Airborne Gravity Gradiometer Survey over the Pelarang Anticline, Onshore Kutai Basin, Indonesia

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SUMMARY

The Pelarang Anticline is part of the NNE-SSW oriented Samarinda Anticlinorium, a detached thrust-and-fold belt in the Tertiary Kutai Basin. Results from an airborne gravity gradiometer survey over the Pelarang Anticline are presented herein.

The Pelarang Anticline is interpreted as a detachment fold ~30km long with steeply dipping (70º-80º) flanks. However, seismic imaging on existing 2D data is poor.

In October 2016 Cue Energy acquired airborne gravity gradiometer survey data over the anticline. The survey revealed a large (~10mGal) gravity signal range, and that the anticline is associated with a strong, positive gravity anomaly. Subsequent application of potential field enhancement filters clearly delineated the crest and the flanks of the feature.

2D modelling of selected profiles across the anticline suggests that it can be modelled as a 1,500m-2,000m wide, by ~2,000m high shale body that is close to breaching the surface in places. This is in alignment with an interpretation that the feature is cored by high-pressure shales, resulting in un-prospective areas.

However, 3D modelling has revealed significant along-strike variations in the depths to the crest of the anticline, suggesting the presence of several anomalous structural lows. Further investigation suggests these features are pull-apart mini-grabens, formed in response to localized shear movements. At least two commercial hydrocarbon accumulations, Sambutan and Mutiara, appear to be genetically related to the newly recognized structural anomalies.

This survey has led to the recognition of a new exploration play in the region, and provided a tool to pursue it.

Key words: Airborne Gravity Gradiometry, Full Tensor Gravity Gradiometer, 3D gravity modelling, Kutai Basin Indonesia

INTRODUCTION

The Kutai–Mahakam Delta Basin, which is situated on the eastern margin of the island of Borneo, is the largest basin in Indonesia (Figure 1) and one of its richest hydrocarbon provinces with several giant fields (Doust and Noble, 2008). The four major hydrocarbon fields in the onshore Sanga-Sanga Production Sharing Concession (PSC) over the Samarinda Anticlinorium (Badak, Nilam, Semberah, and Mutiara) are estimated to contain 2.5 BB of oil (EUR) and 28 TCF of natural gas (EUR) (McClay et al., 2000).

The Pelarang Anticline is located 10km inland from the Sanga-Sanga PSC. The Pelarang Anticline hosts several minor hydrocarbon fields: the 6 MMbbl Binangat oil field, as well as the 5 MMbbl Sambutan oil and gas field, which is currently producing oil and gas from Miocene-aged reservoirs. The smaller South Perlang and Sei Nangka fields are currently shut-in. The Pelarang Anticline is a focus for hydrocarbon exploration by Cue Energy. A number of vintage 2D seismic lines have been acquired over the Pelarang Anticline. However, the seismic imaging of the anticline is poor, due to the steep dips of the flanks of the anticline (Figure 2).

Gravity gradient modelling studies showed that the estimated height and width of the Pelarang Anticline, coupled with the positive density contrast between dense, over-pressured shales in the anticline and less compacted surrounding deltaic sediments, would cause local gravity gradient anomalies of sufficient amplitude to be observed from low-flying aircraft. It was recognized that airborne gravity gradiometry could assist the seismic interpretation by enabling more accurate mapping of the flanks of the anticlinal structures and possibly provide information about along-strike variations in the depths to the crest of the anticline.

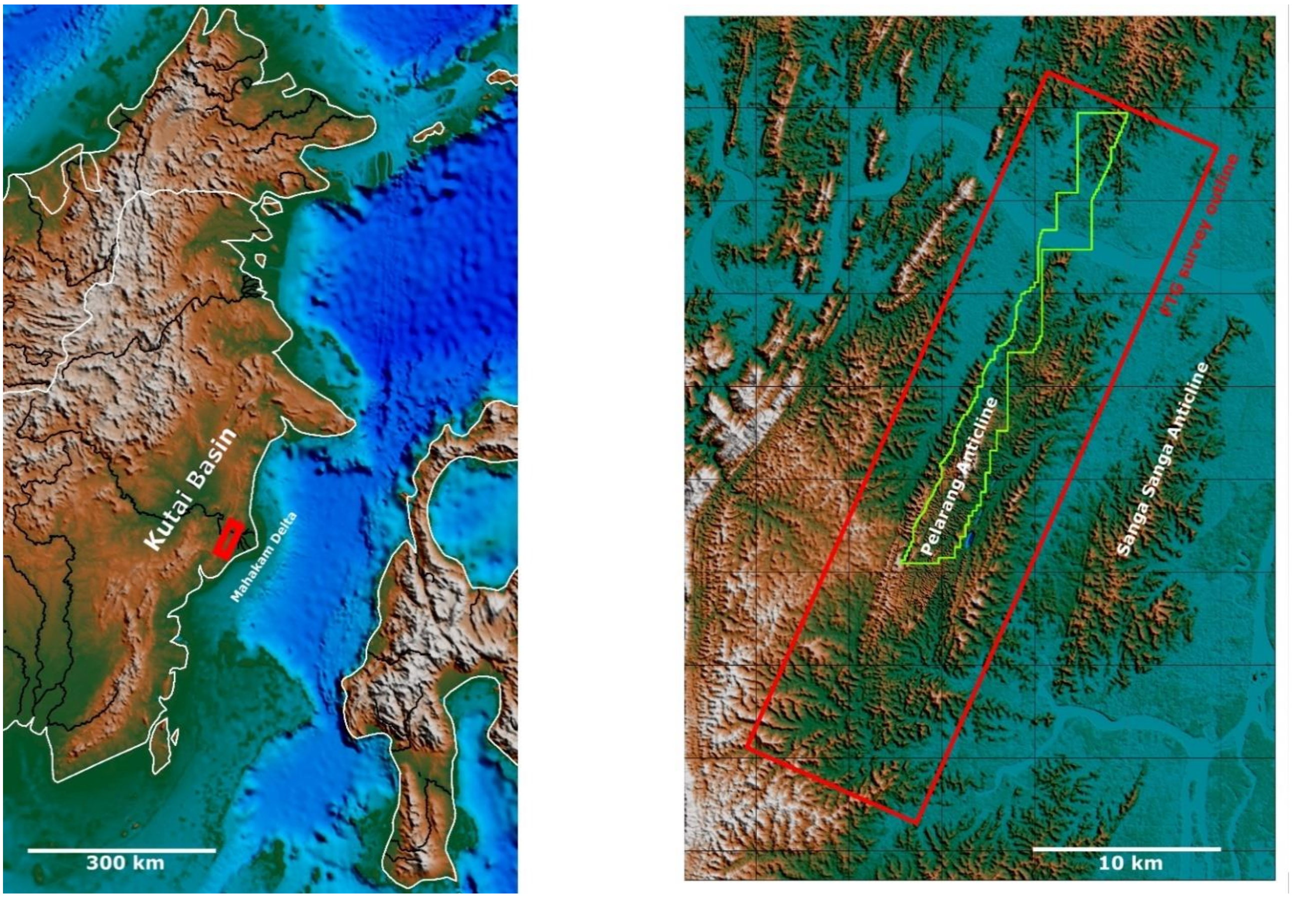

Figure 1: (*Left*) Map of Eastern Borneo. FTG survey outline in red. (*Right*) Close-up map of the Pelarang Anticline and surrounding areas. FTG survey outline in red. Cue Energy exploration tenements in green.

GEOLOGY

The Tertiary Kutai Basin is the result of a Paleogene extensional rifting and subsidence phase. It is the deepest Tertiary basin in Indonesia with an estimated accumulation of 14km of sediments.

Since the Neogene several compressional basin inversion phases, coupled with deltaic progradation and aggradation, have formed extensive thrust and fold structures through a combination of reactivation the Paleogene extension faults and of detachment-style folding, resulting in tight, shale-prone elongated anticlines in the Mahakam fold belt .

The anticlines strike NNE-SSW and are 2km-5km in width and 30km-50km in length. The asymmetric, thrust-fault bounded anticlines are separated by broad synclines and are cored by over pressured shales (McClay et al., 2000).

The western (onshore) sections of the Mahakam fold belt, known as the Samarinda Anticlinorium, are generally strongly deformed, uplifted, and eroded, whereas the eastern (offshore) deeper portion of the Mahakam fold belt show less deformation, buried under the prograding deltaic wedge.

Generally the synrift sections within Indonesian Tertiary basins contain good quality lacustrine source rocks with overlying or adjacent coarse clastics providing the reservoirs (Chambers et al., 2004). Reservoirs in the Mahakam fold belt are delta-top channel sands deposited in structurally controlled sites (Ferguson and McClay, 1997). The inversion anticlines are a major structural trap in the Kutai Basin. Furthermore the anticlinal folds of the Samarinda Anticlinorium have controlled local sedimentation patterns and have influenced the distribution of the reservoir channel sands in the main hydrocarbon fields. The hydrocarbons are trapped in Middle-to-Upper Miocene deltaic sandstone reservoirs that occur mainly in four-way dip closures or in two-way structural stratigraphic traps resulting from delta-plain reservoir sandstones crossing a late structural high at an oblique angle.

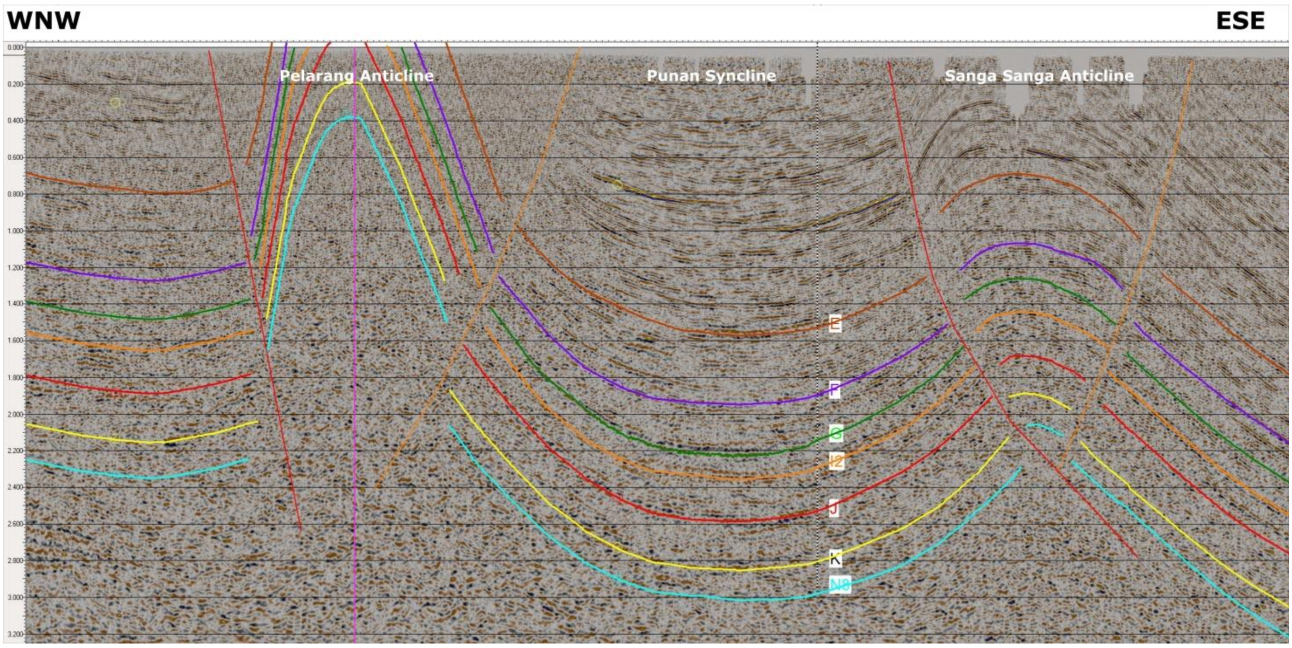

Figure 2: Regional seismic section across the Pelarang Anticline (*left*), Punan Syncline (*centre*) and Sanga-Sanga Anticline (*right*). Note the poor seismic imaging of the strongly deformed and steeply dipping Pelarang Anticline.

AIRBORNE GRAVITY GRADIOMETER SURVEYING

In 2016 Cue Energy commissioned a Full Tensor Gravity gradiometer (FTG) survey over the Mahakam fold belt exploration tenements in order to map the flanks of the Pelarang Anticline and any variations in the depths to the crest of the anticline. Murphy (2004) summarizes the key features of the FTG instrumentation.

FTG aircraft operator Bell Geospace flew the 1,500 line-km survey in a Bassler BT67 over 17 calibration and production sorties over 42 days from September 2016 to October 2016. In all, the survey covered 400km^2. The survey was flown at a nominal terrain clearance of 80 meters (subject to safety considerations) above the terrain, with WNW-ESE oriented main-lines at 400m line spacing and NNE-SSW oriented tie-lines with 4,000m spacing. The south-central part of the survey was flown with 200m line spacing. Generally only moderate turbulence was encountered during surveying, with a survey-wide average turbulence measure of 60 milli-g, resulting in noise levels of 10.2 Eötvos in the survey-wide line-averaged inline sum noise measure (1 Eötvos equals $10^{-9}s^{-2}$- making 1 Eö equivalent to 0.1 mGal/km).

The deployed FTG system did not have on-board laser scanner capability to record and construct a Digital Elevation Model (DEM) for terrain correction of the FTG data. Instead Shuttle Radar Topography Mission (SRTM) data and a third party LiDAR survey over the southern-central part of the survey area was used. The FTG data have subsequently been fully terrain corrected with a terrain density of 2.2 g/cm^3.

Figure 3 shows the resulting fully terrain corrected FTG vertical gravity data, g_D, over the Pelarang Anticline survey area. The data has been high-pass filtered with a 4th order Butterworth filter with a cut-off wavelength of 10,000m. The amplitude range of the data set is quite substantial from -3.8mGal to +6.8mGal, indicating significant local density excess along the narrow, elongated, vertical gravity high along the central part of the survey area. This shows that the anticline is associated with a strong, positive gravity anomaly. A number of gravity lows of limited extent (500m-1,000m) along the edges of the anticline are associated with recently excavated coal mining pits, which are not present in the legacy SRTM data.

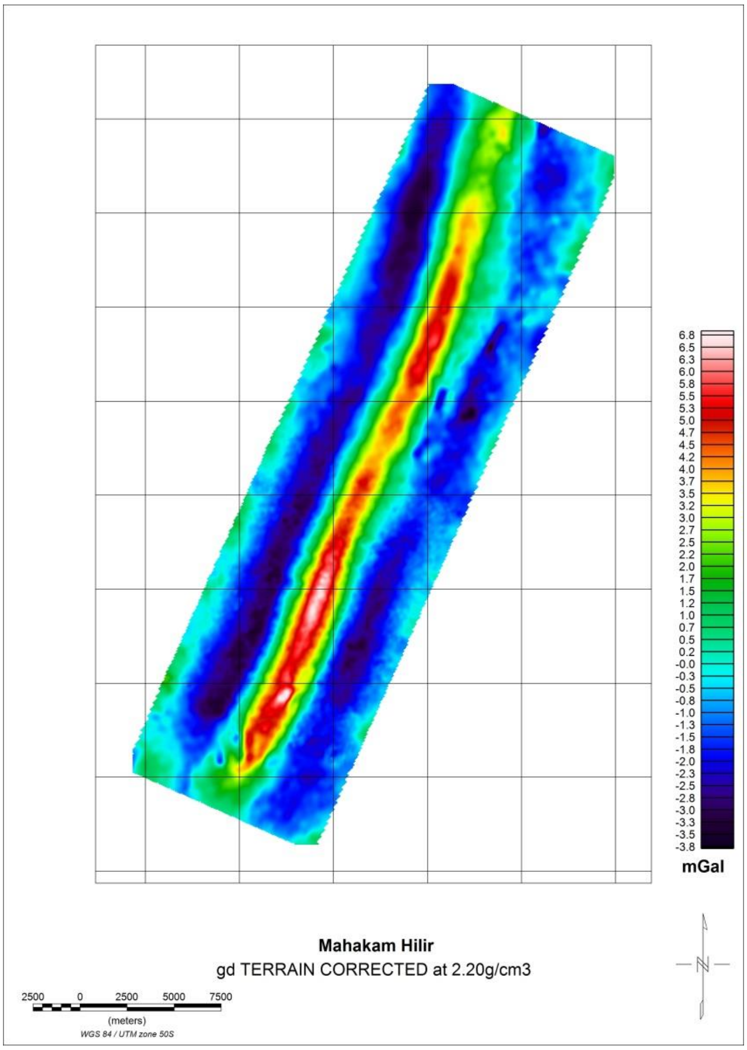

Figure 3: Terrain corrected vertical gravity from the airborne FTG survey over the Pelarang Anticline.

INTERPRETATION

The selective application of potential field enhancement filters was subsequently used to clearly delineate the position and extent of the Pelarang Anticline. The maximum of the tilt-filtered g_D data (Miller and Singh, 2004) provided an objective estimate of the location of the crest of the anticline. Furthermore the maximum of the absolute horizontal gradient of the g_D data provided a clear mapping of the flanks of the anticline (Blakely and Simpson, 1986).

2D modelling of selected profiles across the anticline suggests that it can be modelled as a 1,500m-2,000m wide, by ~2,000m high shale body that is close to breaching the surface in places. This is in alignment with an interpretation that the feature is cored by high-pressured shales, resulting in un-prospective areas. The bulk density of the anticline is modelled as 2.58 g/cm^3 in a background of deltaic sediments with a bulk density of 2.3 g/cm^3. There is a subtle asymmetry in the gravity anomalies suggesting that the anticline is dipping slightly towards the south-east.

3D gravity inversion of the g_D data was performed by discretising the subsurface into a 500m x 500m (width) x 100m (height) voxel model. The 3D gravity inversion process subsequently seeks a smoothly varying density distribution which produces a gravity response matching the observed gravity data. The resulting voxel-based density distribution can be visualised with iso-surfaces. Figure 4 shows the density model derived from smooth-density 3D modelling of the g_D data in a 3D view of the 2.4 g/cm^3 iso-surface as seen from the northwest.

The resulting 3D density model reveals significant along-strike variations in the depths to the crest of the anticline, suggesting the presence of several anomalous structural lows. Re-interpretation of vintage 2D seismic sections over the area suggests that these features are pull-apart mini-grabens, formed in response to localized shear movements. These breaches in the crests of the elongated anticlines may have acted as foci for the deltaic sediment transport and guided the distribution of the coarser reservoir channel sands. At least two commercial hydrocarbon accumulations, Sambutan (Figure 4) and Mutiara (Bachtiar et al., 1998), appear to be genetically related to the newly recognized structural anomalies.

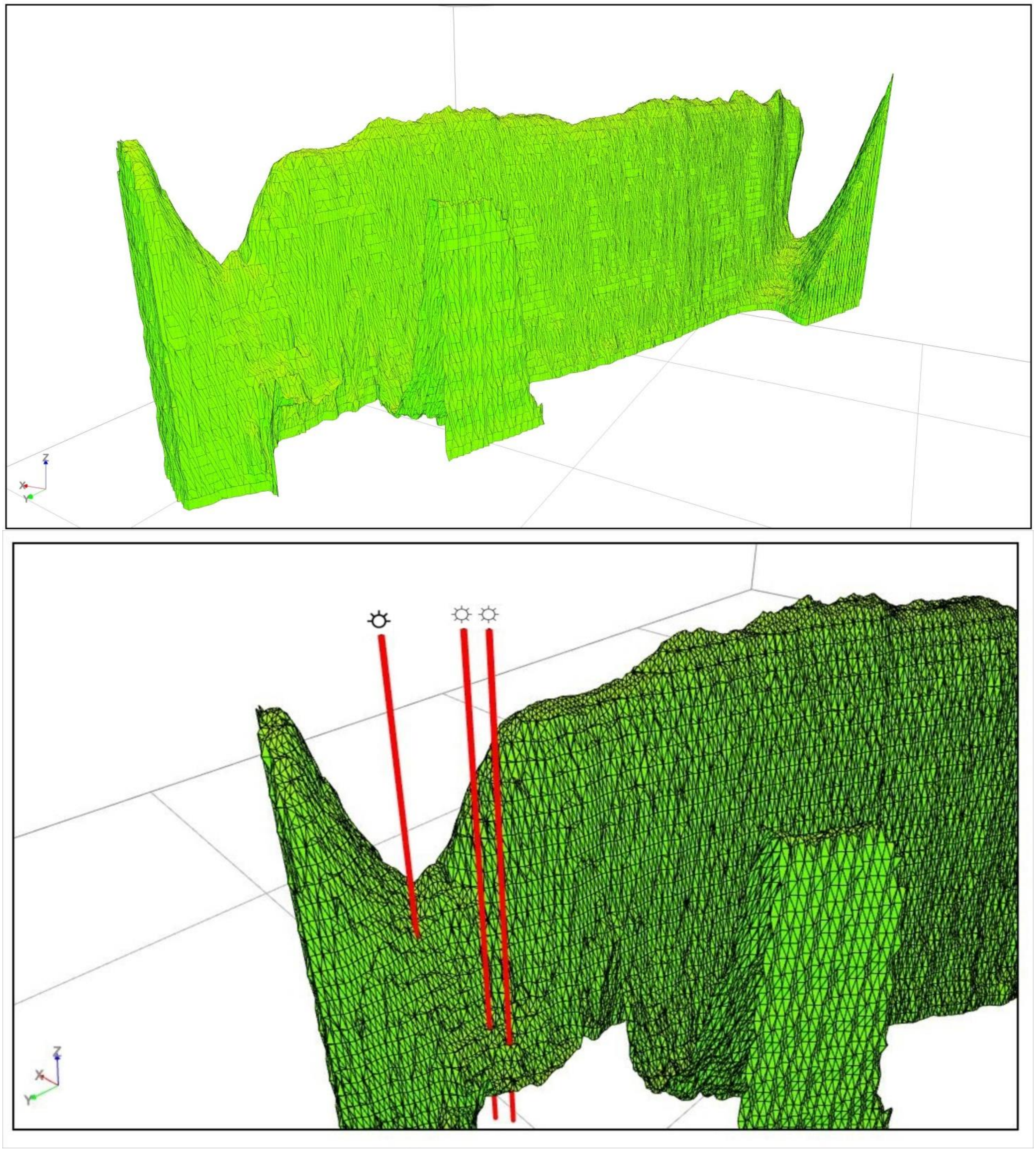

Figure 4: Density model from smooth-density 3D modelling of the g_D data. (*Top*) View of the 2.4 g/cm^3 iso-surface as seen from the NW. (*Bottom*) View of the 2.4 g/cm^3 iso-surface as seen from the NW with Sambutan oil/gas field wells added. Note the structural low in the crest of the anticline near the Sambutan oil/gas field.

CONCLUSIONS

Vertical shale diapirism had been proposed by Biantoro et al. (1992) as possible explanation for the formation of the Samarinda Anticlinorium. Shale diapirs are generally associated with negative gravity anomalies (Jacques et al., 2003) (Campbell et al., 2008). The Pelarang Anticline has now been shown to be associated with a strong positive gravity anomaly, yielding it unlikely that diapirism is the driving force behind the formation of the Samarinda Anticlinorium. The observed positive gravity anomaly is in alignment with an interpretation that the Pelarang Anticline is cored by high-pressured shales. The observed asymmetry in the positive gravity anomalies are in line with the thin-skinned/thick-skinned inversion-related thrust model proposed by Chambers et al. (2004).

The airborne FTG survey has provided Cue Energy with the first ever complete map of the extent of the Pelarang Anticline. Subsequent 3D modelling of the vertical gravity has revealed significant along-strike variations in the depths to the crest of the anticline. This has led to the recognition of a new exploration play in the region, and provided a tool to pursue this. Airborne gravity gradiometry has proven to be a fast and cost-effective tool for mapping the structures of the Samarinda Anticlinorium.

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