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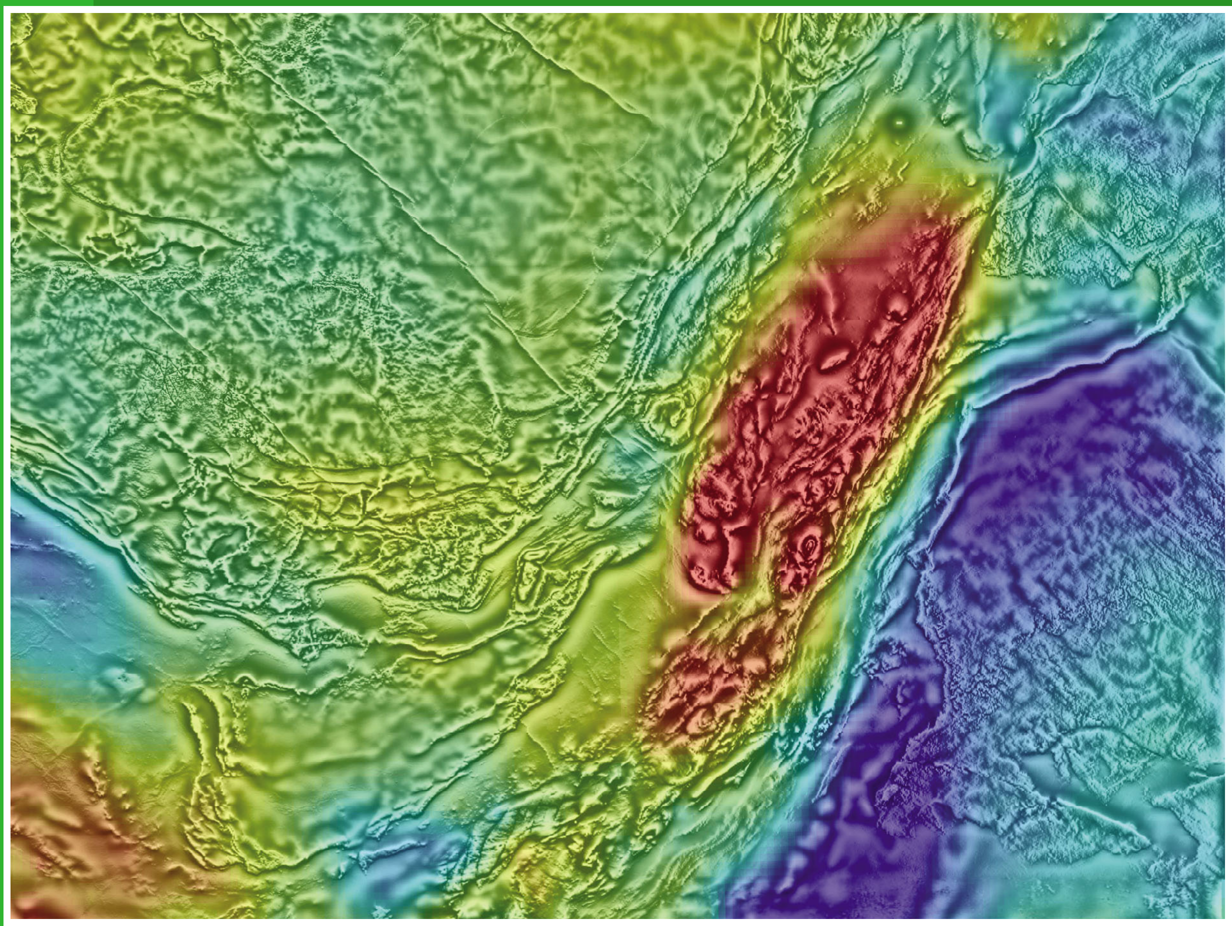

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**MD Lindsay[1], SA Occhipinti[1], JA Hollis[2], AR Aitken[1], V Metelka, MC Dentith[1], JM Miller[1], and IM Tyler**

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**Cover photograph:** Composite geophysical image of the east Kimberley region, showing the southern Halls Creek Orogen (red, yellow and light blue) and the Speewah and Kimberley Basins (yellow–green); it was generated by draping a greyscale magnetic image over colour-mapped Bouguer gravity data.

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# A geophysical investigation of the east Kimberley region, northern Western Australia

by

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## Abstract

The geology of the east Kimberley region was investigated through an integrated geophysical and geological approach. Emphasis was placed on identifying geological structures and features that may be important for assessing the mineral potential of the region. Subsurface architecture was constrained through combined gravity and magnetic modelling along three transects. Significant crustal-scale structures were interpreted and investigated to determine their potential influence on the development of the regional architecture, the emplacement of magma, and the circulation of hydrothermal fluids within the Halls Creek Orogen. Newly interpreted features include three orogen-normal structures, and another regional structure that runs obliquely across the Halls Creek Orogen from beneath the Speewah Dome. The geophysical interpretation delineated a zone of high-grade metamorphic rock that is bounded by two of the orogen-normal structures. A major positive gravity anomaly has been modelled as a source of excess mass in the mid-crust; this is compatible with a large mafic–ultramafic intrusion, or a crustal fragment. We propose a model involving the accretion of this crustal fragment to the Kimberley Craton prior to the 1865–1850 Ma Hooper Orogeny. Accretion of the crustal fragment led to the propagation and creation of the orogen-normal and oblique structures. The structures represent weak zones in the crust, which may have led to differential exhumation of crust during the 1835–1810 Ma Halls Creek Orogeny, and formed fluid conduits in a mineral system.

**KEYWORDS**: crustal structure, geophysical interpretation, hydrothermal deposits, mineralization, structural evolution

## Introduction

The east Kimberley region in northern Western Australia (Fig. 1) is recognized to have significant potential for mineral deposits (Sanders, 1999; Occhipinti et al., 2016). Diamonds at Argyle, Cu–Pb–Zn at Koongie Park, Au at Palm Springs and Ni–Cu–PGE at Savannah and Panton have guided recent exploration in the vicinity of these locations. Rare earth element mineralization at Cummins Range and John Galt, and graphite at McIntosh, have recently re-ignited interest in the region; however, the east Kimberley region remains comparatively underexplored. This Report addresses gaps in knowledge regarding the regional scale structural controls on mineralization in the Kimberley region. This study was undertaken by the Centre for Exploration Targeting (www.cet.uwa.edu.au) at The University of Western Australia, and funded through the Western Australian Government's Exploration Incentive Scheme (EIS).

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The crustal architecture of the region was interpreted using magnetic and gravity data, in combination with petrophysical and geological data. The primary goal was to find links between the regional geology and mineralization. Critical to the success of this analysis is the identification of deep crustal-scale features and regions that might host economic commodities. The results are discussed in the context of mineralization, to reveal new insights into prospective geological features within the east Kimberley. The outcomes of this study were used in a companion mineral systems analysis performed by Occhipinti et al. (2016).

## Regional tectonic setting

The 550 by 200 km study area in the east Kimberley region of northern Western Australia strikes north-northeasterly (Fig. 1). It includes the eastern part of the Kimberley and Speewah Basins, and Lamboo Province. The geological evolution of the east Kimberley region spans more than two billion years of Earth history along a craton margin affected by periods of accretion, convergence and rifting (Tyler and Griffin, 1990; Sheppard et al., 1999; Griffin et al., 2000; Tyler et al., 2012; Hollis et al., 2014). The east Kimberley region comprises the deformed eastern margins of the Kimberley and Speewah Basins in the west, with the Lamboo Province in the centre (Fig. 1a,b), and the Southern Bonaparte and Ord Basins to the east. The Halls Creek Orogen forms the eastern part of the Lamboo Province which is inferred to be a series of northeasterly trending Archean and Paleoproterozoic terranes (Gunn and Meixner, 1998; Hollis et al., 2014), This region is underlain largely by the Kimberley Craton, with the North Australian Craton to the south and east (Fig. 1a). Fast S-wave velocities are observed down to about 250 km, consistent with the presence of a thick and cold lithospheric root beneath the Kimberley Craton (Fishwick et al., 2005). These characteristics extend under the Kimberley and Speewah Basins and the Lamboo Province, suggesting that the predominantly Archean craton extends to the south beneath the Lamboo Province; the latter wraps around the southern Kimberley margin (Fig. 1b).

The 1910–1805 Ma Lamboo Province is exposed as northeasterly and northwesterly trending belts of basement rocks that bound the margins of the younger sedimentary rocks of the Speewah and Kimberley Groups. The Lamboo Province has been divided into Western, Central and Eastern Zones by Tyler et al. (1995) based on differing tectono-stratigraphic characteristics (Figs 2 and 3). The Central, Western and Eastern Zones contain distinct geological units, formed during the early to middle Palaeoproterozoic, that may have originated in different tectonic settings. If so, this suggests that these zones were not juxtaposed before the end of the 1870–1850 Ma Hooper Orogeny (Tyler and Griffin, 1992; Griffin et al., 1993; Page and Hoatson, 2000; Griffin et al., 2000; Page et al., 2001). Subsequently, the Lamboo Province and the margins of the Speewah and Kimberley Basins were deformed and metamorphosed during the 1835–1810 Ma Halls Creek Orogeny (Tyler et al., 1995; Blake et al., 2000b; Bodorkos et al., 2000; Page et al., 2001; Sheppard et al., 2001), the early Neoproterozoic Yampi Orogeny

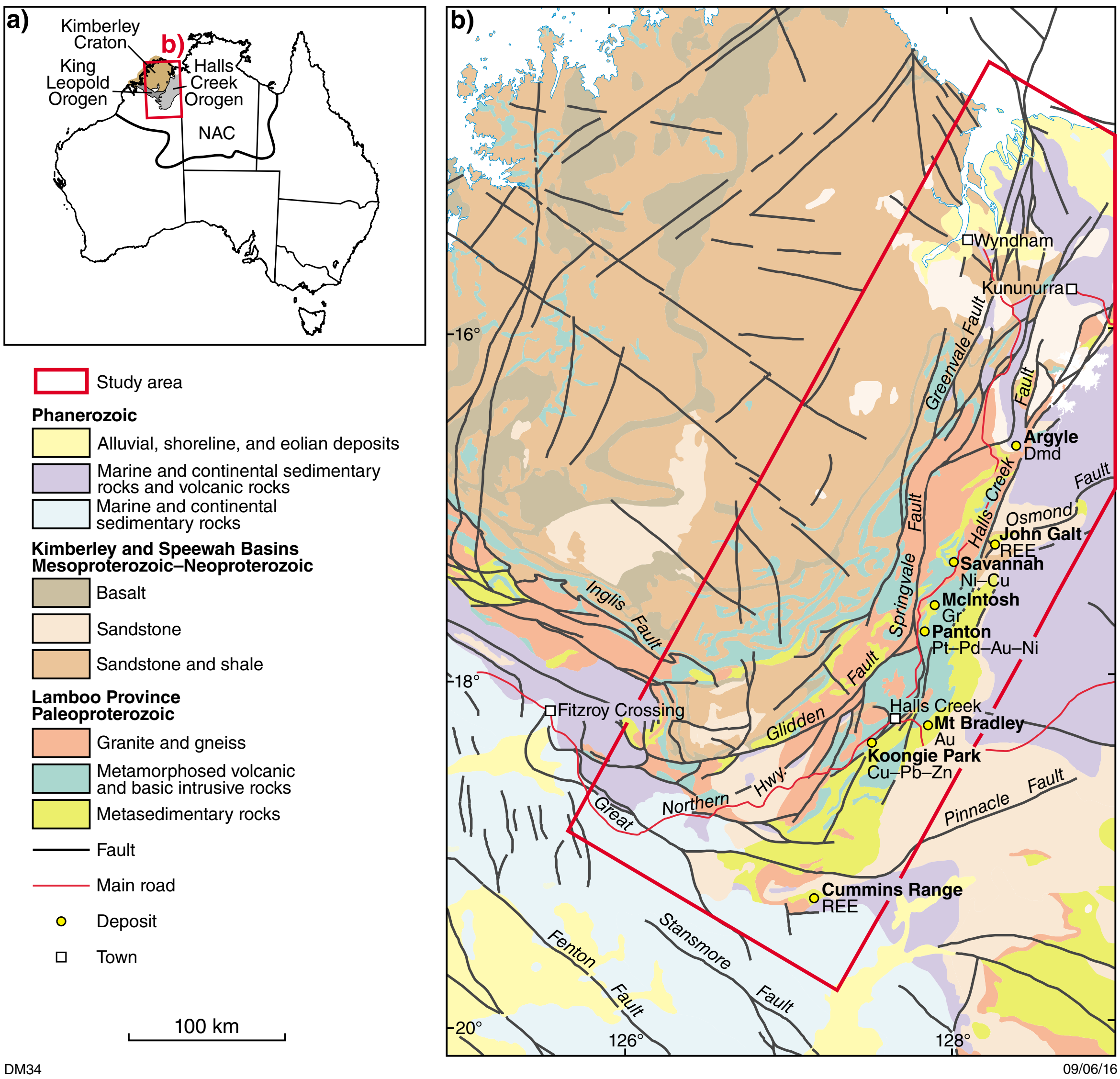



**Figure 1.** **a) Map of the east Kimberley region showing: a) tectonic units in northern Australia (NAC = North Australian Craton); b) major tectono-stratigraphic units of the Lamboo Province (Tyler et al., 2005)**

(Tyler and Griffin, 1990; Shaw et al., 1992; Griffin et al., 1993; Bodorkos and Reddy, 2004), the late Neoproterozoic King Leopold Orogeny (Tyler and Griffin, 1990; Shaw et al., 1992; Griffin et al., 1993; Tyler and Griffin, 1993) and the 450–295 Ma Alice Springs Orogeny.

## 1870–1850 Ma Hooper Orogeny

Griffin et al. (2000) postulated that an exotic crustal fragment was accreted to the Kimberley Craton before 1900 Ma via northwesterly directed subduction (Fig. 4a). Accretion resulted in the intrusion and extrusion of felsic to mafic rocks that form the Western Zone of the Lamboo Province (Paperbark Supersuite, Whitewater Volcanics, Ruins Dolerite). The Western Zone also comprises turbiditic sedimentary rocks of the c. 1872 Ma Marboo Formation, deposited during post-collisional rifting (Tyler et al., 1999; Fig. 4b). The Marboo Formation underwent low- to high-grade metamorphism during the Hooper Orogeny, prior to being overlain by felsic volcanic and volcaniclastic rocks of the c. 1855 Ma Whitewater Volcanics. The Whitewater Volcanics, part of the Paperbark Supersuite, may have formed as a result of localized rifting towards the end of the Hooper Orogeny. The geochemical composition of the 1865–1850 Ma Paperbark Supersuite suggests that it formed in a post-collisional setting (Griffin et al., 2000).

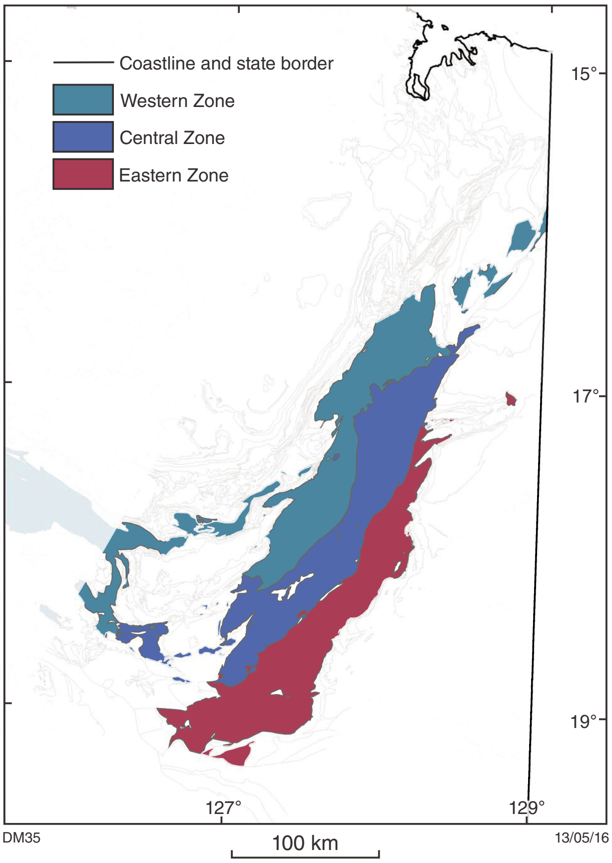



**Figure 2.** **Map showing the tectono-stratigraphic terranes (Tyler et al., 1995) within the Lamboo Province of the Halls Creek Orogen in the east Kimberley region**

Emplacement of layered mafic–ultramafic intrusive rocks in the Western Zone took place between 1859 and 1853 Ma and may be contemporaneous with the intrusion of the Paperbark Supersuite, as indicated by net-veining, back-veining and other magma-mingling textures at the contact with the c. 1855 Ma Corridor Gabbro (Blake et al., 2000a). Layered mafic intrusions of the c. 1857 Ma Springvale and c. 1855 Ma Toby intrusions were emplaced at depths of 8–18 km, within the Paperbark Supersuite and Marboo Formation (Page and Hoatson, 2000; Trudu and Hoatson, 2000) (Fig. 4c).

Easterly directed subduction led to the development of an oceanic arc at c. 1865 Ma, outboard of the Kimberley Craton; this initiated the formation of the Central Zone (Sheppard et al., 2001; Fig. 4b). The oceanic arc included the sedimentary rocks, mafic volcanic and volcaniclastic rocks of the Tickalara Metamorphics, and the tonalite, trondhjemite and quartz diorite sheets of the Dougalls Suite (Sheppard et al., 2001). The Tickalara Metamorphics and Dougalls Suite were deformed and metamorphosed to amphibolite and granulite facies at 1865–1856 Ma and 1850–1845 Ma (respectively), during the Hooper Orogeny (Bodorkos et al., 1999; Blake et al., 2000a; Page et al., 2001; Bodorkos and Reddy, 2004). The c. 1856 Ma mafic–ultramafic Panton Intrusion was emplaced into the Tickalara Metamorphics at 11 km depth (Trudu and Hoatson, 2000; Fig. 4c).

Eastern Zone rocks are associated with a passive continental margin linked to the North Australian Craton (Tyler et al., 2012). The oldest rocks are the felsic and mafic volcanic rocks, and granites of the c. 1910 Ma Ding Dong Downs Volcanics and Sophie Downs Suite. These are unconformably overlain by the 1880–1847 Ma siliciclastic sedimentary and volcanic rocks of the Halls Creek Group (Tyler et al., 1998a; Phillips et al., in prep.). The basal part of the Halls Creek Group is the siliciclastic Saunders Creek Formation, which is overlain by c. 1880 Ma mafic volcanic rocks of the Biscay Formation. The superposition of turbiditic rocks of the c. 1850 Ma Olympio Formation over the Biscay Formation records a transition from a passive to an active margin (Blake et al., 1999; Blake et al., 2000a; Tyler et al., 2012). Intrusion of the Woodward Dolerite into the Halls Creek Group after c. 1850 Ma may indicate a period of relaxation and local extension (Blake et al., 1997).

## Relaxation and plate reorganization between the Hooper and Halls Creek Orogenies

Cessation of the Hooper Orogeny resulted in rifting of the Tickalara Metamorphics during a period of plate reorganization between 1845 Ma and 1835 Ma (Tyler et al., 2012), prior to the Halls Creek Orogeny. The 1845–1840 Ma Koongie Park Formation formed in the Central Zone of the Lamboo Complex and consists of sedimentary, mafic and felsic volcanic rocks (Blake et al., 2000b; Tyler et al., 2012). Layered ultramafic–

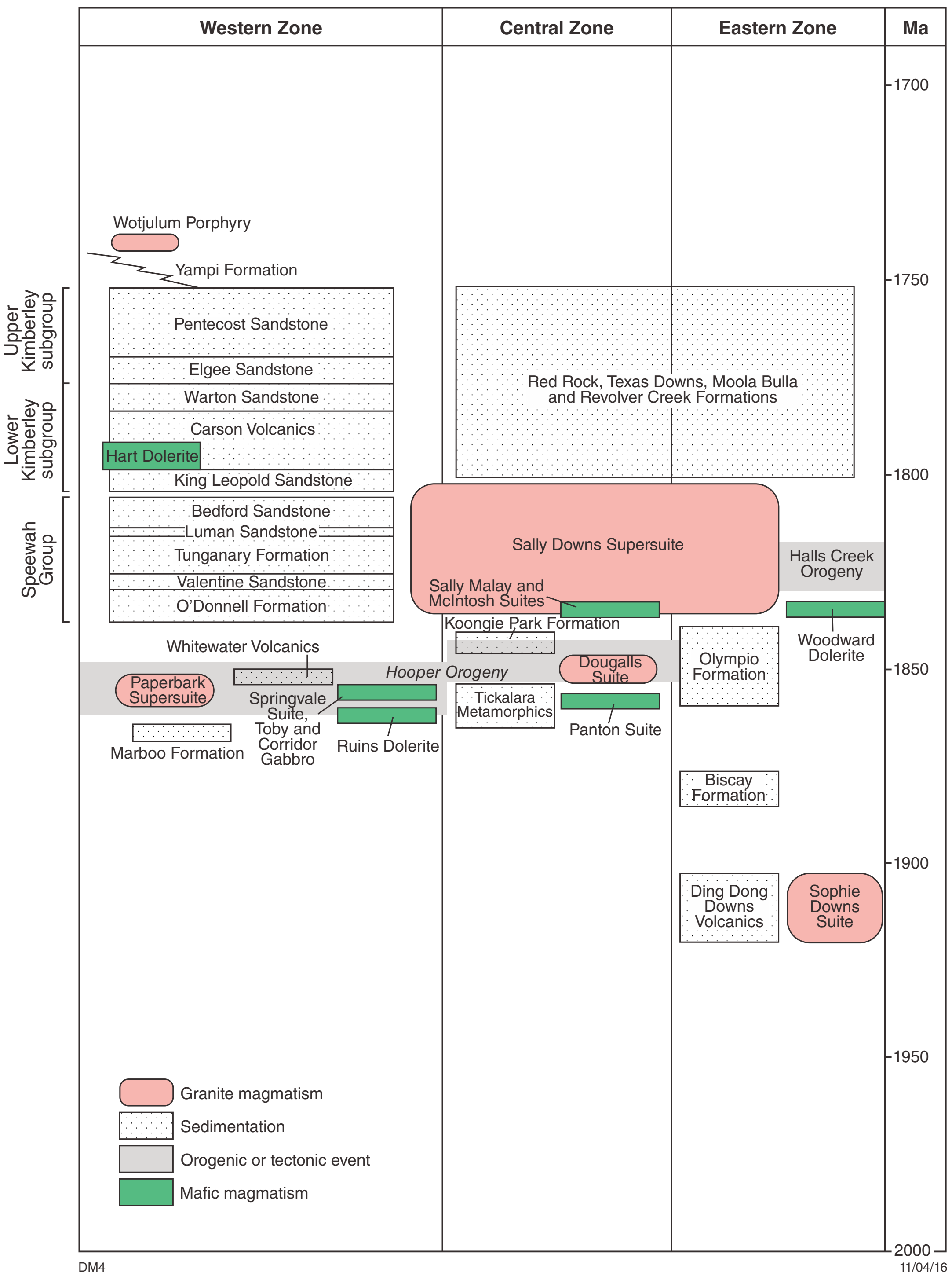



**Figure 3.** **Time and space plot showing the major Paleoproterozoic tectono-stratigraphic units within each terrane of the Lamboo Province and Kimberley Basin**

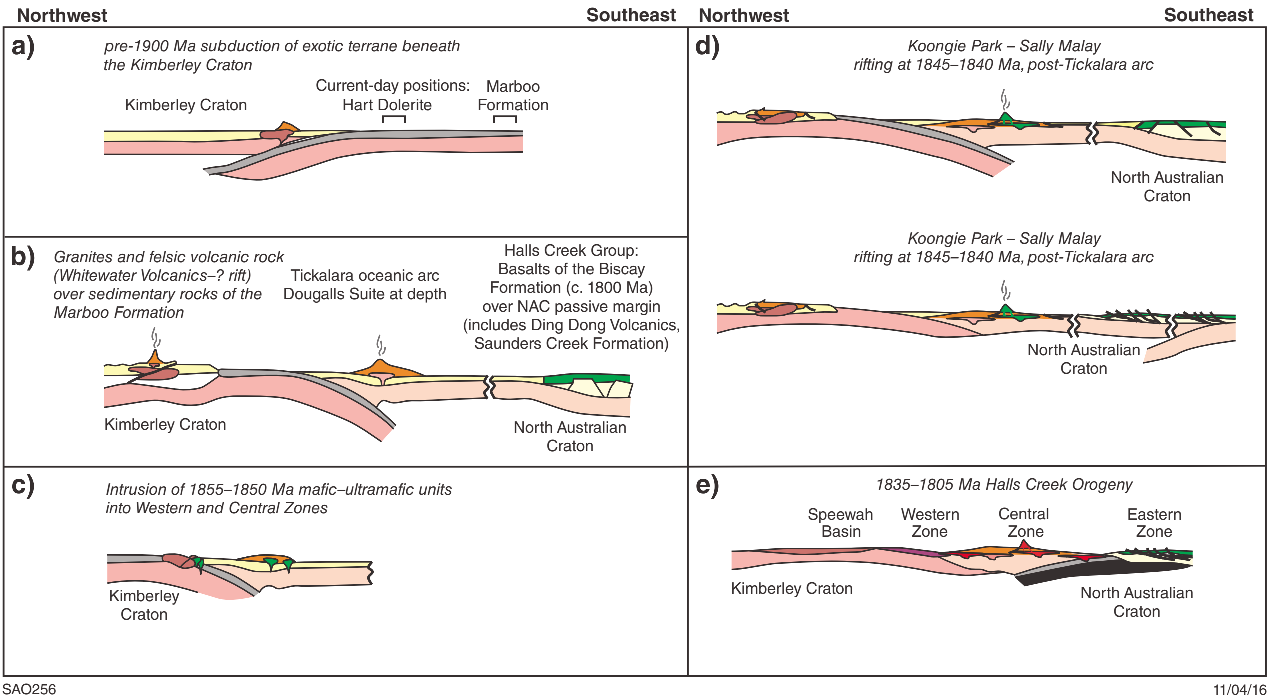



**Figure 4. Tectonic setting of the eastern margin of the Kimberley Craton through time: a) pre-1900 Ma subduction of an 'exotic' continental fragment beneath the Kimberley Craton (modified after Griffin et al., 2000); b) convergence of the Kimberley and North Australian Cratons during the 1870–1850 Ma Hooper Orogeny (modified after Griffin et al., 2000 and Tyler et al., 2012); c) 1855–1850 Ma intrusions of mafic and ultramafic rocks of the Springvale, Toby, Panton and Corridor units; d) 1845–1840 Ma rifting of Tickalara Metamorphics and development of the Koongie Park Formation (top), and continued rifting of the Tickalara arc prior to the Halls Creek Orogeny (bottom); e) 1835–1805 Ma Halls Creek Orogeny**

mafic intrusions of the Sally Malay Suite were emplaced at 22 km depth contemporaneously with the deposition of the Koongie Park Formation (Trudu and Hoatson, 2000; Fig. 4d).

## 1835–1810 Ma Halls Creek Orogeny

The 1835–1805 Ma Halls Creek Orogeny was the first event to affect all zones of the Lamboo Province and is thus considered to represent the suturing of the Kimberley and North Australian Cratons forming the Halls Creek Orogen (Sheppard et al., 1999, 2001; Tyler et al., 2012). The early stages of the Halls Creek Orogeny were characterized by high temperatures and low pressures (Bodorkos and Reddy, 2004); the metamorphic grade of currently exposed rock is highest in the central part of the Central Zone (Fig. 5).

Voluminous felsic to mafic magmas were intruded during this period, forming the Sally Downs Supersuite. The c. 1830 Ma McIntosh Suite was also emplaced into the Central Zone at 18 km depth (Page and Hoatson, 2000; Trudu and Hoatson, 2000). Granitic intrusions of the Sally Downs Supersuite have been broadly subdivided into the Mabel Downs, Syenite Camp and Kevins Dam Suites based on different chemical characteristics, which suggests differing origins (Sheppard et al., 2001). Although the Sally Downs Supersuite intrusions were emplaced across the Lamboo Province, these rocks are most common in the Central Zone. The Nd isotopic and geochemical data of the Sally Downs Supersuite indicate a proportion of mantle-derived material, which suggests all of its units were formed in a subduction zone setting (Sheppard et al., 2001).

The Mabel Downs Suite is considered to be the oldest component of the Sally Downs Supersuite. Its geochemistry shows overlap between Archean high-Al tonalite–trondhjemite–granodiorite suites and Phanerozoic adakites (Sheppard et al., 2001) and has a signature akin to crustally derived adakites. The Syenite Camp Suite granitic rocks have geochemistry indicative of crustally derived melts (Sheppard et al., 2001). These observations suggest that the Kimberley Craton forms the basement to the Central Zone and the Mabel Downs Suite formed over a westerly or northwesterly dipping subduction zone, early in the Halls Creek Orogeny (Sheppard et al., 2001). West of the Lamboo Province, the Speewah Group siliciclastic sedimentary rocks and related minor felsic volcanics were deposited in a basin over the Kimberley Craton during the Halls Creek Orogeny. Unconformably overlying the Speewah Group is the basal unit of the Kimberley Group King, the Leopold Sandstone. Both the Speewah Group and the King Leopold Sandstone are intruded by mafic rocks of the c. 1797 Ma Hart Dolerite, which together with the associated mafic Carson Volcanics may form a large igneous province (Griffin et al., 1993). The upper Kimberley subgroup overlies the Carson Volcanics and includes the Warton Sandstone, Elgee Siltstone and uppermost Pentecost Sandstone. Overlying the Kimberley Group to the northeast of the Lamboo Province are the <1797 Ma Bastion Group sedimentary rocks.

Lamboo Province and Bastion Group rocks are overlain by sedimentary rocks of the c. 1200 Ma Carr Boyd Group (Thorne and Tyler, 1996), and the 720–540 Ma Duerdin Group (Corkeron, 2008) to the northeast. The 1177 Ma Argyle lamproite diatreme (Luguet et al., 2009) intrudes the Carr Boyd Group in the Eastern Zone.

## Early Neoproterozoic Yampi Orogeny

The <1000 to 800 Ma Yampi Orogeny marked the end of a long period of quiescence with the formation of a series of stacked sedimentary basins (Tyler and Griffin, 1990, 1992; Shaw et al., 1992; Griffin et al., 1993; Bodorkos and Reddy, 2004). The Yampi Orogeny is defined by large-scale, northeast-facing folds and thrusts produced in rocks of the Kimberley and Speewah Groups on the Yampi Peninsula, in the west Kimberley region. Deformation resulting from the Yampi Orogeny is difficult to constrain in the east Kimberley (Thorne and Tyler, 1996; Bodorkos and Reddy, 2004).

## Late Neoproterozoic King Leopold Orogeny

The c. 560 Ma King Leopold Orogeny produced widespread and large-scale folding and southwest-directed faulting of the Lamboo Province and Kimberley and Speewah Basins (Tyler and Griffin, 1990; Thorne and Tyler, 1996). Up to 90 km of sinistral strike-slip faulting occurred along major faults in the Halls Creek Orogen; the majority of this displacement is attributed to deformation during the King Leopold Orogeny (Thorne and Tyler, 1996).

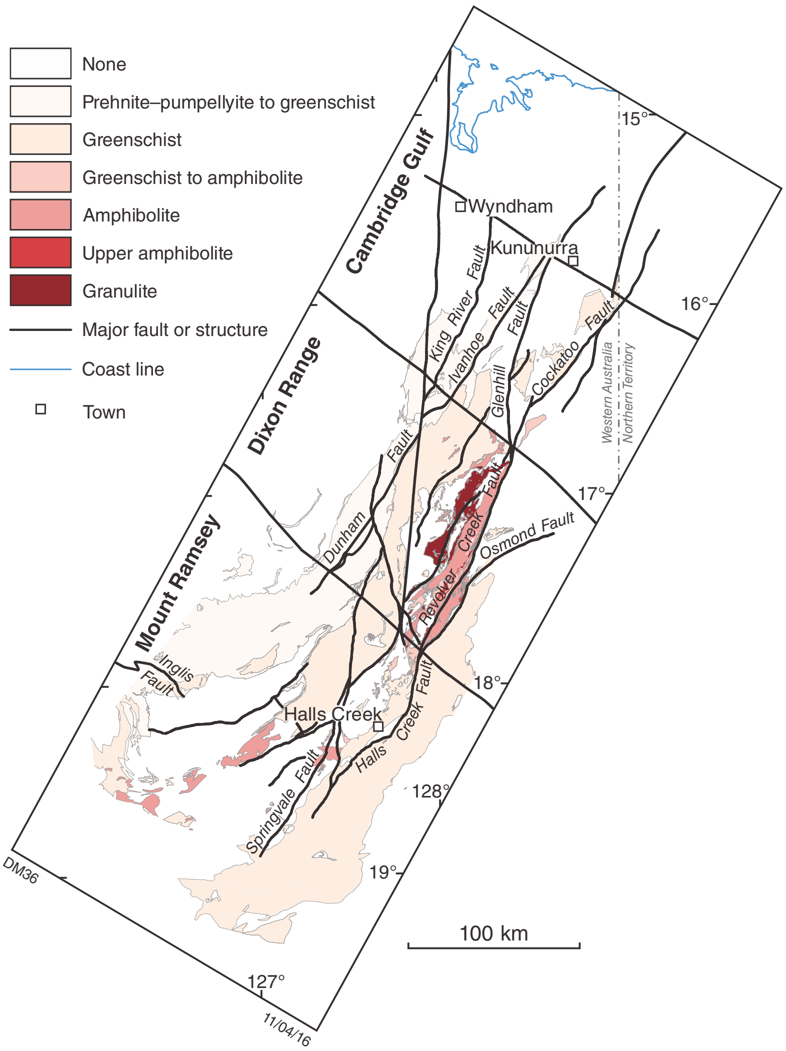



**Figure 5. Major structures in the east Kimberley region that contribute to the tectono-stratigraphic terrane boundaries of Tyler et al. (1995) and separate the Cambridge Gulf, Dixon Range and Mount Ramsey areas; note that major structures delineate zones of different metamorphic grade**

The c. 510 Ma Antrim Plateau Volcanics, part of the Kalkarindji Large Igneous Province, are widespread Cambrian flood basalts that cover large areas of the Eastern Zone (Hanley and Wingate, 2000; Glass and Phillips, 2006) and overlie the Carr Boyd and Duerdin Groups.

## Known major faults

Several known major faults are present in the east Kimberley region and are all restricted to the Lamboo Province. The Western, Central and Eastern Zones form tectono-stratigraphic terranes, defined by Tyler et al. (1995), that are bounded by these structures. The Ramsey Range Fault, the Springvale Fault and the northern part of the Halls Creek Fault form the boundary between the Western and Central Zones. A combination of the Osmond, Halls Creek and Angelo Faults define the boundary between the Central and Eastern Zones. Most, if not all, of these structures are thought to have originated during the Hooper or Halls Creek Orogenies, and have experienced multiple periods of reactivation through time (Thorne and Tyler, 1996).

The terrane-bounding northeasterly trending faults have been offset by north-northeasterly and northwesterly trending faults (Fig. 5). Other significant faults are the Dunham–Ivanhoe Fault, Glenn Hill Fault, Revolver Creek Fault and Greenvale Fault.

# Methods

## Petrophysical analysis

Magnetic susceptibility and density values were measured from rock samples collected in the study area and statistical analyses were performed to calculate representative values. Petrophysical data guided the identification of geological units in the structural interpretation and provided the basis of the density and susceptibility values used in forward modelling (for methodology, see Lindsay et al., 2015).

## Map compilation

Recently released Geologicial Survey of Western Australia (GSWA) 1:100 000 scale (GSWA, 2013) and Statewide 1:500 000 scale digital maps were recompiled to produce a lithostratigraphic map of the east Kimberley that includes interpreted bedrock geology in areas lacking outcrop (Fig. 5). Rock units from the 1:100 000 digital maps were added to the 1:500 000 scale map where complex geology was inadequately represented. This augmentation of the 1:500 000 scale map was mostly necessary in the Central Zone to best represent the mafic–ultramafic intrusions (e.g. McIntosh and Panton Suites) and the various units that form the Sally Downs Supersuite and Tickalara Metamorphics.

## Determination of metamorphic grade

The peak metamorphic grade of each unit was determined from fieldwork observations, existing petrological data available with published digital maps, or various published sources (Bodorkos et al., 1999, 2000, 2002). Temperature, rather than pressure, is considered to be the main factor driving metamorphism in the Lamboo Province. Metamorphic grade has been divided into the following facies: none, prehnite–pumpellyite to greenschist, greenschist, greenschist to amphibolite, amphibolite, upper amphibolite, and granulite (Fig. 5).

## Structural interpretation

Aeromagnetic data were used to interpret the large-scale structural architecture and tectonic evolution of the region (e.g. Gunn et al., 1995; Aitken and Betts, 2009; Stewart and Betts, 2009). Total magnetic intensity (TMI) data were obtained from GSWA and open-file surveys. The data were gridded and stitched by GSWA (Fig. 6a). Surveys were either flown north–south or east–west, and most have a line spacing of 400 m, although some areas have a 200 m line spacing. Each survey was gridded using minimum-curvature with an 80 m cell size prior to stitching. Longer wavelength trends may be misrepresented due to de-trending applied during the stitching process. Few visible artefacts resulting from the stitching process were identified when the areas covered by individual aeromagnetic surveys were superimposed. A differential reduced to pole (dRTP) transform was applied to the stitched TMI grid. To subdue or enhance particular wavelengths and geophysical features, enhancement filters and transforms were applied to the dRTP grid, including the analytic signal, tilt derivatives, vertical and horizontal derivatives and dynamic range compression algorithm (Kovesi, 2012).

Terrain-corrected, spherical-cap Bouguer gravity data were obtained from the national database maintained by Geoscience Australia (Fig. 6b). Terrain corrections were applied only on the younger surveys, so older data within the basin interior may preserve topographic effects. Gravity station spacing is quite sparse (11 km grid) over the Kimberley Basin and east Kimberley, except for a 400 m spaced survey along the Gibb River Road. Grids were produced with cell sizes from 500 m to 2 km, to provide both detail and coverage.

Shallow crustal and deeper geological structure was primarily interpreted from reduced to pole aeromagnetic data, its first vertical derivative, and tilt derivative. A modified high-pass filter tone mapping algorithm, dynamic range compression (DRC), was also applied to the total magnetic intensity data to improve the interpretability of the images (Kovesi, 2012). Bouguer gravity data were used to identify larger, and presumably deeper penetrating, structural features and to provide additional insight to regions where magnetic susceptibility contrast was low.

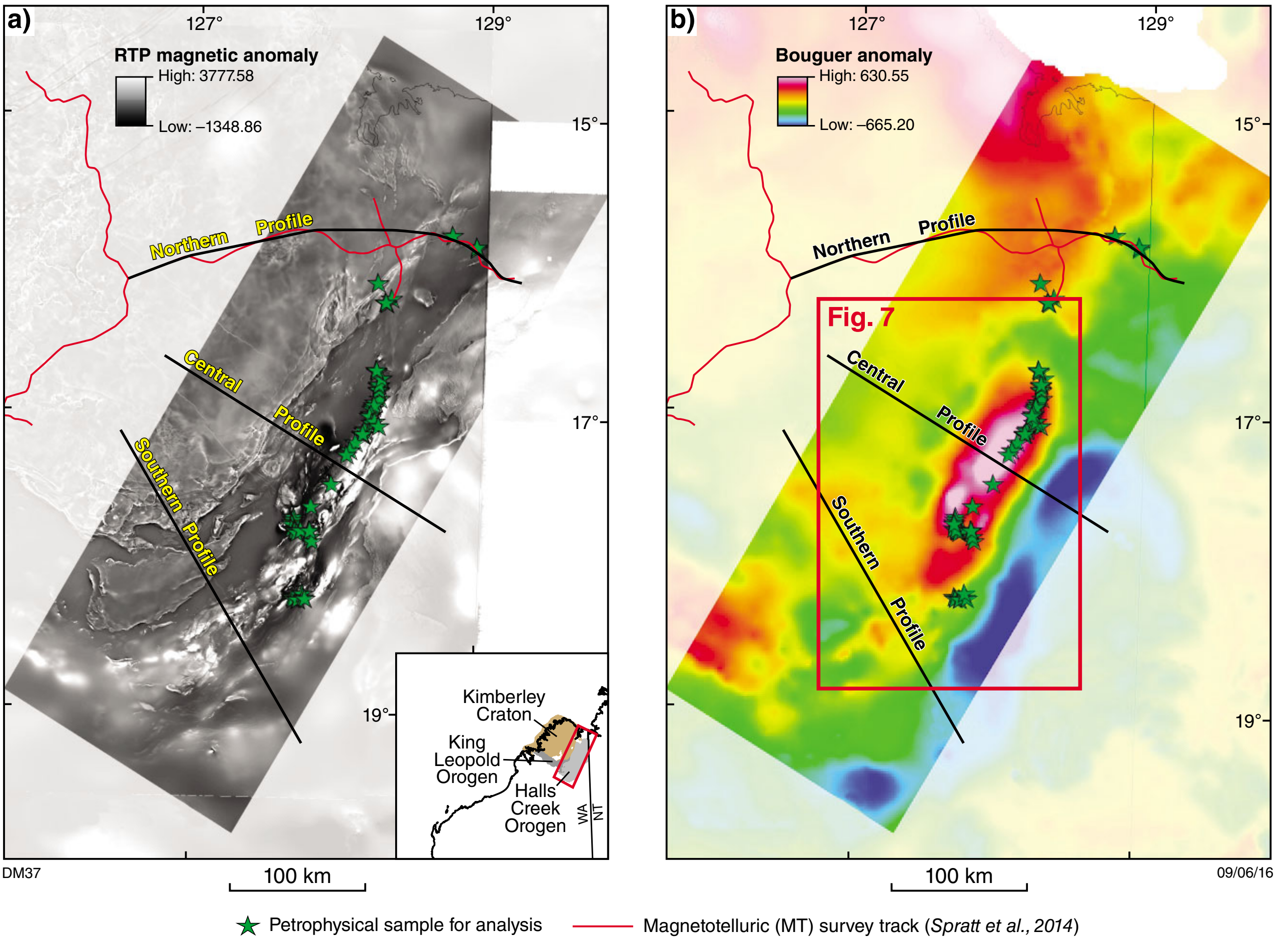



**Figure 6. Geophysical grids used in forward modelling and structural interpretation of the east Kimberley region, with profile locations shown: a) RTP magnetic data gridded at 80 m cell size; b) terrain-corrected, spherical-cap Bouguer anomaly data gridded at 1000 m cell size**

Geological information was used to locate some structures, although it was principally employed to interpret their tectonic significance (Occhipinti et al., 2016). Landsat data presented in 'natural colour' were occasionally used to delineate outcropping geologic units in geophysically complex regions. ASTER geoscience products (Version 1), provided by CSIRO, were used to constrain more detailed surface geology, specifically to determine whether shallow linear features were faults, dykes or veins (or a combination). A variety of geoscientific grids was used during interpretation. However, the grids that proved the most useful were the RTP magnetic anomaly, Bouguer anomaly, first vertical derivative of the RTP magnetic data (Fig. 7a), tilt derivative of the RTP magnetic data (Fig. 7b), and dynamic range compression of the RTP magnetic data (Fig. 7c).

Magnetotelluric (MT) data and modelling, described in Spratt et al. (2014), were used to provide an additional physical field. This reduced ambiguity in the interpretation by enabling us to correlate features detected in other datasets, and reveal features where a lack of magnetic susceptibility or density contrast may have obscured them.

## Geological information and petrophysical constraints

Several sources of geological information were integrated into the interpretation. Primary constraints included these 1:250 000 scale map sheets: Cambridge Gulf (SD 52-14), Mount Elizabeth (SE 52-1), Lissadell (SE 52-2), Lansdowne (SE 52-5), Dixon Range (SE 52-6), Noonkanbah (SE 51-12), Mount Ramsey (SE 52-9), Gordon Downs (SE 52-10), Mount Bannerman (SE 52-13) and Billuna (SE 52-14) as primary constraints. In addition, GSWA's WAROX database of structural measurements and field observations was used to provide structural constraints (for example, strike, dip and type of foliations, trend and plunge of fold axes; Fig. 8). These data were helpful in differentiating generations of deformation in structures identified in aeromagnetic interpretation. Lithostratigraphic constraints, including the metamorphic grade of each rock unit, were also obtained through the WAROX database. The inclusion of metamorphic grade provides an overview of crustal depth and shows the location of transitions between metamorphic gradients.

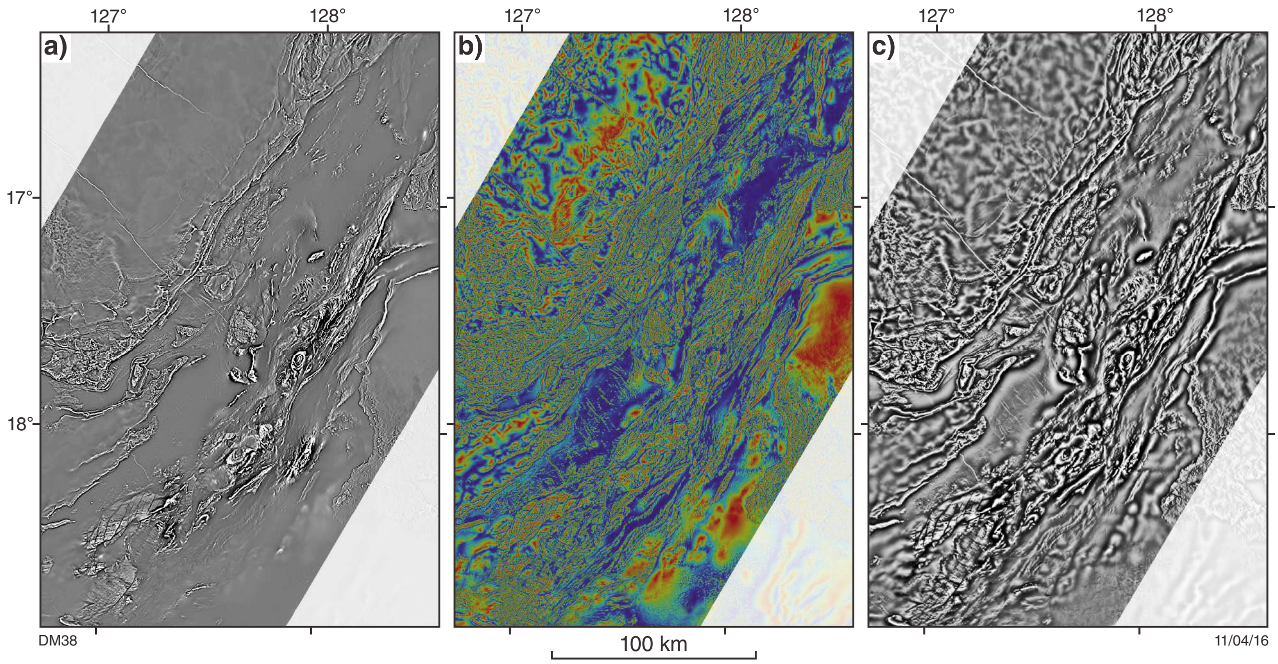



**Figure 7. Additional geophysical data grids used during structural interpretation (see Fig. 6b for location): a) differential reduced-to-the-pole with a first vertical derivative; b) tilt derivative, highlighting structure; c) dynamic range compression (window size = 100 cells)**

Both significantly enhance the digital map and provided a useful constraint to the structural interpretation.

## 2.5D combined gravity and magnetic modelling

The map interpretation was supported by 2.5D forward modelling to provide a 3D understanding of the east Kimberley region. The upper crust was constrained predominantly by geological observations (WAROX) and GSWA 1:250 000 scale maps. The geometry of the Moho and the lower crust – upper crust boundary was constrained by gravity and seismic information derived from the model of Aitken et al. (2013c). Upper crustal geometries were constrained by structural measurements from 1:250 000 scale maps and from the WAROX database. Tables 1.1 to 1.3 (Appendix 1) specify the geological information for each profile. The overall geometry of the Kimberley and Speewah Basins was derived from estimates of the depth to basement and depth to source to the Carson Volcanics and/or Hart Dolerite.

Magnetic data for modelling were sampled at 250 m spacing from the regional TMI grid (Fig. 6a). Magnetic calculations used a sensor height of 80 m above the topographic surface. Bouguer anomaly data were sampled from the regional grid (Fig. 6b) at 250 m spacing. Gravity calculations used in modelling employed a sensor height of 1 m above the topographic surface. The ‘air’ layer is assigned a density of 2670 kg/m$^3$ so as to retain the gravity and magnetic effect of anomalously dense or susceptible topography in the model. The starting models were populated with petrophysical properties consistent with measured petrophysics, or typical values where samples were not available to achieve an approximate fit to the lower crust before modelling upper crustal structure. Assigned petrophysical values were the median of the measured values, although some variation within error was allowed to account for heterogeneity within the rock volume. The upper few kilometres of the model were mostly defined by the observed magnetic data, with some support from short-wavelength gravity anomalies when present in the data. The deeper crust was modelled with an emphasis on the fit to the gravity data, with long wavelength magnetic anomalies when necessary.

The 2.5D sections were modelled to best fit the observed magnetic and gravity data while considering the crustal architecture and surface geology as best predicted from the integration of the above constraints. As such, the modelled sections contain features predicted using geological reasoning; however, they are not required to exactly fit the geophysical data in order to present a likely geological prediction. For example, some magnetic layers may be modelled as continuous beyond that allowed by station spacing. In this case, the interpretation was based on field observations that describe layer continuity and knowledge about petrophysical characteristics associated with the rock type (e.g. lava flows).

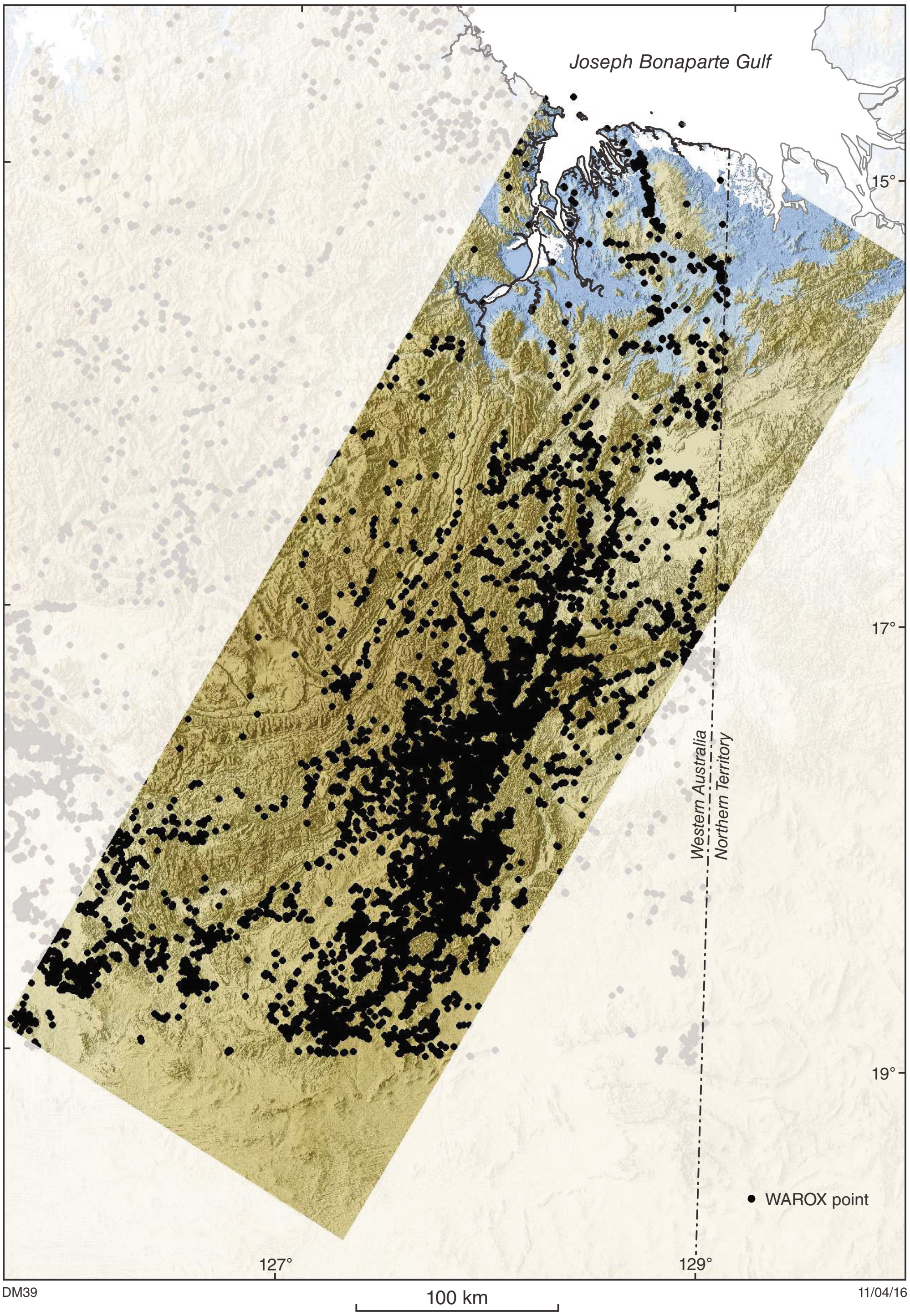



**Figure 8. Location of GSWA WAROX outcrop observations in the study area**

## Interpreting geology from geophysical data

Geological structures were interpreted from magnetic data using basic field mapping techniques. Marker units, such as dykes and other anomalously magnetic units, were useful to identify folds and determine offset along faults. Other structural information, such as discontinuities (shear zones or faults), intrusive and sedimentary contacts, dykes and covered geological units were also identified from increased or reduced magnetization.

Large-scale crustal structure has long been recognized as a key control on tectonic evolution and on many styles of mineralization (Bierlein et al., 2006). These features are often old and deep, accommodate strain during tectonic history, and are subsequently re-activated. They represent the boundaries between different tectonic elements and act as conduits to both magmatic and hydrothermal fluids. They also control the emplacement of intrusive rocks and the location of growth-fault zones in the upper crust. Deep crustal-scale structure is considered to influence the location of mineralized zones and act as a focus of fluid flux. Thus we concentrated on defining large-scale geophysical anomalies that may represent such features.

# Results

## Petrophysics

Rock samples for petrophysical analyses were collected from the east Kimberley region during July 2013 at the locations shown in Figure 6. The box and whisker plot in Figure 9 shows the statistical distribution of density (top) and magnetic susceptibility measurements (bottom; $n = 50$ for each sample) taken from the rock samples.

Most rocks exhibit a median density value between 2.50 and 2.75 g/cm$^3$; however, some rock types do show values outside of this range (Tickalara Metamorphics, 2.85 g/cm$^3$; Moola Bulla Formation, 2.49 g/cm$^3$). Rocks of The Olympio Formation exhibit the lowest median values (2.43 g/cm$^3$) and rocks of the Dougalls Tonalite exhibit the highest median values (3.07 g/cm$^3$). Typically, the median values of the log magnetic susceptibility values exhibit a more varied range than the density values. The highest median susceptibility values are those of the Marboo Formation, and the lowest are those of the Red Rock Formation and the Cockatoo Group.

Most of the rocks exhibit petrophysical values typical of their composition. While the median values are mostly what would be expected from rocks of these compositions, the magnitude of variance for density and susceptibility for the King Leopold Sandstone is high. This suggests that this unit is quite compositionally heterogeneous, or has been subjected to some processes such as weathering, alteration, metamorphism and mineralization that produced rocks that exhibit such extremes. Field observations suggest that while the King Leopold Sandstone has been metamorphosed, it is a low grade, and a sandstone protolith is unlikely to exhibit the chemistry that would allow magnetic metamorphic minerals to form through metamorphism. Alteration and related Fe- and Mg-rich fluids are more likely to have introduced this heterogeneity, and probably reflect the processes that operated in the structurally complex areas from which the samples were collected.

The median values are similar to those obtained from analysis of King Leopold Sandstone rocks sampled in the west Kimberley region (Lindsay et al., 2015). Based on consistency between values from the west and east Kimberley, the median values were used as constraints for interpretation and modelling. Rock properties for the Hart Dolerite and Carson Volcanics were not obtained from the east Kimberley region, so results obtained from the west Kimberley region were used.

## Metamorphic grade

A map of metamorphic grade shows a clear gradient perpendicular to the strike of the Lamboo Province (Fig. 11a). The boundaries of tectono-stratigraphic terranes (Fig. 2), defined by Tyler et al. (1995), largely coincide with the boundaries between metamorphic grade. An obvious high-grade zone is present in the centre of the Central and Eastern Zones, and is marked by relatively steep metamorphic gradients at its northeastern and southwestern ends.

## Structural interpretation

Long, northwesterly trending, linear features that cross-cut the Lamboo Province have been interpreted from magnetic and gravity data (Figs 10 and 11b). These orogen-normal features are interpreted to be present in the Kimberley and Speewah Basins, Lamboo Province and possibly extend further east into the Ord and Birrindudu Basins in the Northern Territory. Figure 12a-d emphasizes these features using a selection of gravity grids: Bouguer anomaly, sun-shaded Bouguer anomaly, a first-vertical derivative (1VD) of the Bouguer anomaly and the Bouguer anomaly upward-continued by 5 km. The features were interpreted where discontinuities exist in the geophysical response, as indicated by the arrows in Figure 12a-d. The 1VD image (Fig. 12c) emphasizes steep gradients in the gravity data. The upward continuation (Fig. 12d) aims to remove shorter wavelengths from the gravity data. Two orogen-normal features appear at the northeast and southwest of a large, high-amplitude gravity anomaly in the centre of the Lamboo Province; this anomaly also coincides with a zone of high-grade metamorphism (Fig. 11a,b).

The three orogen-normal features (Figs 10 and 11) were interpreted as structures and named A, B and C. Notably, some surface features are coincident with these interpreted structures. The northernmost structure is associated with an ellipsoidal feature 18 km west of Kununurra (Fig. 11a). Some Pb and Fe mineralization is associated with the intersection of this orogen-normal and ellipsoidal feature.

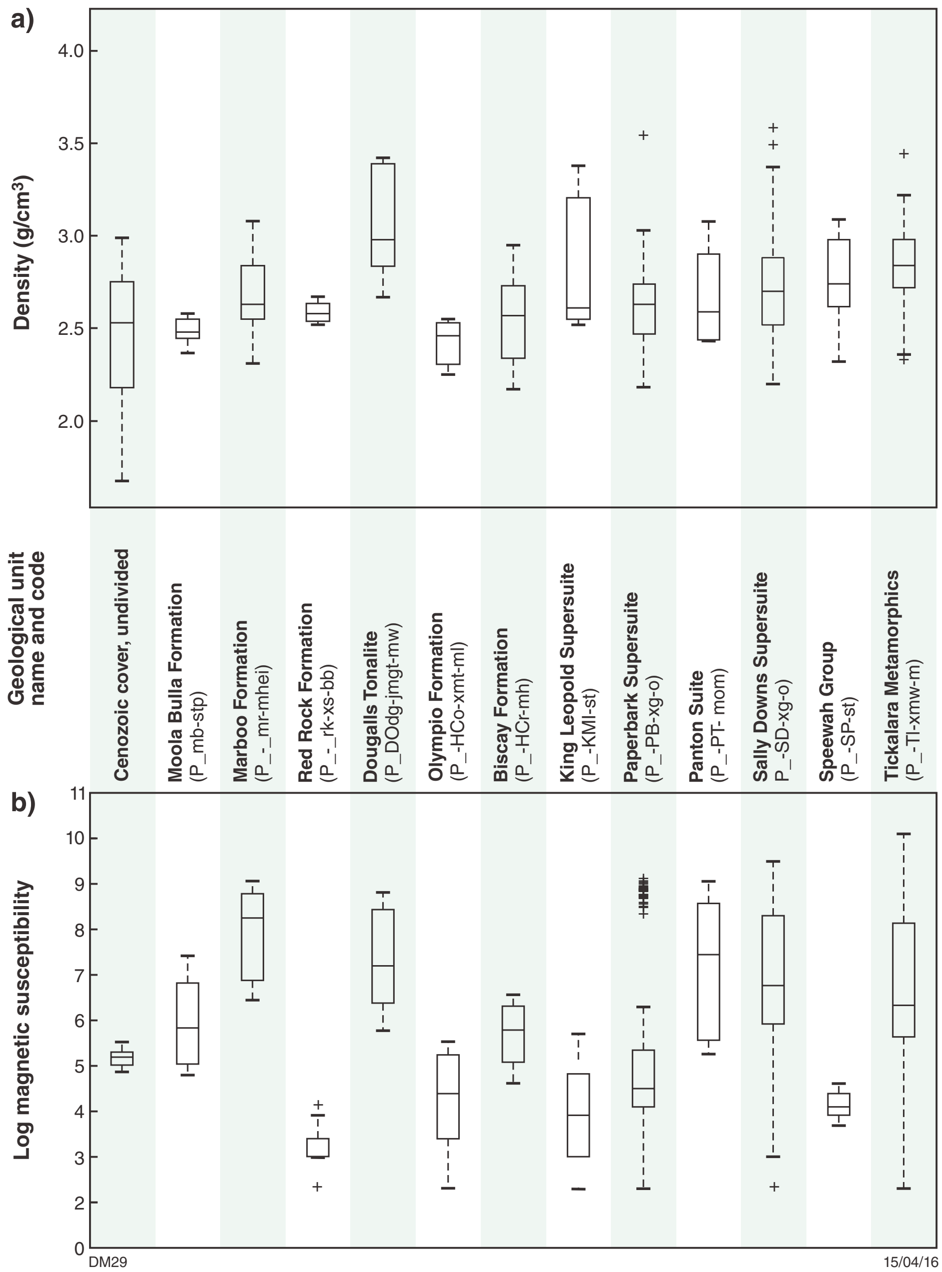



**Figure 9. Boxplots showing the results of petrophysical analyses on samples collected in the east Kimberley region, corresponding to rock unit: a) boxplot of density measurements; b) boxplot of magnetic susceptibility**

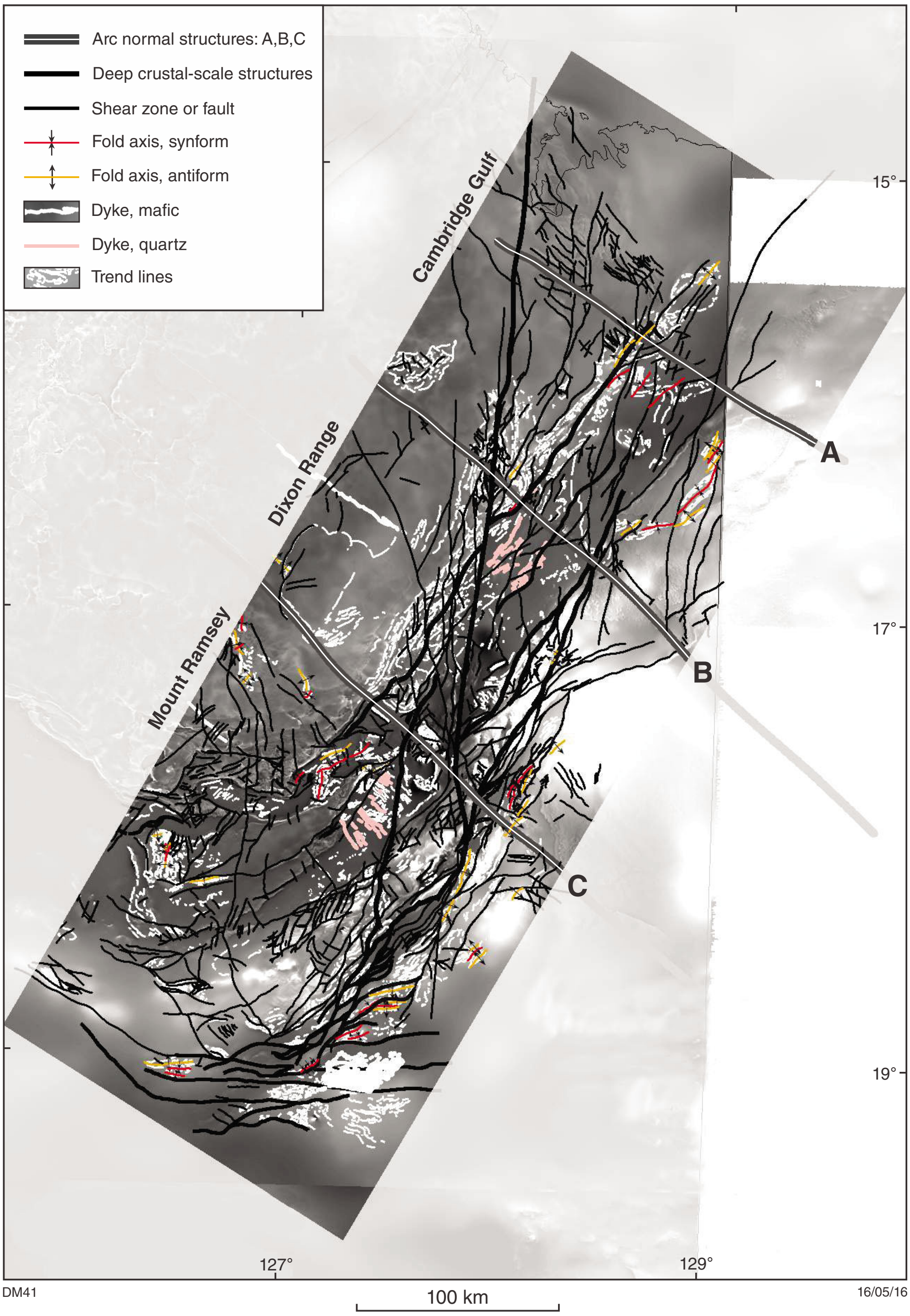



**Figure 10. Structural interpretation of the east Kimberley region superimposed on dRTP magnetic data**

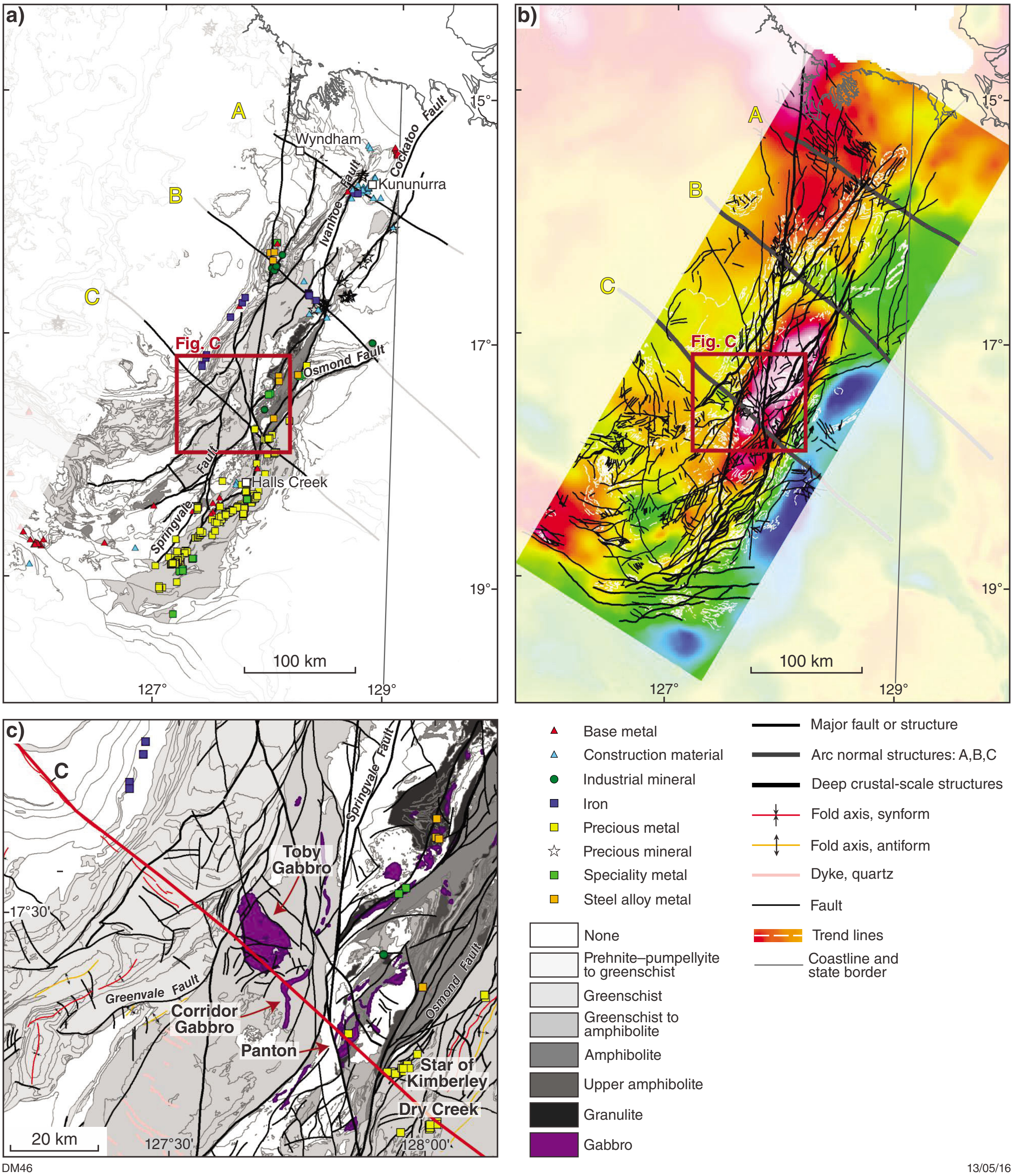



**Figure 11. Northwesterly trending orogen-normal structures (A, B, C) identified through interpretation of gravity data: a) known mineral and resource sites (from GSWA MINEDEX) plotted on a map of metamorphic grade; b) major faults superimposed on gravity data; c) enlargement of the southern orogen-normal structure showing the relationship between metamorphic grade and mineral occurrence**

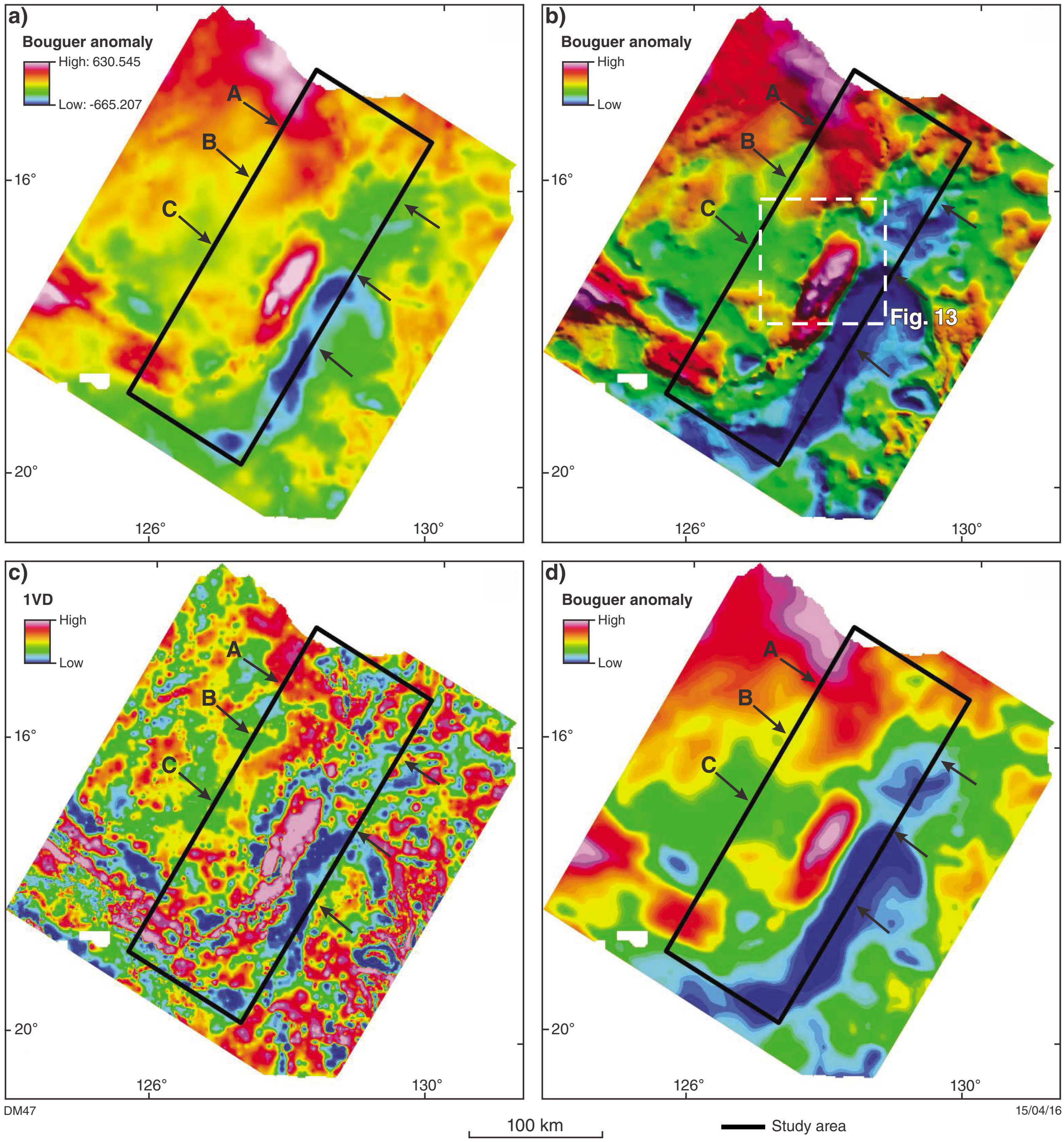



**Figure 12. Different gravity datasets for the study area with arrows showing the location and orientation of the interpreted northwest-trending structures (A, B, C): a) terrain-corrected, spherical-cap Bouguer anomaly; b) terrain-corrected spherical-cap Bouguer anomaly sun-shaded from the north-northeast at 45° inclination, highlighting northwesterly trending anomalies; c) Bouguer gravity with a first vertical derivative (1VD) transform; d) Bouguer gravity upward-continued to 5 km in order to remove short wavelength anomalies and emphasize longer wavelength features**

The central orogen-normal structure also has coincident surface features, including the Speewah Dome, the Ridges magnetite-hosted Fe mine, and the Argyle lamproite diamond mine. The Speewah Dome is host to a variety of mineralization styles, including Cu–Au, Ni–PGE and V–Ti (Fig. 11b). The southernmost orogen-normal structure is coincident with a series of outcropping mafic to ultramafic intrusions (shown in Fig. 11c as purple, 'gabbro'), including the Corridor Gabbro, Panton Suite intrusions and Toby Gabbro. This structure is also coincident with mineralization at the Panton Cr–Ni–PGE prospect, and the Star of Kimberley Au–Ag, Moodys Au–Ag and Dry Creek Au deposits.

These orogen-normal structures are not associated with any continuous faulting at the surface; instead they are associated with mafic to ultramafic rocks, mineralization or complex geological architecture (the Speewah Dome and the ellipsoidal feature west of Kununurra; Fig. 5). These structures appear to exert some influence on the crustal architecture of the east Kimberley region, are likely deep and possibly extend to the base of the crust or beyond. Each of the regions between these orogen-normal structures may have different characteristics to the others, in terms of mineralization style and tectonic history. Thus, the orogen-normal structures may further partition the Lamboo Province into northwesterly trending tectono-metamorphic terranes, in addition to those shown defined by Tyler et al. (1995).

Magnetic data reveal the presence of a distinct northerly trending linear anomaly that also cuts across the Lamboo Province. This anomaly can be traced from the north of the study area, through the Speewah Dome, the Central Zone and into the Eastern Zone in the south (Fig. 13). Sinistral offset can be observed to the south of the Speewah Dome (A, Fig. 13a) where Speewah Group rocks were intruded by Hart Dolerite to the west of the structure, and Whitewater Volcanics outcrops to the east. In the gravity data, the northerly trending feature bisects shorter-wavelength anomalies in the centre of the study area (B, Fig. 13b). The surface expression of this anomaly is seen in the LISSADELL and DIXON RANGE 1:250 000 geological map sheets as a relatively continuous set of anastomosing faults. In the north, the intersection of the northerly trending feature and an orogen-normal structure is at the Speewah Dome, which also coincides with a number of mineralized locations (C, Fig. 13a) including fluorite-rich carbonate veins. In the centre of the Lamboo Province, the northerly trending feature is proximal to the Panton Suite intrusions and the Pt–Pd–Au–Ni–Cu deposit (D, Fig. 13a). To the south, the feature is also proximal to a number of Au mineralized locations in the Eastern Zone and along the continuation of the Angelo Fault.

The more detailed results of the geophysical interpretation are presented in sections named according to 1:250 000 map sheets (Fig. 5b): the 'Cambridge Gulf' area is north of the central orogen-normal structure; the 'Dixon Range' area is between the central and southern interpreted structures; and the 'Mount Ramsey' area is south of the southernmost structure.

The Cambridge Gulf area is marked by a series of north to north-northeasterly trending negative magnetic anomalies that offset northwesterly trending negative anomalies (e.g. A in Fig. 14b). These are interpreted to be faults, with sinistral offset attributed to the north to north-northeasterly trending fault sets. A series of arcuate linear positive anomalies was observed in the tilt derivative of the magnetic data at B and C in Figure 14b. These features are interpreted to be antiform–synform open folds at B, and a series of tight folds at C, the fold axes of which, if linked, are sinistrally offset at D. Tight folding at C may be a topographic effect, combined with shallow dips, and may not be as tight as the geophysical data suggests. Folding is supported by geological mapping and post-dates extrusion of the c. 510 Ma Antrim Plateau Volcanics; it probably related to the Alice Springs Orogeny (450–295 Ma), the last recognized major tectonic event in the Kimberley region.

In the Dixon Range area, one of the arc-normal features is coincident with a northwesterly trending dyke (A, Fig. 15b). This observation further suggests that these orogen-normal structures influence surface geology and magmatism. At B a series of high-amplitude anomalies appear to be offset by north-trending structures (Fig. 15b). The high-amplitude features are interpreted to be mafic units within the Paperbark Supersuite that have been sinistrally faulted by northerly trending faults. Two concentric, high-amplitude magnetic anomalies were observed to the west and south of C, interpreted to be intrusions of the Hart Dolerite, and Toby Gabbro respectively. The Toby Gabbro is also coincident with a gravity high (Fig. 11b,c). A northeasterly trending, high-amplitude magnetic anomaly was observed at D, which appears to be folded by northeasterly trending antiforms and synforms (Fig. 15b). The linear anomaly was interpreted to be a thin unit of Antrim Plateau Volcanics. Tightly folded linear, moderately and highly magnetic anomalies are observed at E (Fig. 15b) and are interpreted to be folded Speewah Group intruded by Hart Dolerite.

The Mount Ramsey area exhibits a change in overall geophysical anomaly orientation, with northeasterly to easterly trending features dominant, especially in the southeast (Fig. 16). A series of curvilinear and anastomosing, northeasterly trending, linear, positive magnetic anomalies can be seen in the centre of the image (A, Fig. 16b). These anomalies are interpreted to be shear zones, and appear to exhibit a C–S-like fabric, which reveals a sinistral sense of shear. At B, a similar series of anastomosing anomalies are observed that exhibit an overall easterly trend. These are also interpreted as shear zones exhibiting a C–S form. These easterly trending anomalies have a dextral sense of shear. A series of folded anomalies are observed at C (Fig. 16), and are interpreted to reflect east-plunging antiformal and synformal folds.

**Figure 14. (right, below) Structural interpretation of the Cambridge Gulf area (see Fig. 5 for location): a) geological units overlain by structural features; b) dRTP magnetic image annotated with MT survey stations and major structures**

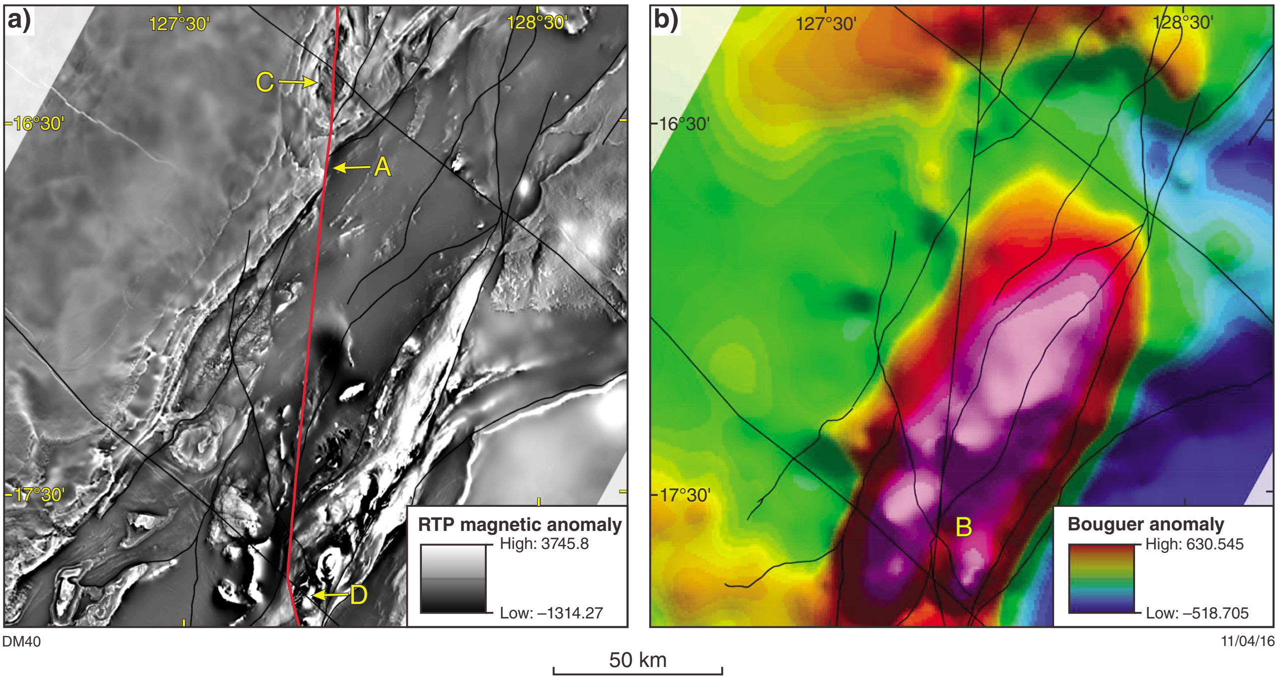
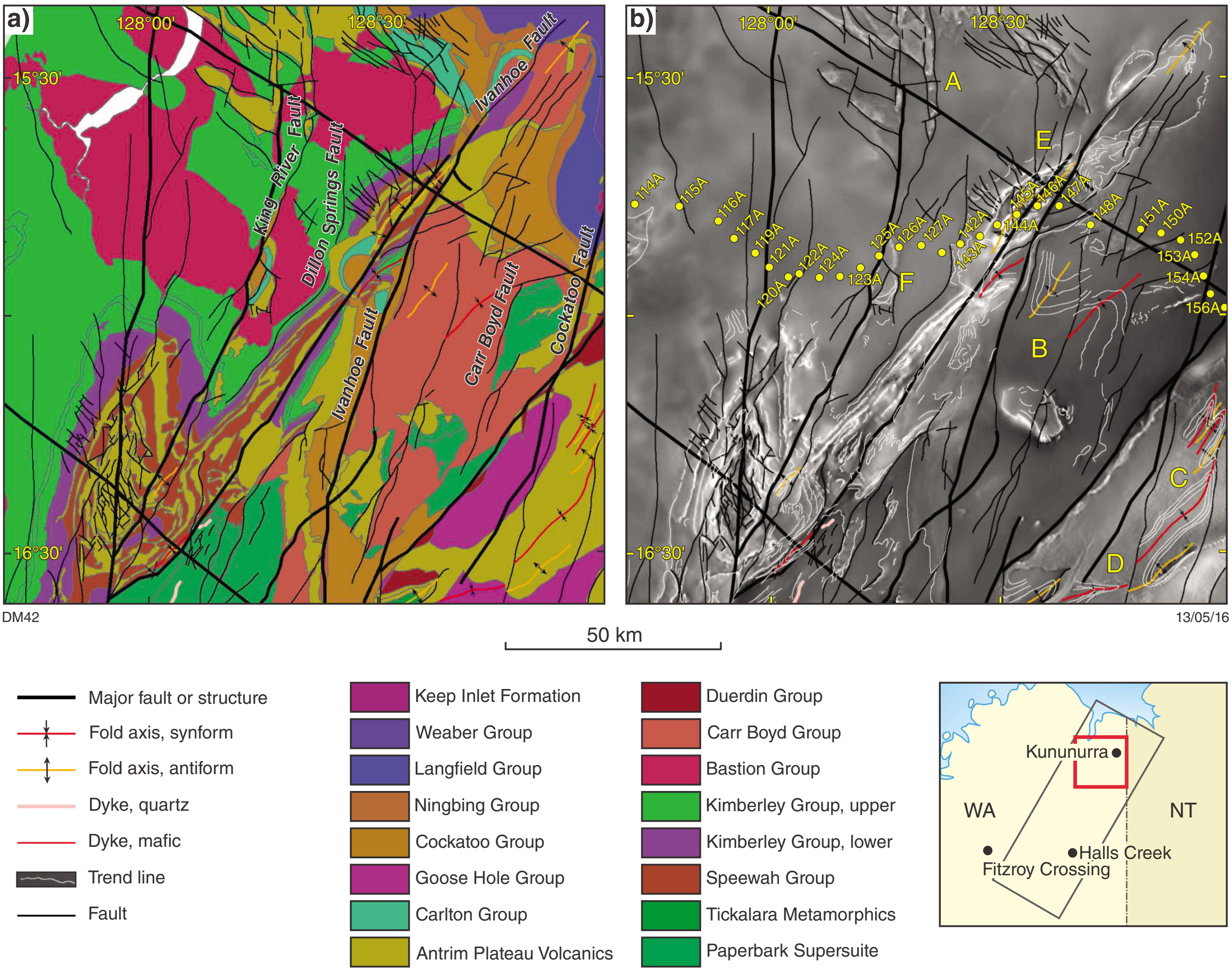



**Figure 13. Regional-scale structures seen in magnetic (a) and gravity (b) data, for area shown by white dashed line in Fig. 12b: a) northerly trending structure (red) showing sinistral offset (at A) in the RTP magnetic data; b) bisection of a gravity anomaly by the same structure (B); the Speewah Dome is at the intersection of two major structures (C), and the northwesterly trending structure is proximal to the Panton Suite intrusions and Pt–Pd–Au–Ni–Cu deposit (D)**



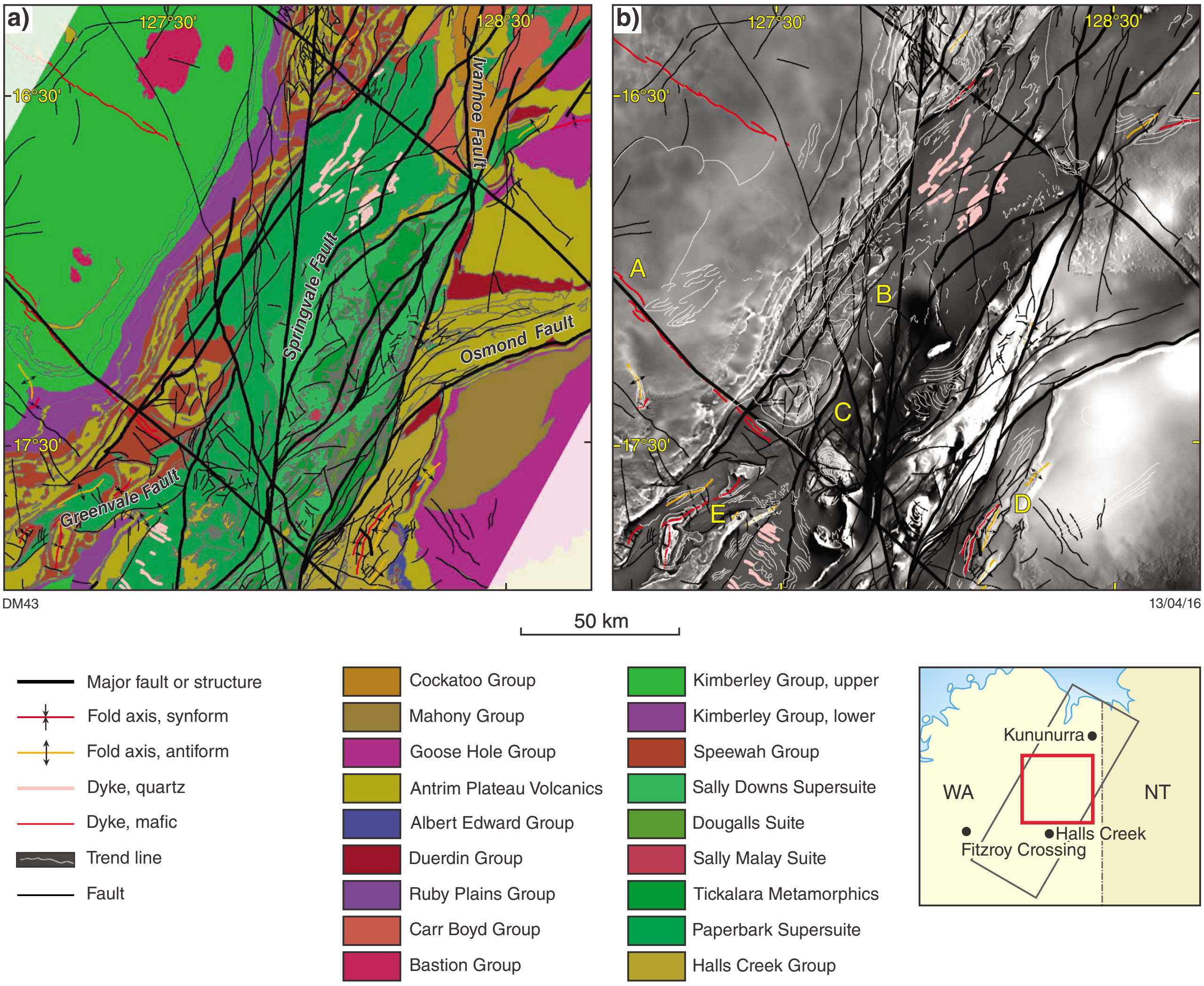



**Figure 15. Structural interpretation of the Dixon Range area (see Fig. 5 for location): a) geological units overlain by structural features; b) dRTP magnetic image annotated with major structures**

# Forward modelling

Three profiles were modelled extending from the Ord Basin into the central Kimberley Basin, focusing on the Lamboo Province and the eastern Kimberley and Speewah Basins (Figs 6a,b and 17). Bouguer gravity and total magnetic intensity data were used to resolve crustal structure using a structural–tectonic forward modelling approach (Aitken et al., 2013a,b). Through this modelling we seek to better understand the deeper structural architecture, and petrophysical and geological properties of the region. In particular:

- What produces the large positive gravity anomaly in the centre of the Dixon Range area?
- Are the Western, Central and Eastern Zones of Tyler et al. (1995) geophysically distinctive at depth?
- What can the Kimberley magnetotelluric data (Spratt et al., 2014) reveal in the northern part of the study area?

## Northern Profile

The Northern Profile is 310 km long and traverses the northeastern Kimberley and Speewah Basins, and the Cambridge Gulf area (Figs 6a,b and 18). The Kimberley and Speewah Basins are mostly 4–6 km thick (x = 0 to 215 km); the deepest part is 6.5 km thick (x = 162 km). A ~1 km thick layer of moderate to high magnetic (0.02 to 0.03 SI) and dense (2800 to 3000 kg/m$^3$) units at variable depths (from 400 m to 2.5 km) characterize the Kimberley Basin, representing the Carson Volcanics (shallower) and Hart Dolerite (deeper). Below and above these are nonmagnetic and lower density units (2650 kg/m$^3$) representing the Speewah Group and lower Kimberley Group rocks (the King Leopold Sandstone), respectively. The Hart Dolerite and Carson Volcanics bodies were modelled to be offset and discontinuous in discrete locations; the offsets are interpreted to be due to normal or reverse faults. At x = 75 to 138 km, the Hart Dolerite and Carson Volcanics bodies exhibit a higher frequency response, which has been interpreted to be folding.

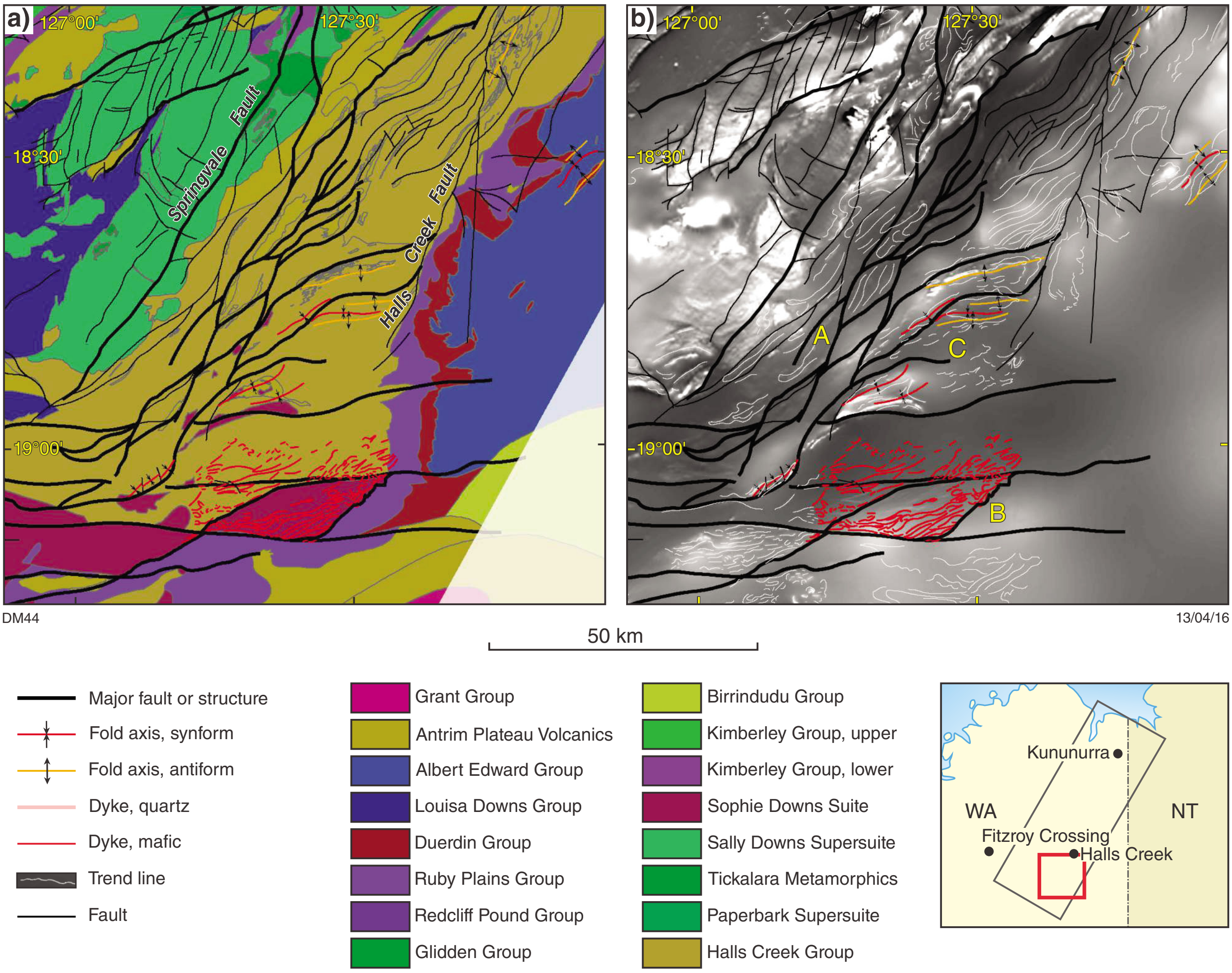



**Figure 16. Structural interpretation of the southeastern part of the Mount Ramsey area (see Fig. 5 for location): a) geological units overlain by structural features; b) dRTP magnetic image annotated with major structures**

A high-frequency and high-magnitude magnetic anomaly, at x = 210 to 226 km, was interpreted to be folding of Speewah Group and Hart Dolerite into an antiform–synform pair. This feature is seen in map view 18 km west of Kununurra (E, Fig. 14). A thin, high-susceptibility (0.023 SI) and dense (2900 kg/m$^3$) unit, at x = 227 to 300 km (profile end), was modelled near the surface. It deepens towards the eastern end of the profile and was interpreted to be the Antrim Plateau Volcanics. This unit is underlain by a nonmagnetic, moderately dense (2650 kg/m$^3$) unit interpreted to be the Carr Boyd Group. Overlying the Antrim Plateau Volcanics is a nonmagnetic, lower density (2520 kg/m$^3$) unit interpreted to be the Devonian sedimentary rocks of the Cockatoo Group in the Southern Bonaparte Basin. Two high-density anomalies (x = 237 and 270 km, and 2840 and 2950 kg/m$^3$, respectively) were modelled at 6–7 km depth; these are interpreted to be mafic intrusions, possibly magma chambers linked to the Antrim Plateau Volcanics.

The basement to the Kimberley and Speewah Basins is nonmagnetic and moderately dense (2700–2760 kg/m$^3$) in contrast to the magnetic (0.005 SI) and more dense (2780–2790 kg/m$^3$) basement of the Halls Creek Orogen. The basement of the Southern Bonaparte Basin, at the eastern end of the profile, is nonmagnetic and less dense than the Halls Creek Orogen basement; it is similar to the basement of the Kimberley and Speewah Basins. A thick (18 km) and wide (>150 km) nonmagnetic high-density body (3200 kg/m$^3$) was modelled between x = 0 and 155 km, and it sits just above the Moho. It is less dense than the modelled mantle density.

### *Electrical conductivity variations from 2D magnetotelluric models*

Two-dimensional MT models from the eastern profile of the Kimberley Craton survey (Spratt et al., 2014) were overlain by the boundaries determined from forward modelling (Fig. 19). The overall architecture defined from potential field modelling is represented in the electrical conductivity variations. The MT survey profile and the potential field modelling profile diverge by up to 10 km from stations 115 to 127 and stations 135 to 146 (Fig. 19;

stations are numbered by their distance in kilometres from the western end of the profiles). Stations 128 to 134 were used in a cross-profile and are not directly used in this analysis, except as constraints. The profiles diverge — gravity sampling was lower along the MT profile than elsewhere along the forward model profile locations. Co-located geophysical anomalies along these profiles, especially where the profiles diverge, are generally accurate to between 5 and 10 km. While every effort has been made to reduce error, the resolution of the MT data suggests that attempting to reduce the error to <5 km would not be feasible. Hence, we only focus on the larger features from the MT data.

The near surface of the Kimberley Basin is shown to have a flat-lying, moderately conductive signature from stations 108 to 146. At station 121, a west-dipping structure, interpreted from the MT (white dashed line), is co-located with a steeply east-dipping feature modelled from the potential field data. The disagreement in dip direction near the surface can be reconciled with the deeper extent of a structure modelled from the potential field that has an overall westward dip. Here it is likely the MT data do not have the resolution to image near-surface structure.

A west-dipping structure at station 125 (Fig. 19) was interpreted from the MT data by Spratt et al. (2014) as the westernmost boundary of a large resistive feature. A deep conductor is located near this structure, providing a possible source for the electrical contrast at this location. This large structure, which could penetrate to the middle and maybe lower crust, is not shown strongly in the potential field data. However, a magnetic anomaly modelled as shallow (Fig. 18, $x \approx 195$ km, $z < 3$ km; Fig. 19, between station 125 and 126) may be the surface expression of this larger structure, and does correspond to a structure in the Cambridge Gulf interpretation (F, Fig. 14b). A similar situation was observed at station 144, where another west-dipping feature was interpreted in the MT data, corresponding to the eastern extent of the large resistive feature; the crust is more conductive to the east. The potential field model shows no dipping structures (Fig. 18, $x \approx 220$ km), although the Cambridge Gulf interpretation indicates the presence of surface structures (E, Fig. 14b). This location corresponds to a contact between Kimberley Basin rocks and Hart Dolerite.

Towards the east at stations 146 and 153 (Fig. 19), the MT and potential field forward model show reasonable agreement in both the location and geometry of structures and anomalous features. The depth to the top of the conductive feature is deeper than that of the thin magnetic layer modelled in the potential field profile; however, shallowly east-dipping conductive features in the MT also agree with dip and dip direction of the potential field model in this location (Fig. 19, between stations 146 and 147). The west-dipping structure interpreted at station 153 also corresponds to the west-dipping feature modelled in the potential field model (Fig. 18, $x \approx 270$ km) and the Carr Boyd Fault on the CAMBRIDGE GULF 1:250 000 map. At station 155, an east-dipping structure was interpreted from the MT and corresponds to an east-dipping feature in the potential field model, though the MT feature appears to be deeper penetrating. The east-dipping structure is at a similar location as the Cockatoo Fault.

## Central Profile

The 247 km long Central Profile (Fig. 20) starts in the western Kimberley Basin, crosses the Western and Central Zones of the Lamboo Province, and ends in the Eastern Zone (Fig. 17). The overall petrophysical model of the Kimberley and Speewah Basins is similar to that modelled in the Northern Profile, so this description focuses on the geometrical differences.

A continuous, highly magnetic (0.022 to 0.028 SI) and dense (2900 to 3000 kg/m$^3$) body at $x = 48$ km (Fig. 20) was modelled to bifurcate. It was interpreted to be two sills of Hart Dolerite separated by King Leopold Sandstone; they are separate as they crop out further along strike to the east on the LANSDOWNE 1:250 000 map. A westerly dipping feature, modelled at $x = 61$ km, was interpreted to be a normal fault with a west-side-down offset. Here the depth-to-basement modelling suggests the basins deepen to ~6 km. The basement on either side of this fault exhibits differences in magnetic susceptibility. Based on this and the thicker basin, the normal fault was modelled to be a basement-penetrating fault.

Another westerly dipping discontinuity was modelled at $x = 84$ km (Fig. 20), this time with a lesser, west-side-up offset. This is also modelled to be a fault, and though the offset suggests reverse faulting, the offset is relatively small and it is probably an apparent offset. Sinistral movement (east side into the image) during the Yampi or, more likely, King Leopold Orogeny (Thorne and Tyler, 1996), in combination with northwesterly trending open folding in the Kimberley Basin, could have produced this effect. Alternatively, a series of alternating outcrops of Hart Dolerite, and sedimentary rocks of the Kimberley and Speewah Basins, could produce a similar effect. A complex pattern of low- and high-magnetic bodies, with low and high densities, were modelled at the surface at $x = 87$ km. They are interpreted to be outcropping Carson Volcanics and Hart Dolerite overlying and intruded into lower Kimberley Group and Speewah Group rocks. A large, nonmagnetic and low-density (2650 kg/m$^3$) body was modelled at $x = 91$ km and $z = \sim 650$ m, and was interpreted to be felsic rocks of the Paperbark Supersuite. The body marks the westernmost extent of the Western Zone in the Central Profile. This body deepens to 6 km toward the east at $x = 135$ km. Overlying the Paperbark Supersuite rocks, between $x = 98$ and 113 km, is a thin, moderately magnetic (0.01 SI) and low-density (2550 kg/m$^3$) body interpreted to be Whitewater Volcanics. A shallow, highly magnetic and dense body can be seen at $x = 117$ km, and was interpreted to be a mafic component of the Paperbark Supersuite.

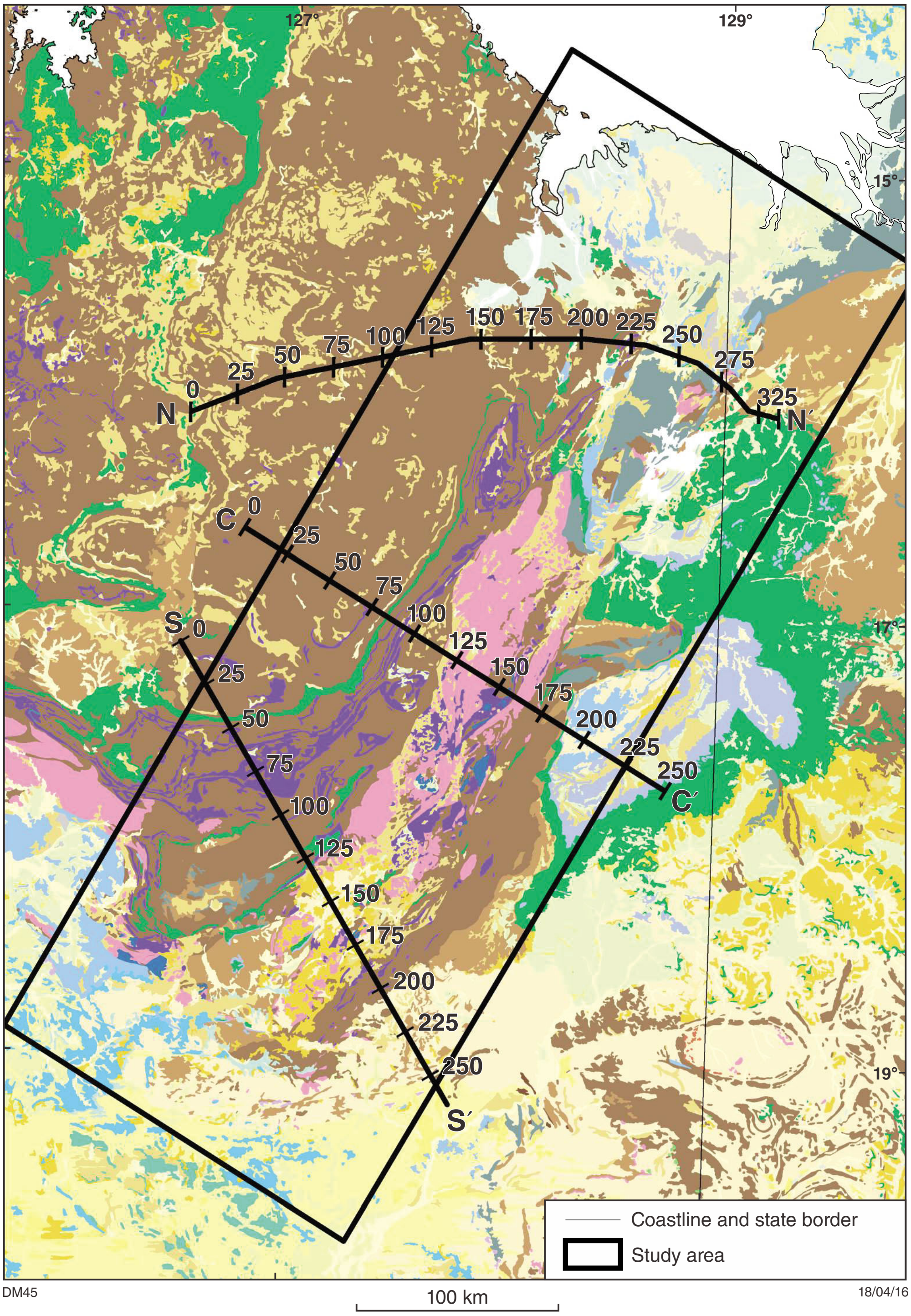



**Figure 17. Simplified geology (1:1 000 000 scale) overlain by forward profile locations (N = Northern, C = Central, S = Southern); distance from the start (eastern end) of each line shown in kilometres**

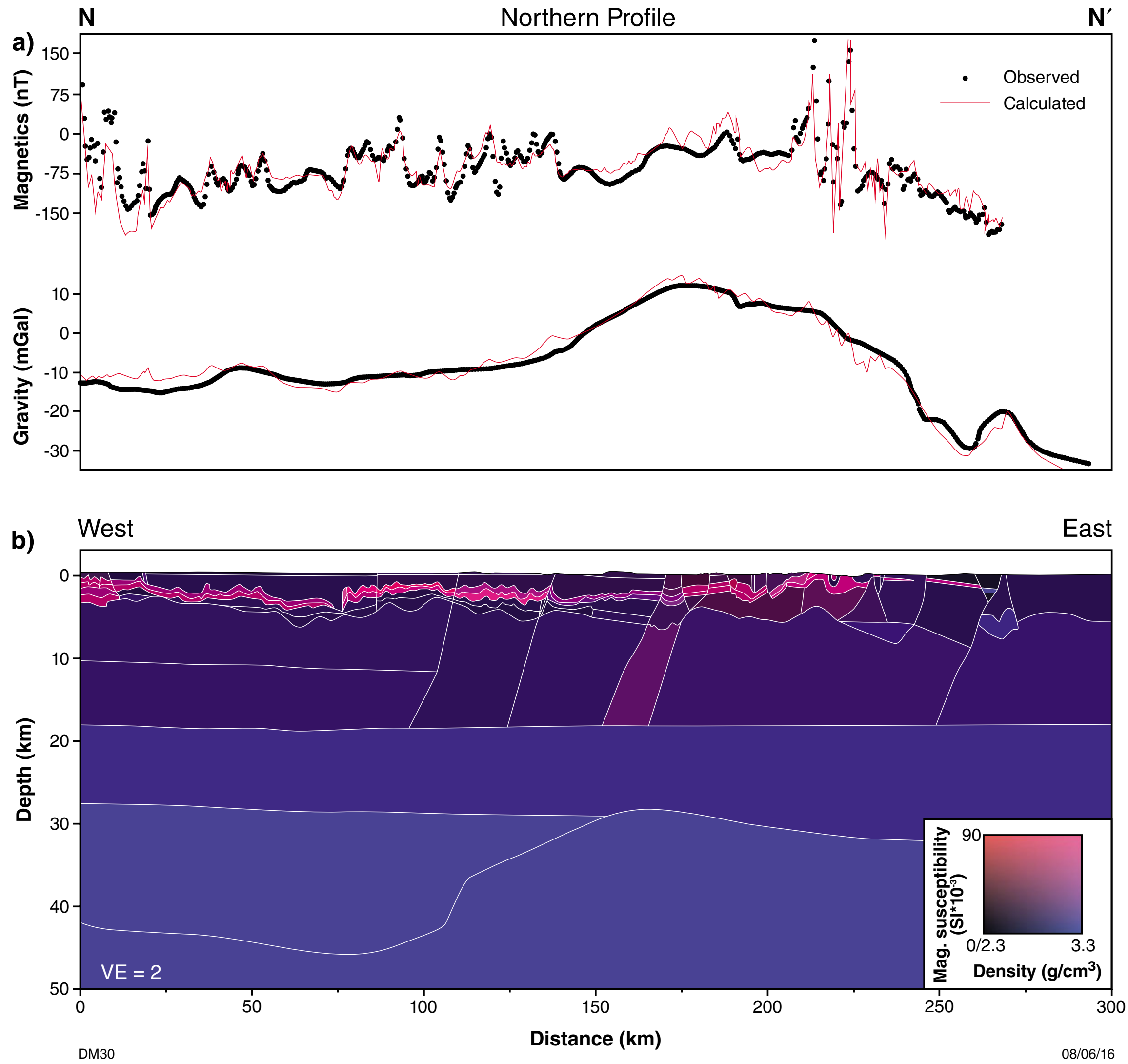



**Figure 18.** Combined gravity and magnetic model along the Northern Profile (see Fig. 17 for location), viewed from the south: a) magnetic susceptibility, density distributions, and the fit to magnetic and gravity data; b) geophysical section model

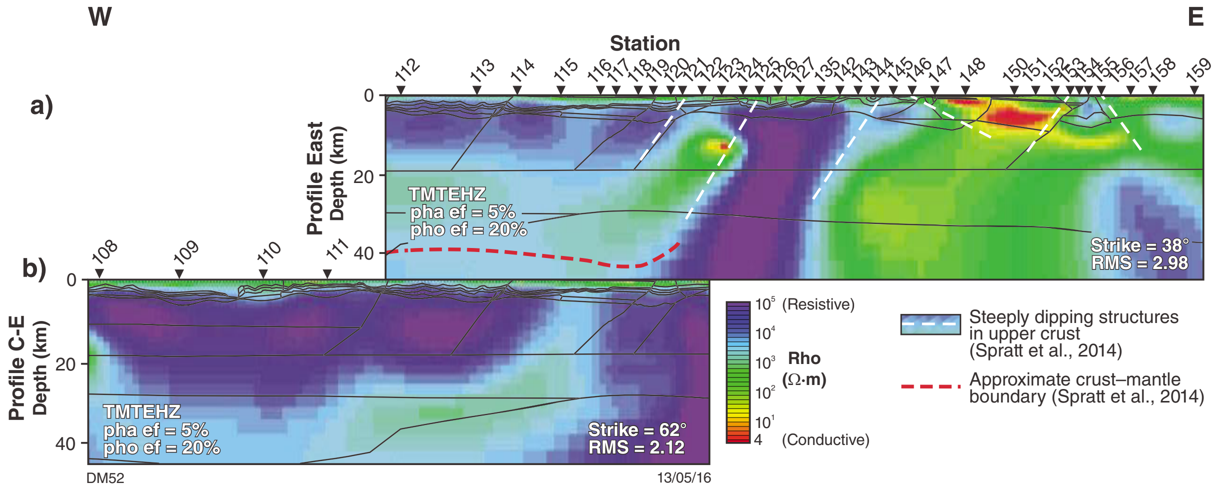



**Figure 19.** The preferred 2D modelled sections along Profile East (Spratt et al., 2014), modelled assuming a geoelectric strike angle of (a) 38° and (b) 62° (angles chosen according to lowest RMS error); the thin solid lines overlying the MT sections are the boundaries modelled from the forward model shown in Figure 18

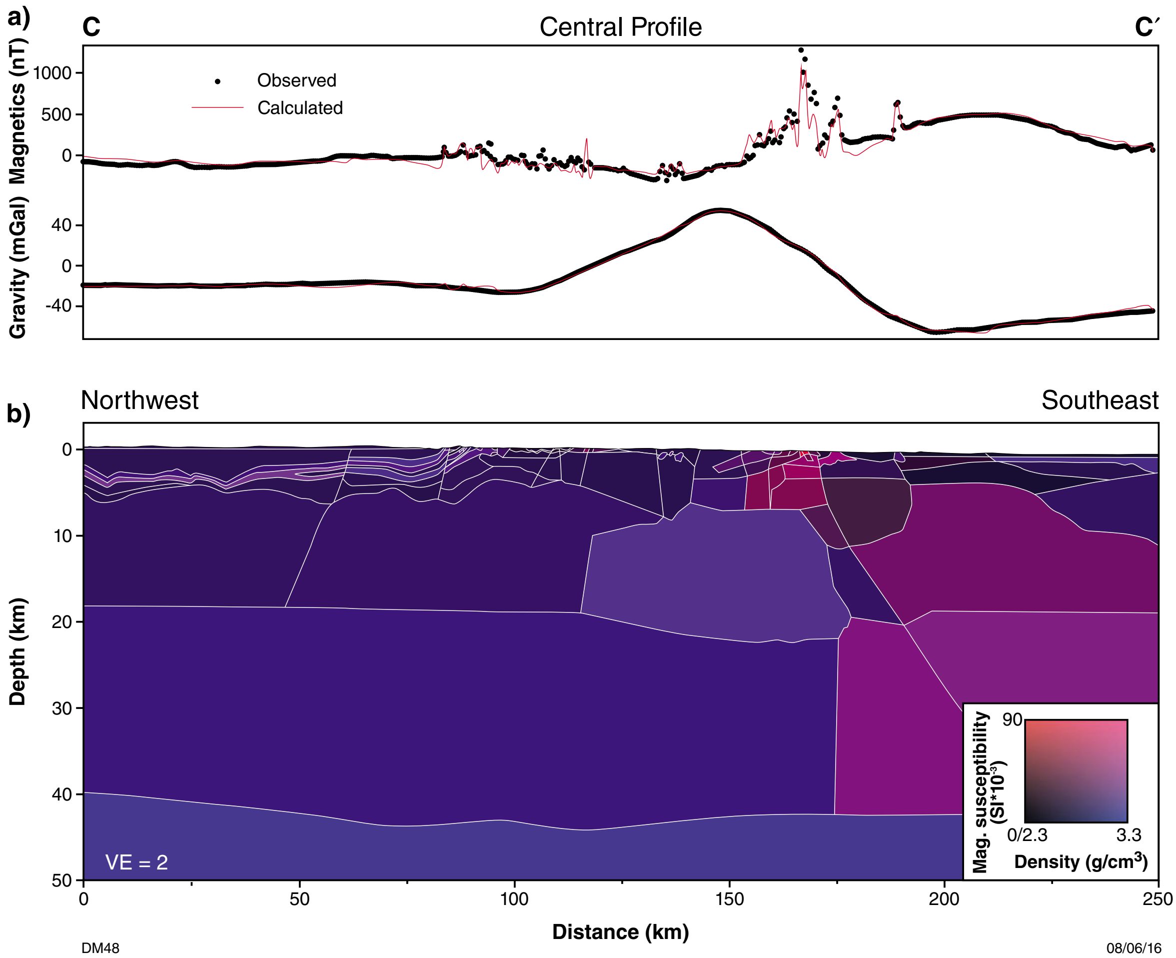



**Figure 20. Combined gravity and magnetic model along the Central Profile (see Fig. 17 for location), viewed from the south: a) magnetic susceptibility, density distributions, and the fit to magnetic and gravity data; b) geophysical section model; this profile shows the high-amplitude gravity anomaly as a voluminous density anomaly**

A slightly less dense, nonmagnetic body was modelled between x = 123 and 144 km (Fig. 20); it was interpreted to be felsic rocks of the Sally Downs Supersuite and marks the boundary between the Western and Central Zones. Three magnetic and dense bodies were modelled at shallow depths between x = 135 and 140 km, and are interpreted to be northeasterly trending mafic intrusions, likely to be small mafic units of the Sally Downs Supersuite. From x = 142 to 172 km there is a series of highly magnetic (0.035 to 0.04 SI), moderately dense (2500 to 2800 kg/m$^3$) bodies interpreted to be parts of the Tickalara Metamorphics. Magnetic and moderately dense bodies from z = 3 to 6 km are interpreted to be intrusions of the Sally Downs Supersuite.

An east-dipping discontinuity was modelled at x = 172 km (Fig. 20), with magnetic and dense rocks on the western side. Less magnetic and less dense rocks were modelled to the east at shallow depths, with high-magnetic susceptibility rocks on the eastern side from z = 10 km to the Moho. This east-dipping discontinuity was interpreted to be the Halls Creek Fault; if correct, the discontinuity marks the boundary between the Central and Eastern Zones. From here to the eastern end of the profile, the shallow part of the Eastern Zone contains low- to moderate-density (2550 to 2650 kg/m$^3$) bodies that are interpreted to be Halls Creek Group rocks overlain by various Devonian sedimentary rocks. Undulating geometry was observed and interpreted to be long-wavelength (tens of kilometres) folding. Higher density rocks (2730 to 2760 kg/m$^3$) underlie the Halls Creek Group and are interpreted to be basement to the Eastern Zone. Basement here (z = 3 km) was modelled to be shallower than in the Central Zone.

Basement units can be separated into three units based on their modelled magnetic susceptibility. The basement to the Kimberley and Speewah Basins has a low modelled susceptibility (0.002 SI), basement to the Western and Central Zones is high (0.02 SI), and the basement to the Eastern Zone is very high (0.047 SI). A highly magnetic (~0.05 SI) lower crust was also modelled under the Eastern Zone basement.

The Central Profile intersects an obvious large, high-amplitude gravity anomaly located approximately between the Central and Eastern Zones (Fig. 6b). This anomaly has been feature tested with three geological scenarios. No other modelled bodies in the section were adjusted during feature testing. Each of these scenarios results in almost exactly the same calculated gravity response, and can all be considered geophysically valid as they match the observed signal. The first scenario (Figs 20 and 24) models a susceptible (0.031 SI) and dense (3020 kg/m$^3$) body at 5–21 km depth, that is 63 km wide and is in contact with the Sally Downs Supersuite intrusions. This scenario was interpreted to be a possible deep mafic part of the Sally Downs Supersuite. The second Central Profile scenario models a large, easterly dipping body between 8 and 28 km depth with a width along the profile of 61 km (Figs 21 and 24). The body was modelled using a high susceptibility (0.031 SI) and high density of 61 km (3060 kg/m$^3$) and has basement between the upper crust (Sally Downs Supersuite) and the top of the body. This scenario could be interpreted as a very large mafic intrusion, or series of intrusions. The third scenario (Fig. 22) shows a relatively thin (5–6 km) and wide (~70 km) westerly dipping, magnetically susceptible (0.031 SI) and dense (3220 kg/m$^3$) body. This body sits in the middle crust at ~18 km depth and has been modelled to be separated from the Sally Downs Supersuite by basement. The third scenario was interpreted to represent a mafic crustal fragment, possibly the dense lower portion of an ophiolite, in order to explain the modelled high density values.

## Southern Profile

The southwesterly trending Southern Profile (Fig. 23) is 266 km long and begins in the western Kimberley and Speewah Basins, crosses the Western, Central and Eastern Zones of the Lamboo Province about 40 km southwest of the town of Halls Creek, and terminates close to the border of the Eastern Zone and the Birrindudu Basin (Fig. 17). The petrophysical and geometrical characteristics of the Kimberley and Speewah Basins are similar to those of the Central and Northern Profiles and show thin and continuous, dense magnetic bodies interpreted to be Carson Volcanics and Hart Dolerite. Both these units are flat lying until x = 45 km where the Carson Volcanics crop out, and from x = 50 to 87 km, where the Hart Dolerite and Speewah Group alternately crop out.

A thin, nonmagnetic and low-density (2600 kg/m$^3$) body at x = 87 to 120 km (Fig. 23) was modelled over a nonmagnetic, higher density (2670 kg/m$^3$) body to the west, and a smaller, moderately dense (2720 kg/m$^3$) body to the east (x = 100 km). The total thickness of these three bodies is 3.5 km. The thin shallow body was interpreted to be Whitewater Volcanics, which overlies felsic to intermediate Paperbark Supersuite rocks. Marboo Formation is mapped between x = 95 to 102 km, but cannot be resolved in the geophysical data and has not been modelled.

A 2–3 km thick, low susceptibility and low-density body was modelled from x = 102 to 147 km. It was interpreted to be sedimentary rocks of the Speewah and Kimberley Groups, with shallow magnetic bodies at x = 103, 121 and 128 km; these were interpreted to be mafic dykes. A moderately dense body underlying the Speewah and Kimberley Groups, from x = 128 to 147 km, was interpreted to be a mafic part of the Sally Downs Supersuite, and marks the boundary with the Central Zone of the Lamboo Province.

A series of moderately magnetic (0.009 to 0.018 SI) and dense (2660–2700 kg/m$^3$) bodies were modelled from x = 147 to 185 km, up to 6.5 km depth (Fig. 23); these were interpreted to be the felsic parts of the Sally Downs Supersuite. More magnetic (>0.02 SI) and dense (~2800 kg/m$^3$) bodies are interpreted to be mafic parts of the Sally Downs Supersuite.

A very high-magnitude and high-frequency magnetic signal is observed at x = 170 to 177 km (Fig. 23). Attempts to model this signal using susceptibility alone proved impossible; however, it can be replicated if magnetic remanance is applied. Magnetic susceptibility is 0.03 to 0.06 SI, with a steep remanent positive magnetization of 1.7 to 5.7 A/m. The body is moderately dense (2750 to 2830 kg/m$^3$) and appears to be folded. This body was interpreted to be the McIntosh Suite intrusions, which were mapped to outcrops in this area at x = 171, 173, 176 and 177 km.

A distinct change in the magnetic signal was noted at x = 178 to 183 km (Fig. 23); a nonmagnetic, moderately dense (2660 kg/m$^3$) body was modelled to 1–2 km depth and was interpreted to be the Koongie Park Formation. A discontinuity was modelled at x = 183 km, due to density contrasts. It coincides with the location of the Halls Creek Fault and marks the edge of the Central and Eastern Zones. A flat-lying discontinuity intersecting the Woodward Fault was interpreted to form a boundary at approximately 10 km depth between a moderate density (2700 kg/m$^3$) body and deeper, higher density basement (2890 kg/m$^3$). The moderate density body from the surface to 10 km depth was interpreted to be the Halls Creek Group. The Halls Creek Group is thought to be approximately 7 km thick, so to achieve the 10 km thickness, this may have been tectonically thickened. Alternatively, the southern part of the group could comprise an older unit at depth, such as less dense units of the Sophie Downs Suite.

Shallow and thin magnetic (0.025 SI) bodies were modelled from x = 194 to 204 km and were interpreted to be Woodward Dolerite intruding Halls Creek Group rocks. The southeastern end of this body exhibits a complex geometry and appears to be folded, in contrast to the flat-lying northwestern end. This suggests either complex, asymmetric folding or, that the flat-lying portion is a primary magmatic structure feeding the Woodward Dolerite.

Angled structures propagating from the flat-lying discontinuity are interpreted to be the deeper extension of interpreted sinistral shear zones (Fig. 16). Mapped northwesterly verging folds support a steep southeasterly dip.

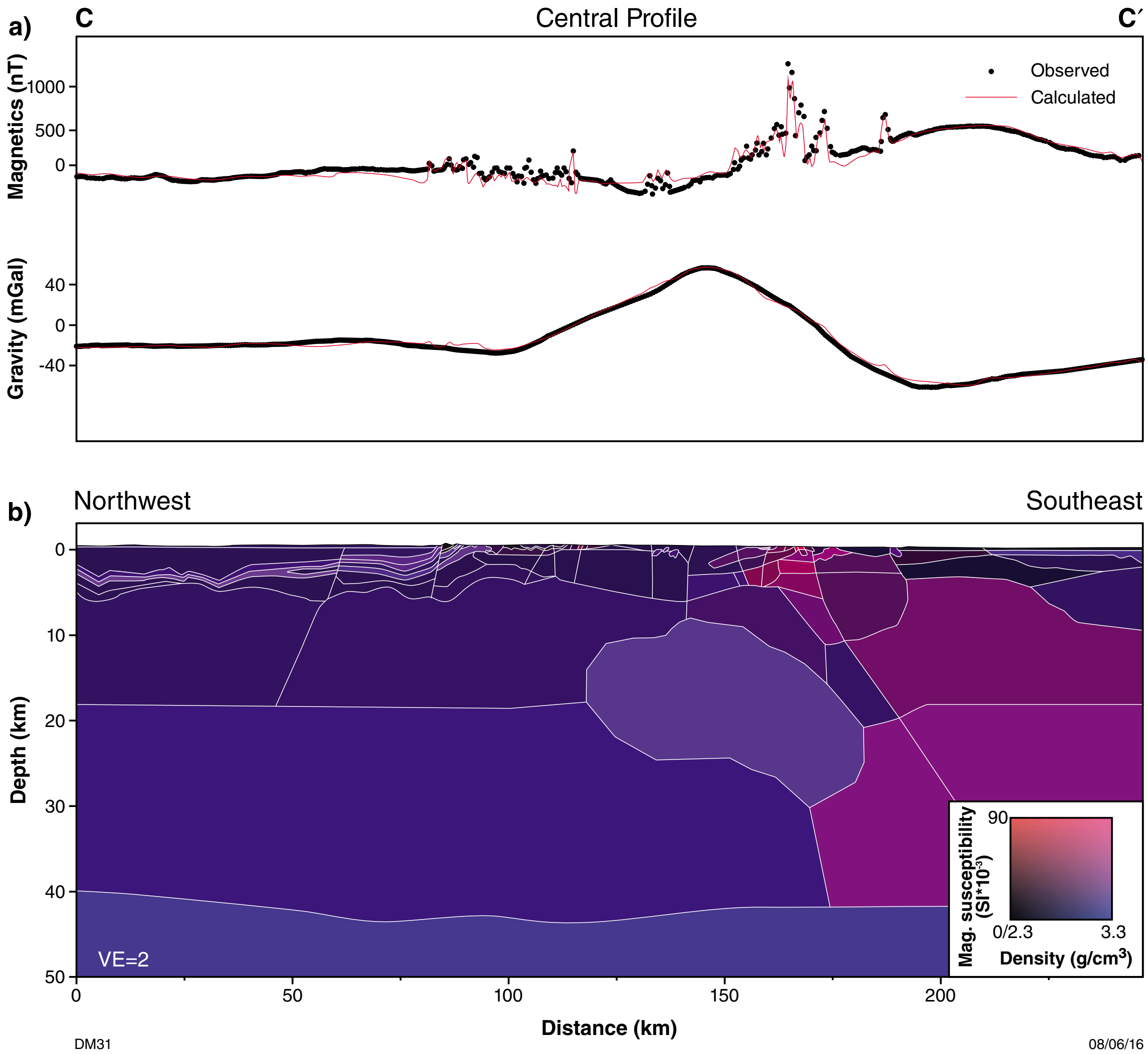



**Figure 21. Alternative combined gravity and magnetic model along the Central Profile (see Fig. 17 for location): this profile shows the high-amplitude gravity anomaly as a gently east-dipping body with its centroid in the middle crust**

Deeper basement bodies modelled in the Southern Profile are all nonmagnetic and can be differentiated based on their density contrast. The basement to the Kimberley and Speewah Basins was modelled as a single volume of moderate density (2715 kg/m$^3$). A westerly dipping discontinuity was modelled between the Kimberley and Speewah Basins and the Lamboo Province based on a two-layer basement model: 2700 kg/m$^3$ from z = 3.5 – 11 km, and 2750 kg/m$^3$ from z = 11 km to the top of the lower crust. Deep in the Eastern Zone, a lower density (2700 kg/m$^3$) basement was modelled to the east of the Central Zone basement; this suggests another major discontinuity at depth which could be a deeper part of the Woodward Fault.

# Discussion

## Metamorphism

Rocks now exposed in the Central and Western Zones were metamorphosed from greenschist to granulite facies during the Hooper Orogeny, whereas rocks in the Eastern Zone were not metamorphosed or deformed at this time (Fig. 5). The later Halls Creek Orogeny variably affected all zones of the Lamboo Province, suggesting that the Lamboo Province tectono-stratigraphic terranes (Western, Central and Eastern Zones) were adjacent by the time peak metamorphism was reached (Bodorkos

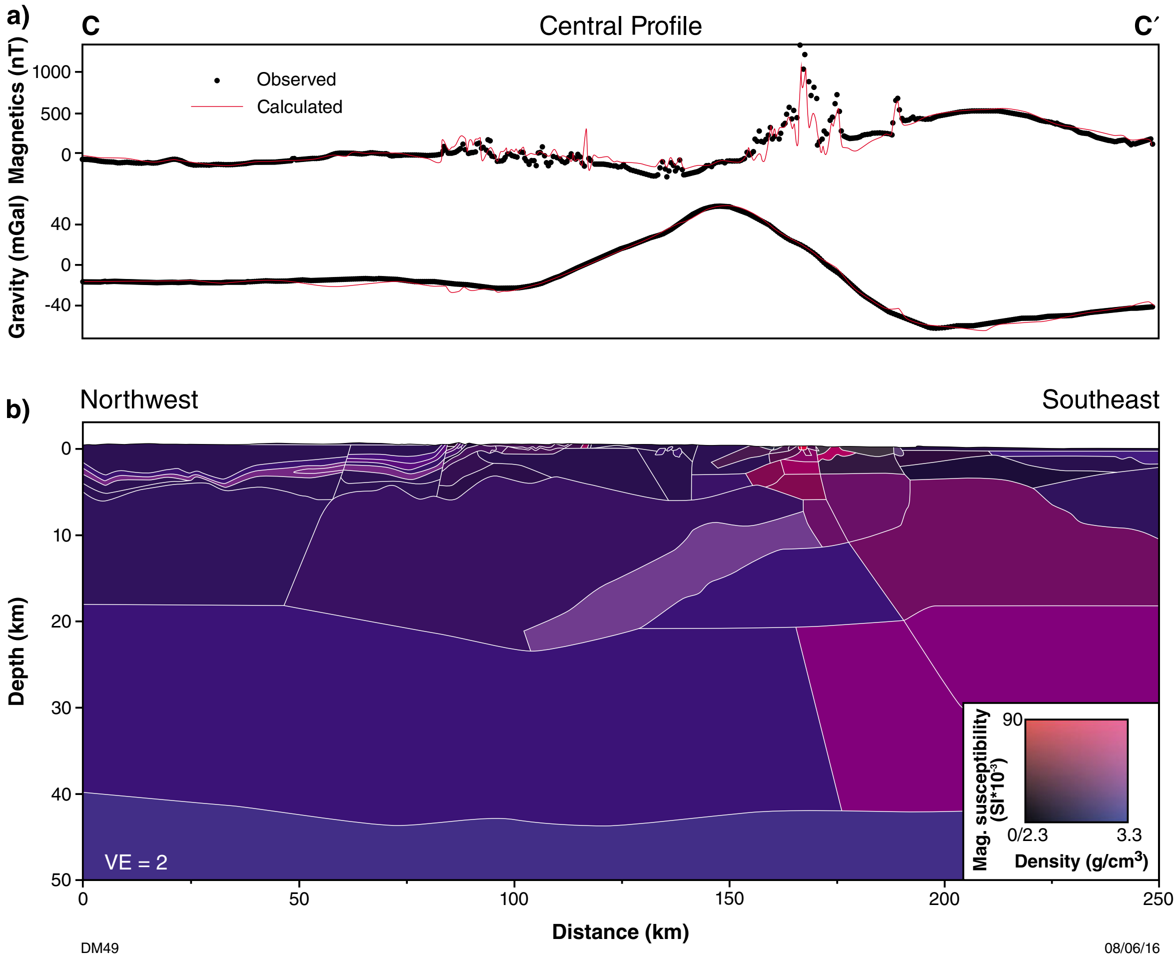



**Figure 22. Alternative combined gravity and magnetic model along the Central Profile (see Fig. 17 for location): this profile shows the high-amplitude gravity anomaly as a thinner, west-dipping body**

et al., 2002; Fig. 5b in Tyler et al., 2012). The present metamorphic grade of outcropping units along the strike of the orogen suggests structurally controlled exhumation of fault blocks at different rates during the Halls Creek Orogeny. The sharp boundaries between low–medium and high metamorphic grades suggest structural control, as the elliptical shape, steep metamorphic gradients and conditions exhibited in adjacent zones are not indicative of temperature being the sole driver for the metamorphic anomaly. If the high-grade zone was a result of elevated temperatures from an asthenospheric upwelling or similar event, the metamorphic gradients along the strike of the orogen would be shallower than what is shown (Bodorkos and Reddy, 2004). Further, a corresponding increase in metamorphic grade is not observed in the adjacent Western Zone, which is considered to have been juxtaposed with the Central Zone at this time. This suggests that temperature was not elevated in this zone, and at the very least, exhumation was facilitated along the Western/Central Zone boundary, at the Springvale Fault. Exhumation likely took place either late in the Hooper Orogeny, during rifting after the Hooper Orogeny and before the Halls Creek Orogeny, or during the Halls Creek Orogeny. Differential exhumation of different regions in the Eastern and Central Zones likely happened during all of the above periods — from 1850 to1805 Ma. The mechanism that drove the exhumation is the focus of the next part of the discussion.

## Large-scale structures

The influence of deep and large-scale structures on controlling the architecture of the middle to upper crust has been established in several studies (e.g. Hill, 1991; Ben-Avraham and Zoback, 1992; White et al., 2014). Structures that are oriented at high angles to orogens may also control crustal architecture (White and Muir, 1989; Hintersberger et al., 2011; Marsellos et al., 2014). Such structures are thought to be zones of low strength and higher permeability that act as fluid conduits supplying metal-rich fluids to the crust (Cox et al., 2001). As zones of weakness, such structures have influenced the geodynamic evolution of the east Kimberley region. If the northeasterly trending region of high-grade metamorphism in the centre of the Lamboo Province (the Dixon Range

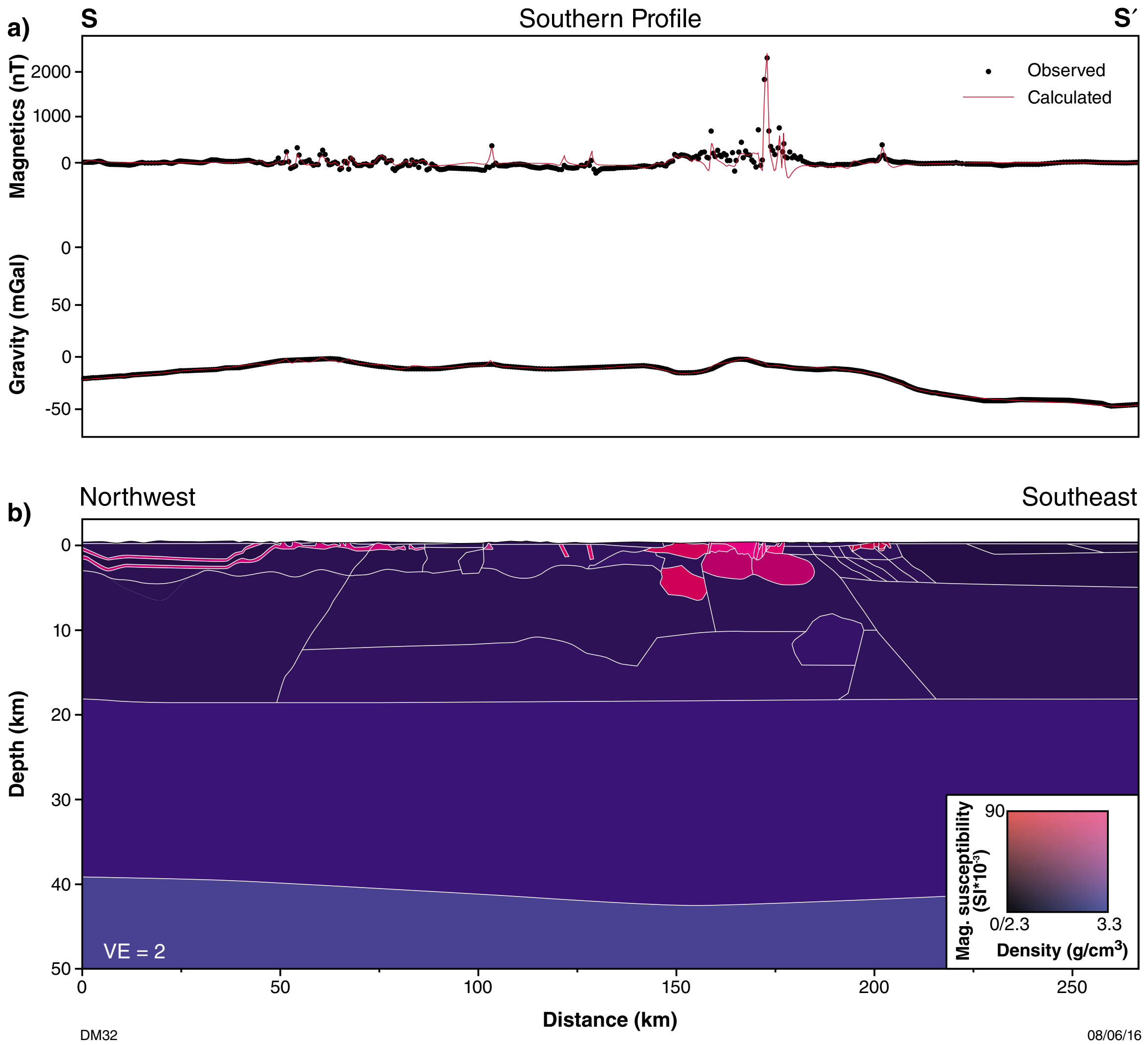



**Figure 23. Combined gravity and magnetic model along the Southern Profile (see Fig. 17 for location), viewed from the south: a) magnetic susceptibility, density distributions, and the fit to magnetic and gravity data; b) geophysical section model**

area, Fig. 11a,b) has been exhumed at greater rates than those to the north (Cambridge Gulf area) and south (Mount Ramsey area), then the southern and central orogen-normal structures most likely accommodated differential uplift, or subsidence.

The association of c. 1850 Ma mafic–ultramafic intrusions (Toby Gabbro and Corridor Gabbro) with the orogen-normal structures suggests that these structures were present from at least the Hooper Orogeny (Fig. 11c). Thus, the orogen-normal structures were almost certainly present early in the tectonic evolution and prior to peak metamorphism (c. 1845 Ma, Bodorkos et al., 2002). While they may have been present during the Hooper and Halls Creek Orogenies, what initiated the formation of these structures is unknown; it requires some evidence of perturbation to the overriding plate during convergence. The dense mid-crustal body in the Dixon Range area may provide evidence for such a mechanism.

## Dixon Range area gravity anomaly

The gravity anomaly in the Dixon Range area reflects a mid- to lower crustal, high-density mass in the region. Three models of the gravity anomaly were produced in order to explore the possible geological explanations of its nature amongst a large number of possible geophysical solutions. Constraints provided by petrophysics helped to reduce the size of the solution space, as did examination of the gravity signal attributed to the anomaly. Together, these forward models provide a basis for alternative interpretations.

The modelled density of the body shown in the Central Profile of Figure 21a is high enough to suggest either mafic or ultramafic rocks, as interpreted by Gunn and Meixner (1998) or a combination of mafic–ultramafic, mafic granulite and metapelitic rocks, as suggested by Shaw and Macias (2000) and Shaw et al. (2000).

The modelled anomaly shown in Figure 21a is consistent with a body with a more homogenous lithological composition than that suggested by the latter authors; however, the combination of overlying metapelitic (Tickalara Metamorphics) and intermediate (Sally Downs Supersuite) rocks contributes to the overall signal shown by the gravity in this area. This anomaly could represent a voluminous magma chamber that fed magmatism leading to the emplacement of the overlying Sally Downs Supersuite rocks. The deeper (~ 20 km), voluminous, lower density (3060 kg/m$^3$) body, shown in Figure 23b, could also represent a lower crust intrusion of mafic material forming a thick underplate to the Lamboo Province basement, a mafic–ultramafic sill, or a layered complex.

An alternative geometry and origin to the mafic–ultramafic bodies is considered here. Close examination of the long-wavelength signal exhibits an asymmetry, where the gradient of the slope is steeper to the east than the west, and shows lower gravitational response to the east (Fig. 20). On this basis, the modelled feature was given a westerly dip (Fig. 24e). The petrophysical values assigned to the westerly dipping body (density = 3220 kg/m$^3$, susceptibility = 0.031 SI) are at the higher end of what is observed in the upper crust, but are not beyond what is considered reasonable at ~18 km depth. The feature extends from the profile location to 65 km to the northeast, and ~100 km to the southwest totalling 165 km (Fig. 6b). It is 5–6 km thick and 68 km along the northwest axis. Assuming a thickness of 7.5 km, it has a volume of 84 150 km$^3$. These characteristics suggest the body to be a crustal fragment that was likely buried and reworked post-accretion by the successive Hooper and Halls Creek Orogenies.

The existence of a crustal fragment was proposed by Griffin et al. (2000) who suggested that a continental fragment formed oceanward of the Western Zone was accreted at >1900 Ma. Accretion of the fragment likely caused subduction to stall, and initiated (1) thrusting, (2) uplift, and (3) differential motion along axes perpendicular to the long axis of the subduction zone, to create transfer faults acting as accommodation zones (Gibbs, 1983, 1987; Lister et al., 1986). Thus, the orogen-normal structures are interpreted to be transfer faults initiated by accretion of a crustal fragment, which now resides in the mid-crust beneath the Central and Eastern Zones of the Lamboo Province.

Bodorkos et al. (2002) documented that high-temperature and high-pressure metamorphism took place at c. 1845 Ma in the central Lamboo Province; they suggested it was caused by anomalous basal heat flux coupled with mantle-derived mafic plutonism and lower crustal anatexis related to intrusive activity. The orogen-normal structures were reactivated to act as sidewall faults to thrusts or reverse faults and shears, allowing subvertical shearing and faulting (Ben-Avraham and Zoback, 1992; Aksu et al., 2000). This, in combination with c. 1845 Ma thermal activity and the 1835–1810 Halls Creek Orogeny, produced faster exhumation rates in the Dixon Range area. A modern analogue for this process is presented by Fuis et al. (2008) and supported by Bauer et al. (2014) where parts of the Yakutat terrane are interpreted to underplate the Alaskan Pacific margin. Features normal to the trench are interpreted by Fuis et al. (2008) to be slab tears, an assertion rejected by Bauer et al. (2014) who claim the data are unable to reliably detect such features.

While these interpretations may be more or less conceptually feasible, detailed geochemical, petrological and geophysical data (seismic or MT) would provide additional constraints to these models.

### North–south feature

Convergent processes can produce oblique fault propagation from collisional zones (Tapponnier et al., 1986; White et al., 2014; Moresi et al., 2014). The northerly trending feature identified from the potential field data (Fig. 13a) is likely to have formed from tectonic processes during the Hooper or Halls Creek Orogenies. The surface expression of this feature is displayed on LISSADELL and DIXON RANGE (1:250 000 map sheets) as a series of anastomosing north–south trending faults, that were also seen during field mapping. The magnetic data show sinistral offset of rock units south of the Speewah Dome (A, Fig. 13), suggesting that this feature is a deep crustal-scale fault or shear zone. The observed offset likely happened during the 450–295 Ma Alice Springs Orogeny. Although this was probably the last major movement on the fault, the feature likely experienced multiple periods of reactivation.

## Magnetic basement to the Eastern Zone – Central Profile

A deep and thick, very highly magnetically susceptible zone was modelled from x = 170 to the end of the Central Profile (Fig. 20). Consideration for the Curie temperature must be made, as at the depths these magnetic bodies were modelled (magnetic basement extent z = 18 km, magnetic lower crust from z = 18 to 40 km), they may no longer be magnetically susceptible. If the geothermal gradient in the Eastern Zone is assumed to be 25 °C/km, then the Curie point temperature for magnetite (~580 °C) would be ~23.2 km, and would disagree with the modelled susceptibilities. However, this gradient is only a typical value, and there is evidence that the geothermal gradient in the Kimberley region is unusually low. Results from Chopping and Kennett (2015) indicate that depth to the base of magnetization in the region of this anomaly range from 35 to 50 km (Fig. 25). From this estimate, it is possible that these bodies can be magnetic to the depths modelled. The long-wavelength signal exhibited by this anomaly indicates that it is either: shallow, wide and has susceptibilities beyond that typically thought to be possible in the crust (>0.3 SI); or (as has been modelled) is deeper, more voluminous and comprises relatively fewer susceptible bodies. Potential candidates for the magnetic source underlying the Halls Creek Group are mafic or metavolcanic rocks of the Sophie Downs Suite, as suggested by Shaw and Macias (2000). However, attributing the magnetic signal to a single rock unit is geologically unsatisfying, as the signal is likely to be the result of a number of units. The identity and composition of the units remain unknown.

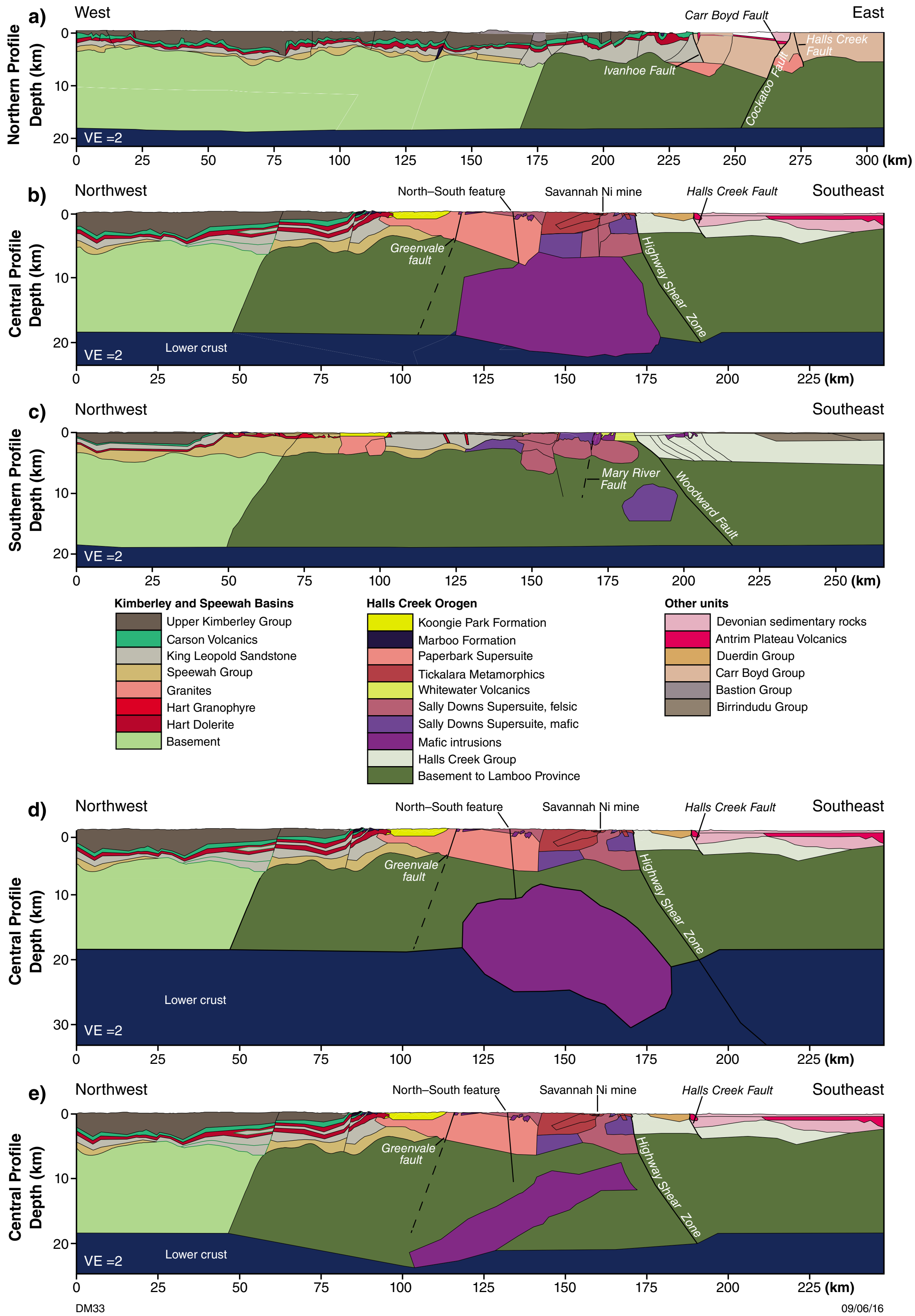



**Figure 24. Geological interpretations of each forward profile showing major structures in bold (dashed where confidence is lower): a) Northern Profile; b) Central Profile; c) Southern Profile; d) alternative model of the Central Profile showing a large, deeper high-density body to represent the high-amplitude gravity anomaly; e) alternative model of the Central Profile showing a westward dipping high-density body to represent the high-amplitude gravity anomaly**

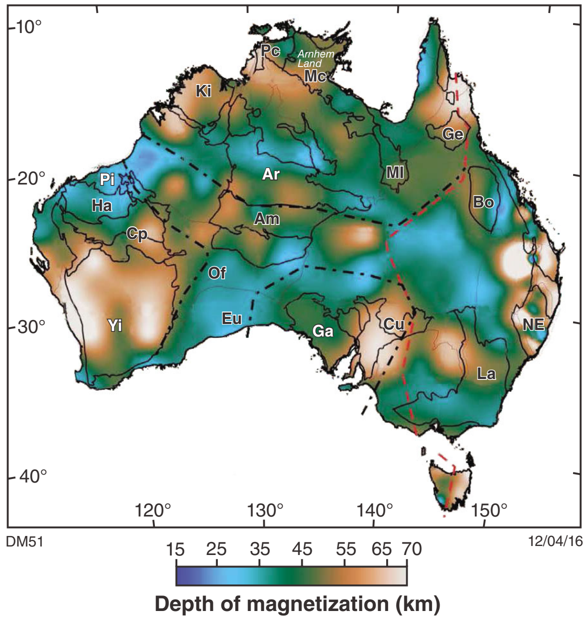



**Figure 25. Depth to base of magnetization (from Chopping and Kennett, 2015); note the high values indicating a base to magnetization of 35–50 km in the east Kimberley region**

# Geophysical characteristics of the Western, Central and Eastern Zones

In the east Kimberley region, the Western, Central and Eastern Zones of the Lamboo Province exhibit distinctive geophysical characteristics. The Eastern Zone can be distinguished from the others by a consistently low-gravity response, indicative of its origins as a passive margin and its relationship with the North Australian Craton (Tyler et al., 1998b; Blake et al., 2000a; Pawlowski, 2008). The Central Zone is characterized by a high, positive-gravity response, punctuated with a high-frequency, high-amplitude magnetic response attributed to a series of discrete but highly susceptible mafic units. The Western Zone is generally consistent, with a low to moderate density response associated with the Paperbark Supersuite. The boundary between the Western Zone and the Kimberley and Speewah Basins is marked by a high-frequency, high-amplitude response attributed to outcropping Hart Dolerite and/or Carson Volcanics. These characteristics reinforce the presence of, and boundaries to, the tectono-stratigraphic terranes of Tyler et al. (1995).

The electrical structure of the east Kimberley was revealed in the MT models of Spratt et al. (2014). The Kimberley and Speewah Basins appear to have a relatively consistent, layered signature with little horizontal variation from the surface down to 30 km depth: a thin near-surface conductive layer, a thicker resistive layer from 2–20 km, and a more conductive layer from 20–30 km. This signature appears to extend into the upper crust from station 108 to 144 or 146 (Fig. 19). A large conductor below station 123 (Fig. 19a) is probably related to local processes, such as connected sulfides and/or graphite, rather than a consistent feature diagnostic of the Kimberley and Speewah Basins. A large west-dipping resistor has been interpreted to be part of the Lamboo province by (Spratt et al., 2014) and could mark the buried western boundary of the province. The Western and Central Zones of the Lamboo Province do not appear to be prevalent in the near surface in this northern part of the study area, as is indicated by the potential-field structural interpretation and GSWA mapping; this suggests the MT profile may coincide with their northernmost extent. The Eastern Zone of the Lamboo Province has a relatively conductive signature in the upper crust, and is relatively resistive at depth. Further east, in the Northern Territory, the Ord and Birrindudu Basins are moderately conductive at the surface, and may be more resistive at depth. However, the data below these easternmost stations (x = 156 to 159, Fig. 19) may not have adequate resolution to state this definitively.

Overall, the MT data helped to identify important characteristics of the east Kimberley, even at the northernmost extent of the Western and Central Zones of the Lamboo Province. Ambiguity of some interpreted features was reduced because the MT data jointly image the geometry of crustal architecture with the potential field and geological data. The MT data proved useful in determining the mid- to lower crustal architecture, especially in locations where strong petrophysical responses near the surface suppressed more subtle, deeper responses from the potential field data at depth.

# Conclusions

An integrated geophysical and geological interpretation has revealed critical mineral system elements in the east Kimberley region. These include a region of anomalously high metamorphic grade in the centre of the study area; deep, crustal-scale, orogen-normal structures; and a northerly trending fault or shear zone. Modelling revealed a large, high-amplitude gravity anomaly located in the centre of the region. We suggest several possible sources for the anomaly: a large mafic intrusion; a thick underplate or layered mafic–ultramafic complex; a voluminous magma chamber linked to the emplacement of the overlying Sally Downs Supersuite; or a crustal fragment accreted and buried during the early to mid-Paleoproterozoic (Fig. 22b). The spatial relationship between the interpreted structural and metamorphic elements and the gravity anomaly was considered and modelled to explain how they may be related to the tectonic evolution of the region. The model that best accommodates the generation of all these geological phenomena involves the accretion and subsequent burial of a crustal fragment. Accretion of the fragment initiated regional-scale deformation involving the combination of vertical movement on the interpreted orogen-normal structures. Vertical movement is proposed to have facilitated accelerated exhumation of the central region of the Halls Creek Orogen, which resulted in the region of high metamorphic grade now observed at the surface.

Other regions in the east Kimberley were also investigated. A distinct and highly magnetic region in the Eastern Zone of the Lamboo Province, located at the end of the Central Profile, has a deep source of magnetism and is linked to the Sophie Downs Suite; however, further investigation is required to develop a stronger association. Finally, in the east Kimberley region, the Western, Central and Eastern Zones of the Lamboo Province were characterized by geophysical data. These data provide further support for the presence of these zones, originally defined by Tyler et al. (1995), and the location of their boundaries.

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# Appendix 1

# Geophysical analysis methods

Geological cross-sections discussed in the text incorporate lithologies mapped from outcrop (where available), and interpreted geology elsewhere. GSWA's WAROX database of structural measurements was used to constrain initial crustal structure (Tables 1.1, 1.2 and 1.3). Measurements include primary structures, such as igneous layering and bedding, and secondary structures, such as fold plunges, cleavages and foliations. While providing a useful guide to subsurface geometry, the measurements are prone to error for three reasons.

1. These measurements are never exactly on the profile, and due to the variable availability of outcrop, are often clustered in dense groups. The geometrical constraints must be projected onto the section, which requires extrapolation and averaging. Further, apparent dip must be considered where measurements describe structures close to or parallel to the profile.

2. The WAROX data describing structures (except for bedding) are not always directly linked to particular deformation events or related larger scale structures.

3. Caution was exercised during modelling as structures described by these structural observations are not necessarily correlated with the features observed in the geophysical data.

**Table 1.1. Lithological and structural information along the Northern Profile**

| *Distance (m) from SOP[(a)]* | *Lithology west of the point at x distance from SOP (column 1)* | *Lithology east of the point at x distance from SOP (column 1)* | *Structure type* | *Strike* | *Dip* | *Apparent dip* | *Direction[(b)]* |
|---|---|---|---|---|---|---|---|
| SOP | King Leopold Sandstone | King Leopold Sandstone | Bedding | 90 | 27 | | South |
| 1650 | King Leopold Sandstone | King Leopold Sandstone | | | | | South |
| 1850 | King Leopold Sandstone | King Leopold Sandstone | | | | | South |
| 1900 | King Leopold Sandstone | Carson Volcanics | Contact | | | | South |
| 8200 | Carson Volcanics | Warton Sandstone | Contact | | | | South |
| 8300 | Warton Sandstone | Warton Sandstone | | | | | South |
| 10500 | Warton Sandstone | Elgee Sandstone | Contact | | | | South |
| 11500 | Elgee Sandstone | Pentecost Sandstone | Contact | | | | South |
| 12250 | Pentecost Sandstone | Pentecost Sandstone | | | | | South |
| 19500 | Pentecost Sandstone | Pentecost Sandstone | | | | | South |
| 105100 | Elgee Sandstone | Elgee Sandstone | | | | | South |
| 126800 | Elgee Sandstone | Warton Sandstone | Contact | | | | South |
| 151250 | Pentecost Sandstone | Pentecost Sandstone | Inferred bedding | 316 | 7 | 5 | South |
| 226800 | Hart Dolerite | Hart Dolerite | | | | | South |
| 233490 | Antrim Plateau Volcanics | Antrim Plateau Volcanics | | | | | North |
| 234450 | Cockatoo Formation | Cockatoo Formation | | | | | South |
| 237200 | Cockatoo Formation | Cockatoo Formation | | | | | South |
| 262400 | Cockatoo Formation | Cockatoo Formation | | | | | North |
| 263200 | Cockatoo Formation | Cockatoo Formation | | | | | South |
| 264000 | Cockatoo Formation | Cockatoo Formation | | | | | North |
| 277400 | Marboo Formation | Marboo Formation | Foliation | 74 | 82 | 80 | South |
| EOP[(c)] | | | | | | | |

**NOTES**: (a) SOP = Start of profile (b) The direction of the WAROX point, north or south of the profile (c) EOP = End of profile

**Table 1.2. Lithological and structural information along the Central Profile**

| *Distance (m) from SOP[(a)]* | *Lithology west of the point at x distance from SOP (column 1)* | *Lithology east of the point at x distance from SOP (column 1)* | *Structure type* | *Strike* | *Dip* | *Apparent dip* | *Direction[(b)]* |
|---|---|---|---|---|---|---|---|
| SOP | Pentecost Sandstone | Pentecost Sandstone | | | | | |
| 120280 | Paperbark Supersuite | Paperbark Supersuite | Metamorphic fabric | 212 | 65 | 65 | South |
| 122238 | Paperbark Supersuite | Paperbark Supersuite | Metamorphic fabric | 219 | 82 | 82 | South |
| 122250 | Paperbark Supersuite | Paperbark Supersuite | Metamorphic fabric | 215 | 78 | 78 | South |
| 123700 | Paperbark Supersuite | Paperbark Supersuite | | | | | South |
| 142675 | Sally Downs Supersuite | Tickalara Metamorphics | Intrusive contact | | | | South |
| 142690 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic fabric | 214 | 64 | 64 | South |
| 147690 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic fabric | 41 | 25 | 25 | North |
| 150150 | Tickalara Metamorphics | Tickalara Metamorphics | | | | | South |
| 153200 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic fabric | 10 | 80 | 79 | North |
| 154300 | Sally Malay Ultramafics | Sally Malay Ultramafics | | | | | North |
| 155000 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic foliation | 255 | 68 | 60 | South |
| 155140 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic foliation | 104 | 74 | 44 | South |
| 159120 | Sally Downs Supersuite | Sally Downs Supersuite | Metamorphic foliation | 227 | 69 | 68 | North |
| 170900 | Tickalara Metamorphics | Tickalara Metamorphics | Bedding | 222 | 51 | 50 | North |
| 170900 | Tickalara Metamorphics | Tickalara Metamorphics | Fold axial surface | 209 | 73 | 73 | North |
| 171130 | Tickalara Metamorphics | Tickalara Metamorphics | Metamorphic foliation | 75 | 87 | 86 | North |
| 174000 | Olympio Formation | Olympio Formation | Metamorphic formation | 40 | 63 | 63 | South |
| EOP[(c)] | | | | | | | |

**NOTES**: (a) SOP = Start of profile (b) The direction of the WAROX point, north or south of the profile (c) EOP = End of profile

**Table 1.3. Lithological and structural information along the Southern Profile**

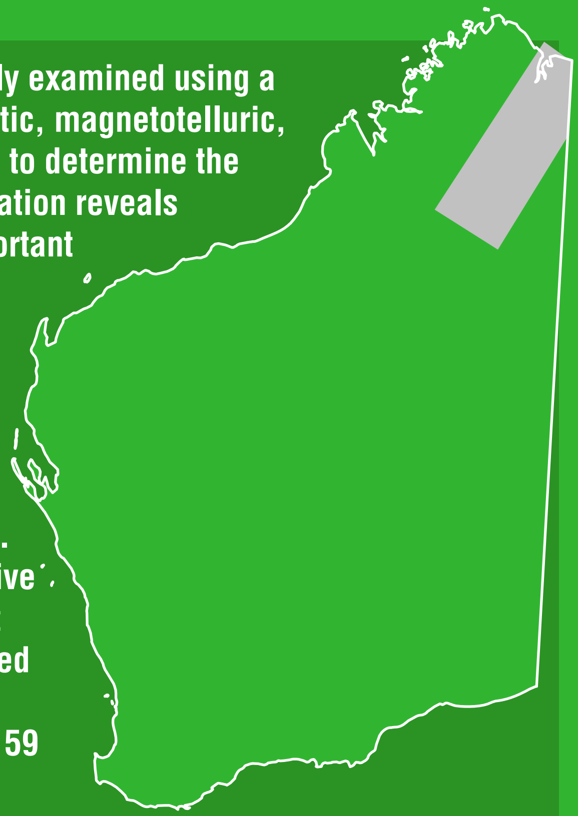
| *Distance (m) from SOP[(a)]* | *Lithology west of the point at x distance from SOP (column 1)* | *Lithology east of the point at x distance from SOP (column 1)* | *Structure type* | *Strike* | *Dip* | *Apparent dip* | *Direction[(b)]* |
|---|---|---|---|---|---|---|---|
| SOP | | | | | | | |
| 95000 | Whitewater Volcanics | Whitewater Volcanics | Fold axial surface | 261 | 71 | 68 | North |
| 96766 | Whitewater Volcanics | Paperbark Supersuite | Bedding | 78 | 76 | 75 | South |
| 163485 | Sally Downs Supersuite | Sally Downs Supersuite | | | | | South |
| 169050 | Tickalara Metamorphics | Tickalara Metamorphics | Cleavage | 176 | 83 | 74 | North |
| 169400 | Tickalara Metamorphics | Tickalara Metamorphics | Cleavage | 32 | 80 | 79 | North |
| 169400 | Tickalara Metamorphics | Tickalara Metamorphics | Fold axis | 302 | 36 | 69 | South |
| 170800 | Sally Downs Supersuite (mafic) | Sally Downs Supersuite (mafic) | | | | | North |
| 170900 | Sally Downs Supersuite (mafic) | Sally Downs Supersuite (mafic) | | | | | South |
| 171500 | Sally Downs Supersuite (felsic) | Sally Downs Supersuite (felsic) | Foliation | 69 | 83 | 83 | North |
| 171505 | Sally Downs Supersuite (felsic) | Sally Downs Supersuite (felsic) | Foliation | 14 | 45 | 35 | North |
| 175750 | Sally Downs Supersuite (felsic) | Sally Downs Supersuite (felsic) | Foliation | 12 | 79 | 74 | South |
| 175750 | Sally Downs Supersuite (felsic) | Sally Downs Supersuite (felsic) | Lineation | 27 | 63 | 59 | South |
| 183600 | Olympio Formation | Olympio Formation | | | | | North |

**Table 1.3. continued**

| *Distance (m) from SOP*[(a)] | *Lithology west of the point at x distance from SOP (column 1)* | *Lithology east of the point at x distance from SOP (column 1)* | *Structure type* | *Strike* | *Dip* | *Apparent dip* | *Direction*[(b)] |
|---|---|---|---|---|---|---|---|
| 189200 | Olympio Formation | Olympio Formation | | | | | South |
| 199560 | Olympio Formation | Olympio Formation | Bedding | 265 | 85 | 84 | North |
| 199560 | Olympio Formation | Olympio Formation | Crenulation cleavage | 227 | 58 | 57 | North |
| 200255 | Olympio Formation | Olympio Formation | Bedding | 66 | 85 | 85 | North |
| 200900 | Olympio Formation | Olympio Formation | Bedding | 64 | 81 | 81 | North |
| 200900 | Olympio Formation | Olympio Formation | Crenulation cleavage | 197 | 73 | 67 | North |
| 201200 | Olympio Formation | Olympio Formation | Fold axial surface | 46 | 90 | 90 | North |
| 201450 | Olympio Formation | Olympio Formation | Bedding | 49 | 67 | 67 | North |
| 201550 | Olympio Formation | Olympio Formation | Bedding | 61 | 70 | 70 | North |
| 202250 | Olympio Formation | Olympio Formation | Bedding | 63 | 82 | 82 | South |
| 227200 | Olympio Formation | Olympio Formation | Bedding | 250 | 70 | 70 | South |
| 227500 | Olympio Formation | Olympio Formation | Bedding | 15 | 65 | 57 | South |
| 227500 | Olympio Formation | Olympio Formation | Cleavage | 85 | 90 | 90 | South |
| 227550 | Olympio Formation | Ruby Plains Group | Bedding | 10 | 40 | 28 | North |
| 227800 | Ruby Plains Group | Ruby Plains Group | | | | | |
| 235900 | Ruby Plains Group | Ruby Plains Group | Bedding | 350 | 30 | 11 | North |
| 237250 | Ruby Plains Group | Ruby Plains Group | Bedding | 320 | 35 | 7 | North |
| EOP | | | | | | | |

**NOTES**: (a) SOP = Start of profile (b) The direction of the WAROX point, north or south of the profile (c) EOP = End of profile

The east Kimberley region was comprehensively examined using a range of geoscientific datasets. Gravity, magnetic, magnetotelluric, and geological field data have been interpreted to determine the crustal architecture of the region. The interpretation reveals characteristics of the Earth's crust that are important for understanding the regional tectonic history, potential zones of mineralization, and ore deposit formation. Structural geophysical interpretation was combined with potential field forward modelling to identify crustal-scale, orogen-normal structures and a large geophysical anomaly centred on the study area. These results were used to develop an alternative hypothesis for the tectonic evolution of the east Kimberley region. The geological insights gained from this study have been used in a companion mineral systems analysis described in Report 159 (Occhipinti et al., 2016).





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