High-heat geodynamic setting during the Palaeozoic evolution of the Mount Painter Province, SA, Australia: evidence from combined field structural geology and potential-field inversions

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SUMMARY
A method for subsurface recognition of blind geological bodies is presented using combined surface constraints and 3-D structural modelling that incorporates constraints from detailed mapping, and potential-field inversion modelling. This method is applied to the Mount Painter Province and demonstrates that addition of low density material is required to reconcile the gravity signature of the region. This method may be an effective way to construct 3-D models in regions of excellent structural control, and can be used to assess the validity of surface structures with 3-D architecture. Combined geological and potential-field constrained inversion modelling of the Mount Painter Province was conducted to assess the validity of the geological models of the region. Magnetic susceptibility constrained stochastic property inversions indicates that the northeast to southwest structural trend of the relatively magnetic meta-sedimentary rocks of the Radium Creek Group in the Mount Painter Inlier is reconcilable with the similar, northeast to southwest trending positive magnetic anomalies in the region. Radium Creek Group packages are the major contributor of the total magnetic response of the region. However field mapping and the results of initial density constrained stochastic property inversion modelling do not correlate with a large residual negative gravity anomaly central to the region. Further density constrained inversion modelling indicates that an additional large body of relatively low density material is needed within the model space to account for this negative density anomaly. Through sensitivity analysis of multiple geometrical and varied potential-field property inversions, the best-fitting model records a reduction in gravity rms misfit from 21.9 to 1.69 mGal, representing a reduction from 56 to 4.5 per cent in respect to the total dynamic range of 37.5 mGal of the residual anomaly. This best-fitting model incorporates a volumetrically significant source body of interpreted felsic, low density material (1012 m3) impinging on the central-west of the Mount Painter Inlier and overlying Neoproterozoic sequences, and the emplacement of more mafic affinities in the northeast and east. The spatial association and circular geometry of these granitoid bodies suggests an affinity with the Palaeozoic ∼460–440 Ma British Empire Granite that outcrops in the Mount Painter Inlier. The intrusion of this additional material in the Palaeozoic could either be the product of, or contributed to, an increased local geotherm and heat flow in the region during the Palaeozoic.

Key words: Gravity anomalies and Earth structure; Magnetic anomalies: modelling and interpretation; Folds and folding; Crustal structure; Australia.

1 INTRODUCTION
Structural mapping is the most common tool available to understand 3-D architecture, overprinting relationships and kinematics that result in a given 3-D geometry. By virtue of the surface constraints of the observations, the validity of the analysis for understanding the subsurface architecture and distribution of rock packages remains subject to considerable ambiguity and erroneous interpretations (Frodeman 1995). Integration of petrophysical and geophysical data sets in the modelling process, such as gravity and magnetic field data, can provide crucial information as to the nature and distribution of density contrasts and magnetic material in the subsurface.
This in turn can be used to inform on potential geometries and rock packages present at depth (e.g. Fullagar et al. 2004; Backé et al. 2010; Crawford et al. 2010; Roy et al. 2010; Baines et al. 2011). The modelling of potential-field data, whilst non-unique, can be used in conjunction with detailed structural analysis to inform on 3-D architecture and distribution of rocks.

Critically, comparison of constrained 3-D density and magnetic susceptibility models with measured potential-field data through inversion modelling places powerful internally consistent constraints on these models. Hence semi-quantitative numerical and visual testing of inversions are powerful tools in understanding the geological history of a terrane.

In this contribution we present a method to construct a 3-D structural model of a complex poly-deformed terrane and test it using constrained potential field inversions. We use the northern Mount Painter Province in South Australia as our natural laboratory, which has been demonstrated to have a protracted magmatic, multiphased metamorphic, poly-deformational and metasomatic evolution (Elburg et al. 2001, 2003; McLaren et al. 2006; Neumann et al. 2009; Fraser & Neumann 2010; Armit et al. 2012). The modelling results are also applied to inform on the Palaeozoic evolution of the region which has been held up as a model for in situ heating (Sandiford et al. 1998; McLaren et al. 2002).

1.1 Regional setting

The Mount Painter Province which encompasses the northern extent of the Flinders Ranges in South Australia is predominately comprised of Early Mesoproterozoic, Neoproterozoic and Palaeozoic rocks (Figs 1 and 2a). The Province is comprised of the Early Mesoproterozoic Mount Painter and Babbage inliers. The inliers are interpreted as part of the Moolawatana Domain (Fig. 1) that defines the northwestern extent of the Curnamona Province (Parker et al. 1993; Teale & Flint 1993; Conor & Preiss 2008). The inliers consist of ca. 1595 Ma meta-sedimentary rock of the Radium Creek Group (Teale 1993; Fraser & Neumann 2010; Armit et al. 2014) which are intruded by Mesoproterozoic A-type granitoids and subvolcanics of the ca. 1585–1569 Ma Mount Neill Suite (Elburg et al. 2001, 2013;...
Evolution of the Mount Painter Province

Figure 2. Geophysical response and simplified geology of the Mount Painter Province; (a) Simplified geology of the region; (b) Bouguer gravity response of the Mount Painter Province based on the 800 m spaced onshore isostatic gravity anomaly grid of the continent (© Commonwealth of Australia; Geoscience Australia, 2011) (locations 1–4, described in the text); (c) Sun-shaded 90° inclination Total Magnetic Intensity (TMI) response of the Mount Painter Province based on the 100 m Total Magnetic Intensity (TMI) anomaly map of South Australia (© Department of Primary Industries and Resources, South Australia) (locations 1 and 2, described in the text); (d) Sun-shaded (135° declination, 55° inclination) Reduction To Pole (RTP) TMI response of the region (locations 1–6, described in the text). Extent of the outcropping Mesoproterozoic Inlier shown in white and the extent of the 3-D model is shown as a black box in all (a)–(d).

Neumann et al. 2009; Fraser & Neumann 2010) and the ca. 1560 Ma Moolawatana Suite (Johnson 1980; Thornton 1980; Fanning 1995; Neumann 2001; Fraser & Neumann 2010; Fig. 2a).

Mesoproterozoic rocks in the region have been interpreted to have undergone Mesoproterozoic ductile poly-deformation comprising an early ca. 1591–1585 Ma and later ca. 1585–1552 Ma deformation phases (Armit et al. 2012). The deformation is characterized by tight folding and shearing in the Mesoproterozoic rocks which are unconformably overlain by ∼12-km-thick Neoproterozoic sedimentary and volcanic packages (Sandiford et al. 1998; McLaren et al. 2002). The Neoproterozoic packages are comprised of rift-related Callana and Burra Groups (Warrina Supergroup) and the glacial to postglacial sediments of the Heysen Supergroup which consists of the Umberatana and Wilpena groups (Preiss 1987, 2000). The Neoproterozoic packages constitute part of the larger Neoproterozoic to Middle Cambrian Adelaide Geosyncline (Preiss 1987; Coney 1990; Flottmann et al. 1994; Marshak & Flöttemann 1996) and associated basin complexes that developed between ca. 830 and ca. 530 Ma (Preiss 1987, 2000; Sandiford et al. 1998). Thick-skinned and basement-involved deformation of the Neoproterozoic and Mesoproterozoic packages in the Mount Painter Province (Paul et al. 1999; Preiss 2000; Armit et al. 2012) is interpreted to be related to basin inversion during the ca. 500 Ma Delamerian Orogeny (Harrison & McDougall 1981; Sandiford et al. 1998; Foden et al. 2006). Orogenesis was characterized by large-scale folding and thrusting of the Neoproterozoic to Middle Cambrian rocks of the Adelaide Fold Belt (Paul 1998) and reactivation of pre-existing basement structures in the Mount Painter and Mount Babbage inliers (Armit et al. 2012).

Intrusion of the Ordovician to Upper Silurian British Empire Granite ca. 460–440 Ma (Elburg et al. 2003, 2013; McLaren et al. 2006) is confined in outcrop to the core of the Inlier (McLaren et al. 2002, 2006; Elburg et al. 2003) and has been interpreted to have been driven by burial of the Radium Creek Group formations which are enriched in high heat producing elements (HPE) leading to mid-crustal anatexis (McLaren et al. 2006). Protracted ca. 430–330 Ma exhumation in the Mount Painter Province is attributed to localization of deformation during the Alice Springs Orogeny along crustal-scale fault systems such as the Paralana Fault Zone (McLaren et al. 2002) which bisects the Mount Painter Inlier (Fig. 2a). Extensive Palaeozoic metamorphic/hydrothermal activity is recorded in the central Mount Painter Inlier (e.g. the Hidden Valley breccia: Elburg et al. 2003; Elburg et al. 2013; Weisheit et al. 2013a, b). A number of different
interpretations surround the mechanism driving this Palaeozoic metasomatic/hydrothermal activity in the region including diapirism (Coats & Blisset 1971), exhumation (Weisheit et al. 2013a, b), magmatism (Elburg et al. 2013) and radiogenic heat production under a thick Neoproterozoic sediment blanket (McLaren et al. 2006). Present-day overthrusting of the Mesozoic to Pliocene sediments by the Mesoproterozoic and dynamic topography imply continued activation along the long-lived Paralana Fault system (Paul et al. 2000; Célérier et al. 2005; Hore & Hill 2009).

1.2 Key terrane
The Mount Painter Province contains Mesoproterozoic granitic complexes which are the most radiogenic rocks in Australia (Neumann 2001). The region is also host to the Palaeozoic Mount Gee U breccia system and the Beverly and Four Mile sandstone-hosted U deposits. The extremely radiogenic Mesoproterozoic granite complexes have been interpreted to have heat production rates of \( \sim 9.9 \mu \text{Wm}^{-3} \) (Sandiford et al. 1998) producing elevated geothermal gradients in the region throughout the Palaeozoic (Mclaren et al. 2002). This in turn has been interpreted by Sandiford et al. (1998) and McLaren et al. (2002) to have led to the amphibolite grade metamorphism recorded during the Palaeozoic in Neoproterozoic sequences proximal to the Mount Painter basement granitic com-
plexes. Elsewhere in the Adelaide Fold Belt metamorphism during the Palaeozoic barely exceeds mid-greenschist facies (Preiss 2000).

1.3 Regional geophysical response and approach
1.3.1 Gravity data
The regional gravity response of the Mount Painter Province (Fig. 2b) is represented by the 800 m spaced onshore isostatic gravity anomaly grid of the continent (© Commonwealth of Australia; Geoscience Australia 2011). The grid is characterized by long-wavelength (>20 km) regional features including a 42 mGal negative anomaly which is coincident with the southern extent of the Mount Painter Inlier (location 1 in Fig. 2b) and a large N–S gravity gradient with positive anomalies with maximum amplitudes of \( \sim 16 \) mGal in the north of the region (location 2 in Fig. 2b). The northcentral region of the Mount Painter Province modelled in this study (extent shown in Figs 2a–d and 3b, d) is dominated by an N–S trending gravity gradient characterized by negative anomalies in the south with a maximum amplitude of \( \sim 40 \) mGal (location 3 in Fig. 2b) and long-wavelength (>20 km) positive anomalies in the north with amplitudes of \( \sim 16 \) mGal (location 4 in Fig. 2b).

The N–S trending gravity anomaly (Fig. 2b) is not readily reconcilable with the NE–SW trend of the Mesoproterozoic magmatic and meta-sedimentary rocks of the Mount Painter Inlier or with

![Figure 3](http://gji.oxfordjournals.org/)

**Figure 3.** (a) Landsat NTL seven image of the northern Mount Painter Province draped on SRTM DTM (data sourced from the U.S. Geological Survey) with a vertical exaggeration of 18; (b) TMI of the modelled region of the northern Mount Painter Province draped on SRTM DTM (USGS) with a vertical exaggeration of 18; (c) Residual Bouguer gravity response (regional Bouguer gravity response removed) of the modelled volume from the northern Mount Painter Province with the outline of the Mesoproterozoic Mount Painter Inlier and state gravity stations overlain (© Department of Primary Industries and Resources, South Australia, 2009) (location 1, described in the text); (d) Initial reference 3-D model (Model 1) of the northern Mount Painter Province constrained from surface field mapping.
the more surficial Phanerozoic packages to the east of the inlier (Fig. 2a). It is likely that the regional gravity response is a composite of deep seated, lower-crustal basement structure and shallower mid to upper crustal geology.

1.3.2 Magnetic data

The regional magnetic response of the Mount Painter Province (Fig. 2c) is based on the 100 m Total Magnetic Intensity (TMI) anomaly map of South Australia (© Department of Primary Industries and Resources, South Australia). It is characterized by a NE–SW trend of linear ~1–5 km wavelength, positive magnetic anomalies with maximum amplitude of 4173 nT corresponding to the trend of the crystalline Mount Painter Inlier (location 1 in Fig. 2c). To the west longer-wavelength (> 5 km) negative anomalies with maximum amplitude of ~454 nT (location 2 in Fig. 2c) are coincident with the Neoproterozoic Adelaide Fold Belt (Fig. 1). The magnetic data were reduced-to-the-pole (RTP; Fig. 2d) using a background field of 36 641 nT with an inclination of ~62.27° and a declination of 7.60°. The reduced-to-the-pole magnetic response of the Mount Painter Province is characterized by mottled, high frequency, short-wavelength positive anomalies coincident with the dominant NE–SW trending structural fabric of the outcropping Mesoproterozoic Mount Painter Inlier (location 1 in Fig. 2d). The linear magnetic anomalies have relatively steep, symmetrical NW and SE oriented gradients indicative of steeply dipping bedding To the east of the Mount Painter Inlier the magnetic response of the region is characterized by a very long-wavelength, smooth textured, positive magnetic anomaly which is associated with Cenozoic cover sequences in the region (location 2 in Fig. 2d).

Linear NE–SW trending short-wavelength (<1 km) negative magnetic anomalies with maximum amplitudes of ~250 nT can be distinguished along the northern (location 3 in Fig. 2d) and southeastern margins (location 4 in Fig. 2d) of the outcropping Mesoproterozoic inlier and are coincident with Early Mesoproterozoic felsic packages including the Mount Neill and Moolawatana suites. The southeast corner of the model region is characterized by a series of relatively long wavelength (>5 km, smooth, moderately negative to positive magnetic anomalies that trend NNE–SSW to N–S (location 5 in Fig. 2d). In the centre of the inlier a moderately negative magnetic anomaly is coincident with the intrusive British Empire Granite (location 6 in Fig. 2d). A number of faults can be interpreted from the magnetic response of the region including steeply dipping NE–SW and NW–SE trending faults that offset magnetic lineaments across the Mount Painter Inlier (Fig. 2d). These structures are documented in Armit et al. (2012).

1.3.3 Topography

Topography in the Mount Painter Province ranges from 55 m to the southeast of the Mesoproterozoic inlier to above 600 m in the vicinity of Mount Gee and the Mawson Plateau (Fig. 3a). A DTM of the Mount Painter Province based on available 90 m SRTM data (U.S. Geological Survey) was integrated in the modelling workflow and inversion of gravity data.

2 MODELLING STRUCTURAL ARCHITECTURE

A forward structural model encompassing the northcentral Mount Painter Province (extent of the model region shown in Figs 2a–d; 3b and d) was produced by Armit et al. (2012) to better understand the structural evolution of the region since the Mesoproterozoic (Fig. 3d). The region was chosen to incorporate previous detailed structural mapping in the Mesoproterozoic Mount Painter Inlier (Armit et al. 2012) and to extend to the Neoproterozoic, Palaeozoic and Mesozoic packages on both the western and eastern sides of the Inlier. This allowed us to better understand the relationships within and between the different geological packages represented in the Mount Painter Province over a period of 1600 Myr. The model was initially generated and modified using the Noddy software (Jessell 1981; Jessell & Valenta 1996) and then imported into Gocad for forward and inversion modelling. The dimensions of the model are 53 km (from west to east), 28 km (from north to south) and 15 km in depth with a total model volume of 2.2 × 10^13 m^3. The aim of the model was not to precisely replicate the detailed geology but to better understand the proposed structural architecture developed through outcrop mapping in the Mount Painter Inlier. This structural framework is outlined below (more details on the parameters and event sequences used in this model are included in Appendix A and follow those developed in Armit et al. 2012). In this communication we consider this model our reference model and assess the structural architecture proposed in Armit et al. (2012) through constrained potential-field inversions.

2.1 Structural framework

A total of 21 ‘Noddy events’ in Armit et al. (2012) were modelled in order to produce the reference model (Fig. 3d). Simplification of this framework provides 12 distinct overprinting structural elements (Table 1).

In the resulting reference model, the modelled events produce a tightly folded corridor consisting of the Radium Creek Group striking NE–SW along the Paralana Fault Zone. The Mount Neill Suite is located predominantly to the southeast of the Radium Creek Group, whilst the Moolawatana Suite intrudes along and into the northwest extent of the Radium Creek Group. A steeply west dipping and NE–SW trending unconformity separates the Neoproterozoic Adelaide Fold Belt from the Mesoproterozoic Inlier. Interference patterns between the Palaeozoic NE–SW trending upfold folds and reclined NW–SE folding occur in the Neoproterozoic packages but also warp the NE–SW trending Mesoproterozoic belt. Dextral faulting representing the ENE–WSW trending Hamilton and Jubilee Faults offset both the Meso- and Neoproterozoic sequences.

In addition to the initial reference model, we develop and test four different 3-D geometrical models in an attempt to honour both the observed potential field data and the geological observations for the region (e.g. Teale 1993; Elburg et al. 2001, 2013; Armit et al. 2012, 2014).

3 ROCK PROPERTIES

Petrophysical properties including density and magnetic susceptibilities measurements can be used to characterize different mineralogy, and by inference, rock type (Fullagar & Pears 2007). The rock property distributions are used to constrain the inversion modelling.

4 METHOD

4.1 Regional-residual gravity response separation

In order to better understand the contribution of the geology within the model volume comprising the upper 15 km of the crust, removal of the longer wavelength gravity contributions is warranted.
This was achieved by subtracting a regional contribution from the original grid and the resulting residual gravity was used for further inversion modelling. At first, the regional gravity was inverted through an unconstrained inversion of the total gravity data thus producing a density distribution that fit the observed data. Within that distribution, the volume of interest (over the Mount Painter Province with a depth of 15 km) was re-assigned a homogeneous density value of 2670 kg m\(^{-3}\). A forward model of that new distribution provided the regional gravity. The residual gravity response of the model space (Fig. 3c) was obtained by subtracting this regional gravity from the original data. This method was previously described by Roy et al. (2010).

### 4.2 Petrophysical constraints

Direct measurement of magnetic susceptibilities from the Mount Painter Province as well as the use of existing petrophysical databases for both magnetic susceptibilities and densities are used to better constrain the inversion process (Figs 4a and b). The petrophysical data are used to assign each modelled lithology a reference value of magnetic susceptibility and density and to provide a range (minimum to maximum) within which the inversion process can optimize the petrophysical property distribution of each unit. For both magnetic susceptibilities and densities of the Neoproterozoic rocks, values from Backé et al. (2010) from the Central Flinders Ranges are used as reference values. Petrophysical values from Backé et al. (2010) for the central and southern Flinders Ranges as well as from Baines et al. (2011) for the Eromanga Basin (Fig. 1—this basin extends from Queensland to South Australia) are used as reference values for the Curnamona Province. The petrophysical properties of similar Late Palaeoproterozoic to Early Mesoproterozoic sediments and intrusives from the Broken Hill Exploration Initiative (BHEI) database (Ruzkowski 1998) for the Curnamona Province; and the Gawler Craton by Baines et al. (2011) are also used in order to develop robust reference petrophysical values and ranges for the magnetic susceptibilities and densities of the 15 different lithologies modelled.

#### 4.2.1 Magnetic Susceptibilities

Samples from 8 distinct lithologies from the Mount Painter Inlier were analysed for their magnetic susceptibilities in order to better constrain the modelling process (Fig. 4a). Twenty one direct measurements of magnetic susceptibility were taken from these distinct lithologies with each measurement recorded in Fig. 4(a) representing the mean of 10 individual magnetic susceptibility readings. Five different lithologies were sampled as representing distinct petrophysical members of the Radium Creek Group (pelitic, paragneiss, quartzite, psammitite and amphibolite) and vary by up to three orders of magnitude from highly magnetic amphibolite bodies and magnetite-bearing schists with a range between 0.01 and 0.15 SI (Figs 4a, 5a and b) to less magnetic quartzites, psammopelites and magnetite-bearing schists with a range between 0.001 and 0.04 SI (but predominantly below 0.0001 SI) most likely relating to both primary magmatic and secondary alteration processes (in particular along the Paralana Fault; Fig. 5c). The sample of British Empire Granite returned a range of magnetic susceptibility values between 0.00001 and 0.04 SI (but predominantly below 0.0001 SI) most likely related to both primary magmatic and secondary alteration processes (in particular along the Paralana Fault; Fig. 5c). The sample of British Empire Granite returned a mean magnetic susceptibility value of 0.0006 SI.

Remanence is modelled as colinear to the Earth’s field but was not directly measured from samples. Remanence is allowed for the mafic intrusives, the amphibolite bodies, the Moolawatana and Mount Neill suites and the pelitic units.

The Mount Neill Granite (Mount Neill Suite) and Terrapinna Granite (Moolawatana Suite) returned a range of magnetic susceptibility values between 0.00001 and 0.04 SI (but predominantly below 0.0001 SI) most likely relating to both primary magmatic and secondary alteration processes (in particular along the Paralana Fault; Fig. 5c). The sample of British Empire Granite returned a mean magnetic susceptibility value of 0.0006 SI.

#### 4.2.2 Densities

Initial densities are assigned to each of the 15 distinct lithologies modelled in the Mount Painter Province (Fig. 4b). Determination of

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**Table 1. Structural framework based on Armit et al. (2012).**

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
<th>Timing</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deposition of Radium Creek Group sedimentary stratigraphy and emplacement of mafic bodies</td>
<td>ca. 1595 Ma</td>
<td>Armit et al. (2014)</td>
</tr>
<tr>
<td>2</td>
<td>D(_1)/D(_2) recumbent northwest verging folding</td>
<td>1591–1585 Ma</td>
<td>Armit et al. (2012)</td>
</tr>
<tr>
<td>4</td>
<td>D(_3) upright NE–SW trending folding</td>
<td>1575–1555 Ma</td>
<td>Armit et al. (2012)</td>
</tr>
<tr>
<td>5</td>
<td>Emplacement of the Moolawatana Suite and late D(_3) sinistral shearing</td>
<td>1555 Ma</td>
<td>Fraser &amp; Neumann (2010)</td>
</tr>
<tr>
<td>6</td>
<td>D(_3) NW–SE extension with normal movement the Paralana Fault and deposition of the Neoproterozoic packages</td>
<td>830–500 Ma</td>
<td>Armit et al. (2012), Preiss (2000)</td>
</tr>
<tr>
<td>8</td>
<td>D(_3) reclined NW–SE folding, dextral faulting on Paralana Fault and oblique faulting on Hamilton and Jubilee Faults</td>
<td>500–340 Ma</td>
<td>Armit et al. (2012), Williams &amp; Betts (2009)</td>
</tr>
<tr>
<td>9</td>
<td>Emplacement of the British Empire Granite</td>
<td>450–440 Ma</td>
<td>McLaren et al. (2006)</td>
</tr>
<tr>
<td>10</td>
<td>D(_7) sinistral faulting on the Paralana Fault</td>
<td>250–0 Ma</td>
<td>Armit et al. (2012), McLaren et al. (2002)</td>
</tr>
<tr>
<td>11</td>
<td>Deposition of Mesozoic–Cenozoic sediments</td>
<td>0 Ma</td>
<td>e.g. Waschbursch et al. (2009)</td>
</tr>
<tr>
<td>12</td>
<td>D(_8) neotectonic overthrusting of basement on Mesozoic–Cenozoic sediments on the Paralana Fault</td>
<td>0 Ma</td>
<td>Teasdale (1993), Célérier et al. (2005)</td>
</tr>
</tbody>
</table>
Figure 4. (a) Assigned and measured magnetic susceptibilities (SI) values for the modelled lithologies in the northern Mount Painter Province; values for the rock packages from central Flinders Ranges (adapted from Backé et al. 2010), Broken Hill (adapted from Ruszkowski 1998) and the Gawler Craton (adapted from Baines et al. 2011) are shown for comparison; (b) Assigned density values for the modelled lithologies in the northern Mount Painter Province; values for the rock packages from central Flinders Ranges (adapted from Backé et al. 2010), Broken Hill (adapted from Ruszkowski 1998) and the Gawler Craton (adapted from Baines et al. 2011) are shown for comparison.
the reference densities are derived from the extensive density data sets for the central and southern Flinders Ranges (Backé et al. 2010), the Curnamona Province (Ruszkowski 1998) and the Gawler Craton (Baines et al. 2011). Five distinct lithologies from the Radium Creek Group are assigned density values between 2800 and 3100 kg m$^{-3}$ (equivalent to residual density values between 280 and 430 kg m$^{-3}$). The five lithologies include the less dense pelitic, psammitic and quartzitic lithologies which are assigned 2800 kg m$^{-3}$, a slightly denser psammopelitic unit at 3000 kg m$^{-3}$ and dense amphibolite bodies at 3100 kg m$^{-3}$. The density variations within the Radium Creek Group are likely to be predominantly controlled by the bulk chemical compositions (Smithson 1971) that have been affected by prograde and retrograde metamorphism and hydrothermal alteration (Figs 5a–d). The intrusive early Mesoproterozoic Mount Neill and Moolawatana suites are assigned an initial density of 2670 kg m$^{-3}$ whilst the younger Palaeozoic British Empire Granite is initially assigned a density of 2500 kg m$^{-3}$ (equivalent to a residual density of $-170$ kg m$^{-3}$). The Neoproterozoic sequence consists of 5 units with assigned densities between 2700 and 3000 kg m$^{-3}$ (30 and 330 kg m$^{-3}$ residual densities) consistent with the values derived by Backé et al. (2010) for the Heysen Supergroup in the Central Flinders Ranges. A density of 2400 kg m$^{-3}$ ($-270$ kg m$^{-3}$ residual density) is assigned to the cover sequence.

4.3 Inversion method

VPmg software (Fullagar et al. 2004, 2008) is used to perform constrained geophysical inversions. The constrained inversions require a reference model which is discretized into a voxel model with voxel dimensions of 250 m in the $x$, $y$ and $z$ directions. This is high resolution with respect to the spacing of the gravity and medium resolution with respect to the magnetics and thus represents a good compromise between computational speed and required geological resolution.

4.3.1 VPmg

VPmg stands for ‘Vertical Prism magnetic and gravity’ modelling (Fullagar et al. 2004, 2008; Fullagar & Pears 2007). The software performs potential-field inversions in a volume discretized using vertical rectangular prisms. Geologic boundaries are defined as a
subdivision of each prism. Each subprism can be further divided into cells of varying thickness within a given lithology and assigned varying petrophysical property values. Forward models are calculated prior to, and after each inversion and can be assessed both visually by comparing the calculated and residual (difference between observed and calculated fields) responses and numerically using a rms (chi-square) misfit estimation. The visual assessment identifies areas of the model that may require modification in order to better fit the observed potential field response whilst honouring the surface mapping of Armit et al. (2012). The rms is used as a global estimator of geophysical fit.

Heterogeneous property inversions are used to calculate the optimum density or magnetic susceptibility distribution within the model volume. Property distributions within the model are varied during each inversion iteration in order to minimize the misfit between observed and calculated data using a steepest descent method (Fullagar & Pears 2007; Fullagar et al. 2008). The inversion process continues as long as the misfit is being reduced during each iteration and stops when an arbitrarily defined rms misfit threshold is reached (successful inversion) or if the misfit cannot be reduced further (failed inversion). In our case, the perturbation of the property distribution followed a stochastic rule, making the resulting distribution highly heterogeneous. Heterogeneous property inversions are carried out sequentially for this study.

4.3.2 Inversion workflow

Initially, heterogeneous inversions were carried out for one lithology at a time (step 1) to assess the contribution of each lithology to the potential-field data. The resulting property distributions are combined into a secondary reference ‘combined model’. This model is subsequently subjected to sequential heterogeneous inversions (step 2) during which each lithology was inverted in a sequential order to reduce the misfit between observed and calculated data as well as to account for the assumed heterogeneous property distribution within each geological unit. The sequence order was arbitrarily chosen to reflect a combination of the level of contribution of each unit to the potential fields (assessed during step 1), slightly modified by our interpretation of what each unit should contribute to the field. We paid more attention to the Mesoproterozoic packages than to the Neoproterozoic sequences as they display larger petrophysical contrasts and are therefore more applicable to geophysical inversion methods used in this study. The Mesoproterozoic packages exposed in the Mount Painter Inlier are also the primary focus of the study in order to test the structural models proposed for the region (e.g. Armit et al. 2012). This workflow was applied for both gravity and magnetic inversions and is summarized in Fig. 6. The order in which each model region is inverted, and the resulting model misfit is outlined in Appendix B for the gravity inversions and in Appendix C for the magnetic inversions. Some of the magnetic field modelling returned calculated fields that exhibit higher frequency anomalies than the observed field. This is expected since an oxidized weathered zone is not modelled. This implies that our modelled magnetic sources are closer to the surface than in the real world and do produce higher frequency responses. The oxidized zoned acts as a dampening horizon and makes the observed magnetic field appear smoother.

4.4 Sensitivity analysis

A suite of geological models was subjected to the inversion workflow described above to try and assess the influence of geological variability on geophysical responses (Jessell et al. 2010; Blaikie et al. 2012, 2014; Lindsay et al. 2013, 2014) and to reconcile and explain residual anomalies. The models are presented and described in the results section.

5 RESULTS

5.1 Regional-residual gravity response separation

The residual gravity response is characterized by a distinct ~20 km wavelength semi-circular negative anomaly with maximum amplitude of ~30 mGal located on the central-west side of the Mount Painter Inlier (location 1 in Fig. 3c). This negative anomaly appears to be coincident with the felsic British Empire granite, however it is not confined to the outcropping extent of this unit, instead the negative anomaly extends to the west where it is seemingly at odds with the trends of the observed Mesoproterozoic geology. We make the assumption that the anomaly is due to felsic lithologies intruded into the Mesoproterozoic and Neoproterozoic successions and this assumption is tested through inversions. In the discussion, we test the validity of the regional-residual gravity separation by assigning the modelled felsic intrusives a density value representing a median density value for the rest of the volume of our favoured model. The forward gravity response of this model exhibits NE–SW trends that are expected as the response of the NE–SW trending Mesoproterozoic lithologies.

In the northeast of the Mount Painter Inlier the residual gravity response is characterized by long-wavelength (10–15 km) positive gravity anomalies with maximum amplitudes of ~5–7 mGal. The positive gravity anomalies appear to be broadly coincident with the outcropping felsic magmatic Moolawatana Suite. However this suite is composed of felsic granitoids, for example Terrapina, Wattleowie and Yerila granitias (Teale 1993) which usually exhibit low densities and is difficult to reconcile with the observed positive gravity anomalies. Positive gravity anomalies situated on the southeast side of the inlier with maximum amplitudes of ~5–6 mGal appear to be in direct conflict with the young sedimentary cover sequences that flank the Proterozoic inlier.

5.2 Forward model: Model 1

Forward models of the potential-field response of the Mount Painter Province are calculated using VPmg to assess the initial misfit of the reference model with the observed field.

5.2.1 Gravity: Model 1

The calculation of the initial forward model of the gravity field (Figs 7a–f) returns a large rms misfit of 21.09 mGal which represents 56 per cent of the total dynamic range (37.5 mGal). The high rms misfit calculated for the reference model can be explained by the homogeneous nature of the density assigned to each lithological unit. Treating each unit as homogeneous does not reflect the true geological variability across each of the lithologies (e.g. Fig. 5d). The forward gravity response is characterized by relatively long-wavelength, high amplitude and positive gravity anomalies in the northwest coincident with the Neoproterozoic sequences (location 1 in Fig. 7b). Long-wavelength, high amplitude negative anomalies in the southeast coincide with the cover sequence (location 2 in Fig. 7b) while the British Empire Granite in the centre of the model (location 3...
in Fig. 7b) and Mesoproterozoic Moolawatana Suite (location 4 in Fig. 7b) in the northeast are characterized by high amplitude negative anomalies. In the south, low amplitude, slightly negative anomalies correspond to the response of the metasedimentary rocks of the Radium Creek Group (location 5 in Fig. 7b). Evaluation of this response (Fig. 7b) in relation to the observed (Fig. 7d) and residual (Fig. 7c) gravity would indicate that the densities assigned for the Neoproterozoic packages are too high (negative anomalies in the residual, location 1 in Fig. 7c). Similarly denser material to the southeast of the Mount Painter Inlier is required (positive anomalies...
Figure 7. All inversions of the gravity field were carried out on the residual gravity after separation from the regional gravity (Fig. 3c). For clarity, the word residual is only used to indicate the difference between the calculated field of one model and the observed data. The observed data (in reality the residual gravity) will be called ‘the gravity’. (a) 3-D distribution of the initial assigned density values for the reference model (Model 1); Note density values are relatives to 2.67 g cm\(^{-3}\) used for the gravity separation (b) the initial forward gravity response of Model 1 (locations 1–5, described in the text); (c) initial residual gravity of Model 1 (locations 1–4, described in the text); (d) the observed gravity (locations 1, described in the text); (e) calculated gravity after the sequentially combined heterogeneous constrained inversions of Model 1; (f) residual gravity after sequential combined heterogeneous constrained inversions of Model 1 (locations 1–3, described in the text); (g) initial 3-D distribution of magnetic susceptibilities for Model 1; (h) the initial forward magnetic response for Model 1 (locations 1–4, described in the text); (i) initial residual magnetic field of Model 1 (locations 1 and 2, described in the text); (j) the observed reduced-to-the-pole magnetic field; (k) calculated magnetic field after sequential combined heterogeneous constrained inversions of Model 1; (l) residual magnetic response after sequential combined heterogeneous constrained inversions of Model 1 (location 1, described in the text).
lies in the residual, location 2 in Fig. 7c). Importantly within the NE–SW trending Mount Painter Inlier, a greater proportion of both less dense material in the southwest (location 3 in Fig. 7c) and more dense material in the northeast (location 4 in Fig. 7c) would seem to be advocated in order to better reconcile the pronounced semicircular, high amplitude negative anomaly in the observed gravity (location 1 in Fig. 7d). This is at odds with the geological strike of the Inlier and would require either extensive density variations within lithological units along strike or additional geological bodies not observed in the field (e.g. Teale 1993; Armit et al. 2012).

5.2.2 Magnetics: Model 1

The forward calculation of the magnetic field response of the reference model (Fig. 7g) yields an rms misfit of 285 nT which corresponds to 6 per cent of the total dynamic range (4688 nT) and could be considered an acceptable level of misfit. The forward calculated magnetic intensity response (Fig. 7h) is characterized by a linear belt of high amplitude, positive anomalies trending NE–SW (location 1 in Fig. 7h) and is broadly reconcilable with the observed magnetic response of the region (Fig. 7i). Within this belt which is broadly coincident with the Mesoproterozoic Mount Painter Inlier, a series of interleaving linear high amplitude, negative anomalies become more pronounced towards the southeast and separate narrow linear positive anomalies (location 2 in Fig. 7h). The linear anomalies have steep NW and SE oriented gradients and are generally coincident with the pelitic, psammopelitic and amphibolite-rich Radium Creek Group units. An oval shaped slightly negative anomaly in the centre of the model is coincident with the British Empire Granite (location 3 in Fig. 7h). A distinctive high amplitude negative anomaly striking NE–SW is coincident with the Mount Neill Suite and the Paralana Fault that forms the interface between the Mesoproterozoic inlier and the cover sequence to the southeast (location 4 in Fig. 7h). The residual (Fig. 7i) of the forward magnetic model would suggest that this southeastern region requires higher magnetic susceptibilities at shallow level (location 1 in Fig. 7i). Negative anomalies in the residual magnetic response coincident with the northern margin of the Mount Painter Inlier (location 2 in Fig. 7i; Fig. 2d) might indicate a slight discrepancy between the relatively linear modelled geometry of this interface with the overlying Neoproterozoic sediments and a more cuspat geometry indicated in the geology (Fig. 2a).

5.3 Constrained inversions

5.3.1 Individual unit gravity inversions: Model 1

Optimisation of the density distribution within each lithology is achieved through constrained heterogeneous property inversions. The individual unit inversions mostly produced relatively small redistributions of the density properties around the median of the distributions (Appendix B) which remains equal to the initial assigned density value for each lithology. The rms misfit for each of the individual unit inversions remains high (~21.09 mGal or 56 per cent of the dynamic range of the inverted gravity) because most of the model was kept homogeneous. More significant redistributions were calculated for the Mesoproterozoic granitic Moolawatana and Mount Neill suites with an increase in the median and mean of the inverted density distributions. This result indicates that these units are more likely to be slightly denser than their assigned reference values. For example, the gravity inversion for the Mount Neill Suite only results in a reduction of the rms misfit (18.62 mGal or 50 per cent of the dynamic range of inverted gravity). Individual unit gravity inversions also predict slightly lower densities for the three uppermost units of the Neoproterozoic sequence and correspond to similar reductions in misfit (56 per cent to 51–49 per cent of the dynamic range of gravity).

5.3.2 Forward model of the combined inverted units model: Model 1

The forward gravity response of the combined inverted units for model 1 has a rms misfit of 11.22 mGal. This represents a dramatic drop in misfit from the initial 21.09 mGal or from 56 to 29.9 per cent of the gravity dynamic range (not shown in figures).

5.3.3 Sequential inversions of the combined Model 1

The sequential inversions of the combined Model 1 further optimize the density distributions (Fig. 8a) of each lithology producing a final rms of 7.33 or 19.5 per cent of the dynamic gravity range (Fig. 7e). This reduction in the misfit is principally produced with an increase in the densities for the Moolawatana and Mount Neill Suites from the initial assigned 0 kg m$^{-3}$ residual density (which equates to 2670 kg m$^{-3}$) to a median residual density of 55 kg m$^{-3}$ (2725 kg m$^{-3}$) for the new density distribution. Additional increases in the average densities were also calculated for the British Empire Granite and cover sequence as well as very slight increases for the psammite and pelitic units of the Radium Creek Group. Decreases in the average density were calculated for the upper 3 units of the Neoproterozoic sequence including the Uppermost Neoproterozoic unit which moved from an assigned initial residual density of 330 kg m$^{-3}$ (equates to 3000 kg m$^{-3}$) to a median residual density of 234 kg m$^{-3}$ (2904 kg m$^{-3}$).

Visually the gravity response of the sequentially inverted combined model (Fig. 7e) shows an increased fit with the observed gravity (Fig. 7d). However the residual gravity response (Fig. 7f) still indicates a pronounced negative anomaly in the south (location 1 in Fig. 7f) and positive anomalies in the northeast and southeast (location 2 and 3, respectively in Fig. 7f). Below the southern, negative gravity anomaly a volume of low density material is predicted through inversions. This volume runs across the trend of the modelled lithologies (location 1 in Fig. 8b) including the relatively low density ~2670 kg m$^{-3}$ Moolawatana Suite (Fig. 8b), and the Upper Neoproterozoic unit and the Radium Creek Group. This distinct across-trend volume of lower density material is difficult to reconcile with the existing reference lithological model.

5.3.4 Magnetics: Model 1

Magnetic susceptibility constrained heterogeneous property inversions are conducted for each individual lithology ($n = 15$). Each inversion allows for the optimisation and redistribution of the magnetic susceptibilities within each lithology from the initial assigned value (Appendix C). Individual inversions however do not significantly decrease the rms misfit of the model and represent less than 40 nT or 1 per cent of the dynamic range reduction in the rms misfit. The most varied redistribution of magnetic susceptibilities occurred within the Radium Creek Group. In particular both the quartzite, which exhibits a highly heterogeneous redistribution, and the pelitic unit, which shows a higher median magnetic susceptibility (shift from the assigned value of 0.05 SI to a median of 0.055 SI), produce the largest reduction in rms misfit (reduction by 265 and
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265 nT or 5.66 per cent and 5.63 per cent of the dynamic range, respectively. Inversion of the Mesoproterozoic granitic suites indicates that these units are fairly homogenous, and unlike the gravity response, do not contribute much to the overall magnetic response. The Neoproterozoic units did not vary during the individual inversions and therefore contribute little to the reduction of the misfit.

Sequential inversions of the combined model (Fig. 8c) produce an rms misfit of 141 nT (4 per cent) (Fig. 7k). Much of this misfit reduction can be attributed to re-assigned higher magnetic susceptibilities for the quartzite and pelitic units of the Radium Creek Group (Fig. 8d). In addition the small volume amphibolite bodies are re-assigned higher magnetic susceptibilities but do not contribute greatly to a reduction in rms misfit due to their limited dimension.

The calculated magnetic response is visually reconcilable with the observed magnetic field of the region (Fig. 7j) and is characterized by the highly magnetic corridor that corresponds to the Mount Painter Inlier. The residual magnetic response (Fig. 7l) indicates a less steep gradient to the southeast of the Inlier (location 1 in Fig. 7l) is required. Whilst small changes to the geometry of the magnetic corridor may further reduce the rms misfit, the required resolution of the individual lithologies with respect to the grid size of the magnetic data is restrictive and the current fit was deemed acceptable. We have tested this assumption by inverting the magnetic field with all of the modelled geometries and the results are briefly presented in the following sections. The inversions showed that the magnetic field is consistent with all proposed geometries and is not diagnostic of a particular model.

5.3.5 Gravity inversions: Model 2

In order to better reconcile the observed gravity of the region a new model is developed (Fig. 9a). Model 2 incorporates the same 15 lithological units and identical density values and ranges as the initial (Model 1) reference model (Fig. 4b and Appendix B). However two additional volumetrically significant units have been added into the model (Fig. 9b) in order to better resolve the large negative anomaly in the south of the model region and the positive anomaly in the northeast. The added units are attributed to the early Palaeozoic intrusion event that produced the British Empire Granite. The bodies are modelled in the subsurface and do not have a surface expression in line with the absence of such units in the outcropping geology as determined by field mapping (e.g. Teale 1993; Armit et al. 2012). Included in these additional bodies is a low density felsic body (location 1 in Fig. 9b) which is assigned an initial density of 2500 kg m$^{-3}$ and has total volume within the model space of $2.2 \times 10^{12}$ m$^{3}$ which represents 10 per cent of the total model volume. The other, volumetrically less significant additional unit is modelled as a denser mafic body (location 2 in Fig. 9b) which is assigned an initial density of 2840 kg m$^{-3}$ with a total volume of $8.9 \times 10^{11}$ m$^{3}$. The location of both intrusives was chosen to reflect the location of residual anomalies remaining after inverting Model 1. Similar depths were chosen to reduce a potential depth bias.

An initial calculated forward model of Model 2 (Fig. 9c) produces a rms misfit of 10.81 mGal which represents 29 per cent of the gravity dynamic range (Fig. 9d). This forward model has a large circular negative anomaly in the central part of the model (location 1

Figure 8. (a) 3-D model of the density distribution following sequential combined heterogeneous constrained inversions for the reference model (Model 1); (b) A distinctive region of low density material cross-cuts the modelled strike of the Moolawatana Suite (Model 1). This low density region is characterized by the light to dark blue colours which indicate residual density values of 0 to −0.1 g cm$^{-3}$ which reflect densities of 2570–2670 kg m$^{-3}$ (location 1, described in the text); (c) 3-D model of the magnetic susceptibility distribution following sequential combined heterogeneous constrained inversions for the reference model (Model 1); (d) inverted 3-D magnetic susceptibility distributions for Model 1, sliced to show a distinctive NE–SW striking belt of highly magnetic material corresponding to the location of the crystalline Radium Creek Group. Intralithological heterogeneity corresponding to rafts and pockets of more micaceous and magnetite rich material within the quartzite are also expressed in the model.
Figure 9. (a) Lithological 3-D model (Model 2) of the Mount Painter Province including additional felsic and mafic intrusive units; (b) 3-D model showing the position of the additional felsic (red) and mafic (green) intrusives included in the refined density model (Model 2) of the Mount Painter Province (locations 1 and 2, described in the text); (c) initial assigned density distributions for Model 2; (d) forward gravity model of Model 2 (locations 1–4, described in the text); (e) residual gravity of Model 2 (locations 1–4, described in the text); (f) observed gravity (regional contribution removed).

in Fig. 9d) coincident with the location of the British Empire Granite and on the southeastern corner coincident with the cover sequences (location 2 in Fig. 9d). Positive gravity anomalies are situated to the north and west of the model and are coincident with the upper part of the Neoproterozoic sequences (locations 3 and 4 in Fig. 9d). The residual gravity response of Model 2 (Fig. 9e) indicates that lower densities are required in the southcentral region (location 1 in Fig. 9e) to better fit the observed gravity of the region (Fig. 9f). The residual gravity would also seem to support lower densities coincident with the upper Neoproterozoic sequences (location 2 and 3 in Fig. 9e) than those initially modelled and higher density material in the southeast (location 4 in Fig. 9e) in the vicinity of the modelled low density cover sequence.

Density constrained heterogeneous property inversions of each of the now 17 individual lithological units in Model 2 produce relatively small reductions in the rms misfit with the largest decrease $\sim 1$–1.5 mGal ($2$–$2.5$ per cent of the gravity dynamic range) corresponding to optimisation of the densities within the quartzite, upper Neoproterozoic units, the cover sequence and the Mesoproterozoic granite suites. The property optimisation in the upper Neoproterozoic units reduces the average densities from the residual assigned values of $0.33$ ($3000$ kg m$^{-3}$) to $0.23$ reflecting average densities of $\sim 2900$ kg m$^{-3}$. Redistribution within the cover sequence is defined by a higher average density of $2500$ kg m$^{-3}$.

A forward model of Model 2 combining the individually inverted units has a rms of $5.54$ mGal or $14.8$ per cent of the gravity dynamic range, accounting for nearly half of the total rms misfit of the initial revised model. Re-inversion of these 17 units in a sequentially combined order is undertaken (Fig. 10). The order in which the units are inverted can be found in Appendix B with the felsic body of interest inverted first to let its volume account for most of the final misfit reduction. The inversions result in a dramatic reduction of the rms misfit to $3.23$ mGal or $8.6$ per cent of the gravity dynamic range and this is shown in the gravity signal (Fig. 10a). Visually the forward gravity response of the inverted Model 2 (Fig. 10b) is more similar to the observed gravity (Fig. 10d) than the response of the
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5.4 Gravity inversions: Model 3

Model 3 is developed in order to better account for some of the local residual gravity anomalies described in the residual field of the inverted refined model (Model 2). In this new model the cover sequence is subdivided vertically assigning a higher density of 2800 kg m\(^{-3}\) to a lower layer and a less dense 2510 kg m\(^{-3}\) upper layer (Figs 11a–d) corresponding to a unconsolidated cover sequence. The lower denser layer may correspond to volcanics of the Benagerie Volcanics Suite (Wade et al. 2012). The British Empire Granite is also extended both in the southwest and in the east as a shallow, sheet-like body. Incorporating these changes sequentially (order in Appendix B) to the existing refined and inverted density model reduced the overall rms misfit to 1.69 mGal or 4.5 per cent of the gravity dynamic range. The final 3-D distribution of density (Fig. 11c) is consistent with the density range constraints; the calculated density distributions do not cluster at the minimum or maximum values allowed.

Visually the forward response of Model 3 is reconcilable with the observed gravity field (Figs 11e–g). The forward gravity model for Model 3 (Fig. 11e) shows a very distinctive negative anomaly and is geometrically similar, spatially coincident with, and has a comparable amplitude to the large negative anomaly in the observed gravity (Fig. 11g). On the basis of these visual similarity and reduced rms, we accept this model as our ‘better fitting model’ with respect to gravity.

5.5 Magnetic inversions: Model 3

The magnetic inversion process for Model 3 returned a rms mis-fit of 107 nT (3.02 per cent of the magnetic dynamic range) which indicates that Model 3 is as geophysically consistent as Model 1. Fig. 12(a) shows the resulting magnetic susceptibility distribution while Figs 12(b) and (c) presents the calculated and residual magnetic field. Visually, the residual shows the consistency of the model with the observed magnetic field (Fig. 12d). The mafic intrusives have a very little contribution to the calculated magnetic field and this is possibly due to their depth of emplacement. The addition of shallow level felsic intrusives although reducing the volume of the magnetic Radium Creek Group has an influence on the inverted magnetic susceptibility distribution but not on the final misfit of the model. Most of the contribution of Radium Creek Group lithologies comes from a shallow level, above the depth of emplacement of the major body of felsic intrusives.

5.6 Alternative geological scenarios

In order to test the sensitivity of the geometries and lithological distributions represented in Model 3, a suite of alternative geological scenarios are also modelled (Figs 13 and 14). The major alternatives modelled include changing the position of the large felsic intrusive body (modelled closer to the surface), by changing the geometrical characteristics of intrusions and testing a scenario where a thrust-ramp developed at the base of the model with the Mesoproterozoic
5.6.1 Higher level intrusives: Model 4

In this scenario a similar evolution to that of Model 3 is utilized and incorporates the large felsic and mafic bodies (Fig. 13a). However, the felsic unit is modelled higher in the model, within 2 km of the surface and some 4 km higher than the same body in Model 3 (location 1 in Fig. 13a). The amount of offset on NW–SE trending Palaeozoic faults (e.g. the Hamilton and Jubilee faults, location 2 in Fig. 13a) is also reduced in this model (Model 4) to determine if the gravity or magnetic response of the region is sensitive to these geometries.

5.6.1.1 Gravity inversions: Model 4

The same densities are assigned to each of the lithologies as in Model 3 (Fig. 4b and 4c at Macquarie University on March 16, 2015 http://gji.oxfordjournals.org/ Downloaded from

Mount Inlier thrusting over Neoproterozoic sediments. These variations correspond to the proposed structural models at the larger scale (Korsch et al. 2010; Elburg et al. 2013; Weisheit et al. 2013a,b).
Appendix B) with the felsic unit incorporated with the British Empire Granite. An initial forward model of the gravity response of this model (Model 4) has a rms misfit of 8.61 mGal or 23 per cent of the dynamic range. Gravity constrained inversion for each of the 17 lithologies reduced the rms misfit to 4.35 mGal or 12 per cent of the gravity dynamic range by optimising the density distributions within each lithology. Further sequential inversions of a combined Model 4, incorporating the individual unit inversions (Fig. 13b) reduces the misfit to 1.73 mGal or 5 per cent of the dynamic range. The forward response of the sequentially combined inversions for Model 4 (Fig. 13c) is visually similar to the observed gravity (Fig. 13e), a smaller negative anomaly to the east and relatively more dense material elsewhere characterized by positive anomalies (location 2 in Fig. 13c). The residual of this forward model (Fig. 13d) is characterized by a relatively flat response and indicates that the gravity signal has been predominantly accounted for by the modelled geology and the calculated density distributions.

The 3-D distribution of density in Model 4 after the combined inversions (Fig. 13b) is predominantly characterized by highly heterogeneous density values within each lithological unit consistent with even redistribution within the assigned range of densities (Appendix B). In this model however a belt of more homogeneous, higher density material is evident trending E–W (location 1 on Fig. 13b) across the southern part of the model and across the strike of the quartzite unit. This may perhaps indicate that the large felsic unit is modelled too close to the surface. In this scenario the VPmg inversion of the overlying quartzite unit has compensated by increasing the densities within a region of this quartzite immediately above the intrusive body.

The lower misfit of this ‘higher level intrusive’ model (Model 4) with respect to the reference model (Model 1) further stresses the importance of the added felsic material common to this model and Model 3. The calculated gravity response is less sensitive to the position of the large felsic body for this and the final model.

5.6.1.2 Magnetics: Model 4

The rms misfit of the magnetic inversions of Model 4 has a rms misfit of 99 nT (2.81 per cent of the magnetic field dynamic range) which indicates that the geometries modelled in Model 4 are also consistent with the magnetic field. Once again, this indicates that the magnetic inversions are not useful in distinguishing between the tested geometries. Fig. 13(f) shows the resulting magnetic susceptibility distributions and Figs 13(g) and (h) shows the calculated and residual fields of the inverted model in comparison to the observed magnetic (Fig. 13i).

5.6.2 Thrust-ramp model: Model 5

This model is developed utilising a Neoproterozoic thrust ramp at the base of the model rather than the intrusive bodies incorporated in Models 2–4. Within this geological framework the older Mesoproterozoic basement and unconformably overlying Neoproterozoic sequences were thrust over a block of Neoproterozoic rocks. Subsequent deformation produced a doubly-plunging NE–SW trending antiformal thrust ramp (Fig. 14a). This scenario provided
Figure 13. (a) 3-D model of lithological units including a felsic intrusive unit of Model 4 (see Fig. 11a for lithology legend), which is of similar volume but intrudes closer \( \sim 2 \text{ km} \) of the surface and \( \sim 4 \text{ km} \) higher than in Model 3 (location 1 and 2, described in the text); (b) 3-D model of the heterogeneous density distributions after sequential combined inversions of 17 distinct lithological units of Model 4. Distinct regions of higher density material and lower density material cross cut the quartzite unit (location 1, described in the text); (c) calculated gravity after sequential combined inversions of Model 4 (location 1 and 2, described in the text); (d) residual gravity after sequential combined inversions of Model 4; (e) observed gravity; (f) 3-D magnetic susceptibility distribution after inversions of Model 4; (g) calculated magnetic field after inversions of Model 4; (h) residual magnetic field after inversions of Model 4 and (i) observed magnetic field.

5.6.2.1 Gravity inversion: Model 5 We assign very similar densities to the units in Model 5 as for Models 1–4 (Appendix B). However unlike the intrusive based models (Models 3 and 4), the Neoproterozoic ramp is assigned a higher residual density equivalent to 2800 kg m\(^{-3}\), chosen to match the density value for the lower Neoproterozoic unit used in Models 1–4. Initial forward models for Model 5 produced a high rms misfit of 12.23 mGal or 33 per cent of the dynamic range. The identical method of individual unit inversion followed by sequential inversions of the resulting combined model is applied to Model 5 (values in Fig. 4b and Appendix B). The forward model of the resulting 3-D redistributed density model (Fig. 14b) of Model 5 indicates a reduction in the overall rms misfit to 2.92 mGal or 8 per cent of the gravity dynamic range. Visually the forward response of the inverted Model 5 (Fig. 14c) is characterized by 2, more elongate NE–SW trending negative anomalies central to the model (location 1 and 2 on Fig. 14c) and distinct from the more circular negative anomaly in the observed gravity (Fig. 14e). This mismatch is also evident in the residual gravity with a negative anomaly in the central region (location 1 on Fig. 14d) and positive anomalies to the northeast still unreconciled (location 2 on Fig. 14d).

5.6.2.2 Magnetics: Model 5 Fig. 14 presents the magnetic susceptibility distribution (Fig. 14f) and the calculated and residual magnetic fields after inversion (Figs 14g and h) in comparison to the observed magnetic field (Fig. 14i). The rms misfit is 98 nt (2.76 per cent of the magnetic field dynamic range) which is comparable to the rms misfits obtained for Models 1, 3 and 4 supporting the idea that all models are consistent with the magnetic field and that only the gravity inversions can be used to assess the validity of the proposed refined geometries.
6 INTERPRETATIONS

6.1 Magnetic inversions

The results of the magnetic inversions of all geological models are interpreted to validate the geological structures proposed. In other words, the magnetic inversions do not invalidate the framework that honours the structural evolution outlined in Armit et al. (2012) and do not better support any of the other tested geometrical hypotheses. Obviously, this does not mean that Model 1 is the best model, but it indicates that the magnetic field is not diagnostic for geometry in this case.

However, all models exhibit a belt of highly magnetic material coincident with the NE–SW strike of the Radium Creek Group within the Mount Painter Inlier. This belt is interpreted as a major contributor with respect to the total magnetic signal. The occurrence of relatively short-wavelength positive anomalies in the residual of the forward responses of the inverted magnetic models is interpreted to be the response of local variations in lithology which may not be resolvable within the coarser geological framework of the reference models. Pervasive hydrothermal alteration interpreted in the Mount Painter Inlier (e.g. Elburg et al. 2013; Weisheit et al. 2013a,b) could also be contributing to local variations in the concentrations and distribution of magnetite in the region (Fig. 5a) and possibly remanent magnetisation.

6.2 Gravity inversions

Results of the gravity constrained stochastic property inversions of the reference model (Model 1) are indicating a relatively poor fit with the observed gravity response of the region. Developing
the gravity response is overwhelmed by the response of the low density felsic intrusives. (d) 1st vertical derivative (1VD) of the gravity. The 1VD process enhances the NE-SW trends. These images indicate that the gravity response is overwhelmed by the response of the low density felsic intrusives.

Figure 15. (a) 3-D model of the density distribution following inversions of Model 3 (preferred model) assigning the British Empire Granite a residual density of 0.0493 g cm$^{-3}$ (equivalent to a density of 2.7193 g cm$^{-3}$). This density value reflects the median density value for the model volume; (b) calculated gravity, note the NE–SW trends visible away from the felsic intrusion which is still marked by a gravity low (effects of the felsic intrusives is not entirely removed); (c) 1st vertical derivative (1VD) of the gravity. The 1VD process enhances the NE-SW trends. These images indicate that the gravity response is overwhelmed by the response of the low density felsic intrusives.

on this initial model by introducing a large volume ($\sim$10$^{12}$ m$^3$ or $\sim$10 per cent) of lower density material in the south of the model volume (e.g. Models 2–4) produces a better fit to the observed gravity response. The model is further improved by the addition of relatively more dense material in the northeast of the model space ($10^{11}$ m$^3$). The additions have a considerable effect on reducing the misfit between observed and modelled gravity. For Model 3, the rms has been more than halved. As there is little evidence of these additional bodies in the outcrop geology of the Mount Painter Province (e.g. Teale 1993; Armit et al. 2012) the bodies are modelled in the subsurface but may be spatially related to the outcropping British Empire Granite. The location of the major lithological additions, in order to best explain the observed gravity response, indicates that they impinge on a number of the initially modelled lithologies rather than being consistently within one particular unit. This might indicate a distinct evolution to that of the folded Meso-Neoproterozoic sedimentary successions and Mesoproterozoic granitic suites that they encroach upon.

Three geologically feasible scenarios are available that explain the suggested model modifications: (1) the bodies represent basement highs; (2) the bodies represent units intruding into the overlying sedimentary and A-type granite suites and (3) the bodies form part of a folded thrust ramp onto which the Mesoproterozoic Mount Painter Inlier has been thrust. We interpret the result of modelling of these different geological scenarios to suggest that the best fit to the observed gravity is produced with intrusive bodies in the model. Primarily, this interpretation is supported by the relative sensitivity of the model to the range of densities assigned to the additional intrusive bodies. The best fit is obtained with relatively low density $\sim$2500–2600 kg m$^{-3}$ for the southern felsic body and relatively high density for the northeastern mafic body $\sim$2800 kg m$^{-3}$ (location 1 and 2, respectively in Figs 11c and d and Appendix B). Such low densities for the southern body are hard to reconcile with any of the inverted or measured densities (e.g. Backé et al. 2010) and may correspond to a leucogranite. Additionally the circular nature of the large negative anomaly in the observed gravity is more easily explained by a source body with a similar geometry to the anomaly, which is often a characteristic of intrusive bodies (Roy et al. 2010; Singh et al. 2014). This is evident in the forward response of the folded thrust ramp model (Model 5; Fig. 14c) which shows a more linear, elongated gravity response. The felsic intrusive models (Models 3–4) produce a distinctly similar geometry (Figs 11e and c) to the negative anomaly in the observed data (Figs 9g and 10e).

We also interpret a number of other smaller bodies within the model in order to best reconcile the observed gravity response. A relatively thin layer of more dense material under the cover sequence to the southeast of the Mount Painter Inlier is interpreted as the mafic volcanics of the Benagerie Volcanic Suite (Model 3; Fig. 11a). Small pockets of less dense material are also modelled in the eastcentral portion of the model which we interpret to be spatially related to the British Empire Granite in the near subsurface. Indeed there appears to be a strong spatial correlation between all of the additional lower density material required during modelling, with that of the outcropping Ordovician to Silurian British Empire Granite (Elburg et al. 2003, 2013; McLaren et al. 2006).

Finally, as previously described, the residual gravity is dominated by a circular deep low anomaly (Fig. 15) which is counterintuitive as it was expected to reflect the trends of the mapped Mesoproterozoic geology and structures in a NE–SW orientation. We checked the validity of the residual-regional separation by artificially removing the effects of the felsic intrusives from our preferred model (Model 3). The felsic intrusives, including the British Empire Granite, are assigned the median density within the entire inverted model (Model 3). The median residual density for these rocks is estimated at 493 kg m$^{-3}$ or an equivalent density of 2719 kg m$^{-3}$ (Fig. 15a) which is consistent with a density assigned to metasediments of felsic or basic origin. The resulting forward gravity field (Fig. 15b) still exhibits a low over the modelled felsic intrusives ($\sim$12 mGals) however the anomaly exhibits NW–SE trends. These trends are highlighted especially in the 1VD of the forward residual gravity field (Fig. 15c). The remaining circular character is probably related to the homogeneous nature of the modelled intrusives. The remaining low gravity feature supports our modelling and the
requirement for a large volume of lighter material (interpreted as felsic intrusions).

6.3 Geodynamic implications

The large volume felsic intrusive material modelled in the subsurface of the Mount Painter Province with a spatial association to the British Empire Granite (Fig. 10) leads us to suggest that Ordovician magmatism in the Mount Painter Province may be far more voluminous than has been previously estimated. In particular the large gravity low to the south of the model area (Fig. 2b) could represent the signature of an even larger felsic intrusive. This anomaly has a long wavelength and cannot be explained by shallow features only. However the lack of field constraints to build a sensible geological reference model precluded the extension of the model area to the south.

Whilst we cannot preclude a Mesoproterozoic age for this intrusive body, the spatial association and increased magmatic activity in the Ordovician to Silurian period which included felsic dykes in the Radium Hill area (Jagodzinski et al. 2006); high-temperature veins; met- and per-aluminous granitoids; leucogranite and pegmatite intrusion coupled with the emplacement of the British Empire Granite ca. 460–440 Ma (Elburg et al. 2003, 2013; McLaren et al. 2006), argue for a strong connection. We would interpret the exposed portion of the British Empire Granite in the centre of the Mount Painter Inlier to represent the nose of larger tilted laccolith.

If these volumetrically significant additional bodies do indeed belong to an Ordovician–Silurian phase of magmatism it is likely that these intrusions could have either; been the product of an increased local geotherm, related to the burial of high heat producing elements (McLaren et al. 2002); or contribute to the overall Palaeozoic heat budget of the region. This increased magmatic volume and resultant increased heat budget may be responsible for the increased, amphibolite grade, Palaeozoic metamorphism recorded in the Mount Painter Province (McLaren et al. 2006) and may have in turn provided a driver for the pervasive Palaeozoic hydrothermal activity throughout the region (e.g. Elburg et al. 2003; Weisheit et al. 2013a,b).

7 Conclusions

Potential-field inversion modelling of the Mount Painter Province provides insight into the subsurface geology of the region. Whilst the dominant magnetic contribution of NE–SW trending Radium Creek Group is well reconciled with the magnetic modelling, the gravity response of the region is not consistent with the initial geological framework. The addition of large volumes (≈10 per cent of the modelled volume) of intrusive units in the subsurface is strongly argued for and subsequently used to develop better fitting models (Models 2–4) with respect to the observed gravity.

The spatial and temporal correlation of these volumetrically significant additional intrusive bodies with the ca. 460–440 Ma British Empire Granite is appealing and could have produced a greater heat budget during the early Palaeozoic within the Mount Painter Province. This increased heat budget may have provided a mechanism for the pervasive Palaeozoic hydrothermal activity throughout the Inlier (e.g. Elburg et al. 2013; Weisheit et al. 2013a,b). It could also perhaps have played some role in the increased local geotherm in the early Palaeozoic that led to metamorphic grades in the region reaching amphibolite grade in the Mount Painter Province (McLaren et al. 2006) whilst elsewhere in the Flinders Ranges the grade rarely exceeded greenschist facies.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix A: Parameters used to define reference model in Noddy software.
Appendix B: Detailed gravity inversion modelling constraints and rms misfits.

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