Australian Government
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North Perth Basin 2D Gravity Models

Peter Petkovic

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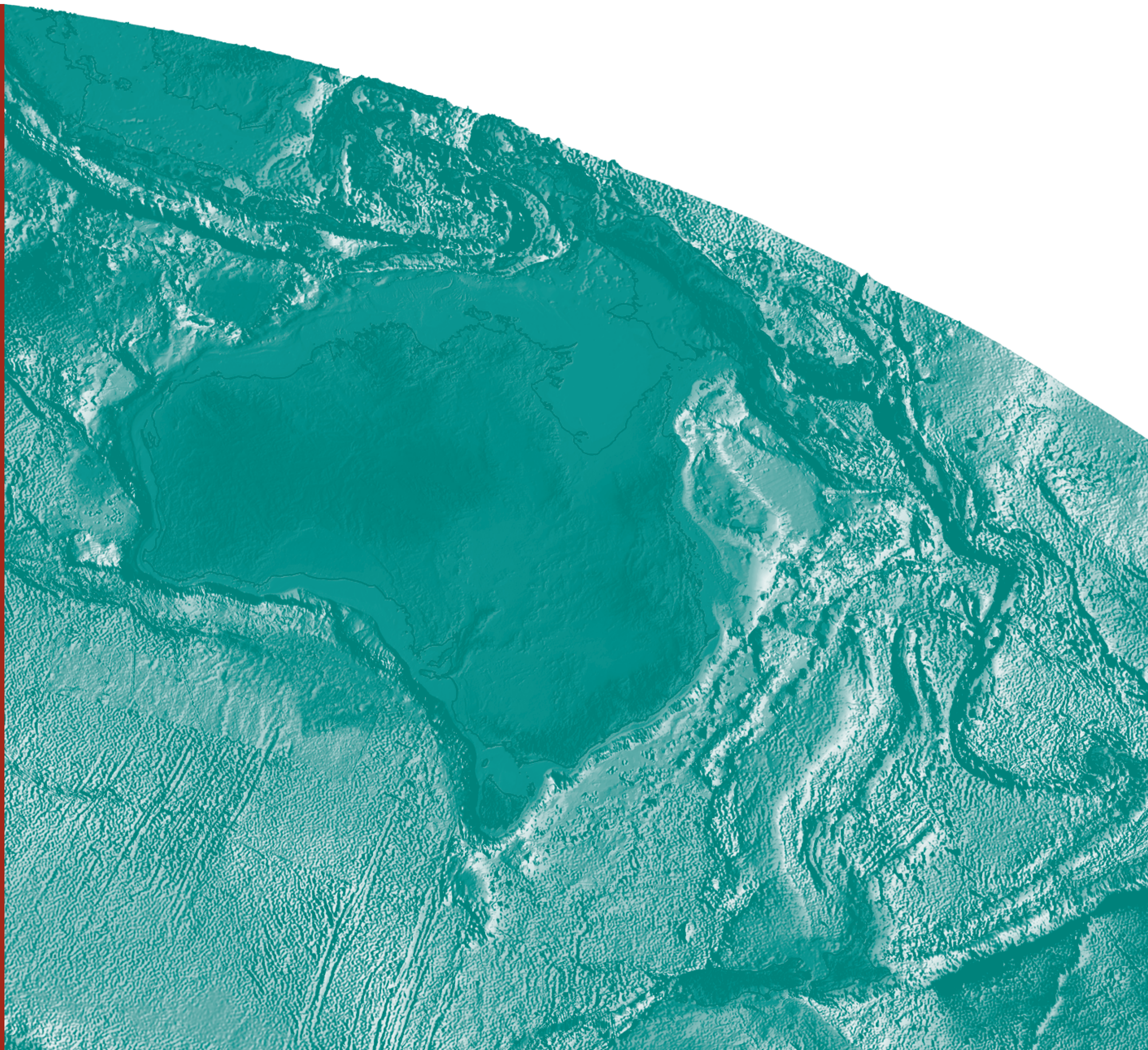

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GEOSCIENCE AUSTRALIA
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by

Peter Petkovic

Australian Government
Geoscience Australia

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Executive Summary

During 2009-11 Geoscience Australia completed a petroleum prospectivity study of the offshore northern Perth Basin as part of the Australian Government's 2007-2011 Offshore Energy Security Program. A significant component of the program was the acquisition of a regional 2D reflection seismic and potential field survey (GA-310) in late 2008 to early 2009.

Basement in the northern offshore Perth Basin is deep and generally not resolved in the reflection seismic data, with very limited basement well control on structrural highs and no basement well control in depocentres. This study models the observed gravity in 2.5D along two southwest trending across margin reflection seismic transects to provide insight into the likely sediment thickness and basement topography. Three cases and ten models are examined according to assumptions about possible target depth to basement and Moho depth. The conclusions are:

- Maximum sediment thickness across the Zeewyck and Abrolhos sub-basins is approximately 12 km.
- The Turtle Dove Ridge models as a basement high near the eastern boundary with the Zeewyck Sub-basin deepening eastwards, beneath 3km of sediment.
- Dense bodies may be present near the sea floor at the southwestern, deep-water end of the profiles.
- A recently published Moho surface from gravity inversion (Aitken, 2010), based on an interpretation of sediment thickness, which is thinner than the current reflection seismic data indicate, is not a suitable model for the study area.
- The 2.5D gravity models along the two chosen profiles do not corroborate the depth to magnetic basement by spectral analysis of Johnston and Petkovic (2012).
- The top of basement is 1-5 km below the visible sedimentary layering interpreted in the reflection seismic data.
- Deep coherent events identified in the reflection seismic data support an alternative shallower Moho along one of the gravity profiles.

These conclusions are tentative and open to further investigation because neither the top of basement nor the Moho — the two principal regional density contrasts aside from the water-sediment interface — are confidently constrained by data other than gravity. The reflection seismic evidence for Moho and top of basement is scant, and depth conversion, in the absence of refraction data, is based solely on seismic stacking velocities.

Introduction

This document outlines the results of gravity models along two transects across the offshore sub-basins of the northern Perth Basin (Figure 1), a thick Paleozoic-Mesozoic rift basin underlain by a deep basement not well imaged in reflection seismic data.

In late 2008 to early 2009, as part of the Australian Government's Energy Security Program (2006–2011), Geoscience Australia acquired 2D reflection seismic and potential field data to assess the prospectivity of deep water frontier regions off the southwest margin of Australia. The survey (GA-310) acquired 7300 km of 2D reflection recorded to 12 s two way time (TWT), as well as some 10000 km of gravity and magnetic data (Foster *et al.*, 2009). This acquisition data set, together with existing industry data, has enhanced our understanding of the basin stratigraphy and structure (Jones *et al.*, 2011). However, due to the thick sediment pile and complex structuring of the basin, reflection seismic data did not image the geologic basement throughout most of the region, defined to be Precambrian. The deepest stratal reflections observable in the seismic data are interpreted to be of Permian strata (Jones *et al.*, 2011; Nicholson and Bernardel, *pers. comm.*). The basement is thought to be Mesoproterozoic and Late Neoproterozoic to Early Cambrian Pinjara Orogen high-grade metamorphic rock (Hall, in prep., Hall *et al.* 2012), outcropping onshore as the Northampton Block (Dentith *et al.*, 1994), or as granites, sampled in wells over the Beagle Ridge (Jones *et al.* 2011). Pre-rift sedimentary strata, immediately overlying basement, are likewise poorly understood, and are speculated to be Late Cambrian to Ordovician sandstones, such as the Tumblagooda Sandstone, which outcrops extensively onshore (Crostella, 2001; Iasky *et al.*, 2003).

Gravity Data

Two marine geophysical and geological surveys by Geoscience Australia in 2008 (GA-310) and 2009 (GA-2476) added 26,000 line km of new marine gravity data to the set of 150 surveys acquired in southwest Australia since 1960. Hackney (2012) integrated these new data with prior compilations (Desmond Fitzgerald and Associates, 1999; Petkovic *et al.*, 2001) to produce a suite of maps extending beyong the area of interest in this study. Figure 1 shows the location of the study area with a background image of the Bouguer gravity residual obtained by subtracting the 25km upward continued field. This effectively removes the longer wavelengths to display the higher frequency components related to shallow density contrasts pertaining to structures such as basins (Zeewyck, Houtman and Abrolhos sub-basins) and basement highs (Turtle Dove Ridge).

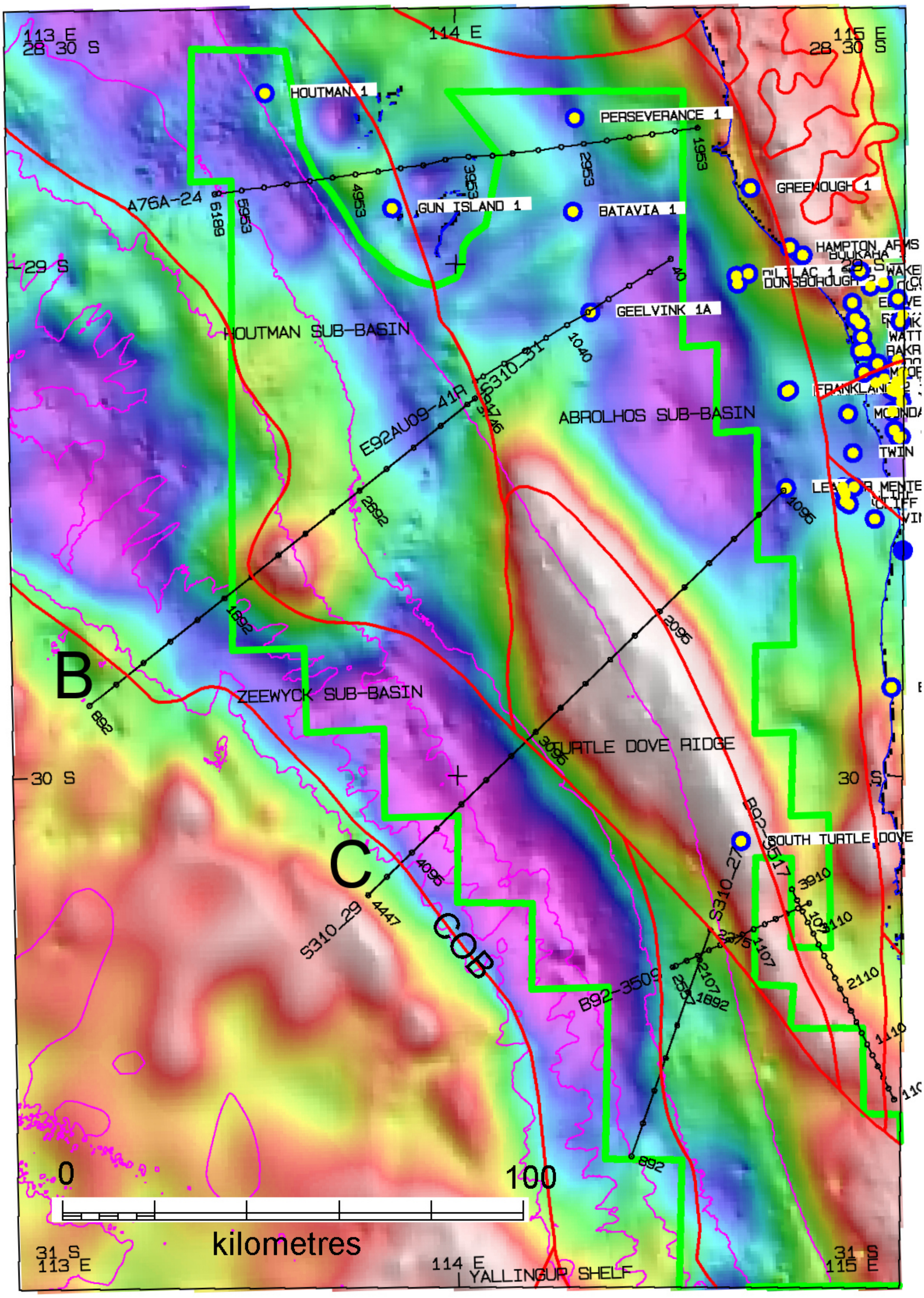

Figure 1. Location of study area in the northern offshore Perth Basin showing petroleum exploration permit area WA11-18 for reference (green), wells (yellow dot), seismic lines modelled (B, C), bathymetric contours (purple), sub-basin boundaries (red) and approximate location of continent-ocean boundary (COB) as western margin of Zeewyck Sub-basin (Hall, in prep.). The base image is residual Bouguer gravity anomaly after subtraction of an upward continuation to 25 km. (Hackney, 2012). Colour is histogram equalised from -40 to +45 mGal.

Modelling Software

Encom's *ModelVision*™ v10 was used for the modelling. This software computes the 3D potential field response of the user's model. The program design favours modelling of mineral environments in which discrete bodies are embedded in a country rock, and is flexible enough to allow the creation of basin style models in simple 2.5D (i.e. a finite strike length and constant cross-section is assumed perpendicular to the profile for all bodies).

The construction of 3D models for basin style work, whilst possible, is laborious as the program requires a build-up of the model by discrete polygonal bodies, that is, as a series of parallel slices of polygonal prisms. For 3D modelling the *3D-GeoModeller* program is preferred, as it is able to compute the 3D horizon map from the observations (i.e. seismic horizon picks).

Reflection Seismic Horizons

A backdrop image of depth converted horizons was used to guide the modelling. The horizons are listed in the table below and shown on two-way travel time reflection seismic sections in Figure 2 and Figure 3.

Table 1. Horizons used in backdrop image to models. All but MoGGIE were mapped in GeoFrame™ (Nicholson, Bernardel and Rollet, *pers. comm*.). 'NAME' is the codified name used in the GeoFrame™ project.

NAME	DESCRIPTION
wb	water bottom
Val	Valanginian regional breakup unconformity
Yarragadee_SB	base Yarragadee SB
lPerm	mid-late Permian regional unconformity
Perm_base	base Early-Mid Permian syn-rift section
base_sect_resol	base of resolvable section, i.e. visibility limit for interpretation of geology (denoted by 'BSR' in figures). Used as a guide to top of basement in some models.
BUS	base of unequivocal sediment. Used as a guide to top of basement in some models.
MoGGIE	Moho after Aitken (2010)

The conversion of interpreted horizons from two-way travel time to depth was achieved via Petrosys software using average velocity to each horizon computed from uncorrected stacking velocities. The horizons were imported to a Petrosys project via direct link to GeoFrame™. A calibration of stacking velocities against interval velocities measured in wells (e.g. Johnston and Goncharov, 2012) was not used to guide 2D modelling, because of the uncertainty of calibration below well depths, as well as the sparse distribution of the wells across the region.

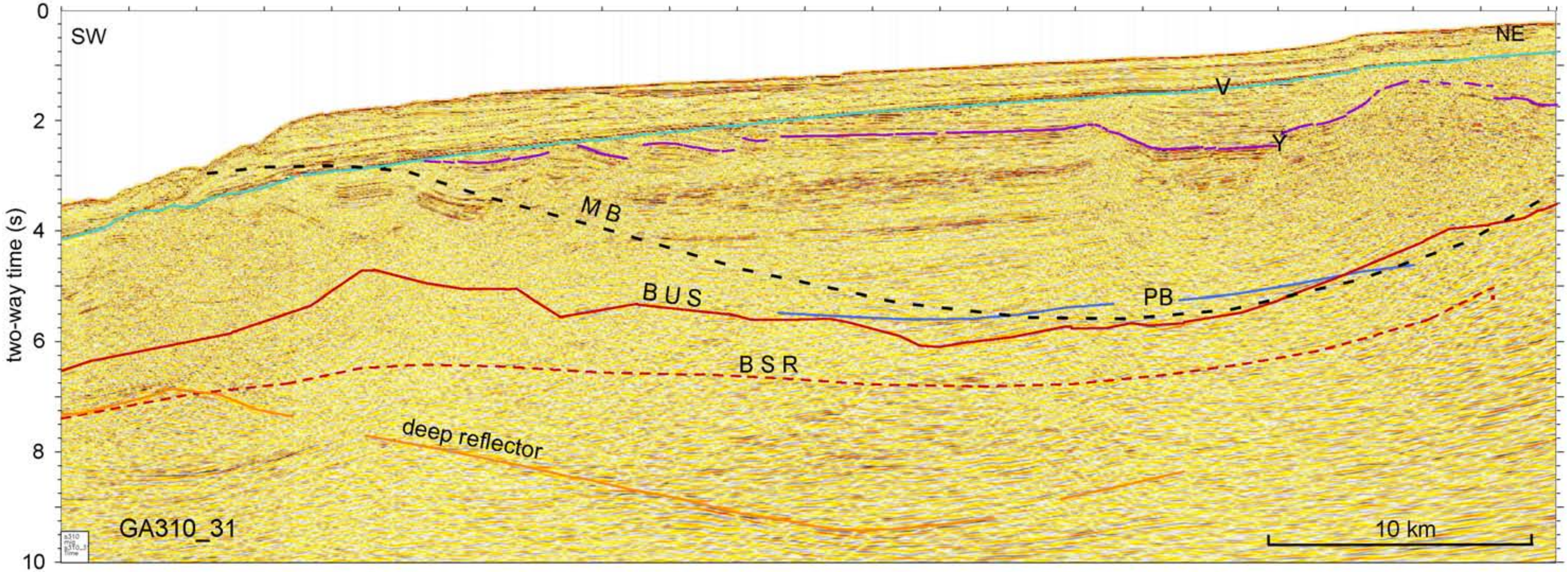

Figure 2. Northeastern portion of profile B (GA310_31) reflection seismic data (shotpoint 2225-3720) across the Houtman Sub-basin showing the top of magnetic sources by the spectral method of Johnston and Petkovic (2012) (MB, dashed line) crossing reflectors from the Valanginian unconformity (V) to base Permian section (PB). Other horizons, for reference, are the base Yarragadee Sequence (Y), base unequivocal sediment (BUS) and BSR.

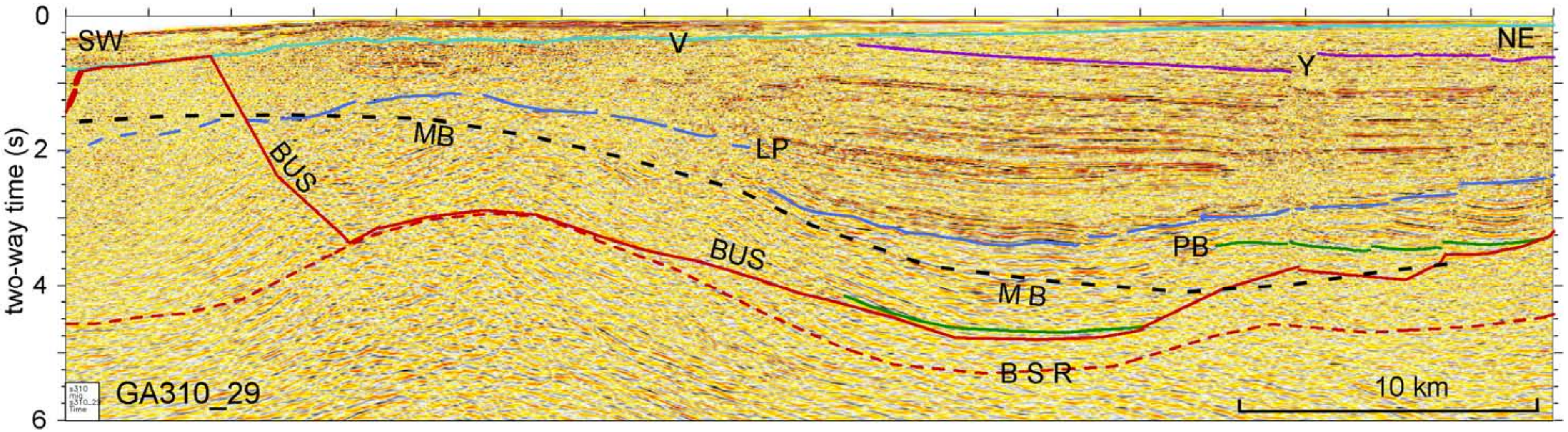

Figure 3. Northeastern portion of profile C (GA310_29) reflection seismic data (shotpoint 1200-2500) across the Turtle Dove Ridge and Abrolhos Sub-basin showing the top of magnetic sources by the spectral method of Johnston and Petkovic (2012) (MB, dashed line) crossing reflectors from the late Permian (LP) unconformity to the base of the Permian section (PB). Other horizons, for reference, are Valanginian unconformity (V) , the base Yarragadee Sequence (Y), base unequivocal sediment (BUS) and BSR.

Models Overview

CHOICE OF PROFILES

The profiles modelled in this study (see Table 2) coincide with reflection seismic lines described by Jones *et al*. (2011). They were also modelled for top of magnetic sources by Johnston and Petkovic (2012) and their nomenclature for profile label (B & C) is retained here.

Table 2. Profiles modelled.

PROFILE	LINE NAME	LENGTH
B	GA310_31 + e92au09-41r	153 km
C	GA310_29	125 km

Each profile crosses the continent-ocean boundary (‘COB’ in the figures) about 10 km from the southwest ends. In the study area, the continent-ocean boundary is approximately the western margin of the Zeewyck Sub-basin, and represents a transition from continental rocks to denser and more magnetised oceanic rocks. The location of the COB, as marked in the figures, has recently been revised by Hall (in prep.).

CASES INVESTIGATED

Three cases were explored with ten models (Table 3 and Figure 4 to Figure 15). The Moho was either Aitken’s (2010) model or an approximate surface to model the long wavelength of the observed gravity. Basement was approximately one of two proposals developed from interpretation of reflection seismic data (Figure 2 and Figure 3) and one from interpretation of 3D magnetic data, as follows:

a) Case ‘BSR’, a ‘base of resolvable section’ from interpretation of reflection seismic data by G. Bernardel and C. Nicholson, (*pers. comm.*),

b) Case ‘MB’, the top of magnetic sources computed using the spectral method applied to 3D magnetic data by Johnston and Petkovic (2012), and

c) Case ‘BUS’, a ‘base of unequivocal sediment’, from interpretation of reflection seismic data by N. Rollet (*pers. comm.*)

MOHO

The Moho is represented in some of the models using the ‘MoGGIE’ model of Aitken (2010). This is an Australia-wide Moho model computed by gravity inversion based in part upon the OZ-SEEBASE™ (FrOG Tech, 2005) depth to basement model. SEEBASE™ is inadequate in the study area because it is several kilometres shallower than our reflection seismic interpretation of the Moho indicates (G. Bernardel, C. Nicholson, and N. Rollet *pers. comm.*). While the continental scale MoGGIE resolves Moho depth to ±3km at wavelengths >200km, it has a resolution of 15 km x 15 km, and fits the observed gravity poorly at the continental margins (Aitken, 2010). Nevertheless, MoGGIE is used, and misfits of observed and computed gravity are noted.

A sub-set of the models ignores MoGGIE and uses an approximate Moho which better attempts to account for the long wavelengths in the observed gravity, assumed due to the density contrast at the Moho and not upper crustal density variations.
Other Moho candidates applicable to Australia were not used. The Moho of Kusznir (2008) extends northwards to just 30°S, truncating the southern profile C, while the Moho of Kennett et al (2011) does not extend reliably offshore .

MODEL DENSITIES

For consistency with MoGGIE, the density profile of Aitken (2010) was used throughout, with values in tonnes/m^3 of: water (1.03), sediments (2.55), upper crust (2.73), lower crust (2.9) and mantle (3.3)[1]. An average sediment density of 2.55 t/m^3 is possibly high, but there are no basin-scale density data to assess the limitation of this assumption. In other areas, a compilation of measurements by Olhoeft and Johnson (1989) give a bulk dry density for sandstone averaging 2.22 t/m^3 with a standard deviation of 0.23 t/m^3. For marine sediments, Klingelhoefer *et al.* (2007) used average sediment densities of 2.4 t/m^3, or less, based on OBS refraction results. Sonobuoy refraction results over the Capel and Faust basins on Australia's eastern frontier indicate basement density of 2.54 t/m^3 and sediment density at 6 km depth of 2.2 - 2.4 t/m^3. Densities measured from sedimentary rocks dredged at 16 locations along the western Australian continental margin during survey GA2476 (Daniell *et al*., 2009) avearged 1.9 t/m^3 (Schmidt, 2012)

The separation of upper and lower crust is not evident in the reflection seismic data for the profiles modelled, so in models of case 'BSR', where a single basement layer is present, a density of 2.9 t/m^3 is used to maintain the density contrast at the Moho of 0.4 t/m^3..

For cases 'MB' and 'BUS' a two-part crust was assumed. Aitken's (2010) upper and lower crustal density was used for basement below horizon 'MB' or 'S' and 'B' respectively.

For consistency with MoGGIE, an average sediment density was set to 2.55 t/m^3, although this figure is possibly high, and there are no basin-scale density data to assess the limitation of this assumption. The compilation of measurements by Olhoeft and Johnson (1989) give a bulk dry density for sandstone averaging 2.22 t/m^3 with a standard deviation of 0.23 t/m^3. For marine sediments, Klingelhoefer *et al.* (2007) used average sediment densities of 2.4 t/m^3, or less. Refraction results over the Capel and Faust basins on Australia's eastern frontier indicate basement density of 2.54 t/m^3 and sediment density at 6 km depth of 2.2 - 2.4 t/m^3.

CASE 'BSR'

In this set of models (Figure 4 to Figure 7) the top of basement is denoted 'B', and approximates the GeoFrame™ project horizon *base_sect_resol*, the base of resolvable section (Bernardel and Nicholson, *pers. comm.*). This surface does not necessarily correlate with the base of sediments, and in some cases marks the base of coherent events below packages of seismic reflections suggesting sedimentary stratification.

The gravity modelling is, therefore, problematic without a clear geological hypothesis to test. Nevertheless, *base_sect_resol* was used as a guide to modelling the top of basement in the gravity models for this case. The horizon 'B' also follows the top of magnetised bodies from the 2.5D magnetic modelling of Johnston and Petkovic (2012), because these bodies are given the same density as the basement in which they are embedded.

[1] one tonne/m^3 = 1000 kg/m^3 in standard units

CASE 'MB'

In a second set of models (Figure 8 and Figure 10) the top of basement is a surface labelled 'MB' (Johnston and Petkovic, 2012) which is the top of magnetic sources as computed by the spectral method (Spector and Grant, 1970). In this method, the depth to randomly distributed simple sources within a spatial window of magnetic total field data is computed from the rate of change of logarithms of azimuthally averaged power spectrum, for those portions of the power spectrum where straight lines can be fitted. Where several straight-line segments were identified on any power spectrum (hence permitting several depths), Johnston and Petkovic (2012) used gravity data as a qualitative guide to selecting a shallow, intermediate or deep solution. The solutions from many overlapping windows were smoothly gridded to produce a "depth to magnetic basement" and presented a new case to test by gravity modelling. This is shown as a smooth curve in all cases several kilometres shallower than either *base_sect_resol* or its approximation 'B'. In these cases 'MB' is taken as the top of an upper crust of density 2.73 t/m^3, while 'B' is top of a lower crust of density 2.9 t/m^3 (Aitken, 2010).

CASE 'BUS'

In a third set of models (Figure 12 to Figure 15 the top of basement is labelled 'S' which approximates *base_unequivocal_sediment* (N. Rollet, *pers comm.*), the base of the sedimentary section to a high degree of confidence, and is a shallower interpretation than *base_sect_resol* (approximated by 'B' in the model of previous cases). In these models 'S' is taken as the top of an upper crust of density 2.73 t/m^3 while 'B' is the top of a lower crust of density 2.9 t/m^3 (Aitken, 2010).

The three models are listed in Table 3, showing the RMS misfit between computed and observed fields for free-air gravity and magnetic anomaly. The latter is from Johnston and Petkovic (2012) and is shown for reference only. Using MoGGIE generally gives a poor fit in the gravity models. The exception is when MoGGIE is combined with 'BUS' in profile C (Figure 14). However, the good fit for this model is achieved by the introduction of a high density body near the sea floor at the southwestern end, proximal to the continent-ocean bounday (Figure 1) and with a density consistent with mantle or igneous intrusions.

Table 3. RMS misfit of computed to observed free-air gravity and magnetic anomaly for profiles B (GA310-31+e92au09-41r) and C (GA310-29) in five variations for each. 'MoGGIE' signifies the Aitken (2010) Moho; 'no MoGGIE' ignores MoGGIE and uses an approximate Moho for best regional fit; '+MB' uses top of basement as depth to magnetic sources by spectral method (Johnston and Petkovic, 2012); '+BUS' uses top of basement near horizon *base_unequivocal_sediment*. Gravity units (gu) are µm/s^2.

FIG	PROFILE	CASE	VERSION	MISFIT (GRAV, gu)	MISFIT (MAG, nT)
2	B	BSR	MoGGIE	34.6	2.1
6	B	MB	MoGGIE+MB	26.9	3.3
3	B	BSR	no MoGGIE	4.3	2.5
12	B	BUS	MoGGIE+BUS	30.6	3.1
13	B	BUS	no MoGGIE+BUS	4.2	3.2
4	C	BSR	MoGGIE	16.3	1.6
8	C	MB	MoGGIE+MB	16.0	2.9
5	C	BSR	no MoGGIE	1.6	2.0
14	C	BUS	MoGGIE+BUS	3.3	2.5
15	C	BUS	no MoGGIE+BUS	1.7	2.3

It is also evident from Table 3 that the 'MB' case is a better fit then the 'BUS' case for profile B, but much poorer for profile C.

The use of an approximate Moho in place of MoGGIE reduces the misfit in each case, but no conclusion can be drawn from this observation as there is no control on Moho. The poor fit of the MoGGIE cases may be attributed to the use by Aitken (2010) of SEEBASE™ (FrOG Tech, 2005) for sediment thickness. Geoscience Australia interpretation of the reflection seismic data in the study area show a greater thickness than SEEBASE (G. Bernardel, C. Nicholson, N. Rollet, *pers. comm.*). The Moho control points nearest to the study area are listed in Table 4:

Table 4. Moho depths nearest to the study area, all located outside the bounds of Figure 1.

REFERENCE	MOHO DEPTH (KM)	LONGITUDE	LATITUDE
Francis and Raitt (1967)	11.4	111.5200	-29.7000
Dentith *et al.* (2000)	35.9	116.2577	-30.9882
Dentith *et al.* (2000)	36.6	116.0250	-32.0683
Mathur (1974)	44.4	116.0536	-32.6344
Clitheroe *et al.* (2000)	36.0	115.9054	-26.5835
Clitheroe *et al.* (2000)	36.0	116.8480	-29.9164

The Models

CASE 'BSR'

The Moho in the Profile B model shown in Figure 4 is based on MoGGIE (Aitken, 2010) with top of basement (B) near BSR and across the tops of the magnetised bodies (Johnston and Petkovic, 2012). These bodies have the same density as the basement in which they are embedded, but are shown as separate entities whose modelled magnetic response is also shown against the observed magnetic field. The gravity response differs from the observed free-air gravity by an RMS of 34.6 $\mu m/s^2$. This is not unexpected as Aitken (2010) developed MoGGIE by gravity inversion using top of basement as SEEBASE™, which is shown considerably shallower than the reflection seismic interpretation of sediment thickness down to BSR (G. Bernardel, C. Nicholson, *pers. comm.*).

It is expected that the fit of computed to observed gravity can be improved by abandoning MoGGIE and applying an approximate Moho which accounts for the long wavelength features in the observed field (Figure 5). Considerable lateral density variation is required at the southwestern end of the profile in order to achieve the close fit as shown, which in the model is entirely incorporated by variation in Moho depth.

The case of Figure 4 is repeated in the southern profile C (Figure 6) where the misfit is less at an RMS of 16.3 $\mu m/s^2$. Again, note that MoGGIE was based on SEEBASE, which is considerably shallower than the reflection seismic data suggests for sediment thickness (G. Bernardel, C. Nicholson, *pers. comm.*), and that it breaks through to the sea floor near the centre of the profile.

As for profile B (Figure 5) the gravity fit can be significantly improved by abandoning MoGGIE in favour of an approximate Moho accounting for the long wavelength components of the observed free-air gravity field (Figure 7).

The gravity and seismic signatures for the BSR case seem to indicate that there exist lateral density variations, which are modelled by variations in Moho depth only. MoGGIE does not appear to be a good representation of Moho along these profiles, perhaps due to its basis in SEEBASE, which is considerably different from sediment thickness mapped from the reflection seismic data.

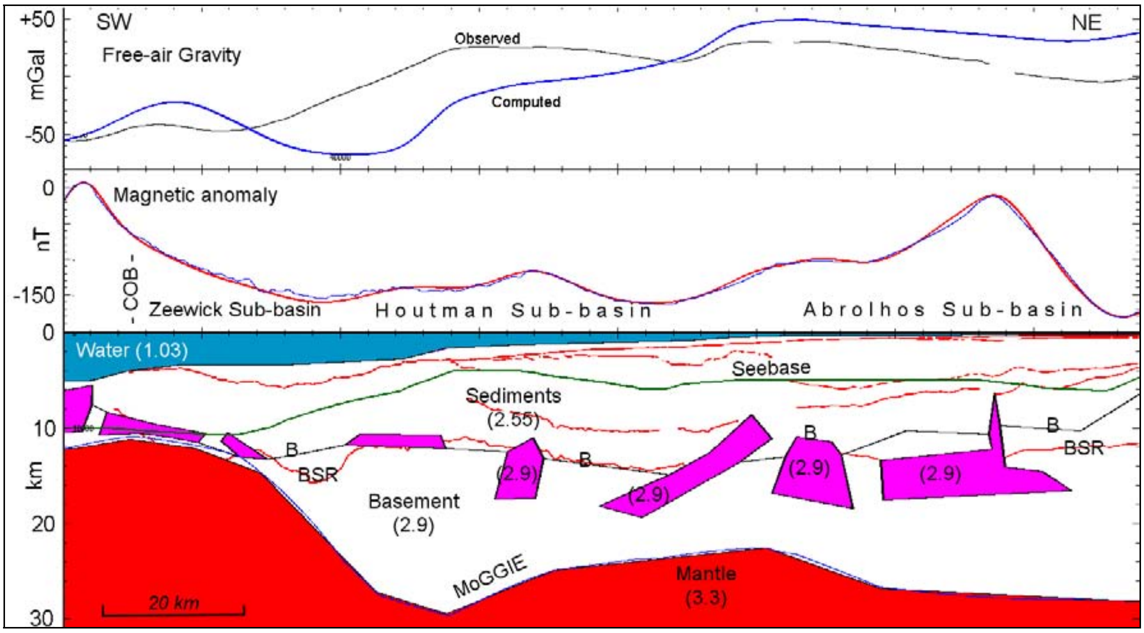

Figure 4. Profile B density model following MoGGIE for Moho and densities after Aitken (2010). The magnetised bodies (purple) have density 2.9 t/m^3. 'B' is top of basement close to seismic horizon *base_sect_resol* (BSR). SEEBASE is shown in green. COB is approximate location of continent-ocean boundary (Hall, in prep.).

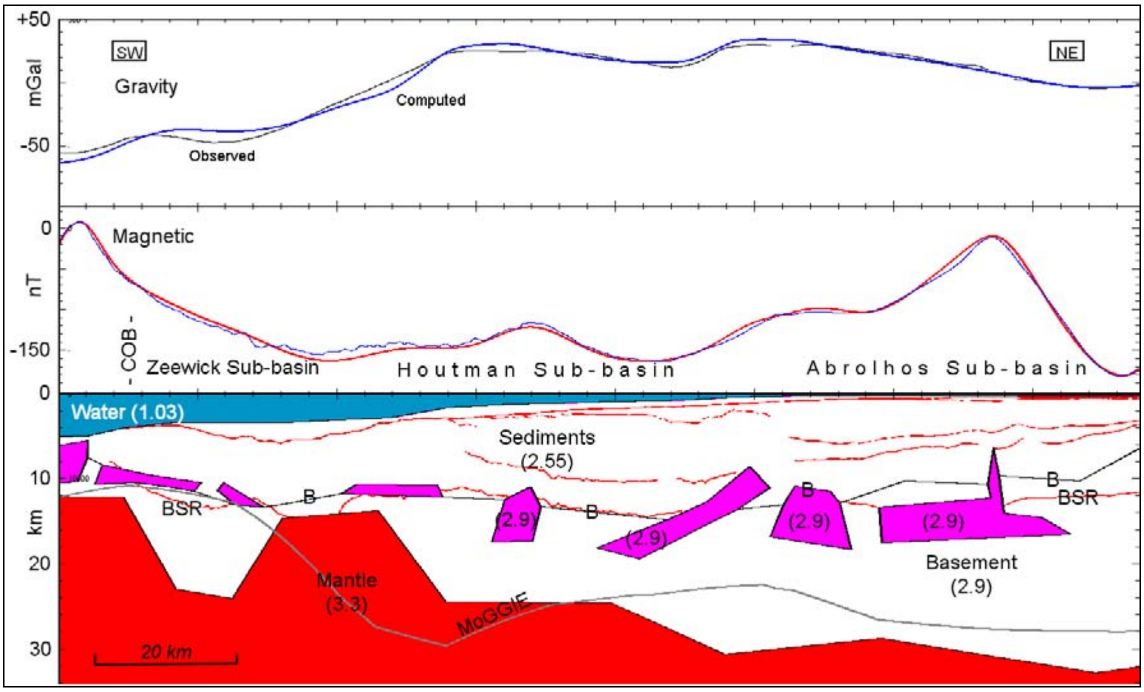

Figure 5. Profile B density model with Moho deviated from MoGGIE (Aitken, 2010) to match computed with observed gravity. The magnetised bodies (purple) have density 2.9 t/m^3. 'B' is top of basement close to seismic horizon *base_sect_resol* (BSR). COB is approximate location of continent-ocean boundary.

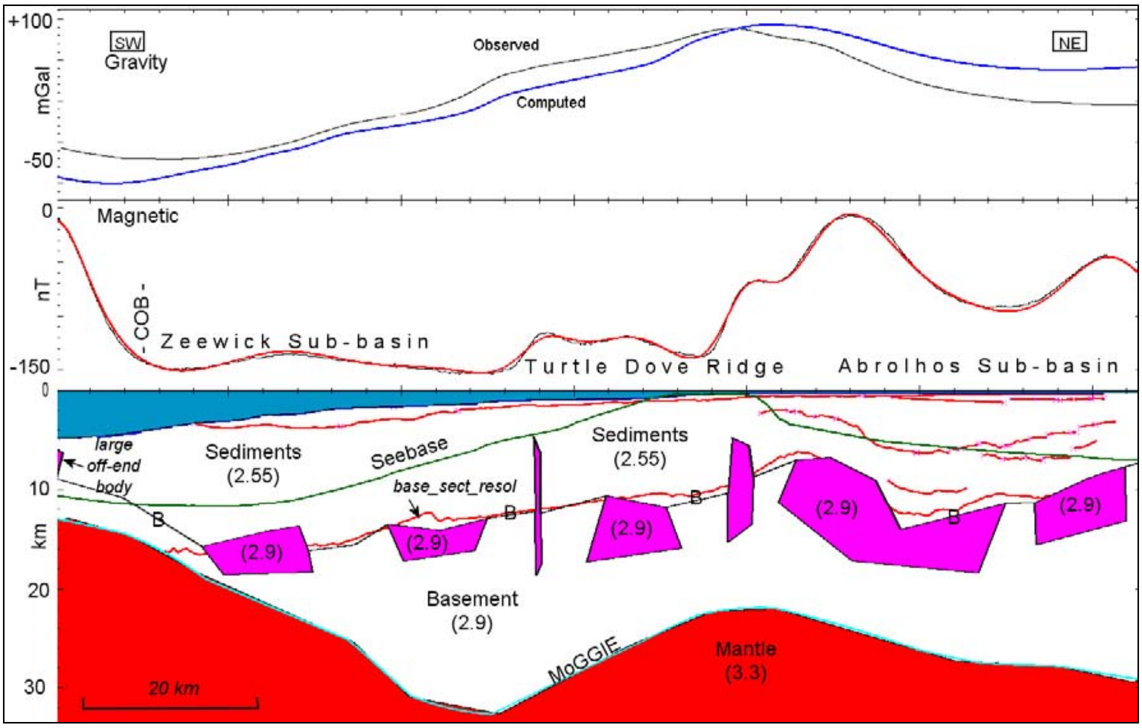

Figure 6. Profile C density model using MoGGIE for Moho and densities after Aitken (2010). The magnetised bodies (purple) have density 2.9 t/m^3. 'B' is top of basement close to seismic horizon *base_sect_resol* (BSR). SEEBASE is shown in green. COB is approximate location of continent-ocean boundary. 'A' is large off-end magnetised body.

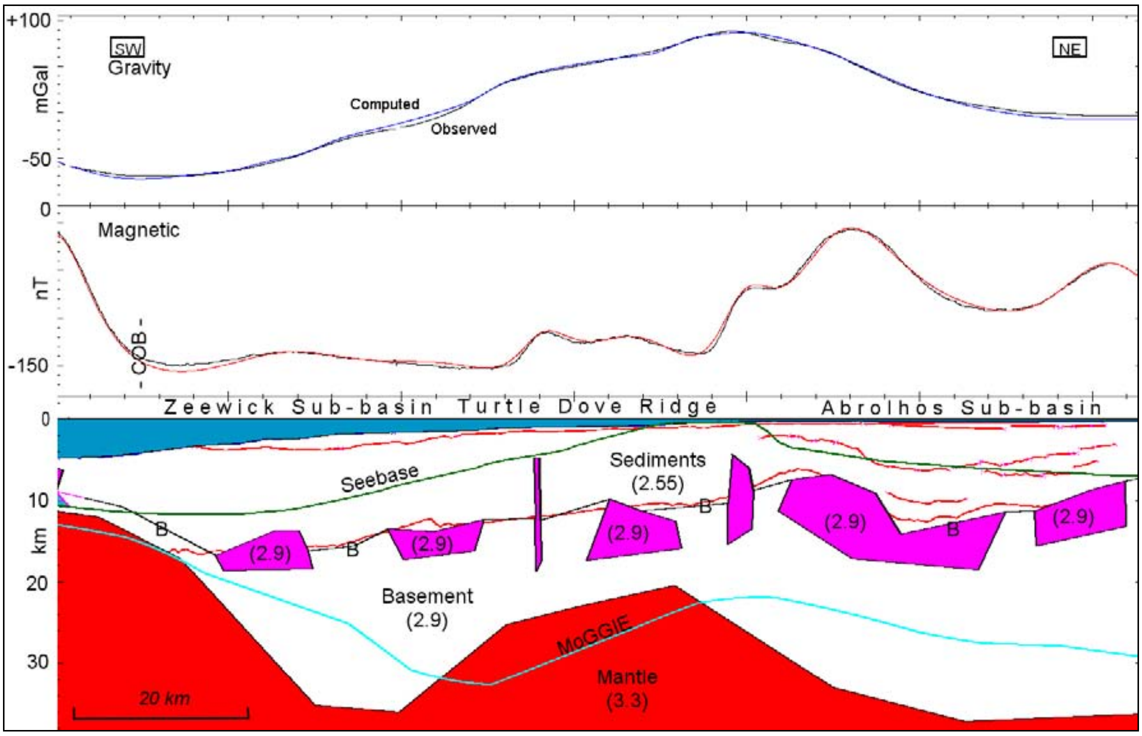

Figure 7. Profile C density model with Moho deviated from MoGGIE (Aitken, 2010) to match computed with observed free-air gravity. The magnetised bodies have density 2.9 t/m^3. 'B' is top of basement close to seismic horizon *base_sect_resol* (BSR). SEEBASE is shown in green. COB is approximate location of continent-ocean boundary.

CASE 'MB'

The depth to magnetic basement surface of Johnston and Petkovic (2012) intersects with profiles B and C as the smooth trace 'MB' in Figure 8 and Figure 10, respectively. Surface 'MB' is shallower than 'B' by 2-8 km and is closer to SEEBASE (FrOG Tech, 2005) than to 'B' (*base_sect_resol* from reflection seismic interpretation). For this reason the two models for case 'MB' use MoGGIE for Moho, and an approximate Moho is not tested. In addition, the horizon 'B' is retained as the top of a lower crust (including magnetised bodies), of density 2.9 t/m^3, and the portion of basement between 'B' and 'MB' is given a density 2.73 t/m^3, as used by Aitken (2010) for the upper crust.

The misfit between observed free-air gravity and gravity response of the two models is a slight, though not significant, improvement on case BSR with MoGGIE Moho. For both profiles there is a mass excess over the northeast regions relative to the southwest.

On profile B (Figure 8) the mass deficiency over the basement high southwest of the middle of the line coincides with a deepening of MoGGIE Moho to 30 km. On the basis of this model, it seems that the mass deficiency in this region can most simply be reduced by a shallowing of the Moho and reducing or eliminating the crustal root. In fact there is some evidence to support this proposal based on the existence of a deep event identified as a structural high in the reflection seismic data (Figure 9) which could be interpreted as elevated Moho (N. Rollet, *pers. comm.*). This possibility is explored in Figure 13 (Case 'BUS', profile B, next section) where the Moho elevated to the deep reflector is sufficient to account for the mass deficit indicated by the gravity and MoGGIE in this region. This mass concentration in the deep crust supported by the lithosphere between the Zeewyck and Houtman sub-basins is clearly imaged as a localised circular positive gravity anomaly on profile B (Figure 1). A similar feature in Scotland is described by Bott and Tantrigoda (1987) as a mafic intrusive complex. A future refraction study would be informative, and may help to identify its cause.

The mass excess over the northeastern portion of profile B can not be reduced simply by increasing the depth to Moho, as it appears to be close to the depth predicted from the 'AusMoho' seismological model of Kennett *et al.* (2011). An alternative is to increase the sediment thickness by increasing the depth to basement. There is some scope for this as BUS (*base_unequivocal_sediment*) is somewhat deeper than either SEEBASE or MB, which are in agreement at the northeastern end of the line (Figure 9).

The gravity response of the 'MB' case for Profile C with MoGGIE Moho is a better fit for observed gravity than profile B, while still exhibiting a mass excess in the northeast and a mass deficit in the southwest (Figure 10). There is a +450 $\mu m/s^2$ and -300 $\mu m/s^2$ difference in observed minus computed gravity at the southwest and northeast ends of the profile, respectively. As can be seen in Figure 11 there is sufficient scope for moving uncontrolled basement and Moho horizons in order to reduce the misfit, so it is not clear what conclusions can be drawn from the model.

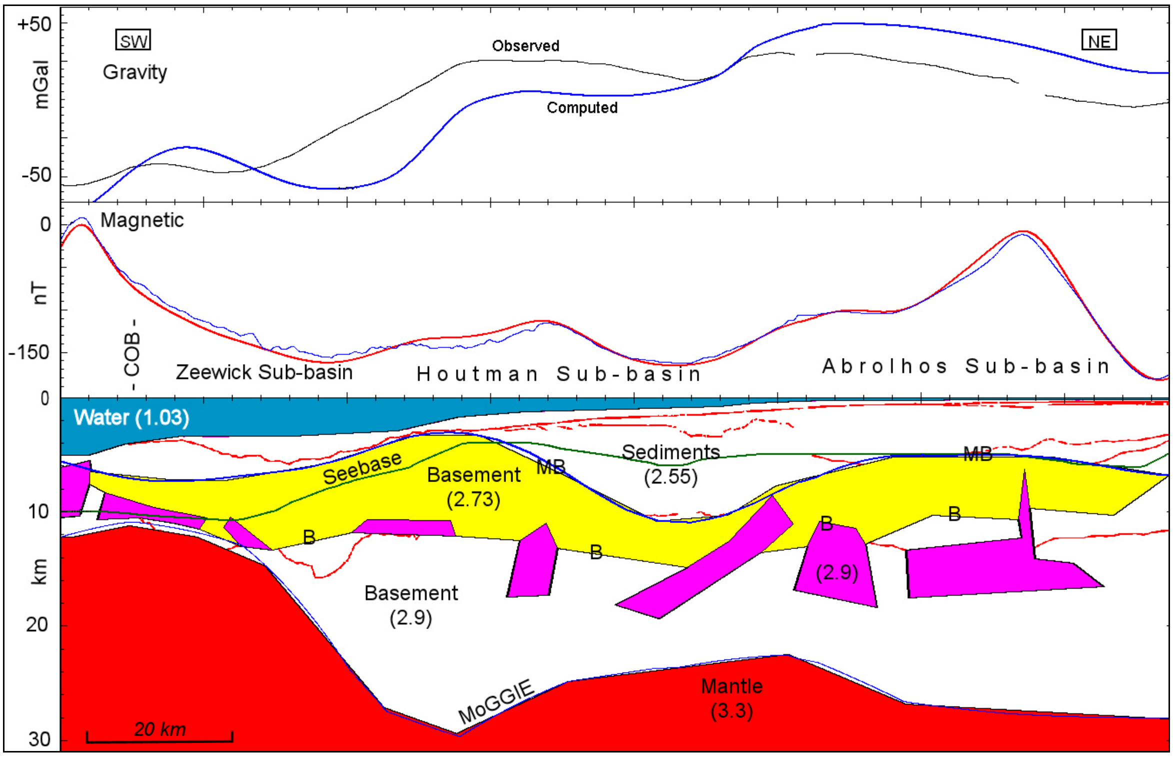

Figure 8. Profile B density model following MoGGIE for Moho and densities after Aitken (2010) with top of basement or upper crust (yellow) at 'MB' (Johnston and Petkovic, 2012), and top of deep basement or lower crust at 'B'. The magnetised bodies (purple) have the same density as the lower crust (2.9 t/m^3). The top of basement used to derive MoGGIE is also shown as 'Seebase' (green). COB is approximate location of continent-ocean boundary.

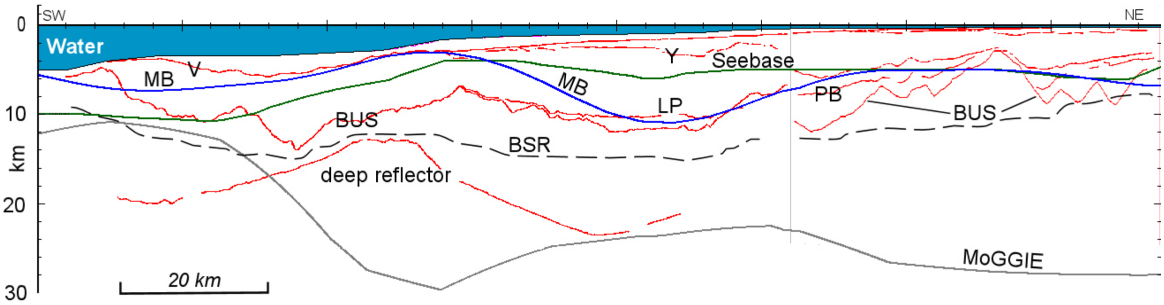

Figure 9. Profile B showing the relationship of MB with other surfaces, Seebase, BUS, BSR and MoGGIE against a background of other reflection seismic events: V=Valanginian unconformity; Y=base Yarragadee Sequence; and PB=base Permian section.

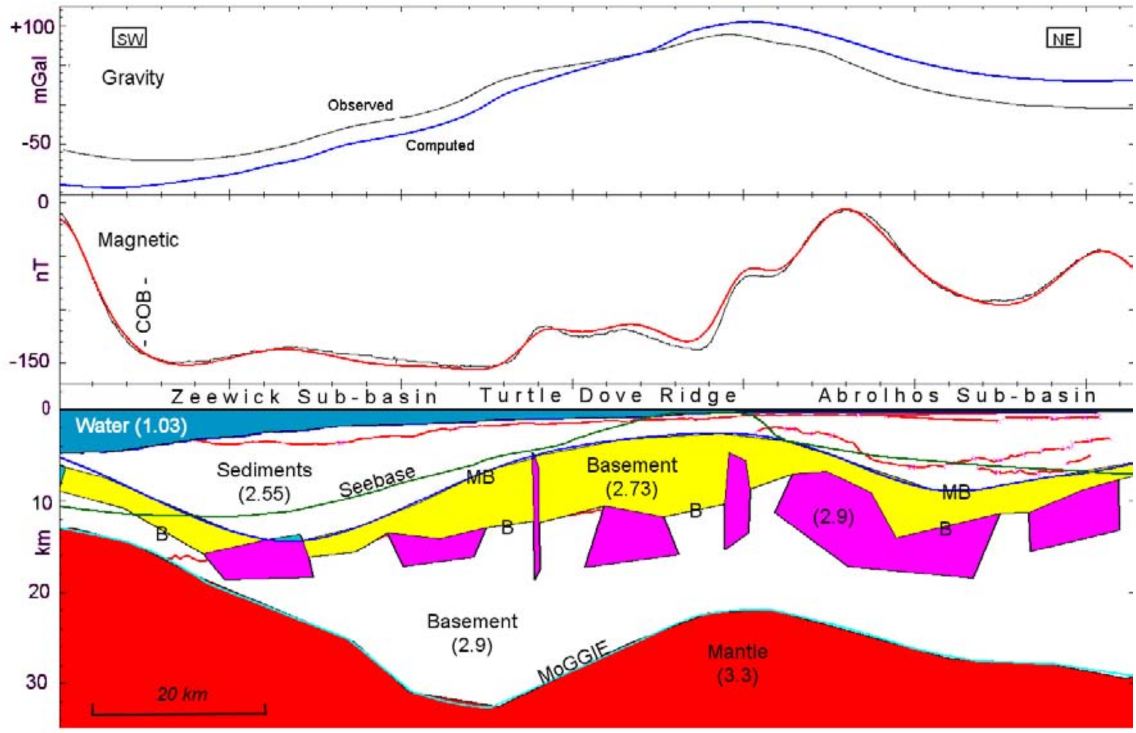

Figure 10. Profile C density model following MoGGIE for Moho and densities after Aitken (2010) with top of shallow basement or upper crust at 'MB' (Johnston and Petkovic, 2012), and top of deep basement or lower crust at 'B'. The magnetised bodies have density 2.9 t/m^3. The top of basement used to derive MoGGIE is also shown as 'Seebase' (green). COB is approximate location of continent-ocean boundary.

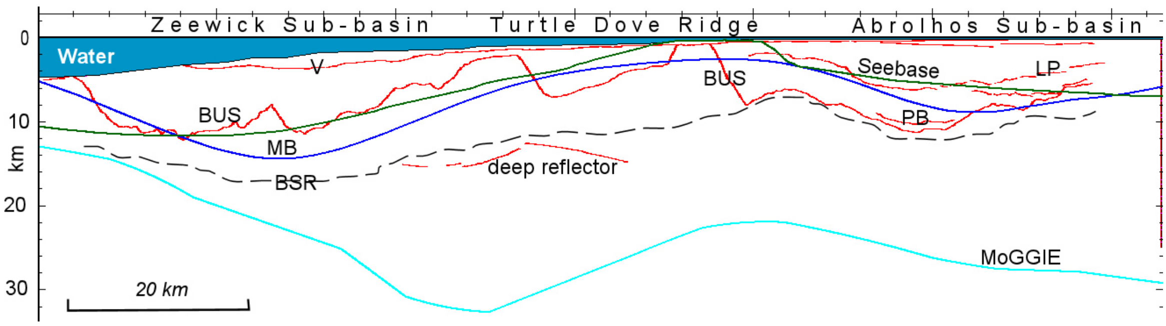

Figure 11. Profile C showing the relationship between MB and other surfaces, Seebase, BUS, BSR and MoGGIE against a background of other reflection seismic horizons: V=Valanginian unconformity; LP=Late Permian unconformity; and PB=base Permian section.

MB and Seismic Data

There is also a question about whether 'MB' can be supported by the reflection seismic data. In Figure 9 and Figure 11 'MB' is found mostly above 'BUS' (i.e. confidently within sediments) but crossing mapped horizons from the shallowest Valanginian to the the base of the Permian section. The reflection seismic data and superimposed interpreted horizons for profile B (G. Bernardel and C. Nicholson, *pers. comm.*) are shown in Figure 2. 'MB' crosses sedimentary reflectors from 0.2 s TWT below sea floor at the southwestern end to 4.5 s TWT below sea floor at the deepest point.

Figure 3 is a corresponding image from a portion of profile C where 'MB' is again seen crossing sedimentary reflectors from above the Lower Permian to below the base Permian.

In these two examples (Figure 2 and Figure 3) the reflection seismic data do not support the 'MB' of Johnston and Petkovic (2012) as a surface representing the geological entity magnetic basement, prompting the questions:

- What are the upper and lower confidence bounds about the surface 'MB'?
- Is it valid to represent solutions of spectral analysis of overlapping but discrete windows as a surface?
- Was the window of suitable dimensions to capture random source distribution in each window?
- Is a constant window size a suitable choice for a study area of this size?
- How did gravity-guided selection of depths, in cases of multiple solutions per window, influence the topology of 'MB'?

CASE 'BUS'

In this category there are two models for each profile, using MoGGIE for Moho in one and an approximate Moho in the other (Figure 12 to Figure 15). As in case 'MB' there is a two-part crust below sediments using densities after Aitken (2010). The base of sediments (labelled 'S') is close to, but below, BUS (*base_unequivocal_sediment*). The top of the lower crust ('B') is close to BSR (*base_sect_resol*), as previously. Between 'S' and 'B' is basement with a density of 2.73 t/m^3. Below 'B' is basement (or lower crust) with density 2.9 t/m^3 down to the Moho.

Profile B with MoGGIE Moho is shown in Figure 12. There is a poor fit of modelled to observed gravity, again with mass excess in the northeast and mass deficit to the southwest, and the position of Moho seems to be the primary candidate for modification.

When MoGGIE is abandoned for an approximate Moho which accounts for the long wavelength components of the observed gravity field, together with some modifications in top of basement, a much improved fit can be achieved (Figure 13). The crust is thickened in the northeast to reduce the overall mass excess. In the middle of the southwestern half of the profile the crustal root is largely removed and both the top of basement and Moho are shallower. There is some evidence in the reflection seismic data to justify the inversion of the crustal root to a mantle high, where the elevated Moho approximately corresponds to a deep reflector noted by N. Rollet (*pers. comm.*). The area of elevated Moho and basement divides the Zeewyck and Houtman sub-basins and coincides with a circular gravity residual high at longitude 113.5°E and latitude 29.6^{o}S (Figure 1). The model mantle is very shallow at the southwestern end of the profile, though not shallow enough, and the magnetised body at the extreme southwestern end has been given a mantle density in order to better match the observed gravity.

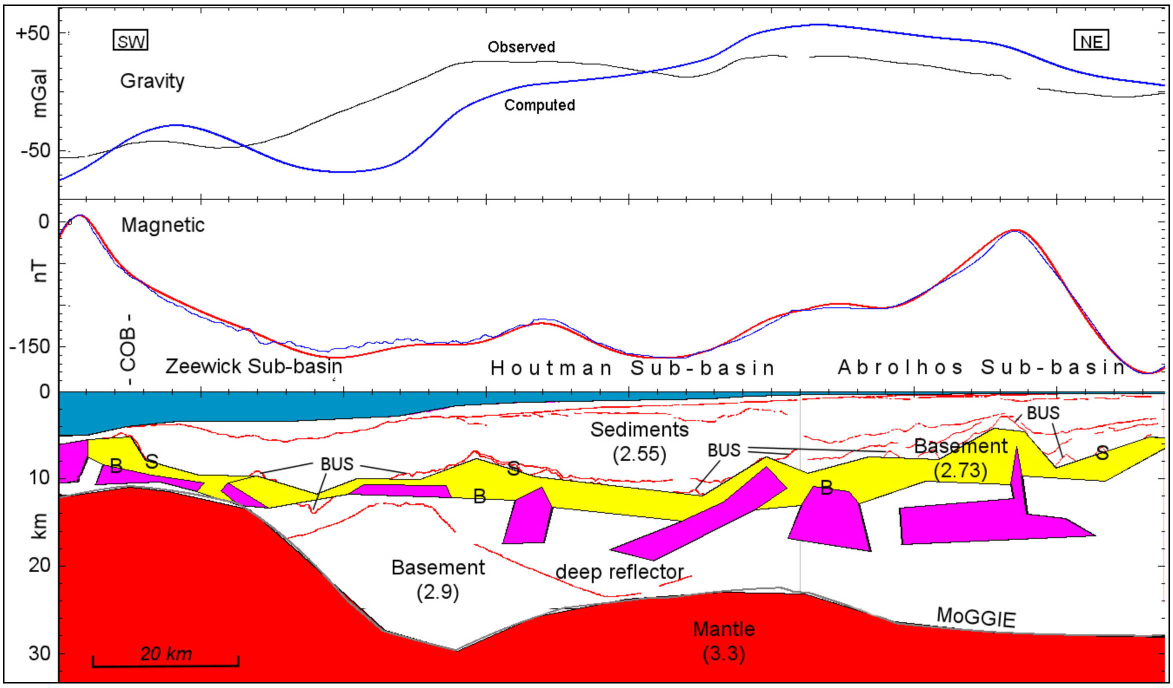

Figure 12. Profile B density model showing *base_unequivocal_sediment* (BUS) and a two-part crust. Basement (yellow) has the same density as Aitken's (2010) upper crust (2.73 t/m^3). The top of basement is modelled close to BUS. The top of the lower basement (B) is close to *base-sect_resol*, and includes tops of magnetised bodies in previous images. The Moho is after Aitken (2010).

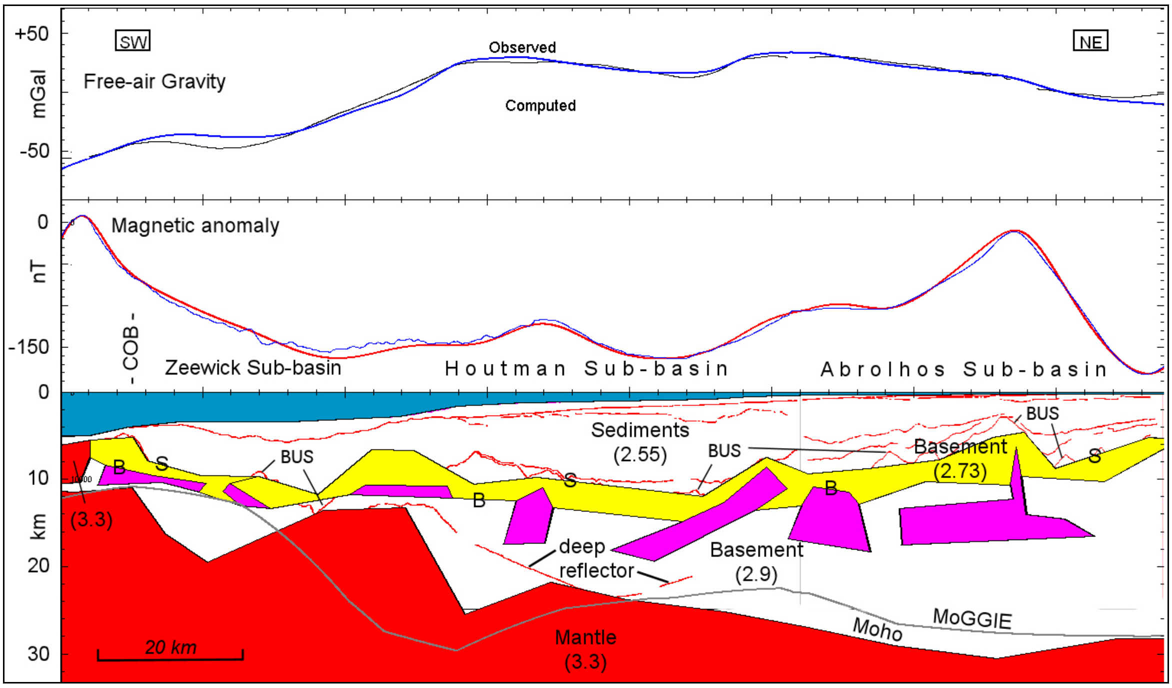

Figure 13. Profile B density model with approximate Moho showing *base_unequivocal_sediment* (BUS). Basement (yellow) has the same density as Aitken's (2010) upper crust (2.73 t/m^3) and the top of basement is modelled close to BUS. The lower basement has the same density as Aitken's (2010) lower crust of 2.9 t/m^3 and the magnetic bodies have the same density. MoGGIE is shown for reference. Note the placement of a high density body at the southwest end of the line. COB is continent-ocean boundary.

The final two figures are for profile C. Figure 14 depicts a model using MoGGIE for Moho and a close fit of modelled to observed gravity. However, to achieve this, a non-magnetic body of mantle density is placed close to the surface, but below BUS, at the southwest end of the line at the continent-ocean boundary, and a basement high is modelled above the crustal root. The already good fit can be improved by minor modification of the long wavelength component of the field by adjusting Moho (Figure 15), which also avoids the need for a shallow body of density 3.3 t/m^3 at the southwest end.

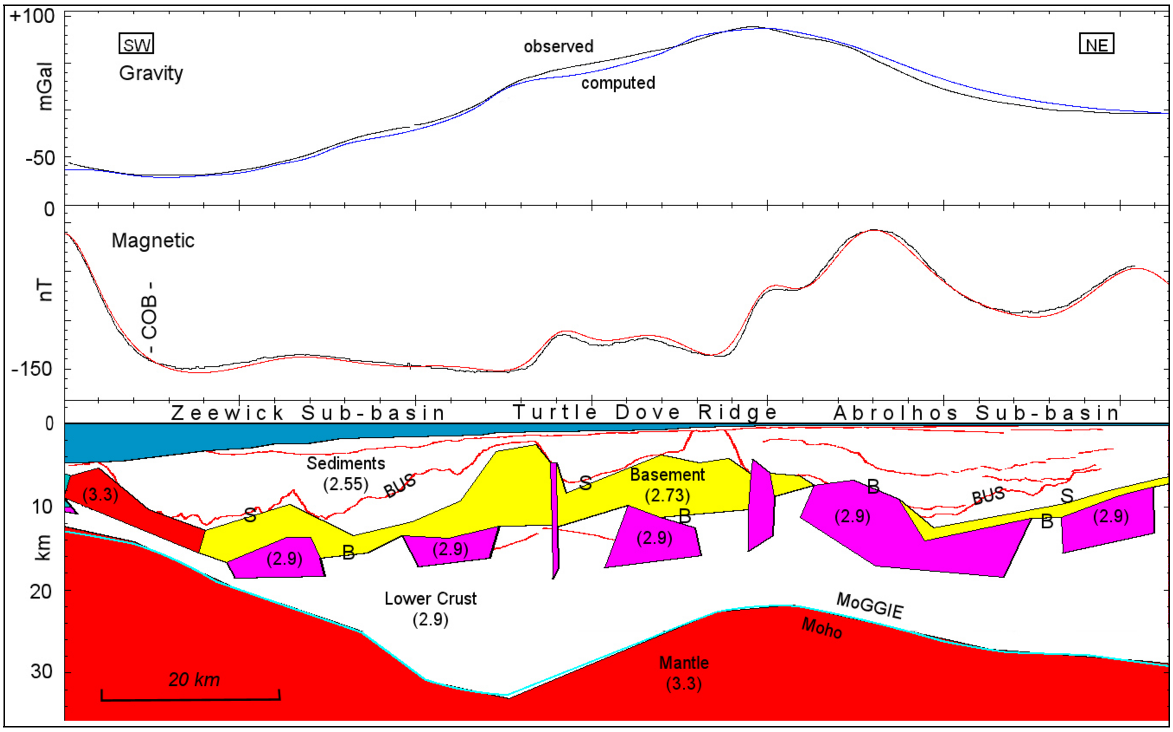

Figure 14. Profile C density model using MoGGIE Moho and base of sediments 'S' near *base_unequivocal_sediment* (BUS) in the background image. The top of the lower crust is close to *base-sect_resol*. Magnetic bodies (purple) have the same density as the lower crust. The basement (yellow) has a density of 2.73 t/m^3. Note the basement body at the southwestern end with a density of 3.3 t/m^3.

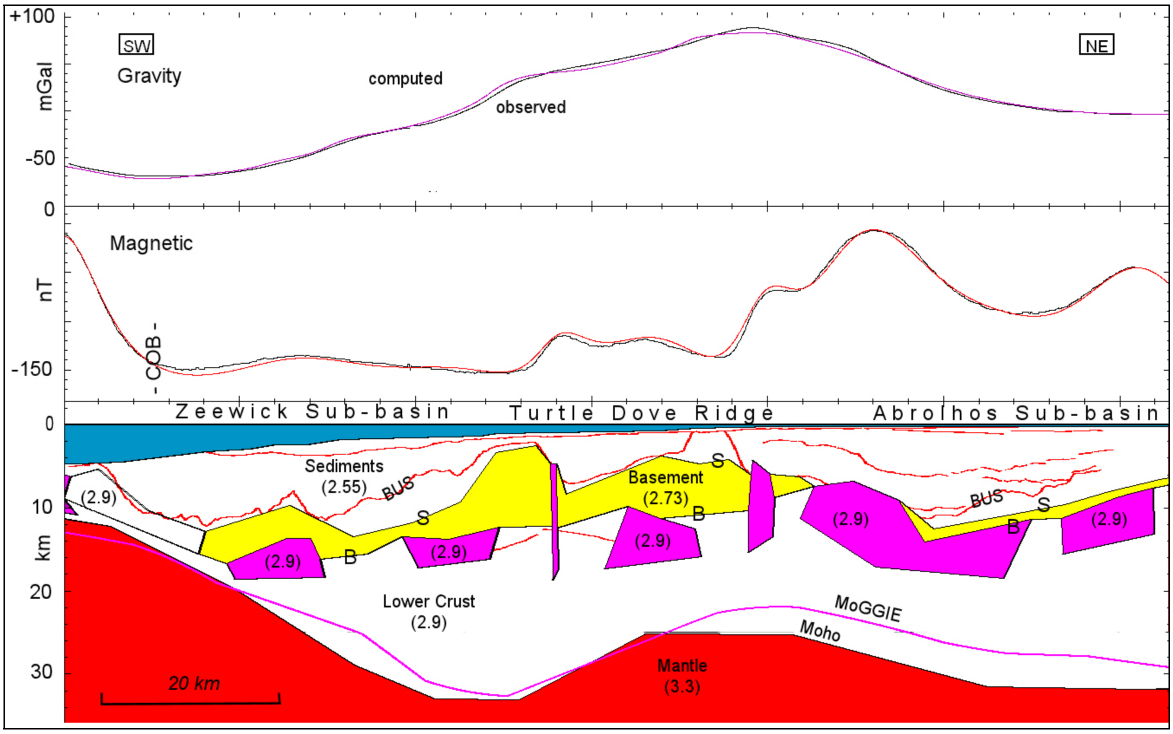

Figure 15. Profile C density model with approximate Moho and base of sediments 'S' close to *base_unequivocal_sediment* (BUS) in the background image. The basement (yellow) has density of 2.73 t/m^3. The Moho is configured to give the best long-wavelength fit of computed to observed gravity with an approximate 30 km depth at the northeast end (Kennett *et al.* 2011).

The two Case 'BUS' profile C models indicate that maximum sediment thickness across the Zeewyck and Abrolhos sub-basins is approximately 12 km. The Turtle Dove Ridge models as a basement high near the eastern boundary of the Zeewyck Sub-basin and a less prominent basement high eastwards, beneath 3km of sediment. Vertical magnetised dykes, or dyke complexes, are modelled at the margins of the Turtle Dove Ridge, as well as at 10 km depth within its core (Johnston and Petkovic, 2012).

Conclusions

Two southwest to northeast profiles across the margin of the North Perth Basin were modelled for their gravity response in an attempt to better understand the sediment thickness and structural expression of basement. Ten models were constructed grouped in three categories according to information available from reflection seismic data on the likely depth to basement, in conjunction with a Moho model. Basement in the northern Perth Basin is deep and generally not resolved in the reflection seismic data, and the only available model of Moho (Aitken, 2010) was developed by gravity inversion. These are two of the three primary density contrasts pertinent to the study — the third being the well constrained water-sediment interface. Geophysical modelling of potential field data alone does not yield unique results and, so, the conclusions are tentative and open to further investigation. Furthermore, the guidance provided by depth-converted interpretation of reflection seismic data was based on stacking velocities, which in the absence of velocity models based on P-wave measurements by refraction methods adds additional uncertainty.

The conclusions are summarised as follows:

- The most reliable models in Figure 14 and Figure 15 show gravity is consistent with base resolvable section from seismic data, where sediment thickness is up to 12 km in the Abrolhos Sub-basin.
- The top of basement may be up to 5 km below the visible sedimentary layering interpreted in the reflection seismic data for the Zeewyck and Abrolhos sub-basins.
- The Turtle Dove Ridge models as a basement high near the eastern boundary of the Zeewyck Sub-basin and a less prominent basement high eastwards, beneath 3 km of sediment, based on the seismic evidence (Figure 14 and Figure 15). It also models as a basement high when considering depth to magnetic basement in the gravity model of Figure 10.
- High density bodies may be present near the sea floor at the southwest, deep-water end of the profiles (Figure 13 and Figure 14), with densities equivalent to mantle or igneous intrusions, though this interpretation is strongly dependent on the Moho model. In Figure 15, where an approximate Moho is used, the need for such a body is removed.
- The MoGGIE Moho surface (Aitken, 2010) developed by gravity inversion is based on the SEEBASE™ (FrOG Tech, 2005) interpretation of sediment thickness, which is considerably less than the survey GA310 reflection seismic data indicate. It appears from the several models presented that MoGGIE may not be a suitable model for the study area.
- Deep coherent events identified in the reflection seismic data, coinciding with a circular positive residual gravity anomaly along profile B (Figure 1), indicate that mantle (or other high density rock) is shallower than MoGGIE in this region (Figure 13).
- Case 'MB' assumes the magnetic basement (MB) by spectral analysis of Johnston and Petkovic (2012) as the top of basement in the gravity models. The gravity and reflection seismic data do not support this assumption.

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