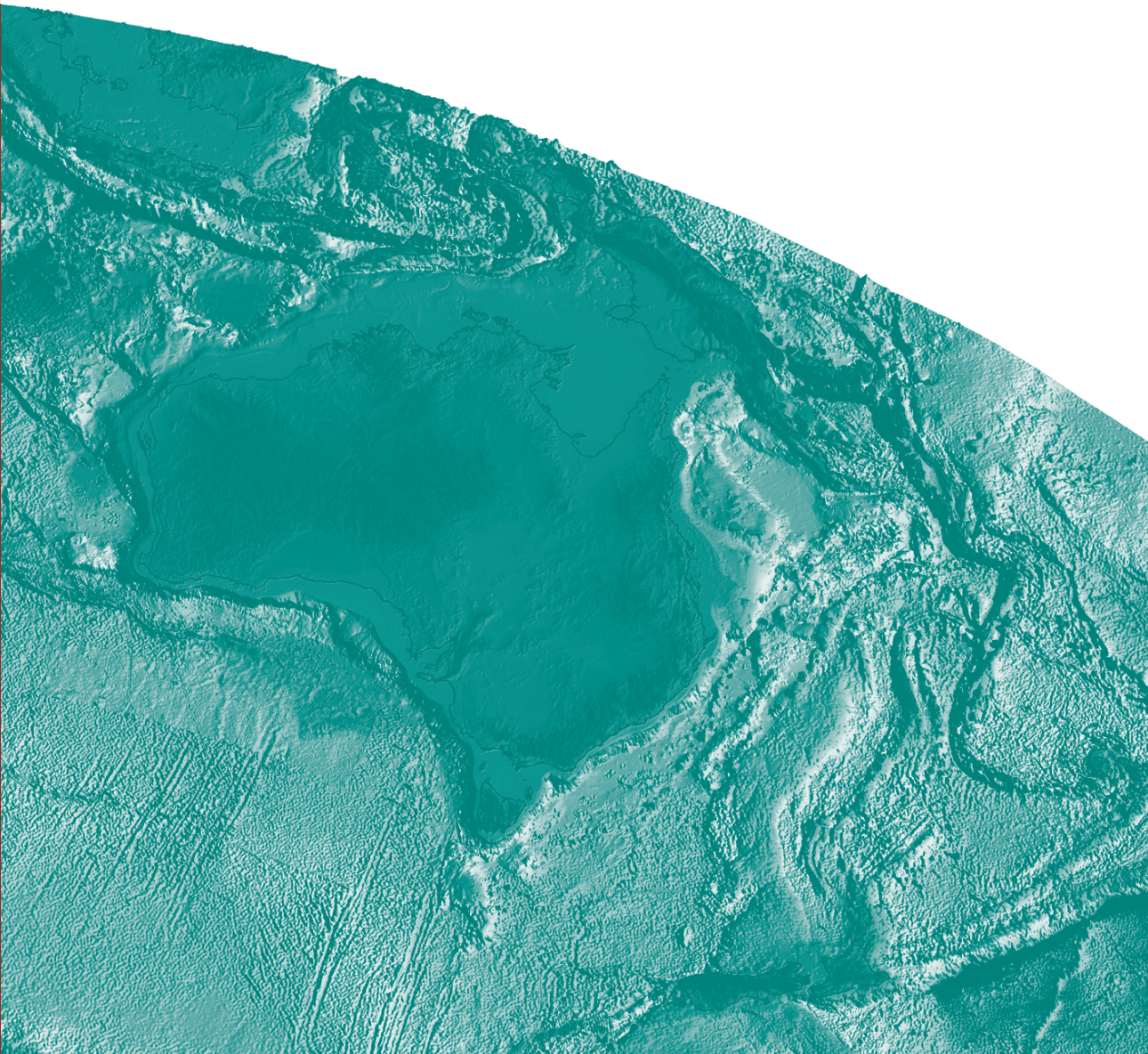
Depth to Magnetic Basement of the Capel and Faust Basins, Lord Howe Rise

Goutam Kumar Nayak and Peter Petkovic

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by

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Executive Summary

As a part of the Australian Government's Energy Security programme, Geoscience Australia acquired pre-competitive ship-borne geophysical data over the Capel and Faust basins, about 800 km east of Brisbane. Marine surveys GA-302 and GA-2436 were conducted during 2006 and 2007, over an area of more than 100,000 km², at water depths of 1000–3000 m to acquire reflection and refraction seismic, swath bathymetry, gravity and magnetic data.

This document describes how magnetic spectra were used in an attempt to estimate depth to magnetic basement and give additional constraint on the basement architecture of these frontier basins where seismic coverage is sparse and there is only one shallow well. A semi-automated method was developed using a combination of commercial and in-house developed software in order to improve the utility of the spectral method.

The results confirm the seismic interpretation of a substantial depocentre, about 6 km thickness trending north-northwest in the northwest part of the Capel and Faust Basins study area. The magnetic analysis indicate the presence of a north trending ridge in the central part of the study area, also evident in the reflection seismic data.

The results indicate that our semi-automated magnetic spectral method is viable and points to areas where it can be improved. We propose the technique may be useful in the study of other frontier basins where the magnetic data coverage is of comparable detail and resolution.

Introduction

The Capel and Faust basins of the Lord Howe Rise were surveyed during 1996 and 1998 as part of Geoscience Australia's Law of the Sea programme to define Australia's legal continental shelf margin. The data from these surveys indicated that sediment pockets existed (Ramsay *et al.*, 1997, Bernardel *et al.*, 1999) creating interest in the region as a possible petroleum province (Stagg *et al.*, 1999), although it was unclear just how extensive and thick the sediments were.

Geoscience Australia completed a seismic survey (GA-302) of these basins during the summer of 2006/07 to explore the area in detail, using 2D acquisition technology to image the sedimentary sequences and the underlying crust. The survey was conducted on behalf of Geoscience Australia by Compagnie Générale de Géophysique (now CGG Veritas) on the platform *Pacific Titan*, collecting 5920 km of high-quality 106 fold 2D seismic reflection data to 12 s two-way travel time at 37.5 m shot interval using an 8 km streamer (Compagnie Générale de Géophysique, 2007), as well as magnetic, gravity, bathymetry and sonobuoy refraction data. The potential field and bathymetry data were processed by Fugro Robertson (2007). The reflection seismic data from this survey was interpreted by Colwell *et al.* (2010) and the refraction data by Petkovic (2010).

Following survey GA-302 in 2007, Geoscience Australia survey GA-2436¹ collected multi-beam bathymetry data and sea-floor samples as well as magnetic and gravity data over the northwest part of the GA-302 survey area at a 4 km line spacing (Heap *et al.*, 2009). The location of surveys GA-302 and GA-2436 is shown in [Figure 1](#). The potential field and bathymetry data on this survey were acquired and processed by Fugro Robertson (2008).

¹ GA-2436 is also known by the acquisition platform name "R/V Tangaroa" or the National Institute of Water & Atmospheric Research (New Zealand) code TAN-713.

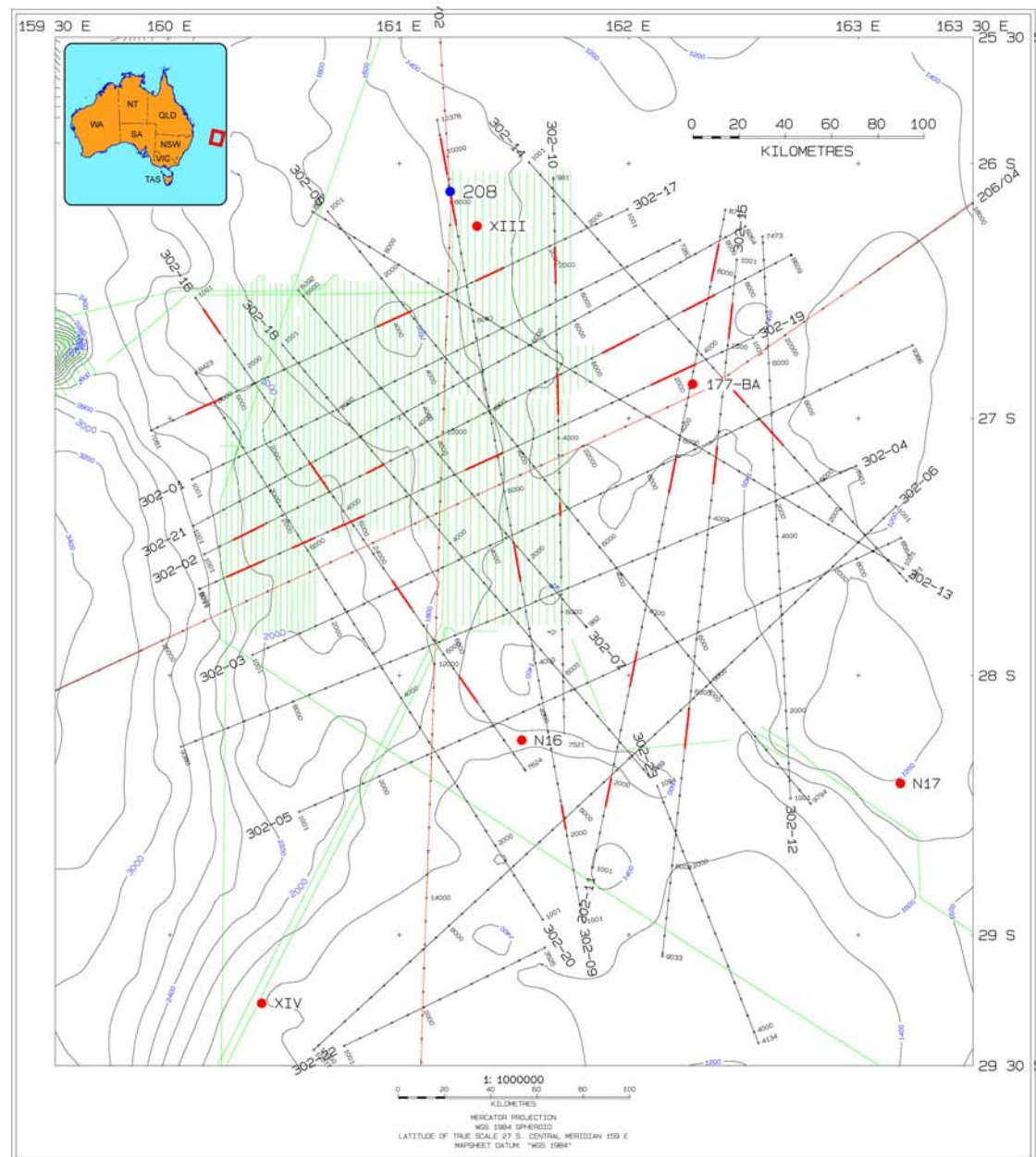


Figure 1. Location of the ship track profiles from survey GA-302, sonobuoys from GA-302 [red segments on seismic lines], two lines from earlier survey GA-206, the location of DSDP 208 [●], pre-existing velocity models [●], and closely spaced lines from multi-beam bathymetry and potential field survey GA-2436 (also known as ‘Tangaroa’ survey). Bathymetric contours are background.

The results of stratigraphic studies using reflection seismic data from GA-302 are reported in Colwell *et al.* (2010), who supported earlier notions (e.g. Gaina *et al.*, 1998; van de Beuque *et al.*, 2003) that the Lord Howe Rise is underlain in this region by continental crust which was part of greater Australia before its Late Cretaceous breakup and the formation of the Tasman Sea. Reflection seismic data from GA-302 provides evidence for this proposition by the variable

character of basement which includes both characterless transparent zones and sections where layering is clearly present, indicative of intruded and altered older Mesozoic basins. In addition, Colwell *et al.* (2010) opined that the entire seismic stratigraphic sequence is intruded or interbedded with volcanic sills and dykes throughout the sedimentary succession. Thus, at the outset of the study it remained difficult to determine sediment thickness, one of the fundamental parameters of petroleum potential, despite the high quality seismic data and adequate penetration of seismic energy. To test various seismic basement depth ideas Petkovic (2008) and Petkovic *et al.* (2011) developed 2.5D and 3D gravity models using sediment and basement densities inferred from velocity models of refraction data.

This study focuses on the magnetic data and describes the method for estimating depth to magnetic basement on the assumption that the basement is composed of randomly distributed magnetic sources. It provides an independent estimate of sediment thickness, alongside the refraction and reflection seismic models and the gravity models.

Data Acquisition and Processing

Total magnetic field measurements were acquired on surveys GA-302 and GA-2436 using a proton precession SeaSpy marine magnetometer towed between 210 and 245 m astern by a floating tow cable and recorded at 1 second intervals. The magnetometer head was towed at least two ship lengths astern to avoid recording the magnetic field of the ship (Bullard & Mason, 1961).

The GA-302 and GA-2436 datasets were processed by Fugro Robertson Inc LCT Gravity and Magnetics Division (Fugro Robertson) and provided to Geoscience Australia in the first half of 2008. Processing involved:

- position correction for the distance between sensor and navigation antenna,
- subtraction of the International Geomagnetic Reference Field (IGRF) value extrapolated from the 2005 formula,
- diurnal correction,
- filtering using a Butterworth filter with a cutoff at 60 seconds², and
- network adjustment to minimise misties.

² ship speed on GA-302 was ~150 m/minute and GA-2436 ~300 m/minute

The network adjustment reduced mistie rms from 10.1 nT (before adjustment) to 5.6 nT for survey GA-302 and from 8.8 nT to 1.3 nT for survey GA-2436.

The magnetic line data from each survey were gridded with a cell-size of 0.01° using minimum curvature technique and merged with grids from data obtained on earlier surveys (Hackney, 2010). [Figure 2](#) shows the reduced to pole anomaly with respect to the IGRF of the integrated dataset, which was the basis for estimating depth to magnetic basement.

Gridding and Reduction to the Pole

The IGRF-corrected total magnetic intensity (TMI) profile data were gridded with 5000 m grid cell size using the minimum curvature algorithm with Oasis MontajTM software. This cell size minimises gaps in the grid image of the area where the approximate line separation for GA-302 is 40 km and 4 km for GA-2436 in the northwest of the study area ([Figure 1](#)).

The measured magnetic field at any point is the combination of the Earth's magnetic field and the field due to crustal induced and remnant magnetisation. It will be assumed that the remnant magnetisation is in the direction of induced magnetisation or the magnitude of remnant magnetisation is small compared to the induced magnetisation. Except at the magnetic poles, where the Earth's magnetic field is vertical, the anomaly due to the induced magnetisation will be displaced away from the bodies that cause them. To restore the position of anomalies, a reduction-to-pole process (RTP) was applied ([Figure 2](#)) and is the basic data set for all depth computation in the following sections.

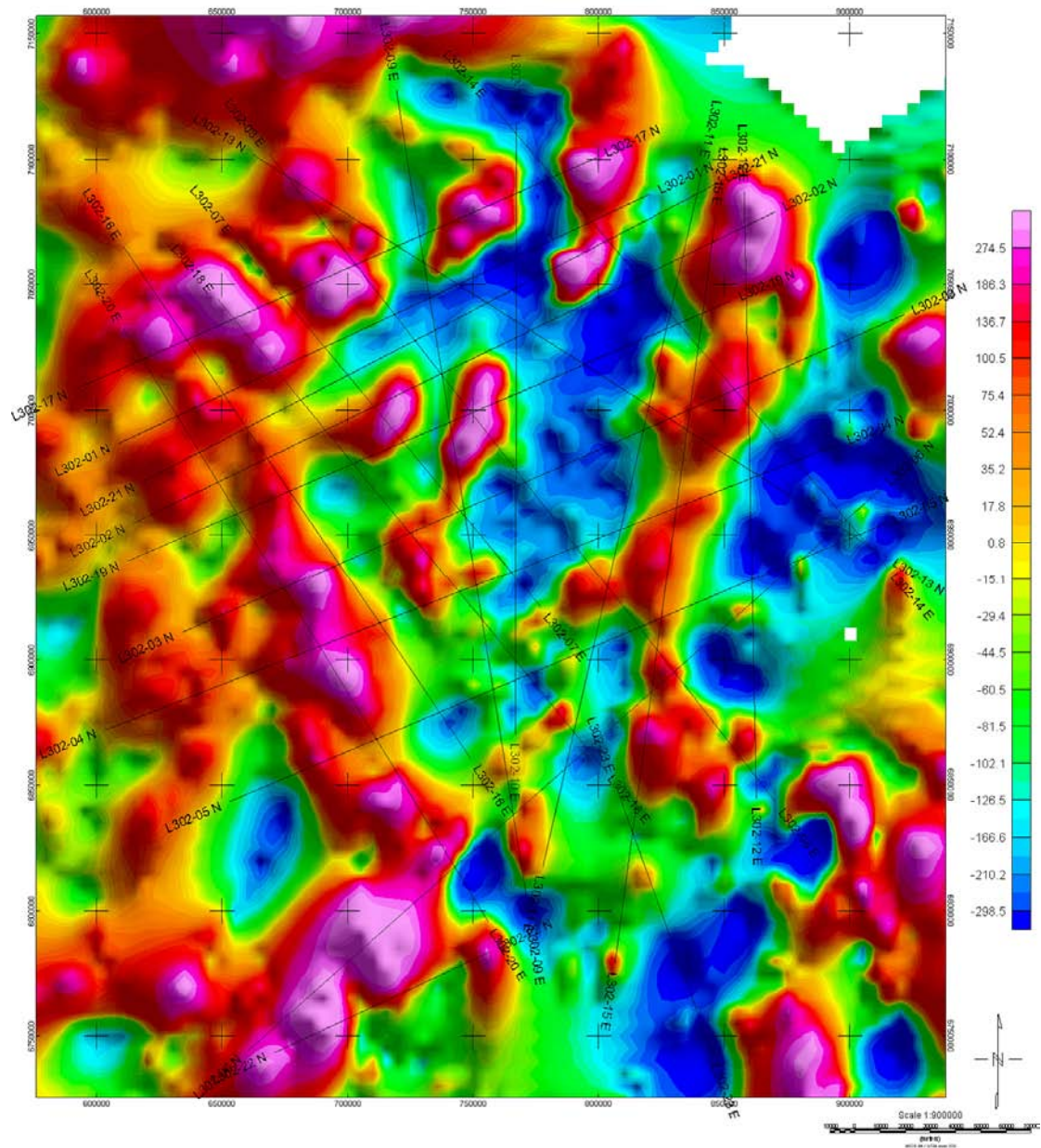


Figure 2. Total magnetic intensity (nT) after reduction to the pole incorporating all data available in the Geoscience Australia levelled potential field database. The projection zone is UTM57S. Seismic lines from surveys GA-302 are also shown for reference.

Depth to Magnetic Basement

The basement rocks of sedimentary basins commonly consist of igneous or metamorphic rocks, while the overlying sediments are non-magnetic. This means that the interface between the basement and the sediments represents a strong magnetic contrast. In such cases the depth to magnetic sources determination by magnetic methods gives reliable estimates of the depth to geological basement. In the present case the situation is complicated because the geological basement is believed to consist of older sedimentary basin material and the overlying sedimentary pile shows evidence of magmatic intrusion. Nevertheless we conducted magnetic depth estimation and compared the results to depths derived from reflection seismic data by Colwell et al. (2010). We used the spectral method of Spector and Grant (1970) which works best in situations where magnetic anomalies are due to randomly distributed sources.

Spectral Analysis Method

Magnetic depth estimation methods such as Euler and Werner deconvolution don't work well in areas where magnetic anomalies represent the superposition of individual anomalies from multiple discrete bodies. In such cases, power spectrum analysis of the magnetic data can be used to estimate an ensemble average depth to magnetic marker horizons which separate two different sets of randomly distributed magnetic source bodies (Spector and Grant, 1970). In the present case we assumed magnetic anomalies are caused by:

- sources of magnetic materials lying within the sedimentary succession, and/or
- possible magnetic rocks present within the basement (up to Curie isotherm).

The magnetic power spectrum method, which does not use magnetic field gradients, allows an interpreter to separate magnetic signatures arising from magnetic horizons lying at different depths. These will appear as discrete straight line segments on log-power vs frequency plots. The slopes of these segments are a function of the depth to the top of magnetic marker horizons.

The process is described as follows: the RTP-corrected grid ([Figure 2](#)) was smoothed by upward continuation to 500 m then split into 50 km x 50 km sub-grids with 90% overlap (centres 5 km apart) using program 'splitdomain'³. The size of the sub-grid determines the frequency content in the spectrum and hence the depth of investigation. Nayak and Rama Rao (2002) and Odegard and

³ 'splitdomain' is an in-house program written in Fortran by Indrajit Roy

Weber (2005) working on sedimentary basins in different parts of the world suggested that a window of 45–55 km was optimum for investigating depth to basement. We calculated the power spectrum for each 50 km x 50 km sub-grid, of which there were ~7000, using the Fast Fourier Transform (FFT) in the IntrepidTM software run in batch mode. The radially averaged energy spectrum was calculated for each window by averaging the energy from all directions for the same wavenumber. The results (wavenumber vs energy) were tabulated to one output text file per window so that a plot of the result for each window could be inspected and slopes determined.

The slope of the straight line fit to the plot of the wavenumbers (cycles/meter) versus the energy (log P) is proportional to the ensemble average depth to the different magnetic marker horizons.

The depth to the magnetic marker is given by:

$$h = \frac{1}{4\pi} \times \frac{\Delta E}{\Delta N} \quad \text{①}$$

where,

E = Energy in log power,

N = Frequency/wave-number, and

$\Delta E/\Delta N$ is the slope of the straight line segment of the spectrum.

To compute the depth from the energy spectrum for each of ~7000 power spectrum reports we developed an approach to automate the slope determination process. The tabulations of ΔE and ΔN were read into program '*powerspec_rpt_fixed.pl*' which computed the slope of the line of least-squares best fit between user specified fixed lower and upper values of N. To determine this frequency band ten windows were randomly selected and depth to basement determined manually for each (Table 1). By inspection, basement lay in the 0.015 to 0.095 cycle/km band which was then given as the program parameter.

A companion program, '*powerspec_rpt_variable.pl*', computed the slope from a fixed lower frequency (0.015 km⁻¹, as did *powerspec_rpt_fixed.pl*) to a variable upper frequency. The upper frequency was determined for each window using a change-of-slope search algorithm.

Table 1. Ten randomly selected windows showing a comparison of slopes calculated by inspection (Columns 2 and 3) and by automated methods using software ‘powerspec_rpt_fixed.pl’ (Column 4) and ‘powerspec_rpt_variable.pl’ (Columns 5 and 6). The frequency ranges listed correspond to approximately straight graph segments except where the fixed range was used.

Window	Depth (km) by inspection	Frequency (km^{-1}) by inspection	Depth (km) fixed band (0.016-0.095 km^{-1}) automated	Depth (km) variable band automated	Frequency (km^{-1}) for variable band automated
3710	7.5	0.015 to 0.085	7.5	8.6	0.015 to 0.0777
2776	5.0	0.015 to 0.085	4.9	5.0	0.015 to 0.0993
3398	5.2	0.015 to 0.090	5.1	5.4	0.015 to 0.0928
3104	7.2	0.015 to 0.090	6.3	7.5	0.016 to 0.0842
1309	5.3	0.015 to 0.090	4.5	5.1	0.016 to 0.0856
284	6.1	0.020 to 0.090	4.5	6.1	0.016 to 0.0928
4139	7.5	0.015 to 0.085	6.4	7.8	0.016 to 0.0749
5541	6.2	0.025 to 0.095	5.4	6.9	0.016 to 0.0813
6298	8.3	0.015 to 0.080	7.0	8.2	0.015 to 0.0835
418	6.0	0.015 to 0.085	5.3	5.5	0.015 to 0.0900

For *powerspec_rpt_fixed.pl*, poorly defined gradients were rejected if the standard deviation of points about the line of best fit exceeded a user-specified heuristically-determined value (we used a standard deviation threshold of ‘5’). The companion program, *powerspec_rpt_variable.pl*, had this feature and also:

- allowed rejection of slopes where less than a user-defined minimum number of points were used, and,
- allowed the user to control a deviation threshold for the change-of-slope seeking algorithm.

The thresholds were determined by heuristic means and in the final run about ~20% of windows were rejected for giving poorly determined slopes.

The three methods (manual by inspection, automated fixed band, automated variable upper frequency) produced comparable depths (Table 1) and gave us confidence that the automated methods gave reasonable results. Each program wrote an output file containing X,Y and Z

coordinates (a depth for each window and the coordinates of its centre) to which a gridding process was applied to compute our depth to magnetic basement image (Figure 3). From this we derived a sediment thickness (Figure 4) by subtracting water depth which varies between 1200 m and 6000 m. This “magnetic sediment thickness” differs from the actual sediment thickness because we may be detecting magnetic sources within sediments.

The depth to basement and sediment thickness maps give evidence of several depocenters which are separated by N–S trending basement highs. There are two major depressed zones trending NNW and E–W, intersecting at a maximum sediment thickness of 6000 m (B in Figure 3). There are additional smaller isolated depocenters in the northern-most part of the study area, where the maximum depth to magnetic basement is ~5000 m, and in the southern most part of the study area where the sediment thickness is comparable to that of the northern-most depocenter. There is a NNE trending ridge separating narrow, eastern depocentre from the main depocentre in the northwest.

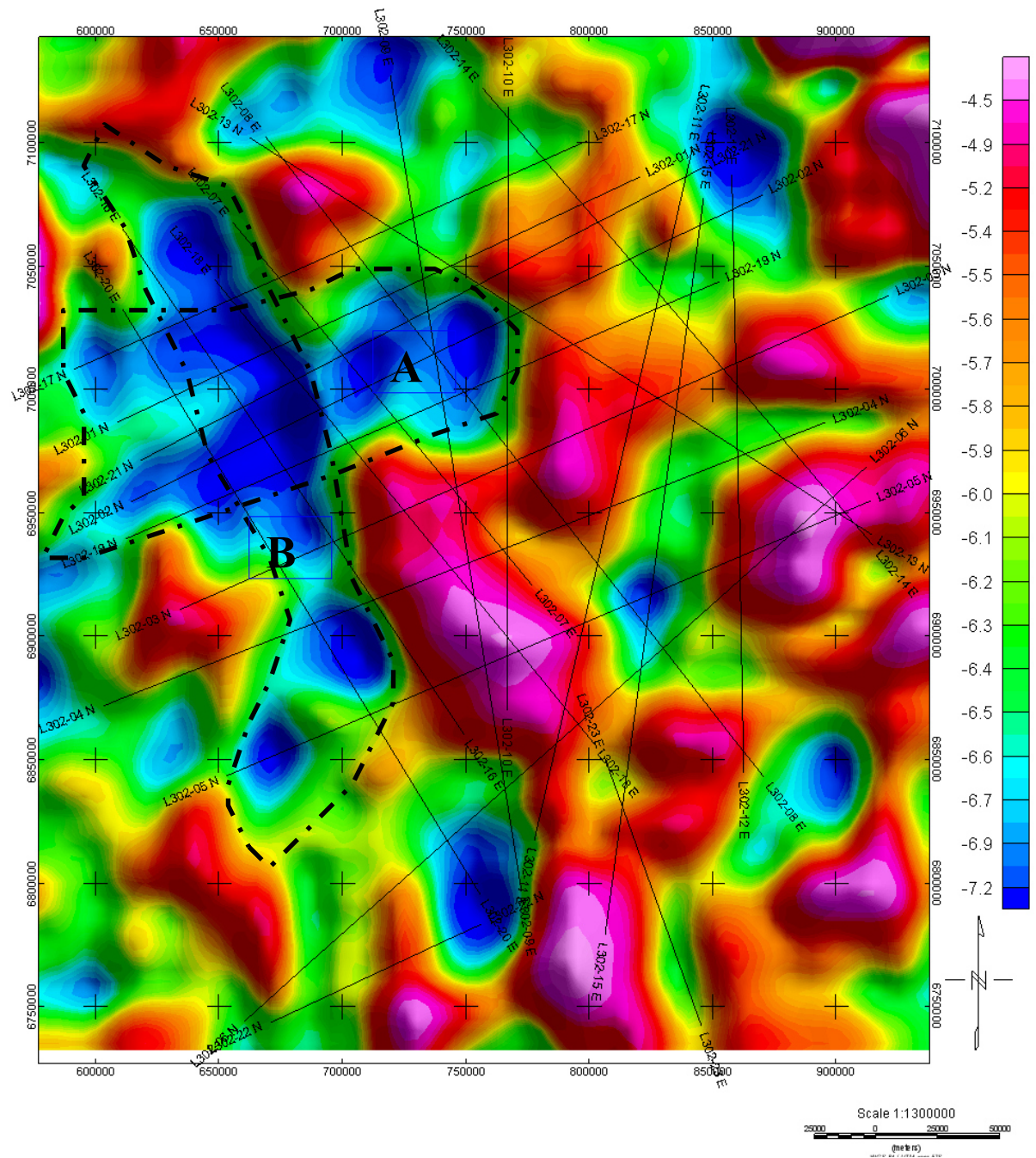


Figure 3. Depth to top of magnetic basement (km) measured from sea level derived using the spectral analysis method. Two major depressed zones in the study area are marked A and B. The projection zone is UTM57S. Seismic lines from surveys GA-302 are also shown for reference.

Depth to magnetic basement of the Capel and Faust Basins

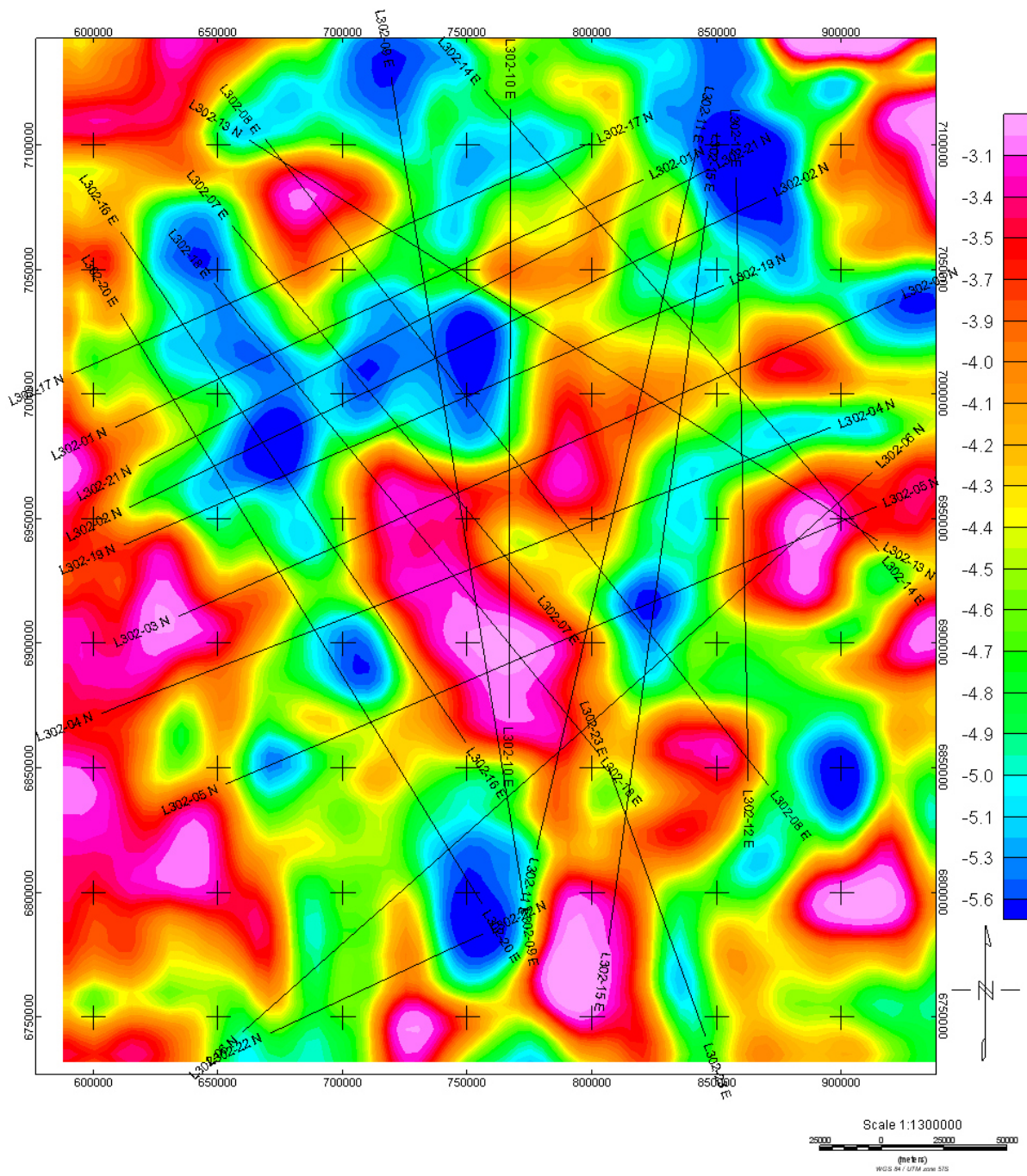


Figure 4. Sediment thickness derived by subtracting the bathymetry from magnetic basement depth (km). The projection zone is UTM57S.

Error Analysis

To estimate the error associated with the depths derived using the spectral method for our study, we consider a rectangular prism of dimensions 40 km x 30 km x 5 km (order of magnitude of expected basement bodies) placed 5 km below the sea surface and located with sides parallel to the coordinate axes ([Figure 5](#)).

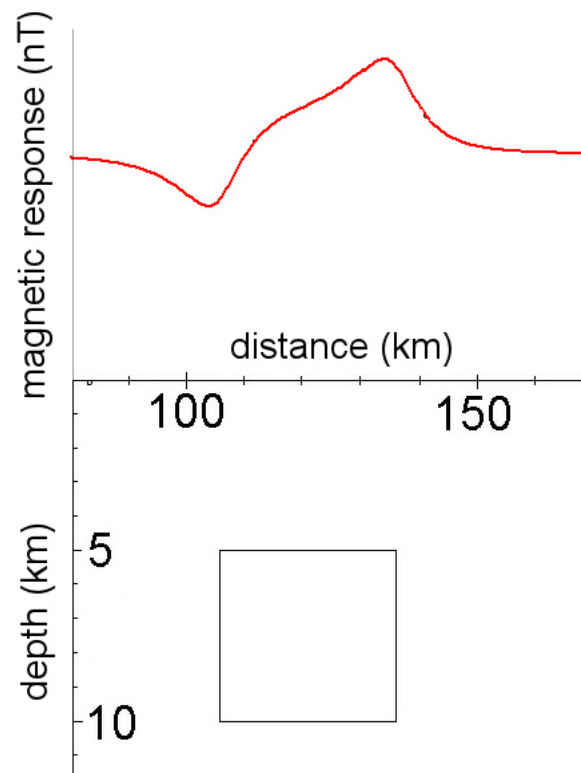


Figure 5. Magnetic response of a rectangular prism of size 40 km x 30 km x 5 km located 5 km below zero depth.

We assign an arbitrarily chosen susceptibility of 0.09 SI and compute the magnetic response of this body over a 50 km x 50 km area with three different grid cell sizes (80 m, 2000 m and 5000 m) to test the optimum grid spacing for locating the basement most accurately ([Figure 6](#)). Theory suggests that the coarse grid will reflect the deeper structure while the fine grid will be dominated by the effects of shallow magnetic surfaces.

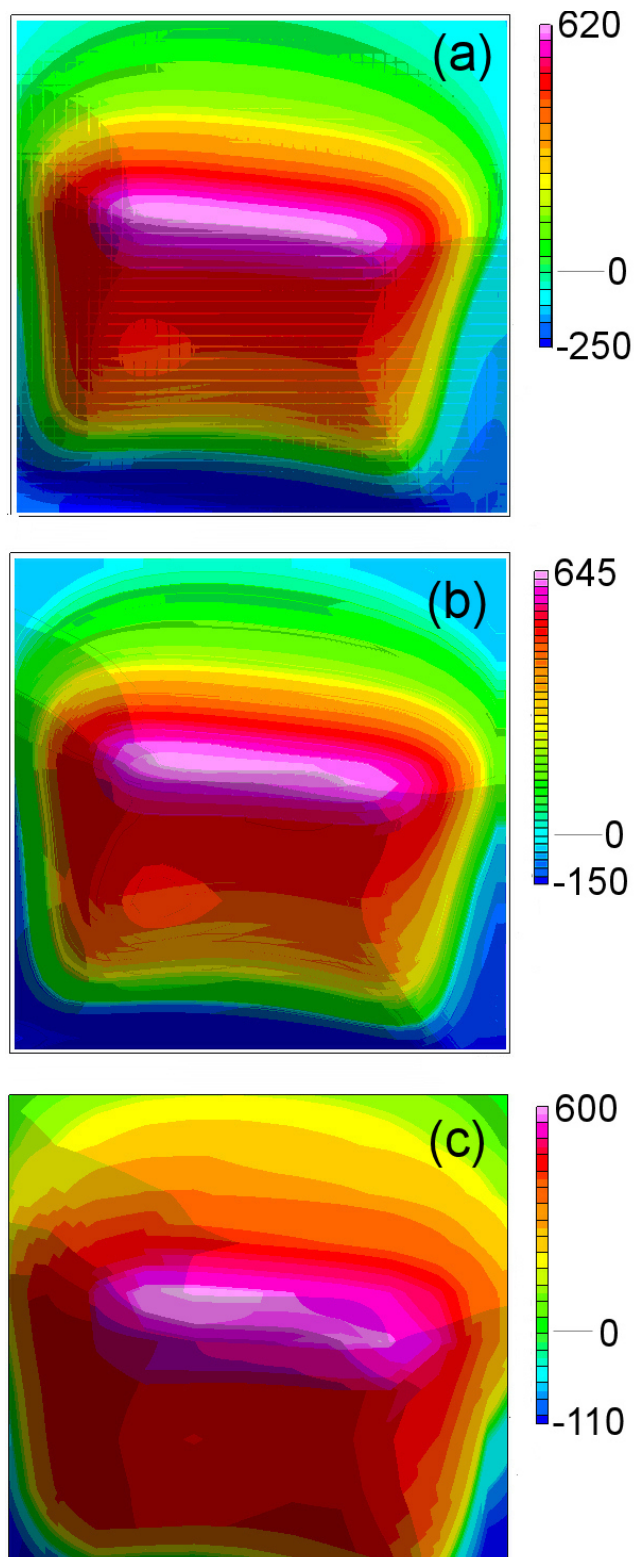


Figure 6. Magnetic response (nT) for the rectangular prism shown in [Figure 5](#) with grid spacing (a) 80 m, (b) 2000 m and (c) 5000 m.

Figure 7a represents the power spectrum for the 80 m grid-spacing. We consider three different slopes that may be picked within the frequency band 4.2 to 19.9×10^{-5} cycle/km. The average depth from these is 4700 m with a range of 4600–4800m, and the average depth is in error by ~6%.

Similarly, Figure 7b and Figure 7c represent three different slopes that may be used to compute the depth for the grid spacing 2000 m and 5000 m respectively. In Figure 7a and Figure 7b the top of basement lies in a common frequency band of 4.2 to 20.0×10^{-5} cycle/km. Figure 7a is mostly dominated by high frequency noise and Figure 7b is almost equally dominated by high and low frequency noise.

A summary of the errors is given in Table 2. This error analysis indicates that the likely uncertainty in the method, under the assumptions given, is less than 10%.

Table 2. Table showing the results obtained from the spectral analysis of the synthetic model where 30x40 km body with thickness 5 km at a depth of 5 km. the average depth is calculated using three slopes from each spectrum. The table also shows the maximum and minimum error corresponding to each spectrum.

cell size (m)	Window (km ²)	Frequency range (cycle/km)		Depth (m)	Mean Depth (m)	Max and Min Deviation (m)		Deviation from mean depth (m)
80	50 x 50	4.2×10^{-5}	19.9×10^{-5}	4800	4700	400 (8 %)	200 (4 %)	300 (6%)
		3.0×10^{-5}	22.9×10^{-5}	4600				
		4.2×10^{-5}	22.3×10^{-5}	4700				
2000	50 x 50	8.7×10^{-5}	20.8×10^{-5}	4600	5000	460 (9 %)	100 (2 %)	0 (0%)
		8.9×10^{-5}	19.6×10^{-5}	4900				
		8.7×10^{-5}	17.9×10^{-5}	5400				
5000	50 x 50	52.2×10^{-3}	98.4×10^{-3}	5400	5300	400 (8 %)	200 (4 %)	300 (6%)
		49.9×10^{-3}	98.4×10^{-3}	5200				
		49.0×10^{-3}	92.8×10^{-3}	5400				

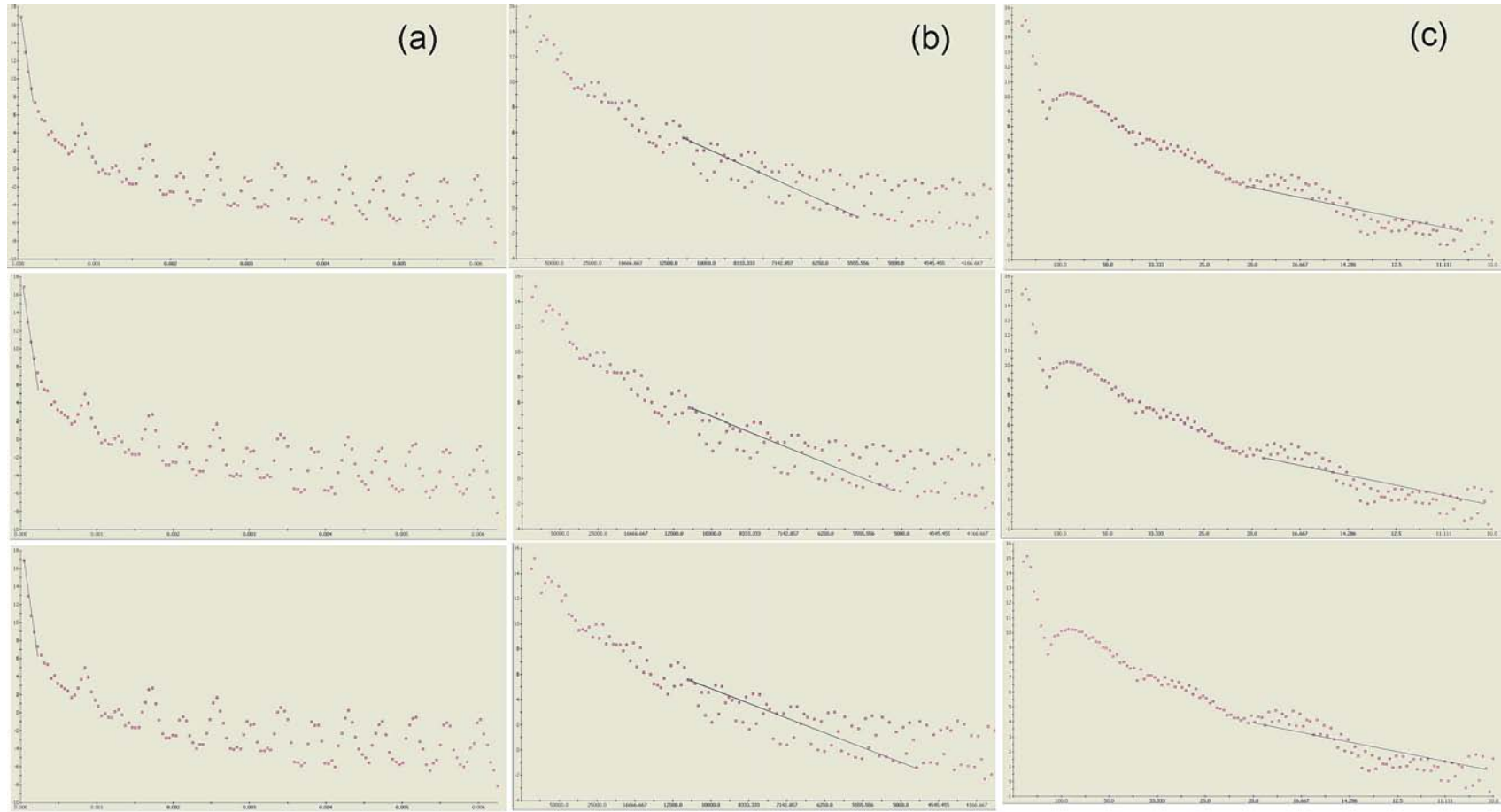


Figure 7. Schematic plots of log power (vertical axis) vs wave number (km^{-1} , horizontal axis) for 80 m grid in column (a), 2000 m grid in column (b) and 5000 m grid in column (c) of the magnetic response over rectangular prism showing, by row, three different slopes an interpreter may pick.

Comparison with Reflection Seismic Model

Reflection seismic data from survey GA-302 over the Capel and Faust Basins was interpreted by Colwell et al. (2010), whose identification of top of basement was corroborated by velocity modelling of sonobuoy data (Petkovic, 2010) and gravity modelling (Petkovic et al. 2011). In this report the depth to magnetic basement over the Capel and Faust basins was derived independently using the spectral analysis method, without constraints from these previous studies, in order to develop and test the method and confirm or negate earlier work.

A comparison of the depth to magnetic basement by spectral analysis and the depth from combined seismic and gravity studies is shown in several reflection seismic profiles in which the magnetic basement depth has been displayed as travel-time horizons (Figure 8 to Figure 11). To effect these displays, the magnetic basement depth (Figure 3) was converted to two-way travel time (blue line in the figures) using the velocity model of Petkovic (2010) and back-interpolated to the seismic sections in the Geoframe™ seismic interpretation environment. For comparison, the top of basement by Colwell et al. (2010) is shown in yellow.

Interpretation of the seismic reflection data and gravity modelling suggests that the layer below the yellow line in Figure 8 to Figure 11, with a modelled maximum density of 2.67 g/cm^3 (Petkovic et al., 2011), represents the pre-rift basement to the basins. The reflectivity pattern from inferred basement is discontinuous and very subtle in many places due to tilting, faulting and folding, and exhibits an inhomogeneous character suggestive of a mix of older sedimentary, igneous and metamorphic rocks (Colwell et al., 2010). In addition, the yellow line is thought to represent an erosional surface that marks initial extension leading up to the opening of the Tasman Sea (Colwell et al., 2010). The sequences both above and below the yellow-lined unconformity show numerous instances of high reflectivity events which are interpreted as due to volcanic sills, dykes or the lava flows. As such, the magnetic source bodies within the study area are fairly random in geometry and distribution, making the area a suitable candidate for the spectral depth-to-basement method.

Depth to magnetic basement of the Capel and Faust Basins

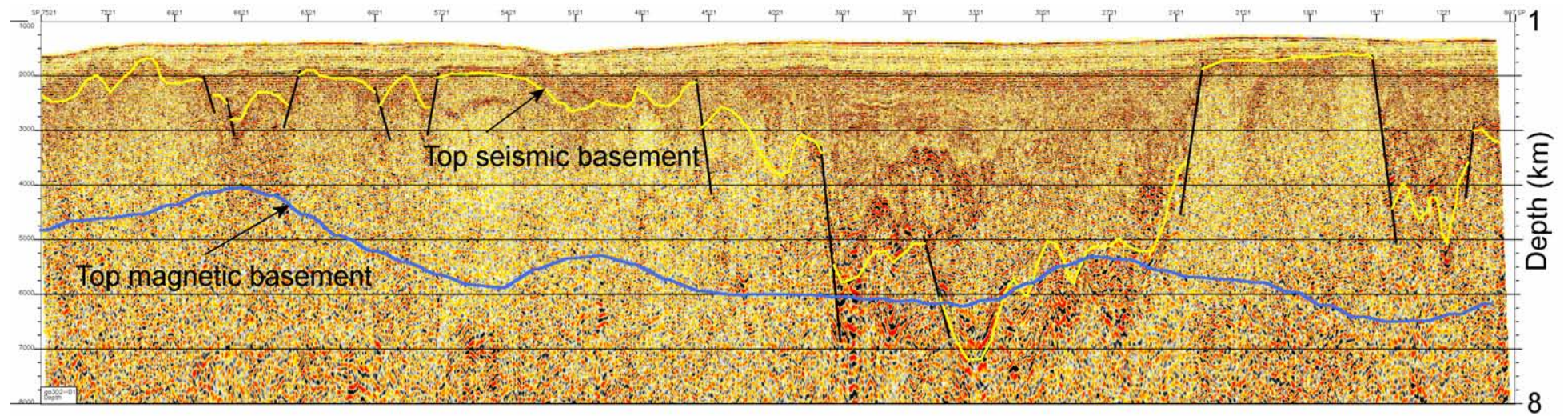


Figure 8. Seismic section along line GA302-10. The top of seismic basement (yellow) and magnetic basement converted two-way travel time (blue) are shown. The line is 244.5 km long and the vertical exaggeration is 9.1.

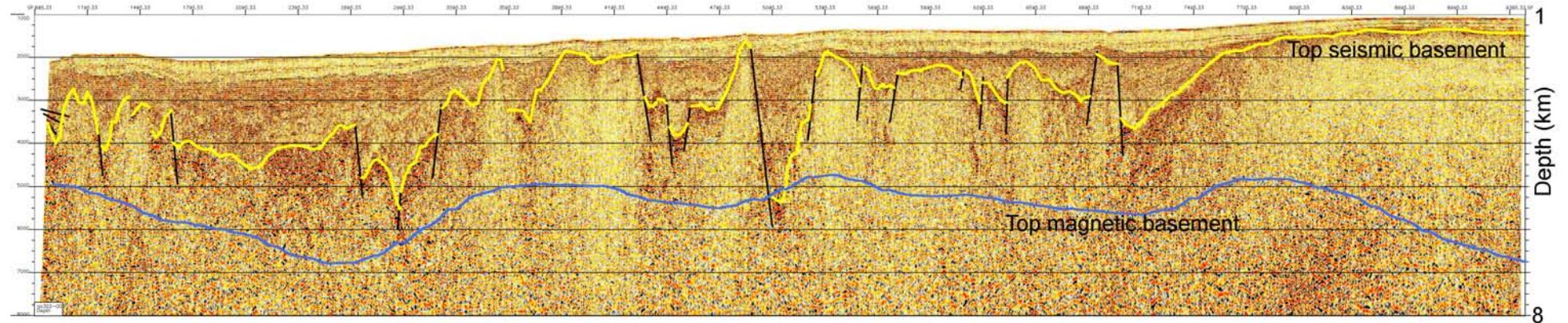


Figure 9. Seismic section along line GA302-03. The top of seismic basement (yellow) and magnetic basement (blue) are shown. The line is 314.4 km long and the vertical exaggeration is 9.1.

Depth to magnetic basement of the Capel and Faust Basins

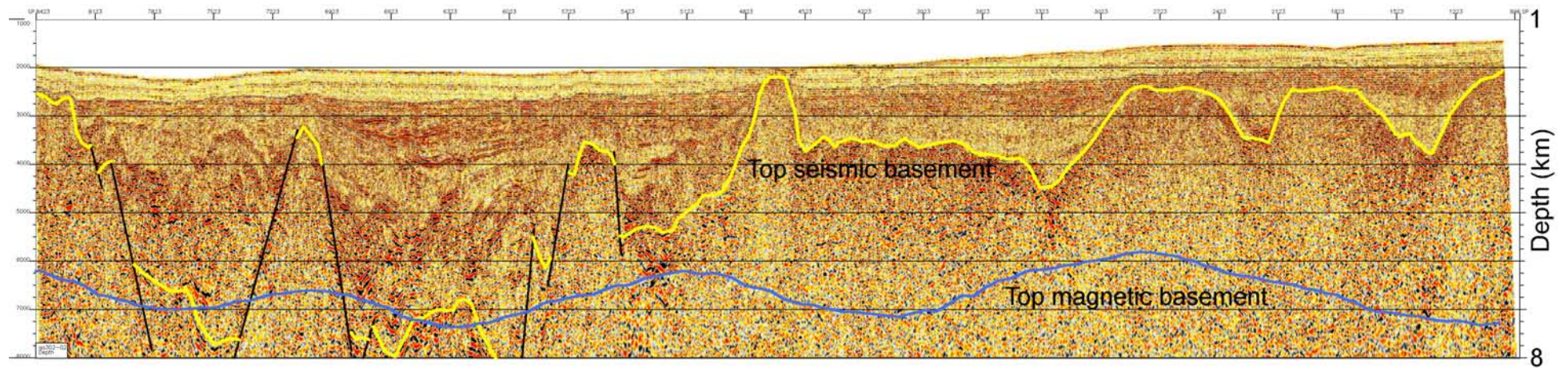


Figure 10. Seismic section along line GA302-20. The top of seismic basement (yellow) and magnetic basement (blue) are shown. The line is 278.3 km long and the vertical exaggeration is 9.1.

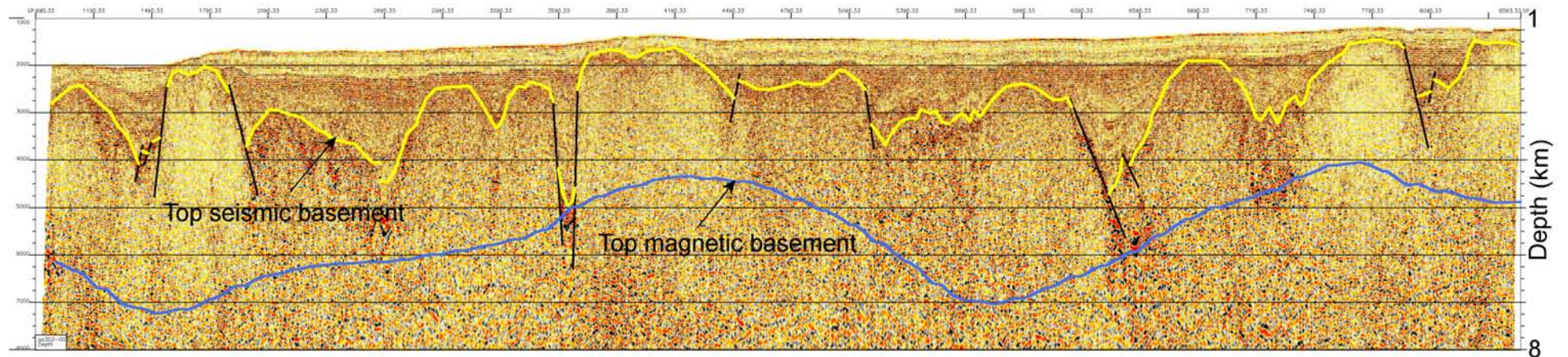


Figure 11. Seismic section along line GA302-05. The top of seismic basement (yellow) and magnetic basement (blue) are shown. The line is 283.6 km long and the vertical exaggeration is 9.1.

In the representative sections shown in [Figure 8](#) to [Figure 11](#) (above) the basement topography determined by the two methods are in agreement only in the deeper part of the section, within the 10% error margin predicted from our synthetic example. For example, in [Figure 8](#) and [Figure 10](#) the depths are approximately the same where the seismic basement horizon is at about 7.2 sec two-way travel time, but at the shallower levels, less than ~5 sec, the two interpretations do not match. Similarly, in [Figure 9](#) and [Figure 11](#) the seismic interpretation of the central basement-high is at shallower level compared to the magnetic basement depth.

The greater depths obtained in general by the spectral method outlined in this report may be due to:

- a) an excessively large grid spacing (5000 m) which is not optimum for picking the shallow magnetic basement surface,
- b) the 0.016 to 0.096 frequency band we considered may not be suitable for a shallower magnetic basement signal, and/or
- c) a lack of magnetic materials in the basement of the central high.

The first two points could be addressed by further work, such as using a variable window size in several passes and developing a better method for automated slope picking of the log power – frequency plots and error analysis. These methods are currently under investigation by Johnston and Petkovic (in prep.). A realistic investigation would require use of high performance hardware combined with fully automated computation for realistic turn-around time, as well as software development as indicated.

It would then be possible to draw geological conclusions on the third point, viz. the degree of magnetisation and intrusion by magnetic rocks into the shallower parts of what has been interpreted as basement by reflection and refraction seismic and gravity methods. It would be an important question to address in order to enhance our understanding of the petroleum potential of these remote frontier basins.

Despite the discrepancies in depth and lateral offsets obtained by the two methods the power spectrum method for determining depth to magnetic basement is able to delineate the top of basement in deeper areas, where the resolution of the seismic is reduced.

Conclusions

The results of the magnetic data analysis over the Capel and Faust basins show that the whole area is divided into a number of sediment depocentres with variable size and shape. The position and dimensions of the main features agree with earlier work based on seismic and gravity methods.

We can make the following conclusions:

- the deepest and most extensive depocenter lies in the northwest of the study area, and
- the maximum sediment thickness in the study area is between 5 and 6 km.

Further work could be done to improve the method outlined in this report and allow more definitive geological conclusions to be drawn.

Acknowledgements

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