Is there room for gravity in petroleum exploration or is the door shut?

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SUMMARY

A detailed gravity survey carried out by the Geological Survey of Western Australia (GSWA) used seismic grids over the Beharra Springs and Mondarra gas fields in the northern Perth Basin. In this part of the basin, seismic data are poorly imaged where the near surface Tamala Limestone is present, whereas major structural elements are easily recognised using gravity data.

The new gravity data reveal a major transfer zone and show distinctive signatures for the Dongara Terrace, Beharra Springs Terrace, and Allanooka High. Gravity lineaments within these structural units correlate with major faults interpreted from detailed seismic data. Additional features interpreted from gravity, but not identified on seismic sections, may lead to a revision of previous seismic interpretations. Furthermore, the majority of positive residual gravity anomalies correlate with seismically mapped structural highs that coincide with known hydrocarbon fields. Other positive gravity anomalies in the area may correspond to unidentified fields.

Key words: gravity data, magnetic data, lineaments, structure, northern Perth Basin.

INTRODUCTION AND GEOLOGICAL SETTINGS

The northern Perth Basin lies west of the Yilgarn Craton between latitudes 29?S and 31?S in Western Australia (Figures 1, 2) and contains a relatively thick Lower Permian to Lower Cretaceous sedimentary succession overlaid by thin flat-lying Cretaceous and younger strata (Figure 3). The region had previously been regarded as prospective for hydrocarbons (Hall and Kneale, 1992; Mory and Iasky, 1996), but with recent discoveries at High Cliff, Jingemia, and Hovea, is now regarded as highly prospective. To date, eight commercial oil and gas fields have been discovered (Figure 1). The primary objectives are Upper Permian to Lower Triassic sandstones, whereas Lower Permian and Lower to Middle Jurassic sandstones are usually secondary objectives (Figure 3). In this part of the Perth Basin most of the proven petroleum system is within the Permian–Triassic succession, and the identification of feasible traps remains the greatest challenge.

Seismic surveys are the most acceptable method of mapping structures, but in the northern Perth Basin the near-surface Tamala Limestone interferes with the acquisition good-quality data. The limestone is widespread along the coastal plains and covers most of the highly prospective Dongara Terrace. The quality of seismic data acquired over this area is poor because of reduced seismic wave propagation through this cavernous limestone. Structural interpretation is further complicated by complex wrench tectonics (Hall and Kneale, 1992; Song and Cawood, 2000).

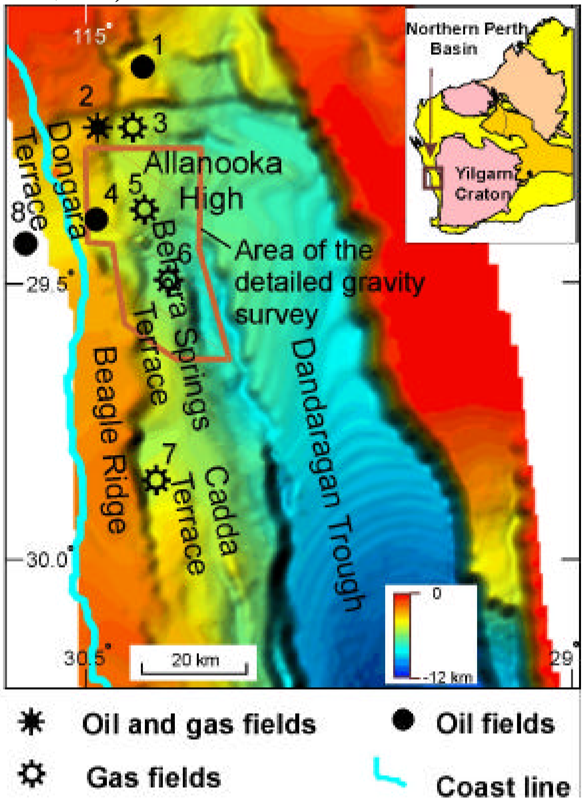


Figure 1. Depth to the crystalline basement with major structural elements in the northern Perth Basin (from Mory and Iasky, 1996). 1-Mt. Horner, 2-Dongara, 3-Yardarino, 4Hovea, 5Mondarra, 6Beharra Springs, 7-Woodadda, 8-Cliff Head.

Well data — basement was penetrated by 18 wells in the northern Perth Basin — and outcrops of the Mullingarra Inlier and Northampton Complex indicate that basement in the Northern Perth Basin is an extension of the Proterozoic Pinjara Orogen Complex (Playford et al., 1976; Myers, 1990), which consists mainly of psammitic paragneiss, with conformable lenses of pelite, quartzite and mafic gneiss (Fitzsimons, 2003: Myers, 1990). The Mullingarra Inlier and Northampton Complex are known to have only minor mafic and no ultramafic rocks (Baxter and Lipple, 1985, Fitzsimons, 2003) that would result in significant gravity and magnetic anomalies. The regional magnetic low over Northampton Complex is overprinted with linear, high frequency anomalies caused by narrow dolerite dykes. Therefore, the uniformly weak magnetic field over the basin is similar to that observed over the outcrop area of the Northampton Complex (Figure 30 in Iasky et al., 2003) and is here interpreted as largely

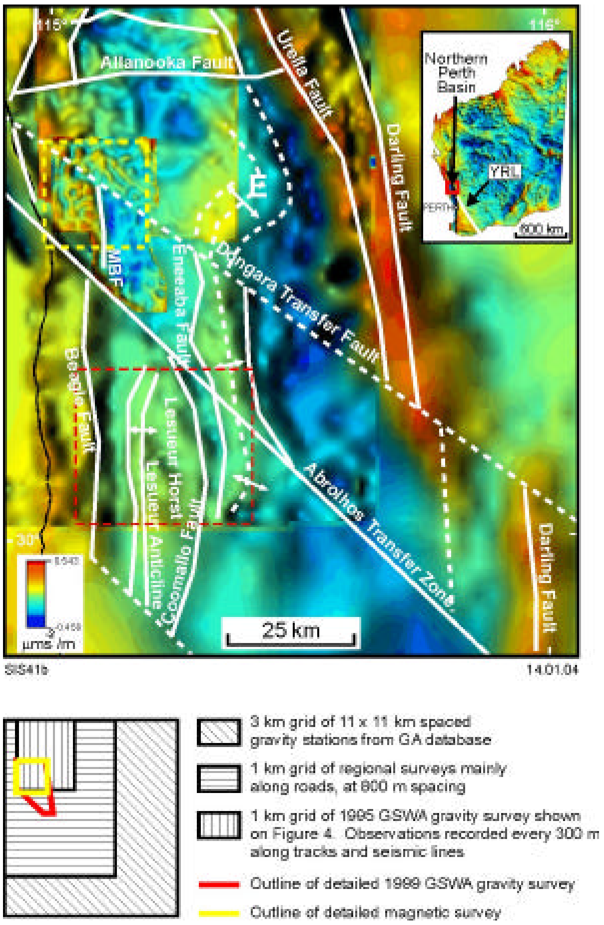


Figure 2. First vertical derivative of Bouguer gravity of northern Perth Basin. The image is a mosaic of four grids with various gravity station spacing shown in the legend above. The major structural tectonic elements, shown as white solid lines, are from Hall and Kneale (1992) and Mory and Iasky (1996). White dashed lines are interpreted structures. Abbreviations: MBF – Mount Bridge Fault, E – Erregulla basement high. Insert: YRL – Yandanooka-Cape Riche Lineament. Red dash rectangle is outlines of 1995 GSWA gravity survey shown on Figure 5. Note that the bull's eye anomalies of 5-10 km in diameter west of the Darling Fault on the 1 km grid are artefacts generated from the use of variable accuracy gravity surveys.

homogeneous over the basin. Where basement is shallow and homogeneous, gravity anomalies can be directly related to basement topography as the greatest component of such anomalies are caused by lateral changes between the low-density sedimentary section and high-density crystalline basement. In the northwestern part of the northern Perth Basin the relatively shallow (2–5 km) crystalline basement (Mory and Iasky, 1996) allows gravity to be an effective tool in delineating structures such as faults, grabens and horsts that displace basement. As the major Permian–Triassic reservoirs in this area are close to basement, gravity highs may coincide with structures prospective for hydrocarbons.

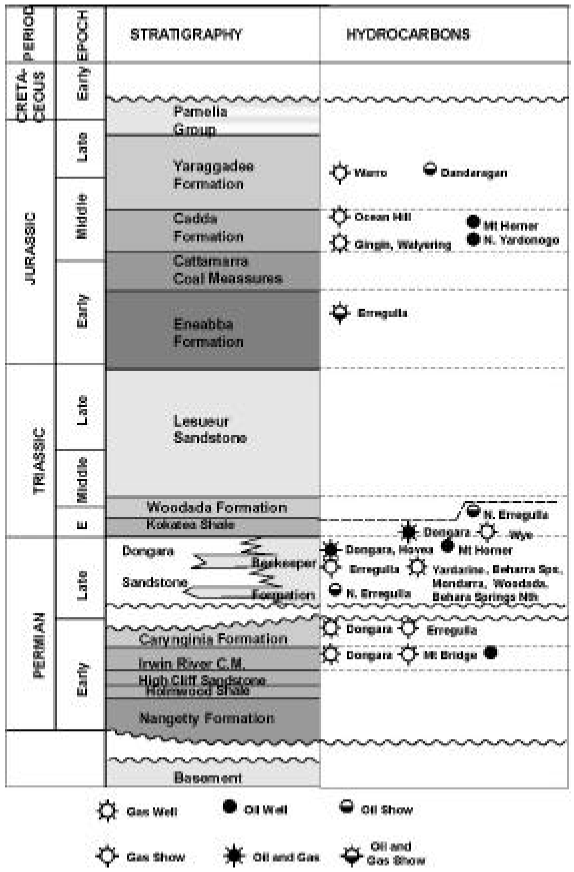


Figure 3. Stratigraphy of the northern Perth Basin (from D'Ercole et al., 2003)

PREVIOUS GRAVITY MAPPING

In the 1950–60s, gravity data were widely collected by petroleum exploration companies in Western Australia as a regional reconnaissance tool. Since then, seismic acquisition and processing methods have improved, and gravity data play only a minor role in modern petroleum exploration.

In 1995, GSWA initiated a cooperative project with West Australian Petroleum, Discovery Petroleum, Victoria Petroleum, and Consolidated Gas, in which gravity was recorded along existing 2D and 3D seismic lines (Iasky and Shevchenko, 1995). Gravity stations were recorded every 300 m along seismic lines in two areas: southeast of Dongara and southwest of Eneabba (Figures 4 and 5). Although the data coverage was irregular with distance between traverses varying between 500m to 5 km and the vertical control was poor (±0.5 m), the major structural elements were resolved by these data. It became apparent that oil and gas fields southeast of Dongara are either on horst blocks (Dongara, Mondarra; Owad-Jones and Ellis, 2000) or in anticlines (Mt. Horner, Yardarino), and correspond to positive gravity anomalies (Figure 4), and that major faults correspond to steep gravity gradients. However, the survey was not detailed or accurate enough to pick up small structures and some anomalies are artefacts of the gridding caused by irregularly spaced traverses. For example, the data are too sparse to clearly delineate the southern part of the Mountain Bridge Fault and anomalies *A, B, C* are not real (Figure 4).

In the Eneabba area, the Woodada gas field is within a north-plunging anticline cut by series of north-south-trending faults (Owad-Jones and Ellis, 2000). Even though only a few gravity

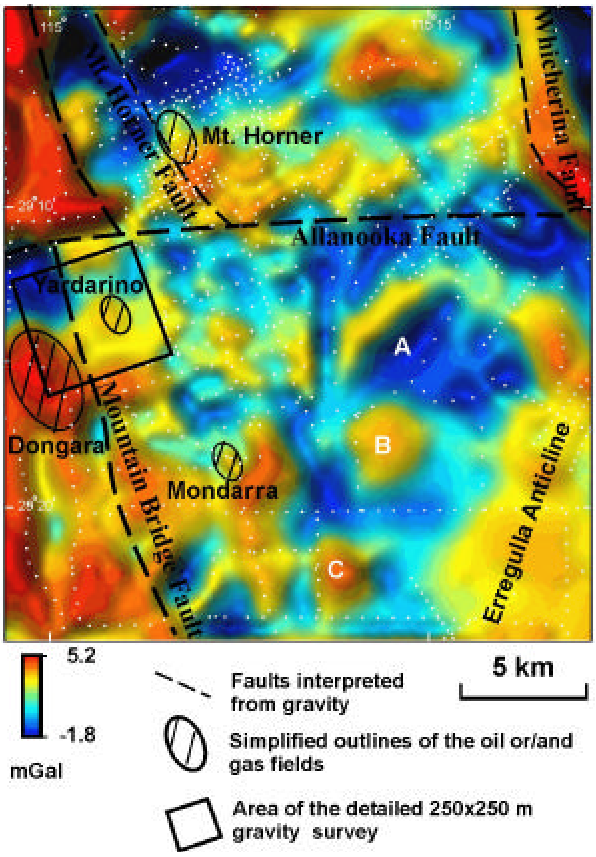


Figure 4. Residual Bouguer gravity over the Dongara and Mt. Horner oil and gas fields area. White dots are gravity stations of GSWA 1995 year survey (every second station is shown).

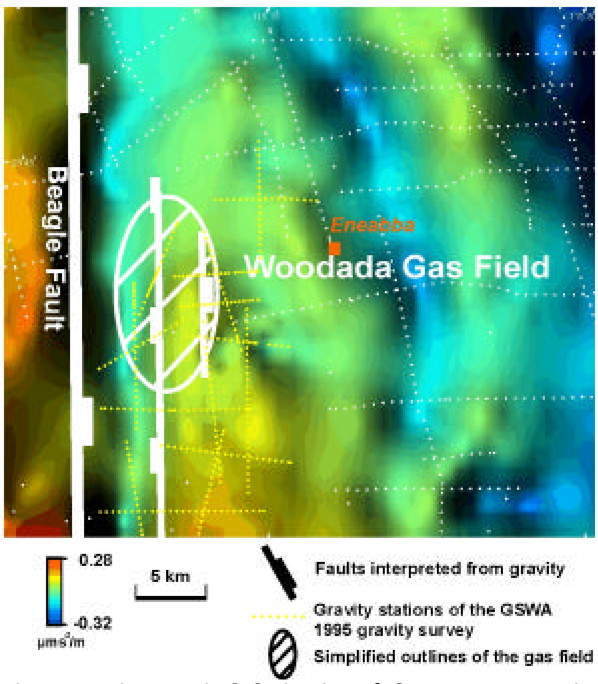


Figure 5. First vertical derivative of the Bouguer gravity over the Eneabba area. White dots are gravity stations of the regional surveys from GA gravity database.

traverses were recorded in this area, the anticlinal structure is discernible as a residual positive anomaly bound by northerly trending steep gradients (Figure 5).

NEW DATA

In 1999 GSWA carried out a detailed gravity survey over seismic grids covering the Beharra Springs and Mondarra gas fields (Figure 6) to see if gravity data could be used to complement seismic data to identify possible leads in the area. An aeromagnetic survey, flown at 80 m above ground level along east-west lines 333 m apart for WAPET in 1993 that covers most of the northern part of the gravity survey (Figures 2 and 8a) was also used for the structural interpretation.

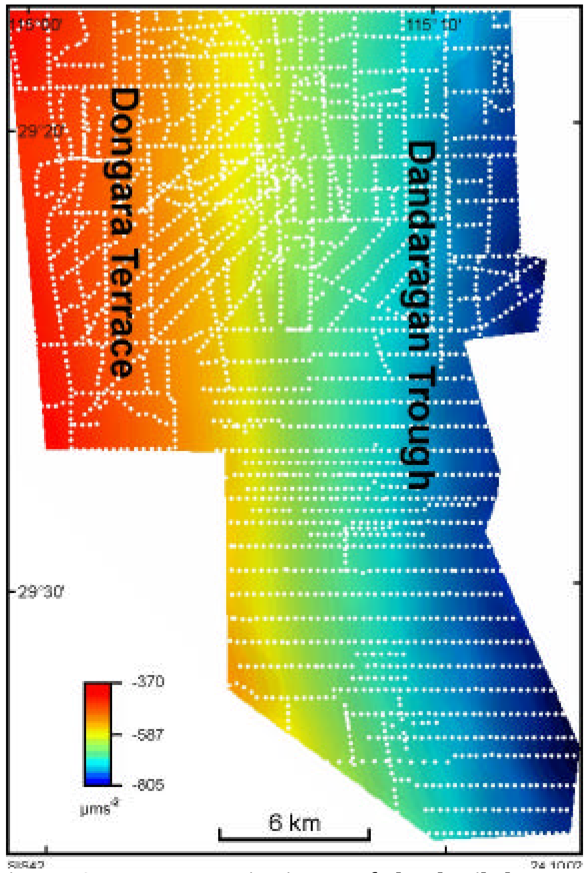


Figure 6. Bouguer gravity image of the detailed survey with the stations shown as white dots.

Gravity data acquisition

The vehicle-supported gravity survey covered an area of approximately 30 km × 15 km (Figure 2) over existing seismic lines and tracks (Shevchenko, 2002). A total of 2676 gravity observations were recorded every 300 m along traverses 1 km apart (Figure 6) using LaCoste & Romberg gravity meters with an accuracy ±0.4 ?ms^{-2}. Positions for the sites were determined with a vehicle-mounted Ashtech Z-12 dual frequency GPS receivers operating in kinematic mode. One gravity and three GPS base stations were set up in the area, from which rover GPS receivers operated at no more than 15 km. The elevation and Bouguer accuracy for the survey were estimated from independent control readings as ±0.06 m and ±0.5 ?ms^{-2} respectively.

Seismic data.

Origin Energy acquired the Beharra Springs 3D Seismic Survey over Beharra Springs gas field area in 1999 (Origin Energy, 1999). Non-interpretive data were made available to the public in 2001 and included a 2 km × 2 km grid of 2D seismic lines extracted from the 3D dataset. Three horizons — Intra Cathamara Coal Measures, Top Carynginia Formation and Top of the basement — were mapped (Figure 10) to compare seismic and gravity mapping. The detailed seismic mapping of the Beharra Springs area is additional work to that submitted by the authors in an earlier version of this paper as an extended abstract at the ASEG Conference in 2003 (Shevchenko and Iasky, 2003).

INTERPRETATION

On the Bouguer gravity image (Figure 6), the western gravity high broadly corresponds to the Dongara Terrace (Jones and Pearson, 1972) and the eastern gravity low to the Dandaragan Trough (Thyer and Everingham, 1956). The steep easterly-dipping gradient on the Bouguer gravity image indicates a thickening sedimentary section to the east towards the Dandaragan Trough.
On the first vertical derivative of Bouguer gravity three distinctive zones, which correspond to established structural units (Mory and Iasky, 1996) are recognised (Figures 7 and 9):

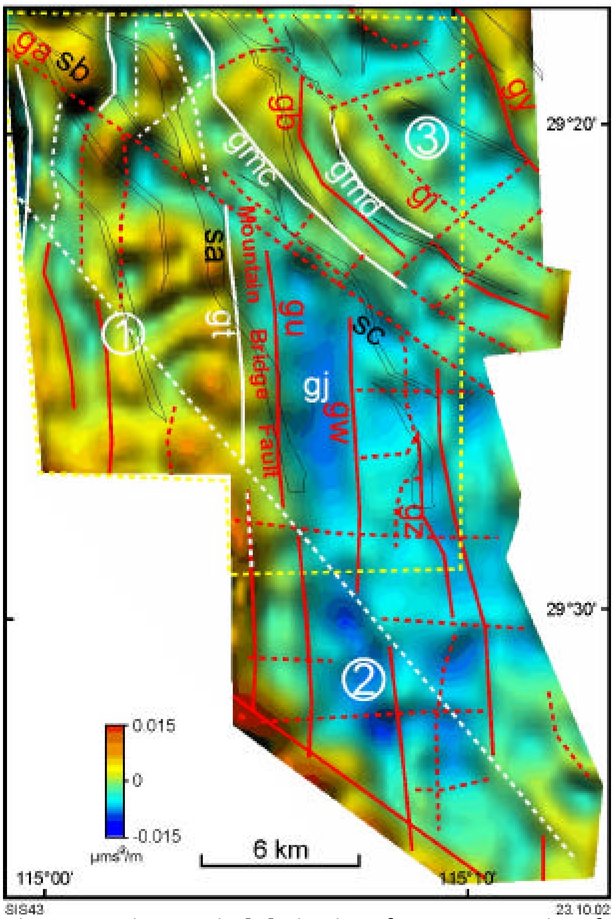


Figure 7. First vertical derivative of Bouguer gravity of the detailed survey. 300 m grid. Low pass FFT filter: 0.01 cy/m – cut off, 0.0005 cy/m – roll over. Structural units of the area are: 1 – Dongara Terrace, 2 – Beharra Springs Terrace, 3 – Allanooka High. White lineaments are interpreted as faults from both gravity and magnetics; red, from gravity only. Area of magnetic data is shown as yellow dashed line. Black polygons are faults at the Cattamara Coal Measures horizon interpreted from seismic data by ArcEnergy at 1998 (published with permission of Arc Energy).

(1) The western fragmented gravity high with predominantly north-trending lineaments corresponds to the Dongara Terrace, west of the Mountain Bridge Fault. The fragmented appearance is caused by east-trending gravity lineaments truncating north-trending ones, and is probably related to an intricate network of basement faults such that the relative gravity highs and lows are directly related to individual fault blocks.
(2) The southeastern gravity low with mostly north- and some east-trending gravity lineaments, especially in the southern part of this zone, corresponds to the Beharra Springs Terrace east of the Mountain Bridge Fault.
(3) The northeastern area with northwest trending lineaments corresponds to the Allanooka High, south of the Allanooka Fault (Figure 1; Mory and Iasky, 1996).
Lineament *ga* (Figures 7 and 9) separates northerly trending gravity lineaments (*gt*, *gu* and *gw*) to the south from northwesterly trending lineaments (*gb*, *gmc* and *gmd*) to the north. This lineament, as other northwesterly oriented lineaments in the basin (Mory and Iasky, 1996), is interpreted as a transfer fault within basement (here named the Dongara Transfer Zone, Figure 2) between the Beharra Springs Terrace and the Allanooka High. The Dongara Transfer Fault (DTF) appears to have sinistral movement and is inferred to have controlled normal faulting perpendicular or nearly perpendicular to the transfer fault, within a zone in the sedimentary succession (O'Brien et al., 1996). The DTF is probably associated with a Precambrian shear zone within basement that has been reactivated in the Phanerozoic. This shear is represented in the gravity field with lineaments *gb*, *gmc* and *gmd* that appear to be affected by drag along the plane of the DTF (Figures 7 and 9). The abrupt change in the direction of these gravity lineaments across the transfer zone is also noticeable on the magnetic data (*gmc* and *gmd* on Figure 8), although not as clear as on the gravity image.
On the regional gravity image (Figure 2) the DTF crosses the Urella and Darling Faults where the positive gravity anomaly of both faults decreases markedly, implying that the throw of the Darling Fault is transferred to the Urella Fault across a relay ramp (Mory and Iasky, 1996). The transfer fault appears to converge with the Yandanooka – Cape Riche Lineament (insert in Figure 2; Everingham, 1968), which is the focus of recent seismic activity in the Yilgarn Craton (Doyle, 1971; Wilde, 2001), indicating possible reactivation of the DTF up to the present. Another feature along the transfer zone is the change in direction of gravity anomaly *E* (Figure 2), interpreted as a fold within the Erregulla basement high, north of the transfer fault, shown as Erregulla anticline on Figure 4.
The northwest-trending DTF is sub-parallel to the Abrolhos Transfer Fault (Hall and Kneale, 1992; Mory and Iasky, 1996) and may be associated with the sinistral movement that initiated in the Early Cretaceous as Australia separated from Greater India (Mory and Iasky,1996). The wrench tectonics along the DTF may have provided a mechanism for hydrocarbon migration and the formation of fields such as Dongara, Hovea and Eremia.
In the northern part of the area, gravity lineaments correlate well with faults interpreted from seismic at the top Cattamarra Coal Measures horizon by ArcEnergy (Figure 7). For example, the Mountain Bridge Fault (*sa*) can be directly correlated to a northerly gravity lineament (*gt*). Other faults (*sb* and *sc*) around the Dongara Transfer Zone either align or

swing along the direction of the transfer fault, as indicated by

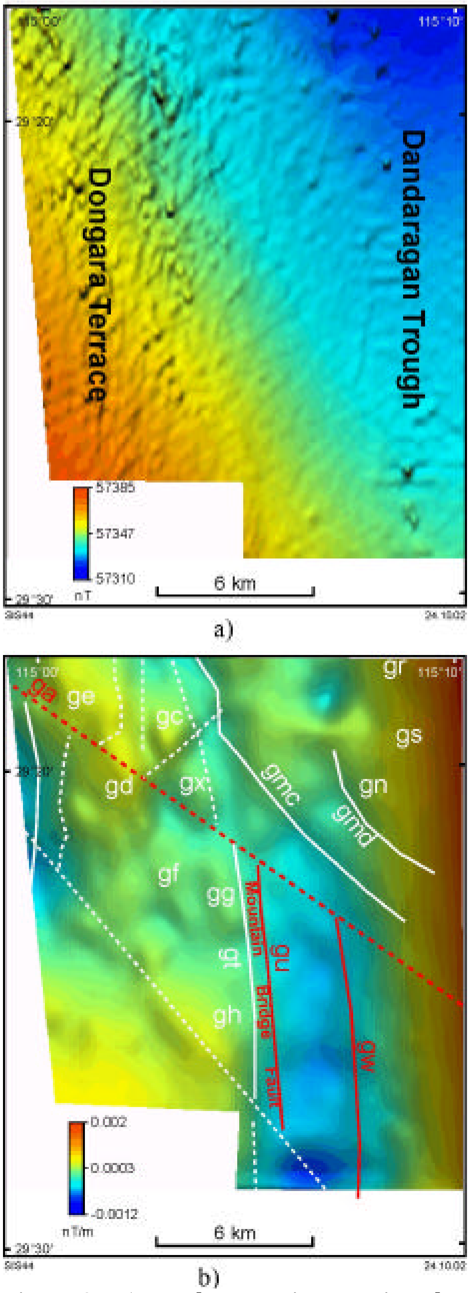


Figure 8. a) Total Magnetic Intensity, showing a subtle decrease magnetic field from Dongara terrace towards Dandaragan Trough. The high frequency anomalies are cultural and near sub-surface magnetic sources. b) First vertical derivative of TMI upward-continued to 1000 m, showing basement topographyfrom a weekly magnetic basement. 80 m grid; Low Pass FFT filter: 0.01 cy/m – cut off, 0.00001cy/m – roll over. White lineaments are interpreted as faults from both gravity and magnetics; red, from gravity only. Positive anomalies (white symbols) are interpreted as prospects from both gravity and magnetic.

the gravity data. In places the gravity data indicates that faults mapped from seismic data should extend along gravity lineament *gmd*. On the northeast part of the image a north-northwest gravity lineament (*gy*) appears to correspond to two northwesterly trending faults. These faults may represent the up-dip extension of basement structure near the Cattamarra Coal Measures. Alternatively, a revision of the fault correlation may be required. Gravity lineaments *gmc*, *gb* and *gy*, (Figure 7), which are probably faults close to or in the basement, have not been identified in the seismic interpretation at the top Cattamarra Coal Measures horizon.

Most of the hydrocarbon fields in the area are trapped in tilted fault blocks or basement horst structures and appear to correlate to positive residual gravity anomalies. These anomalies overlie or are slightly offset from the field, depending on the degree of tilt of the basement structure. The main reservoir in this area is the Upper Permian Dongara Sandstone (Figure 3), which is close enough to basement for the horst structures at the level of the fields to be broadly represented by positive gravity anomalies. An example is the recently discovered Hovea oil field that lies on an upthrown, tilted to the west basement block (Origin Energy, 2001) and is at the edge of the positive gravity and magnetic anomaly *gc* (Figures 8b and 9). The field is at the western edge of this anomaly because the highest part of the westerly-tilted

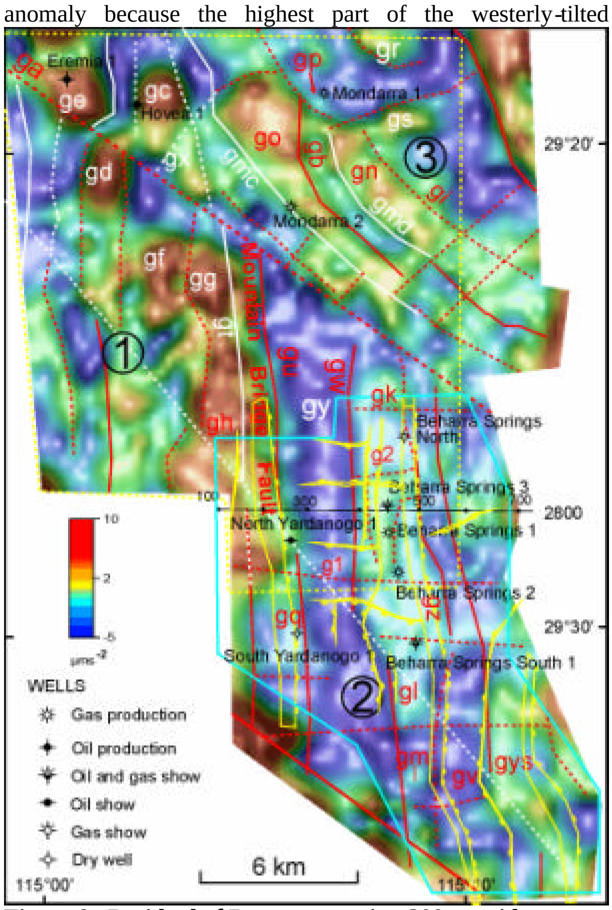
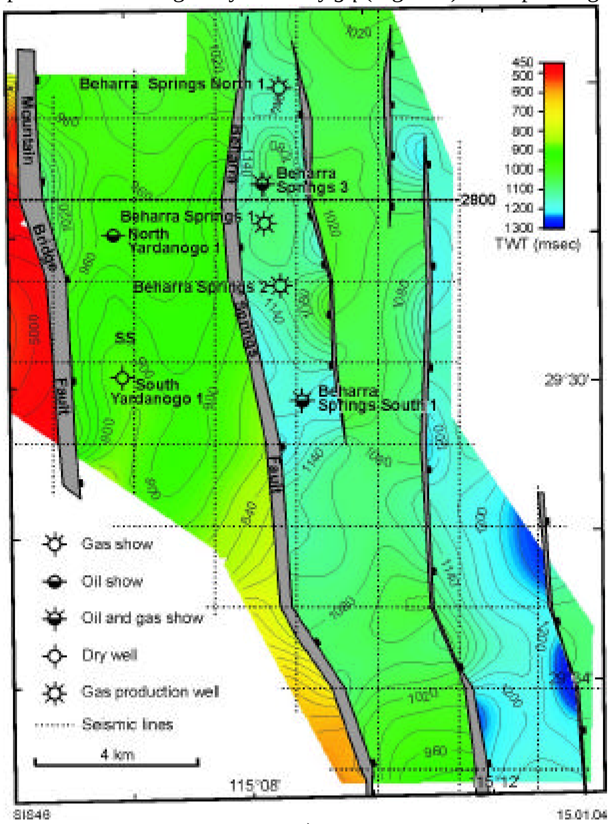


Figure 9. Residual of Bouguer gravity. 300 m grid. Regional gravity (matrix smooth window – 5000 m) was subtracted from the Bouguer Gravity. White lineaments are interpreted as faults from both gravity and magnetics; red, from gravity only. Positive anomalies (white symbols) are interpreted as prospects from both gravity and magnetic; red from gravity only. Area of magnetic data is shown as yellow dashed line. Area of the seismic interpretation over Beharra Springs gas field is shown as blue line with interpreted faults within Top Caryngina Formation from Figure 10b shown in yellow. Black line is seismic line 2800 with the shot points shown.

basement block is to the east, against the easterly-dipping Mountain Bridge Fault (www.arcenergy.com.au/Latest Drilling Results/Hovea Field/Prospect Cross Section). Anomalies *gd*, *ge* and *gx* (Figures 8b and 9) can represent similar basement horsts, which could contain hydrocarbons if reservoir and seal rocks are present. Based on the gravity mapping, the authors suggested that anomaly *ge* (Figure 9) was a potential lead (Shevchenko and Iasky, 2003), and in subsequent drilling of the structure by Arc Energy in March 2003, oil was discovered in Eremia 1. Gravity and magnetic anomalies of similar frequency and amplitude *gd, gf* and possibly, *gg* and *gh* (Figures 8 and 9) are also interpreted as uplifted basement blocks within the Dongara Terrace.

In the Beharra Springs Terrace, the Beharra Springs structure is a westerly tilted fault block (Figure 11) in which the reservoir is a near basement sandstone within the Upper Permian Beekeeper Formation (Figures 3; Owad-Jones and Ellis, 2000). Although the Beharra Springs field is located on a tilted fault block within the Top Carynginia and Basement horizons, further up the succession it is a graben at the Intra Cattamarra Coal Measures horizon (Figures 10 and 11). The field is confined to the centre of a distinctive positive gravity anomaly *c* (Figure 11) between northerly lineaments *gw* and *gz* and easterly lineaments *g1* and *g2* (Figure 9). Lineament *gz* and *gw* are gravity gradients that correspond to the seismically mapped Beharra Spring Fault (BSF) and fault *sw* respectively, whereas lineaments *g1* and *g2* appear to correspond to the faults *s1* and *s2* (Figure 10b and 10c). Three positive gravity anomalies *gm, gl* and particularly *gk* are probable basement highs within the Beharra Springs Terrace and could be investigated as possible leads. The anomaly *gl* corresponds tentatively with the anticlinal structure mapped as *sl*, although our mapping was constrained by a 2 km grid of seismic lines (Figure 10b).

The North Yardanogo oil accumulation (Figure 9) lies within a rollover anticline on the hanging wall of the Mountain Bridge Fault at the top Cattamarra Coal Measures horizon (Owad-Jones and Ellis, 2000). Again, the structure lies within a subtle positive residual gravity anomaly *gq* (Figure 9) corresponding



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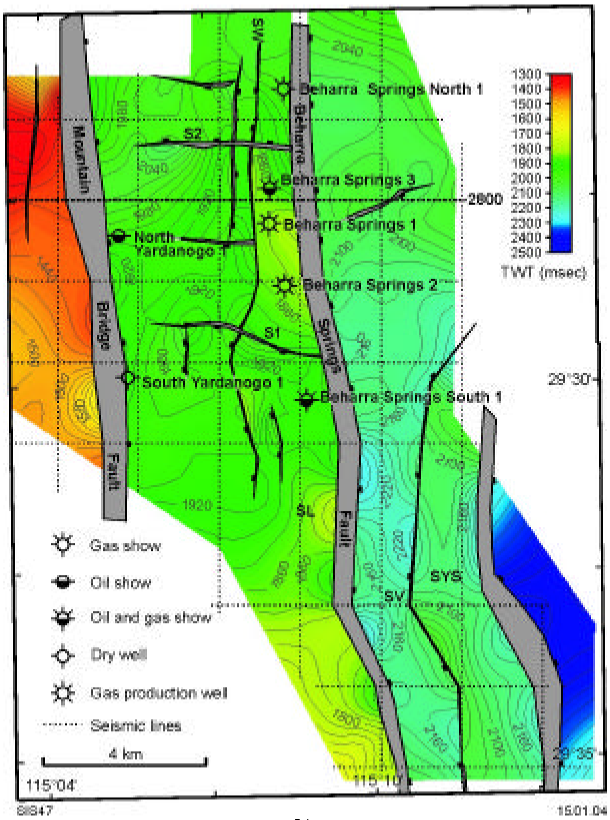

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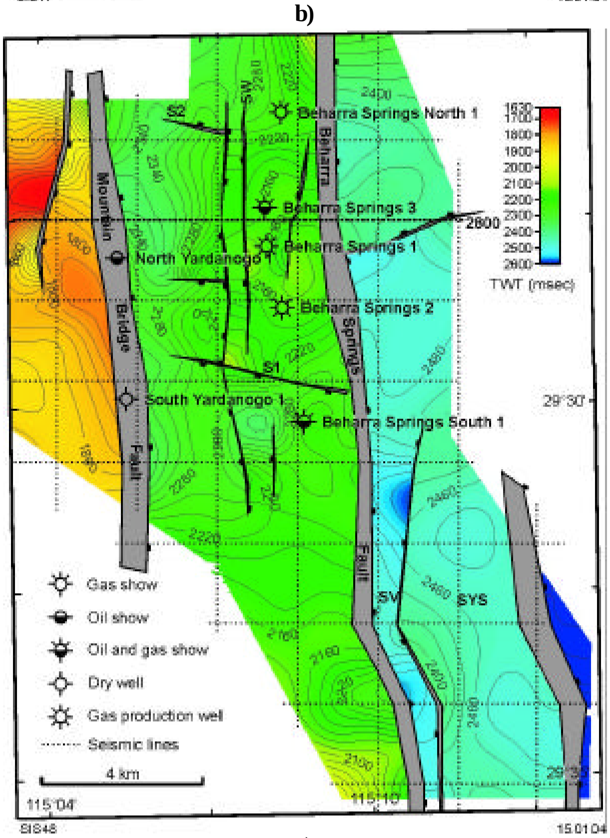

c)

Figure10. Seismic interpretation of the a) Intra-Cattamarra Coal Measures Formation, b) Top Carynginia Formation, c) Top of the granitic Basement.

to the anticline *sq* in the Cattamarra Coal Measures horizon (Figure 10a).

East of the Beharra Springs Fault on the southeastern portion of Figure 9, there is a very good correlation between gravity low *gv* and gravity high *gys* with seismically mapped graben and horst *sv* and *sys*, respectively (Figures 10b and 10c). However, the enhanced north trending gravity trough *gy* between the Mountain Bridge and Beharra Springs Faults (Figures 9 and 11) is not fully reconciled with the seismic mapping, which displays only a slightly thicker sedimentary section where the basement block is tilted to the west towards the Mountain Bridge Fault (Figure 10c). The larger than expected gravity low is a processing problem caused by not completely removing the regional curve to correct for the effects of the large throw of the Mountain Bridge Fault.

On the Allanooka High, well defined, northwest-trending gravity and magnetic anomalies *go* and *gn* (Figures 8 and 9) are interpreted as horst blocks bounded by lineaments *gmc*, *gb*, *gmd* and *gi* respectively, which are interpreted as faults.

Within the Mondarra gas field on the Allanooka High, Mondarra 2 is located at the western edge of the gravity anomaly *go*, but Mondarra 1 appears to be located on a different smaller anomaly *gp* (approximately 1 km in diameter), at the eastern edge of *go* (Figure 9). Unexplored gravity anomalies *gr*, *gn* and *gs* (Figure 9) may be related to uplifted basement structures.

CONCLUSIONS

Three distinctive gravity zones coincide with the Dongara Terrace, Beharra Springs and Allanooka High. A northwest-trending gravity lineament, interpreted as the Dongara Transfer Zone, separates north-trending lineaments to the south from northwest-trending lineaments to the north that correspond to faults within basin and basement. The transfer zone converges with the Yandanooka – Cape Riche Lineament implying that it represents reactivation along a major shear within basement. Wrench tectonics along the shear may have provided a mechanism for both trap formation and a path for hydrocarbon migration in this area.

In the area of the detailed gravity survey, most hydrocarbon accumulations are in structures that appear to be associated with gravity anomalies. Some fields have a direct expression as a positive residual anomaly, whereas for others, the relationship is more subtle. This is likely dependent on the relationship of the structure at the reservoir level to that at the level of the basement. Modelling, (beyond the scope of this paper) would be required to fully interpret such features. However, to a first order approximation, the evidence suggests that positive potential-field anomalies are associated with uplifted basement. Therefore, in areas of poor quality seismic data, the door should be opened for detailed gravity coverage to help identify potential structural traps. Even in areas of good quality seismic data, gravity is a cost-effective method that can help identify areas to focus with more expensive exploration techniques such as seismic.

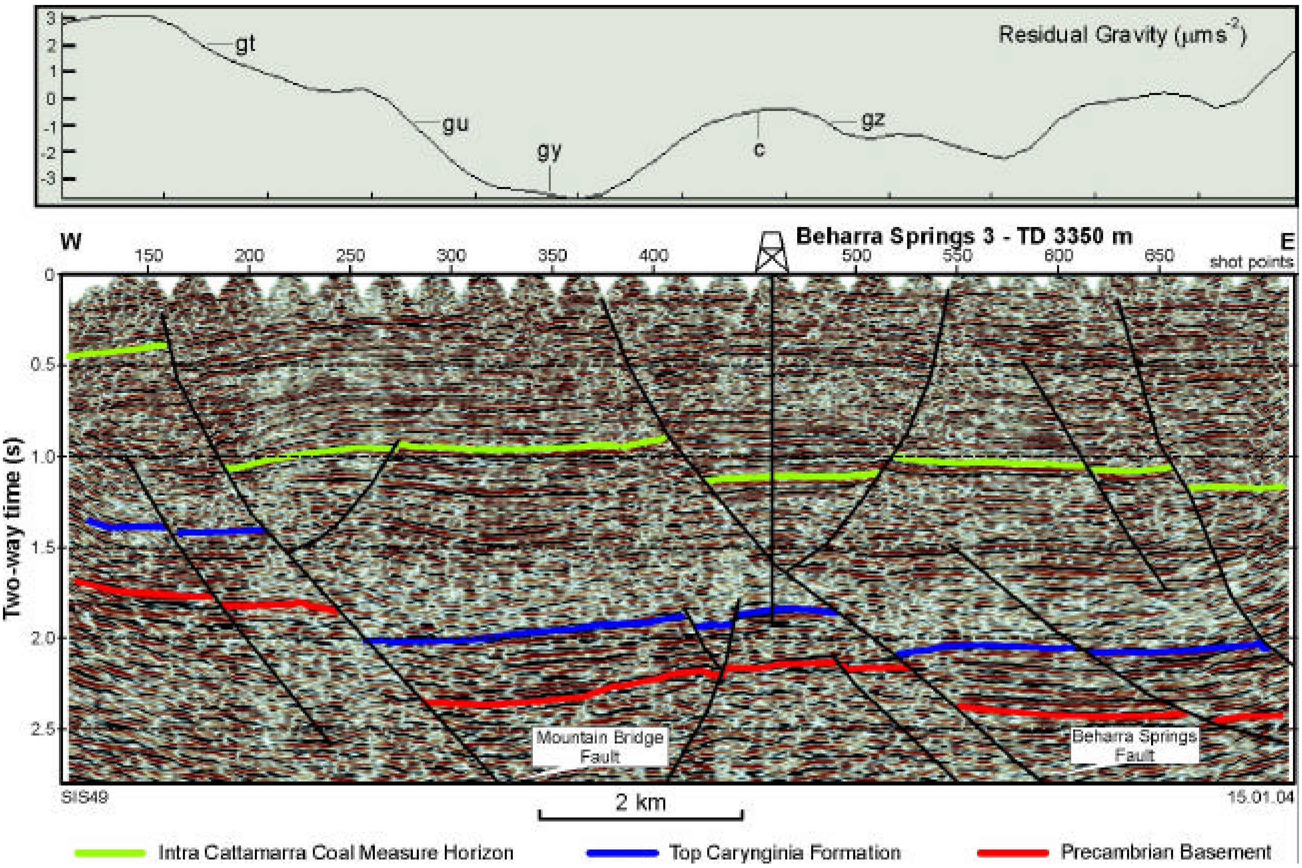

Figure 11. Seismic cross-section of the Beharra Springs structure along the line 2800 with interpretation. At the top is the residual gravity along the line with the marked gradients referring to the lineaments on Figure 9. Location of the section is shown on Figures 9 and 10.

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