Targeting oil and gas in the Perth Basin using an airborne gravity gradiometer

P. Kovac[1]*, C. Cevallos[1] and J. Feijth[1] present the results of the Black Swan geophysical survey in Western Australia.

In recent years there has been renewed interest in the hydrocarbon potential of the Perth Basin in Western Australia. It is close to the regional capital city and the gas pipeline that runs between Dampier in the north and Bunbury in the south. Recent discoveries of gas by AWE have shown that there is a working hydrocarbon system within at least the northern and central parts of the basin. In most parts of the basin, modern seismic data is relatively scarce. In the current low oil price environment, explorers are looking for cost-effective ways of exploring and targeting seismic acquisition. Airborne gravity gradiometry is such a technique. It has been widely used in frontier basins to understand the basin architecture (Bain et al., 2013, Roberts et al., 2015), sedimentary structure (Feijth et al., 2015 and Kovac et al. 2013) and planning of seismic acquisition (Moore et al., 2012).

The Black Swan geophysical survey was conducted by CGG to assist oil and gas producer, Empire Oil and Gas, in identifying target areas for hydrocarbon exploration. The main tools employed were the Falcon Airborne Gravity Gradiometer (AGG), magnetic and digital terrain data. The survey was flown east-west with a nominal flying height of 100 m with 1 000-m line spacing, using a flight line to tie line ratio of 10:1. Structural interpretation has been carried out in two phases. Regional interpretation provided an overview of major regional structures and aimed to analyse the linkage between segments within the exploration blocks. It was derived from regional, publicly available gravity and magnetic data. Detailed structural interpretation was derived from the AGG (Airborne Gravity Gradiometer) data in order to improve current understanding of the tectonic pattern within Empire Oil's exploration blocks. Depth to magnetic basement was calculated using publicly available government data. The survey identified areas containing large structural leads and trends for targeting future gas exploration activities, including infill 2D seismic acquisition.

Geological structure of the Perth Basin

The Perth Basin forms part of the continental margin of south-western Australia. It is bounded by the Archean Yilgarn Craton to the east, the Southern Carnarvon Basin to the north, the Bight basin to the southeast and oceanic crust of the Indian and Southern oceans to the west and south, respectively. The formation of the basin is related to the breakup of Gondwana and the formation of the Indian Ocean. The basin contains up to 15 km of mid-Carboniferous to Lower Cretaceous sedimentary rocks (Thomas, 2014), which record a long-lived, mostly non-marine depositional environment with occasional marine incursions (FrOG Tech, 2006; Playford et al., 1976). A Valanginian (Early Cretaceous) break-up unconformity truncates the sediments deposited during the breakup of Gondwana (Thomas, 2014). A thin cover of post-rift sediments overlies the unconformity. An overview of the stratigraphy and lithology, age controls and interpretations of depositional environments has been provided by Playford et al. (1976), Mory and Iasky (1996), Crostella and Backhouse (2000), Norvick (2004), Mory and Hocking (2008) and Thomas (2014) (Figure 1). Metamorphic rocks of the Meso- to Neoproterozoic Pinjarra Orogeny, which are exposed in the Leeuwin, Mullingarra, and Notthampton Inliers, form the basement of the Perth Basin.

Methodology

The structural interpretation was developed as a synthesis of the geological structure, tectonic evolution and principles of magnetic and gravity data behaviour. It is important to understand that the gravity and magnetic techniques respond to two different physical properties. The magnetic data responds to the quantity of magnetically susceptible material in the geological structure and the gravity data to lateral changes in density in the subsurface. While the gravity and magnetic grids might show similar trends due to the tectonic forces experienced in the area, they respond to different properties and may show different characteristics. Potential confusion can be generated by overprinting of similar-wavelength responses caused by either: (i) deep features; (ii) laterally distal features; and, (iii) broad, centrally located shallow features. Resolving this confusion is invariably achieved by seeking consistency between the gravity and magnetic data while adhering to sensible geological principles and experience.

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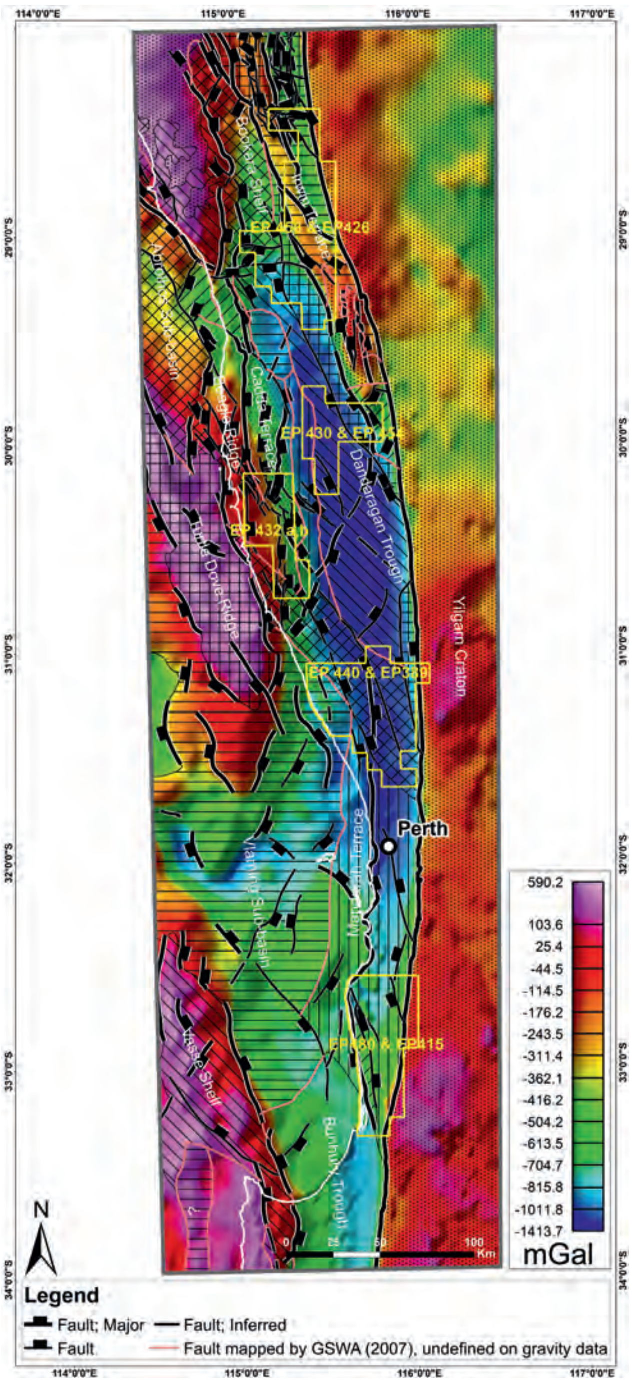

***Figure 1** Regional structural interpretation of the Perth Basin derived from gravity and magnetic data. Location of Empire Oil's exploration blocks EP 368 & EP 426, EP 430 & EP 454, EP 440 & EP38, EP 440 & EP389 and EP 480 & EP 416 is shown.*

The interpretation workflow included:

- Merging the newly acquired gravity data with the publicly available gravity data to form a continuous data grid covering the area surrounding the survey blocks. The data grid extends from the Darling Fault in the east (edge of the Perth Basin) to the coast in the west.
- Generation of appropriate filters and enhancements of the gravity and magnetic data, including reduction to pole, depth slices, vertical derivatives, horizontal gradients, total gradients, structural index and curvatures of the AGG tensors in order to highlight and interpret structural features in various depths.
- Incorporation of all applicable proprietary and public data into a GIS, ready for interpretation.
- Interpretation of gravity and magnetic data to produce a structural interpretation integrating structures interpreted from seismic data.
- Profile-based depth estimation using Werner and Euler deconvolution gridded to provide a magnetic basement depth model within the exploration blocks.
- Discussion between the structural geologist completing the structural interpretation and the geophysicist finishing the basement model to ensure consistency between their interpretations.

Gravity, in particular the AGG, and magnetic data allowed imaging of intrasedimentary structures and crystalline basement architecture due to lateral contrasts in rock density and susceptibility. The Perth Basin sedimentary infill contains mostly siliciclastic deposits interlayered with minor carbonate, carbonate shale, coal and mixed siliciclastic and coal beds. These stratigraphic horizons are of higher density then surrounding siliciclastic deposits and were identifiable in AGG data. The shape and intensity of the gravity anomalies were interpreted to be due to a combination of tectonic control, lithological thickness variations and depth of higher-density geological units. Several stratigraphic horizons were assigned as the most probable source of gravity anomalies; including the Holmwood shale, the Irvin River Coal Measures, the Beekeeper Formation, the Kockatea Shale, the Cattamarra Coal Measures and the Cadda Formation in the northern Perth Basin. In the southern Perth Basin, the Sue Group, Cattamarra Coal Measures and South Perth Shale may be the source of AGG anomalies. The gravity response can be highlighted by the shallow crystalline basement, particularly in the northern part of the basin.

Regional interpretation of the Perth Basin

A good understanding of the regional setting and the basement architecture of the Perth Basin was required for the structural interpretation of the exploration blocks. Merged public-domain gravity and magnetic data was used for a regional interpretation. Bouguer gravity and free-air gravity data was used for onshore and offshore interpretation respectively. Magnetic data was used, mainly for mapping faults that offset shallow basement. For the interpretation of the deeper basement structure, the merged gravity data was most useful. The major regional faults were mapped predominantly from the horizontal gradient of merged gravity data. The resulting regional interpretation map (Figure 1) shows the regional basement structure of the basin and the distribution of troughs, sub-basins, terraces, shelfs and ridges.

The latest principal subdivision of the Perth Basin by the Geological Survey of Western Australia (2007) can be applied to the new regional interpretation. The main differences between the interpretation based on the regional public-domain data and the map produced by the Geological Survey (2007) can be explained by the different structural levels of interpretation. The principal subdivision of the Perth Basin by the Geological Survey of Western Australia (2007) is based on the fault structure at the level of the breakup unconformity, as mapped from seismic data. The deepest parts of the basin were defined with more accuracy from the merged public-domain gravity and magnetic data. Local modifications to the boundaries of the troughs, sub-basins, terraces, shelfs and ridges were required to accommodate the deep basement faults identified in the potential field data (Figure 1).

Detailed structural interpretation

Detailed structural interpretation of the AGG survey in the Perth Basin covers Empire Oil's exploration blocks EP 368 & EP 426, EP 430 & EP 454, EP 432 a & b, EP 440 & EP389 and EP 480 & EP 416 (Figure 1). The survey was the largest of its type acquired in the basin to date, and acquired state-of-the-art data. Interpretation of the data was completed by the end of 2015. The most promising leads have been interpreted in EP 389, EP 432 and EP 454. The prospectivity of some identified leads has been significantly increased by the gas discovery at wells Red Gully North-1 and Gingin-1, located in EP 389 (Figure 2, Figure 3 and Figure 4).

Structural interpretation of EP 440 and 389

Exploration blocks EP 440 & 389 are located in the central part of the Perth Basin (Figure 1). The tectonic structure of the blocks is subdivided into the following units: the major part of the blocks belongs to the Beermullah Trough, the south-west part of the blocks is represented by the northern margin of the Vlaming Sub-basin and the Mandurah Terrace is located in the southern part of the blocks (Thomas, 2014). The Barberton Terrace is located between the Yilgarn Craton and the Beermullah Trough along the eastern limits of the exploration blocks (Figure 2, Figure 3 and Figure 4).

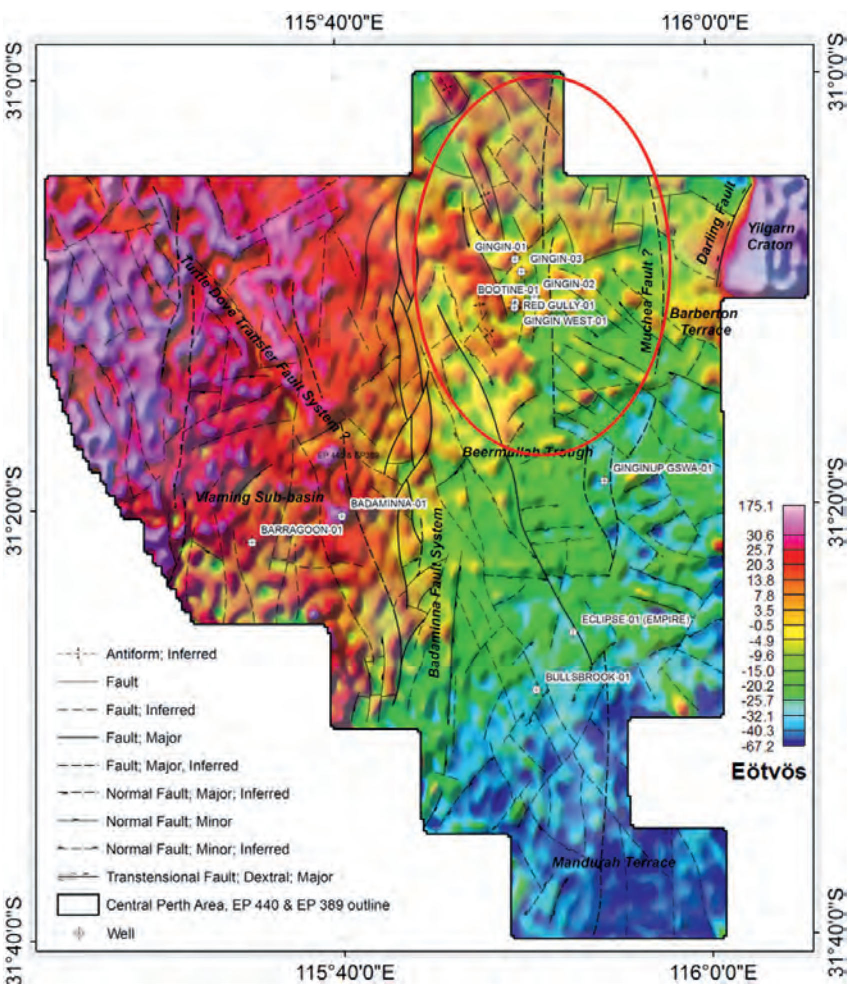

***Figure 2** GDD Fourier 2p0 sun shaded from north-west data overlain by a structural interpretation map of exploration blocks EP 440 & 389. The survey identified areas containing large structural leads and trends in a fairway in northern EP 389 (red ellipse). The prospectivity of some identified leads has been significantly increased by the gas discovery at wells Red Gully North-1 and Gingin-1.*

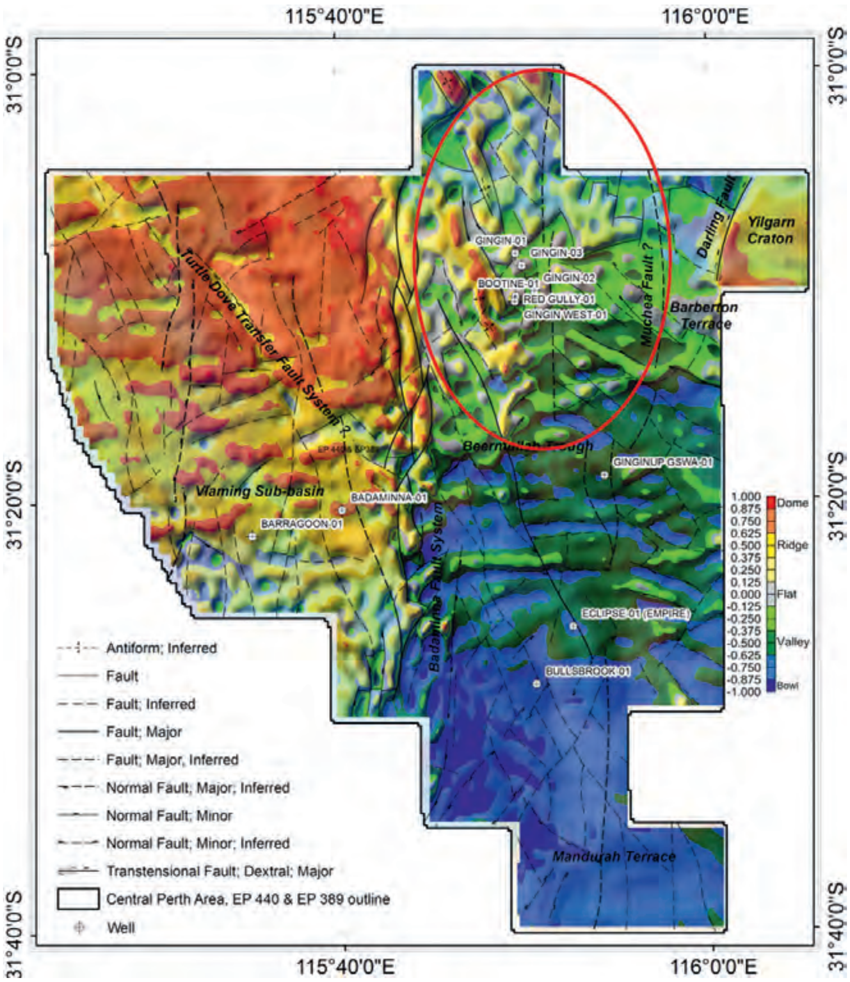

***Figure 3** Shape Index Fourier 2p0 Final sun shaded from northwest data overlain by a structural interpretation map of exploration blocks EP 440 & 389. The survey identified areas containing large structural leads and trends in a fairway in northern EP 389 (red ellipse).*

Crostella and Backhouse (2000) considered the Beermullah Trough to be an unconnected depocentre to the Dandaragan Trough. In AGG data the Beermullah Trough shows low gravity values increasing towards the north (Figure 2, Figure 3 and Figure 4), which would support such an interpretation. Towards the Mandurah Terrace in the south, the gravity values gradually diminish. As the Beermullah Trough has been interpreted to be structurally lower than the Mandurah Terrace (Crostella and Backhouse, 2000), the higher gravity values of the Beermullah Trough are generated by higher-density rocks in its sedimentary sequence. The tectonic pattern of the Beermullah Trough mapped from AGG data consists of north-west and north-east trends, which are offset by north-trending faults. The trough also contains anticlines (Figure 2, Figure 3 and Figure 4), which Crostella and Backhouse (2000) interpreted as compressional structures related to the 'convergence' of the Turtle Dove Transfer Fault and the Cervantes Transfer Fault. The Gingin Anticline west to the Darling Fault in the north-eastern section of the exploration blocks is similarly interpreted as an inversion structure, which has formed from localized compression at a restraining bend along north-northwest trending faults during oblique extension of the final rifting phase.

The Barberton Terrace (Mory and Iasky, 1996) is interpreted as an elongate half-graben bounded by the Darling and Muchea Faults. In the AGG data, the terrace is represented by moderate gravity values, located between the gravity high of the Yilgarn Craton in the east and the gravity low of the Beermullah Trough in the west (Figure 2, Figure 3 and Figure 4). The gravity response is interpreted to be related to the relatively shallow basement, highlighted by overlying higher-density sedimentary rocks. The terrace is cut by north-west faults, partly offset by north faults, parallel to the Muchea and Darling faults

The Mandurah Terrace (Crostella and Backhouse, 2000) is defined as a structurally intermediate fault block between the Yilgarn Craton to the east and the Vlaming Sub-basin to the west, bounded by the Darling Fault and Badaminna Fault System, respectively. Its northern boundary with the Beermullah Trough is vaguely defined and its relationship with the Beermullah Trough is uncertain (Thomas, 2014). In

AGG data the Mandurah Terrace is shown as a gravity low (Figure 2).

Wilkes et al. (2011) interpreted a pervasive set of predominantly northwesterly and northerly striking normal faults in the central Mandurah Terrace (Perth metropolitan area) to explain present-day topographic ridges or depressions and river-bends. This is in good accordance with the fault pattern mapped from newly acquired AGG data to the north (Figure 2, Figure 3 and Figure 4).

The Vlaming Sub-basin (Jones and Pearson, 1972) is located in the western section of the exploration blocks. In AGG data, it is represented as a distinct gravity high, which decreases towards the east (Figure 3). It is cut by north, north-west and north-east trending faults. The north trending set of sub-parallel faults along the eastern margin of the gravity high has been tentatively assigned as the Badaminna Fault System. It has been interpreted as a westerly dipping fault (Thomas, 2014). The Badaminna Fault System separates the Mandurah Terrace in the east from the Vlaming Sub-basin to the west. An elongate residual gravity anomaly straddling the interpreted Vlaming Sub-basin – Mandurah Terrace boundary has been interpreted as a shallowing of basement.

The major regional structures include the north-trending Darling Fault, the Muchea Fault, the Badaminna Fault and the inferred north-west trending Turtle Dove Transfer Fault System. In the AGG data, the Darling Fault is clearly visible as a sharp gradient in the north-eastern tip of the exploration blocks (Figures 2 and 3). The Muchea Fault is tentatively mapped as a north-trending inferred fault system bounding a weak gravity high west of the interpreted Yilgarn Craton. Additionally, the deep-seated Turtle Dove Transfer Fault may be expressed by north-west oriented faults in the middle of the gravity high in the western section of the exploration blocks. The faults are interpreted to propagate from a single major fault zone at depth upwards to the basinal infill in the form of soft-linked sub-parallel secondary faults. The Badaminna Fault System separates the Mandurah Terrace in the east from the Vlaming Sub-basin to the west in a form of north-trending set of sub-parallel faults.

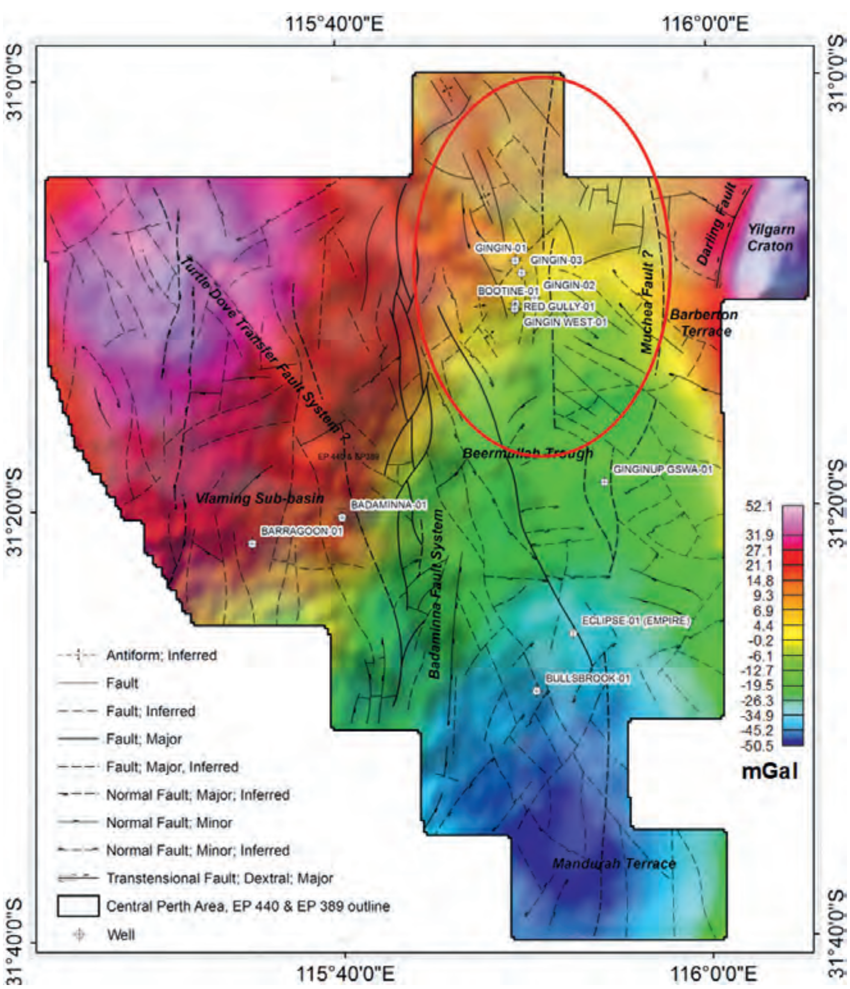

Figure 4 *gD Fourier 2p0 sun shaded from north-west data overlain by a structural interpretation map of exploration blocks EP 440 & 389. The survey identified areas containing large structural leads and trends in a fairway in northern EP 389 (red ellipse).*

Magnetic depth estimation

The aeromagnetic and AGG data in all areas were acquired at a nominal flight height of 100 m along lines oriented east-west with a spacing of 1000 m. When this data is gridded it yields a grid cell size of 250 m. The government magnetic data covers all the areas of interest, has a grid cell size of 87.7 m and also has coverage in between the areas and around them. The data is a compilation of different surveys, and comes from merging surveys carried out mainly by CGG and for which CGG possesses the original databases. If a depth to magnetic basement is calculated using only data inside the exploration block, it would be unable to define deep features, as there is a relationship between the width of an area and the deepest defined magnetic sources of about 10 or 6 to 1, i.e. if magnetic data is defined in a square of 6 km x 6 km the deepest magnetic sources that are possible to define are between 1 km to 600 m in general. It was therefore decided to take the line positions of the CGG databases and sample the government grid over them and interpolated lines at the correct distances over a much large area in to order to: firstly, be as close as possible to the original acquisition positions; and secondly, be able to find meaningful deep magnetic source solutions within the exploration block. Despite extensive drilling programmes undertaken in the Perth Basin, drilling has been largely confined to testing prospects at shallow depths in the NW or W. As a result, detailed geological logs of the wells that reached the deeper sedimentary section and basement are limited. In the exploration blocks, only one well log that has intersected the basement is available: Cadda 1. This well intersected the basement at a depth of 2662 m. This well has been used to calibrate the results. A combination of profile-based automated and manual magnetic depth estimation techniques were used to generate a depth to magnetic basement model. Werner Deconvolution (Ku and Sharp, 1983) and Extended Euler Deconvolution (Mushayandebvu et al., 2001; Thompson, 1982) have been undertaken using the CGG MultiPhysics MAGPROBE magnetic depth analysis toolkit to derive a theoretical depth to magnetic basement solution within windows along both flight lines and tie lines. For the depth to magnetic basement model for exploration blocks EP 440 & 389, the solution window size was varied between 1000 m and 10,000 m and

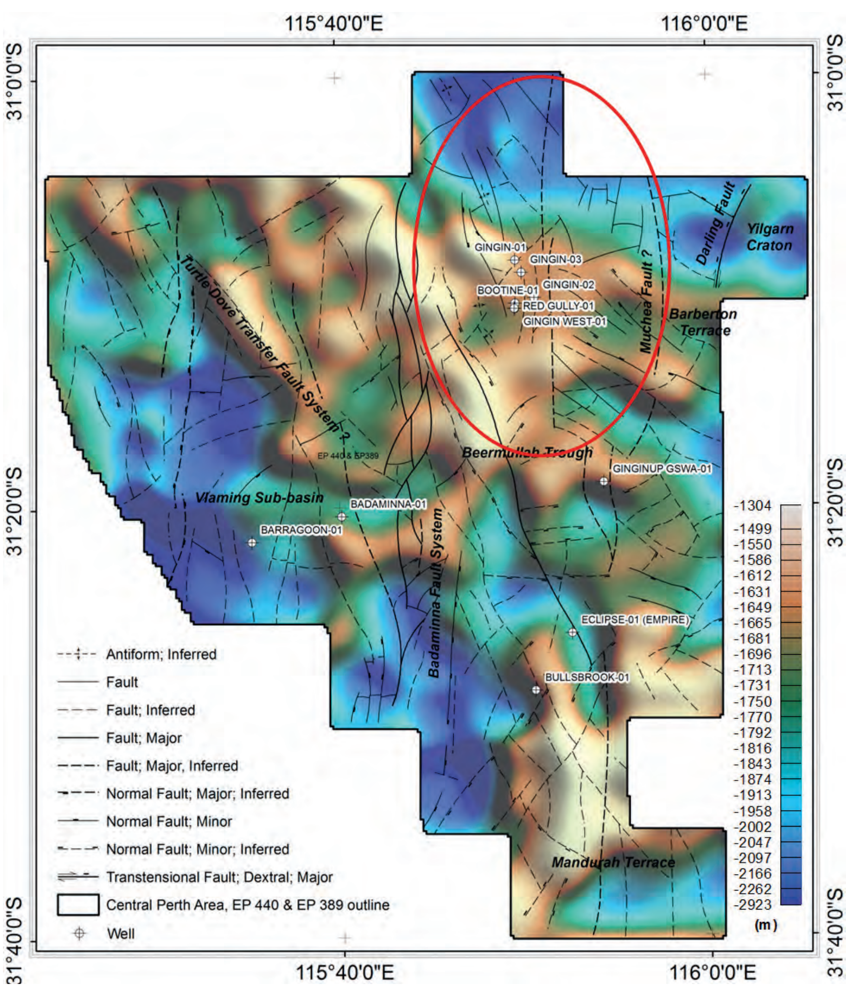

Figure 5 *Depth to magnetic basement overlain by a structural interpretation map of exploration blocks EP 440 & 389. Note that the structural interpretation is derived from AGG data. The survey identified areas containing large structural leads and trends in a fairway in northern EP 389 (red ellipse).*

contact/fault (structural index = 0.0) solutions sets were created in order to obtain magnetic source solutions generated by geological contacts only. Each magnetic source solution set was interpreted and clustered in order to determine an average 'true solution' for the depth to basement that was independent of the solution windows defined above. Results of the clustering process were supplemented with depth estimates from both the Half Slope (Peters, 1949) and Straight Slope (Vacquier et al., 1951) manual methods available within MAGPROBE. Magnetic depth estimation for each flight line was completed by manual interpretation of the magnetic source solution data, from which the depth to basement grid was visually interpolated and generated. The results of this process are presented as a grid of basement elevation relative to the WGS 84 datum. Most of the observed magnetic source solutions fall into two main categories of behaviour of the total magnetic intensity field: high spatial frequencies, associated with close-to-surface magnetic sources; and low spatial frequencies with significant changes in their amplitude, associated with strong changes in the topography of the magnetic basement. Exploration blocks EP 440 & 389 (Figure 5) appear to have three levels of magnetic sources, which makes it very difficult to find the deepest solutions. It is important to point out that the basement here may define a magnetic marker horizon.

Summary and conclusion

The integrated interpretation of the airborne Falcon Airborne Gravity Gradiometer (AGG) survey was designed to assist oil and gas producer Empire Oil and Gas in identifying target areas for hydrocarbon exploration in the Perth Basin. It was developed as a synthesis of the geological structure, tectonic evolution and principles of gravity and magnetic data behaviour. The survey identified areas containing large structural leads and trends for targeting target future gas exploration activities, including infill 2D seismic acquisition.

A recent discovery at Red Gully North-1 shows that there is an active hydrocarbon system within EP389/440. Structural highs identified on the AGG data adjacent to the Red Gully North-1 well (Figure 2) are of particular interest and will be followed up with a 2D seismic campaign. This shows the value of AGG in identifying structural leads and focusing on follow-up seismic.

The integrated interpretation of the airborne AGG data acquired over exploration blocks EP 440 & EP 389 was developed as a synthesis of the geological structure, tectonic evolution and principles of gravity and magnetic data behaviour. Major tectonics include the Beermullah Trough, the northern margin of the Vlaming Sub-basin, the Mandurah Terrace and the Barberton Terrace. The tectonic pattern of the Beermullah Trough consists of north-west and north-east trends, which are offset by north-trending faults. Existing anticlines were interpreted as inversion structures, which were formed from localized compressions at restraining bends along north-northwest trending faults during oblique extension of the final rifting phase. The elongate half-graben Barberton Terrace, presented by medium gravity values, is cut by north-west faults, partly offset by north faults, parallel to the Muchea and Darling faults. The Mandurah Terrace is a structurally intermediate fault block between the Yilgarn Craton and the Vlaming Sub-basin, shown as a gravity low, cut by predominantly northwesterly and northerly striking faults. The Vlaming Sub-basin is a distinct gravity high, which decreases towards the east. It is cut by north, north-west and north-east trending faults.

The major regional structures within exploration blocks EP 440 & EP 389 include the north-trending Darling Fault, the Muchea Fault, the Badaminna Fault and the inferred north-west trending Turtle Dove Transfer Fault System.

The survey identified areas containing large structural leads and trends in a fairway in northern EP 389 (Figures 2, 3 and 4) as the target of future gas exploration activities, including infill 2D seismic acquisition. The prospectivity of some identified leads has been significantly increased by the gas discovery at wells Red Gully North-1 and Gingin-1.

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