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Understanding the variability of sedimentary basin's gravity response through stratigraphic modelling

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SUMMARY

It is well known that inversions of gravity data are non-unique and this means that if one model can be found that fits data then there is also a set of alternative models that fit the data equally well. This non-uniqueness also extends to the choice of model parameterisation, a voxelised model is likely to explain the data as well as a model with layers with constant density and variable thickness.

A practical consequence of the non-uniqueness of gravity inversions is that a measured gravity response above a sedimentary basin can be explained by (1) sediments with constant densities above a highly heterogeneous basement or by (2) a basement with a constant density combined with variations of densities within the sedimentary strata. Understanding the sedimentary cover's gravity response and its variability is therefore central to localise the cause for anomalies in the observed gravity response particularly in the context of whether or not they are caused by density anomalies in the basement or the sediment cover.

Here, we use stratigraphic modelling to assess the variability of sedimentary strata's gravity response. We employ process-based numerical simulations to generate density distributions and focus on geologically plausible models. Results from a study of a 2D section in the Northern Carnarvon basin (offshore of north-western Australia) show that even with a wide range of input parameters for the stratigraphic models, the gravity response has a limited variability when compared with the gravity response of a model where the subsurface density distribution and its uncertainty is parameterised using voxels or layers. Further to this, our numerical experiments provide insight into the global sensitivity of the gravity response to stratigraphic model parameters. We find that the gravity response is most sensitive to parameters related to creation and filling of the accommodation space.

Key words: Undercover Resources, Gravity Modelling, Stratigraphic Modelling, Geological Realism.

INTRODUCTION

Gravity modelling involves either calculating a gravity response of a subsurface density distribution (forward modelling) or using an inversion algorithm to estimate the subsurface density distribution given a set of gravity observations (inverse modelling). Inherent to that is the choice of a model parameterisation. The two most common parameterisations are (1) polygonal prisms, which allow for a more geologically realistic description of subsurface bodies; and (2) voxels, that is more general but incorporate a large number of parameters, amplifying the inherent non-uniqueness of gravity modelling. This means that if a model can be found to fit the data, a large number of other models are going to fit the data equally well. Nevertheless, a large fraction of these models will only present a geophysical perspective on the sedimentary basin heterogeneities.

Only a subset of these models is likely to be geologically plausible. Using a process based simulation to parameterise the density model allows to bring a geological perspective to the description of the sedimentary basin density distribution. We employ stratigraphic modelling to simulate the filling of basin accounting for the erosion, transportation and deposition of multiple sediment class. Using stratigraphic modelling allows us to generate density models integrating multiple lithology and the evolution of their porosity attributed to compaction and diagenesis over large area (10^4-10^6 km^2).

Here we explore this new parameterisation of density models on a 2D section of the Cainozoic strata of the Northern Carnarvon basin. We use stratigraphic modelling to understand the variability of the gravity response along this section. We aim to present a comparison of the gravity response variability using stratigraphic model parameterisation to voxel and polygonal prism parameterisations. This is followed by a sensitivity analysis of the gravity response to stratigraphic modelling input parameters.

CASE STUDY, DATA AND METHODS

The Northern Carnarvon basin is located on the North-West shelf of Australia (Figure 1). This area contains Palaeozoic to recent sediments hosting multiple proven petroleum systems with recent estimations of the hydrocarbon reserves in the basin of ~1 GBbl of oil and 24 TCF or gas and condensate (Geoscience Australia, 2018). The Cainozoic strata of this basin mainly consist of carbonate deposits with occasional clastic layers forming a prograding margin (Marshall and Lang, 2013). This study is based on a 2D seismic line oriented NW-SE, 50km offshore of Karratha (Figure 1B.). A total of five horizons are picked on this line and interpreted using the work from Moss *et al.* (2004) and Cathro and Karner (2006). Time to depth conversion is performed using interval velocities and calibrated to the Zeus-1 well, drilled on the seismic line.

Our 2D stratigraphic forward model is based and calibrated to the uppermost four horizons. To conduct the stratigraphic model we use DionisosFlow, a process-based multi-lithology diffusion driven simulation software (Granjeon, 2014). DionisosFlow simulates the transport of different classes of

sediments at the basin scale. Simulations of both carbonate and clastic sedimentation are possible, and multiple model runs can be utilised (using COUGARFLOW) to test the impact of model parameters on the basin fill architecture and distribution of resulting densities, with parameters such as sediment flux, source location, and subsidence history and eustatic sea level variations, carbonate production rates can be varied. Diffusion of the sediments in the model mainly depends on three factors: (1) the gravity, (2) the water flux (3) and the wave activity. These are captured, for each sediment class i in the diffusion coefficients $K_{i_{gravi}}$, $K_{i_{wave}}$ and $K_{i_{water}}$, respectively linked to the slow creeping transport and the wave and water driven displacement. Our stratigraphic model contains 4 carbonate and 3 clastic sediment classes and simulates the period 30.2 Ma to present day using a time step of 0.1 Ma.

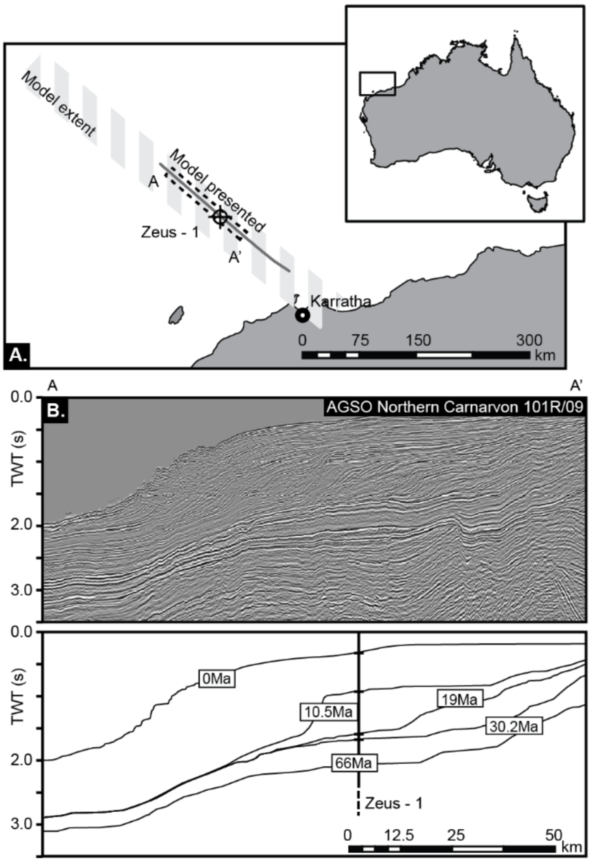

Figure 1. A. Location of the study area. B. Seismic data available and interpreted time horizons.

Table 1. Input parameters used to model the density distributions in each parameterisation.

Polygonal prisms density model
Input 1: Depth of main horizons (m)
Input 2: Interval 1 density (g cm^{-1})
Input 3: Interval 2 density (g cm^{-1})
Input 4: Interval 3 density (g cm^{-1})
Voxelised density model
Input 1: Bottom horizon depth (m)
Input 2: Density-Depth trend parameters
Geologically motivated density model
Input 1: Eustatic amplitudes (m)
Input 2: Subsidence rate (m Ma^{-1})
Input 3: Sediment Supply (km^3 Ma^{-1})
Input 4: Water discharge (m^3 s^{-1})
Input 5: Carbonate production (m Ma^{-1})
Input 6: Initial bathymetry (m)
Input 7: Transport model (km^2 ka^{-1})

Using the depth converted horizons from seismic data and the stratigraphic model, we compute the variability of the gravity response using 700 simulations for each parameterisation. In each simulation, different density distribution are generated by varying the input parameters presented in Table 1 within a +/- 10% range from a prior belief. The input parameters of the model are sampled using a Latin hypercube algorithm to minimise the sample number while reasonably covering the parameter space. The relations between stratigraphic model input parameters and the gravity response is investigated using a global sensitivity analysis based on Delta Moment-Independent Measure (Borgonovo, 2007). The sensitivity analysis is conducted using the Python SALIB package (Usher et al., 2017) using two additional sets of 700 gravity responses calculated from geologically plausible density models with inputs varying by +/- 20% and +/- 5%.

RESULTS

Figure 2 presents different types of parameterisation for density model: a polygonal prisms model (Figure 2A.), a voxelised model integrating a density-depth trend (Figure 2B.); and a geologically motivated model parameterised using stratigraphic models (Figure 2C.). There is a gradual increase of geological realism across the density models. In Figure 2C., the geologically motivated model presents density heterogeneities related by sediment and facies heterogeneities linked to the evolution of the accommodation space (partly controlled by the subsidence, the bathymetry and the eustatic variations), the evolution of the sediment supply and carbonate production rates, the transport of the sediments and their compaction.

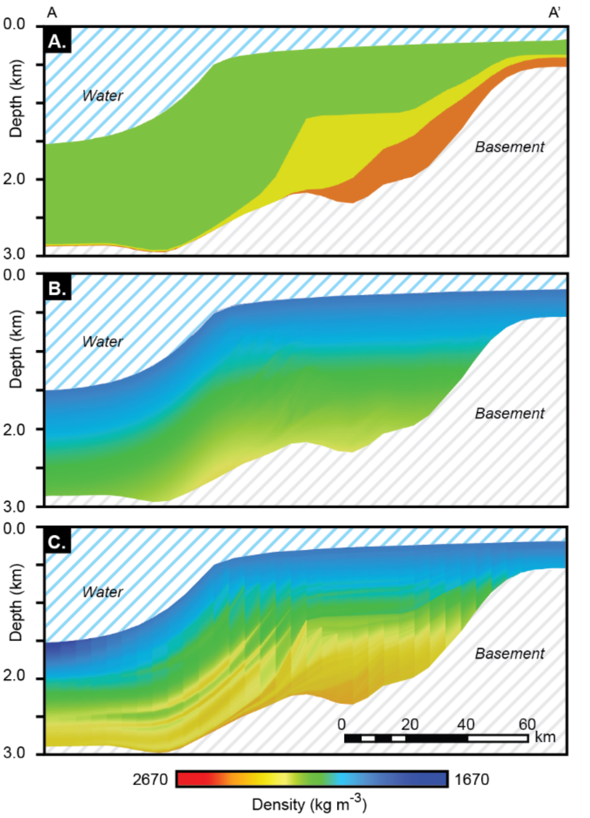

Figure 2. Different parameterisation for density models used in gravity modelling showing and increasing geological realism. A. polygonal prisms, B. voxelised and C. geologically motivated.

Figure 3 presents the variability of the gravity responses for polygonal prisms density models (Figure 3A.), voxelised density models (Figure 3B.) and geologically motivated density models (Figure 3C.) using a +/- 10% input parameter range. The gravity responses computed with geologically motivated density models present a difference between their first and third quartile under 4 mGal. Using polygonal prisms or voxelised parameterisation, the gravity responses vary around 17 and 16 mGal between their first and third quartiles. By using geologically plausible models from stratigraphic modelling we significantly decreased the variability of the gravity response (Figure 3).

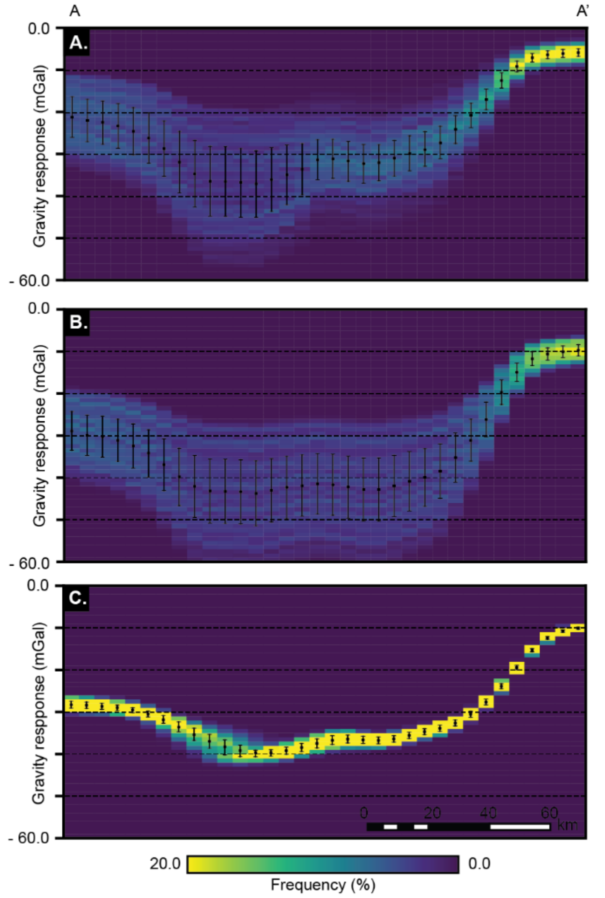

Figure 3. Variability of the gravity response for polygonal prism models (A), voxelised models (B.) and geologically motivated models (C) including 10% uncertainties on the input parameters.

The sensitivity analysis of the gravity response to stratigraphic modelling input parameters is presented in Figure 4. This figure shows that three parameters have a significant effect on the gravity response:

- The proximal bathymetry where the total sedimentary thickness is less than 500 m;
- The subsidence, on the shelf and in the deep basin, where more than 2 km of sediments are present; and,
- The carbonate production rates, on the shelf edge and down continental slope.

Figure 4 also emphasises four stratigraphic the parameters with negligible effects on the gravity response: the water discharge, the transport model, the eustatic variations and the sediment supply.

Our sensitivity analysis shows the parameters that control the gravity response primarily are the generation and filling of the accommodation space. The sedimentary supply and eustatic variations do not affect the gravity response along this section although they also control accommodation space creation and filling. It is likely this result comes from two main causes:

- The Carnarvon Basin mainly presents carbonated layers with few clastic inputs; and,
- Eustatic variations are cyclic and have low relative amplitudes, producing only a second order control on the generation of accommodation space.

These results allows for a model parameter reduction of the geologically motivated density distribution. In this case study, only the input parameters related to accommodation space creation and filling significantly impact the gravity response. Therefore, additional accuracy on the gravity response prediction can be acquired by having a narrower range of uncertainties on the initial bathymetry, the rate of carbonate production and the subsidence rates.

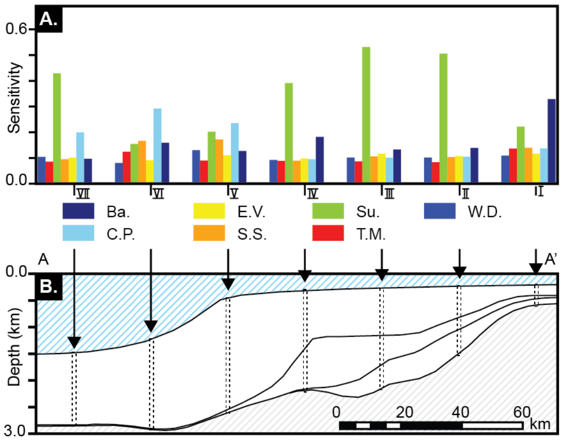

Figure 4. Sensitivity of the gravity response along a 2D section of the Cainozoic strata of the Northern Carnarvon Basin. E.A., Eustatic amplitudes; Su. Subsidence rate; S.S., Sediment Supply; W.D., Water discharge; C.P., Carbonate production; Ba., Initial bathymetry; T.M., Transport model.

CONCLUSIONS

Here, we used stratigraphic modelling to parameterise density models and compute the gravity response of the Cainozoic strata of the Northern Carnarvon basin. Accounting for stratigraphic processes, we only focussed on geologically plausible density models for sedimentary layers. Our results illustrate that:

- Even for a wide range of parameters, gravity models using this parameterisation present a reduced variability when compared to workflow using voxel or polygonal prism based parameterisation; and,
- The gravity response to stratigraphic model inputs is more sensitive to parameters related to the creation and the filling of the accommodation space than to the parameters related to the type and the distribution of the sediments.

By incorporating more realistic models of the density distributions within sedimentary basins we are better able to understand the causes for a gravity anomalies in general. Our approach might be useful in situations where one needs to understand if gravity anomalies are basin or basement sourced.

In addition, focussing on geologically plausible density models could open new perspectives when discussing correlation between two wells. Using gravity inversion parameterised with stratigraphic models, we could focus on models fitting the gravity data and the two wells while being geologically plausible.

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