# Resolving basement crustal architecture and extensional tectonics using 3D inversion modelling of airborne gravity data in the Otway Basin region, Victoria.

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## SUMMARY

Seismic reflection surveys remain a very effective way of imaging the sub-surface crustal architecture of sedimentary basins. They can also often image the base of the basin (or top of basement) which is an important interface for understanding the structural controls imposed on basin fill and the prospectivity of a basin system because the basin base represents the lower boundary of effective pore space.

However, imaging basement in places where basin fill is thick can be problematic in seismic data optimised for near-surface resolution, and in vintage seismic data which is noisy and/or does not penetrate deeply. Airborne gravity and gravity gradiometry surveys can be effective and complementary in these scenarios, and also in proximity to the coast where seismic acquisition is problematic (logistics and high ambient noise).

3D geometries of geological structures can be tested quantitatively against geophysical data – specifically airborne gravity and gravity gradiometry in this example – using a 3D forward modelling and inversion approach. Three-dimensional forward modelling is a technique that involves construction of geological 3D computer models, assigning rock property data (such as density) to packages of rocks, and calculating the synthetic gravity response of the theoretical model. The difference between the calculated and observed response (the residual gravity response) indicates a mis-match, where changes to the 3D model need to be made.

This study aims to provide a workflow to tackle the problem of superposition of geophysical anomalies. We use the Otway Basin in southeast Australia as a 'laboratory' to provide a systematic approach for understanding basin and underlying basement geometry, using airborne gravity data in conjunction with other geophysical and geological datasets. A new regional 3D model of the Otway Basin is presented which is not only consistent with airborne gravity gradiometry data acquired over the on- and near-shore Otway Basin, but which also integrates the current understanding of the crustal architecture in the Otway region with previous studies including seismic interpretation of the basin and of the basement, previous 3D geological framework models of the basement, and also insights gained through surface mapping.

**Key words:** gravity, gradiometry, modelling, inversion, Otway Basin.

## INTRODUCTION

Understanding sedimentary basins is important for a variety of earth resources including hydrocarbons, water, geothermal energy and carbon and hydrogen storage. To be predictive about these resources, we require a thorough understanding of the basin architecture including the geological history of how the basin developed. Traditionally, seismic reflection surveys have been used and still remain an effective way of imaging the sub-surface geological structures in sedimentary basins. However seismic reflection remains problematic where the basin is thick and/or where interpretations are being made from vintage seismic data that does not penetrate deeply.

Airborne gravity and gravity gradiometry surveys can be effective for sedimentary basins where seismic fails to resolve crustal architecture but also in proximity to the coast where seismic acquisition is problematic. Gravity data is particularly effective in resolving basement architecture where a significant density contrast exists between rocks in the basin and in the underlying basement geology, and where the basin fill is of known – and laterally uniform – density. In such circumstances, three-dimensional (3D) geometries of geological structures can be tested quantitatively against geophysical data using a 3D forward modelling and inversion approach (eg. Pears et al., 2017; McLean et al., 2008; Lindsay et al., 2020).

Gravity data comes with its own challenges however. Gravity surveys ultimately measure the magnitude of gravity at any given location. This includes everything that could influence the gravitational field. Data are typically processed to remove the effect of several unwanted influences like latitude, tides, effects of topographic variations etc. While these processing steps leave the cumulative gravity signature of the rocks in the subsurface, this gravity response will invariably be made up of not only the gravity response of the basin fill, but also the gravity response of the rocks in the basement, and even deeper into the mantle. Therefore, to effectively use gravity data to model and interpret the gravity response of a geological basin, its critical to 'break-up' a gravity dataset and determine which geological structures are responsible for which gravity anomalies.

This study aims to provide a workflow to tackle the problem of superposition of geophysical anomalies. We use the Otway Basin in southeast Australia as a 'laboratory' to provide a systematic approach for understanding basin and underlying basement geometry using airborne gravity data. A new regional 3D model of the Otway Basin is presented which is not only consistent with airborne gravity gradiometry data acquired over the on- and near-shore Otway Basin (Carter et al., 2019), but also integrates the current understanding of the crustal architecture in the Otway region with previous studies including seismic interpretation of the basin (Romine et al., 2020) and of the basement (Cayley et al., 2011), previous 3D geological framework models of the basement (Rawling et al., 2011; Cayley et al., 2018), and also insight gained through surface mapping (Welch et al., 2011). While this example is focused on a sedimentary basin, the workflow could be adapted to regions where relatively thinner cover sequences obscure underlying basement geology, as is common in minerals applications.

## GEOLOGICAL SETTING

Victoria's basement geology is divided up into several different structural zones which display approximately north-south aligned structural grains. These structural zones comprise parts of the Delamerian and Lachlan orogens accreted to the east-Gondwana margin during successive orogenic cycles in the Early Palaeozoic. This basement geology is known collectively as the 'Tasmanides'. The zones which intersect the area of interest for this study are the Glenelg Zone, the Grampians-Stavely Zone, the Stawell Zone and the Selwyn Block (Figure 1). The basement geology within the Glenelg, Grampians-Stavely and Stawell zones is interpreted to extend south under the Otway Basin. Selwyn Block crust underlies parts of the Otway Basin just outside the study area (east of the Sorrel Fault and southeast of the Bambra Fault).

The Otway Basin is a northwest-southeast trending basin that extends for 500 km along the onshore and offshore parts of south-eastern Australia. It is a passive margin, rift basin (Brown et al., 2003) that formed during the Cretaceous break-up of southern and eastern Gondwana and is infilled with a Cretaceous to Pliocene sedimentary succession. Rifting was superimposed orthogonally over the predominant north-south structural grain of Tasmanide geology.

Rifting in the Late Jurassic-Early Cretaceous resulted in the development of grabens and half grabens of limited lateral extent (Krassay et al., 2004) and varying orientations (Stacey et al., 2013) including local reactivation of pre-existing basement structures. Up to eight kilometres of Otway Group continental and fluvio-lacustrine sediments were deposited in the Early Cretaceous depocentres. This early basin fill succession is overlain by a thick sequence of Sherbrook Group fluvial, deltaic and shallow marine sediments deposited in the Late Cretaceous depocentres. Subsequent basin margin subsidence and the deposition of the transgressive siliciclastic Wangerrip Group reached a maximum thickness of more than 1200 m in the Portland Trough (Holdgate & Gallagher, 2003). The overlying Nirranda Group has a maximum thickness of about 200 m in the Portland Trough and the Port Campbell Embayment (Holdgate & Gallagher, 2003). Lastly, the marine marls and limestones of the Heytesbury Group are separated by two regional unconformities from the underlying Nirranda Group and the overlying thin Pliocene to Pleistocene shallow marine sediments and basalts of the Bridgewater Formation.

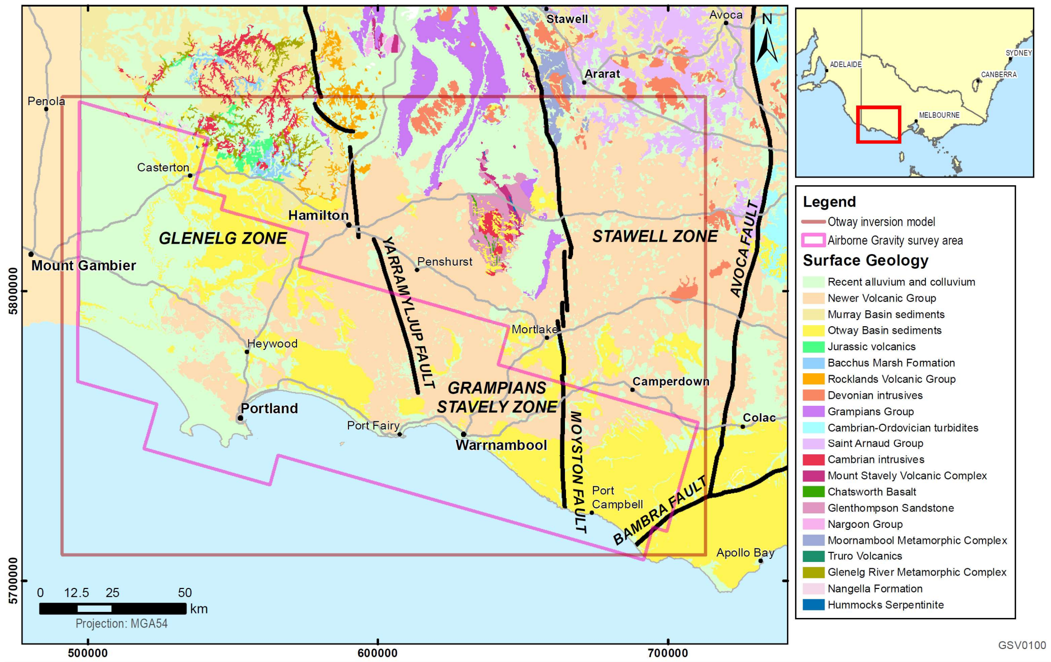


**Figure 1. Geological map of the Otway region (geological data from Welch et al., 2011).**

## GEOLOGICAL AND GEOPHYSICAL DATA

The 3D model presented in this paper was primarily tested against airborne gravity gradiometry data, acquired by CGG Aviation (now Xcalibur Multiphysics) for the Geological Survey of Victoria (Carter et al., 2019). The survey acquired more than 31 000 line kilometres over a region approximately 16 000 km$^2$. Data were acquired at 500 m flight lines (northwest-southeast) and 15 000 m tie lines (Figure 2). Airborne gravity gradiometry data were conformed with conventional airborne gravity data to produce a “Full Spectrum Vertical Gravity” dataset. This approach facilitated capture of both the short to medium wavelengths (Falcon gDD) and also the medium to long wavelengths (sGrav gD).

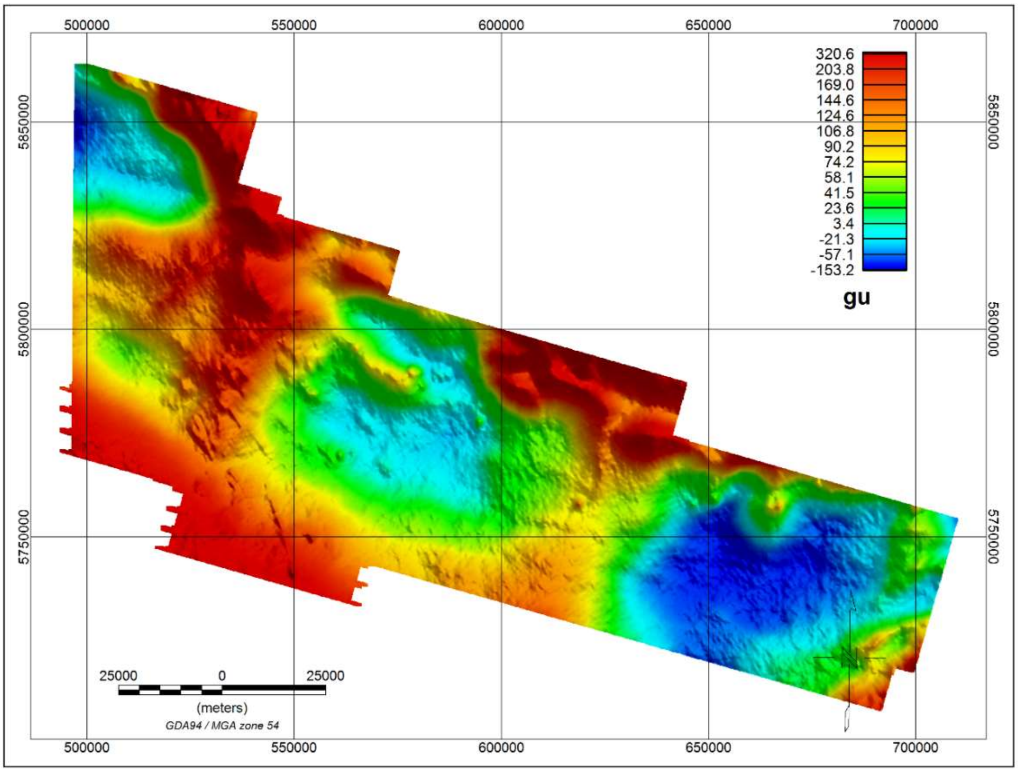


**Figure 2 - Full Spectrum Vertical Gravity (gD). These data capture a wide range of wavelengths through conforming short wavelengths from the Falcon instrument with longer wavelengths from the sGrav.**

In addition to airborne gravity gradiometry, the 3D model was also constrained by other geophysical datasets including high resolution aeromagnetic data to constrain basement geology (Colac VIMP and Offshore Otway Basin surveys) and reflection seismic surveys to constrain basin geological horizons and fault geometries. Pre-existing 3D models were also used to guide the modelling process for the Otway Basin inversion model. The Stavely regional 3D model (Cayley et al., 2018) was used to constrain the basement architecture in the central region of Otway Basin inversion model and parts of the 3D Victoria model (Rawling et al., 2011) were used to constrain some major structures, which have been previously modelled.

Density data were used to constrain geophysical forward modelling and inversion in the Otway Basin inversion model. Density data for the rocks in the Otway Basin were largely obtained from laboratory measured values by Power & Goldie Divko (2019), Skladzien, (2007), Cayley et al., (2018), Skladzien et al., (2016) and Skladzien, (2018).

## MODELLING AND RESULTS

Airborne gravity and gravity gradiometry data can be tested quantitatively against geophysical data using a 3D forward modelling and inversion approach. Three-dimensional forward modelling is a technique that involves construction of geological 3D computer models, assigning rock property data (such as density) to packages of rocks and calculating the synthetic gravity response of the theoretical model. This calculated gravity response of the model can be compared with the observed response which was acquired by aircraft. Differences between the calculated and observed response (the residual gravity response) indicate a mismatch where changes to the 3D model need to be made. Geophysical inversion involves stepwise process whereby the boundaries between geological horizons are iteratively adjusted to achieve a match between the calculated and observed response. Three-dimensional inversion modelling was undertaken using a combination of software including Mira Geoscience's GOCAD Mining Suite (an adaption of AspenTech's SKUA-GOCAD to the mining industry) and VPmg (for the inversion modelling). Potential field data were gridded and enhanced using Oasis Montaj (Geosoft®, 2015).

The approach applied for the Otway Basin was to use the existing seismic interpretations as a starting model and systematically add geophysical domains to represent interpretations of the residual gravity with a view to finally matching the observed data. The challenge with gravity modelling is that the observed data is the net measurement of the gravity signature of all rocks from the surface down to the Moho and beyond. Not only does this mean that the geology of the entire crust needs to be modelled (or accounted for somehow), but it also means that high amplitude gravity signatures most likely attributed to the diversity of geology in the basement must be explained first, before any refinements can be made to the comparatively small gravity variations that can be attributed to the sedimentary basin fill. If density variations within the basement are not accounted for appropriately prior to inversion, the inversion process may make large and unreasonable changes to the basin's sedimentary fill in an attempt to compensate for gravity variations which actually reside within the basement.

To ascertain which gravity anomalies are attributed to the basin and which are the response of the basement, a simple starting model of the basin was built (Figure 3). This model was constrained by the four horizons: the top Wangerrip Group, top Sherbrook Group, top Otway Group and top of Palaeozoic basement. Average densities were assigned to these rock packages using published rock properties (Figure 3b). A bathymetry surface (Carter et al., 2019) was used to constrain the shape of the seafloor in the model. The model covered an area of 158 km x 222 km and had a cell size resolution of 2 km x 2 km (Figure 3a).

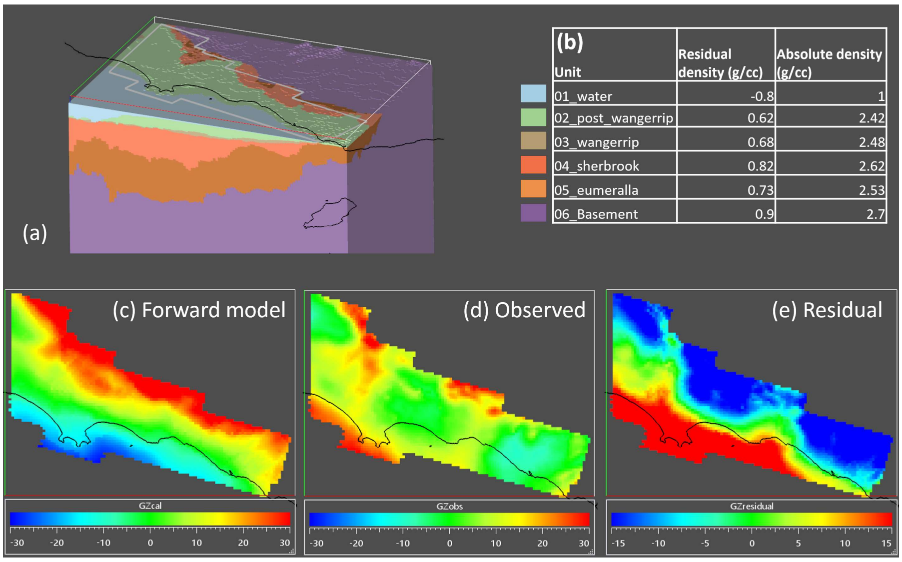


**Figure 3. Starting model for the Otway Basin (a) Discretised 3D model (vertical exaggeration = x5); (b) Table of densities assigned to each geological unit; (c) Forward model; (d) Observed response; (e) Residual response.**

The forward model (Figure 3c) is dominated by a north-south gradient with a strong gravity high in the north and a gravity low in the south. This is as expected because the geometry of the basin as interpreted from reflection seismic is a sedimentary sequence that thickens (deepens) steadily toward the south. The largest density contrast in this initial starting model is the discrepancy between the basement and the overlying sediments. Therefore, the forward response is dominated by the geometry of the top of basement. The forward model fails to explain the high amplitude response, particularly in the southwest region of the observed data (Figure 3d). This is exemplified in the residual (Figure 3e) which shows the largest mis-match is on the southern margin of the airborne dataset.

These results demonstrate that a model which includes the basin alone is far from sufficient to explain the observed data. This suggests that the diversity of geology in the underlying basement needs to be included to achieve a fit with the observed data. However, understanding the 3D geometric structure of the basement underneath the relatively thick sequences within the Otway Basin is a difficult exercise because of limited constraints. The basement only outcrops north of the Otway Basin sediments and there are few wells that penetrate through the basin and into the basement. Seismic data has also been acquired with a view to imaging the geometry of the basin (rather than the basement), and so the seismic data below the top of the basement is often noisy and difficult to interpret. Therefore, resolving crustal architecture of the basement under the Otway Basin remains problematic despite the detailed seismic coverage.

However, there is some understanding that comes from the gravity and magnetic datasets. The basement geology in western Victoria is understood to be largely north-south trending. This trend is recognisable in magnetic and gravity datasets which can be used in map view to qualitatively extend interpreted structures underneath the Otway Basin. This approach has been used to inform a model of the basement geology underneath the Otway Basin. Because different geological terranes in the basement have been juxtaposed along regional fault structures, a fault network of surfaces was built, and used to separate these geological terranes. We divided the basement under the Otway Basin using faults built by Rawling et al. (2011), Cayley et al (2018), and also this study. Similarly to the sedimentary basin, densities were also attributed to the basement rocks constrained by published values measured from outcropping geology (eg. Skladzien 2007; Cayley et al., 2018).
In addition, a Moho surface was included to account for the high amplitude gravity signal associated with the continental shelf margin (e.g. Grow et al., 1979). We used a combination of Moho interpretations from Kennett et al., (2011) and FitzGerald et al., (2009), and refined the surface to honour deep reflection seismic constraints both on and offshore.

Incorporating basement geology and the Moho resulted in a much better fit with the observed data, but some differences remained. A number of geological scenarios could explain the remaining mis-match, however, much of the remaining signature was characterised by an east-west trend which is consistent with the extensional structures observed in the basin, rather than the basement. These residual gravity highs are interpreted as the response of the top basement that has not been accounted for with this model, and therefore requires further adjustment to achieve a closer fit. The final step therefore involves a geometry inversion that focuses on the top of the Palaeozoic basement.

To focus the geometry inversion on the top of basement, we ‘fixed’ the top of basement at locations with greater confidence (where there are clear seismic reflectors) but allowed modification to the top of basement elsewhere. The entire boundary of all sedimentary horizons above the top of basement was also fixed since near-surface seismic interpretations were made with a high degree of confidence (Romine et al., 2020). Similarly, the Moho was also fixed because it was constrained by deep reflection seismic interpretations and previous Moho models (Kennett et al., 2011; FitzGerald et al., (2009).
The final inverted model shows a significant improvement in the residual gravity response (Figure 4d) particularly considering the maximum/minimum for the colour stretch has been narrowed from ±15 mGal (Figure 3e) to ±2 mGal (Figure 4d). With such a small range of gravity amplitudes in the residual response, we suggest the majority of geological structures have been accounted for in this model.

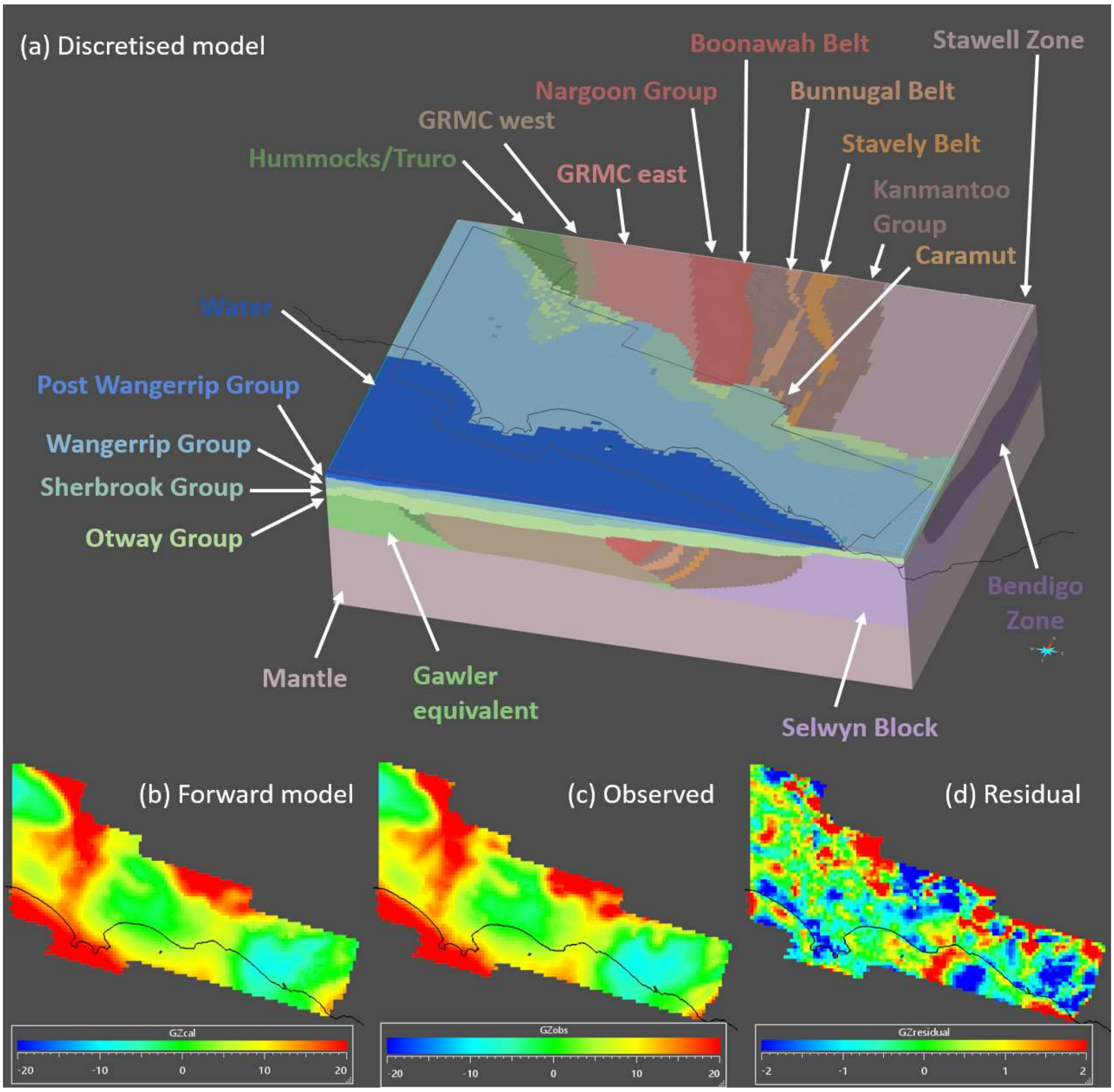


**Figure 4. Basement and basin of the Otway Basin. (a) Local discretised model showing all geological units (vertical exaggeration = x1). Coastline (black) and airborne survey outline (grey) overlaid; (b) Forward model of the discretised model; (c) Observed response; (d) Residual response.**

## DISCUSSION

The top of basement interface on the western end of the Portland Trough required the most significant modification to obtain a match with the observed response. The inversion 'pushed down' the top of basement surface in this region by as much as 3000 m (Figure 5). This is a substantial change, and we acknowledge there may be other geological solutions to explain the measured gravity amplitude; however, seismic control on the top of basement in this region is poor at best, so we suggest our proposed geometry is certainly plausible and is also a geological solution to explain the gravity anomalies because the trend of this miss-match is closely aligned to the known extensional structures. The inversion process only made relatively small changes to the remainder of the top of basement surface – particularly where we have confidence in this interface. This suggests that the gravity inversion is making geologically realistic alterations to the top of basement surface and that significant change the southwest region was indeed required. Moreover, the northwest trend of these differences is also consistent with the orientation of the Tartwaup Fault (Figure 5) which is known to have accommodated extension during the Cretaceous (Rawling et al., 2011; Romine et al., 2020). This supports the interpretation that the residual gravity low can be attributed to a significant depocentre in the southwest.

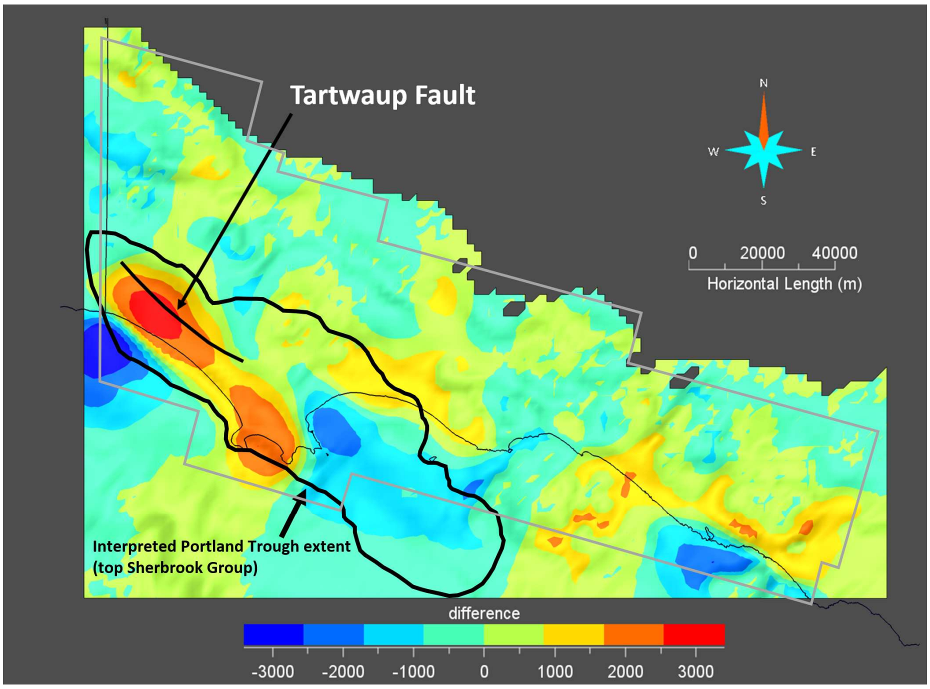


**Figure 5. Map of the differences between the depth to the top of basement for the inverted model, and the depth to the top of basement for the starting model.**

## CONCLUSIONS

A new quantitative 3D gravity inversion model has been built over the Otway Basin region, incorporating both the basin and basement geology. The modelled basement incorporates known geology as interpreted from exposed outcrops further north of the Otway Basin, whereas the modelled basin geology incorporates highly detailed interpretations from reflection seismic of the sedimentary horizons in the basin. However, top of basement interpretations from seismic remained uncertain, particularly close to the coast. This study provided a new top of basement surface constrained with seismic interpretations where there was confidence in that data, and consistent with the airborne gravity data elsewhere.

This study also demonstrated the importance of implementing careful assessment of the geophysical responses, discerning what geological sources the data is responding to, then adapting the methodologies to address and incorporate these geological sources into the model. Here, the result of this process identified the requirement to model the full crust, particularly including the Moho, but also basement variations, to sufficiently explain the observed gravity response.

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