Improved Imaging of the Subsurface Geology in the Mowla Terrace, Canning Basin using Gravity Gradiometry Data

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SUMMARY

A study was undertaken to test whether it is possible to map basement configuration and sedimentary horizons from the gravity gradiometry (AGG) data. This was within the EP431 Buru Energy permit on the Mowla Terrace in the onshore Canning Basin.

By applying the Horizon Mapping method, using Energy Spectral Analysis Multi-Window-Test as described in the Methodology section (ESA-MWT), to AGG data, we conducted a test study on a narrow 8km long swath along 2D seismic traverse HCG-300, and at three wells: Pictor -1, Pictor-2 and Pictor East-1, with three additional wells located nearby.

ESA-MWT was applied to gridded Bouguer and tensor gravity data. The ESA-MWT procedure was conducted at stations 1km apart. At each station, multiple spectra were computed over incrementally increasing windows. For each spectrum, the depth was interpreted and plotted versus window size, and from these graphs, multiple *Depth-Plateaus* were detected at each station. These *Depth-Plateaus* correspond to density contrasts within the sediments and the underlying basement. These were then laterally merged with those from adjacent stations to form density interfaces. The results were validated with seismic and the litho-stratigraphy from well data which showed a good correlation with the tops of several sedimentary formations and intra-formational lithological boundaries. Ten density interfaces were mapped: Top Precambrian Basement, Top Nambeet Formation, Intra-Willara Interface, Top Acacia Sandstone, Top Willara Formation, Intra-Goldwyer Interface, Top Goldwyer Formation, Top Nita Formation, Intra-Tandalgoo Group Interface and Intra-Tandalgoo Group Interface.

The geological model built along the Test Profile from interpretation of the AGG data shows good correlation with the wells and seismic data.

Key words: Gravity gradiometry, Sedimentary horizon mapping, Correlation with wells and seismic.

INTRODUCTION

Potential field data integrated with seismic and well data can assist in petroleum exploration especially in an area where seismic is limited or has difficulties, such as the onshore Canning Basin. The thick carbonate sequences makes the interpretation of seismic data difficult and challenging due to poor signal penetration. In this area, magnetic data can be used to map basement configuration and faults in 3D, but mapping sedimentary boundaries is difficult due to weak magnetic susceptibility contrasts within the sedimentary sequences. The use of gravity gradiometry data facilitates the mapping of density contrasts between basement and overlying sediments, and also multiple intra-sedimentary density interfaces, such as the top of carbonates.

By applying the Horizon Mapping (ESA-MWT) and Fault Detection (using Automatic Curve Matching or ACM; see Methodology) methods to high resolution airborne gravity gradiometry and aeromagnetic data, a study was conducted along the seismic traverse HCG-300 located within the EP431 permit over the Mowla Terrace in the onshore Canning Basin, Western Australia (Figure 1). This study was undertaken to test the possibility of mapping the basement configuration, sedimentary horizons and major faults in this area from the potential field data.
Both of the applied methods have been used successfully in many other petroleum provinces, with complex geology and thick carbonates or problems due to the presence of volcanics, thick salt layers or salt diapers. The successful results of this test could add significant value to exploration and be applied to other areas of the Canning Basin.

The test area is a narrow 8km long swath along the vintage 2D seismic traverse HCG-300 and utilised three wells located nearby (Figure 1). Lithological and stratigraphic information from these petroleum exploration wells: Pictor-1, Pictor-2 and Pictor East-1 was used to correlate the detected density contrasts with the geology. Horizon Mapping tests were conducted at the location of three additional petroleum wells: Antares-1, Mowla-1 and Edgar Range-1 located in the vicinity of the project area. The results from the Horizon Mapping tests together with the litho-stratigraphic data from these wells, was used to gain an insight into the subsurface geology of the region. It also provided valuable geological constraints during the Horizon Mapping procedure (Figure 2). The next phase of this study would apply these methods in adjacent areas where there is sparse seismic coverage.

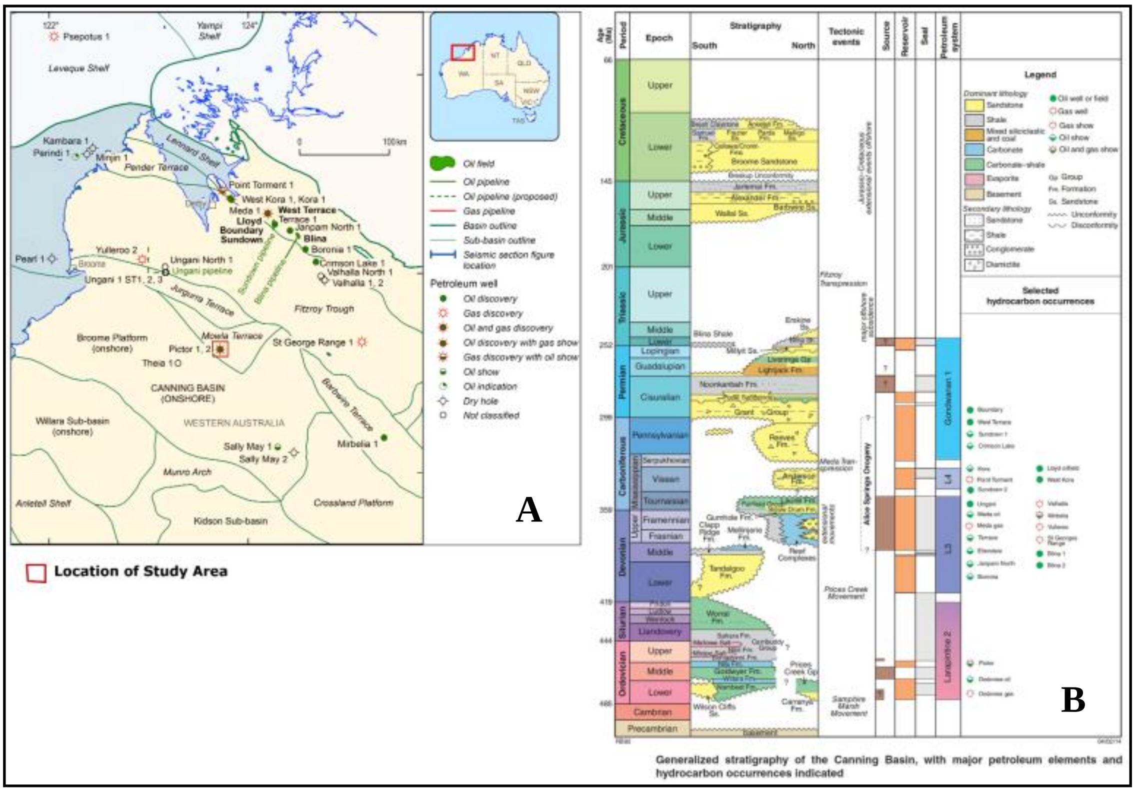


Figure 1 A; Location of study area
Figure2 B; Stratigraphy of the Canning Basin (after WA Mines & Petroleum)

DESCRIPTION OF THE GRAVITY GRADIOMETRY DATASET

The airborne gravity gradiometry (AGG) survey data was acquired in 2015 by CGG over the EP431 permit in the onshore Canning Basin. The survey was flown using 1km spaced NS traverses with EW tie lines, 10km apart, at an altitude of 100m. The magnetic data was publically available on the GA website.

As the sample spacing along the flight lines is significantly less than flight line spacing, a two-stage gridding procedure was conducted to utilise all of the observed data. The data was first gridded over a 500m by 50m mesh using the minimum curvature algorithm with a 50m interval along the flight lines, followed by a bicubic spline algorithm to generate the final grids at 50m by 50m. The two-stage gridding process was applied to all six tensor components, as well as the Bouguer gravity (gD) data (Figure 3 A & B).

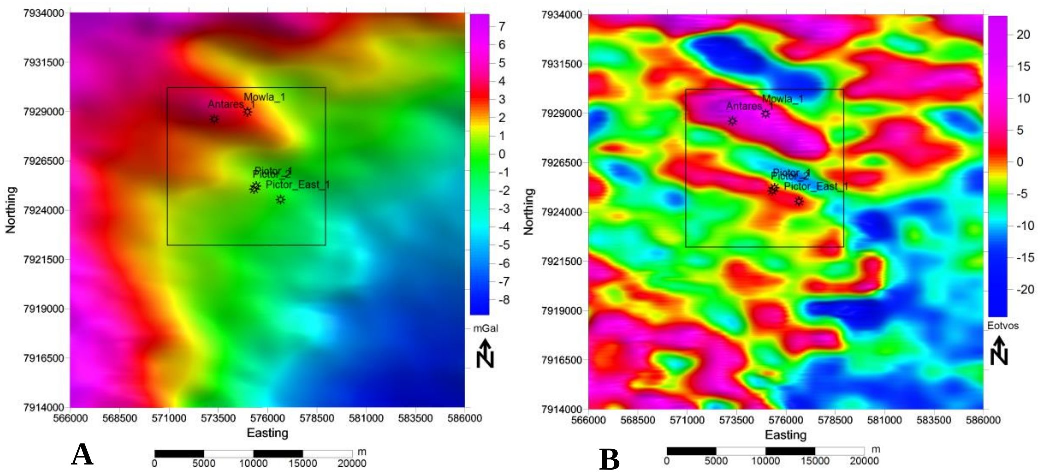


Figure 3 Bouguer Gravity (A) and Vertical Gradient or GDD (B) images covering the Study Area.

DESCRIPTION OF THE AEROMAGNETIC DATA

The airborne magnetic survey over the study area was acquired by UTS Geophysics in 2009. The survey was flown with north-south flight lines spaced 400m apart while the east-west tie lines were spaced 4km apart. The magnetic data was supplied by Geoscience Australia and was gridded on a 100x100m mesh. The average terrain clearance for the magnetic survey was 60m. The datum used in this study was GDA94 and projection MGA 51S.

The magnetic data covering the study area in EP431 was extracted and standard processing was applied to the Total Magnetic Intensity (TMI) grid to produce the Reduced To Pole (RTP) field and the 1st and 2nd vertical derivatives of RTP (Figures 4 A & B). The magnetic inclination for the centre of the study area is -50.01 degrees and the declination is 2.6 degrees. The total magnetic intensity for the area is 50,755 nT.

Profiles for ACM processing were extracted in north-south and east-west directions at 100m intervals, and at 71m intervals for NW-SE and NE-SW direction profiles.

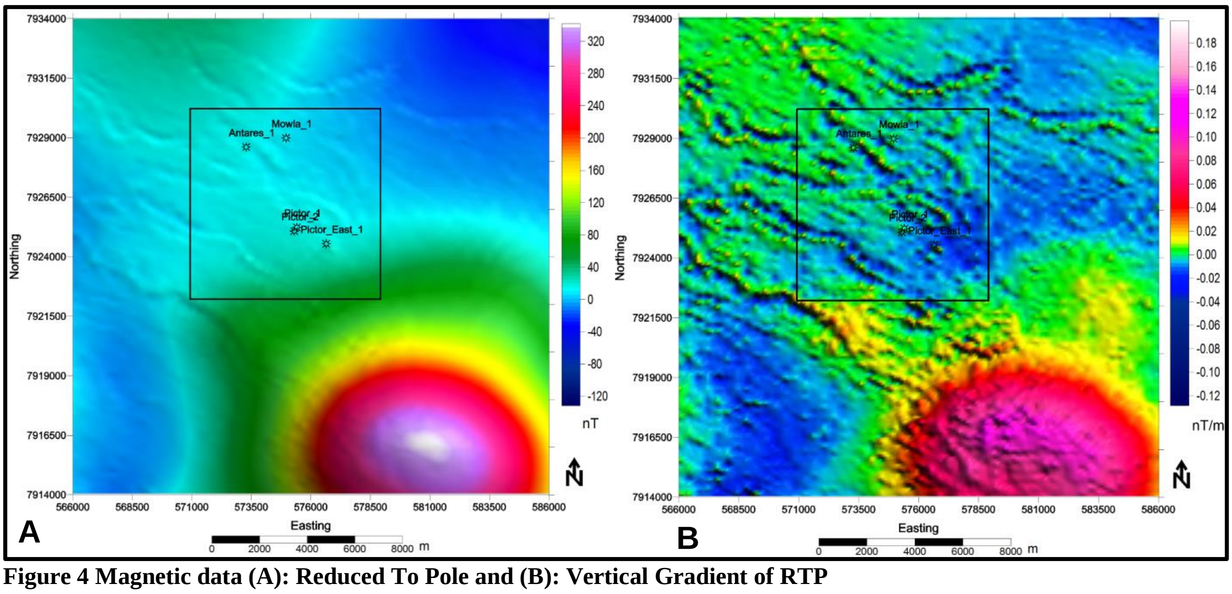


Figure 4 Magnetic data (A): Reduced To Pole and (B): Vertical Gradient of RTP

METHODOLOGY

Two main techniques were applied in this study:

- **Horizon Mapping** applied to gridded gravity gradiometry data to map basement and sedimentary horizons
- **Fault Detection** applied to located magnetic profile data

Horizon Mapping

The horizon mapping technique is based on energy spectral analysis applied to gridded gravity data. This technique detects density contrasts between basement and the overlying sediments as well as between sedimentary sequences overlain by less dense cover, e.g. carbonates covered by sands.

It is well known that the decay of the energy spectrum indicates the depth to an ensemble of causative bodies. The size of gravity data window over which the spectrum is calculated is essential for correct depth estimation. If the gravity data window is too small, the depth is too shallow as the gravity anomalies are not covered fully, if the window is too large the depth is also incorrect due to radial averaging. It is therefore crucial to establish the optimal gravity data window to properly determine depth to the causative bodies.

Energy Spectral Analysis – Multi-Window Test

To detect density contrasts within the sedimentary section and the underlying basement, the multi-window test procedure (ESA-MWT) was conducted at stations located at a regular interval of 1km along the profile. At each station, multiple spectra were computed over incrementally increasing window sizes. For each spectrum, the depth was interpreted and plotted against window size. When the window covers about 60% of the gravity anomaly, the interpreted depth stabilises over a range of increasing window sizes, forming a *depth-plateau*. As the window further increases in size, further depth-plateaus are detected, corresponding to deeper density contrasts. Each *depth-plateau* provides the optimal window size for higher resolution detailed mapping. This was not conducted in this study (Kivior et al., 2015).

In this study, the ESA-MWT was conducted using the Bouguer gravity data and the specially transformed tensor components to attenuate or enhance different frequencies of the gravity field in order to detect depth-plateaus. These then correspond to several shallower and a few deeper sedimentary formations as well as the underlying basement.

The average depth from each *depth-plateau* was laterally merged with those of *depth-plateaus* from adjacent MWT-stations thus forming the density interface. Such interfaces can then correspond to basement, unconformities, lithological, sedimentological and stratigraphic boundaries within the sedimentary sequences. Each detected density interface was validated by comparison with the seismic and well data.

Fault Detection

To detect magnetic lineaments, at different depths within the sediments and underlying basement, the Automatic Curve Matching (ACM) technique was applied to located magnetic profile data. Profiles extracted from the TMI grid in four directions: EW, NS, NE-SW, NW-SE were analysed. Each individual anomaly along a profile was interpreted in a purely automatic manner and depth to the causative body with its geometry and magnetic susceptibility being computed. The magnetic sources detected were visualised in a 3D cube and magnetic lineaments at different depths were delineated. Spatially correlated magnetic lineaments were traced, and fault faces were constructed in 3D. The major faults dislocating basement and overlying sediments were mapped.

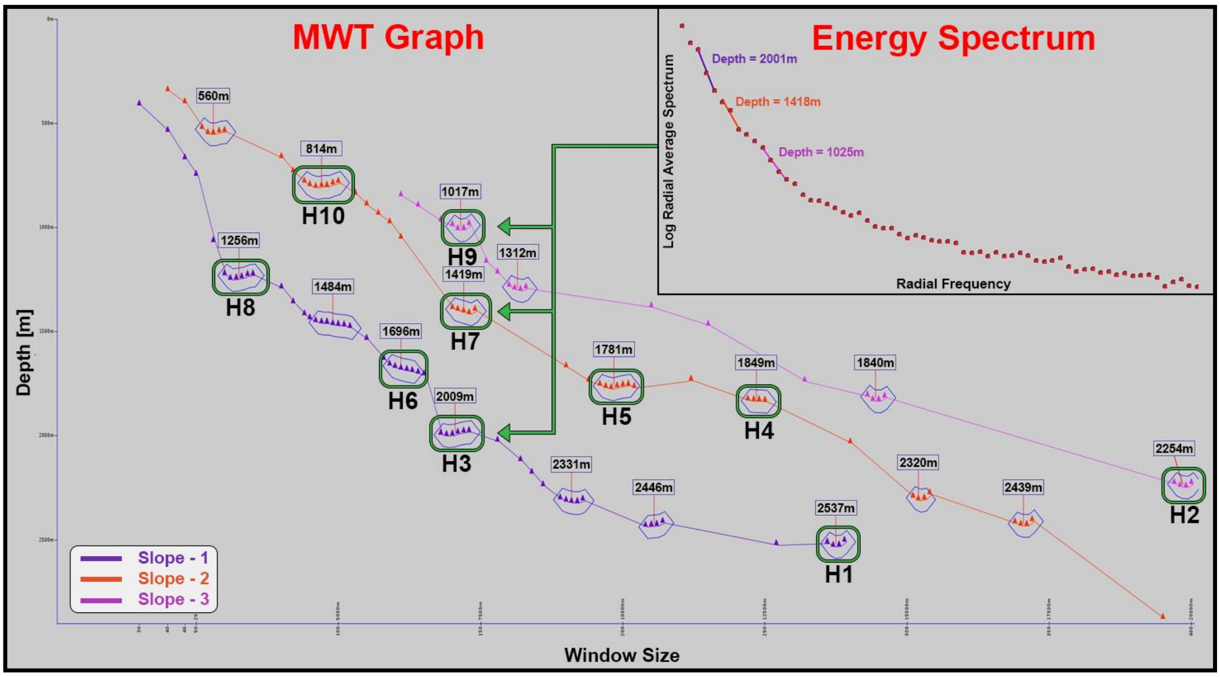


Figure 5 Example of ESA-MWT graph: Window Size vs Spectra-Depth, showing multiple *depth-plateaus* detected from AGG data.

MAPPING SUB-SURFACE GEOLOGY

The main objectives of this study was to map the basement configuration and sedimentary interfaces by applying the Horizon Mapping technique to AGG data. This in turn provided a way to detect density contrasts and map as many interfaces as possible.

The ACM method was applied to located magnetic data to detect and map in 3D, major faults within basement and overlying sediments.

Mapping Density Interfaces

The ESA-MWT procedure was conducted at stations 1km apart along the 8km long seismic traverse, HCG-300. This methodology was also conducted at the location of the wells: Pictor-1, Pictor-2 and Pictor East-1. At each station, the MWT procedure detected numerous *depth-plateaus* which correspond to density contrasts at different depths. An example of the MWT graph is shown in Figure 5.The MWT tests conducted at the well locations also detected multiple *depth-plateaus*, some of which show a good correlation with the depth of the tops of several sedimentary formations or intra-formational lithological boundaries.

Detected *depth-plateaus* were laterally merged between the stations forming ten continuous density interfaces: H1, H2, H3, H4, H5, H6, H7, H8, H9 and H10 (Figure 6).These interfaces correspond to basement and the sedimentary horizons:

- H1:Top Precambrian Basement
- H2: Top Nambeet Formation
- H3: Intra-Willara Interface
- H4: Top Acacia Sandstone
- H5: Top Willara Formation
- H6: Intra-Goldwyer Interface
- H7: Top Goldwyer Formation
- H8: Top Nita Formation
- H9: Intra-Tandalgoo Group Interface
- H10: Intra-Tandalgoo Group Interface

COMPARISON WITH SEISMIC AND WELL DATA

The 2D seismic line HCG-300 was acquired in 1986. As shown in Figure 7, this seismic line does not have a well defined section beneath the Pillara/Mellinjerie Limestones and has poorly defined reflectors beneath the Nita Dolomite. Poor seismic data quality, possibly due to loss of energy within the Devonian Carbonates, makes the seismic interpretation of the underlying older units, particularly the deeper Ordovician section, quite challenging (Figure 7a).

As mentioned above, the specially processed AGG data enabled the detection and lateral mapping of three major litho-stratigraphic boundaries within the Late Ordovician to Late Devonian section and three interfaces within the deeper Mid to Late-Ordovician sequences. The next three density interfaces were detected in the deeper part of the basin's sedimentary infill, the Early Ordovician section. The deepest density interface, the top of the Precambrian basement, was detected from specially filtered Bouguer gravity data (Figure 7b.

The AGG density interfaces were computed and interpreted with the depths in metres. The results were converted from metres to TWT using check-shot data from nearby wells. The density interfaces in TWT were overlain on the interpreted seismic section. As can be seen in Figure 7c, there is a good correlation between the density interfaces and seismic interpretation. Some of the density interfaces are not clearly visible on the seismic interpretation, in particular in the poorly imaged deeper section of the seismic traverse. Based on these results, it is suggested that integrated interpretation of the vintage 2D seismic data, in conjunction with the AGG data interpreted using the ESA-MWT technique, could add value to image the sub-surface geology in the onshore Canning Basin.

The other validation of the ESA-MWT results was undertaken using the gamma ray and bulk density logs from Pictor-1 well (Figure 8). The results show a good correlation between the density interfaces and the corresponding sedimentary boundaries intersected in the well. As shown in Figure 8, the density interfaces show good correlation with the lithological changes indicated on the geophysical logs, particularly with abrupt changes in gamma ray counts.

The Absolute Error was calculated relative to depth to lithological boundary in the well versus the average depth value of the *Depth-Plateau* for each mapped horizon while the Relative Error percentages were calculated from the degree of Absolute Error relative to the depth to the lithological boundary, Table 1-3 presents a comparison between average depth values from *Depth-Plateaus* and depth values of the corresponding lithological boundaries from three wells: Pictor-1, Pictor East-1 and Pictor-, as well as absolute and relative errors. These are summarised in Figures 9a-9d.

Table 1. Pictor-1 well: Summary of depths to lithological boundaries (TVDSS) and average depth values from *Depth-Plateaus*.

WELL TOPS			DENSITY INTERFACES FROM *DEPTH-PLATEAS*			DEPTH ERROR	
Formation	**MD[m]**	**TVDSS [m]**	**Depth (MSL)**	**Density Interface**	**Sedimentological Boundary**	**Absolute [m]**	**Relative [%]**
Grant Group Unit	108	32					
Pillara/Mellinjerie Lst	386	-245	-274	H10	Top Pillara Lst	29	11.84%
Tandalgoo Fm	517	-376					
Worral Fm	576	-436	-454	H9	Intra-Tandalgoo Int	18	4.13%
Carribuddy Group	733	-593					
Nita Fm	879	-739	-760	H8	Top Nita Fm	21	2.84%
Goldwyer Fm	1041	-901	-906	H7	Top Goldwyer Fm	5	0.55%
			-1155	H6	Intra-Goldwyer Int		

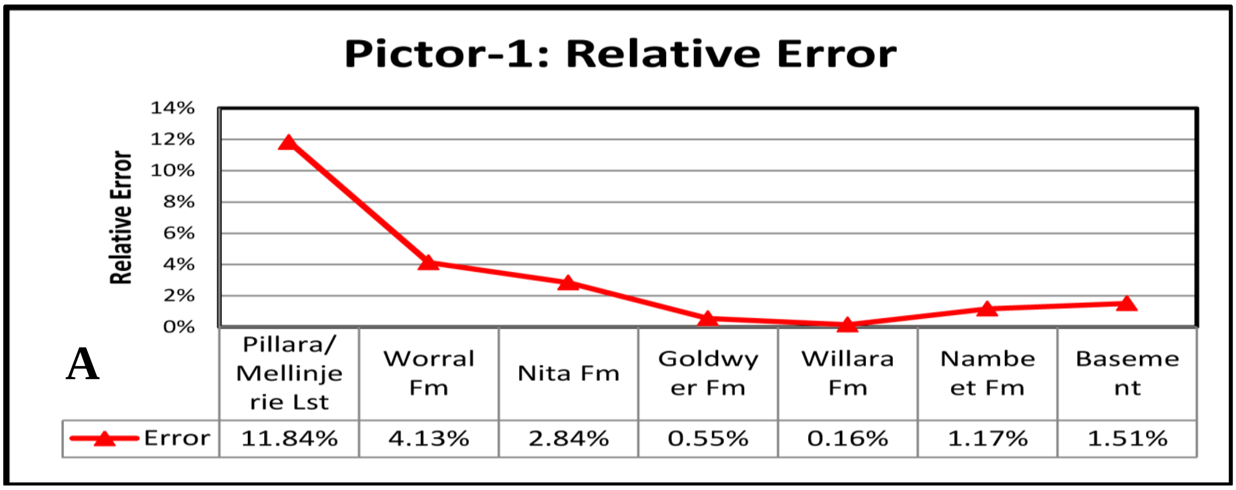
Willara Fm	1415	-1275	-1273	H5	Top Willara Fm	2	0.16%
Acacia Sst			-1405	H4	Top Acacia Fm		
			-1601	H3	Intra-Willara Inter		
Nambeet Fm	1932	-1792	-1771	H2	Top Nambeet Fm	21	1.17%
Basement	2121	-1981	-1951	H1	Top Basement	30	1.51%
TD	2146	-2006					

Table 2. Pictor East-1 well: Summary of depths to lithological boundaries (TVDSS) and average depth values from *Depth-Plateaus.*

WELL TOPS			**DENSITY INTERFACES FROM *DEPTH-PLATEAS***			**DEPTH ERROR**	
Formation	**MD[m]**	**TVDSS [m]**	**Depth (MSL)**	**Density Interface**	**Sedimentological Boundary**	**Absolute [m]**	**Relative [%]**
Alluvium	5	143					
Walla Sandstone	16	132					
Grant Group Unit	126	22					
Pillara/Mellinjerie Lst	404	-256	-263	H10	Top Pillara Lst	7	2.73%
Tandalgoo Fm	501	-353					
			-469	H9	lntra-Tandalgoo Int		
Carribuddy Group	675	-527					
Nita Fm	870	-722	-736	H8	Top Nita Fm	14	1.94%
Goldwyer Fm	1052	-904	-880	H7	Top Goldwyer Fm	24	2.65%
			-1156	H6	Intra-Goldwyer Int		
Upper Willara Fm	1527	-1379	-1383	H5	Top Willara Fm	4	0.29%
Acacia Sst	1605	-1457	-1456	H4	Top Acacia Fm	1	0.07%
Lower Willara Fm	1657	-1509					
	1706	-1558					
			-1578	H3	Intra-Willara Int		
			-1728	H2	Top Nambeet Fm		
			-1980	H1	Basement		

Table 3. Pictor-2 well: Summary of depths to lithological boundaries (TVDSS) and average depth values from *Depth-Plateaus*.

Well Tops			**Density Interfaces from *Depth-Plateas***			**DEPTH ERROR**	
Formation	MD[m]	TVDSS [m]	Depth (MSL)	Density Interface	Sedimentological Formation	**Absolute [m]**	**Relative [%]**
Wallal Sst	8	135					
Upper Grant Fm	108	35					
Lennard River Group	394	-252	-273	H10	Top Pillara Lst	21	8.33%
Tandalgoo Fm	548	-406					
			-476	H9	lntra-Tandalgoo Int		
Carribuddy Group	747	-604					
Nita Fm	872	-730	-749	H8	Top Nita Fm	19	2.60%
Goldwyer Fm	1056	-914	-903	H7	Top Goldwyer Fm	11	1.20%
TD	1086	-943					
			-1152	H6	Intra-Goldwyer Int		
			-1273	H5	Top Willara Fm		
			-1392	H4	Top Acacia Fm		
			-1607	H3	Intra-Willara Interface		
			-1779	H2	Top Nambeet Fm		
			-1967	H1	Top Basement		



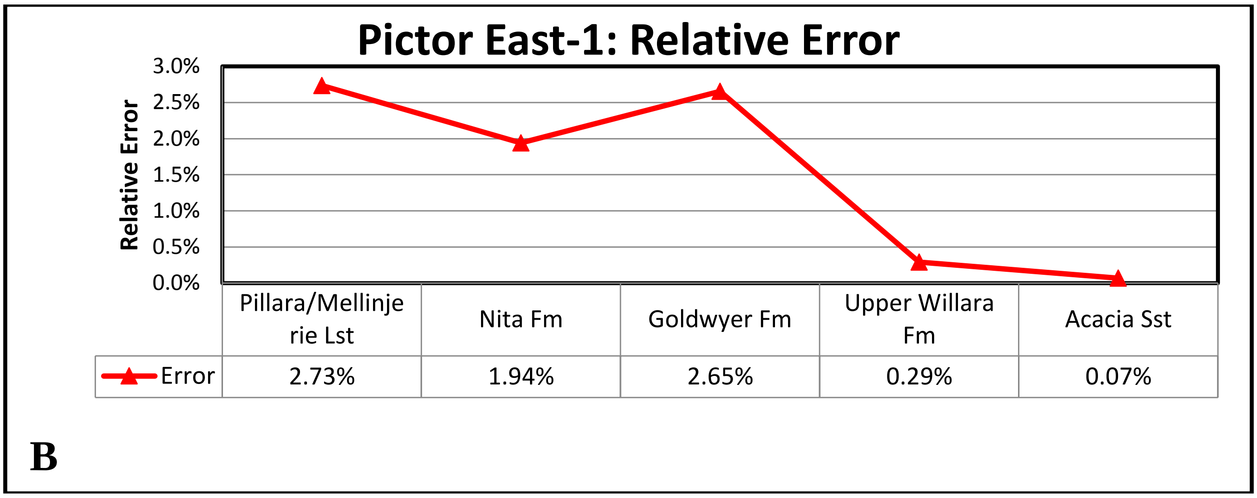


Figure 9a & b Relative Errors of *Depth-Plateaus* versus Well Intersections at Pictor-1 (A) and Pictor East-1 (B)

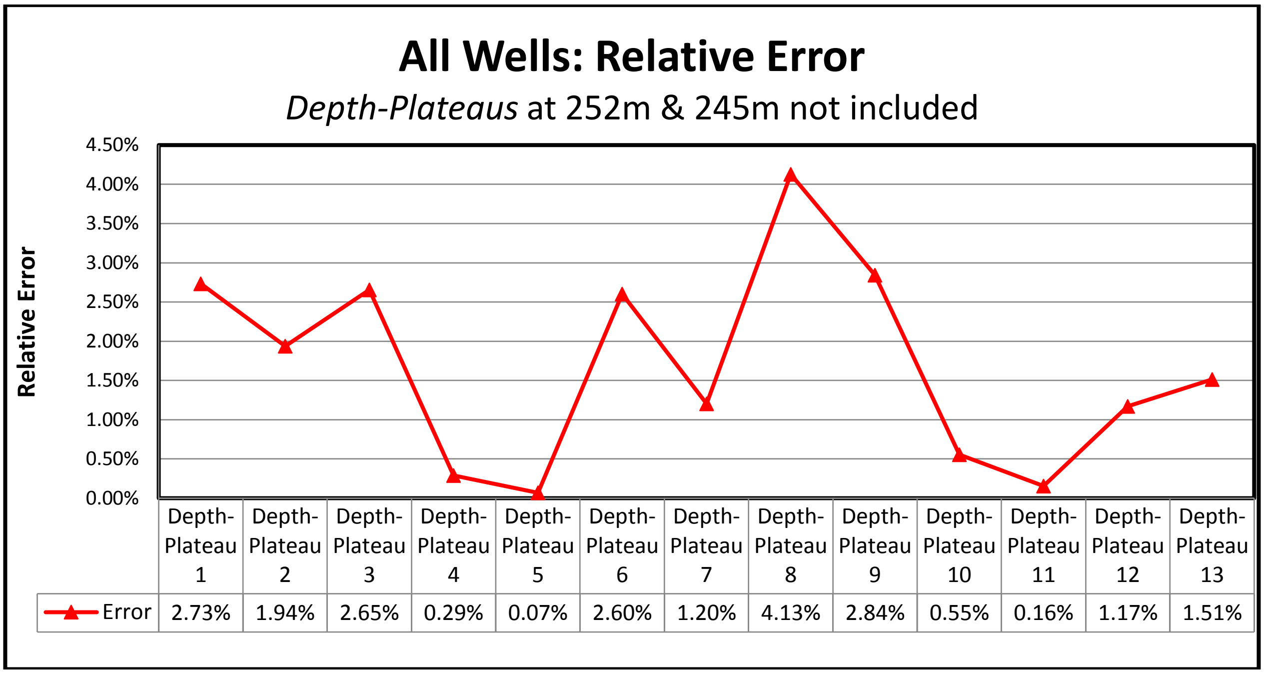


Figure 9c Relative Errors of *Depth-Plateaus* versus Well Intersections at all wells

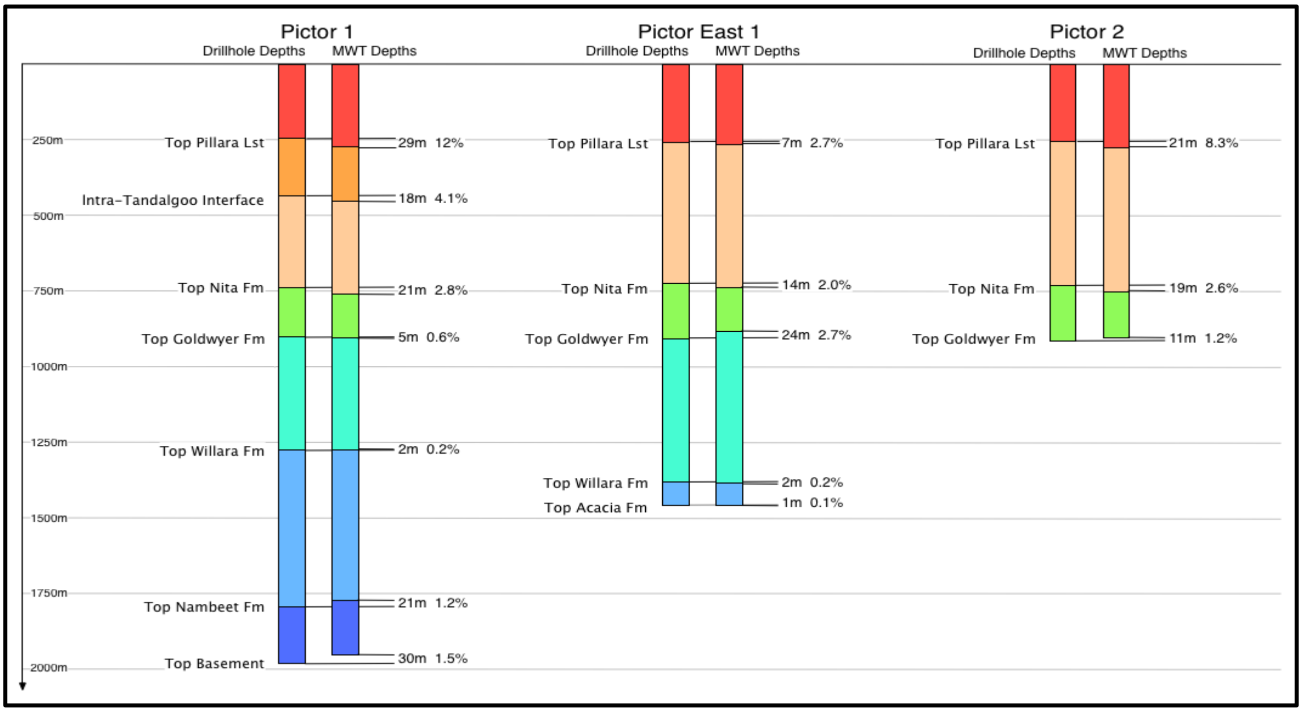


Figure 9d Comparison of Relative Error between Density Interfaces detected by MWT from AGG data with Well Intersections from Pictor-1, Pictor-East-1 and Pictor-2 wells

CONCLUSIONS

ESA-MWT detected numerous depth-plateaus which appear to indicate density contrasts within the sediments, and also between the sediments and the underlying basement. Detected density contrasts were then laterally merged. Nine intra-sedimentary horizons and top of basement were detected:

- Horizon H1: Basement
- Horizon H2: Top Nambeet Fm
- Horizon H3: Intra-Willara Interface
- Horizon H4: Top Acacia SST?
- Horizon H5: Willara Fm
- Horizon H6: Intra Goldwyer Fm
- Horizon H7: Top Goldwyer Fm
- Horizon H8: Top Nita Fm
- Horizon H9: Intra Tandalgoo Gr
- Horizon H10: Top Pillara Limestone

The resolution at which the sedimentary section has been imaged affirms the level of detail recorded in the gravity gradiometry data in which density interfaces within the 2.5km thick sedimentary section were able to be identified.
Horizons mapped from AGG correspond to the lithological changes between the formations or represent intra-formational interfaces due to the density contrasts between the sediments. The ESA-MWT technique was also applied to magnetic grid data where numerous depth-plateaus were detected and laterally merged. The detected interfaces were used to QC some of the horizons mapped from AGG data.
ACM detected numerous Magnetic Lineaments corresponding to regional structural trends. Several major faults intersecting the Test Profile were mapped in 3D. Faults mapped from magnetics using ACM were integrated with structural interpretation of AGG data and sedimentary interfaces and the underlying basement mapped by ESA-MWT.
The geological model built along the Test Profile from interpretation of the AGG and magnetic data shows good correlation with the wells and seismic data. Comparisons of the Depth Plateaus with the well intersections show that the error is small except for the shallowest horizon, perhaps because of the 1km survey spacing. The test line shows good correlations between mapped anomalies using the potential field data and validated geology in the petroleum exploration wells and would provide exploration companies a new technique in the exploration toolkit to explore where seismic imaging is poor

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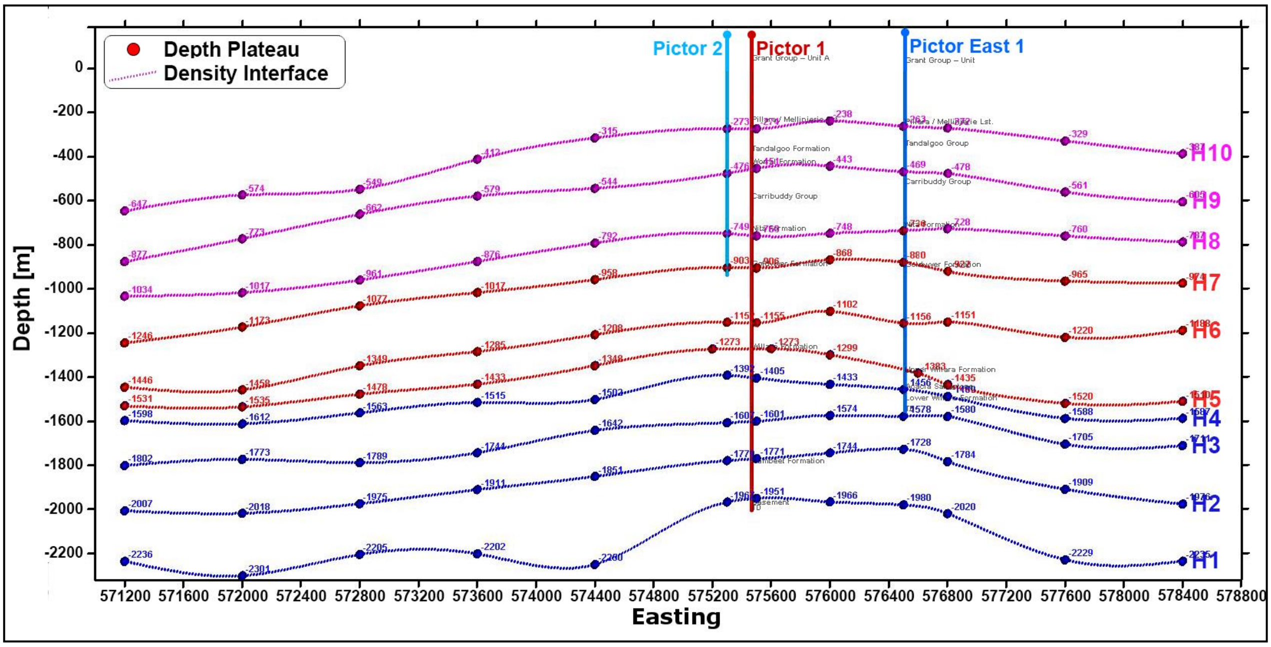


Figure 6 Density interfaces detected by ESA-MWT from the AGG data

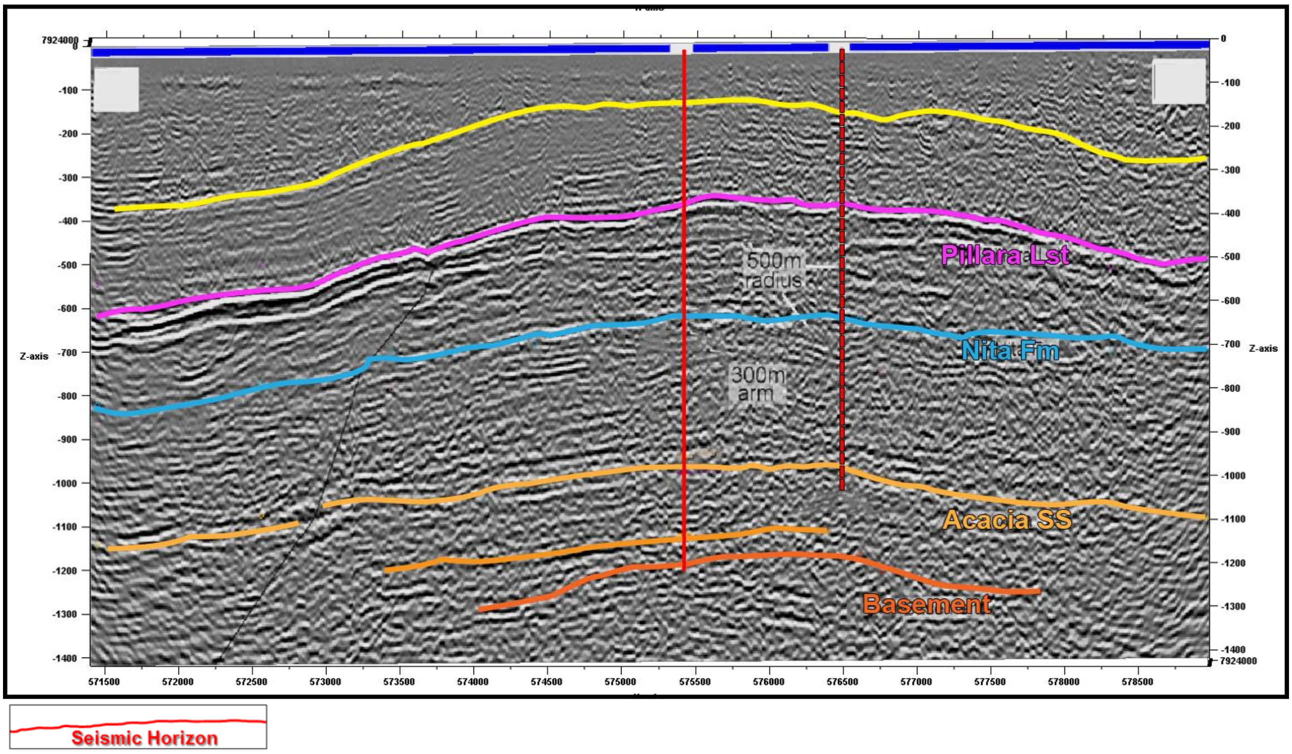
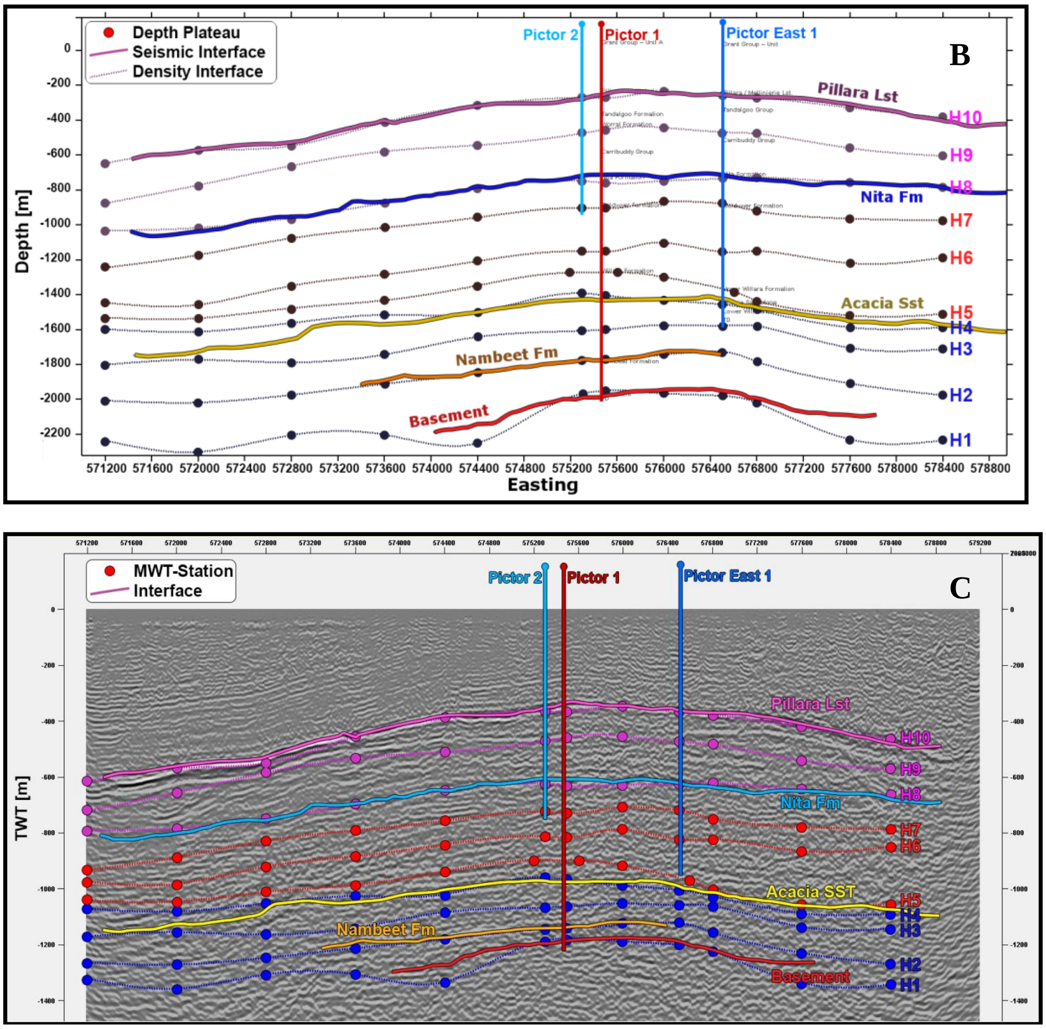


Figure 7a. Seismic Line HCG-300 along which MWT was conducted.



Figures 7 b & 7c Comparison of density interfaces detected from the AGG data with seismic interpretation. Figure 7b shows depth in metres. Figure 7c shows TWT.

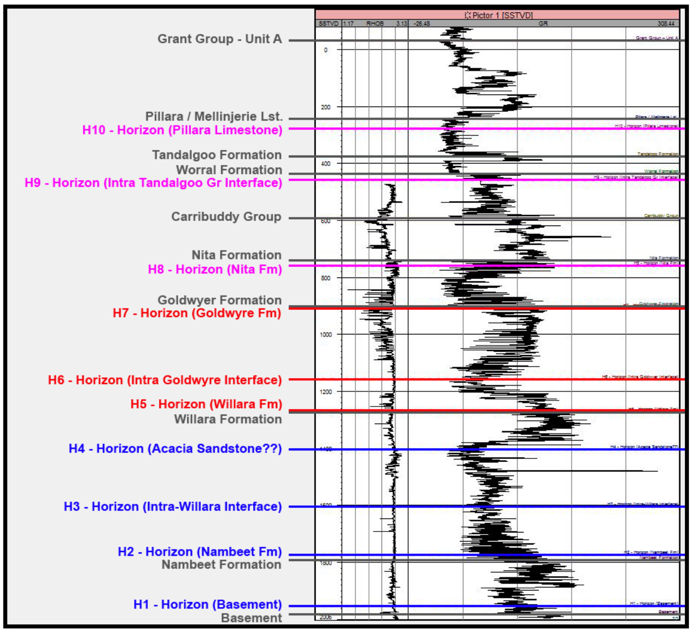


Figure 8 Comparison of density interfaces detected by ESA-MWT from AGG data with Gamma Ray and Bulk Density logs from Pictor-1 well