Imaging a mafic underplate in 3D: an example from the east Albany–Fraser Orogen and Yilgarn Craton margin

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SUMMARY

In this study a mafic underplate along the margin of the Proterozoic east Albany–Fraser Orogen and Archean Yilgarn Craton is imaged using 3D gravity forward modelling. The 3D model was constructed in GeoModeller and tested by 3D gravity forward modelling, an approach selected due to the distinct, regional-scale gravity anomalies observed along the margin. Important constraints on the model include an interpreted bedrock geology map, Moho depth points from a passive seismic survey and three deep crustal reflection seismic lines. The Moho model shows a zone of thickened crust extending, parallel to the Albany-Fraser Orogen, along the length of the orogen. 3D gravity forward modelling demonstrates that dense material is required in this zone of thickened crust and also demonstrates that this dense material is most likely in the lower crust, coincident with a large non-reflective zone imaged in reflection seismic data. This zone is interpreted to represent a mafic underplate that formed in the lower crust of the Yilgarn Craton during the Proterozoic. Some of the possible tectonic settings for the emplacement of this voluminous mafic underplate include Paleo-Mesoproterozoic extension that occurred along the margin or during the Mesoproterozoic Albany–Fraser Orogeny.

Key words: 3D modelling, gravity, mafic underplate

INTRODUCTION

In this study constrained 3D gravity forward modelling is used to determine the density structure of the east Albany-Fraser Orogen and Yilgarn Craton margin. These methods are typically applied to smaller scale studies, but the increasing number of regional-scale geophysical datasets makes it possible to construct orogen-scale models of the crust. The regional-scale model constructed in this study contributes to our understanding of the crustal density distribution along the Archean-Proterozoic margin and within the Albany-Fraser Orogen and to our understanding of the tectonic history of the orogen.

The east Albany–Fraser Orogen and southeast margin of the Yilgarn Craton is covered by regional gravity surveys (2.5 km station spacing). Gravity data images several distinct, high and low amplitude, orogen-scale anomalies. These include the gravity high produced by the dense gabbro-dominated Fraser Zone of the east Albany–Fraser Orogen (Figure 1a). Another is the Rason Gravity Low, a long wavelength, low amplitude Bouguer gravity anomaly that extends along the margin of the orogen (Fraser and Pettifer 1980; Figure 1b). The change in gravity between the Fraser Zone and the Rason Gravity Low is ~ 100 mGal, one of the largest on the Australian continent.

METHOD

Model Construction

The east Albany–Fraser Orogen 3D model is a regional-scale model with the dimension 600 (x) by 400 (y) by 75 (z) km. The model has been constructed in Intrepid Geophysics implicit modelling software GeoModeller. Implicit modelling refers to the use of an interpolation algorithm to produce 3D surfaces from sparse 3D point and line data. The GeoModeller scalar potential field interpolator allows the rapid construction of 3D surfaces, although an artefact of this method is smooth model geometries.

Constraints on the model geology include, at the surface, a 1:250 000 scale interpreted bedrock geology map (Figure 1a; Spaggiari, 2016). This map is compiled from geological observations as well as aeromagnetic and gravity image interpretation. The surface of the model is defined by SRTM data (Jarvis et al., 2006). At depth the geology has been constrained by interpretations of three deep crustal reflection seismic profiles that traverse the southeast part of the Yilgarn Craton and the east Albany–Fraser Orogen (12GA-AF1, 2 and 3; Spaggiari et al., 2014a). Seismic profiles allow us to constrain the geometries of tectonic units at depth, and to image seismic provinces, seismically distinct units in the mid and lower crust. 2D density forward models constrain the 3D model in between seismic lines. The geology at the surface and along sections has been digitised in GeoModeller. Digitised point and line data have been interpolated in GeoModeller to produce surfaces that represent the tops of units.

The Moho is constrained by the ALFREX passive seismic survey, in particular the passive seismic P-wave receiver function analysis (Sippl et al., 2017). The array has ~50 km station spacing and extends across most of the 3D model volume. A high-resolution Moho map has been produced by calculating Moho depths at individual piercing points for all single receiver functions (Sippl et al., 2017). The Moho model shows a v-shaped zone of thickened crust along the margin of the orogen that extends to a maximum depth of 15 km (Figure 1d; Sippl et al., 2017). The significant Moho topography makes it an important constraint on crustal scale 3D modelling, particularly gravity modelling. Moho depth points have been supplemented with Moho picks along active seismic lines and result in a total of 1503 Moho depth points, constraining the Moho surface, in the model volume. Moho depth points and digitised Moho picks have been interpolated in GeoModeller to produce a surface representing the Moho. Surfaces representing the tops of geological units and the Moho have been used to divide the model volume into twelve geological units.

3D Gravity Forward Modelling

The geological model has been tested using 3D gravity forward modelling. The modelling approach used here was to assign starting densities to the 3D model using local specific gravity data, values from previous 2D gravity forward modelling, and values from the literature (Murdie et al., 2014; Tassel and Goncharov, 2006; Poudjom Djomani, 2001). Model densities were then adjusted, within reason of the petrophysical data, to achieve the best fit between the observed and calculated gravity data. In this study, best fit is defined as a model that reproduces the major features of the observed Bouguer gravity.

The model has been discretised into 1 x 1 x 1 km voxets and the Bouguer gravity response of the model calculated in Geomodeller (Figure 1c). The model misfit is assessed by comparing the observed and calculated gravity, and can be quantified by calculating the residual gravity (observed gravity – calculated gravity). Some misfits are expected, given the regional scale of the model and the forward modelling method which permits only one density to be assigned to a unit.

RESULTS AND DISCUSSION

Results of Gravity Forward Modelling

One of the major outcomes of 3D gravity forward modelling is that dense material is required in the zone of thickened crust that extends along the margin of the orogen, and identified in passive seismic data (Sippl et al., 2017). 3D gravity forward modelling demonstrates that the Moho trough produces a long wavelength Bouguer gravity low along the margin. However, to fit the observed Bouguer gravity data, dense material is required to shift the calculated Bouguer gravity low to the northwest, and to reduce the amplitude. Constrained by geometries from reflection seismic, 3D modelling demonstrates that this dense material is most likely in the lower crust, coincident with a large non-reflective zone imaged in reflection seismic data.

The non-reflective zone, imaged in the lower crust of reflection seismic profiles 12GA-AF2 and AF3, is ~25 km in maximum thickness and ~90 km in maximum length (northwest to southeast). Forward modelling has demonstrated that this unit can be modelled with a density of 2.95 g/cm^3. In 3D the dense, non-reflective zone extends from southwest to northeast, along the length of the study area (Figure 1e). The Rason Gravity Low continues to the northeast of the model area, along the length of the Albany–Fraser Orogen, as does the Moho trough and dense non-reflective unit.

Mafic Underplate Characteristics

The geophysical properties of this dense non-reflective unit suggest it can be defined as a mafic underplate. The process of mafic underplating is defined after Thybo and Artemieva (2013) as the addition of mafic magma to the lower crust and uppermost mantle around the Moho. This zone has been modelled with a density of 2.95 g/cm^3 which suggests it is mafic in composition. Seismic P-wave data (Sippl et al., 2017) show that this interpreted mafic underplate is spatially coincident with a dense zone in the crust. The non-reflective seismic character suggests it is a large intrusion that cooled over a long period of time, creating a body with smoothly varying properties which may be reflection free (Thybo and Artemieva, 2013).

Timing of Mafic Underplate Formation

The Albany–Fraser Orogen is composed of Archean crust that has been extensively reworked during the Proterozoic (Kirkland et al., 2011). The Paleoproterozoic to early Mesoproterozoic history of the orogen is dominated by extensional tectonics, including the formation of the intracontinental Barren Basin (1815-1600 Ma) and the Arid Basin (1600-1455 Ma), which is interpreted as a passive margin on an ocean-continent transition (Spaggiari et al., 2014b).

The Mesoproterozoic is dominated by crustal shortening that occurred during the Albany–Fraser Orogeny, in two tectono-thermal stages. Stage I (1330-1280 Ma) is interpreted to record the accretion of the Loongana Arc, of the Madura Province, onto the Eastern Nornalup Zone (Spaggiari et al., 2015). Stage II (1225-1140 Ma) is interpreted as intracratonic reactivation accompanied by magmatism (Spaggiari et al., 2015).

The mafic underplate in the lower crust of the Yilgarn Craton, parallel to the strike to the Albany-Fraser Orogen, is interpreted to have formed during the Proterozoic. There are several possibilities as to the timing of emplacement. Cross-cutting relationships in reflection seismic data suggest the non-reflective zone may have formed late in the Albany-Fraser Orogeny and may be related to the c. 1210 Ma Gnowangerup-Fraser Dyke Swarm (Spaggiari et al., 2014a). Alternatively, it is also possible that this voluminous mafic underplate formed in the Paleoproterozoic to early Mesoproterozoic, during the long history of extension along the Yilgarn Craton margin.

CONCLUSIONS

3D gravity forward modelling allows us to image a dense, non-reflective zone interpreted as a mafic underplate along the margin of the Archean Yilgarn Craton and the Proterozoic east Albany–Fraser Orogen. This mafic underplate is interpreted to have been emplaced in the Proterozoic, either during extension along the craton margin or during crustal shortening of the Albany–Fraser Orogeny.

The non-uniqueness of gravity forward modelling means the 3D density model is one of many that will fit the observed gravity data. However, constraints on the model from available geological and geophysical data reduces the number of possible models that will fit the data. Results from 3D gravity forward modelling presented here are consistent with previous results from 2D gravity modelling constrained by refraction seismic (Tassel and Goncharov, 2006) and 2D gravity modelling constrained by reflection seismic (Murdie et al., 2014).

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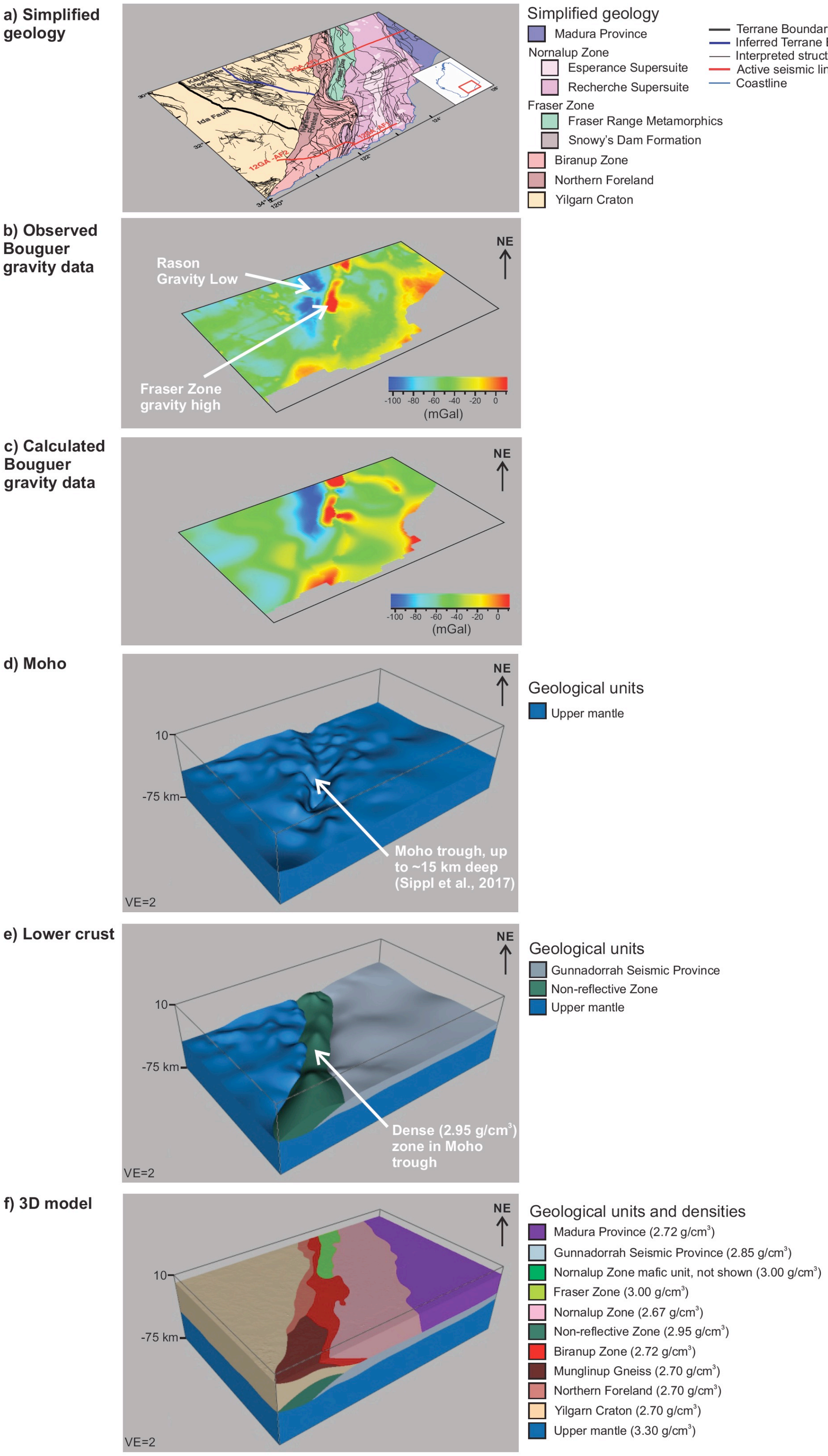

Figure 1. East Albany-Fraser 3D model, a) Simplified geology (after Spaggiari, 2016), b) Observed Bouguer gravity, c) Bouguer gravity calculated from the model, d) the upper mantle, showing Moho topography, e) units of the lower crust including the dense, non-reflective zone in the Moho trough (in green), f) units at the model surface.