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IMAGING A MAGMATIC UNDERPLATE WITH 3D GRAVITY MODELLING: EAST ALBANY–FRASER OROGEN MARGIN

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LI Brisbout and RE Murdie

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Cover image: Packing up the campsite in a claypan about 5 km south of Minilya in the southern Pilbara (photo by Olga Blay, DMIRS)

Contents

Figures

Table

Appendix

Available with the PDF online as an accompanying digital resource

Imaging a magmatic underplate with 3D gravity modelling: east Albany–Fraser Orogen margin

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Abstract

3D gravity forward modelling demonstrates that dense material is required in a zone of thickened crust that extends along the Archean Yilgarn Craton margin and Proterozoic east Albany–Fraser Orogen. This dense material has been modelled in the lower crust, coincident with a non-reflective zone in deep-crustal active seismic profiles, confirming results from previous 2D gravity forward modelling of the orogen. The geophysical properties of this voluminous lower-crustal zone are consistent with an interpretation of a magmatic underplate. One possibility is that the underplate formed during Paleo- to Mesoproterozoic extension along the Yilgarn Craton margin. Alternatively, it is possible that the underplate is related to the Gnowangerup–Fraser dyke swarm, part of the Marnda Moorn Large Igneous Province (1218–1202 Ma), that was emplaced in the southern Yilgarn Craton, subparallel to the margin, during Stage II of the Mesoproterozoic Albany–Fraser Orogeny.

KEYWORDS: gravity anomalies, orogenic margin, seismic profiles, three dimensional models

Introduction

Over the past 15 years, the Geological Survey of Western Australia (GSWA) has acquired new geological and geophysical data in the east Albany–Fraser Orogen (Fig. 1). The current study has used some of these datasets to construct a regional-scale 3D model of the east Albany–Fraser Orogen and Yilgarn Craton margin. This model and supporting datasets are available from the Department of Mines, Industry Regulation and Safety (DMIRS) **Data and Software Centre**. The 3D model was constructed using the implicit modelling software package GeoModeller. Major constraints on the model include:

- an interpreted bedrock geology map (Spaggiari, 2016)
- a recently acquired high-resolution Moho model from passive seismic data (Sippl et al., 2018)
- three crustal-scale reflection seismic lines — 12GA-AF3 in the north (Fig. 2a), and 12GA-AF1 and its western continuation 12GA-AF2 in the south (Fig. 2b; Spaggiari et al., 2014c).

The 3D model was further constrained by the construction of seven 2D gravity forward models.

The regional-scale 3D model was then tested using 3D gravity forward modelling. This method was selected due to the distinct gravity anomalies produced by the orogen. The forward modelling approach used was to vary the densities applied to the 3D model, based on constraints provided by petrophysical data, with the aim of reproducing the major observed Bouguer gravity anomalies. One of these is the Rason Gravity Low (Fraser and Pettifer, 1980), a continental-scale, northeast-trending gravity low that is observed along the southeastern edge of the Yilgarn Craton, and within the Northern Foreland and Biranup Zone of the east Albany–Fraser Orogen (Fig. 3). The gravity low extends to the northeast for ~500 km, parallel to the dominant trend of the east Albany–Fraser Orogen. Previous 2D gravity forward modelling has suggested that the Rason Gravity Low is the product of a northeast-trending zone of thickened crust that contains a large dense unit in the lower crust (Tassell and Goncharov, 2006; Murdie et al., 2014; Sippl et al., 2018).

Regional geology

Tectonic units

The 3D model volume includes the southeastern Archean Yilgarn Craton and the adjacent Paleoproterozoic to Mesoproterozoic east Albany–Fraser Orogen (Fig. 1). The Albany–Fraser Orogen is composed of Archean and Proterozoic crust that has been extensively reworked during the Proterozoic (Kirkland et al., 2011). The orogen is divided into two main tectonic units: the Northern Foreland and the Kepa Kurl Booya Province (Fig. 1).

The Northern Foreland is composed mainly of Yilgarn Craton rocks modified by Proterozoic events (Myers, 1990, 1995a; Spaggiari et al., 2014a). These rocks are predominantly greenschist to lower amphibolite facies Archean granites and greenstones. The Northern Foreland also includes upper amphibolite to granulite facies Archean

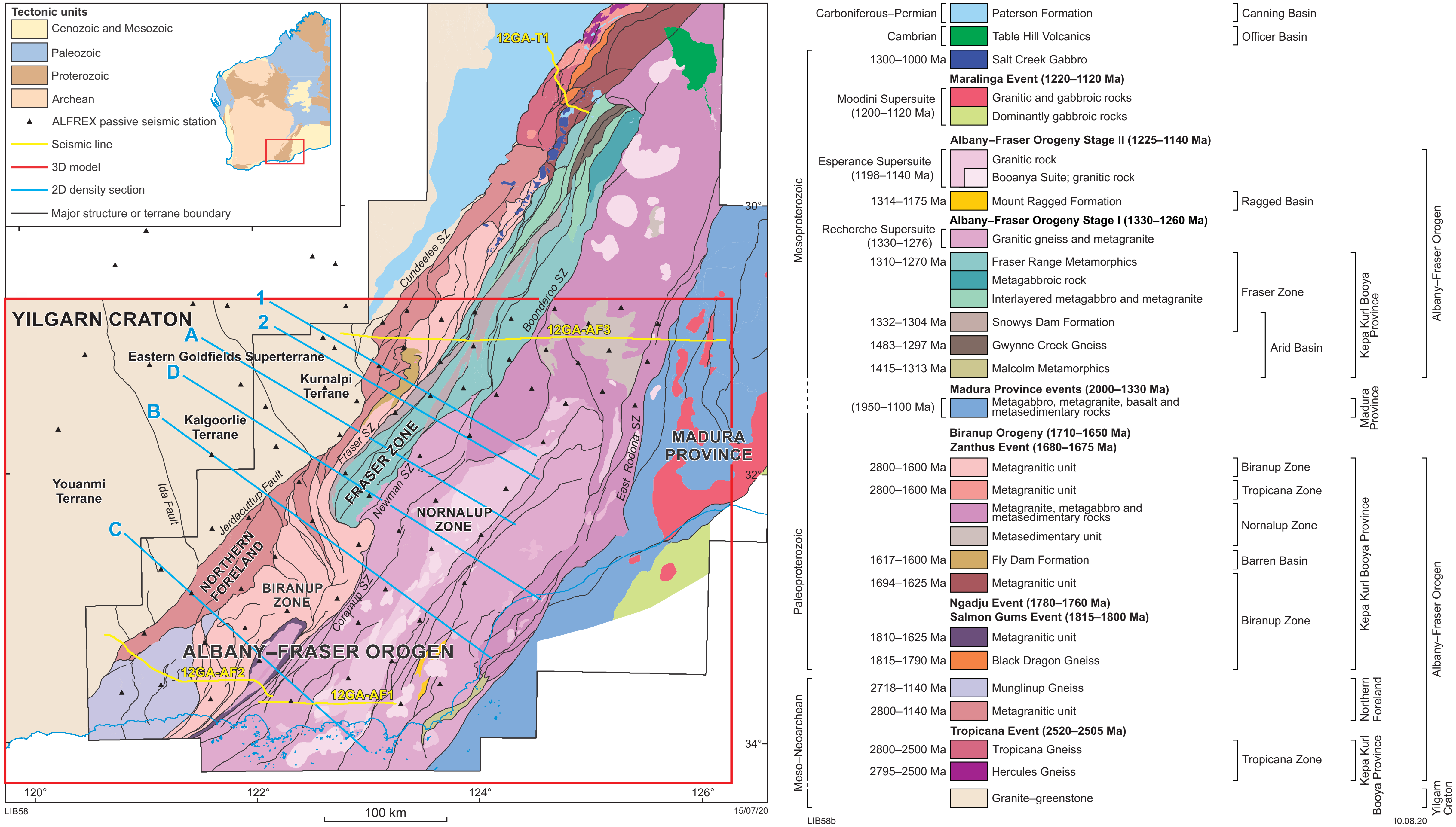

Figure 1. Geology of the east Albany–Fraser Orogen after Spaggiari (2016) showing the location of the 3D model, 2D sections and some of the geophysical datasets used in model construction. Legend after Quentin de Gromard et al. (2017). Yilgarn Craton terrane boundaries from 1:500 000 State interpreted bedrock geology of Western Australia (GSWA, 2016)

rocks of the Munglinup Gneiss (Beeson et al., 1988; Myers, 1990; Spaggiari et al., 2009; Quentin de Gromard et al., 2017). In the east Albany–Fraser Orogen, the Northern Foreland is separated from the Yilgarn Craton by the Jerdacuttup Fault and the Cundeelee Shear Zone (Fig. 1a,b). These are imaged in active seismic lines 12GA-AF2 and 12GA-AF3 as listric southeast-dipping structures that extend from the surface to the middle crust (Fig. 2; Spaggiari et al., 2014c).

The Kepa Kurl Booya Province is divided into four tectonic zones: the Tropicana, Biranup, Fraser and Nornalup Zones. With the exception of the Tropicana Zone, which is located north of the model area, all are included in the 3D model. The Biranup Zone extends along the length of the orogen and is dominated by Paleoproterozoic orthogneiss with lesser amounts of metagabbroic and hybrid rocks, and paragneiss (Spaggiari et al., 2011). The Biranup Zone is separated from the Northern Foreland by the Red Island Shear Zone in the southwest (Fig. 2b), and by a series of shear zones that include the Frog Dam and Oak Dam Shear Zones in the northeast (Fig. 2a). Both structures dip southeast and sole onto the top of the lower-crustal Gunnadorrah Seismic Province (described below; Fig. 2a,b; Spaggiari et al., 2014c).

In the east Albany–Fraser Orogen, the Fraser Zone produces a distinct, high-amplitude Bouguer gravity anomaly (Fig. 3). The Fraser Zone contains the Fraser Range Metamorphics, which comprises amphibolite to granulite facies metagabbro with lesser metagranitic and metasedimentary rocks (Spaggiari et al., 2011; Smithies et al., 2013; Maier et al., 2016). Metasedimentary rocks of the Fraser Zone belong to the Snowys Dam Formation of the Arid Basin (Spaggiari et al., 2014b). The Fraser Zone is separated from the Biranup Zone by the linked Fraser Shear Zone and Harris Lake Shear Zone, imaged in 12GA-AF3 as southeast-dipping structures that extend from the surface to the middle crust (Fig. 2a; Spaggiari et al., 2014c).

The eastern Nornalup Zone comprises Paleoproterozoic granitic and mafic gneisses that have been extensively intruded by the Mesoproterozoic Recherche and Esperance Supersuites (Spaggiari et al., 2011; Smithies et al., 2015). The Recherche Supersuite (1330–1276 Ma) is dominated by amphibolite to granulite facies metasyenogranite, metamonzogranite and metagranodiorite (Myers, 1995b; Nelson et al., 1995; Spaggiari et al., 2011), but also includes metagabbros and metagranites of the Fraser Zone (Smithies et al., 2015; Maier et al., 2016). The Recherche Supersuite was emplaced during Stage I of the Albany–Fraser Orogeny and includes the Southern Hills Suite and Gora Hill Suite. Granitic rocks of the Gora Hill Suite record a southeast to northwest trend of increasingly juvenile compositions and decreasing age (Smithies et al., 2015).

The Esperance Supersuite (1198–1140 Ma) comprises greenschist to amphibolite facies metagranitic rocks and undeformed granites emplaced during Stage II of the Albany–Fraser Orogeny (Myers, 1995b; Spaggiari et al., 2011; Smithies et al., 2015). The Esperance Supersuite is part of a widespread magmatic event named the Maralinga Event, which includes the Moodini Supersuite of the Madura and Coompana Provinces, and the Pitjantjatjara Supersuite of the Musgrave Province (Spaggiari et al., 2016). This event is interpreted to have resulted in cratonization of the crust between the West Australian Craton and the South Australian Craton (Kirkland et al., 2017; Spaggiari et al., 2018).

To the southwest, the Nornalup Zone is separated from the Biranup Zone by the Coramup Shear Zone, imaged in 12GA-AF1 and 12GA-AF2 as a southeast-dipping structure that soles onto the top of the Gunnadorrah Seismic Province (Fig. 2b; Spaggiari et al., 2014c). To the northeast, the Nornalup Zone is separated from the Fraser Zone by the Newman and Boonderoo Shear Zones. The Boonderoo Shear Zone is imaged in 12GA-AF3 as a northwest-dipping structure that terminates at the Fraser Shear Zone (Fig. 2a; Spaggiari et al., 2014c). To the east, the Nornalup Zone is separated from the Madura Province by the East Rodona Shear Zone, imaged in 12GA-AF3 as a southeast-dipping structure that extends from the upper to lower crust, terminating at the top of the Gunnadorrah Seismic Province (Fig. 2a; Spaggiari et al., 2014c).

Moho

Active seismic reflection (Spaggiari et al., 2014c) and passive seismic data (Sippl et al., 2018) have imaged a zone of thickened crust along the Yilgarn Craton and Albany–Fraser Orogen margin (Fig. 2). The Moho model, generated by receiver function analysis of the ALbany–FRaser EXperiment (ALFREX) passive seismic data, shows a V-shaped Moho depression beneath the Northern Foreland and Biranup Zone, parallel to the craton margin (Sippl et al., 2018). The Moho depression reaches a maximum depth of ~10 km, relative to the Moho beneath the Yilgarn Craton and the Nornalup Zone. The depression steepens to the southwest, particularly on the northwestern side. This change in dip coincides with the inferred surface location of the Ida Fault (Sippl et al., 2018).

Along 12GA-AF3, there are two interpretations of the geometry of the Moho depression. The reflection seismic interpretation shows the upper mantle extending in a wedge between the non-reflective zone and the Gunnadorrah Seismic Province (Fig. 2; Spaggiari et al., 2014c). In contrast, the Moho model from receiver function analysis images a symmetric V-shaped geometry (red dashed line in Fig. 2; Sippl et al., 2018).

The crust is interpreted to have been thickened during the Albany–Fraser Orogeny by underthrusting of the Gunnadorrah Seismic Province, in the lower crust of the Albany–Fraser Orogen, beneath the Yilgarn Craton (Sippl et al., 2018). The possibility that the Moho depression was produced by subduction to the northwest, beneath the Yilgarn Craton, is considered unlikely given the lack of continental arc or subduction-related rocks in the Albany–Fraser Orogen and the lack of geochemical or isotopic evidence for subduction (Smithies et al., 2015; Spaggiari et al., 2015).

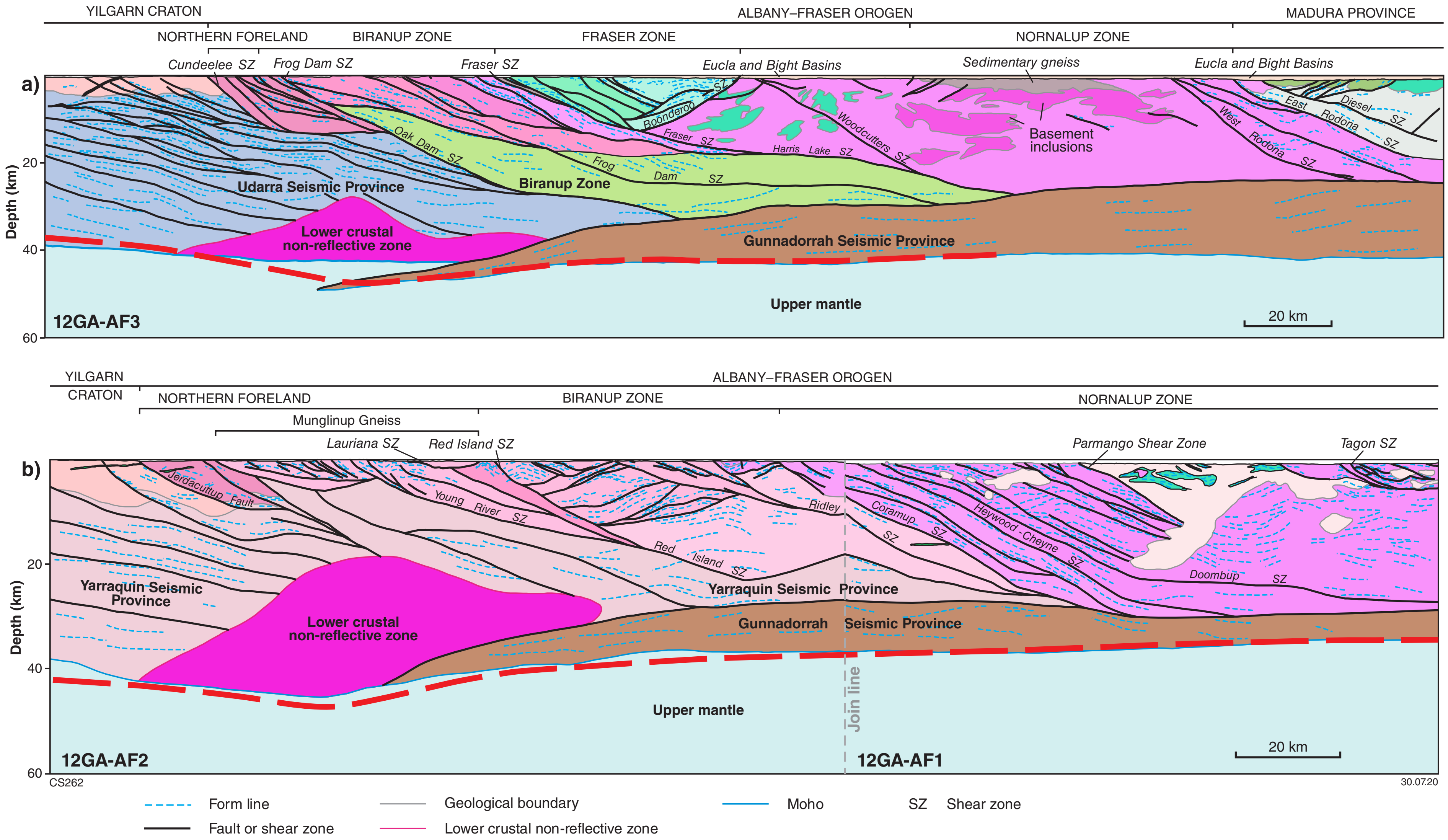

Figure 2. Geological interpretation of deep-crustal seismic lines: a) 12GA-AF3; b) 12GA-2 and 12GA-AF1 (after Spaggiari et al., 2014c). Sections shown from north to south. Thick, red dashed line is the Moho interpreted from receiver function analysis (Sippl et al., 2018) Abbreviation: SZ, Shear Zone

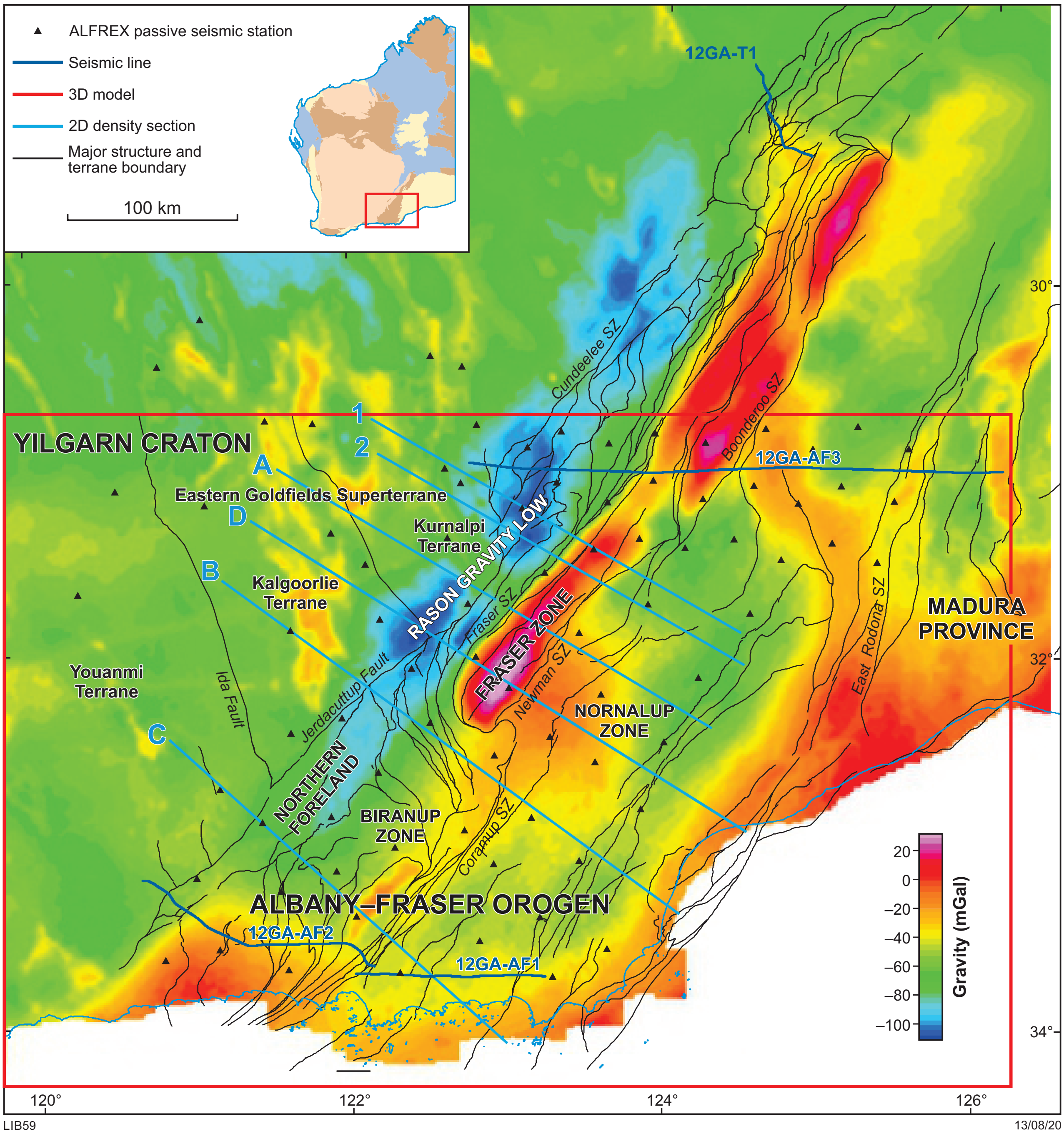

Figure 3. Observed Bouguer gravity data of the east Albany–Fraser Orogen and southeast Yilgarn Craton margin, showing the distinct Rason Gravity Low and the Fraser Zone gravity high

Lower crust

Non-reflective zone

Reflection seismic profiles 12GA-AF2 and 12GA-AF3 image a large (~25 km thick) non-reflective body in the middle to lower crust, within the zone of thickened crust (Fig. 2; Spaggiari et al., 2014c). This non-reflective zone has been interpreted as a zone of alteration, deformation or magmatism (Korsch et al., 2014). The truncation of shear zones by this non-reflective zone indicate that it may have formed late during the Albany–Fraser Orogeny (Spaggiari et al., 2014c). Geologically constrained 2D gravity forward modelling along seismic lines 12GA-AF2 and 12GA-AF3 suggest the non-reflective zone is dense (Murdie et al., 2014).

Southwest of our study area, a refraction seismic profile traversing the Yilgarn Craton and west Albany–Fraser Orogen imaged a ~30 km deepening of the Moho depression, referred to as a crustal root (Tassell and Goncharov, 2006). 2D gravity forward modelling along the profile, with initial model densities calculated from the velocities retrieved from seismic refraction, demonstrates that the crustal root is very dense (3.25 g/cm^3; Tassell and Goncharov, 2006). The dense, non-reflective zone imaged in the current study is most likely equivalent to this crustal root, which Tassell and Goncharov (2006) proposed to have formed by Proterozoic taphrogenesis (rifting).

Gunnadorrah Seismic Province

The Gunnadorrah Seismic Province is a 10–15 km thick unit in the lower crust of the east Albany–Fraser Orogen and Madura Province (Fig. 2; Spaggiari et al., 2014c, 2017). It is defined in reflection seismic data by subhorizontal, weak to moderate amplitude reflectors. The Gunnadorrah Seismic Province thickens to the northeast reaching a maximum thickness of 16 km at the eastern end of 12GA-AF3. To the northwest, the Gunnadorrah Seismic Province thins, terminating in the Moho trough beneath the non-reflective zone where it is interpreted to underthrust the non-reflective zone and Yilgarn Craton (Spaggiari et al., 2014c).

Seismic reflection profile 13GA-EG1, which continues to the east of 12GA-AF3, suggests the Gunnadorrah Seismic Province extends beneath the Madura Province, terminating at the Mundrabilla Shear Zone (Spaggiari et al., 2017). The lower-crustal Gunnadorrah Seismic Province could be interpreted as a magmatic underplate formed during the Maralinga Event. Previous 2D gravity forward modelling suggests the Gunnadorrah Seismic Province is relatively dense (2.85 g/cm^3) and possibly decreases in density to the west (Murdie et al., 2014).

Tectonic events and models

Several Archean events are recognized in the Archean Tropicana Zone of the Kepa Kurl Booya Province, northeast of the model volume. The oldest is the 2722–2445 Ma Atlantis Event, characterized by sanukutoid magmas and protracted amphibolite to granulite facies metamorphism (Kirkland et al., 2015; Tyler et al., 2015). This was followed by the 2520–2505 Ma Tropicana Event, characterized by fluid-induced gold mineralization and greenschist facies metamorphism, interpreted to result from exhumation of the Tropicana Zone along the Plumridge Detachment (Tyler et al., 2015; Occhipinti et al., 2017).

During the Proterozoic, the southeastern margin of the Yilgarn Craton underwent major modification. This began with the formation of the 1815–1600 Ma Barren Basin, an interpreted continental rift or distal back-arc basin (Spaggiari et al., 2014b; Smithies et al., 2015). Formation of the Barren Basin was accompanied by magmatism during the Salmon Gums (1815–1800 Ma) and Ngadju Events (1780–1760 Ma), and widespread magmatism in the eastern Biranup Zone during the Biranup Orogeny (1710–1650 Ma). Biranup magmas between c. 1800 and 1650 Ma are divided into an early phase involving the remelting of Archean crust and addition of mantle material, and a late phase of recycling previously recycled Archean felsic crust with an increase in the proportion of mantle material (Smithies et al., 2015).

The Biranup Orogeny was followed by a period of quiescence and the formation of the Arid Basin, for which the tectono-sedimentary setting is interpreted as an ocean–continent transition and passive margin (Spaggiari et al., 2014b, 2018). Tectonic quiescence was interrupted by a switch to convergence at the onset of the Mesoproterozoic Albany–Fraser Orogeny (Spaggiari et al., 2015).

The Albany–Fraser Orogeny is divided into Stage I (1330–1260 Ma) and Stage II (1225–1140 Ma) (Clark et al., 2000; Bodorkos and Clark, 2004; Smithies et al., 2015). Stage I is characterized by high-temperature metamorphism, deformation, and the voluminous felsic and mafic magmatism of the Recherche Supersuite (Clark et al., 2000; Bodorkos and Clark, 2004; Quentin de Gromard et al., 2017). This stage is interpreted to have been associated with the collision and accretion of the Loongana Arc of the Madura Province onto the eastern Nornalup Zone (Spaggiari et al., 2015, 2018). Collision is interpreted to have resulted from the east-dipping subduction of oceanic crust outboard of the Albany–Fraser Orogen, beneath the Loongana Arc. Recherche Supersuite magmatism is interpreted to have migrated from southeast to northwest, possibly due to mantle upwelling during slab detachment from east-dipping subduction (Smithies et al., 2015). In an alternative model, the Arid Basin is interpreted as a back-arc basin, and collision of the Madura Province and the Albany–Fraser Orogen occurred due to west-dipping subduction of oceanic crust beneath the Loongana Arc (Morrissey et al., 2017).

Stage II of the Albany–Fraser Orogeny is characterized by high-temperature metamorphism (Clark et al., 2000; Kirkland et al., 2011; Quentin de Gromard et al., 2017) and intense craton-vergent deformation (Bodorkos and Clark, 2004), and emplacement of the Esperance Supersuite into the Nornalup Zone (Clark et al., 2000). Stage II is interpreted to have occurred in an intracratonic tectonic setting (Spaggiari et al., 2011). Esperance Supersuite magmatism took place during the 1220–1120 Ma Maralinga Event (Spaggiari et al., 2016, 2018). This widespread and voluminous event is interpreted to have cratonized the basement of the Madura and Coompana Provinces, joining the West Australian and South Australian Cratons (Spaggiari et al., 2016; Kirkland et al., 2017).

3D modelling method

Model construction

The 3D model has been constructed using implicit modelling software GeoModeller (Intrepid Geophysics). Implicit modelling uses an interpolation algorithm to connect point and line data to create 3D surfaces. These surfaces are then used to create 3D volumes. In contrast, explicit modelling methods do not use an interpolator and the 3D surfaces are constructed directly from the data. An advantage of implicit modelling is that it can be a fast way of constructing 3D surfaces, although one consequence is that the interpolator can introduce artefacts into the model. An outcome of GeoModeller's scalar potential field interpolator (Lajaunie et al., 1997) is smoothed model geometries.

The interpreted bedrock geology map and geological sections, including the geological interpretations of the seismic lines and geological sections from 2D forward modelling, have been digitized in GeoModeller. The Moho depth points from passive seismic data have been imported as 3D points. These and other data that have been used to constrain the model are described in detail below (Model constraints).

Gravity forward modelling

The 3D model has been tested by gravity forward modelling. There are several benefits to testing a model against gravity data. One is the lithospheric scale (at least) of gravity data which makes it possible to test crustal-scale models. Another is that densities retrieved from modelling can be directly related to rock type, although often not uniquely. One of the major limitations of forward modelling is that the results are non-unique; in other words, there are many possible density models that will satisfy the gravity data, although this number is reduced by the use of geological constraints. Another limitation is that regional-scale gravity forward modelling can produce large residual values due to a single density being assigned to an entire tectonic unit.

In the modelling approach used here, the geological boundaries at the surface and in sections were fixed, as was the Moho. Densities were assigned to the 3D model using specific gravity data and 2D model densities as a starting point. In an iterative process, model densities were manually adjusted, the Bouguer gravity response of the model was calculated and compared to the observed gravity, and model densities were adjusted to improve the fit between the observed and calculated data. The observed and calculated gravity are compared by calculating the residual gravity, which is the observed Bouguer gravity subtracted from the calculated Bouguer gravity. The residual shows quantitatively where the model densities or geometries need to be modified. Positive residual values indicate density deficits and negative residual values indicate density excess. Here, we aim to construct a geologically constrained model that can produce the major features of the observed gravity data.

In the model area, gravity data have been collected at ~2.5 km station spacing, and at 400 m station spacing along the seismic lines. Data were gridded to a 400 m cell size and a spherical cap correction has been applied using a crustal density of 2.67 g/cm^3 (Fig. 3). We assume the source of all the observed components of the Bouguer gravity data are within the crust, or due to the crust and upper mantle boundary (the Moho), and consequently no regional trend has been removed from the observed gravity data.

To perform 3D gravity forward modelling, the geological model has been discretized into voxels 1 km^3 in volume. This voxel size was determined by the resolution of the gravity data (2.5 km station spacing) and is a compromise between the higher-resolution geological data (1:250 000) and the much sparser data from the Moho depths (50 km station spacing).

Model constraints

Topography

The topographic surface of the model has been sampled from the Shuttle Radar Topographic Mission (SRTM) digital elevation model (Jarvis et al., 2004).

Surface geology

Geological units at the surface have been modelled on the scale of tectonic structural zones. Unit boundaries have been digitized in GeoModeller from the recently interpreted bedrock geology map (Fig. 1; Spaggiari, 2016).

Moho

The Moho has been constrained by a Moho model obtained from P-wave receiver function analysis of the ALFREX passive seismic data (Sippl et al., 2018). The ALFREX array covers an area of ~200 000 km^2 with stations spaced ~50 km apart. The array extends from the margin of the Yilgarn Craton to the eastern Nornalup Zone (Fig. 1). Included are two permanent stations and five temporary stations from the West Australian Craton deployment. A high-resolution Moho map has been produced by computing Moho depths at individual piercing points for all receiver functions at each station (Sippl et al., 2018). These points and Moho picks along the active seismic lines have been used to constrain the Moho in the model volume.

The Moho depth points have been imported into GeoModeller as 3D points and interpolated, in GeoModeller, to produce a surface (Fig. 4). The Moho surface produced in GeoModeller has been compared to a Moho depth grid produced by interpolation (kriging) of Moho depth points in Geosoft's Oasis Montaj. This was done to ensure the Moho depth points have been interpolated reasonably well in GeoModeller. Any topographic errors introduced into the Moho surface will produce spurious, long-wavelength gravity anomalies. Comparison of the Moho surface from kriging (Fig. 5a) with the Moho surface produced in GeoModeller (Fig. 5b) shows very minor differences.

Densities

Densities assigned to the 3D model have been constrained by specific gravity data and 2D gravity models (discussed below). Specific gravity has been calculated for 213 Albany–Fraser Orogen rock samples retrieved from the GSWA archive (Fig. 6a; Appendix). Specific gravity has been calculated using the following equation:

$$m_{dry}/(m_{dry} - m_{wet})$$

where m_{dry} is the mass of the dry rock sample and m_{wet} is the mass of the rock sample submerged in water (Emerson, 1990). This specific gravity dataset makes it possible to assign realistic densities to the model but also has limitations. These include the sparsity of data compared to the model volume, the bias towards exposed rocks, and the lack of data for the unexposed middle-crustal and lower-crustal rocks units.

Specific gravity data have been grouped by tectonic zone and displayed in histograms and box and whisker plots (Fig. 6b,c). The histograms show that the Northern Foreland, Biranup Zone and Fraser Zone have multimodal specific gravity distributions but the basic rock types within tectonic zones (mafic, felsic and metasedimentary rocks) generally have unimodal distributions. Multimodal distributions are difficult to represent in gravity forward modelling, where only one density can be assigned to each unit. This is one of the limitations of regional-scale gravity forward modelling. Despite this, outliers have been removed from the specific gravity distributions and the mean and median have been calculated for each unit (Table 1). These are the starting values assigned to the 3D density model.

The upper mantle has been modelled with a density of 3.3 g/cm^3. This value is consistent with upper-mantle densities calculated from a P-wave seismic velocity model (Tassell and Goncharov, 2006) and studies of lithospheric mantle samples (Poudjom Djomani et al., 2001).

Geology at depth

Active seismic

Three deep-crustal reflection seismic profiles traverse the model volume: 12GA-AF1 and 12GA-AF2 in the southwest, and 12GA-AF3 in the northeast (Fig. 1). Geological interpretations of these profiles (Spaggiari et al., 2014c) on the scale of tectonic zones and seismic provinces have been digitized in GeoModeller.

The geometry of the non-reflective zone in 12GA-AF3 has been simplified by removing the sliver of upper mantle and extending the base of the non-reflective zone to the top of the Gunnadorrah Seismic Province (see Fig. 7). This simplified geometry is more consistent with the Moho model from passive seismic data (red dashed line in Figure 2).

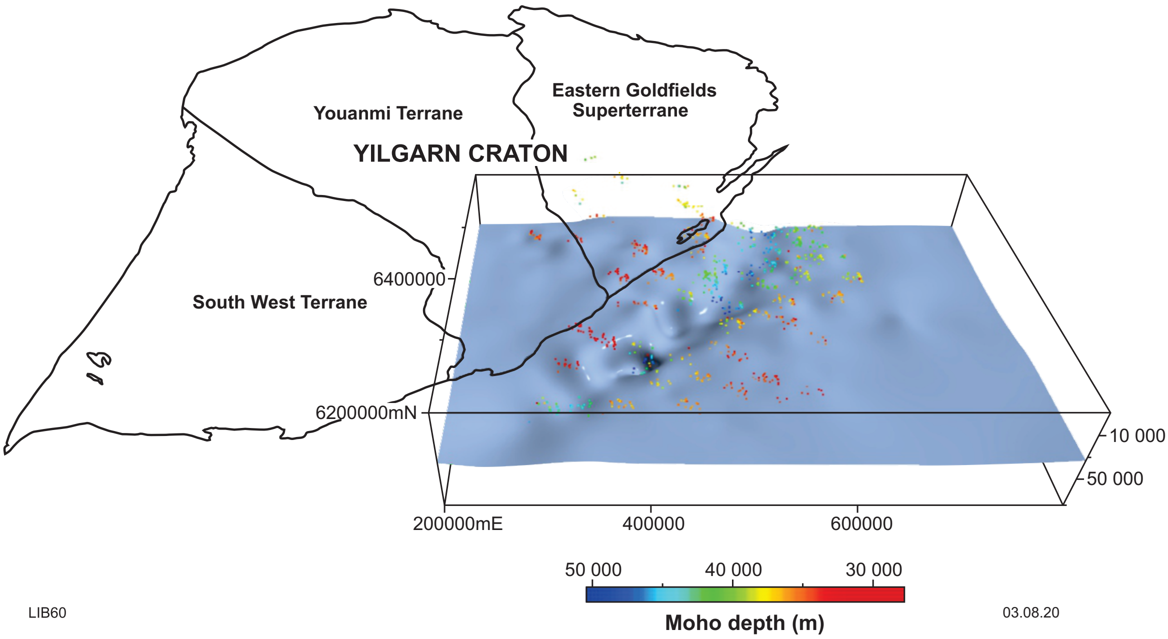

Figure 4. Moho surface constructed in GeoModeller from Moho pierce point data from the ALFREX passive seismic survey (Sippl et al., 2018). Vertical exaggeration = 1.5. Yilgarn Craton margin and terrane boundaries from 1:500 000 tectonic units of Western Australia (GSWA, 2017)

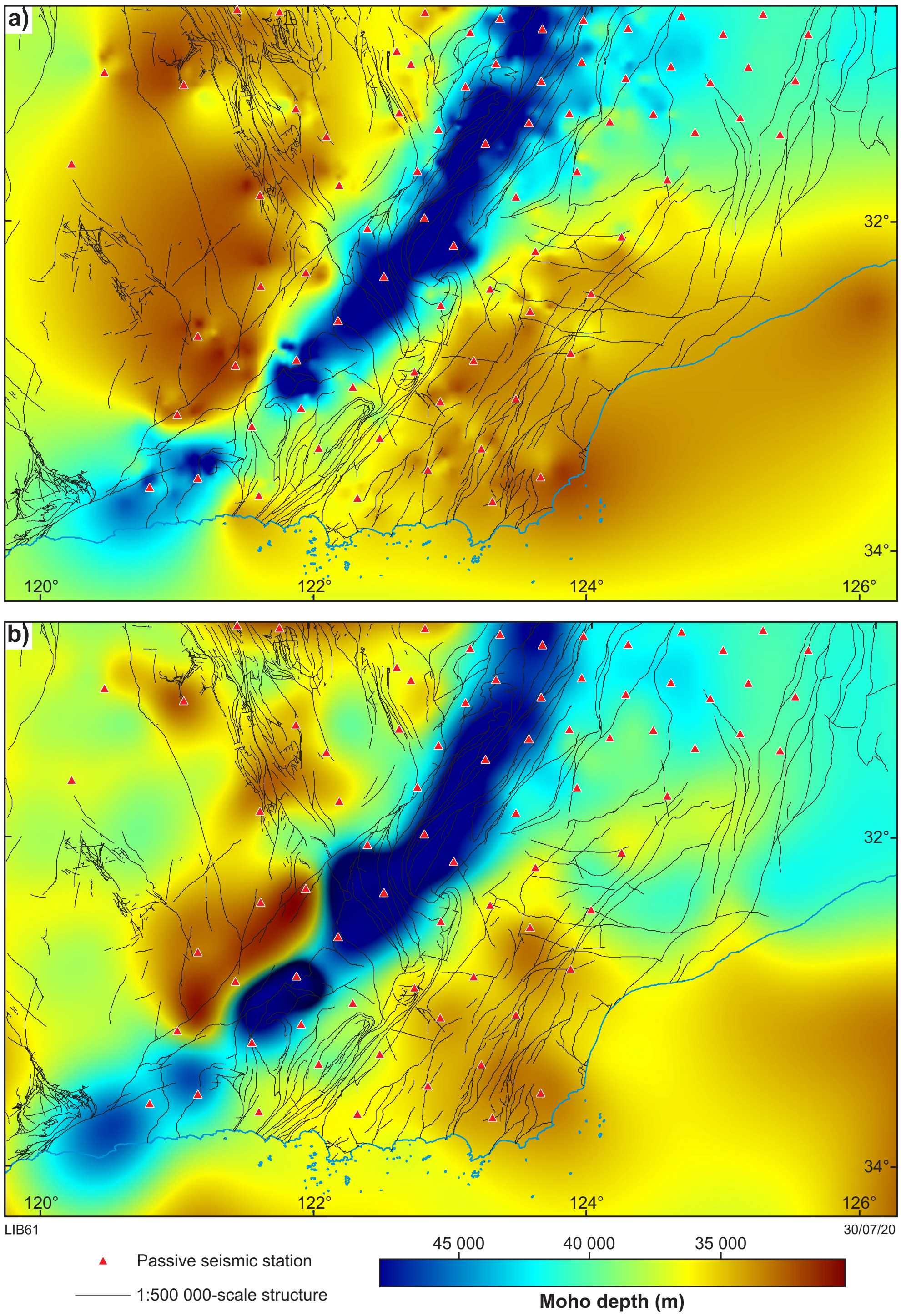

Figure 5. Comparison of two Moho depth models from different interpolation methods: a) Moho depth grid interpolated from pierce point data using kriging in Oasis Montaj; b) Moho surface interpolated from pierce point data using GeoModeller scalar potential field interpolator. The models show 1:500 000-scale structures (GSWA, 2016)

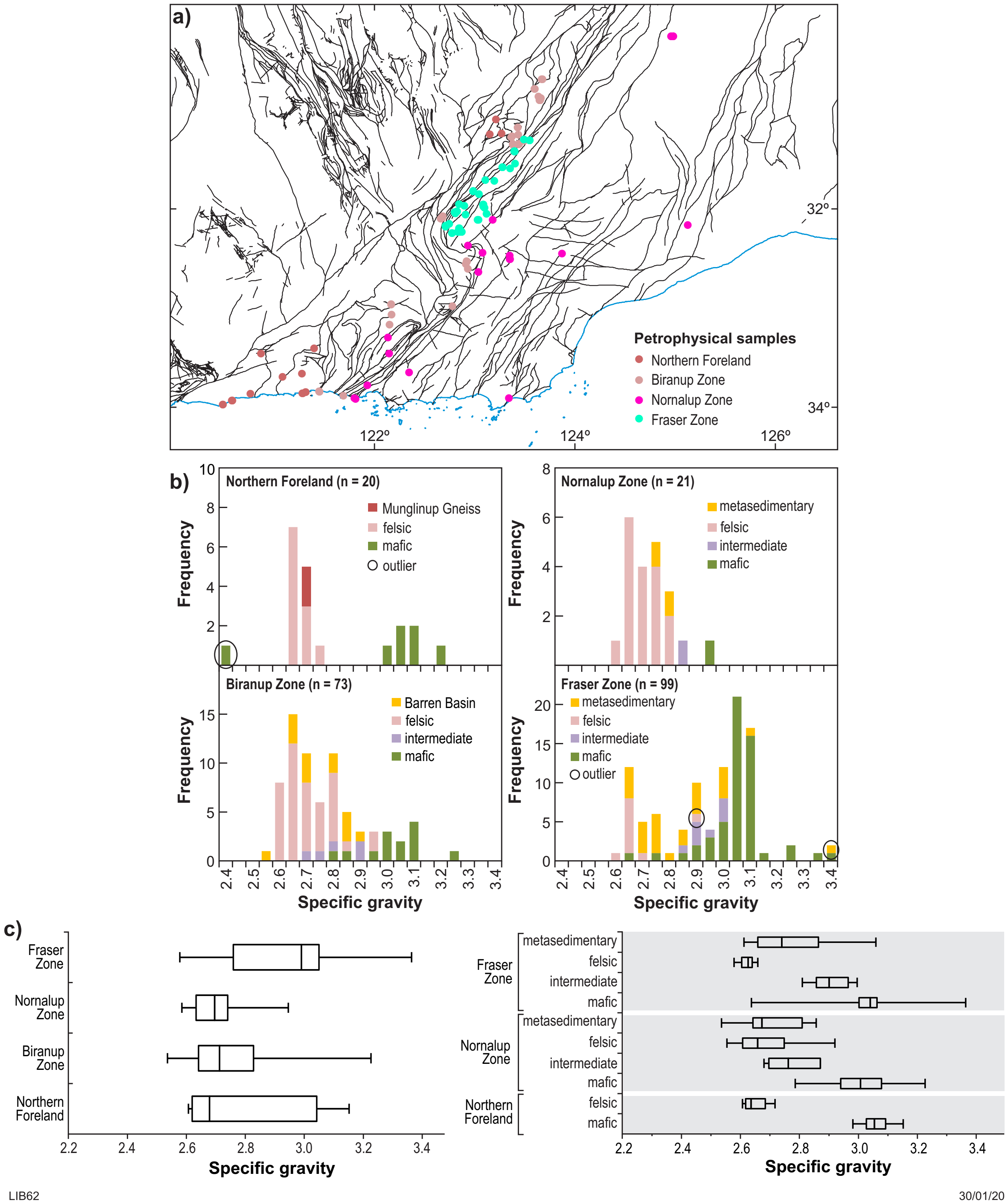

Figure 6. Albany–Fraser Orogen specific gravity data and analysis: a) location of specific gravity samples on a map showing 1:500 000-scale structures (GSWA, 2016); b) histograms showing specific gravity data for the Northern Foreland, Biranup Zone, Nornalup Zone and Fraser Zone, coloured by general rock type; c) box and whisker plots with specific gravity data grouped by general rock types within tectonic units

Table 1. Units of the 3D model with rock types, final model densities, mean and median specific gravity data, and datasets used to constrain model geometry

3D unit (sample number)	*Rock type*	*Specific gravity mean ± std deviation (g/cm³)*	*Specific gravity median (g/cm³)*	*3D model density (g/cm³)*	*Constraints on unit geometry*
Madura Province	metagabbro and metagranite	–	–	2.70	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Nornalup Zone mafic unit 2	not exposed	–	–	3.00	Interpreted reflection seismic and 2D density models
Nornalup Zone mafic unit 1	not exposed	–	–	3.00	2D density models
Nornalup Zone (n = 21)	granitic gneiss and metagranite, minor metamafic rocks	2.70 ± 0.08	2.70	2.67	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Fraser Zone (n = 97)	metagabbro, metaganite and minor metasedimentary rocks	2.92 ± 0.18	2.99	3.00	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic, and 2D density models
Biranup Zone (n = 73)	metagranite, granitc gneiss and metamafic rocks	2.75 ± 0.15	2.71	2.72	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Munglinup Gneiss (n = 2)	granitic gneiss and minor mafic rocks	2.68	–	2.70	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Northern Foreland (n = 19)	metagranite and metamafic rocks	2.78 ± 0.20	2.679	2.70	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Yilgarn Craton	metagranite and metamafic rocks	–	–	2.70	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Lower crustal non-reflective zone	not exposed	–	–	2.95	Interpreted reflection seismic (Spaggiari et al., 2014b) and 2D density models
Gunnadorrah Seismic Province	not exposed	–	–	2.85	Interpreted bedrock geology (Spaggiari, 2016), interpreted reflection seismic (Spaggiari et al., 2014b), and 2D density models
Upper mantle	not exposed	–	–	3.30	Surface constructed from Moho piercing points (Sippl et al., 2018)

2D density forward models

Seven crustal-scale 2D density models have been constructed to constrain the 3D model: three along the reflection seismic profiles and four in between the seismic profiles (Sections A–D; Fig. 1). 2D models have been constructed using gravity forward modelling in GM-SYS (Oasis Montaj) and model geometries have been digitized in GeoModeller.

In the three models along the seismic lines, the geometry of tectonic zones and the Moho are fixed according to the reflection seismic interpretations. The densities of the tectonic zones were allowed to vary, constrained by the petrophysical data, until an acceptable fit was achieved between the calculated and observed gravity. These final model densities were applied to models A–D that are unconstrained by seismic.

In models A–D, the Moho has been constrained by different methods depending on the available data. In sections A–C, the Moho has been constrained from common conversion point profiles. In section D, the Moho has been sampled from gridded Moho pierce point data.

At the surface, model geometries along sections A–D have been constrained by the interpreted bedrock geology map. At depth, model geometries have been extrapolated from adjacent seismic profiles and constrained by structural observations where available. The 2D model densities and the geological boundaries, except for the Moho, have then been adjusted to achieve a best fit between observed and calculated gravity. The final geometries of these models have been digitized in GeoModeller.

The most prominent feature in the observed gravity profiles is the Bouguer gravity high produced by the dense Fraser Zone (Fig. 7). In models A–D, the northwestern margin of the Fraser Zone is bounded by the linked Harris Lake and Fraser Shear Zones and dips moderately to the southeast. This is constrained by the interpretation of 12GA-AF3 (Fig. 2a), and is consistent with density models from gravity inversion (described below).

The southeastern margin of the Fraser Zone, within the model volume, is bounded by the Newman Shear Zone. In sections A and D, this structure has been modelled as subvertical, based on structural measurements of mylonite zones at Newman Rocks (Spaggiari et al., 2011; Quentin de Gromard et al., 2017). A more complex geometry for the density contrast at the southeastern margin of the Fraser Zone is suggested by density models from unconstrained gravity inversion (see below). To satisfy the observed gravity data, the Newman Shear Zone has been modelled with a low density (Fig. 7b,c). Low density material is also required to the northwest of the Newman Shear Zone in section A. This has been modelled as a wedge of lower density material above the Fraser Zone (Fig. 7b).

Another major feature of the observed gravity profiles is the long wavelength Rason Gravity Low (Fig. 3, 7). Gravity profiles show that the minimum of the Rason Gravity Low is located to the northwest of the zone of thickened crust. In the model profile for 12GA-AF3, the gravity low produced by the thickened crust is shifted to the northwest by modelling a large non-reflective zone in the lower crust with a high density (2.95 g/cm^3; Fig. 7a). This unit has also been included in sections A–D, where it shifts the calculated gravity minimum to the northwest, and in section 12GA-AF2, where it produces a broad gravity high (Fig. 7f). An attempt was made to shift the calculated gravity minimum to the northwest by increasing the density of the Biranup Zone and Munglinup Gneiss. However, when constrained by the geometries interpreted in reflection seismic data and measured specific gravity data, this was not possible.

2D density modelling shows that the Biranup Zone varies in density between 2.70 and 2.75 g/cm^3 (Fig. 7). The Biranup Zone is denser where it is adjacent to the Fraser Zone, in sections 12GA-AF3, B and D, and has highest density in the S-bend region (2.75 g/cm^3) in section D.

Observed Bouguer gravity data show two distinct gravity anomalies in the Nornalup Zone, to the southeast of the Fraser Zone (Fig. 7a–c). The northeastern anomaly is coincident with linear magnetic horizons, suggesting the source may extend into the upper crust. This gravity anomaly is traversed by 12GA-AF3, but was not well imaged. Along 12GA-AF3, unexposed subhorizontal reflective rafts are imaged in the middle to upper crust of the Nornalup Zone. However, even modelled with a high density, the gravity anomaly produced by these rafts is not large enough to fit the observed anomaly (Murdie et al., 2014). Hence, in the 2D density model along 12GA-AF3, these reflective rafts have been modelled as part of a larger dense unit (3 g/cm^3) to satisfy the observed gravity data. A unit with a similar geometry has been included in sections A and D to satisfy the observed gravity data.

Most observed gravity profiles show that the east Albany–Fraser Orogen is associated with a broad gravity high compared to the Yilgarn Craton (Fig. 7). This is enhanced in upward continued Bouguer gravity images (described below). In 2D density models, this gravity high is interpreted to be produced, in part, by a relatively dense Gunnadorrah Seismic Province (2.85 g/cm^3) in the lower crust of the east Albany–Fraser Orogen.

3D gravity inversion

Density and susceptibility models from gravity and magnetic inversion, respectively, have also been used to guide the model geometries. This method has the advantages of being rapid to run and producing 3D models of density or susceptibility. Inversions have been run using Geosoft's VOXI Earth Modeller. Gravity inversion assumes density contrasts within a 40 km-thick crust with no Moho topography (models were run before the Moho model was available). The range of possible model densities has been constrained in some inversions. Magnetic inversion assumes magnetic contrasts within the top 15 km of crust. Density models have been useful for imaging the dense Fraser Zone, particularly where no outcrop or reflection seismic data are available.

The Fraser Shear Zone is located on a steep gravity gradient between the Biranup Zone and the denser Fraser Zone. In density models this gradient is imaged as a sharp density contrast that has a consistent, steep southeast dip (~75°; Fig. 8). In the southwestern Fraser Shear Zone, this orientation is consistent with the dominant, moderate to steeply east or southeast-dipping foliation (Quentin de Gromard et al., 2017).

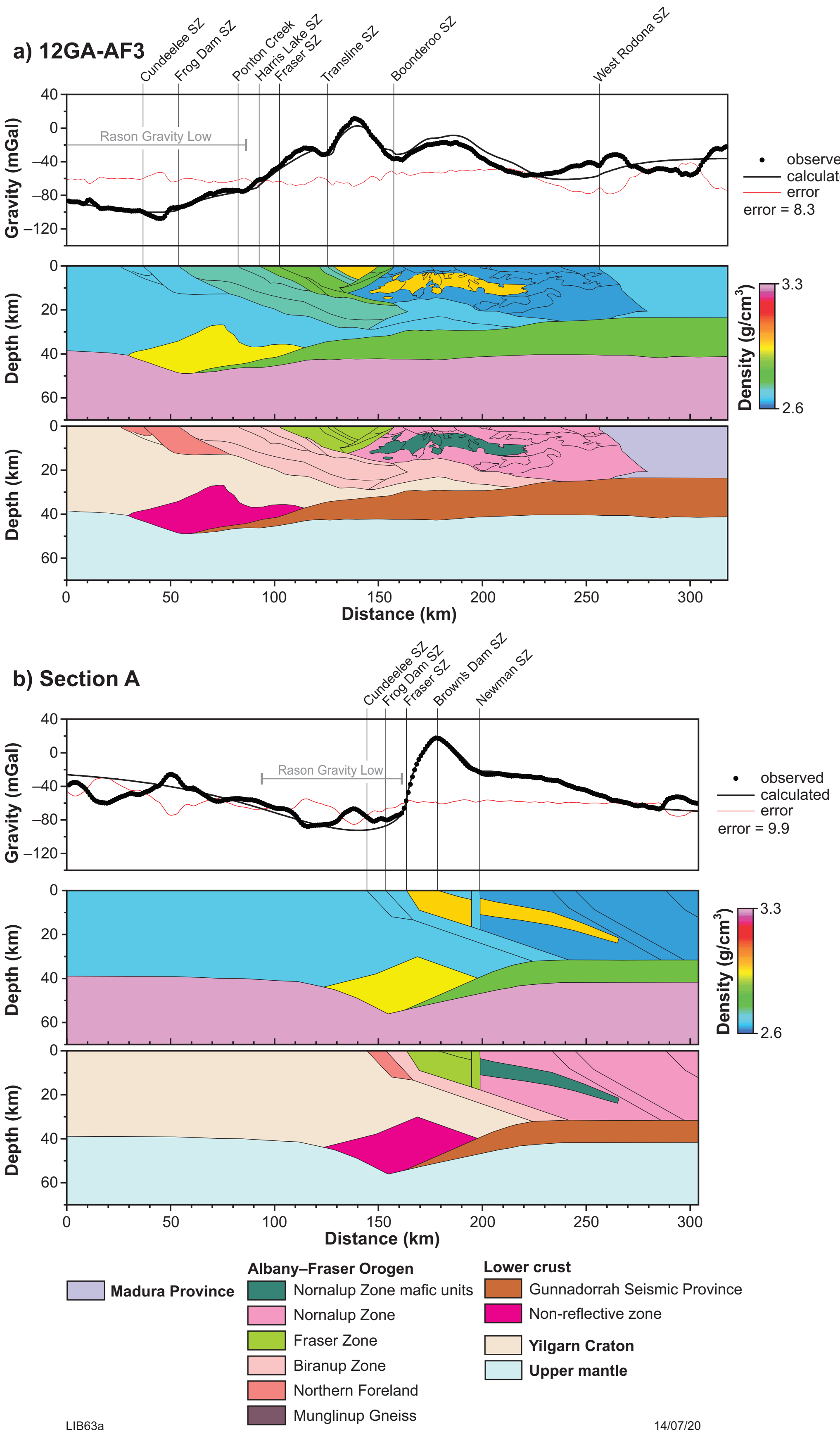

Figure 7. 2D sections constructed from gravity forward modelling. Each section shows the observed and calculated gravity data (upper image), the 2D density model (middle image, with density key) and the geological interpretation (lower image, with geological key). Sections are shown from north to south: a) 12GA-AF3, with geometries constrained by seismic interpretation; b) section A. Section naming after Sippl et al. (2018). Location of sections shown on Figures 1 and 2. Abbreviations: F, Fault; SZ, Shear Zone

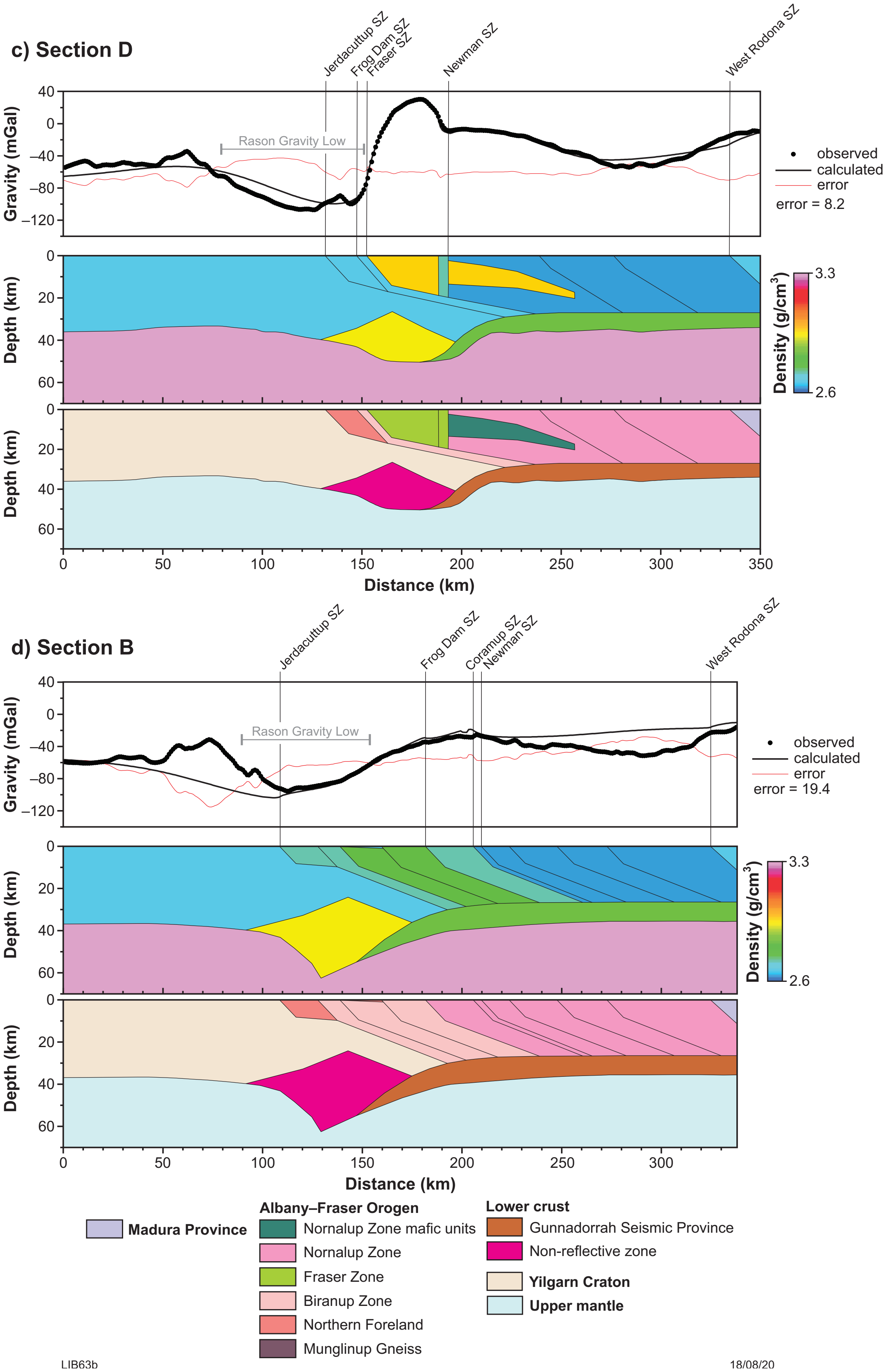

Figure 7. (continued): c) Section D; d) Section B

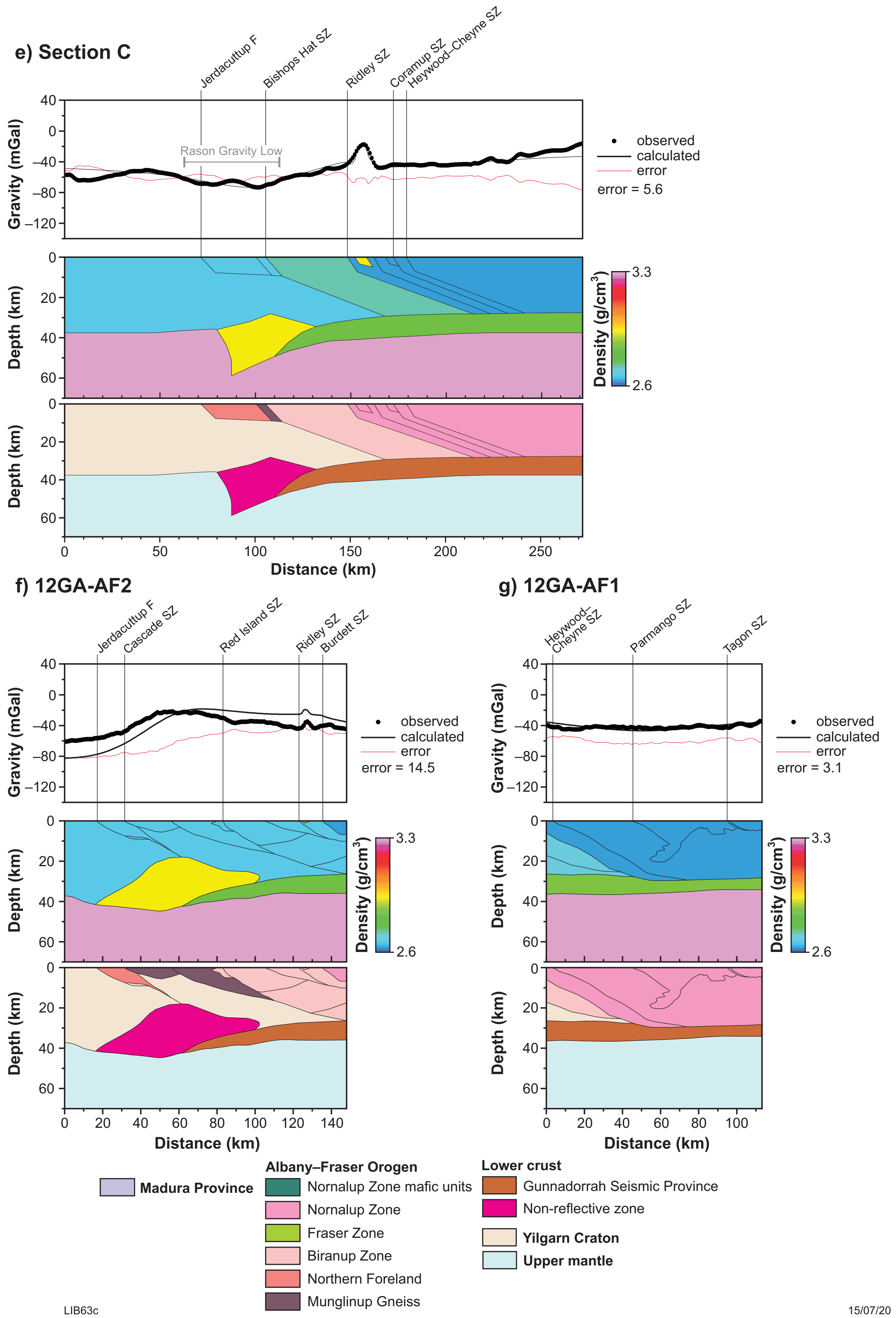

Figure 7. (continued): e) Section C; f) 12GA-AF2, with geometries constrained by seismic interpretation; g) 12GA-AF1, with geometries constrained by seismic interpretation

This orientation is also broadly consistent with the dip of the Fraser Shear Zone in reflection seismic profile 12GA-AF3. However, in 12GA-AF3, the Fraser Shear Zone has a much shallower dip (~35°) than in the density model.

The Newman Shear Zone is defined by a demagnetized zone up to 60 km long and 5 km wide. It is also located on a steep gravity gradient, in this case between the dense Fraser Zone and the less dense Nornalup Zone. Sections through the density model show that the southeastern margin of the Fraser Zone varies in dip direction along strike, but is generally subvertical to steeply northwest or southeast dipping (Fig. 8). Newman Rocks, within the demagnetized zone that defines the Newman Shear Zone, is one of the few locations where the Newman Shear Zone is exposed. Here, mylonite zones within a metagranite are steeply southeast dipping to subvertical (Quentin de Gromard et al., 2017). The orientations of these mylonite zones are broadly consistent with the subvertical density contrast imaged at this location.

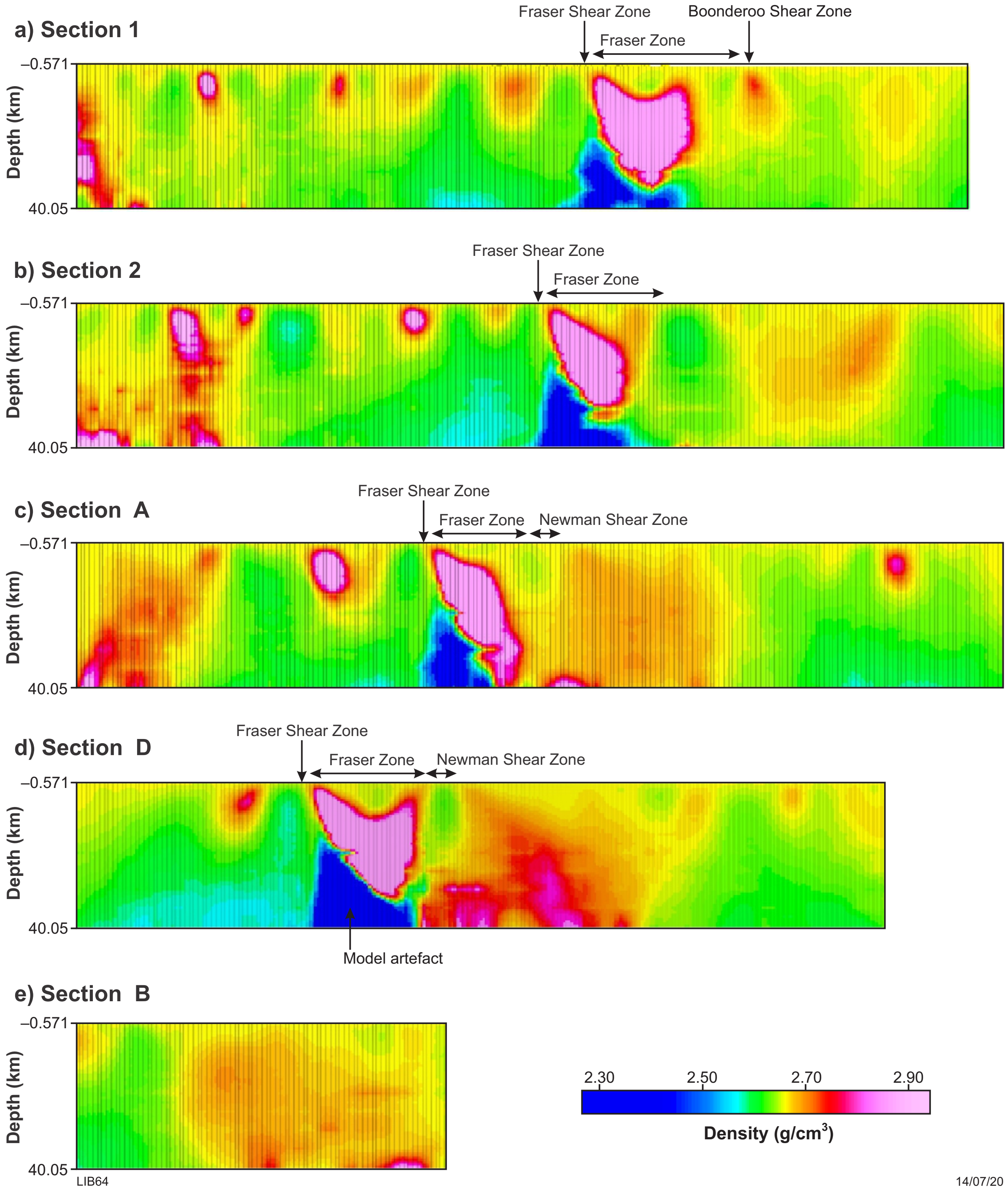

Figure 8. Sections through the 3D density models from gravity inversion showing the geometry of the Fraser Zone. Density models image the moderately southeast-dipping Fraser Shear Zone that bounds the northwestern margin of the Fraser Zone. Locations of sections shown on Figures 1 and 2. VE = 1

Magnetic inversion was performed in an attempt to image the southwestern Newman Shear Zone, where the demagnetized zone is over 5 km wide. In susceptibility models (voxel size 500 m) and density models (voxel size 1000 m), the Newman Shear Zone is imaged as a steeply northwest-dipping magnetic and density contrast (Fig. 9a,b). The susceptibility model also suggests the southeastern margin of the Newman Shear Zone dips southeast below magnetic material of the Nornalup Zone (Fig. 9a).

The models from inversion also contain artefacts that are the result of assumptions applied to the model and the method itself. The density model from gravity inversion shows a large, very low-density body in the lower crust (Fig. 8). The body is an artefact of the density model, and is partly a result of the incorrect assumption that the Moho is flat. A large low-density body in the lower crust contradicts the results from much better constrained 2D and 3D gravity forward modelling, that show a dense body in a zone of thickened crust. However, comparing these models does illustrate the importance Moho topography can have on crustal-scale gravity modelling.

Another artefact of the density model is the exaggerated depth of the Fraser Zone. In density models, the Fraser Zone density anomaly extends to a maximum depth of ~40 km. This is unrealistic and much deeper than in reflection seismic where the Fraser Zone extends to a depth of ~15 km, and 2D forward modelling which suggests that the Fraser Zone has a maximum depth of ~20 km using a density of 3 g/cm^3. This smearing of anomalies at depth is a common feature of models from unconstrained inversion.

Upward continued Bouguer gravity

Upward continuation is a mathematical filter used to calculate the magnetic or gravity field at a height above the measured data, enhancing long-wavelength features. As a rule of thumb, Jacobsen (1987) suggests that the upward continued height is equal to or less than half the depth of the source.

Bouguer gravity data upward continued to 60 km shows a long-wavelength gravity high underlying the east Albany–Fraser Orogen and Madura Province, and increasing in amplitude towards the coast (Fig. 10). This anomaly is broadly coincident with the extent of the lower-crustal Gunnadorrah Seismic Province and is interpreted to indicate a relatively dense Gunnadorrah Seismic Province, possibly associated with the Maralinga magmatic event during Stage II of the Albany–Fraser Orogeny (Spaggiari et al., 2016).

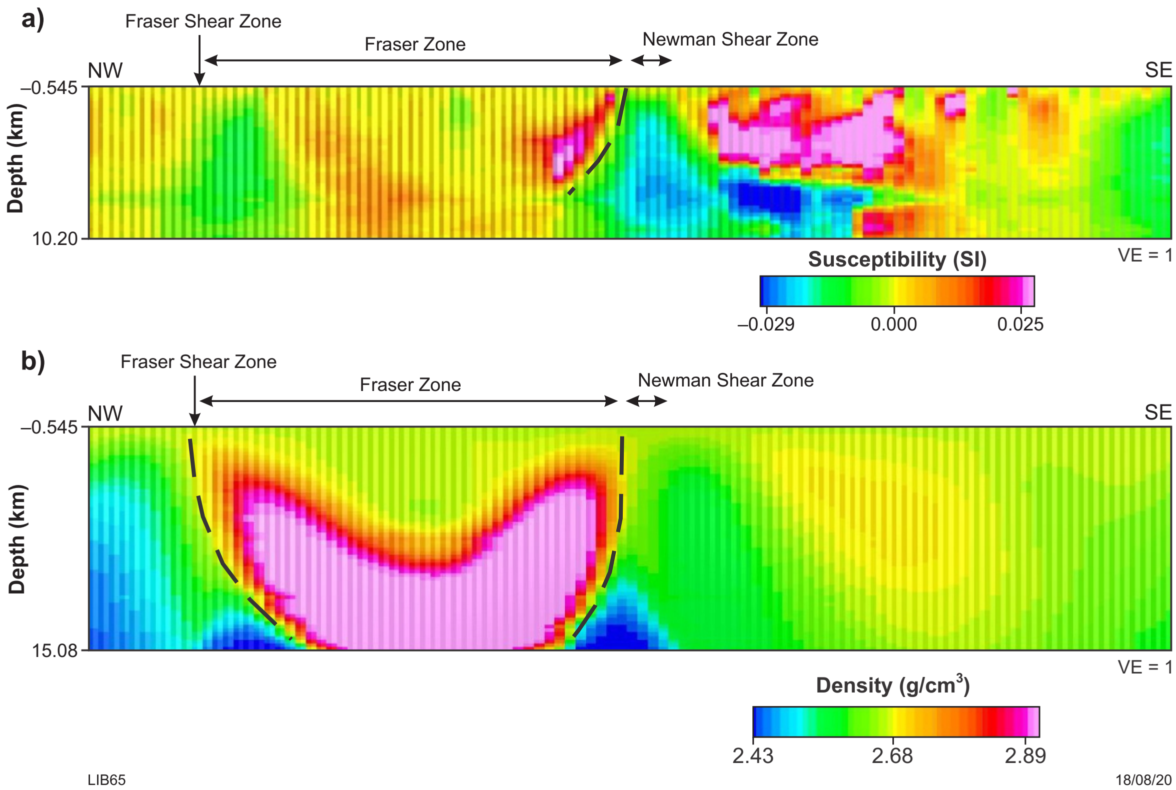

Figure 9. Northwest-trending sections through susceptibility and density models from inversion showing the geometry of the Fraser Zone in the S-bend region (between Sections D and B). Both models image the Newman Shear Zone as a steeply northwest-dipping structure. VE = 1

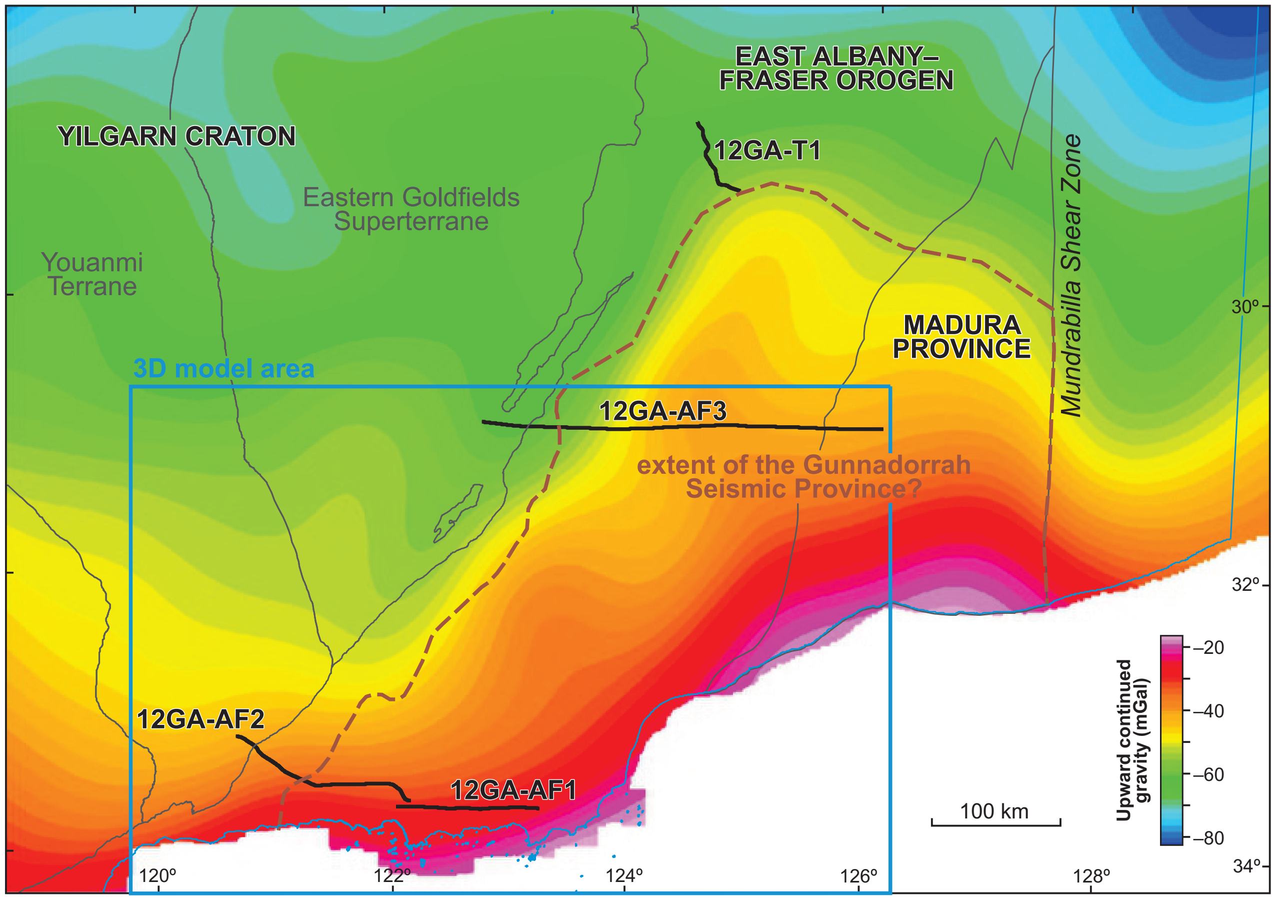

Figure 10. **Bouguer gravity data, upward continued to 60 km, showing a long-wavelength gravity high in the east Albany–Fraser Orogen broadly coincident with the Gunnadorrah Seismic Province**

Results

3D geological model

The final 3D geological model has dimensions 600 km (x) x 400 km (y) x 75 km (z) and comprises 12 units (Fig. 11). Model units are listed in Table 1 along with the datasets used to constrain the geometry of each unit. Some of the major features of the model include the ~10 km deep, northeast-trending Moho depression along the craton margin (Fig. 11a). Units of the lower crust include the voluminous non-reflective zone within the Moho depression and the Gunnadorrah Seismic Province in the lower crust of the east Albany–Fraser Orogen (Fig. 11b). The Gunnadorrah Seismic Province thickens to the northeast, and tapers out to the northwest, terminating in the Moho depression beneath the non-reflective zone. In the northwest of the model, the Yilgarn Craton has been modelled as one unit, comprising the Youanmi Terrane and the underlying Udarra Seismic Province, together with the Eastern Goldfields Superterrane and underlying Yarraquin Seismic Province (Fig. 11c). At depth, the Yilgarn Craton extends to the southeast beneath the units of the east Albany–Fraser Orogen.

Adjacent to the Yilgarn Craton, the Northern Foreland and Munglinup Gneiss extend to depths of ~10 km and dip to the southeast beneath the Biranup Zone (Fig. 11c,d). The Munglinup Gneiss has been modelled separately from the rest of the Northern Foreland to test whether it could be the source of the gravity high observed along strike southwest of the Rason Gravity Low (Fig. 3). The Biranup Zone extends to the southeast, beneath the Fraser and Nornalup Zones, terminating in the lower crust on the top of the Gunnadorrah Seismic Province. In the northern half of the model, the Fraser Zone extends to a maximum depth of ~15 km. The northwestern margin of the Biranup Zone, bounded by the Fraser Shear Zone, has been modelled as dipping moderately southeast (Fig. 11c). The southeastern margin, bounded by the Newman Shear Zone, has been modelled as subvertical although, as previously described, this southeastern contact is not well constrained. The Nornalup Zone and Madura Province occupy the southeastern half of the model. Two poorly constrained mafic units, Nornalup Zone mafic units 1 and 2, have been modelled in the middle to upper crust of the Nornalup Zone (Fig. 11c). These mafic units are included to satisfy two long-wavelength gravity anomalies and are discussed further below. To the southeast of the Nornalup Zone, separated by the West Rodona Shear Zone, the Madura Province has been modelled as one unit.

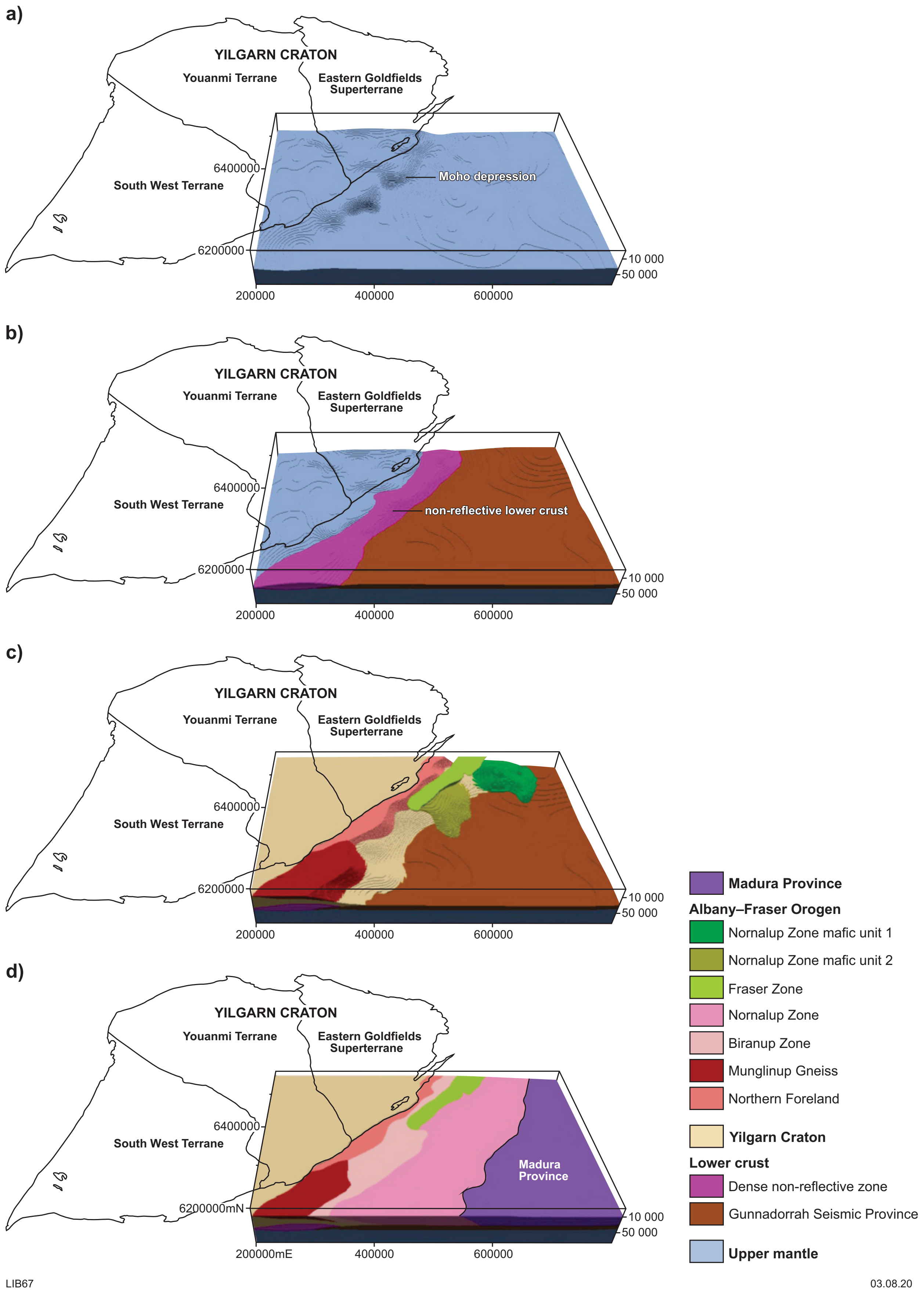

Figure 11. 3D geological model: a) upper mantle; b) lower crust; c) middle and upper crust; d) model ground surface. Yilgarn Craton margin and terrane boundaries from 1:500 000 tectonic units of Western Australia (GSWA, 2017)

Final 3D density model

The final 3D density model is shown in Figure 12. This model reproduces several of the regional-scale observed Bouguer gravity anomalies, including the Rason Gravity Low and the Fraser Zone gravity high. The model also produces some large residual values, which is a consequence of performing gravity forward modelling on a regional-scale model.

In the final density model, a gravity low similar to the Rason Gravity Low (feature 1 in Fig. 13a,b) has been produced by a zone of thickened, dense lower crust, as suggested by previous 2D gravity forward modelling (Tassell and Goncharov, 2006; Murdie et al., 2014; Sippl et al., 2018). This zone extends to the northeast along the length of the model (~500 km) and in cross-section has a flying saucer shape and a maximum thickness of ~30 km (Fig. 12b).

Both 2D and 3D gravity forward modelling show that the northeast-trending zone of thickened crust, constrained by the Moho model, produces a long-wavelength gravity low along the craton margin. However, compared to the observed Rason Gravity Low, the minimum of the gravity low is too far to the southeast and, in places, the amplitude is too low. This indicates dense material is required in the thickened crust, to shift the gravity low to the northwest. This has been achieved by modelling the non-reflective lower-crustal zone with a high density (2.95 g/cm^3). An attempt was also made to shift this anomaly to the northwest by increasing the density of the units of the upper crust, the Northern Foreland, Biranup Zone and Munglinup Gneiss. However, these models had large residual values and specific gravity data do not support a high-density Munglinup Gneiss or Northern Foreland.

Broadly along strike of the Rason Gravity Low, to the southwest, is an observed gravity high (feature 2 in Fig. 13a). In gravity forward modelling along 12GA-AF2, the source of this gravity high is interpreted to be the dense non-reflective zone in the lower crust (Murdie et al., 2014). In 3D, a gravity high similar to the observed high can also be produced by dense, thickened crust (feature 2 in Fig. 13b). A gravity high, rather than a low, is the result of a shallower Moho depression (~5 km deep) and a larger lower-crustal dense zone (~20 km thick). Several models attempted to produce this anomaly by increasing the density of the Munglinup Gneiss, exposed at the surface below this anomaly; however, these models had large residual values and are not supported by specific gravity data.

The Biranup Zone has been modelled with a relatively high density of 2.72 g/cm^3, but in places still contains density deficits. The largest deficit is in the region of the S-bend (feature 3 in Fig. 13c), indicating that in this region the Biranup Zone is most likely denser and more mafic.

The Fraser Zone has been modelled with a density of 3.00 g/cm^3 and a maximum depth of ~15 km. The Fraser Shear Zone bounds the northwestern margin of the Fraser Zone and has been modelled with a southeast dip. The southeastern margin is bounded by the Newman Shear Zone and has been modelled with a subvertical dip. This geometry generally produces low residual values; however, an exception is along the Newman Shear Zone, where model density excesses (feature 4 in Fig. 13c) indicate that the Fraser Zone is dominated by felsic rather than mafic material.

The Nornalup Zone has been modelled with a density of 2.67 g/cm^3 and contains two dense units, Nornalup Zone mafic units 1 and 2 (3.00 g/cm^3; Fig. 12c). These unexposed units have been modelled in the middle to upper crust, as suggested by the depth of mafic rafts in interpreted seismic line 12GA-AF3. This unit is not well imaged in reflection seismic but has been included in an attempt to reproduce the two moderate-amplitude gravity anomalies in the Nornalup Zone, southeast of the Fraser Zone (features 5 and 6 in Fig. 13a).

A poorly constrained, approximately west-oriented increase in the depth of the Moho, broadly aligned with the southwest end of the Fraser Zone, produces large residual values (density deficits) in the northeastern Nornalup Zone (feature 7 in Fig. 13c). This is despite the addition of the two mafic units to the northeastern Nornalup Zone, and the northeast thickening of the dense Gunnadorrah Seismic Province. The crust to the south of this Moho feature has negative residual values (density excess; feature 8 in Fig. 13c). These results suggests that the crust (Nornalup Zone or Gunnadorrah Seismic Province) to the north of this west-oriented increase in Moho depth has a higher density (more mafic composition) than the crust to the south of this structure.

Discussion

Dense, non-reflective magmatic underplate

The dense, non-reflective zone imaged at the margin of the Yilgarn Craton and east Albany–Fraser Orogen has many of the geophysical properties typically associated with a magmatic underplate. Magmatic underplating is defined by Thybo and Artemieva (2013) as the addition of mafic magma to the lower crust and uppermost mantle above and below the Moho. Discriminators of underplated material are non-unique but include high P- and S-wave velocity, high V_p/V_s ratio, and high density (Thybo and Artemieva, 2013). The ALFREX passive seismic data show high V_p/V_s ratios coincident with the non-reflective zone (Sippl et al., 2018). In the northeast of the survey area, high V_p/V_s values are coincident with the dense Fraser Zone. In the southwest, high V_p/V_s values extend beyond the extent of Fraser Zone (Sippl et al., 2018) and are interpreted to be due to the magmatic underplate.

In the geological record, interpreted magmatic underplates include bodies with reflective and non-reflective seismic character (Thybo and Artemieva, 2013). McBride et al. (2004) suggested that reduced reflectivity in the lower crust beneath the Greenland–Iceland–Faroe Ridge is due to hot crust at the time of emplacement, causing sill-like bodies to be subsumed or develop diffuse non-reflective boundaries. Thybo and Artemieva (2013) interpreted reflection-free magmatic underplates to represent large intrusive bodies that have cooled over a long period of time, creating bodies with smoothly varying properties that are reflection free at seismic frequencies.

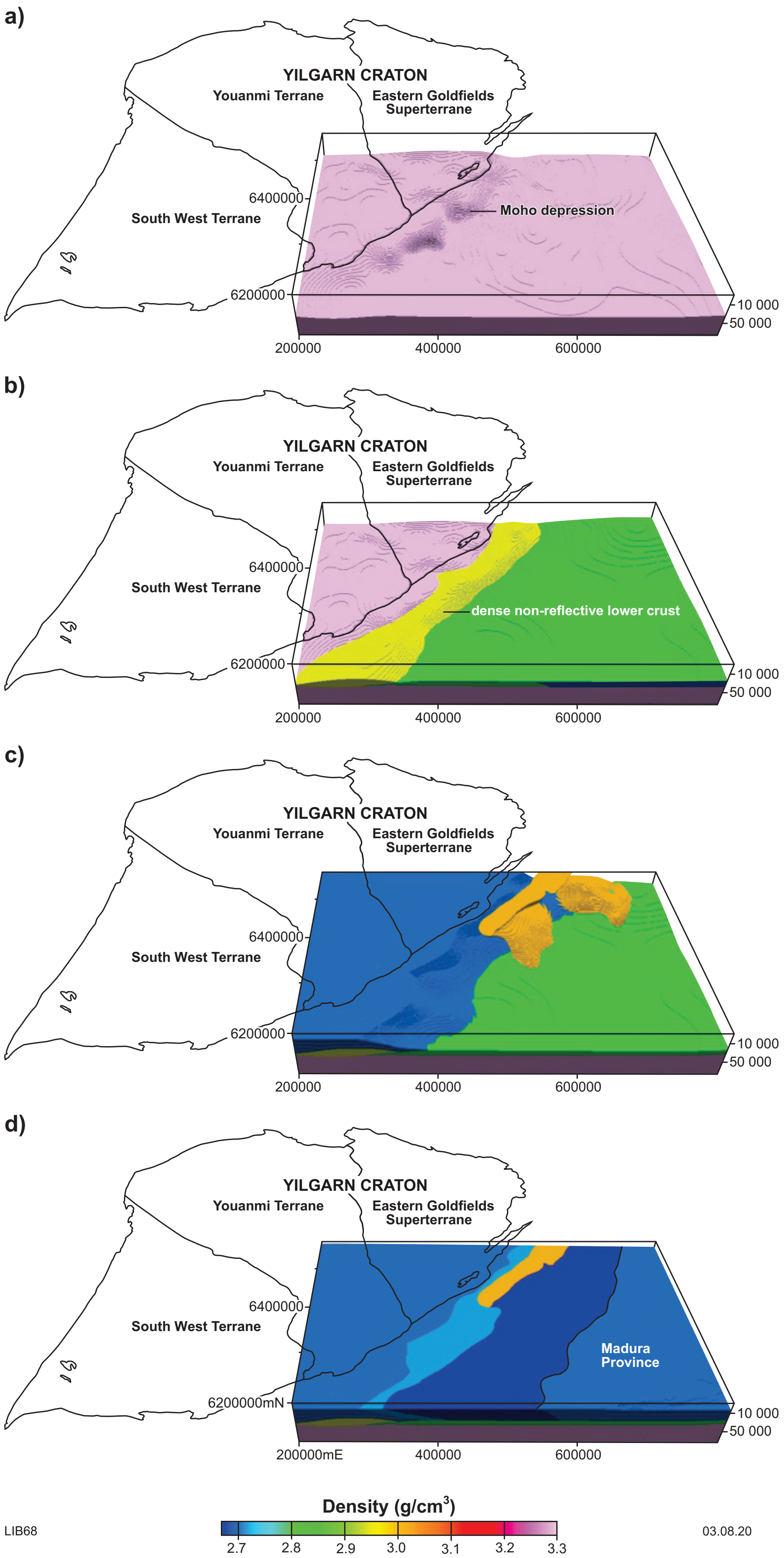

Figure 12. 3D density model: a) upper mantle; b) lower crust; c) middle and upper crust; d) model ground surface. Yilgarn Craton margin and terrane boundaries from 1:500 000 tectonic units of Western Australia (GSWA, 2017)

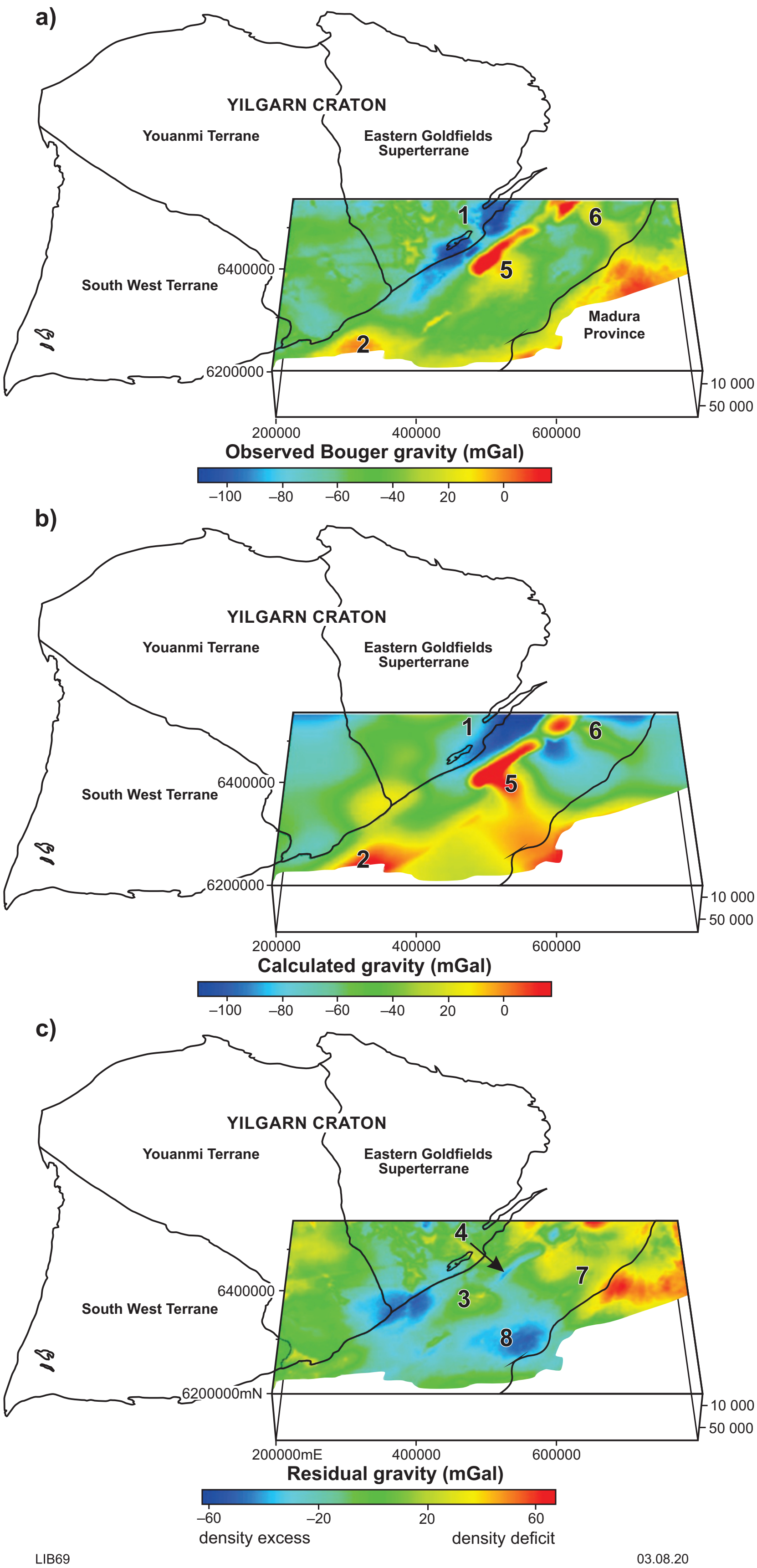

Figure 13. Results of 3D gravity forward modelling: a) observed Bouguer gravity data; b) calculated Bouguer gravity data; c) residual Bouguer gravity data where high values indicate a density deficit and low values a density excess. Yilgarn Craton margin and terrane boundaries from 1:500 000 tectonic units of Western Australia (GSWA, 2017)

Hence, reduced reflectivity observed in the thickened lower crust, at the margin of the Yilgarn Craton and east Albany–Fraser Orogen, may be due to magmatic material either emplaced into a hot crust or cooled over a long period of time.

Emplacement of magmatic underplate

Crosscutting relationships in reflection seismic data indicate that the interpreted underplate is younger than Archean and may have formed during Stage II of the Albany–Fraser Orogeny (1225–1140 Ma; Spaggiari et al., 2014c) One possibility is that the magmatic underplate formed during Paleoproterozoic to early Mesoproterozoic extension along the southern Yilgarn Craton margin. Extension along the margin was accompanied by the formation of two regional basin systems the Barren Basin (1815–1600 Ma) and Arid Basin (1600–1305 Ma) (Spaggiari et al., 2014b). The Barren Basin is interpreted to have formed in an intracontinental rift or distal back-arc setting (Spaggiari et al., 2014b). One proposed tectonic setting of the Arid Basin is an ocean–continent transition and passive margin, formed by east-dipping subduction of oceanic crust beneath the Loongana Arc (Spaggiari et al., 2015). Alternatively, the Arid Basin may have formed in a back-arc setting by west-dipping subduction of oceanic crust beneath the Loongana Arc (Morrissey et al., 2017).

It is possible the magmatic underplate formed during intracontinental extension, synchronous with the formation of the Barren Basin. Corti et al. (2003), in their review of analogue modelling of continental extension, observed that, during orthogonal rifting, magma and lower crust are squeezed from an axial position towards the footwall of major normal faults, resulting in major magma accumulations in a lateral position with a rift-parallel trend. The lateral flow of magma and partially melted lower crust is driven by pressure gradients created during extension. This model may apply to Paleoproterozoic rifting along the southeastern Yilgarn Craton margin where northwest–southeast intracontinental extension resulted in the emplacement of a large volume of magma in the footwall of one of the major southeast-dipping shear zones; for example, the Coramup and Heywood–Cheyne Shear Zones.

It is also possible that the non-reflective underplate formed at the continent–ocean transition during c. 1600 Ma breakup, as the intracontinental rift of the Barren Basin evolved into the marginal ocean basin of the Arid Basin. Breakup underplates have been observed at many modern continent–ocean transitions, including the Faroe Islands (White et al., 2008) and Hatton Bank, Iceland (Fowler et al., 1989), on the North Atlantic margin. In the Faroe Islands seismic profile, a large reflection-free zone is interpreted as an underplated body that formed during breakup as a substantial volume of magma was emplaced and solidified slowly (Thybo and Artemieva, 2013).

Another interpretation is that the dense, non-reflective zone, interpreted here as a magmatic underplate, was emplaced at the same time as the c. 1210 Ma Gnowangerup–Fraser dyke swarm (Spaggiari et al., 2014c). This interpretation is consistent with crosscutting relationships that indicate the non-reflective zone formed during Stage II of the Albany–Fraser Orogeny (Spaggiari et al., 2014c). The Gnowangerup–Fraser dykes intrude the Northern Foreland and southern Yilgarn Craton, subparallel to the Yilgarn Craton margin, just northwest of the interpreted magmatic underplate (Fig. 14). These dykes belong to the 1218–1202 Ma Marnda Moorn Suite, which is part of the extensive Marnda Moorn Large Igneous Province (Wingate and Pidgeon, 2005; Wingate, 2017). This province includes dykes that intrude subparallel to the southern, western and northwestern margins of the Yilgarn Craton (Fig. 14). This voluminous magmatic underplate imaged along the Yilgarn Craton and Albany–Fraser Orogen could be a remnant of the craton-wide 1218–1202 Ma Marnda Moorn Large Igneous Province.

The interpreted magmatic underplate occupies a zone of thickened crust that extends along the Yilgarn Craton margin. Crustal thickening has been interpreted to have occurred during the Albany–Fraser Orogeny, as the Gunnadorrah Seismic Province was thrust beneath the Yilgarn Craton margin (Sippl et al., 2018). However, a model where crustal thickening is due to magmatic underplating is also possible and more consistent with the interpretation of the Gunnadorrah Seismic Province as a widespread magmatic underplate related to magmatism of the Esperance (Albany–Fraser Orogen) and Moodini Supersuites (Madura and Coompana Provinces) during Stage II of the Albany–Fraser Orogeny and the Maralinga Event.

Conclusions

Regional-scale 3D gravity forward modelling has allowed us to image an interpreted magmatic underplate along the margin of the Yilgarn Craton and east Albany–Fraser Orogen. Some of the datasets that have made it possible to construct this model include a high-resolution Moho model from passive seismic data, an interpreted bedrock geology map, and three deep-crustal reflection seismic profiles. Modelling demonstrates that thickened continental crust, occupied by a dense and non-reflective zone, can produce the Rason Gravity Low, a continental-scale gravity anomaly that extends for over 500 km at the margin of the southeastern Yilgarn Craton and east Albany–Fraser Orogen. The magmatic underplate is interpreted to have been emplaced in the Proterozoic, either during Paleo- to Mesoproterozoic extension along the craton margin, or as a source for the c. 1210 Ma Gnowangerup–Fraser dyke swarm, emplaced during Stage II of the Albany–Fraser Orogeny.

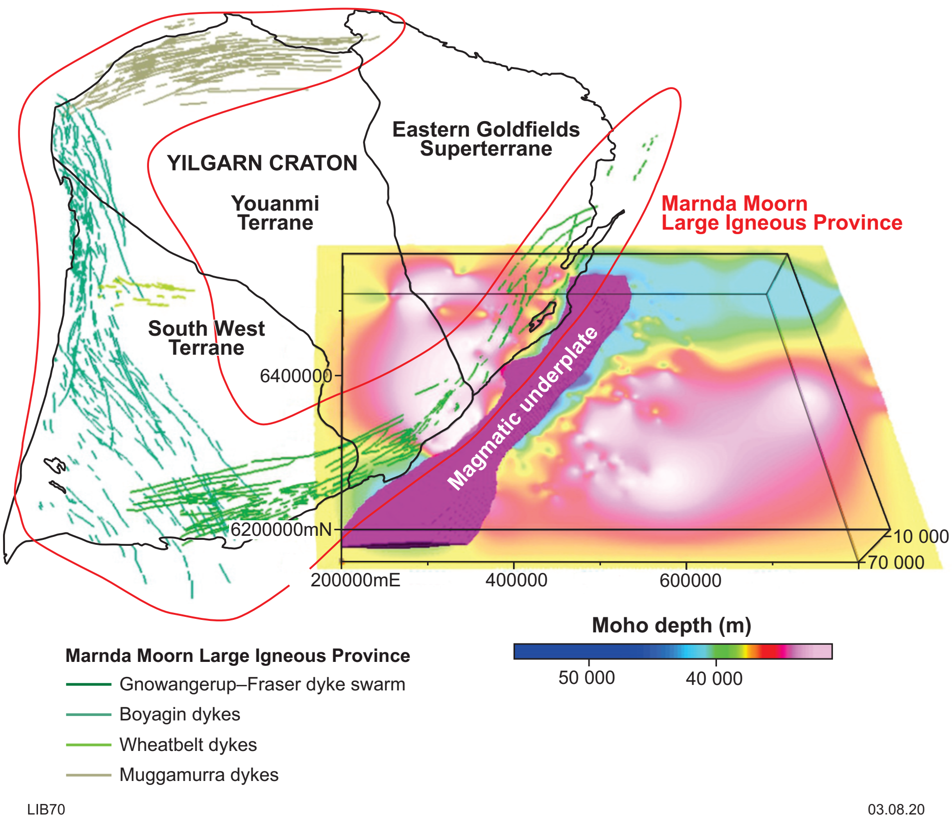

Figure 14. Marnda Moorn Large Igneous Province, which includes the Gnowangerup–Fraser dyke swarm (GSWA, 2015), shown in relation to the interpreted magmatic underplate. Yilgarn Craton margin and terrane boundaries from 1:500 000 tectonic units of Western Australia (GSWA, 2017)

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IMAGING A MAGMATIC UNDERPLATE WITH 3D GRAVITY MODELLING:
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