Government of **Western Australia**
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RECORD 2017/8

THE DEEP SEISMIC REFLECTION PROFILE 11GA-YO1 IN THE WEST MUSGRAVE PROVINCE: AN UPDATED VIEW

by
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Geological Survey of Western Australia

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Cover image: Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph taken by I Zibra for the Geological Survey of Western Australia

Contents

Figures

Tables

The deep seismic reflection profile 11GA-YO1 in the west Musgrave Province: an updated view

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Abstract

The deep seismic reflection profile 11GA-YO1 (YOM) was acquired in 2011 and the first interpretation of the data was released in 2013. Since then, the Geological Survey of Western Australia (GSWA) has completed, in 2017, a 13-year geological mapping project in the west Musgrave Province. The main aim of this contribution is to provide an updated interpretation of the YOM section in agreement with our current understanding of the evolution of the west Musgrave Province. The crustal architecture of the west Musgrave Province results from at least three major crust-forming events: the 1345–1293 Ma Mount West Orogeny, the 1220–1150 Ma Musgrave Orogeny and the 1090–1040 Ma Giles Event, and from the amagmatic 580–520 Ma Petermann Orogeny. One main focus is the interpretation of the major structures. The Mitika Fault is interpreted as a steeply south-dipping reverse fault that offsets the Moho, and the Woodroffe Thrust is interpreted as a shallow south-dipping structure that soles into the Mitika Fault. Between these two crustal-scale structures, the Wanarn area displays a regional-scale, antiformal-stack geometry within which basement slivers of the Mesoproterozoic Musgrave Province are tectonically interleaved with paragneiss of the 1085–1075 Ma Kunmarnara Group. To the northeast of the Woodroffe Thrust, the Petermann Nappe Complex marks the transition between thick- and thin-skinned tectonics and is characterized by tectonic repetitions of cover sequences up to 25 km deep and then by stacked basement slivers in the lower crust. Several unconformable sedimentary basins overlie the Musgrave region. The interpreted extent of Ordovician sedimentary rocks of the Cobb Embayment (Canning Basin), over the southern end of the Petermann Nappe Complex, forms a new addition to the interpretation of the YOM section. Another conclusion that arises from this study is the need to redefine the minimum age of the Giles Event. Three U–Pb zircon dates at 1039 ± 7, 1035 ± 6 and 1031 ± 6 Ma, interpreted as magmatic crystallization ages obtained from rocks of the Tjauwata Group and of the Warakurna Supersuite in the Petermann Nappe Complex, indicate that magmatism associated with the end of the Giles Event is younger than previously recognized. The new age range for the Giles Event is therefore 1085–1030 Ma.

KEYWORDS: crustal evolution, crustal structure, deep seismic surveys, geochronology, geological province, orogeny, regional geology, tectonics, uranium thorium lead dating

Introduction

The 11GA-YO1 (YOM) seismic line extends from Tjukayirla, in the Laverton Shire of Western Australia, and runs northeast following the Great Central Road up to Warakurna, near the eastern border of Western Australia (Figs 1, 2). It images the northeastern edge of the Yilgarn Craton, the Officer Basin and the western end of the Musgrave Province. One of the main aims of the seismic line was to characterize the boundary between the Yilgarn Craton and the Musgrave Province which, at the current exposure level, is obscured by the Officer Basin. As a result of the first interpretation of the YOM seismic section, this boundary is now interpreted as a southwest-dipping structure that juxtaposes the strongly reflective and northeast-dipping Yilgarn crust with the less reflective, more seismically homogeneous, crust of the Musgrave Province (Neumann, 2013). Across this boundary, the Moho depth varies from about 15 s two-way-time (TWT) which corresponds to an approximate depth of 45 km assuming a crustal velocity of 6000 m/s (i.e. 1 s TWT is approximately equal to 3 km depth, Korsch et al., 2013) under the Yilgarn Craton, to up to 20 s TWT (~60 km depth) under the Musgrave Province (Korsch et al., 2013; Howard et al., 2013a).

Data for the YOM profile were acquired in a collaboration between Geoscience Australia (GA) and the Geological Survey of Western Australia (GSWA) in June 2011. The first interpretation of the YOM section was released in a GA publication (Neumann, 2013). GSWA has since completed a 13-year geological mapping project in the west Musgrave Province and released 1:100 000-scale geological maps of the area including Bentley (Howard et al., 2013b), Warburton Range (Howard et al., 2014), Golden Point (Quentin de Gromard et al., 2015) and Diorite (Quentin de Gromard et al., 2016a) as well as the digital interpreted bedrock geology (IBG) of Dickenson (GSWA, 2016). The proposed updated interpretation of the YOM section includes this recently acquired knowledge obtained from mapping, the drawing of four geological cross-sections near the YOM seismic line, and from geophysical and geochronology datasets. Additional U–Pb zircon geochronology data from 16 igneous rocks and 11 metasedimentary rocks relevant to the interpretation of the YOM section were obtained after the original interpretation. These data provide an excellent control on the age of the rock units in the subsurface of the YOM section. In this contribution, we present an up-to-date simplified IBG map of the west Musgrave Province, a summary of the recently acquired

U–Pb zircon geochronology data, and propose an updated view of the northeastern end of the YOM seismic section. Some characteristics of the original interpretation of the YOM section in the Musgrave Province still stand in the interpretation proposed here. The deep crustal architecture of the Musgrave Province remains interpreted as a three-layered crust: a moderately to strongly reflective, inhomogeneous, upper crust; a moderately reflective, relatively homogeneous, middle crust; and a poorly reflective, relatively homogeneous, lower crust. The crustal-scale faults are still interpreted as north-verging structures that resulted from intracontinental reworking during the 580–520 Ma Petermann Orogeny.

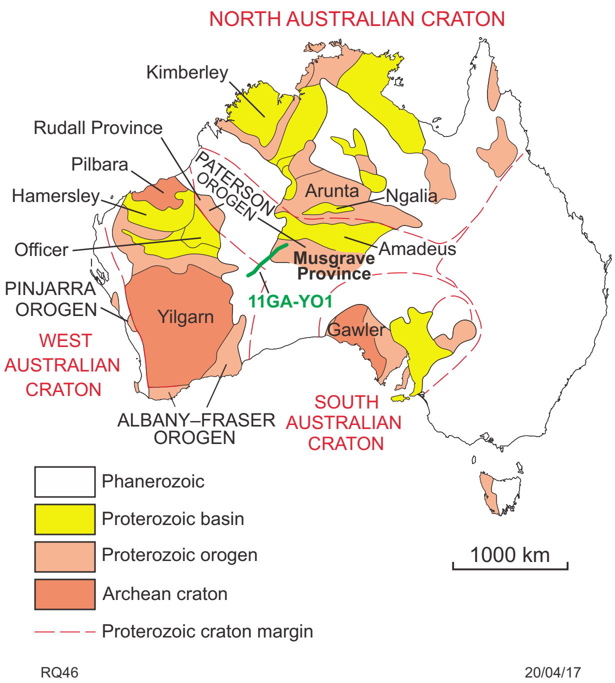

Figure 1. Tectonic map of Australia showing the location of the Musgrave Province and the trace of the deep seismic reflection line 11GA-YO1 across some of the main tectonic elements of Western Australia

Regional geology

The Musgrave Province is an 800 km long and 350 km wide, east-trending Mesoproterozoic orogen that lies at the triple junction between the North, South and West Australian Cratons (Fig. 1). The province is mainly exposed along the border between the Northern Territory and South Australia and extends into Western Australia, where it is referred to as the west Musgrave Province. It is bounded to the north and south by the younger Amadeus and Officer Basins, respectively. For a comprehensive review of the geology of the west Musgrave Province, see Howard et al. (2015) and references therein. A brief summary is presented here.

The oldest known rocks of the west Musgrave Province are poorly exposed orthogneisses of the 1607–1542 Ma Warlawurru Supersuite and granitic rocks of the c. 1400 Ma Papulankutja Supersuite (Howard et al., 2011; Quentin de Gromard et al., 2016b). The first main tectono-magmatic event identified is the Mount West Orogeny, during which granitic magmas of the 1345–1293 Ma Wankanki Supersuite were emplaced (Smithies et al., 2010; Howard et al., 2011). The volcano-sedimentary rocks of the 1340–1270 Ma Wirku Metamorphics are interpreted as a syn- to post-orogenic sequence deposited into the Ramarama Basin (Evins et al., 2012). All of these rocks were metamorphosed at ultra-high temperature during the Musgrave Orogeny, which was accompanied by the emplacement of the voluminous 1219–1148 Ma Pitjantjatjara Supersuite (Edgoose et al., 2004; Smithies et al., 2010). The Musgrave Province includes all rocks formed during, or affected by, the Musgrave Orogeny and constitutes the basement to rocks of the 1085–1040 Ma Giles Event. The Giles Event started with the deposition of siliciclastic sediments and the extrusion of mafic magmas of the 1085–1075 Ma Kunmarnara Group into the Bentley Basin (Evins et al., 2010). Igneous rocks formed during the Giles Event are assigned to the Warakurna Supersuite and include the giant layered mafic–ultramafic Giles intrusions (G1 intrusions), mixed and mingled gabbros and leucogranites (G2 gabbros) and the Alcurra Dolerite intrusions and bimodal volcanic rocks of the Talbot Supervolcano (Howard et al., 2009; Evins et al., 2010; Smithies et al., 2013a,b). Apart from minor mafic dyke intrusions at c. 1000, 825 and 750 Ma (Wingate et al., 1998; Howard et al., 2015), the Musgrave Province is commonly regarded as tectonically quiescent until intracontinental reactivation during the 580–520 Ma Petermann Orogeny. Deformation during the Petermann Orogeny produced east-trending crustal-scale faults and shear zones that dissect the entire Musgrave Province, including the Hinckley, Mann and Mitika Faults, and the Woodroffe Thrust (Bell, 1978; Lambeck and Burgess, 1992; Camacho and McDougall, 2000; Aitken et al., 2009; Quentin de Gromard et al., 2016b). In the central part of the Musgrave Province, the Woodroffe Thrust consists of a south-dipping, 3 km wide zone of mylonite and pseudotachylite, interpreted to offset the Moho by approximately 20 km (Bell, 1978; Lambeck and Burgess, 1992; Camacho and McDougall, 2000). In the west Musgrave Province, the most significant exhumation related to the Petermann Orogeny is in a wedge, the Bates region, bounded to the north by the gently south-dipping Woodroffe Thrust and to the south by the steeply south-dipping Mann Fault via a crustal channel-flow process (Fig. 2; Raimondo et al., 2009, 2010). The western extent of the Mann Fault on HOLT is lost in numerous splays, but the similarly oriented, steeply south-dipping, Mitika Fault that bounds the Wanarn area to the south may be regarded as a potential extension of the Mann Fault (Fig. 2; Quentin de Gromard et al., 2016b, 2017). Metamorphic conditions during the Petermann Orogeny approached eclogite facies south of the Woodroffe Thrust and up to amphibolite facies in the north-verging Petermann Nappe Complex (Scrimgeour and Close, 1999; Edgoose et al., 2004; Raimondo et al., 2010).

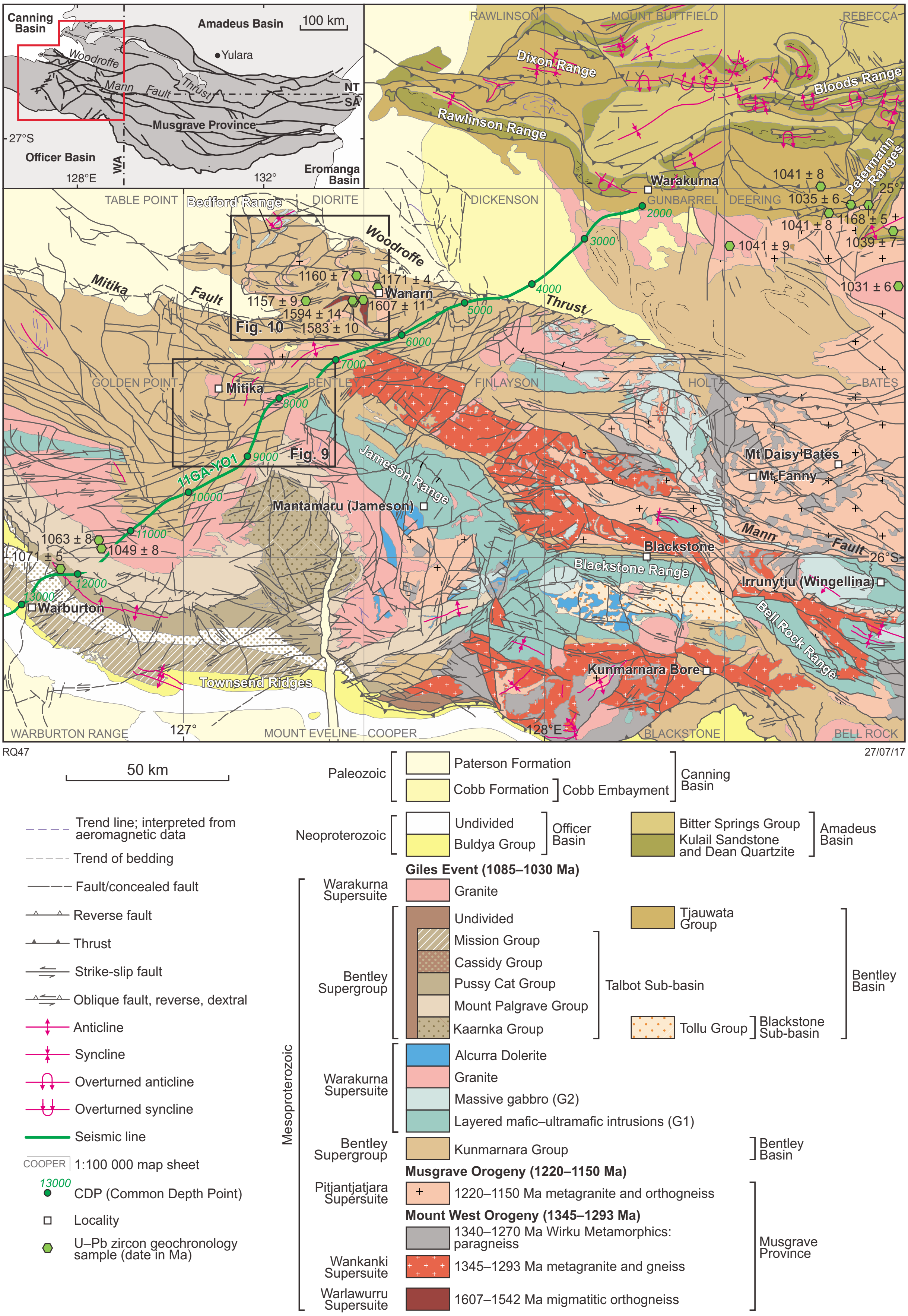

Figure 2. Interpreted bedrock geology of the west Musgrave Province (see inset for location) showing the main tectonic subdivisions, the trace of the deep seismic reflection line 11GA-YO1 and the location of U–Pb zircon geochronology data for igneous samples cited in the text

Surface geology along the northeastern end of the YOM seismic line

The interpreted portion of the YOM line proposed in this Record starts in the Officer Basin and traverses the west Musgrave Province towards the northeast (Fig. 2). Along the YOM line, the west Musgrave Province is divided from southwest to northeast into the Talbot Sub-basin, the Mitika and Wanarn areas, and the Petermann Nappe Complex (Fig. 2). The extent of the Talbot Sub-basin is defined by the preserved extent of rocks of the Kaarnka, Mount Palgrave, Pussy Cat, Cassidy and Mission Groups (Fig. 2). The Mitika and Wanarn areas, whose names are derived from the name of the respective localities, are located on either side of the Mitika Fault (Fig. 2). The Petermann Nappe Complex starts north of the Woodroffe Thrust and extends towards the north and northeast; the topographic expression of the Petermann Nappe Complex in Western Australia consists of the Rawlinson, Dixon, Bloods and Petermann Ranges (Fig. 2). In this section, we present the stratigraphy and lithology, structure, and U–Pb zircon geochronology of these subdivisions.

Along this portion of the YOM line, outcrops of the Officer Basin consist of northwest-trending ridges of laminated to very thick-bedded, well-sorted, medium- to coarse-grained quartz arenite and feldspathic arenite assigned to the Townsend Quartzite of the Neoproterozoic Buldya Group (Fig. 3a,b). The Townsend Quartzite dips approximately 20 degrees towards the southwest and, although the contact with the underlying rocks of the Mission Group is not exposed, the general parallelism of strike and dip of the Townsend Quartzite with strata of the Mission Group suggests that they are concordant in the Warburton area.

The Talbot Sub-basin preserves the upper part of the stratigraphy of the more extensive 1090–1026 Ma Bentley Basin. Along the YOM line, the stratigraphy of the Talbot Sub-basin is divided, from south to north and from youngest to oldest, into the Mission, Cassidy, Pussy Cat and Mount Palgrave Groups, all of which are dominated by interlayered bimodal volcanic and sedimentary rocks (Fig. 2). The Mission Group consists of vesicular and amygdaloidal basalt and basaltic andesite interlayered with fine- to coarse-grained siliciclastic rocks, minor dolostone, chert and possible microbialite (Fig. 4). The underlying Cassidy Group consists of massive, vesicular and amygdaloidal basalt and porphyritic rhyolite (Fig. 5), with locally common volcanogenic conglomerate and sandstone. Whereas the Mission and Cassidy Groups are exposed on the southwestern limb of a regional-scale northwest-trending open anticline, the Pussy Cat Group is exposed in the hinge of the fold. The Pussy Cat Group is dominated by vesicular and amygdaloidal basalt, locally with voluminous volcaniclastic rhyolite and intercalated fine- to coarse-grained volcaniclastic and siliciclastic rocks (Fig. 6). Southwest-directed reverse faults that parallel the anticline fold axial trace bring in contact deeper level rocks of the Mount Palgrave Group with those of the Pussy Cat Group, as shown on the map and A–B cross-section of WARBURTON RANGE (Howard et al., 2014). This parallelism is consistent with a contemporaneous folding and faulting event, and the orientation of these structures suggests they were produced during a period of north–south to northeast–southwest compression. The Mount Palgrave Group consists of felsic volcanic and volcaniclastic rocks interlayered with sandstone, siltstone and mudstone, and minor mafic volcanic rocks (Fig. 7). The Pussy Cat and Mount Palgrave Groups overlie and are intruded by fine- to medium-grained granitic rocks of the Warakurna Supersuite. Three granite intrusions into the Mount Palgrave and Pussy Cat Groups yielded U–Pb zircon dates of 1071 ± 5, 1063 ± 8 and 1049 ± 8 Ma (Fig. 2; #3, 4 and 6 of Table 1). These dates are interpreted as the ages of magmatic crystallization, suggesting that granitic rocks of the Warakurna Supersuite both intrude and form the source to the volcano-sedimentary succession of the Talbot Sub-basin (Smithies et al., 2013b). Dolerite dykes intrude mainly the granitic rocks, locally forming over 30% of the rock volume; dolerite dykes and sills also intrude the volcano-sedimentary rocks of the Talbot Sub-basin, although less abundantly.

Outcrops in the Mitika area are dominated by metasedimentary rocks of the Kunmarnara Group, assigned to the MacDougall Formation, and consist of interbedded quartzite, quartzofeldspathic metasandstone and quartz-pebble metaconglomerate (Fig. 8). The regional-scale structure of the Mitika area consists of a west-verging fold and thrust system (Fig. 9). Regional folds are overturned and tight to isoclinal, as indicated by the well-clustered stereonet data of poles to bedding (Fig. 9a) that have similar orientation to poles to axially planar foliations (Fig. 9b). East-plunging sheath folds on the long limbs of the regional folds suggest local intense shearing (Fig. 8c). Regional fold axes are mainly gently south plunging, although gently north-plunging fold axes also occur (Fig. 9c). Secondary upright, moderately east-plunging, open folds affect the regional folds (Fig. 9d). The approximately east-trending A–B cross-section on BENTLEY, through the most deformed part of the Mitika area, shows our interpretation of the west-verging fold and thrust system (Howard et al., 2013b).

In the Mitika area, the YOM seismic line runs north to northeast, which is subparallel to the strike of regional structures (Fig. 9). Consequently, we can expect the seismic image of the Mitika area to reveal a series of subhorizontal seismic reflectors representing apparent dips of bedding and tectonic structures. U–Pb detrital zircon geochronology of metasedimentary rocks of the Mitika area, the MacDougall Formation, was described in detail in Quentin de Gromard et al. (2016b), and a summary of the results is presented in Table 2 (#1–9). Detrital zircon age spectra show broad peaks at 1650–1550 Ma, minor peaks at c. 1415 Ma and dominant peaks around 1220–1150 Ma. A robust maximum age for deposition of the unit is 1177 ± 4 Ma (Quentin de Gromard et al., 2016b). However, deposition of the siliciclastic sediments of the Kunmarnara Group is interpreted to have resulted from development of the Ngaanyatjarra Rift at the onset of the 1085–1040 Ma Giles Event (Evins et al., 2010). A minimum age for

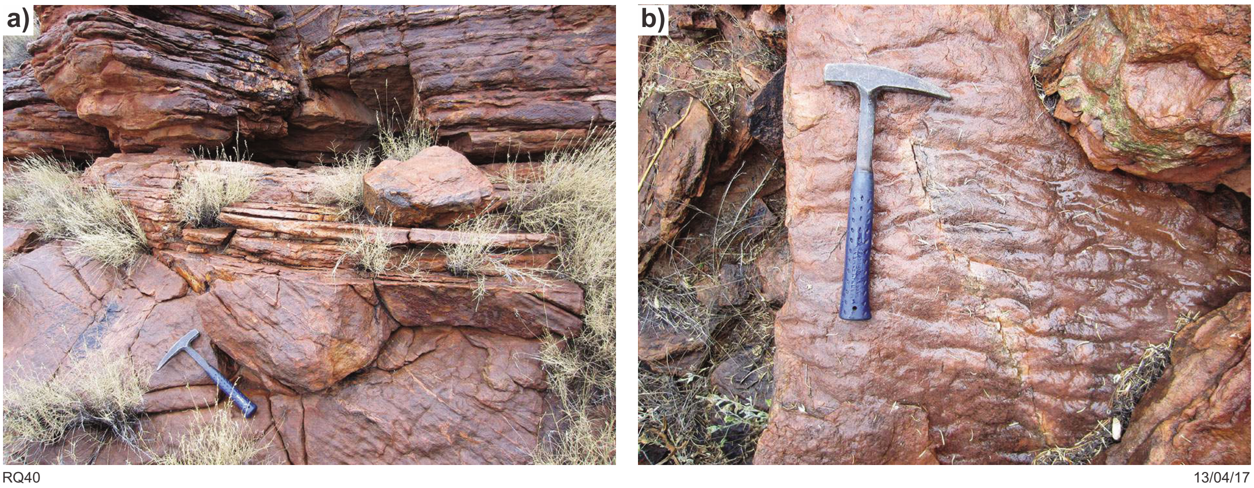

Figure 3. Field photos of the Townshend Quartzite, Buldya Group, Officer Basin in the Warburton area: a) thick-bedded, trough cross-bedded sandstone; b) bedding-parallel view exposing dominantly asymmetric ripples in cross-bedded sandstone

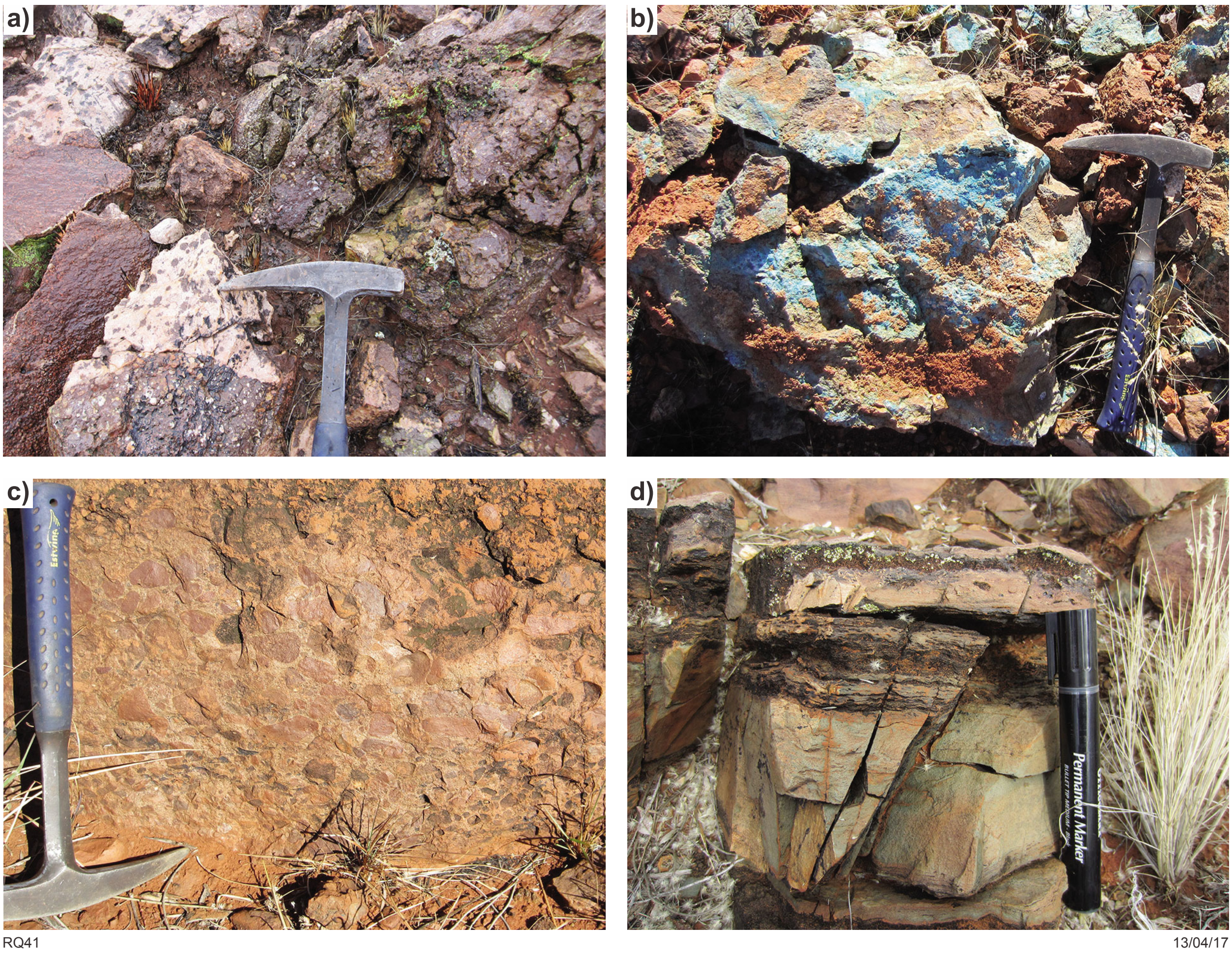

Figure 4. Field photos of representative rocks of the Mission Group, Bentley Supergroup, Talbot Sub-basin along the YOM line: a) amygdaloidal basalt in contact with white, hematite-stained sandstone; b) immature sandstone with abundant azurite and malachite staining; c) matrix-supported, poorly sorted pebble/cobble conglomerate containing well-rounded siltstone clasts; d) grey-green siltstone interbedded with thin carbonaceous layers, interpreted as microbial laminations

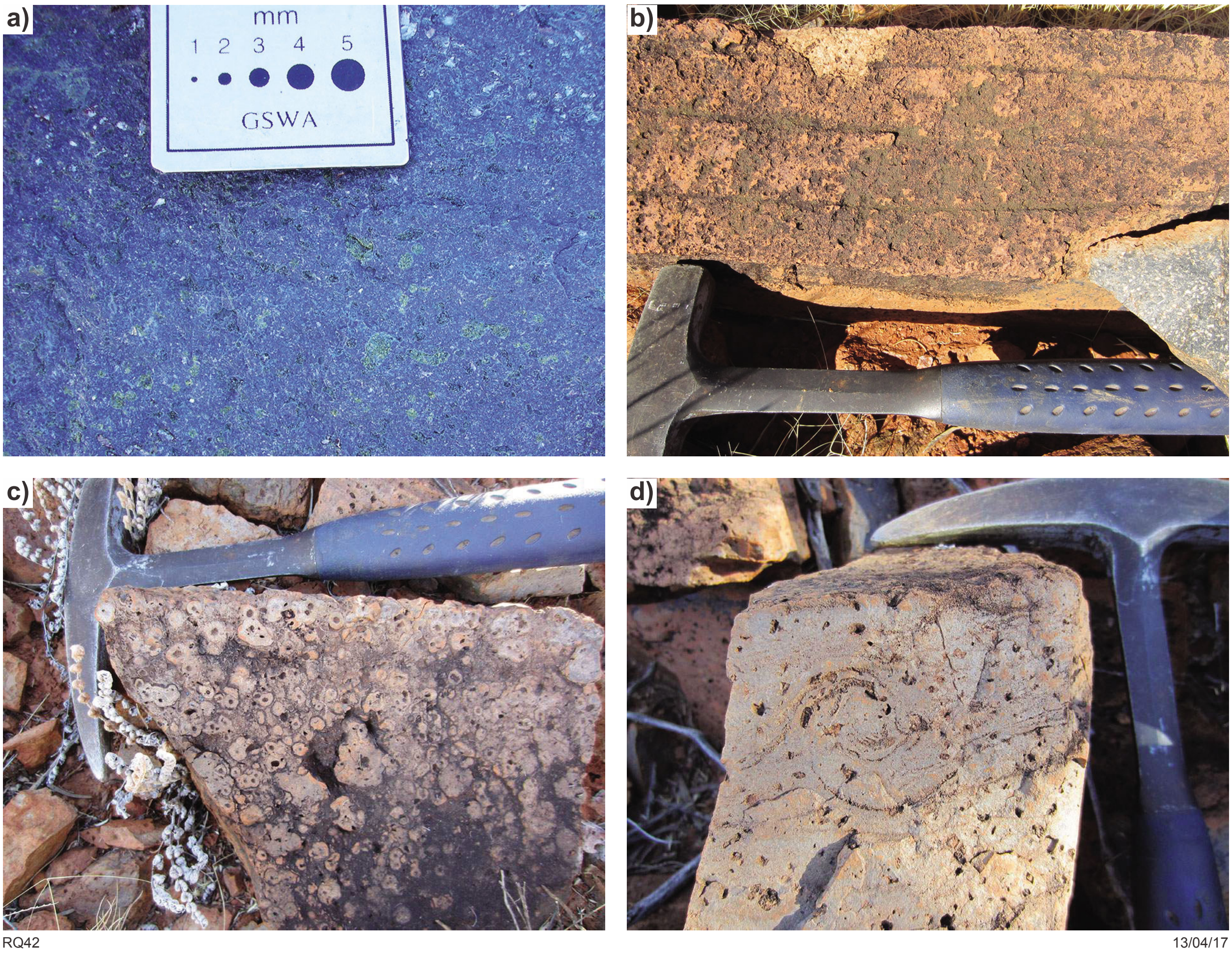

Figure 5. Field photos of representative rocks of the Cassidy Group, Bentley Supergroup, Talbot Sub-basin along the YOM line: a) blue-grey, fine-grained, amygdaloidal basalt containing 10% epidote-filled amygdales; b) flow-banded, microcrystalline, crystal-poor, feldspar-phyric rhyolite; c) devitrification texture in rhyolite, indicated by the presence of spherules; d) rotational flow-fold in crystal-poor, microcrystalline rhyolite

sediment deposition is provided by the date of 1078 ± 4 Ma for a syenitic volcanic rock of the Kunmarnara Group and by the intrusion of a 1076 ± 7 Ma leucogabbro into the Kunmarnara Group (GSWA 194762, Kirkland et al., 2011b; GSWA 183847, Kirkland et al., 2012b).

The Wanarn area is a zone of complex pervasive ductile deformation, bounded to the north and south by the west-northwestly trending Woodroffe Thrust and Mitika Fault, respectively (Fig. 10). The Mitika Fault is steeply south dipping and extends along strike for a minimum of 130 km, while the moderately south-dipping Woodroffe Thrust transects the whole Musgrave Province for a minimum strike length of about 800 km (see inset in Figure 2). Their strike length suggests these are two crustal-scale structures. The fact that these structures are subparallel and only 30 km apart suggests they may merge at depth, forming a wedge structure, the exposed portion of which is represented by the Wanarn area (Figs 2, 10). The Wanarn area is largely exhumed along the Woodroffe Thrust and is interpreted as the gneissic core of a post-Mesoproterozoic orogen (Quentin de Gromard et al., 2017). Rocks of the Wanarn area consist of paragneisses of the Kunmarnara Group tectonically interleaved with orthogneisses of the Warlawurru and Pitjantjatjara Supersuites (Fig. 10; Quentin de Gromard et al., 2016b). The cross-section from C to D to E of DIORITE shows the overall northwards exhumation of the Wanarn area along the moderately south-dipping Woodroffe Thrust, and the tectonic interleaving of basement rocks of the Musgrave Province into rocks of the c. 1085 Ma Kunmarnara Group (Quentin de Gromard et al., 2016a). Three metasyenogranite samples collected from a northeast-directed thrust sheet in the southern part of the Wanarn area yielded crystallization ages between c. 1607 and 1583 Ma (Fig. 10; #14–16 of Table 1; Quentin de Gromard et al., 2016b). These rocks are assigned to the Warlawurru Supersuite and constitute the oldest basement component identified in the west Musgrave Province. In the central and western parts of the Wanarn area, northwestwards to westwards thrusting interleaved rocks of the main basement component of the Musgrave Province (i.e. the Pitjantjatjara Supersuite) with paragneisses of the

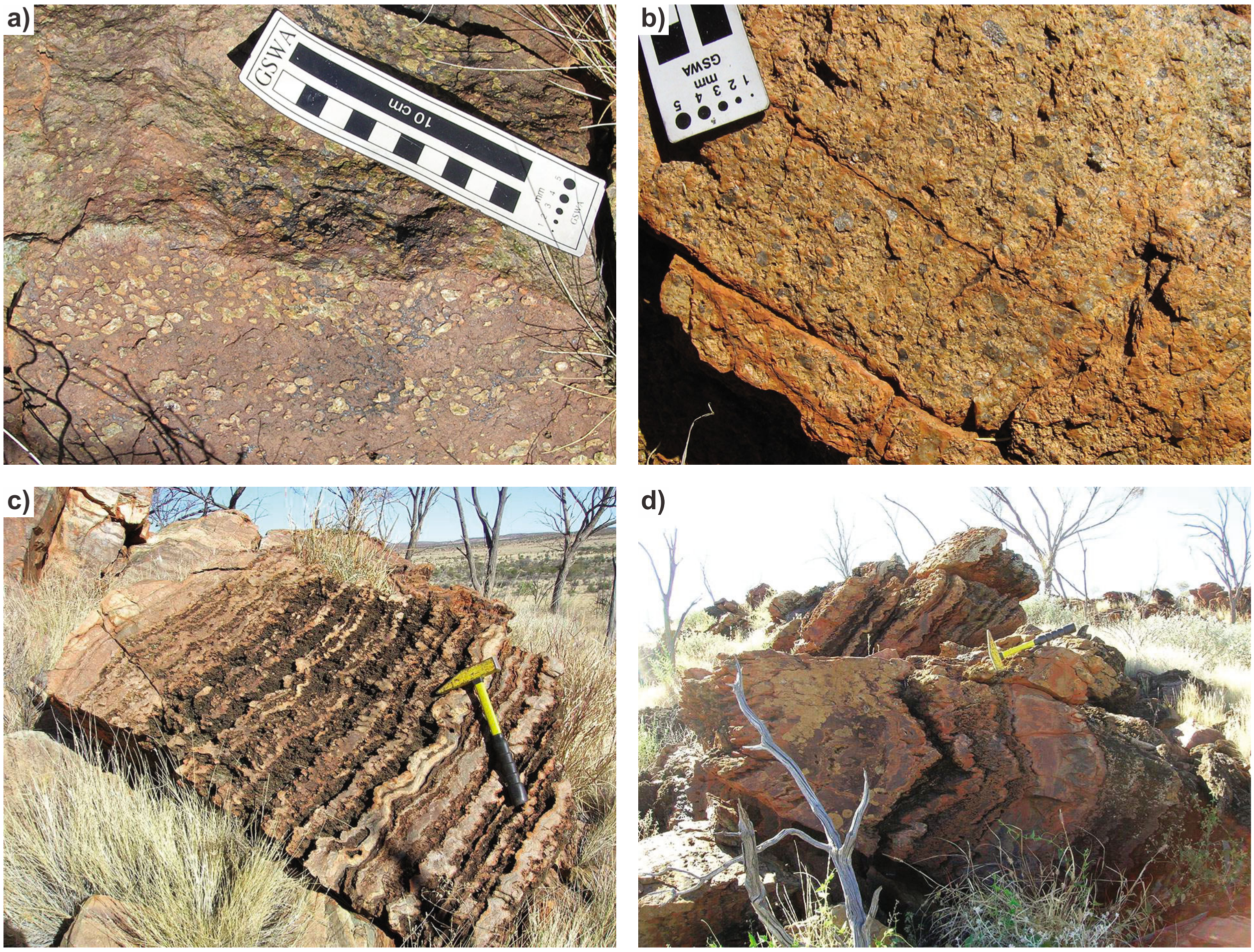

Figure 6. Field photos of representative rocks of the Pussy Cat Group, Bentley Supergroup, Talbot Sub-basin along the YOM line: a) green-grey, amygdaloidal to vesicular basalt; b) crystal-rich, volcaniclastic felsic rock with abundant rounded quartz phenocrysts up to 7 mm wide; c) pale-pink carbonaceous beds with possible microbial laminations, interbedded with green-grey volcaniclastic siltstone or basalt; d) folded pale-pink carbonates and green-grey volcaniclastic siltstone

Kunmarnara Group (Fig. 10; #10, 12 and 13 of Table 1; Quentin de Gromard et al., 2016b).

Immediately north of the Woodroffe Thrust, the YOM line runs through scattered outcrops of flat-lying to gently dipping Ordovician shallow-marine sedimentary rocks of the Cobb Embayment of the greater Canning Basin (Fig. 2; Haines et al., 2015). The Cobb Embayment is interpreted to be approximately 30 km wide in the area intersected by the YOM line. Sedimentary rocks of the Cobb Embayment unconformably overlie granitic rocks of the Warakurna Supersuite, as well as volcano-sedimentary rocks of the Kunmarnara Group (Fig. 2). The northeastern end of the YOM line extends into variably deformed rhyolitic subvolcanic rocks of the Tjauwata Group. Farther north and northeast, crystalline rocks of the Musgrave region are tectonically interleaved with sedimentary rocks of the Amadeus Basin forming a distinct structural domain, referred to as the Petermann Nappe Complex (Scrimgeour and Close, 1999; Flöttmann et al., 2004; Edgoose et al., 2004; Raimondo et al., 2010). The Petermann Nappe Complex consists of multiple structural repetitions of strongly folded ridges of Dean Quartzite interleaved with rhyolite-dominated rocks of the Tjauwata Group (Fig. 2). Seven granitic and rhyolitic rock samples were collected on Deering and Rebecca, about 25–75 km east and southeast of the end of the YOM line, for U–Pb zircon geochronology (Fig. 2; Table 1). Six of the samples yielded magmatic crystallization ages between c. 1044 and 1031 Ma (#1, 2, 5, 7, 8 and 9 of Table 1). The remaining igneous sample yielded a magmatic crystallization age of 1168 ± 5 Ma (#11 of Table 1). Conservative estimates of the maximum age of deposition for two quartzite samples, assigned to the Karukali Quartzite, within the Petermann Nappe Complex are provided by ages of 1177 ± 18 and 1163 ± 13 Ma for the youngest age component in each sample (#10 and 11 of Table 2). These results suggest that the surface geology of the area northeast of the Woodroffe Thrust is largely dominated by rocks formed during the 1085–1030 Ma Giles Event, with only minor exposure of rocks formed during the 1220–1150 Ma Musgrave Orogeny.

Table 1. Summary of U–Pb zircon geochronology samples and results for the Warlawurru, Pitjantjatjara and Warakurna Supersuites, and for felsic volcanic rocks of the Tjauwata Group

#	GSWA sample ID	Rock type	1:100 000 map sheet	Easting (m)	Northing (m)	Magmatic age (Ma)	Metamorphic age (Ma)	Inheritance (Ma)	Reference
	Tjauwata Group								
1	201708	feldspar-phyric rhyolite	Rebecca	476418	7235710	1041 ± 6			Lu et al. (2017a)
2	208489	metarhyolite	Deering	496622	7222309	1039 ± 7		1100 ± 13	Lu et al. (2017b)
	Warakurna Supersuite								
3	185486	feldspar-phyric microgranite	Warburton Range	265657	7118740	1071 ± 5			Lu et al. (2017c)
4	208453	granite	Golden Point	276148	7127600	1063 ± 8			Kirkland et al. (2014a)
5	201702	feldspar-phyric metamicrogranite	Deering	478743	7227730	1044 ± 8			Lu et al. (2017d)
6	208443	syenogranite	Golden Point	277020	7125011	1049 ± 8			Lu et al. (2017e)
7	201372	biotite monzogranite	Deering	450924	7217809	1041 ± 9			Kirkland et al. (2014b)
8	208497	folded granite vein	Deering	484828	7230260	1035 ± 6			Lu et al. (2017f)
9	208486	migmatitic metamonzogranite	Deering	498403	7205741	1031 ± 6			Wingate et al. (2017a)
	Pitjantjatjara Supersuite								
10	201320	leucogranite vein	Dickenson	352722	7204670	1171 ± 4		1186 ± 4 (1σ)	Kirkland et al. (2014c)
11	208495	foliated porphyritic syenogranite	Deering	489714	7230172	1168 ± 5			Lu et al. (2017g)
12	208506	biotite–hornblende metamonzogranite	Diorite	332784	7200123	1157 ± 9			Wingate et al. (2015b)
13	208504	hornblende–biotite metamonzogranite	Diorite	346858	7207892	1160 ± 7			Wingate et al. (2015a)
	Warlawurru Supersuite								
14	208502	biotite–hornblende metasyenogranite	Diorite	348637	7200884	1607 ± 11	1185 ± 11		Wingate et al. (2015e)
15	208455	hornblende–biotite metasyenogranite	Diorite	345809	7200319	1594 ± 14	1166 ± 5		Wingate et al. (2015d)
16	201304	biotite metasyenogranite	Diorite	346137	7200012	1583 ± 10	1179 ± 11 (1σ)	1678 ± 30 (1σ)	Wingate et al. (2015c)

NOTE: Eastings and northings refer to MGA Zone 52; ages are quoted with 95% confidence intervals, except where noted otherwise

Table 2. Summary of U–Pb zircon geochronology samples and results for the MacDougall Formation and the Karukali Quartzite

#	*GSWA sample ID*	*Rock type*	*1:100 000 map sheet*	*Easting (m)*	*Northing (m)*	*Maximum deposition age (Ma)*	*Age components (Ma)*	*Metamorphic age (Ma)*	
	MacDougall Formation								
1	205194	psammitic gneiss	BENTLEY	315092	7169700	1190 ± 12	1190	628 ± 4	Kirkland et al. (2014d)
2	194806	metasandstone	BENTLEY	312342	7172295	1179 ± 5	1539, 1186		Kirkland et al. (2014e)
3	208414	quartzite	BENTLEY	313654	7172427	1179 ± 13	1424, 1187	631 ± 12	Kirkland et al. (2014f)
4	201311	metasandstone	DIORITE	345248	7199002	1180 ± 8	1615, 1592, 1565, 1197		Kirkland et al. (2014g)
5	201307	metasandstone	DIORITE	345864	7200322	1172 ± 10	1643, 1568, 1174		Kirkland et al. (2014h)
6	185414	quartzite	BENTLEY	315618	7151266	1153 ± 9	1518, 1491, 1185		Kirkland et al. (2013)
7	190233	phyllite	HOLT	411877	7162469	1172 ± 8	1520, 1171		Kirkland et al. (2012a)
8	190292	metasandstone	FINLAYSON	388680	7139970	1176 ± 7	1577, 1179		Kirkland et al. (2011a)
9	194420	feldspathic sandstone	COOPER	372425	7091845	1173 ± 6	1578, 1173		Kirkland et al. (2010)
	Karukali Quartzite								
10	208466	quartzite	DEERING	494423	7222561	1163 ± 13	1788, 1746, 1649, 1620, 1595, 1523, 1475, 1195, 1160, 1126		Wingate et al. (2017b)
11	208494	quartzite	DEERING	489774	7230269	1177 ± 18	1850, 1757, 1620, 1553, 1492, 1323, 1191		Wingate et al. (2017c)

NOTE: Eastings and northings refer to MGA Zone 52; ages are quoted with 95% confidence intervals

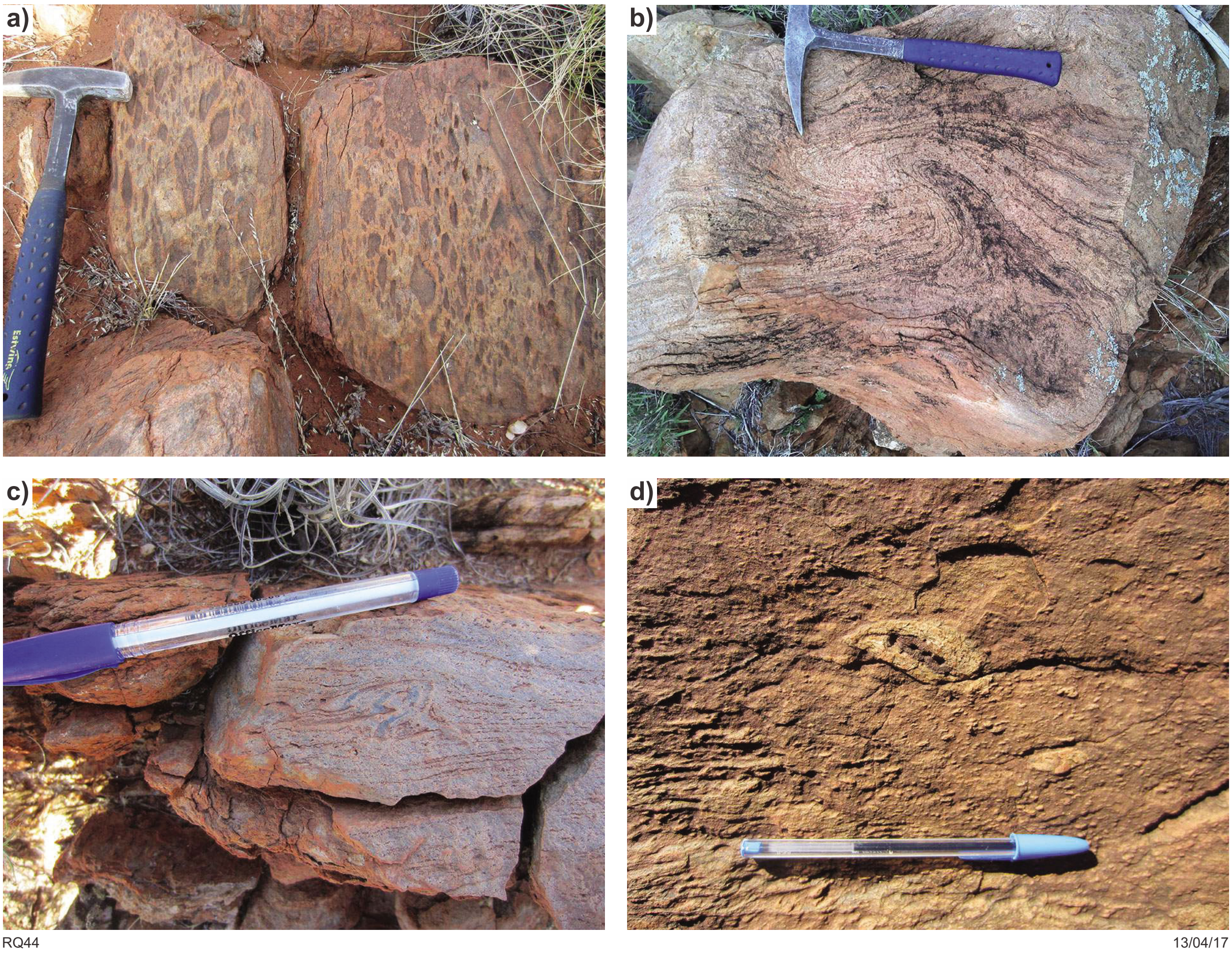

Figure 7. **Field photos of representative felsic volcanic and volcaniclastic rocks of the Mount Palgrave Group, Bentley Supergroup, Talbot Sub-basin: a) clast-rich, rhyolitic ignimbrite containing well-aligned and elongated clasts of feldspar porphyritic rhyolite; b) dark-grey, microcrystalline, crystal-poor, flow-folded rhyolite; c) rheomorphic flow-fold in grey-blue, crystal-poor rhyolite; d) large accretionary lapilli in flow-banded feldspar porphyritic rhyolite ignimbrite**

An updated interpretation of the northeastern end of the YOM seismic section

The new interpretation of the northeastern end of the YOM seismic section is shown, step by step, on Figure 11. The top panel shows the migrated, noninterpreted seismic data. The display extends to 22 s TWT, which is equivalent to about 66 km depth, assuming a crustal velocity of 6000 m/s (i.e. 1 s TWT is approximately equal to 3 km depth, Korsch et al., 2013), and no vertical exaggeration. The upper part of the section is weakly to strongly reflective, and shows strong variations in reflection intensity, indicating a strongly heterogeneous upper crust with regard to seismic wave velocities. Reflectors are commonly subhorizontal but locally moderately inclined. The thickness of the strongly heterogeneous upper crust varies greatly along the profile, from about 2.5 s TWT (~7.5 km depth) in the southwest to about 8 s TWT (~24 km depth) in the northeast.

At mid-crustal levels, seismic data show broad, weakly reflective, relatively homogeneous areas (e.g. the area within Common Depth Points [CDP] 11000–12000, between 7 and 13 s TWT, i.e. ~21–39 km depth; top panel of Figure 11). These areas indicate homogeneous volumes within the crust that show very little internal variation in seismic wave propagation velocities and are commonly interpreted as large and weakly deformed magmatic intrusions. Moderately reflective, strongly heterogeneous areas, such as the area within CDP 8000–9000 and between 5–9 s TWT (~15–27 km depth), form the background to the mid-crustal level and likely represent areas of relatively heterogeneous basement. Reflectors are subhorizontal to moderately inclined and most probably represent lithological boundaries, as well as the orientation of secondary layering such as gneissic fabrics.

The lower crustal level extends from about 11 to 17 s TWT (~33–51 km depth). It is commonly characterized in seismic data as a weakly reflective and homogeneous zone, with the exception of two areas, located within CDP 3500–5000 and 6000–7000 and between 12 and 17 s TWT

Figure 8. **Field photos of representative rocks of the MacDougall Formation, Kunmarnara Group, Bentley Supergroup in the Mitika area (a–c) and of basement rocks of the Warlawurru Supersuite in the Wanarn area (d): a) interbedded quartzite and quartzo-feldspathic schist; b) strongly lineated, quartz-pebble schistose conglomerate; c) east-plunging sheath fold in interbedded quartzite and quartzo-feldspathic schist; d) ptygmatic folds in migmatitic orthogneiss**

(~36–51 km depth), that show subhorizontal to gently inclined reflectors. These two heterogeneous areas likely image a layered lower crust. The base of the heterogeneous area between CDP 3500 and 5000 is also where the seismic Moho is best defined as a series of subhorizontal reflectors, at about 16.5 s TWT (~49.5 km depth). The Moho is interpreted to deepen to 17 s TWT (~51 km depth) at about CDP 6700 and then to 18 s TWT (~54 km depth) at around CDP 8500; this surface is generally not imaged by seismic data farther to the southwest.

The first stage of this interpretation, shown on the second panel of Figure 11, involved the drawing of the representative reflectors within all crustal levels, interpreting boundaries such as the base of the Bentley Supergroup and the Moho and its continuation towards the southwest. The base of the Bentley Supergroup is regularly well imaged and defined by subhorizontal to moderately inclined, continuous reflectors that truncate the orientations of the underlying reflectors. The series of moderately southwest-dipping reflectors within CDP 12500 and 13000 and between 0 and 2 s TWT (~0–6 km depth) are in agreement with outcrop data from the southwestern end of the Talbot Sub-basin, which consists of interlayered bimodal volcanic rocks and sedimentary rocks dipping about 30° to the southwest (Fig. 2). Mapping identified a west- to northwesterly trending open anticline within the Talbot Sub-basin, the hinge line of which intersects the YOM line at about CDP 12200 and is well imaged in seismic data. Northeast-dipping reflectors, in the northeastern limb of the Talbot Sub-basin anticline, extending to about CDP 11650 and up to 4 s TWT (~12 km depth), define the deepest base of the Bentley Supergroup south of the Woodroffe Thrust. The shallowest base of the Bentley Supergroup is interpreted within CDP 6800–10500 and between 1 and 2.8 s TWT (~3–8.4 km depth), which is in agreement with field observations suggesting that only the basal unit of the Bentley Supergroup, i.e. the Kunmarnara Group, is exposed in the Mitika Area (Fig. 2). Within CDP 5100–6000, in the northern Wanarn Area, the repeated base of the Bentley Supergroup, between 0.5 and 3.2 s TWT (~1.5 – 9.6 km depth), is interpreted to reflect structural repetitions due to tectonic interleaving of Musgrave Province basement

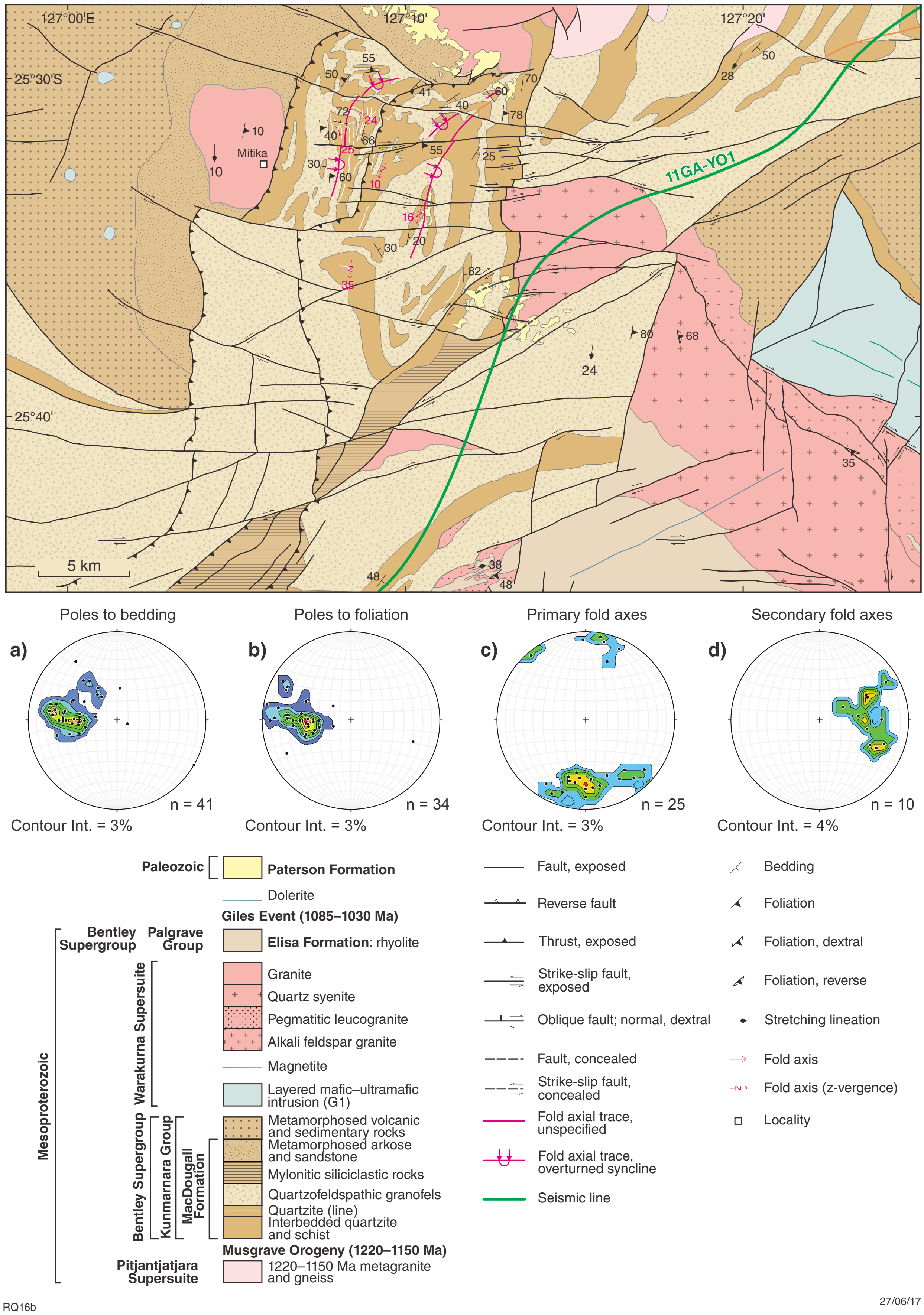

Figure 9. Interpreted bedrock geology of the Mitika area, showing the location of the YOM line and equal-angle plots of structural data: a) poles to bedding; b) poles to foliation; c) F_2 fold axes; d) F_3 fold axes. Stereonets statistics: 1% area contouring; contour interval is indicated for each stereonet and n = number of measurements

with rocks of the Kunmarnara Group (Fig. 2; Quentin de Gromard et al., 2016b). Towards the northeastern end of the YOM section, between CDP 5000 and 6000, the base of the Bentley Supergroup is interpreted to be structurally repeated to as deep as 8.5 s TWT (~25.5 km depth), in the footwall of the Woodroffe Thrust. The base of the strongly reflective upper crustal level is then interpreted to lie at approximately 5 s TWT (~15 km depth) from CDP 3000 to the end of the section.

The third panel of Figure 11 shows the interpreted extent, at depth, of known faults identified during mapping. These are placed within a crustal architecture consistent with our current understanding of the structural evolution of the west Musgrave Province (Howard et al., 2015; Quentin de Gromard et al., 2016b, 2017). The major faults to the southwest of the Mitika Fault are interpreted here as northeast-dipping listric structures (Fig. 11). This updated view differs significantly from the original interpretation of the YOM section, in which all major faults were interpreted as southwest-dipping structures (Howard et al., 2013a). This updated interpretation is in agreement with mapping of WARBURTON RANGE (Howard et al., 2014); however, it conflicts with the interpretation made on GOLDEN POINT, where the nonexposed southwestern end of the Mitika area was interpreted to have been exhumed along a southwest-dipping normal fault (Quentin de Gromard et al., 2015). Our new interpretation is that exhumation of the southwestern end of the Mitika area occurred along a northeast-dipping reverse fault system that intersects the surface at around CDP 10500 (Figs 2, 11).

The Mitika Fault is interpreted as a steeply south-dipping reverse fault, while the Woodroffe Thrust is seen as a moderately to gently south-dipping thrust that soles into the Mitika Fault. This configuration is supported by the combined gravity and magnetic model along Profile 4 of Aitken et al. (2013). However, the TPZ_F1 fault of Aitken et al. (2013), equivalent to the Mitika Fault, did not extend past the middle crust, as its extension into the lower crust was not required by the method. The limited extent of the TPZ_F1 of Aitken et al. (2013) is a limitation imposed by the method, rather than an interpretation of the geometry of this fault at depth. The available crustal-scale seismic data allow for the interpretation of the Mitika Fault as extending to the base of the crust and offsetting the Moho (Fig. 11). It intersects the surface at around CDP 6700 and forms the boundary between the amphibolite facies Mitika area to the south and the granulite facies Wanarn area to the north (Fig. 2; Quentin de Gromard et al., 2016b). The YOM line runs subparallel to the interpreted trace of the Woodroffe Thrust between CDP 4900 and 4400 explaining the branching of the Woodroffe Thrust towards the surface in the seismic section (Fig. 11).

Finally, the lower panel shows the full interpretation of the northeastern end of the YOM seismic section and includes the distribution of basins and provinces, including the nonexposed seismic provinces (Fig. 11). The surface geology indicates that the upper crustal level of the seismic section is dominated by units of the Bentley Supergroup. In the Talbot Sub-basin, we have grouped the Mission, Cassidy, Pussy Cat and Mount Palgrave Groups into a combined interlayered sedimentary and bimodal volcanic unit, underlain by the Kunmarnara Group. The Talbot Sub-basin comprises a broad open anticline, with southwest-directed reverse faults disrupting its northeastern limb. The main southwest-directed reverse fault of the Talbot Sub-basin, intersecting the YOM line around CDP 12000, shows a vertical offset of the base of the Kunmarnara Group of about 0.8 s TWT (~2.4 km) equivalent distance. This offset is likely close to the fault net slip, since the YOM line runs perpendicular to the fault trace and only a dip slip component is identified on this fault. The estimated slip is in agreement with that inferred from field data, which require ~2.5 km of displacement across the same fault, in order to juxtapose the Scamp Formation of the Mount Palgrave Group with the younger Pussy Cat Group (Fig. 2; A–B cross-section of WARBURTON RANGE, Howard et al., 2014). To the southwest, a series of gently folded reflectors appears discordant to the southwest-dipping reflectors of the Talbot Sub-basin. This is interpreted as a folded sedimentary unit of the Officer Basin, unconformably overlying units of the Talbot Sub-basin. The Officer Basin unit is in turn overlain by flat-lying, gently southwest-dipping reflectors, interpreted as the unconformable contact with the overlying Paterson Formation. To the northeast of the reverse fault described above, rocks of the Talbot Sub-basin are intruded by quartz syenite and syenogranitic rocks of the Warakurna Supersuite, which intersect the surface along the YOM section between CDP 10800 and 11500. The extent at depth of this intrusive body is interpreted by connecting the broad, weakly reflective, relatively homogeneous areas (i.e. the zones lacking seismic reflectors), which possibly represent the lateral extent of the magma chamber of the Talbot Supervolcano (Smithies et al., 2015a).

In the Mitika area, only the Kunmarnara Group is exposed, suggesting that substantial exhumation and erosion removed all evidence of a younger bimodal volcanic succession. The YOM line runs subparallel to the strike of regional structures of the Mitika area. Consequently, the Mitika area is imaged in the seismic data as a series of subhorizontal reflectors that only show apparent dips of strata and structures in this region. The Wanarn area is bounded by crustal-scale structures represented by the Mitika Fault and Woodroffe Thrust. Internally, the Wanarn area is interpreted as a zone of stacked basement slivers of metagranites and gneisses of the Warlawurru and Pitjantjatjara Supersuites, tectonically interleaved with metasedimentary rocks of the Kunmarnara Group. This structural architecture, involving crustal-scale bounding faults and the interleaving of basement rocks with cover sequences in a thrust system, corresponds to a tectonic style characteristic of thick-skinned and basement-involved thin-skinned tectonics (Coward, 1983; Pfiffner, 2006). This tectonic style is characteristic of that found in the core of thickened orogens (Coward, 1983; Pfiffner, 2006), arguably demonstrating that the Wanarn area represents a section through the core of a post-Mesoproterozoic orogen in central Australia.

To the north of the Woodroffe Thrust, a thick and strongly reflective upper crust down to around 8.5 s TWT (~25.5 km depth), is interpreted as thickened upper crust showing a foreland-dipping duplex within CDP 3700–4500 and an antiformal stack structure within CDP

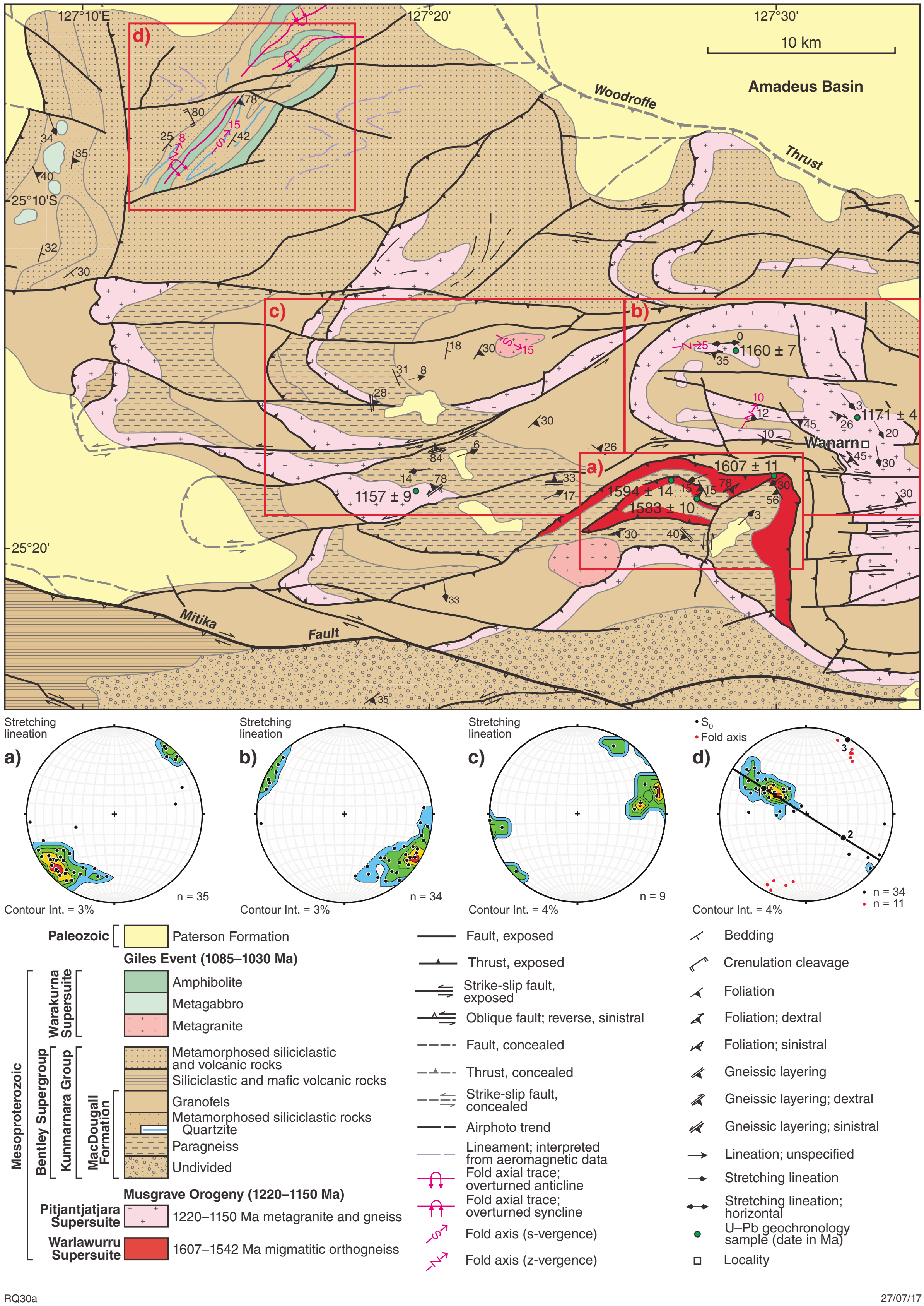

Figure 10. Interpreted bedrock geology of the Wanarn area, showing the location of the geochronology samples as well as the following stereonets: a) stretching lineations from the northeast-directed thrust sheet; b) stretching lineations from the northwest- to west-directed thrust sheet; c) stretching lineations in the west-directed thrust sheets; d) poles to bedding and fold axes of the Bedford Range. A cylindrical best-fit girdle and Eigen values (1, 2 and 3) are shown for bedding data; note the similar orientation of Eigen value 3 with the measured fold axes. Stereonet statistics: 1% area contouring; n = number of measurements

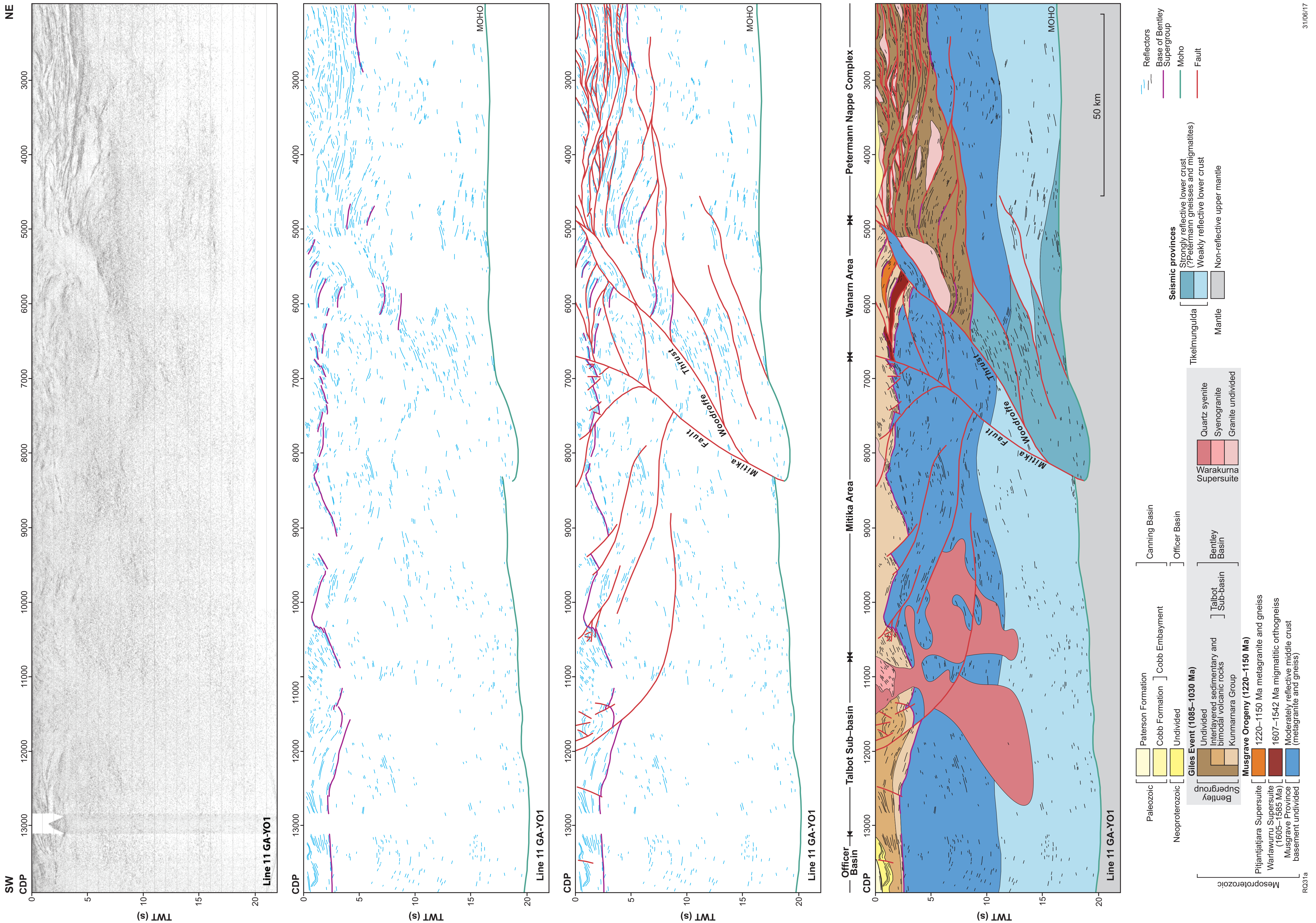

Figure 11. New interpretation of the YOM section in the west Musgrave Province: a) migrated, noninterpreted seismic data; b) seismic data with interpreted reflectors; c) seismic data with interpreted structures; d) geological reinterpretation

2700–3400, both of which are between 1 – 2.5 s TWT (~3 – 7.5 km depth) of the crust. This crustal architecture is interpreted as the expression of the southern end of the Petermann Nappe Complex. These geometries reflect particularly well the structural style of the central and northern part of the Petermann Nappe Complex, exposed 50 to 100 km to the east and northeast of the northeastern end of the YOM line (Fig. 2). The Petermann Nappe Complex shows the transition from basement-involved thrusting towards the hinterland, where basement slivers are tectonically interleaved within cover sequences of the Bentley Supergroup and of the Amadeus Basin, to a region closer to the foreland where the thrust system affects only the cover sequences, requiring a detachment fault at the base of the Bentley Supergroup. This indicates that the Petermann Nappe Complex represents the transition from thick- to thin-skinned tectonics (Chapple, 1978; Coward, 1983; Pfiffner, 2006). Subhorizontal reflectors within the subsurface immediately to the northeast of the Woodroffe Thrust, within CDP 4500–3200 down to about 0.5 s TWT (~1.5 km depth) are interpreted as the manifestation of the flat-lying to gently dipping Ordovician shallow-marine sedimentary rocks of the Cobb Embayment identified during mapping. The Bentley Supergroup was deposited on a Musgrave Province basement which includes, by definition, all rocks formed during or affected by the 1220–1150 Ma Musgrave Orogeny. The Musgrave Province basement is interpreted to extend to mid-crustal levels averaging around 11 s TWT (~33 km depth). The lower crustal level was termed the Tikelmungulda Seismic Province in the original interpretation of the YOM section (Neumann, 2013) and is retained in this interpretation. The middle to lower crust in the footwall of the Woodroffe Thrust shows strong reflectors with a consistent orientation; this is interpreted as related to Petermann-age gneisses and migmatites separated by shear zones defining stacked basement slivers that accommodate, at depth, some of the crustal shortening observed at the surface.

Minimum age of the Giles Event

Another aspect that arose from this study was the need to redefine the minimum age of the Giles Event. Indeed, new geochronology data from metamorphosed felsic igneous rocks of the Warakurna Supersuite in the Petermann Nappe Complex impose new age constraints. The Giles Event is a major magmatic event in central Australia that includes, but is not limited to, the c. 1075 Ma Warakurna Large Igneous Province (Wingate et al., 2004; Morris and Pirajno, 2005; Howard et al., 2015; Smithies et al., 2015b). Although Evins et al. (2010) recognized at least eight phases of magmatism during the Giles Event, four major tectono-magmatic stages can be rationalized (Smithies et al., 2015b). Stage 1 corresponds to an early rift phase with the deposition of the 1085–1075 Ma Kunmarnara Group, comprising siliciclastic rocks of the MacDougall Formation and basalt flows of the Mummawarrawarra Basalt (Evins et al., 2010). Equivalent units form the base of the volcano-sedimentary succession of the Tjauwata Group, exposed in the Petermann Nappe Complex (Edgoose et al., 2004). Stage 2 is marked by the intrusion of c. 1075 Ma layered mafic to ultramafic rocks — the Giles intrusions — that occur across most of the strike length of the Musgrave Province (Howard et al., 2011; Maier et al., 2014). Stage 2 also comprises the intrusion of massive gabbro bodies co-mingled with leucogranitic magmas near synchronous to the emplacement of the Giles intrusions (Smithies et al., 2015b). The Giles Event is perhaps best known for the emplacement of dykes and sills of the Warakurna Large Igneous Province across large parts of central and Western Australia between c. 1078 and 1073 Ma (Wingate et al., 2004). However, in the Musgrave region, the Warakurna Large Igneous Province forms a short-lived event within, and corresponding to stage 3 of, the approximately 50 Ma long evolution of the Giles Event (Smithies et al., 2015b). Stage 4 can be seen as the fireworks finale (although a long-lasting finale!) of the long-lived Giles Event. The volume of bimodal volcanic rocks produced during stage 4 provide evidence that they were erupted during periods of supervolcano-sized activity, between c. 1075 and 1040 Ma (Smithies et al., 2013b, 2015a). The volume of the felsic volcanic rocks of the Talbot Sub-basin alone indicate up to four superimposed, supervolcano-sized eruptions, encompassing an overall period of magmatism exceeding 30 Ma (Smithies et al., 2015a). A similarly aged, but younger, sequence of magmatic rocks is found in the Petermann Nappe Complex; these are the rocks that are considered here to redefine the minimum age of the Giles Event.

Previous studies in the Petermann Nappe Complex suggested temporal correlations between the Tjauwata Group, in the Northern Territory, and magmatic rocks of the Giles Event in the west Musgrave Province (Close et al., 2003; Edgoose et al., 2004). The basal sequence of the Tjauwata Group — the Karukali Quartzite and the conformably overlying Mount Harris Basalt — can be interpreted as time and lateral equivalents to the basal sequence of the Kunmarnara Group — the MacDougall Formation and Mummawarrawarra Basalt (Edgoose et al., 2004; Howard et al., 2015). Indeed, U–Pb zircon geochronology of two quartzite samples assigned to the Karukali Quartzite (#10 and 11 of Table 2) yielded similar maximum depositional ages to those of the MacDougall Formation (#1–9 of Table 2). Although no age constraint could be obtained for the Mount Harris Basalt in the Western Australian portion of the orogen, field relationships and geochemical data indicate that the Mt Harris Basalt is likely equivalent to the c. 1085 Ma Mummawarrawarra Basalt (Howard et al., 2015). In the Western Australian portion of the Petermann Nappe Complex, U–Pb zircon geochronology from rocks of the Tjauwata Group and of the Warakurna Supersuite yielded magmatic crystallization ages between c. 1043 and 1031 Ma (Fig. 2; Table 1). None of the dated rocks yielded crystallization ages ranging between c. 1075 and 1040 Ma, commonly found elsewhere in the west Musgrave Province. The magmatic rocks preserved in the Petermann Nappe Complex in Western Australia seem to have been produced during a late magmatic history at the end of the Giles Event. This perhaps indicates that they were produced from a different magmatic centre than that of the Blackstone and Talbot Sub-basins. Furthermore, U–Pb zircon dates from a metagranite, a folded granite vein, and a metarhyolite yielded magmatic crystallization ages of 1039 ± 7 Ma, 1035 ± 6 Ma and 1031 ± 6 Ma, respectively (#2, 8 and 9 of Table 1). Therefore, the minimum age of the Tjauwata Group of the Bentley Supergroup and of the Warakurna Supersuite must now include these younger dates; hence the revised age range for the Giles Event is 1085–1030 Ma.

Conclusion

An updated view of the deep seismic reflection profile 11GA-YO1 in the west Musgrave Province is proposed. The proposed updated interpretation of the YOM section is in agreement with our current understanding of the evolution of the region. The crustal architecture of the west Musgrave Province results from at least three major crust-forming events: the 1345–1293 Ma Mount West Orogeny, the 1220–1150 Ma Musgrave Orogeny and the 1085–1030 Ma Giles Event (updated minimum age from this study), and from crustal-scale, intracontinental reactivation during the amagmatic 580–520 Ma Petermann Orogeny. In the new interpretation, major faults within the Talbot Sub-basin and Mitika area dip towards the northeast and allowed the exhumation of the Mitika Area and the south-verging deformation front of the Talbot Sub-basin. This is consistent with field observations but differs from the southwest dip of these structures in the original interpretation of the YOM section. The Wanarn area, bounded by the crustal-scale and south-dipping Mitika Fault and Woodroffe Thrust, is interpreted as the core of a post-Mesoproterozoic orogen and is characterized by a basement-involved, antiformal thrust stack. North of the Woodroffe Thrust, in the Petermann Nappe Complex, basement-involved thrusting progressively transitions to thrusting that solely affects the cover sequences. This interpretation is consistent with a crustal architecture resulting from thick- to thin-skinned tectonics, from the hinterland to the foreland of an orogen that was produced during intracontinental reactivation after the Giles Event.

Several unconformable sedimentary basins overlie the Musgrave region. To the southwest, rocks of the Mesoproterozoic Talbot Sub-basin are overlain by rocks of the Neoproterozoic Officer Basin, which are in turn overlain by Carboniferous–Permian rocks of the Paterson Formation (Canning Basin). To the northeast, Ordovician shallow-marine sedimentary rocks of the Cobb Embayment (Canning Basin) overlie the southwestern end of the Petermann Nappe Complex. The Cobb Embayment forms a new addition to this updated view of the YOM section and is interpreted to deepen to 1.5 km.

Another conclusion that arises from this study is the need to redefine the minimum age of the Giles Event. Three U–Pb zircon dates, obtained from rocks of the Tjauwata Group and of the Warakurna Supersuite in the Petermann Nappe Complex, yielded magmatic crystallization ages at 1039 ± 7, 1035 ± 6 and 1031 ± 6 Ma. The minimum age of the Giles Event must include these younger dates; the new age range for the Giles Event is therefore 1085–1030 Ma.

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