TO: Tom Oates
FROM: Kim Frankcombe
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SUBJECT: EP304 and EP307 Gravity Survey, review and interpretation

This memo reviews the recent gravity survey over two petroleum exploration tenements in the Northern Territory.

A memo covering the acquisition and processing has already been completed so those matters will not be covered here.

The aim of the survey was three fold: to better define the extents, shapes and potentially depths, of the Proterozoic basins covered by the survey; to refine the single point gravity high, near coincident with a magnetic feature, in the east of the area; acquire higher resolution data along a corridor around the West Baines fault in order to better understand it. Coverage prior to the survey consisted of the regional Geoscience Australia 12km grid of stations with some detail along the Duncan Highway, acquired as part of a WA Government sponsored regional roads programme as well as some semi-detailed open file data around Stockman’s Creek in the north west.

Background Geology:

The project area is shown overlain on a simplified basin outline map taken from Munson (2014) in Figure 1. The basins use Munson’s colour scheme of with pink representing Neoproterozoic to Palaeozoic basins, buff outlining the surface extents of the Palaeo to Mesoproterozoic basins and brown the Palaeo to Mesoproterozoic Orogens. The current extent of the Antrim Plateau Volcanics, as interpreted by Munson, is also shown along with the location of two major NE-SW trending faults which are discussed in the following text.
The Birrindudu Basin is interpreted to extend below the younger basins to underlie the entire project area. A stratigraphic section from basement, through the Birrindudu, to the overlying Victoria Basin is shown in Figure 2. Basement rocks from the Inverway Metamorphics crop out on Limbunya station about 60km to the south of the project area while sediments of the Limbunya Group crop out about 8km to the south and 40km to the east and north east of the tenement area. Mapped dips are flat (<10°) and to the west or north west, suggesting that these rocks will form the base of the Birrindudu Basin below the tenement area.
Figure 2: Stratigraphic column for the Birrindudu Basin from Munson 2014
The Birrindudu Basin is overlain in the east, north and far south west by the Victoria River Basin and in the west by the Ord Basin and north by the Wolfe Basin which both postdate and onlap the Victoria River Basin. The basal unit of the Ord Basin is the Antrim Plateau Volcanics a Lower Cambrian package of basalt and interflow sediments, which across the border, in the eastern Kimberley, reaches 1100m in thickness. Within the project area, water bore drilling shows that it thickens to the west and is at least 270m thick. These volcanics are overlain by the Headleys Limestone and Nelson Shale from the Negri Subgroup which are the basal units of the Goose Hole Group. However within the project area these sediments are limited to small residual erosional caps on hills.

A schematic north south section running along the Western Australian side of the border, just to the west of the project area, is shown in Figure 3. The Rosewood Syncline, shown on the section, underlies the western border of EP307 and the Baines Creek and BlackFellow faults extend through the project area. These faults are thought to have been formed during the Barramundi Extension (2000-1870 Ma), initially as transfer faults for NE-SW directed extension. They would then have been reactivated as thrust faults during the Barramundi Orogeny (1870-1840 Ma) but clearly have been active through to recent time as they are now evident in digital elevation models and satellite images.

![Figure 3: Schematic north-south Section through the Ord Basin. Taken from NTGS Rept 22 after Mory and Beere 1988](image)

There are no published petrophysical data within the tenement area, however the NTGS do maintain a petrophysical database which includes densities and susceptibilities from four drill holes with lithological units present in the project area. Figure 4 shows a classed post plot of the measured magnetic susceptibilities for samples from these holes coloured by their stratigraphic group and ordered by hole and depth, shallowing to the right. The Antrim Plateau Volcanics stand out as the most magnetic rock type in the area with the remainder being considered weakly to non magnetic.
Figure 4: Classed post plot of magnetic susceptibility by rock unit, coloured by stratigraphic group and ordered by hole and depth.

Figure 5 shows the same plot for density. Note that the densities measured in hole MSFDD001 are in general significantly lower than the other holes. Jasper Gorge sandstone occurs in both MSFDD001 and Bullo River 1 yet the measured densities are over 0.4 T/m$^3$ different. This does not seem likely, just as measured densities of 1.9 T/m$^3$ for the Jasper Gorge Sandstone are almost certainly too low. While Phanerozoic sandstones might be expected to have densities around 2.2 T/m$^3$ one would expect Proterozoic sandstones to be more compact. The range of values for each rock type in hole MSFDD001 is also significantly greater than the other holes. It is suspected therefore that the measurement technique used on this hole was faulty and that the densities of the sediments should be greater.

There is a suggestion in these data that the older rocks are more dense which intuitively makes sense. However, assuming that the densities in MSFDD001 are in error and excluding them for the moment, the densities lie within a small range and we would not expect to see large variations based on these rock types, more likely a gentle increase in density with depth and age meaning that the thicker basins should be represented by gravity lows and basement highs by gravity highs.
Based on the magnetic susceptibilities it is not surprising that the aeromagnetic data over the area clearly show the extent of the Antrim Plateau Volcanics and indicate that they are more extensive than suggested by the simplified basin map in Figure 1. It is also clear from the TMI image (Figure 6) that there are two distinct and vertically separated magnetic sources, the surficial volcanics and much deeper basement. This is consistent with the low susceptibilities measured for the sediments likely to be encountered here. Other features worthy of note are the Blackfellow Creek Fault, which stands out as a linear magnetic high which bellows in places. The lack of any obvious dipole response suggests that the source of the anomaly is flat lying and thinner than it is deep. It is therefore likely to be pools of Antrim Plateau Volcanics which were perhaps trapped against a fault scarp formed by Cambrian reactivation of the fault. To the south, the West Baines Fault can be seen as a more sharply defined magnetic feature ranging from magnetically dead zones to narrow magnetic highs. Some of this response is probably due to the effects of topography incising a relatively flat lying magnetic body but it may also reflect changes in the thickness of the basalt.

The strong circular magnetic dipole anomaly near 575000E, 8144000N stands out clearly in these data as something which does not belong to any other trend or regional feature.

Parallel to the Blackfellow Creek Fault and offset to the south east, a broad magnetic high probably reflects basement, as does a magnetic ridge running at right angles to it and heading off the image to the south east.
The magnetic data have been processed using fractional local wave number to produce an automatic depth to source map and this is overlain on a grey scale image of the 1\textsuperscript{st} vertical derivative (1VD) of the TMI in Figure 7. The high pass filtering by the vertical derivative has enhanced the relative response from the faults and clearly differentiates those areas of volcanic cover. The depth to source overlay highlights the large gap between the magnetic basalts at surface (purple dots) and the basement magnetic rocks (red dots) with little between. Magnetic basement appears to vary in depth from 1000m to 3000m below surface. Because of the interference from the surficial volcanics it is not possible, using this depth estimation approach, to obtain meaningful depths to basement below the cover.
Figure 7: Greyscale image of the 1st VD of the TMI overlain with automatic depth to basement picks, coloured by depth.

Figure 8 shows an image of the final processed terrain corrected Bouguer gravity computed for a density of 2.5 T/m$^3$. The more detailed coverage within the project area has resolved a considerable amount of detail not obvious in the 12km regional data.

The magnetic dipole anomaly is now coincident with the gravity anomaly rather than offset from it, as it appeared in both the regional data and a later survey by BHP in 1984 when they held title over the anomaly. BHP surveyed two orthogonal lines over the anomaly and essentially reproduced the anomaly shape and position produced by the 12 km regional data with very little improvement in detail. Looking at the raw field notes in their report (CR19840033) it appears that they may have reversed the station locations on the north south line so that stations south of the line cross over are plotted to the north of the crossover and vice versa, thus shifting the anomaly to the south.

The traces of the Blackfellow Creek Fault and West Baines Fault show up clearly with elevated gravity responses on their northern sides. The mapped offset on at least part of the West Baines fault has the northern side uplifted relative to the southern side, no sense of movement is shown on the published geological map for the Blackfellow Creek Fault. However the schematic cross section in Figure 3 shows the same sense of movement as the West Baines. The gravity suggests that a denser unit has been moved closer to the surface on the northern side of these faults. It also suggests a third fault, parallel to the Blackfellow Creek fault and offset about 14km to the south east. Unlike the other two, this fault is not mapped although it has been interpreted in the published geology and is evident as a limited strike length topographic feature, suggesting that it too was active for a long time. What may be happening on these faults is shown schematically in the example shown in Figure 9, taken from a NE-SW section to the North of the project area and published on the Waterloo 250k map sheet.
The gravity suggests that the half grabens interpreted by Mory and Beere for the Ord Basin also exist for the Birrindudu and Victoria Basins but are facing north west and thickening in that direction. This view is reinforced if we overlay contours of the terrain corrected Bouguer gravity on an image of the magnetic data filtered to enhance the faults. (Figure 10). If we assume that the gravity lows reflect thicker sediment packages we see that they thicken to the fault then thin on the northern side, consistent with the half graben model in Figure 3.

Note that the main NE-SW trending gravity low to the north of the West Baines Fault is coincident with the broad magnetic high, while the magnetic ridge at right angles to it is broadly coincident with a gravity high. That would suggest that the NW-SE trending magnetic ridge reflects shallower basement due to uplift while the NE-SW trending magnetic high and gravity low may reflect a change in basement chemistry.
At the eastern end of the gravity scarp along the West Baines fault, is a NNE trending gravity ridge. This is slightly offset from a mapped syncline. The axis of the syncline is shown 500m to the east of the gravity ridge and it is not clear at this stage if this is due to an error in mapping, a registration problem, an asymmetric fold bringing the denser material closer to the surface on its western side or an unmapped fault to the west of the syncline achieving the same thing.

On the eastern edge of EP304, to the east of the lone gravity high are two prominent gravity troughs. The northern of these two troughs, in the NE corner of EP304, deepens to the east and terminates in a near circular low against a north-south trending fault (see Figure 11). Mapped dips around the northern and eastern edge of this feature steepen inwards, pointing to the axis of the gravity trough. Faults are mapped around the boundaries of this gravity trough and it is thus possible that this represents a narrow steep sided half graben. If so, it would be trench shaped (12km wide and 25km long).

Although the geology map shows soil cover in the area of the gravity low it is very unlikely that this would be the cause of the gravity low although it could well be contributing to it, if the soil cover were thick. This conclusion is based on the gravity response of soil covered areas elsewhere in the survey area and the spatial distribution of soil relative to the gravity response which at 1km station spacing is adequately sampled to resolve these spatial differences.
The southern gravity trough is shorter and narrower and coincides with a mapped short strike length fault (see Figure 12).

Although deeper weathering of faults can result in gravity lows it is difficult to imagine that this would be resolved on 1km station spacing and have an apparent width of nearly 2km. It is possible that the fault represents an axial fault along a narrow synclinal fold containing a keel of lighter rocks. The small gravity high to the west, near Mt Kimon, may reflect thicker volcanics as we would expect these to be more dense than the underlying sandstones and carbonates.

As noted above, the current topography reflects some of the apparently deeper features seen
in the potential field data, particularly the gravity, as shown in Figure 13.

The close correlation between gravity and topography would normally raise alarm bells and suggest the use of an inappropriate reduction density. Indeed prior to undertaking the terrain correction the gravity image showed a very strong correlation to topography at a local scale and each small hill produced a noticeable gravity response. The terrain correction removed these entirely. In this case rather than being artefacts of the terrain, it is more likely that the gravity features and topography variations have the same source which, in the case of the faults, have been active over a long period.

The coincident gravity and magnetic anomaly on Limbunya station was initially modelled by BHP using the limited magnetic and gravity data they had at the time (CR19840033). They produced a model consisting of a deep mafic intrusion with its top cutting through basement into the relatively less dense Limbunya Group rocks. They estimated that the depth to the top of the body was between 1000 and 1500m below surface. Based on better magnetic and gravity data available today a similar but slightly deeper magnetic model could be obtained but a range of possible gravity models could be generated which fitted the data. These varied from something looking like the BHP model with a single intrusive body in a two layer earth generating a density contrast in the upper layer, through to an irregular basin of lighter (2.4 T/m$^3$) sediments. This range of gravity models is shown in Figure 14 as wireframe outlines of the various bodies. Each model included the stock like body used to model the magnetic data and assigned some positive density contrast to it. In order to get a reasonable fit between the gravity and a model akin to that derived by BHP a veneer of less dense surficial sediments were required in an annulus around the body, otherwise it was not possible to model the relatively steep sides of the anomaly using deep sources only. This seemed contrived, as did a model using a near circular basin of lighter sediments. Although the Jasper Gorge Sandstone had measured densities below 2.4 T/m$^3$ in hole MSFD001, to the east of the project area, we have already suggested that these measurements appear flawed and we would expect Jasper Gorge sandstone to have densities closer to 2.5-2.6 T/m$^3$ as measured in hole Bullo River 1. Olympic Dam style Iron-Oxide Copper Gold deposit (IOCG) models with a dense disk of material over a magnetic and slightly more dense intrusive did
Figure 14: Wireframe outlines of various bodies used to match the gravity response over the coincident gravity and magnetic anomaly. Section looks to the NE.

Fit the data but as seen from the models in Figure 14 the upper disk could be modelled as shallow as 200m and as deep as 800m while still fitting the data. Some other independent data set is required to resolve this ambiguity.

The gravity data can be processed to produce a depth to basement model if we simplify the geology and force some simple assumptions. If we say that we only have two layers, basement and the overlying Proterozoic and younger sediments and that we have a single density contrast between the two of 0.6 T/m$^3$ (2.6 vs 3.2 T/m$^3$) we can generate a contour map of the sediment thickness which, not surprisingly, has the same shape as the gravity response, see Figure 15. It is obviously in error because of the assumption that the basement and overlying sediments are each homogenous but it does give some idea of the likely numbers involved. In the west the cover of Antrim Plateau Volcanics is likely to be more dense than the underlying sediments, reducing the density contrast there from that used in the example here and thus pushing the calculated basement deeper than suggested. The sediment thickness contours derived from the gravity compare well in shape with the

Figure 15: Contours of sediment thickness inferred from gravity using a simple two layer model, overlain on a published 250k geology mosaic. Contour interval 100m
sediment thickness contours generated as part of the Seebase project by Frogtech and Geoscience Australia (Figure 16) However the Seebase depths are at least twice those computed from the gravity and deeper than those from the magnetics as well.

Because of the scale the Seebase project used the shapes are similar however it misses a lot of the fine detail. For example the interpreted basement saddle around the West Baines Fault does not show, nor does the small sub basin south of Blackfellow Fault or the trench in the north east of EP304. I suspect that the depths derived in the gravity exercise are closer to the mark than the Seebase depths although the gravity depths are still probably underestimates, particularly under the Antrim Plateau volcanic cover.

MT traverses are planned to assist in defining the depth to basement and thickness of some of the rock packages. As long as they are thick enough it should be possible to discriminate between carbonates, sandstones and shales. It may be difficult to differentiate between siliceous sandstones and siliceous basement so the lower interpreted interface may end up being the base of the carbonates however this is still useful information from a petroleum prospectivity perspective. The MT can be used to guide the location of more expensive seismic lines.

Conclusions:

The gravity survey points to a thick package of sediments contained in a series of half grabens in the west of the project area. The coincident gravity and magnetic anomaly on Limbunya station is now better resolved and the steep sides of the gravity anomaly require a density anomaly above the deep magnetic body, either in the form of lighter sediments near the surface or a positive density anomaly between surface and the magnetic body. The latter possibility constitutes the response we would expect from an Olympic dam style IOCG deposit and therefore warrants some follow up. The area around the West Baines Fault is prospective for MVT style base metal targets and a follow up program should be considered.
References:

