Geodynamic implications of the Capricorn deep seismic survey: from the Pilbara Craton to the Yilgarn Craton

by

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Introduction

The Capricorn Orogen in Western Australia records both the punctuated assembly of the Pilbara and Yilgarn Cratons to form the West Australian Craton, and nearly one billion years of subsequent intracratonic reworking and basin formation (Cawood and Tyler, 2004; Sheppard et al., 2010a). The orogen is over 1000 km long, and includes the passive margin deposits of both the Pilbara and Yilgarn Cratons, variably deformed and metamorphosed granitic and metasedimentary rocks of the Gascoyne Province, and the sedimentary and low-grade metasedimentary rocks that overlie these three tectonic units (Frontispiece 1; Cawood and Tyler, 2004; Sheppard et al., 2010a).

In April and May 2010, 581 km of vibroseis-source, deep seismic reflection and gravity data were acquired along three traverses (10GA–CP1, 10GA–CP2, and 10GA–CP3) through the Capricorn Orogen. The lines started in the southern part of the Pilbara Craton, crossed the Gascoyne Province, and ended in the Narryer Terrane of the Yilgarn Craton (Frontispiece 1; Plate 1). This was a collaborative project between the Geological Survey of Western Australia (GSWA), AuScope (a component of NCRIS, the National Collaborative Research Infrastructure Strategy), and Geoscience Australia. The aim of the survey was to image the crustal architecture in the region, and thereby examine the relationships between the three tectonic units (Kennett et al., 2011). Crustal-scale magnetotelluric data were also collected along, or adjacent to, the seismic traverses (Heinson et al., 2011).

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Companion papers present summaries of the geological evolution of the region, interpretations of the three seismic lines (Thorne et al., 2011a,b; Johnson et al., 2011a,b; Cutten et al., 2011), and discussions of the potential field geophysics (Goodwin, 2011). The approximate north–south orientation of the seismic lines is essentially perpendicular to the major domains and structures in the region (Frontispiece 1–3; Plate 1), and provides crustal-scale geometries that can be compared with existing geological interpretations. Overall, the crust in the vicinity of the seismic section has variable reflectivity, with some parts of the section containing strong reflections, and other areas having very low reflectivity (Figs 1–3).

Here, we discuss some of the geodynamic implications that arise from interpretation of the new deep seismic reflection data obtained during this project. Of greatest interest is whether there is evidence for a suture between the Pilbara Craton and the Glenburgh Terrane, considered by Johnson et al. (2011c) to be located at the Talga Fault; whether there is a suture between the Glenburgh Terrane and the Narryer Terrane of the Yilgarn Craton, considered by Occhipinti et al. (2004) and Sheppard et al. (2004) to be located at the Errabiddy Shear Zone (Frontispiece 1–3; Plate 1); and whether the Fortescue and Hamersley Groups can be shown to continue south in the subsurface beneath the Ashburton Basin.

Moho

In the region of the Capricorn Orogen seismic sections, the Mohorovičić discontinuity ('the Moho') is not well imaged, but is commonly interpreted to occur at the base of the weakly reflective packages, the nonreflective material below which is considered to represent the upper mantle (Figs 1–3). The transition from crust to mantle is most likely gradational along a considerable part of the line length. In the vicinity of seismic line 10GA–CP1, the Moho is gently undulating between the depths of 11.5 to 13 seconds two-way travel time (s TWT; 34–39 km) (Fig. 1; see also Thorne et al., 2011b).

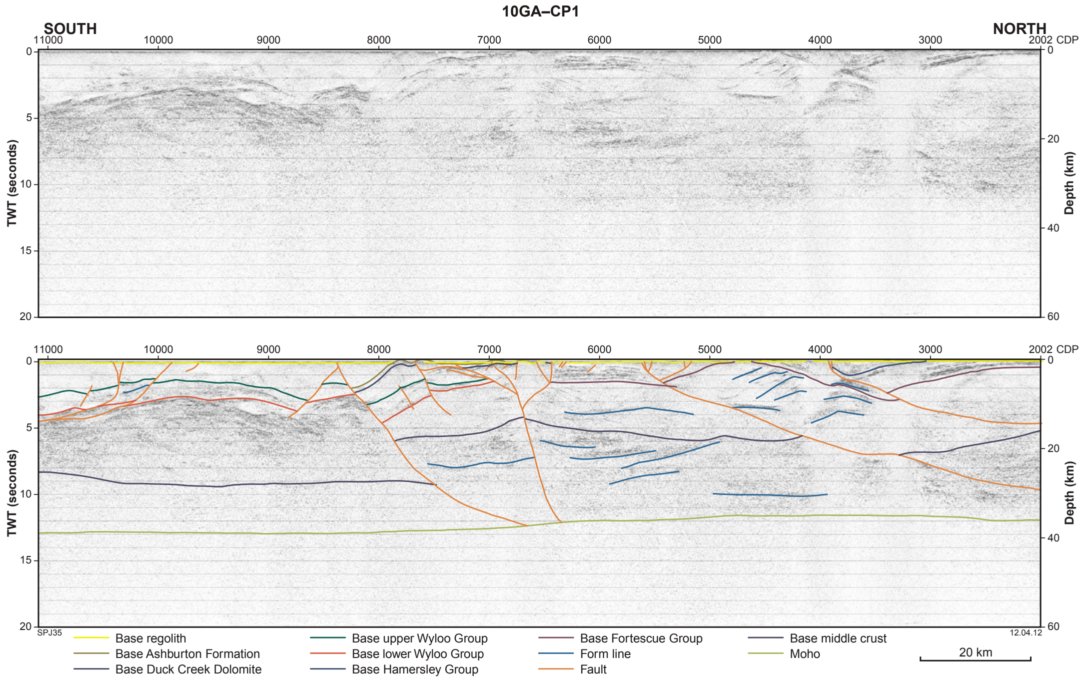

Figure 1. **Migrated seismic section for seismic line 10GA–CP1, showing both uninterpreted and interpreted versions. Display is to ~60 km depth, and shows vertical scale equal to horizontal scale, assuming an average crustal velocity of 6000 m/s.**

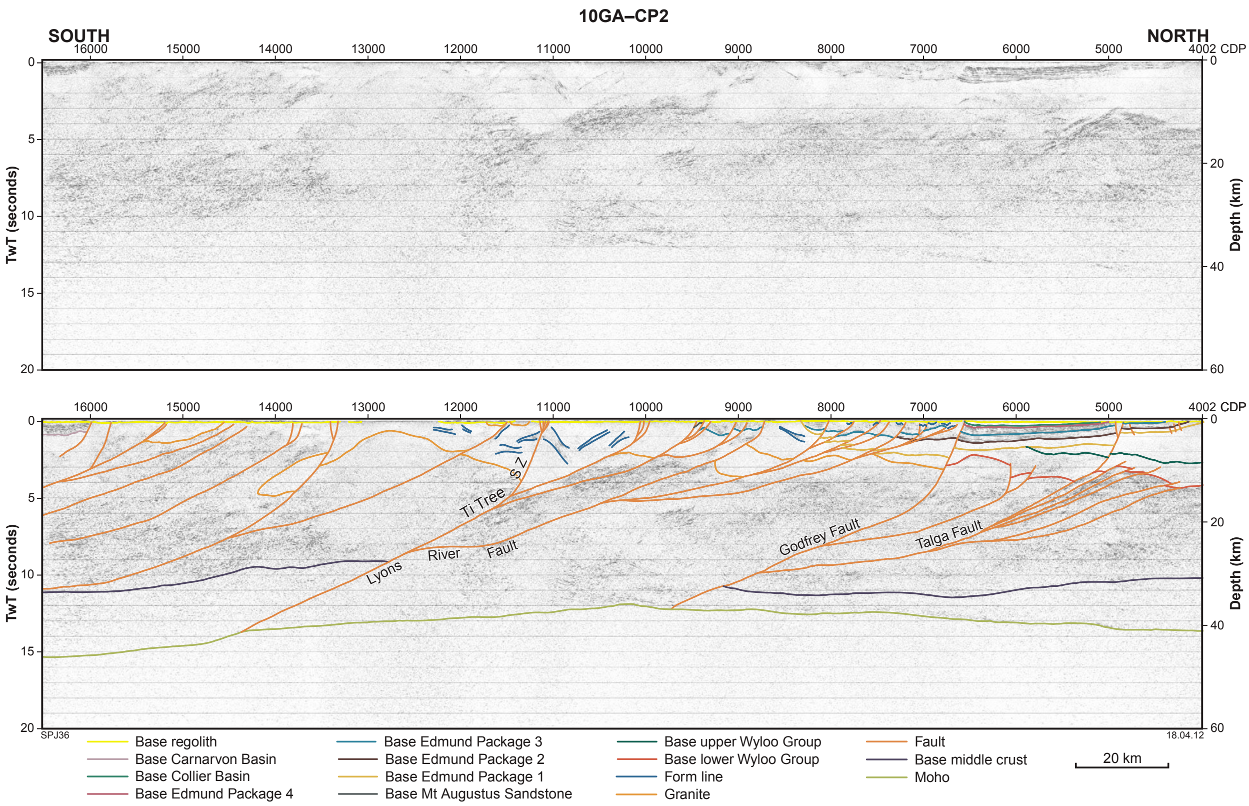

Figure 2. **Migrated seismic section for seismic line 10GA–CP2, showing both uninterpreted and interpreted versions. Display is to ~60 km depth, and shows vertical scale equal to horizontal scale, assuming an average crustal velocity of 6000 m/s.**

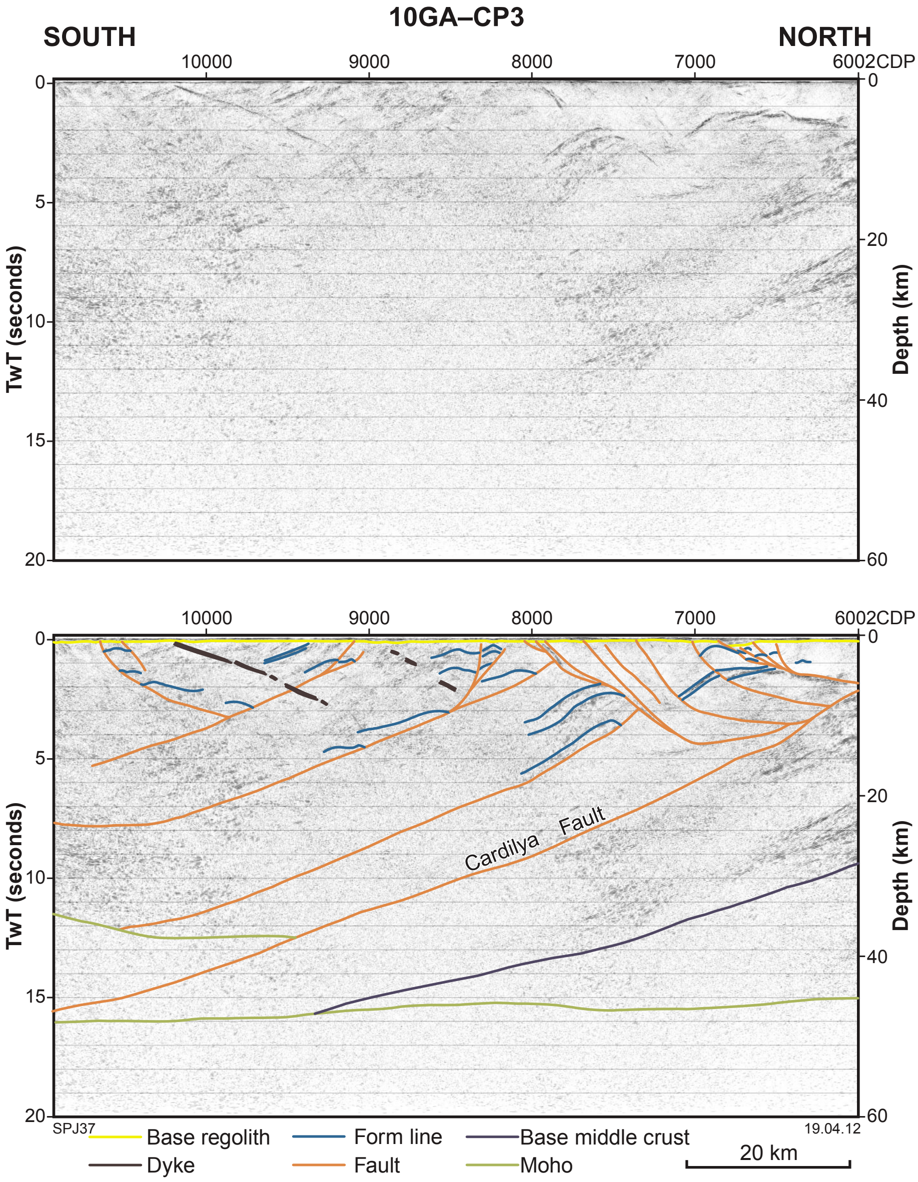

Figure 3. Migrated seismic section for seismic line 10GA–CP3, showing both uninterpreted and interpreted versions. Display is to ~60 km depth, and shows vertical scale equal to horizontal scale, assuming an average crustal velocity of 6000 m/s.

In the vicinity of seismic line 10GA–CP2, the crust is thinnest in the centre of the section, with the Moho at about 12 s TWT (~36 km) depth, and thickest at its southern end, where the Moho is at about 15.3 s TWT (~46 km) depth (Fig. 2; see also Johnson et al., 2011b). This section contains bands of reflections 0.3 – 1.0 s TWT (1–3 km) thick in the lowermost crust, the base of which is interpreted to be the Moho lying above a nonreflective mantle.

On seismic line 10GA–CP3, we have interpreted a complex pattern for the Moho (Figs 3 and 4). At the northern end of the seismic line, the Moho is interpreted to be at about 15 s TWT (~45 km) depth, on the basis of a similar pattern of reflectivity obtained for the lower crust as interpreted on seismic line 10GA–CP2 (Fig. 2). A band of reflections between CDPs 9200 and 10000, at depths of 13–16 s TWT (39–48 km), are interpreted to occur in the lower crust, and thus, the Moho is interpreted to be below these reflections, at about 16 s TWT (~48 km) depth. At the southernmost end of seismic line 10GA–CP3, the Moho is difficult to interpret (Fig. 3); however, this seismic line ties to another, more recently acquired, line across the southern Carnarvon Basin, 11GA–SC1, and ends 40 km to the west of the start of the Youanmi seismic line, 10GA–YU1. In the vicinity of the tie to line 10GA–CP3, the Moho on line 11GA–SC1 is at a depth of about 11 s TWT (~33 km); it is at a similar depth on line 10GA–YU1. This presents a complication in the geometry of the Moho at the southern end of line 10GA–CP3: either the Moho has a very steep ramp from a depth of about

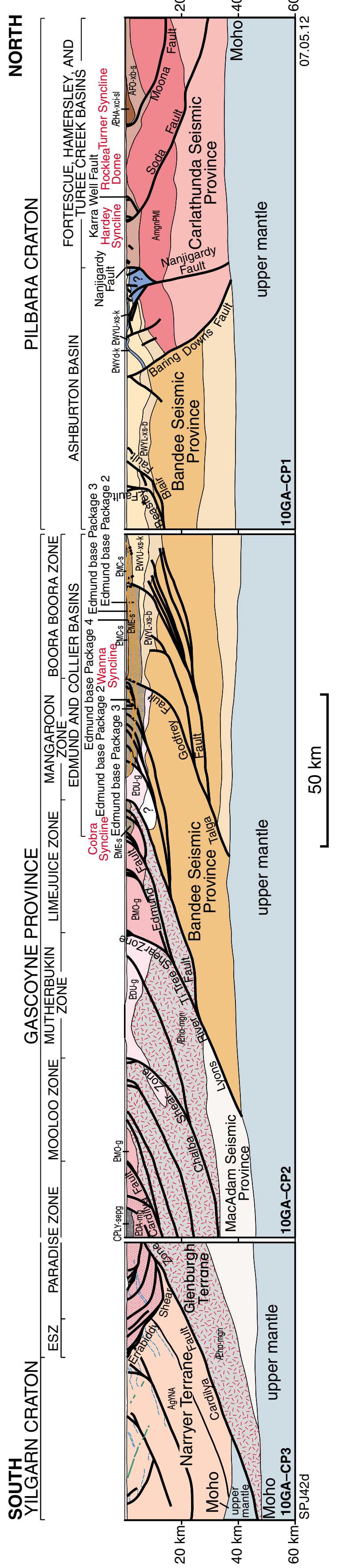

Figure 4. **Cross section of the transect across the Capricorn Orogen, combining seismic lines 10GA–CP1, 10GA–CP2, and 10GA–CP3, and showing key faults, terranes, zones, basins, and seismic provinces.**

48 km to about 33 km, over a horizontal distance of just over 20 km, or else it has been faulted and duplicated by crustal-scale thrusting. Our preferred interpretation is that the Moho has being faulted (Fig. 3; see also Johnson et al., 2011b) with a substantial localized offset, and that the crust has been duplicated on a crustal-scale thrust fault that also marks the subsurface boundary between the Yilgarn Craton and the Glenburgh Terrane (see below). Therefore, the Glenburgh Terrane may be present below the Narryer Terrane on seismic line 10GA–YU1 at around 15–16 s TWT (45–48 km).

Crustal architecture

In the region of the seismic sections, the upper crust can be subdivided into several provinces, basins, and zones, based principally on surface geological mapping and potential-field data. By comparison, the lower crust appears to consist of at least three discrete seismic provinces. Following Korsch et al. (2010), we use the term ‘seismic province’ to refer to a discrete volume of middle to lower crust, which cannot be traced to the surface, and whose crustal reflectivity is different to that of laterally or vertically adjoining provinces.

Pilbara Craton

At the northern end of the seismic survey, granite–greenstone rocks of the Pilbara Craton are exposed within the Rocklea Dome, roughly coinciding with CDPs 4620–4780 (line 10GA–CP1; Fig. 1), where they are overlain by sedimentary and igneous rocks of the Fortescue, Hamersley, and Wyloo Groups (Thorne et al., 2011a). The age of the granite–greenstones is constrained to greater than 2775 Ma, which is the age of the overlying lower Fortescue Group. The rocks of the Pilbara Craton sensu stricto are only weakly to moderately reflective, and can be tracked into the middle crust to a depth of about 4–7 s TWT (12–21 km).

Carlathunda Seismic Province

In the subsurface, we have interpreted that the base of the Pilbara granite–greenstone rocks coincides with the top of a highly reflective seismic package in the middle to lower crust (Figs 1 and 4). We term this package the Carlathunda Seismic Province (new name, after Carlathunda Bore), and interpret it to extend to the Moho. As we have not been able to track these rocks to the surface, we have no direct constraints on their lithology or age. Despite this, we consider this seismic province to be a discrete package of rocks that forms the current basement to the granite–greenstones of the Pilbara Craton sensu stricto.

As yet, no study has been undertaken on the age, geochemistry, or isotopic characteristics of the granites in the Rocklea Dome, but such a study is clearly warranted as it could provide information of the composition of the crust in the Carlathunda Seismic Province, below the dome.

The Carlathunda Seismic Province is bounded in the south by the Baring Downs Fault (new name, after Baring

Downs plain). This is a north-dipping fault separating sections of the middle to lower crust with differing seismic reflective characteristics, which we consider to represent different seismic provinces.

Bandee Seismic Province

Between the Baring Downs Fault and the Lyons River Fault, there are sedimentary rocks at the surface that were deposited in the Ashburton, Edmund, and Collier Basins, plus granites of the Durlacher Supersuite (1680–1620 Ma, Sheppard et al., 2010b). Beneath these rocks is a highly reflective middle crust, with a lower crust immediately above the Moho that is only weakly reflective (Figs 1 and 2); we use the term Bandee Seismic Province (new name, after Bandee Bore) to refer to the middle and lower crust in this region (Fig. 4).

Since we cannot track this seismic province to the surface, we do not have direct constraints on its composition or age. Nevertheless, the oldest rocks interpreted above this seismic province are the basal units of the lower Wyloo Group (Fig. 1), which are dated at 2209 ± 15 Ma (Martin et al., 1998), in turn implying that the seismic province is older than about 2210 Ma. The ages of inherited zircons sampled from younger granite intrusions to the south of the Talga Fault suggest the possibility that the Bandee Seismic Province contains material in the age range 2850–2600 Ma (GSWA, unpublished data). In an alternative interpretation, Thorne et al. (2011b) proposed that the Fortescue and Hamersley Groups extend well to the south of the Baring Downs Fault, thereby making the Bandee Seismic Province older than 2775 Ma.

At about CDP 6500 on seismic line 10GA–CP2, the Bandee Seismic Province comes as close to the surface as 2.2 s TWT (~6.5 km) depth, and is up to 11 s TWT (~33 km) thick (Fig. 2). The upper reflective part of the seismic province mostly dips gently to the south, but in places, the fabric is gently folded (Fig. 2). The lower weakly reflective part is up to 4.7 s TWT (~14 km) thick in the north on line 10GA–CP1 (Fig. 1), but thins towards the south, and is eventually truncated by the merged Godfrey and Talga Faults near the Moho (Fig. 2).

Glenburgh Terrane

The Glenburgh Terrane of the Gascoyne Province extends from the Errabiddy Shear Zone in the south, to the Lyons River Fault in the north (Fig. 4). The oldest rocks in this terrane are the granitic protoliths of the Halfway Gneiss in the Mooloo Zone, which have crystallization ages between c. 2555 and c. 2430 Ma (Johnson et al., 2011c). A hafnium isotopic study of these rocks, reported by Johnson et al. (2011d), indicates that the Halfway Gneiss is exotic to both the Pilbara and Yilgarn Cratons (see also Occhipinti et al., 2004). The Glenburgh Terrane also contains the Dalgaringa Supersuite, which was interpreted by Sheppard et al. (2004) to represent an Andean-type, continental-margin magmatic arc active from 2005 Ma to 1975 Ma.

At the present, we have included within the Glenburgh Terrane the reflective packages that extend from close to the surface to the lower crust on seismic line 10GA–CP2 (Fig. 2) and to the Moho on seismic line 10GA–CP3 (Fig. 3). Nevertheless, it is possible that these reflective packages actually represent the basement to this terrane. Thus, for the crust below the Errabiddy Shear Zone, we currently interpret the Glenburgh Terrane as extending from the Lyons River Fault in the north to the Cardilya Fault (new name, after Cardilya Creek) in the south (Fig. 4).

MacAdam Seismic Province

The MacAdam Seismic Province (new name, after MacAdam Plains) is bounded to the north by the Lyons River Fault, and to the south by the Glenburgh Terrane; it is presently confined to the weakly reflective lower crust immediately above the Moho on the southern end of line 10GA–CP2, and the northern end of line 10GA–CP3 (Figs 2–4). It forms the lower crustal basement to the Glenburgh Terrane, and is up to 5.5 s TWT (~16.5 km) thick. As this seismic province is limited to the lower crust, we have no direct constraints on its lithology or age.

Narryer Terrane

At the surface, the Narryer Terrane (as defined by Cassidy et al., 2006) of the northwest Yilgarn Craton occurs to the south of the Errabiddy Shear Zone (Fig. 3), whereas in the subsurface, it is interpreted to extend to the Moho, and is up to 12.5 s TWT (~37.5 km) thick. In seismic line 10GA–CP3, the Errabiddy Shear Zone is interpreted to sole onto the Cardilya Fault, and as a result, this shear zone marks the northern boundary of the Narryer Terrane in the subsurface (Fig. 3).

Crustal sutures

Relationship between Pilbara Craton – Carlathunda Seismic Province and Bandee Seismic Province

There are significant differences in crustal reflectivity across the Baring Downs Fault, which in the north borders the Pilbara Craton in the upper to middle crust and Carlathunda Seismic Province in the middle to lower crust, and in the south edges the Bandee Seismic Province, in turn suggesting that these units are discrete blocks of continental crust (Figs 1 and 4). Thus, we interpret the Baring Downs Fault to mark the site of a fossil suture zone. Given the different seismic character seen in the middle crust on either side of the fault, and considering that the lower Wyloo Group is interpreted to occur on both sides of the fault (Fig. 1), the suture probably formed prior to the deposition of the lower Wyloo Group at c. 2210 Ma, and was later reactivated to displace the sedimentary units. It is also possible that the Fortescue and Hamersley Groups were deposited on both sides of the fault (see Thorne et al., 2011b), which would suggest that the suture is older than the oldest unit in the Fortescue Group (c. 2775 Ma). Furthermore, the northern part of the Bandee Seismic Province may be the same age as the Archean Sylvania Inlier, which is located along-strike about 250 km to the east; this implies that the Baring Downs Fault is a suture that formed prior to 2775 Ma.

Relationship between the Bandee Seismic Province and Glenburgh Terrane

There is a pronounced step in the Moho where the Lyons River Fault soles onto it, rising from 15.5 s TWT (~46.5 km) in the south beneath the MacAdam Seismic Province, to less than 12 s TWT (~36 km) in the north beneath the Bandee Seismic Province (Figs 2 and 4). The fault also separates distinctive blocks of crust, with the Bandee Seismic Province to the north and the Glenburgh Terrane and MacAdam Seismic Province to the south. This raises the question of whether the Lyons River Fault is a fossil suture zone marking the site of a collision between two different continental blocks, and if so, at what time did this collision occur?

Previous tectonic models have inferred subduction followed by collision, either between the Pilbara and Yilgarn Cratons (e.g. Tyler and Thorne, 1990), or between the Pilbara Craton and the Glenburgh Terrane, possibly at the Talga Fault (e.g. Sheppard et al., 2001; Johnson et al., 2011c). Our interpretation suggests that the key structure is the Lyons River Fault, making the location of the suture farther to the south than previously thought.

The collision between the Bandee Seismic Province and the Glenburgh Terrane (Fig. 5) would have occurred sometime after the formation of the oldest rocks in the Glenburgh Terrane, namely the granitic protoliths of the Halfway Gneiss (with crystallization ages between c. 2555 and c. 2430 Ma). The oldest rocks interpreted to occur above the Bandee Seismic Province belong to the lower Wyloo Group, considered by Martin and Morris (2010), and Johnson et al. (2011c), to be foreland-basin deposits associated with the Ophthalmian Orogeny (dated at 2215–2145 Ma by Rasmussen et al., 2005), and which constrains the onset of collision to about 2215 Ma.

Later fault reactivation during one or more subsequent orogenies then allowed the Lyons River Fault to propagate towards the surface, cutting younger rocks in the Edmund Basin.

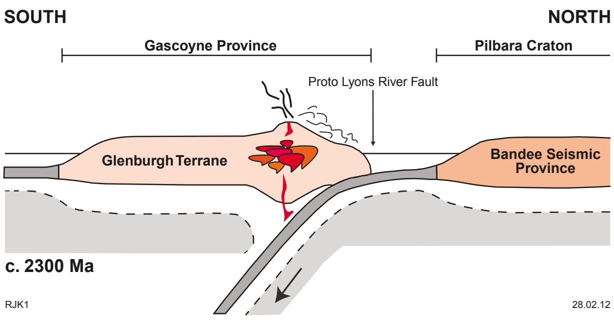

Figure 5. Schematic cross section, showing the evolution of the subduction and magmatic arc leading up to collision between the Glenburgh Terrane and Bandee Seismic Province, and the 2215–2145 Ma Ophthalmian Orogeny. Note that polarity of subduction is poorly constrained.

Relationship between Glenburgh and Narryer Terranes

The Glenburgh Terrane is considered exotic to both the Pilbara and Yilgarn Cratons (Occhipinti et al., 2004; Johnson et al., 2011c,d), and as such, the Narryer and Glenburgh Terranes represent discrete continental blocks sutured by a fossil collision/suture zone. At the surface, the boundary corresponds to the north-dipping Errabiddy Shear Zone, but, as proposed in the models of Sheppard et al. (2003), Hackney (2004), and Johnson et al. (2011c), and as shown in the seismic data, a key structure is another south-dipping, middle- to lower-crustal fault, known as the Cardilya Fault (Fig. 4).

Sheppard et al. (2004) demonstrated that the Dalgaringa Supersuite in the Glenburgh Terrane was an Andean-type, continental-margin magmatic arc that was active from 2005 Ma to 1975 Ma, although Johnson et al. (2011c) instead considered that the initiation of arc magmatism occurred at about 2080 Ma. The magmatic arc developed along the southern margin of the Glenburgh Terrane (Sheppard et al., 2004; Johnson et al., 2011c), constraining the polarity of subduction; that is, dipping northwards under the Glenburgh Terrane (Fig. 6).

There are at least two scenarios that could explain the architecture observed along seismic lines 10GA–CP2 and 10GA–CP3. In the first scenario, both major terrane-bounding structures are related to the Glenburgh Terrane – Yilgarn Craton collision, but their geometric relationship suggests that the Cardilya Fault post-dates the formation of the Errabiddy Shear Zone. The imbrication of the Glenburgh Terrane and Yilgarn Craton lithologies along the Errabiddy Shear Zone suggests that this earlier structure is probably the suture zone. Following the initial collision and interleaving of lithologies along the Errabiddy Shear Zone, this zone was reworked by the Cardilya Fault, which underthrust the southern margin of the Glenburgh Terrane beneath the Narryer Terrane (see Johnson et al., 2011b).

However, the preferred alternative is that during oceanic closure and collision, which occurred at 1965–1950 Ma during the latter part of the Glenburgh Orogeny (Johnson et al., 2011c), the Narryer Terrane was obducted onto the Glenburgh Terrane at the present site of the Cardilya Fault. During the post-collisional phase of the Glenburgh Orogeny, backthrusting at the Errabiddy Shear Zone resulted in a slice of the Glenburgh Terrane being thrust back to the south, over the upper part of the Narryer Terrane, thus producing the present crustal architecture imaged in seismic line 10GA–CP3 (Fig. 4).

Geodynamic implications

Crustal architecture of the Capricorn Orogen

The new deep seismic imaging, extending from the southern Pilbara Craton to the northern Yilgarn Craton, provides, for the first time, a holistic view of the crustal

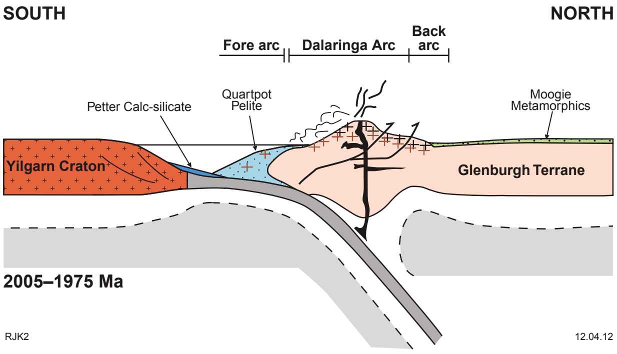

Figure 6. Schematic cross sections, showing the evolution of the Dalgaringa Arc, leading to the collision between the Yilgarn Craton and the Glenburgh Terrane.

architecture of the Capricorn Orogen. Based on the nature of seismic reflectivity, the orogen can be subdivided into several crustal-scale terranes and provinces, with sedimentary basins occupying the upper crust along the northern half of the transect. The region to the north of the Baring Downs Fault is dominated by north-dipping crustal scale structures, whereas to the south of the Baring Downs Fault, the majority of the transect is dominated by south-dipping structures, many of which cut the entire crust through to the Moho. Interestingly, the southern end of the transect is interpreted to have been duplicated by thrust faulting.

Assembly of the West Australian Craton

The new deep seismic lines across the Capricorn Orogen show that the West Australian Craton was built through the progressive accretion of continental slivers onto the southern margin of the Pilbara Craton (and its basement, the Carlathunda Seismic Province). Initially, the Bandee Seismic Province was sutured to the Pilbara Craton, most likely before 2775 Ma. Suturing of the Glenburgh Terrane to the amalgamated Pilbara – Bandee craton most likely occurred at about 2215 Ma during the Ophthalmian Orogeny. The final assembly of the West Australian Craton occurred when the Narryer Terrane of the northern Yilgarn Craton was sutured to the composite Pilbara – Bandee – Glenburgh continental block at about 1950 Ma, during the Glenburgh Orogeny.

Intracontinental reactivation

Following the final assembly of the West Australian Craton, reactivation in an intracontinental setting occurred at several discrete times, with most major faults imaged in the seismic sections showing evidence of post-collisional reactivation during one or more of the later orogenies recognized in the craton (Sheppard et al., 2010a; Johnson et al., 2011a). For example, the Baring Downs Fault significantly displaces units in the Ashburton Basin, including the youngest Ashburton Formation. The Lyons River Fault was reactivated as an extensional fault during deposition of the Edmund Group (Cutten et al., 2011; Johnson et al., 2011b), and was later inverted as a thrust to produce hangingwall anticlines. Splays to the north leading off the Talga Fault show a thrust sense of displacement, but near the surface, the Talga Fault itself appears to have had extensional movement during deposition of the Edmund Group, and later inversion as a positive flower structure. Crustal-scale faults within the Bandee Seismic Province and Glenburgh Terrane, such as the Godfrey Fault and Chalba Shear Zone, also show evidence of late reactivation.

Summary

Interpretation of the Capricorn deep seismic reflection survey has allowed us to examine the geodynamic relationships between the Pilbara Craton, Gascoyne Province, and Yilgarn Craton, which together form the Western Australian Craton. Prior to the seismic survey, suture zones were proposed between the Pilbara Craton and the Glenburgh Terrane at the Talga Fault, and between the Yilgarn Craton and the Glenburgh Terrane at the Errabiddy Shear Zone. Our interpretation of the seismic lines indicates that there is a suture between the Pilbara Craton and the newly recognized Bandee Seismic Province. Our interpretation also suggests that the Gascoyne Province can be subdivided into at least two discrete crustal blocks, with the suture between them interpreted to occur at the Lyons River Fault. Finally, the seismic interpretation has confirmed previous interpretations that the crustal architecture between the Narryer and Glenburgh Terranes consists of a south-dipping structure in the middle to lower crust, indicating where the Glenburgh Terrane has been thrust southward beneath the Narryer Terrane. The Errabiddy Shear Zone therefore represents an upper-crustal thrust system, where the Glenburgh Terrane has been thrust over the Narryer Terrane, possibly as a backthrust.

Acknowledgements

This paper forms part of a collaborative project between GSWA, AuScope, and Geoscience Australia. We thank the following for their contributions to the project: Josef Holzschuh, Ross Costelloe, Tanya Fomin, and Jenny Maher, who were involved in the acquisition and processing of the seismic data; Lindsay Highet and Weiping Zhang, who produced the maps and digital versions of the interpretations of the seismic sections, respectively; and Richard Chopping for input and discussions on the potential field data. We also thank Geoff Fraser and Natalie Kositcin for reviewing this abstract.

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