FALCON® AIRBORNE GRAVITY GRADIOMETRY PROVIDES A SMARTER EXPLORATION TOOL FOR UNCONVENTIONAL AND CONVENTIONAL HYDROCARBONS: CASE STUDY FROM THE FITZROY TROUGH, ONSHORE CANNING BASIN

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A FALCON® airborne gravity gradiometer (AGG) survey was flown over the Yakka Munga area of the Fitzroy Trough, onshore Canning Basin in December 2011. The 3336.8 line km survey centred on the Ungani oil field over a survey area of approximately 1400 sq. km. Regional gravity and 2D seismic data, along with the Ungani-1 and 2 wells in the area and wells Yulleroo-2 and Frome Rocks-1 in the vicinity were utilised in an integrated interpretation of the AGG data. Integrated geological and geophysical interpretation, including depth to basement, 2D modelling and 3D inversion, revealed the particular usefulness of AGG data for mapping intra-sedimentary and basement faults, basement highs, sedimentary depocentres, salt diapirs and volcanic intrusions. Additionally, prospective structural and stratigraphic plays in the area are highlighted.

Conventional vertical gravity (gD) from the AGG survey better defined the longer wavelength features, typically the major tectonic elements such as basin bounding faults, and relative sediment thickness. Comparisons with the regional gravity data showed that the gD reproduced all the information available in regional gravity. At shorter wavelengths, the vertical gravity gradient (GDD) of the AGG data has much higher sensitivity than the regional gravity dataset. The GDD is more sensitive to subtle density contrasts and has greater spatial resolution than gD, therefore, it provides more detail than gD by imaging smaller and shallower sources. The increase in resolution allows for contacts to be mapped more accurately, and significantly increases the confidence of the 2D seismic interpretation. Enormous potential exists for conventional and unconventional oil and gas in the Fitzroy Trough, a proven petroleum province. The AGG survey flown includes the simultaneous acquisition of high resolution gravity gradiometer, magnetic and DTM data from one airborne platform. The data acquired is used to generate a high resolution geological model over the study area which is then used as input in the

3D inversion. Following the calibration of the structural information present in the geologic model, the output density model and basement surface can be used to optimize exploration programs and plan future seismic acquisition through improved knowledge of the subsurface structural, density and depth distribution. A number of plays identified by the associated structural and stratigraphic interpretation may provide leads for shale gas, tight gas and conventional oil & gas exploration.
***KEY WORDS**: Onshore Canning Basin, Fitzroy Trough, FALCON® Airborne Gravity Gradiometry, Structural Interpretation, 2D Models, 3D Inversion, Depth to Magnetic Basement, Oil & Gas Exploration, Shale Gas, Tight Gas.*

Introduction. For many decades, seismic data has been the industry standard exploration tool in the search for hydrocarbons. There has been a general reluctance throughout the industry to embrace potential field data and in particular gravity data in their exploration workflows. Traditionally, conventional gravity data has been time consuming to collect and the resolution of available data is often inadequate for delineating prospect scale features.

FALCON® Airborne Gravity Gradiometry (AGG) challenges that viewpoint and combines a cost effective, low noise, high resolution vertical gravity gradient (GDD) and gravity (gD) product with the rapid acquisition of an airborne platform.

The use of this technology is becoming more widely accepted throughout the industry, with recognition that the data benefits all stages of the exploration workflow. From regional reconnaissance to prospect evaluation FALCON® AGG can mitigate risk and add value through;

- Mapping of key structures, depocentres and basement highs
- Optimizing planning of seismic programs
- Validating seismic interpretation
- Enhancing 2D seismic structural correlation
- Integrated interpretation and modeling projects

This paper describes the results of the "Yakka Munga" AGG survey flown over Buru Energy's recent oil discovery at Ungani-1, in the Fitzroy Trough of the onshore Canning Basin in Western Australia.

Fugro Airborne Surveys has acquired FALCON® AGG and aeromagnetic data at 500m line spacing, for 3,337 line-km over nearly 1,400 sq. km of Buru Energy's EP 391 and EP428 JV holdings in the onshore Canning Basin. The initial survey objectives were to prove the concept that FALCON® AGG can provide detailed structural information over an area that has the control of relatively extensive 2D seismic data.

From the outset, the expectation was to be able to map the half-grabens and rotated fault blocks of the basin as the basement falls away towards the north from the Broome platform into the Fitzroy Trough. In essence though, the FALCON® AGG survey went significantly further than that. Integrated interpretation of the survey data, utilizing available well information and seismic data, has demonstrated the ability of FALCON® AGG to map the four-way closure extent of the Ungani-1 oil discovery, and potentially identify additional analogous closures that warrant follow up.

Fitzroy Trough. The survey area lies to the east of Broome on the southern flank of the Fitzroy Trough, where it dramatically shallows up onto the Broome Platform (*Figure 1*). The dominant structural feature within the survey area is the Fenton fault system, where the trough deepens northwards off the Jurgurra Terrace.

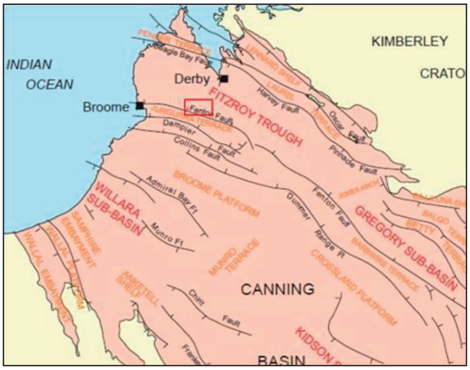

Figure 1 – **General tectonic elements, onshore Canning Basin including survey location (red). (modified from Brown et al., 1984)**

It is postulated that the Fitzroy Trough began to open in the Devonian (Drummond et al., 1991) with a number extensional phases through to the Permian, resulting in the normally faulted trough. Later transpression during the Jurassic inverted some of the larger faults and created a series of

Figure 1 General tectonic elements, onshore Canning Basin including survey location (red). (modified from Brown et al., 1984)

rolling folds within the sedimentary package, which has been estimated to be 10km thick or greater at its deepest. It is at the core of one of these anticlines on which the Ungani-1 discovery is located. The reservoir is hosted in Famennian limestone (*Figure 2*), equivalent to the Yellow Drum and Nullara formations of the Blina field, on the northern side of the trough. Since the Jurassic compression, very little deformation (other than minor down warping) is evident in this portion of the Fitzroy Trough.

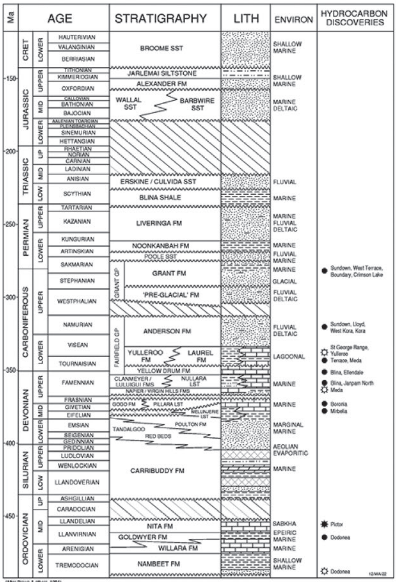

Figure 2 – **Generalized stratigraphy of the Canning Basin with major petroleum occurrences indicated (after Cadman et al., 1993)**

Other play types will vary both geographically and stratigraphically. Fracture systems associated with transfer faults connect the margins to the deeper Fitzroy Trough and may impact migration and permeability in the carbonate reservoirs on the trough flanks. Unconformity traps and draping reservoirs over rotated fault blocks, inversion folds, stratigraphic traps and possible salt related traps, all have real potential in this large, and under explored basin with proven producing ability.

Potential Field Data

Regional Data. In any interpretation project, the available regional data is extremely useful in anticipating the structures present in the survey area. Regional scale structures and trends tend to be repeated on the survey scale and larger structures have the potential to be missed when only looking at the ‘postage stamp’ dimensions of a discrete survey. The Geoscience Australia (GA) national gravity and magnetic datasets were utilized in this case, and proved to be of good quality, each delineating different, broad aspects of the general basin architecture. The Fitzroy Trough is clearly defined on the gravity and magnetic images, as are some interpreted intrusive complexes within the trough itself. These are defined by large positive anomalies in both the gravity and magnetic datasets. Northeast - southwest transfer faulting is evident across the Fitzroy Trough, perpendicular to extension, truncating or offsetting linear features.

FALCON® Survey Data. The survey was acquired at 500m line spacing and as a result the Geoscience Australia regional magnetic dataset (compiled from tighter linespaced surveys in this area) is actually an improvement on the magnetic data survey from the survey itself; however that is where the usefulness of the magnetic method reaches its limitation. As far as interpretation goes, the magnetic dataset offers very little structural information due to the magnetically transparent basin sediments and the very deep basement which is estimated to be between 4 and 8km depth across the survey area (*Figure 3*). A number of dykes were identified in the northeast, and Euler depth to source calculations undertaken, but beyond that there was very little structural or geological information to be extracted from the magnetic data, especially from the target levels within the sedimentary package.

The FALCON® AGG GDD response however, provides a very clear representation of the anticipated trends, paralleling the main basin fabric (*Figure 4*).

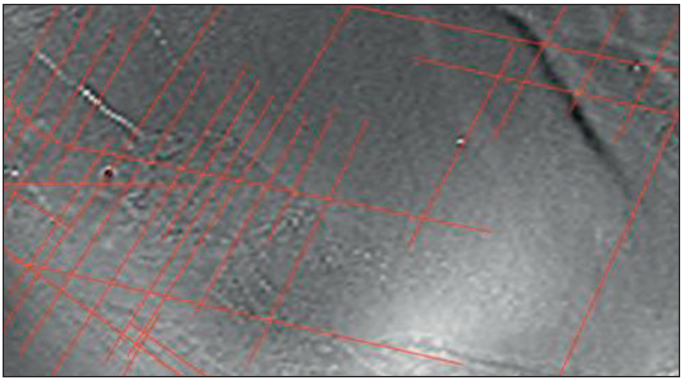

Figure 3 – **Magnetic First Vertical Derivative from the Yakka Munga AGG survey area, with available seismic lines shown (red)**

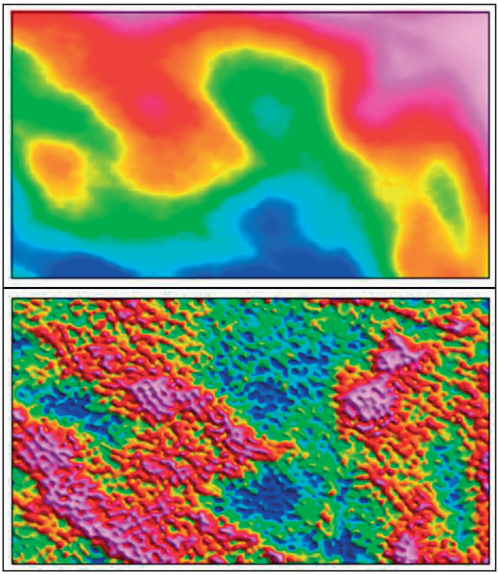

Figure 4 – **Conformed g_D image (Top) and the unfiltered GDD image (Bottom) from the Yakka Munga AGG survey.seismic lines shown (red)**

The G_{DD} data also exhibits a significant improvement in spatial resolution which enables detailed integrated interpretation. Instrument noise is always a consideration with airborne surveys, and the system noise results for this survey were excellent, with values of 1.35 and 1.34 Eotvos for the FALCON® AGG system's NE and UV curvature components respectively. The system noise is defined to be the standard deviation of half the difference between the A & B complements, for each of the NE and UV curvature components.

Data processing and transformations. The FALCON® AGG data was terrain corrected at a standard 2.67g/cm3. There is a very minor terrain component in the data over one or two of the dunes in the northeast of the survey area, but overall, the terrain density value appears adequate over the relatively flat survey area. A number of products were derived from the FALCON® AGG data of which, the pseudo-depth sliced images (Figure 5; top) proved to be most valuable in the interpretation of the area. Filtering by this method effectively removes the high-frequency response of some of the shallow sources that are inconsequential for hydrocarbon exploration and allows for better imaging of the interpreted dolomitised limestone at depth.

As with any airborne survey, the maximum wavelength that can be resolved is directly related to the survey size, so the FALCON® AGG gD data is conformed to the longer wavelengths of the Geoscience Australia "Gravity Anomaly Grid of the Australian Region (June 2009)" (GAGAR09) to provide a full bandwidth gravity image (Dransfield, 2010). In this case the two datasets were merged with a cosine squared filter tapering between 20 and 30 km, and provides a seamless dataset, capturing the full spectrum of the gravity field (Figure 4). It shows a strong gravity low in the south-west corner and along the southern flank of the survey potentially indicating that the Jurgurra terrace is a rotated fault block, with basement surface dipping south, back towards the Broome platform.

Interpretation and discussion. Closer investigation of the G_{DD} data in conjunction with the available seismic and well information suggests that the G_{DD} is imaging the density contrast between typical basin fill sandstone/shale/limestone assemblages and a dolomitised limestone of higher density. This contrast is in the order of 0.2 to 0.25 g/ cm^3 and is ideal for gravity surveying, particularly with the increased resolution that FALCON® AGG offers over conventional methods.

The major normal fault system, and a number of northeast trending transfer faults in the area are clearly identified as are a number of folds which trend generally east-west, one of which contains the Ungani-1 well and oil accumulation. It is worth reiterating that none of this information is evident in the magnetic dataset.

There is no doubt that the geology in this particular survey area is favourable for the FALCON® AGG method, however there is also strong evidence to suggest that these geological conditions will extend throughout a large portion of the Fitzroy Trough. The Blina oilfield reservoirs for example, on the Lennard Shelf on the opposite side of the trough, also consist of dolomitised limestones. The extent of the dolomisited limestones and reefal facies parallel to the trough boundary can be reasonably expected to continue for some distance along the trough margins, given the similarity of the deformation and burial history along the length of the Fitzroy Trough. There is also the possibility of some reef development on basement highs within the trough itself which may prove to be suitable FALCON® AGG targets.

Comparison with simulated airborne gravity. As demonstrated with this survey, the FALCON® AGG system is clearly mapping structure where the sources are 2 to 4 km deep. Depending on the geological structure the GDD wavelengths observed from this depth are between typically between 1 and 5 km which may not be recovered from a conventional airborne gravity survey due to the heavy filtering required. There is no doubting that the larger gravity anomalies will be detected by conventional airborne gravity (Figure 5), however the subtle lineaments and amplitudes that define the structures of

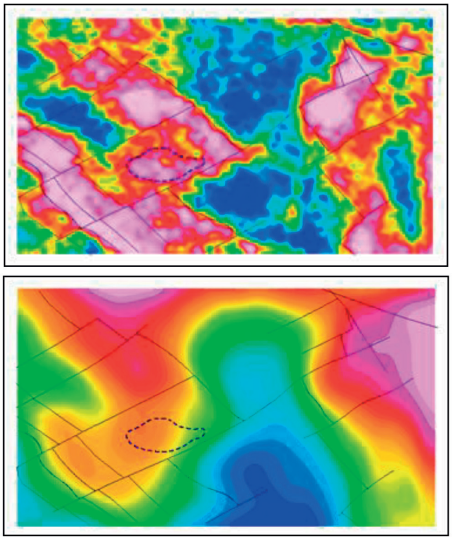

Figure 5 – **Filtered FALCON® GDD image (top) and simulated airborne gravity image (bottom). Basic AGG derived lineament interpretation and possible Ungani closure (dashed) interpreted from AGG shown for comparison. Survey width is ~48km.**

interest at the prospect scale mean that the increased resolution provided by FALCON® AGG is imperative to the success of any interpretation project with that goal.

Figure 5 shows the G_{DD} image and interpretation compared with a simulated conventional airborne gravity survey. The simulated data was derived from the FALCON® AGG conformed g_D dataset, but at 2km line spacing and with a 100 second low pass filter applied to the line data, consistent with published survey specifications (Dentith and Cowan, 2011). It is also worth noting that in their discussion of the Amadeus Basin airborne gravity survey, Dentith and Cowan (2011) reported that the tie-line crossover point mismatch approaches 0.75 mGal and for repeat survey lines approaches 1 mGal rms difference. The FALCON® AGG interpreted lineaments along with the interpreted Ungani closure have been overlaid on the simulated airborne gravity result for comparison.

One of the critical aspects with respect to a successful geological interpretation of geophysical data is integration. All of the geophysical measurements are measuring the geophysical properties of the same rocks and therefore must tell a common story. There is little point in modelling a gravity or magnetic profile with extremely low misfit if those models don't concur with the seismic data or density and susceptibility measurements from well data. Conversely, if the seismic interpretation does not fit with the observed gravity gradient or magnetic data without a valid explanation (e.g. off-line anomalies or depth to source), then that interpretation must be re-visited. Once the model has accord with all available data, one can have a much greater degree of confidence in that interpretation.

In the case at Yakka Munga, the primary focus of the integrated interpretation was the gravity gradient data and the seismic imaging, coupled with the available logs from the nearby wells. The magnetic dataset in this case does not reflect any structure in the intra-sedimentary sequence, where the petroleum traps are located.

Efficient future 2D seismic survey planning. 2D seismic coverage in the west of the survey area is relatively dense with various vintages of data from the 70's to present day, and as proof of concept and validation of the FALCON® AGG method, this information is invaluable, which is why this area was chosen as a test of FALCON® AGG's capability. Consider the case though, where only 10% of those seismic lines were available; the structural trends obtained from the FALCON® AGG survey would allow clear line to line correlation of faults, including any transfer fault offsets that may be missed in the seismic interpretation. The FALCON® AGG result would most certainly allow the explorer to identify many of the major structures and focus areas of interest for future seismic work.

The next obvious (and arguably most valuable) application is where there is no pre-existing seismic data. Given the geological setting at Yakka Munga, a FALCON® AGG survey alone would allow rapid mapping and identification of key structures. While certainly not suggesting FALCON® AGG alone will provide drill ready targets, it will provide an extremely cost effective way of planning the most efficient seismic survey for the area in question, saving many kilometers of unnecessary seismic data over non-prospective areas. It could be argued that the cost of an FALCON® AGG survey will be clawed back through the savings it can grant on any future seismic program, and once acquired at the early stage of a project, FALCON® AGG also provides an excellent validation tool for the seismic interpretation, constantly adding value throughout the life of an exploration program. Once integrated with seismic and some understanding of the geology and density relationships have been obtained, FALCON® AGG will certainly provide a tool to assist and possibly improve well positioning, with FALCON® AGG's ability to build a third dimensional element from 2D seismic data.

Ability to map closures. The four way dip closure of the Ungani oilfield as interpreted from seismic is an elongate, roughly east-west trending anticlinal closure. That same geometry is exhibited in the GDD data with an approximately 5 to 7 Eotvos GDD high anomaly over the anticline (*Figure 6*), which matches extremely well with existing interpretations. Not surprisingly, this structure is not seen in the magnetic data and from the airborne gravity comparison above, would not have been defined well with conventional airborne gravity due to its relatively short wavelength and low amplitude of ~0.7 mGal.

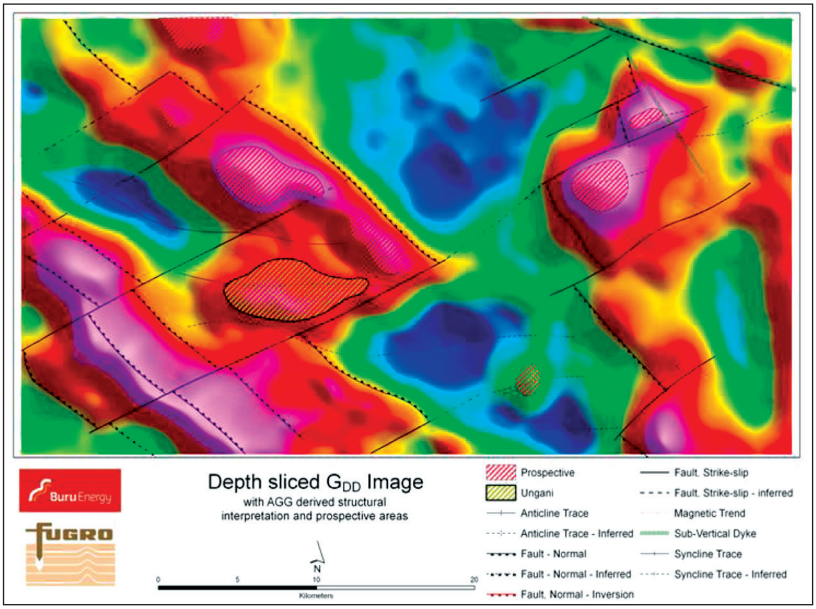

Figure 6 – **Pseudo depth sliced G_{DD} image with interpretation and the gravity high over the Ungani oil discovery outlining the potential closure as interpreted from AGG. Other potential closures identified**

Modelling suggests that the vertical relief of the dolomitised limestone surface is largely responsible for the GDD response with the anticline effectively bringing the high density unit(s) closer to the gravity gradient sensor, hence the anomalous GDD values. A simple search for nearby analogues reveals a number of targets in the immediate area that may very well have the same causative structural geometries (Figure 6).

Effectively map basin architecture. The deeper basin architecture is also mapped to some extent by observing the major margin parallel structures in the FALCON® AGG data. The sharp, laterally extensive breaks indicate large faults offsetting the high density carbonate layers, with the downthrown side exhibiting a gravity low. These faults are interpreted to be basement controlled, and part of the normally faulted blocks and terraces making up the southern flank of the Fitzroy Trough.

Structural interpretation. The GDD image shows generally elongate basin parallel gravity highs in the western side of the survey area. It is interpreted that these represent the northern edge of the Jurgurra terrace and the trace of the Fenton Fault that has undergone inversion in this area. The Fenton fault system may be stepped across the area here through soft accommodation mechanisms. Numerous splays and the discontinuous nature of the fault system are evident from the FALCON® AGG data and can be also identified on seismic data.

On the eastern third of the survey area, the elongate, northwest-southeast trending character of the western portion is not evident and the area is dominated by a relatively isolated high, cross-cut by the major dextral transform of the area. This portion of the area is interpreted to contain a series of normal faults, antithetic to the Fenton Fault system, which may be offset by a north-south trending fault related to the Jurassic compressional event (SRK Consulting, 1998). This leaves a zone between the two fault blocks, where the high density limestone units are interpreted to be downthrown relatively deeply in contrast to the level of the adjacent fault blocks. This is imaged through the centre of the survey as a general area of G_{DD} low crossing the area from north to south.

A large dextral transfer fault trending northeast-southwest across the centre of the area is clear and the gD response may indicate that the southeast side of this fault is downthrown as well, with the gravity response distinctly lower on this side. The g_D is also trending towards a high on both the northern and eastern sides of the survey. These are most likely the effects of the high amplitude magnetic and gravity anomalies associated with interpreted intrusive bodies to the north and the east of the area.

To complete the interpretive structural map, faults have been identified on the g_D and G_{DD} images (and their enhancements) by truncations and terminations in continuous anomalies, along with areas that exhibit a steep gradient as would be expected from a vertical offset of strata and associated density contrast. It can be difficult at times to distinguish between the anomalies created by faulting and folding in the area given the causative geology, however these were quickly confirmed where possible with seismic data and/or forward modelling. Once the structure type is confirmed, it is a relatively straightforward task to map the trace of the structure in question due to the quality of the data (*Figure 7*).

The orientation of the major normal faults within the survey area is consistent with the regional picture, as are the transform faults. The observable range in offset of these transform faults in the FALCON® AGG data is from only a few hundred metres to an apparent offset of nearly 10km on the major structure in the centre of the survey.

Magnetic Modelling. The magnetic image and enhancements show a number of relatively sharp linear anomalies, particularly in the northeast of the survey area. These are interpreted to be Permian to Triassic mafic dykes and have been modelled as sub-vertical bodies with a depth to top of approximately 1400m. Given their orientation and location, these are most probably related to the interpreted intrusives some 30 km to the north and east of the area although no dating or relative timing investigation was undertaken during the course of this paper.

2D Gravity Modelling. FALCON® AGG surveys have traditionally been pitched at minerals exploration companies in Australia, because of its high resolution and ability to detect shallow sources. While this is certainly true, FALCON® AGG appears to have been erroneously designated as being more applicable over very shallow targets. The

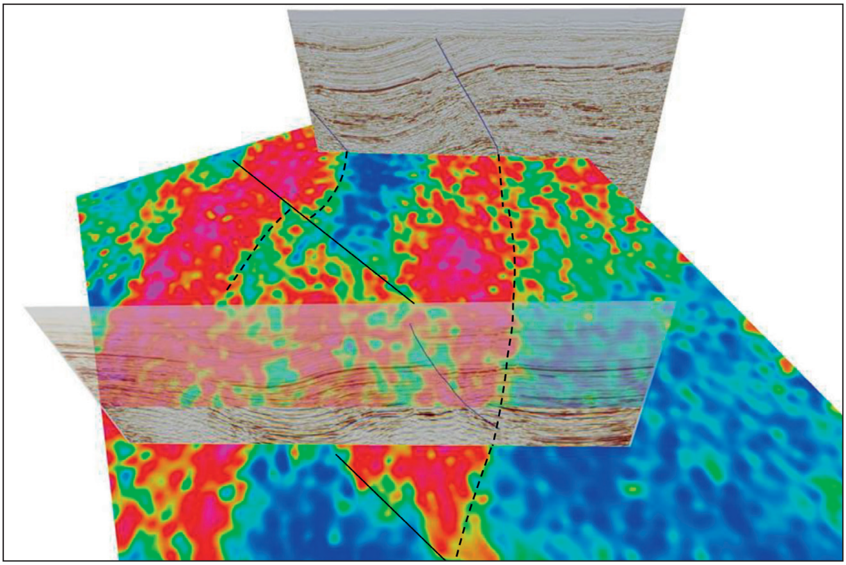

Figure 7 – **Example of the relative ease of interpreting between wide spaced seismic lines. Blue faults on seismic are joined with confidence (black dashed trace) and transfer faults readily identified**

results from this survey show that FALCON® AGG provides an extremely accurate and cost effective way of measuring the gravity anomaly at wavelengths applicable to the petroleum industry, with targets of several kilometres depth being clearly resolved.

A 2D model was constructed over one of the key seismic lines that runs through the Ungani-1 well (*Figure 8*). Having the well on the section allowed the model to be constructed with depth control, lithological and density information. It also allows extrapolation of these physical properties along the seismic horizons, which provide the required constraint to the model.

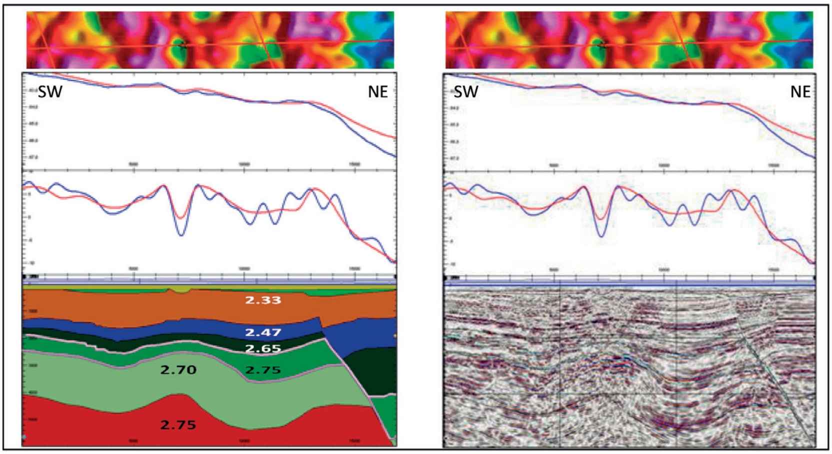

Figure 8 – **2D model over the Ungani oil field showing the geophysical model and the depth converted seismic image, both with the G_{DD} and g_D modelled and observed data curves above. A G_{DD} image is shown (top) along the seismic line**

The results of this modelling show that structure in the high density dolomitised limestone is dominating the GDD signal, which allows visualization of the faults (where high density units are juxtaposed against lower density units) and folds (where the high density units move nearer or further from the sensor) in the sedimentary sequence.

The broad GDD high over the Ungani anticline mimics the geometry of the folded geology below and the sharp drop in gD and GDD to the northeast clearly represents the displacement of a major fault interpreted from both seismic and FALCON® AGG data.

3D models and inversion. A 3D model was created over the survey area (*Figure 9*), consisting of a number of depth converted horizons interpreted from seismic. Fault planes were interpreted in 3D using interpreted traces derived from the FALCON® AGG data and dip information coming from seismic imaging. A deeper basement surface was derived from a number of sources including SEEBASE and selected 3D Euler solutions from the magnetic and gravity data. This model was constructed to test the interpreted geological model against the geophysical data from the FALCON® AGG survey.

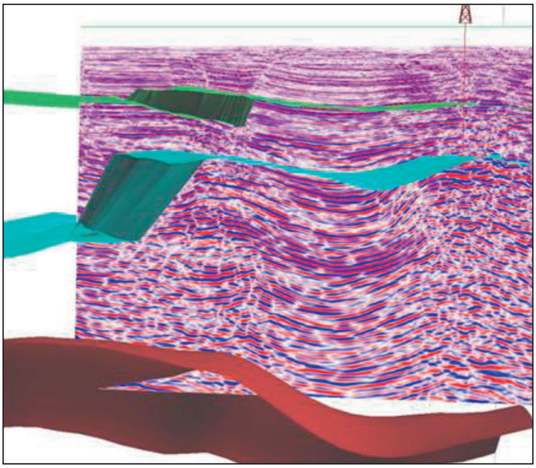

Figure 9 – **Example of 3D model constructed using seismic horizons and well information. Basement surface derived from AGG data inversion**

Density values were applied to the various layers of the model based on the available well data and the gravity gradient and gravity responses were forward calculated. The result from this model is, in general terms, very similar to the measured data. This again highlights the fact that the majority of the signal is coming from the high density dolomitised limestone, which is the key density contrast in this model.

Inversion of the 3D model, where the physical properties or geometry of the model are iteratively altered to better fit the measured data were conducted in an attempt to resolve the depth to basement for the survey area. Using the gD measurement and allowing the basement surface to move, resulted in a basement depth ranging between 4km in the southwest to 8km in the centre of the area. While these are reasonable figures, and the misfit between the observed and calculated anomalies are very low (Figure 10), more work is required to better constrain the basement topography as there are discrepancies between the magnetic depth estimates, the FALCON® AGG derived depth estimates and the modeling results.

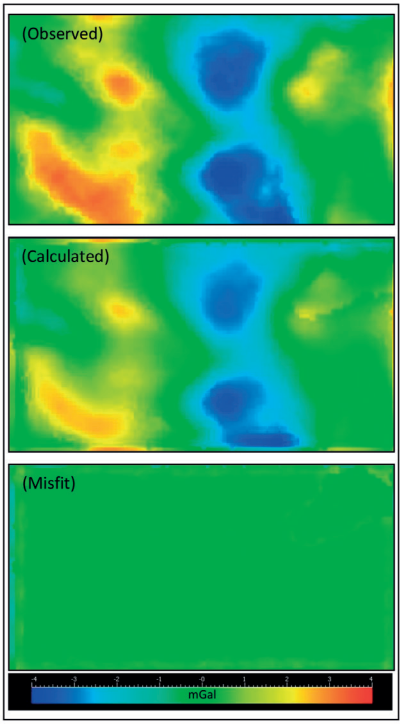

Figure 10 – **Observed, calculated and misfit gravity grids of the constrained inversion for depth to basement. All images have identical colour stretch between -4 to 4 mGals.**

Summary and Conclusions. The FALCON® AGG survey over an approximate 50km x 27km area surrounding the Ungani-1 discovery well was commissioned by Buru Energy as a 'proof of concept' survey for the FALCON® AGG technology and its ability to map structures that may not be observed with magnetic methods and therefore more efficiently plan future seismic work. The area had good geological control from relatively dense 2D seismic and also the geological constraint provided by the well logs and lithologies.

The g_D and G_{DD} images and a series of derivative images were produced and an integrated interpretation project undertaken by Fugro Airborne Surveys (Perth). The FALCON® AGG interpretation has identified the key faults and folds in the area. The local geology and associated density contrasts of the limestones/sandstones +/- salt, coupled with the stratigraphic traps identified, open up the entire Fitzroy Trough to FALCON® AGG being one of the key exploration methods from early reconnaissance project generation through to enhanced prospect definition.

The proof of concept objective was surpassed and the data quality allowed the project to go beyond simple structural mapping and towards prospect targeting. The anticline containing the Ungani oil accumulation is imaged quite clearly with the FALCON® AGG system, as are several other potentially similar structures. None of the structural or prospect generation information is evident in the magnetic data in the area. Transfer faults, perpendicular to the trough edge were also imaged very well by the FALCON® AGG. These features are again, not evident in the magnetic data and are very difficult to define on seismic sections. This highlights the fact that FALCON® AGG data can greatly benefit interpretation results when integrated with seismic data where available.

Key outcomes for this survey:

- Mapped the structural framework of the basin in the survey area by clearly defining the normal faults that control the geometry of the basin in this area.
- Identified and outlined the approximate geometry of the closure of the known producing structural trap.
- Identified other areas of potential interest for hydrocarbon exploration.
- Provided clear evidence that FALCON® AGG can add significant value to the exploration workflow in the Fitzroy Trough and in sedimentary basins in general.

Used early in the exploration workflow, FALCON® AGG can considerably reduce the cost of exploration by improved positioning and allowing the total number of kilometers of seismic data to be reduced while still covering the areas of key interest. Additional to these seismic survey efficiencies, the FALCON® AGG data significantly increase the value of that seismic data by 'infilling' between the lines and effectively giving the 2D seismic data a 3D component, allowing much greater confidence in any forthcoming interpretation. By utilizing the data in this way the cost of any FALCON® AGG acquisition program will typically be repaid many times through the life of a project area to maturity.

In summary, FALCON® AGG surveys are being acquired and delivered in a timeframe of months, at 5-10% of the cost of a loose grid of 2D seismic data. This is allowing operators to focus their seismic programs towards prospect-delineation sooner, and get to drill ready prospects faster and more cost-effectively.

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