The nature of the Moho in Australia from reflection profiling: A review

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**Abstract**

The transition between the crust and mantle across the Australian continent shows considerable variations in both depth and sharpness. Recent extensive seismic reflection profiling provides a comprehensive data set to investigate the nature of the Moho in a wide range of geological environments. In reflection seismology the crust is normally characterized by distinct reflectivity whose base is taken as the location of the reflection Moho. This attribution to the base of the crust ties well to refraction and receiver function studies that make a more direct estimate of the depth to the base of the crust. The character of the reflection Moho varies widely across the Precambrian areas of Australia with no consistent link to the surface geology or the estimated age of the crust. In a number of places a double Moho is preserved with underthrusting, suggesting that the reflection Moho is a very ancient feature (at least 1400 Ma in the Capricorn Orogen). Elsewhere, the current Moho reflects multiple generations of crustal reworking.

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1. Introduction

Extensive use of seismological methods has been made in Australia in the study of the crust and upper mantle using both man-made and natural sources. In particular there has been a sustained program of using seismic reflection profiling to characterise the whole crust. Reflection studies of the whole crust have grown from short experimental spreads in the 1960s to large-scale transects (see, e.g., [1]). A nearly 2000 km long reflection transect, using explosive sources, with 20 s recording was built up across southern Queensland in the 1980’s. Explosive sources in drill holes continued to be used until 1997, when they were replaced with arrays of powerful vibrator sources. From 1998 to 2007 reflection acquisition was carried out using vibrators and recording equipment from the ANSIR Major National Research Facility. Since 2007 commercial contractors have been used, with the same style of acquisition parameters.

Since 2004 there has been a major national investment in seismic reflection work funded through investment from Geoscience Australia, State and Territory Geological Surveys and, since 2007, the AuScope infrastructure initiative. Over 14,000 km of full crustal reflection profiles have been acquired with recording to 20 s or more. Surveys in 2013–2014 have added more than 2000 km of full-crustal profiling and provide reflection results in a number of areas with little outcrop, which had not been previously studied.

This large and sustained effort has provided new insights into crustal structure, architecture and evolution across much of the Australian continent (Fig. 1). The dense sampling provided by the reflection transects has been of considerable value in mapping the character and geometry of the Moho on the continental scale [2,3].

Across Canada, Cook et al. [4] have presented a synthesis of results from the Lithoprobe program (1984–2003) on the character of the crust–mantle transition. Lithoprobe provided extensive reflection profiling in transects across major features of Canadian geology, including work in Archean and Proterozoic domains that may well have been linked to Australia in past supercontinent cycles. A feature of the Lithoprobe work was extensive use of seismic reflection so that many areas have good seismic wavespeed control for the deep crust and uppermost mantle. Across the Fennoscandian Shield, marine reflection profiles in the Gulf of Bothnia are complemented by 2000 km of land acquisition in the FIRE experiment [6] that provides good coverage of the major Archean and Proterozoic units, including the region of rather thick crust in southern Finland. Reflection work in Australia’s Gondwana neighbour India [7] has concentrated on Proterozoic suture zones. Fine examples of reflection results from a wide range of geologic environments are provided by Carbonnell et al. [8], who also discuss the way in which refraction and receiver function analysis can be used to build up a more coherent picture of the many different styles of transition between crust and mantle in the continents. Unlike the Canadian program of focussed transects in Lithoprobe, the extensive reflection coverage in Australia has been built up by investment from Geoscience Australia in partnership with State and Territory Geological Surveys directed mainly at economic targets. Since 2007 the AuScope infrastructure project has provided support directed at major scientific questions. The result is a mixture of long line-profiles and areas with stronger 3-D control on structure.

1.1. Major patterns of Moho variation across Australia

The Moho in seismic reflection records is identified as the base of crustal reflectivity, since the upper mantle shows few distinct reflections – probably because the horizontal scale length of structures is rather longer than in the crust. Other major sources of information on Moho depth across Australia come from early seismic refraction work, and from receiver function studies that exploit the conversions and reflections in the crust, which follow the major seismic phases from distant earthquakes recorded at permanent and portable seismic stations.

Kennett et al. [2] have assembled a wide range of information on Moho depth across Australia, and have demonstrated the strong consistency between the estimates obtained using different techniques. Seismic reflection profiling provides much of the detailed control on the depth to Moho in Australia, supplementing more localised information from refraction and receiver function studies. Recent experiments have added much information in areas that hitherto had very limited sampling, particularly in Western Australia. The compilation in Fig. 1 extends the results of Kennett et al. [2], and Salmon et al. [3], and includes Moho depth estimates from the extensive campaign of reflection profiles in 2013–2014 in regions of cover, not only over the Eucla basin to the Gawler craton, to the east of the Mt. Isa block, and in the Canning basin.

Fig. 1 shows the full current suite of information on Moho depth across Australia from both active and passive seismology, including the most recent reflection profiles, superimposed on a simplified tectonic representation. The individual points are colour coded by the depth to Moho with a symbol shape showing the nature of the technique employed. One of the striking features in the pattern of crustal thickness is the trend for the major tectonic blocks to be outlined by a narrow belt of somewhat thickened crust. This is particularly noticeable for the Yilgarn craton in Western Australia and for the Gawler craton in South Australia.

In this paper we present a number of examples of the nature of the reflection Moho, working geographically from west to east across the Australian continent, and approximately ordered in age from the Archean to the Proterozoic–Phanerozoic transition in the east. We look at way in which the reflectivity at the base of crust relates to the rest of the crust and the implications this has for crustal evolution, with comparisons to similar configurations in Canada [4], Fennoscandia [5,6], India [7], and elsewhere.

1.2. Reflection profiling and the character of the Moho

The reflection seismic method relies on the return of seismic energy to the surface from physical contrasts in the subsurface, associated with local changes in seismic wavespeed and/or density. In sedimentary basins, reflectors tend to be distinct and continuous, so that individual horizons can be tracked over considerable distances. In contrast, in the crystalline crust individual reflection segments tend to be short, and many crustal features become apparent from a change in the character of the reflection sequence in horizontal position or time. Full-crustal reflection surveys are carried out along nearly linear profiles, frequently exploiting access along public roads, though logistic considerations may require bends in the line. Only in a few cases is full 3-D control available from intersecting lines. Recording and processing are car-
ried out with respect to the two-way time from the source to receivers at the surface. The results are presented as a two-dimensional profile along the line, but can include energy return from 3-D structure off the line of survey. Such “side-swipe” features are normally less problematic at later reflection times.

Compared with the crust, the upper mantle shows low reflectivity, and this means that the base of the crust can be mapped by recognising the change in the character of the reflections as a function of two-way time from source to surface. The reflection Moho is taken as the base of the set of crustal reflectors, and shows considerable variation in character on different reflection profiles, and indeed sometimes along a single reflection line.

A convenient summary of Moho properties on seismic reflection profiles is provided by the character of the base of subhorizontal crustal reflectivity (cf. [4,8]). In this work we use a classification based on the nature of the reflectivity at the base of the crust and its visibility in the seismic records:

- **Class A** – very sharp reflections marking the base of reflectivity;
- **Class B** – a distinct change in character with depth, but the actual base of reflectivity is more difficult to pick;
- **Class C** – the reflectivity fades downwards so that the Moho is rather nebulous and difficult to pick, even though the general location is evident;
- **Class D** – no clear reflections in the vicinity of the Moho (Class D), even though it has been visible elsewhere on the profile.

Cook et al. [4] provide a different set of categories from the Lithoprobe reflection transects in Canada:

1. no clear reflections in the vicinity of the Moho, including either no reflections at all or a downward fading of reflectivity (corresponding to Classes C and D);
2. structures underlain by a subhorizontal distinct reflection that delineates the base of reflectivity (Classes A and B);
3. reflections that project below the Moho into the upper mantle.

The last category is not common in the Lithoprobe transects across Canada, but has been seen in the western Superior province and in central Alberta. There are equivalent structures in Australia in northern Queensland and the Curnamona craton.

The classifications of the reflection Moho can be linked to, e.g., receiver function studies to provide information on the sharpness of the crust–mantle transition. They do not, however, link directly to the nature of the Moho as a record of geological processes. Indeed, the diverse character of the reflection Moho in continental areas suggests that it does not arise from the action of a single process, but rather reflects the action of the full geological history of a region. In some places though, the configuration of the Moho can provide hints as to the age of the feature.

Among the mechanisms that have been invoked to generate or modify the continental Moho are [4,8]:

-...
(a) infusion of old oceanic material at the base of the crust so that the former oceanic Moho becomes the new continental Moho;
(b) partial melting and removal of lighter crustal fractions so that remaining restite has less internal contrasts and higher velocities, this is likely to be accompanied by modified rheology that could subsequently localize deformation or detachment;
(c) magmatic underplating that adds material with relatively high densities and seismic wavespeeds to the base of the crust, in which case the Moho may lie near the base of layers that are younger than the bulk of the crust;
(d) metamorphic transitions that transform lower crustal granulites into eclogites that cannot be distinguished from the mantle.

The different mechanisms can influence the character of crustal reflectivity at the base of the crust, but even where good seismic wavespeed information is available it can be difficult to identify the most likely mechanism for Moho generation. Mechanism (a) is likely to leave a band of distinct reflectivity at the base of the crust, but this can also occur where the modern upper crust has been built on a former oceanic crust substrate. Mechanism (b), with delamination, has been invoked for Archean domains to explain a very flat and well-defined reflection Moho. Mechanism (c), with underplating, is likely to suppress contrasts in wavespeed and density and hence lead to a more diffuse character of basal reflectivity. In zones of compression it is possible that a narrow zone can be pushed into the scenario where phase transformation takes place with consequent loss of crustal reflections (mechanism d).

2. Character of reflection Moho across Australia

The extensive program of full-crustal reflection profiling in Australia, undertaken with vibrator sources since 2000, samples a wide range of crustal ages and geological environments with a consistent style of data acquisition. This provides an unusual opportunity to compare the character of the crust–mantle transition across Precambrian regions of Australia. The set of figures below display reflection segments up to 130 km long, at approximately true scale. Fig. 2 presents the suite of full-crustal reflection profiles across Australia superimposed on a geological map taken from the 1:2.5 M digital representation of Australian Geology from

![Fig. 2. The locations of the seismic reflection profiles across Australia superimposed on the 1:2.5 M compilation of surface geology from Geoscience Australia. Surveys conducted with explosive sources are indicated in orange and those with vibrator sources in red. The extensive surveys conducted since the compilation of results on the Australian Moho by Kennett et al. [2] are shown in purple. The lines used for examples of Moho character are indicated with thicker dark red lines and are labelled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
Geoscience Australia. Profiles acquired with explosive sources are shown in orange, and those with vibrator sources in red and purple for the most recent work. Record sections for all full-crustal reflection profiles collected up to 2011 are available at uniform scale together with geological strip maps in the compilation [9].

The selected seismic lines that are illustrated below are shown in thick dark red lines in Fig. 2, with annotated names by line and year of acquisition. All of these reflection profiles have been acquired using vibrator sources with a minimum of 60-fold cover for the entire crust using, typically, a 6-km active spread symmetrically arranged about the source point. The variable regolith has been handled with careful refraction statics, a major undertaking for these long lines. The acquisition and processing parameters vary little between the lines, so that the apparent differences in Moho character relate to structure at depth. Some variability in the appearance of the record sections relate to variations in near surface conditions that affect source coupling.

For each seismic line a smooth line is generated to even out the effects of bends and so aid the use of 2-D seismic processing. This Common-Depth-Point (CDP) line is a curve of best fit through the midpoints between sources and receivers, which optimises the fold of the data while minimising the subsurface area of reflections contributing to each nominal CDP. Each trace (source–receiver pair) is allocated to the nearest CDP bin to its midpoint. The data in each gather are stacked together with corrections for the vertical variations in velocity (normal moveout), and for more recent sections for dip at depth (dip-moveout). This produces a single stacked trace as a function of two-way time for each CDP point, typically at 20–40 m intervals. The stacked records are migrated in time to improve structural rendering.

The segments of reflection profiles are displayed as migrated time sections to 20 s two-way-time; an approximate depth conversion can be made by using a mean crustal stacking velocity of 6 km/s and this depth scale is indicated on the figures. In a number of parts of the continent it has been possible to calibrate the depth conversion using results from receiver functions exploiting the reflections and conversions following the onset of the P waves on the records from distant earthquakes. The typical difference between the receiver function estimates of the depth to Moho and those derived from the reflection analysis is around 1 km.

We start our survey of Moho character in the Archean Yilgarn craton, and then generally move eastwards to areas with progressively younger surface rocks. We illustrate the different behaviour seen in the transition between crust and mantle with 120 km long segments of reflection profile presented at approximately 1:1 horizontal to vertical scale. The location of the reflection Moho is highlighted on the record sections below with a light green band, which is lightened when the Moho is less clear. The highlighting is placed behind the reflection section so that it does not obscure the actual reflectors.

2.1. Western Australia

2.1.1. Line 10-YU2

The reflection segment illustrated in Fig. 3 is from the YU2 line carried out in 2010 across the Southern Cross domain of the Youanmi terrane in the Yilgarn craton, for which crustal age is 2.9 Ga or older, with intrusives around 2.8 Ga. The prominent strong reflections, in the otherwise relatively transparent shallow part of the section correlate well with dykes that outcrop across this region [9]. The middle crust is more complex with a distinct base that deepens from 6 s to nearly 8 s two-way-time from east to west (the direction of increasing CDP number). The reflectivity at the base of the crust is nearly horizontal with a very distinct base that has little variation in reflection time. Receiver function results from this region show a very sharp Moho discontinuity, at a depth around 33 km, that ties to the reflection results with differences of less than 0.5 km. The Moho in Fig. 3 is among the most distinct seen across the continent and is easy to track across the whole domain.

Such a flat distinct reflection Moho is seen in modern settings in extensional domains such as the Basin and Range province (Klemperer et al. [10]), where the Moho is judged to be a young feature. In the Archean environment we could expect a much hotter lower crust, so that the rheological state could be similar to that in a modern extension leading to a laminar configuration in basal shear. An alternative viewpoint advocated by Abbot et al. [11], is that the flat sharp Moho in many Archean domains has been produced by delamination of dense garnet rich lithologies resulting in a flat, sharp Moho reflector and a thinner crust with an enhanced felsic component.

2.1.2. Lines 10-CP2, 10-CP3

The base of the crust is less distinct in the Proterozoic Capricorn Orogen that abuts the Yilgarn craton to the north (Fig. 4). A detailed interpretation of the 2010 reflection survey is presented by Johnson et al. [12]. The Glenburg terrane of the Gascoyne province fused with the northern Yilgarn craton at around 1950 Ma, with underthrusting beneath the Narryer terrane – the oldest component of the craton. Line CP2 shown in the upper part of Fig. 4 lies
in the middle of the Gascoyne province with a clear base to crustal reflectivity in the north (CDP 10,000) that becomes less distinct toward the south. In contrast to Fig. 3 there is little structure to the deep reflectivity and reflection segments are rather short. Nevertheless the reflection Moho can be traced reasonably well across the whole section.

Line CP3 starts in the Glenburgh terrane (CDP 6000) and crosses into the Narryer Terrane at CDP 8000 with a noticeable change in the dip of shallow reflectors across the Errabiddy shear zone. A very prominent dipping reflector appears to sole out at around 14.5 s two-way-time at CDP 1000 matching up with the base of the significant reflections further north (CDP 6000). At the southern end of the line, in the Narryer Terrane, the coherent crustal reflection packet terminates at 12 s two-way-time, with some localised bright reflections.

In contrast, in the Musgrave province shown in the lower panel of Fig. 5, the base of the crust is significantly deeper at around 16 s at the northern edge, and reaching at least 18 s at the southern end of the segment (CDP 8500). The precise nature of the transition between the two geological provinces has not proved easy to unravel because restricted logistics mean that the quality of the reflection section is somewhat poorer in the critical zone. Nevertheless, the results would be compatible with a underthrust of the Musgrave province beneath the extended edge of the Yilgarn craton, most likely associated with the Musgrave Orogen around 1200 Ma.

2.1.4. Imbricate Moho

On both the northern and western margins of the Yilgarn craton, the reflection Moho lies much deeper in the abutting Proterozoic terrane. For the Capricorn Orogen (10-CP3) there is clear evidence for a doubled Moho with underthrusting from the north that can be linked to the fusion of the Western Australia cratons at \(\sim 1950\) Ma. The last tectonic activity in this region occurred at around 1400 Ma [12], so that we have evidence for a very long-lived complex Moho structure.

2.1.3. Line 11-YOM

In 2011 the YOM reflection profile extended from the west of the Yilgarn craton to the Proterozoic Musgrave province, crossing a zone with very little surface outcrop (Korsch et al. [13]). Portions of the YOM reflection results are shown in Fig. 5. The upper panel starts in the western part of the Yilgarn craton and displays the distinctive eastward dipping reflection packages associated with the Yarmana terrane (around 2700 Ma) that grade into rather more diffuse reflectivity towards the northeast (increasing CDP number) as the line progresses across the Officer basin at the surface. A moderately distinct reflection Moho lies at around 14.5 s two-way-time, with some localised bright reflections.

In contrast, in the Musgrave province shown in the lower panel of Fig. 5, the base of the crust is significantly deeper at around 16 s at the northern edge, and reaching at least 18 s at the southern end of the segment (CDP 8500). The precise nature of the transition between the two geological provinces has not proved easy to unravel because restricted logistics mean that the quality of the reflection section is somewhat poorer in the critical zone. Nevertheless, the results would be compatible with a underthrust of the Musgrave province beneath the extended edge of the Yilgarn craton, most likely associated with the Musgrave Orogen around 1200 Ma.
reaches at least 54 km. An underthrust is again likely, but in this case would extend only about 20 km beneath the Yarmana province. The configuration is similar to that imaged by Juhlin et al. [15] in the middle Urals as the result of a much younger convergence event.

2.2. Central Australia

In Central Australia exceptionally large gravity anomalies are associated with major changes in crustal thickness (e.g., Lambeck et al. [16]). Early reflection profiling with explosive sources provided strong evidence for ‘thick-skinned’ tectonics (Goleby et al. [17]), with a large contrast in crustal thickness associated with the Red Bank Shear Zone in the Arunta block that brings lower crustal material right to the surface. Subsequent reflection surveys have examined regions slightly further north that were joined to the North Australian craton around 1800 Ma [18].

2.2.1. Line O5-T1

Reflection profile T1 conducted in 2005 extended from the Tanami region to the Arunta province of the North Australian craton. This O5-T1 profile formed the main part of the Tanami seismic experiment (Goleby et al. [19]). The reflection work also included a number of perpendicular cross-lines so that 3-D control is quite good. At the northern end of line O5-T1 in the Tanami zone, shown in the upper panel of Fig. 6, there is a strong band of reflectivity near the base of the crust at around 13–14 s two-way-time with very little apparent energy returned from the upper mantle.

Further south (beyond CDP 12,000) there is a rapid change with ultimately no distinct base to reflections that reach almost 20 s two-way-time. The lower panel of Fig. 6, has a slight overlap from the upper, but it hard to see any affinity in the nature of crustal reflectivity between this Arunta domain and the Tanami results. The zone of crustal thickening (around 80 km wide) is marked by dipping structures on either side that dip in towards the thickest crust. Goleby et al. [19] interpret the profile in terms of a southeast dipping suture zone that links into the zone of indistinct Moho. This feature is indicated in Fig. 6 by a light blue highlight. The suture zone truncates the northwest dipping lower crustal reflectors seen at the southern end of the profile.

2.2.2. Line 09-GA

A similar character is seen further east in a 2009 reflection profile that extends from the Arunta block in the south across the Georgina basin in an area with modest surface exposure (Korsch et al. [20]). Portions of the record section are shown in Fig. 7, with a short break of about 25 km between the upper and lower panels. The upper panel of Fig. 7 commences in the Arunta block, with a well-defined crustal base at around 14 s two-way-time. To the north, the crust thickens rapidly though the base is somewhat indistinct. At the other end of the profile beneath the Georgina basin (lower panel Fig. 7,) there is again a well defined base to the crust below a set of southward dipping reflectors in the mid- to lower-crust (CDP 7000–5000). To the south the crust reaches at least 18 s two-way-time, and the progression to thicker material is
clearer than from the Arunta side. Korsch et al. [20] infer a dipping suture indicated in Fig. 7 by a light blue highlight.

2.2.3. Localised crustal thickening

For each of the 05-T1 and 09-GA profiles the thickest crust is approaching 60 km thick with no distinct base. Indeed the deepest reflectivity is rather diffuse and might be associated with transformation of crustal material to eclogite. A somewhat similar situation is seen in the URAL-95 transect presented by Carbonnell et al. [8] where a central zone of about 100 km width with little reflectivity is flanked by a clear reflection Moho that tends to deepen and then can no longer be tracked.

Korsch et al. [20] link the thickened crust on both the profiles 05-T1 and 09-GA to a single suture created in one of the compressional stages of the Alice Springs Orogeny (450–300 Ma). Thus the two light blue highlighted features in Figs. 6 and 7 would result from the same event; the different apparent orientations resulting from the orientation of the profiles.

Further south, at the Red Bank zone also of Alice Springs age, earlier seismic reflection work with explosive sources (Goleby et al. [17]) imaged a major upward displacement of the Moho from around 45 km to 25 km in the hanging wall of the Red Bank thrust that brings lower crustal material to the surface, whilst the Moho in the footwall lies at about 50 km. Comparable displacements of the Moho are seen beneath the Musgrave province on the 2008 GOMA line linking from the Gawler craton through the Officer basin to the Musgrave province and on into the Amadeus basin (Korsch et al. [21]).

2.3. South Australian craton

A number of reflection profiles have been carried out in the South Australian craton with both east–west and north–south profiles in both the Gawler province [21–23] and the Curnamona province [24]. We have selected examples from the Gawler province and its margin, and a north–south profile in the Curnamona craton.

2.3.1. Line 08-G1

Fig. 8 displays a portion of the 2008 profile across the Eyre Peninsular in South Australia that is characteristic of the crustal reflectivity in this dominantly Archean area [22]. A relatively transparent near-surface zone is underlain by strong mid-crustal reflectors with little dip that slowly fade to a modest level with only a few elongated reflection features and then finally simply stop. It is still relatively easy to determine where the crustal reflectivity ceases, and so most of the line lies in class B, grading to class C at the eastern end. Receiver function results from close to the line suggest a gradient from crust to mantle with a thickness of about 5–6 km, which ties closely with the extent of the blander reflection signal from the base of the crust.
2.3.2. Lines 03-OD1, 03-OD2

The Gawler province hosts a number of iron oxide–copper–gold (IOCG) deposits and in 2003 two perpendicular reflection profiles were carried out across the largest of these features at Olympic Dam ([23]), which lies beneath thick Proterozoic to Phanerozoic sedimentary successions. The world-class Olympic Dam deposit lies on the boundary between two distinct pieces of crust, the southern interpreted as the Archean–Paleoproterozoic core to the craton, the northern as a Meso–Neoproterozoic belt. Fig. 9 shows the portion of the north–south line in the immediate vicinity of the ore deposit and also the short cross-line. At the southern end of the line OD1 (CDP 8000–9500) there is a distinct reflector at the base of the crust at 13 s two-way-time that can be tracked for over 60 km. Whereas at the northern end of line crust, the southern interpreted as the Archean–Paleoproterozoic core to the craton, the northern as a Meso–Neoproterozoic belt. Fig. 9 shows the portion of the north–south line in the immediate vicinity of the ore deposit and also the short cross-line. At the southern end of the line OD1 (CDP 8000–9500) there is a distinct reflector at the base of the crust at 13 s two-way-time that can be tracked for over 60 km. Whereas at the northern end of line

Fig. 7. Migrated record sections for portions of line 09-GA, across the Proterozoic of the North Australian craton, with a highly localised zone of crustal thickening. The upper panel starts in the Amadeus basin which extends to at least cDP 16,000, and then lies in the Aileron zone of the Arunta province. The lower panel includes the very distinctive southerly dipping reflectors associated with the Davenport province beneath the Georgina basin to the north of the zone of crustal thickening. The transition from the Aileron to the Davenport is placed at cDP 7200 based on the change in crustal reflectivity [20], with a suture indicated in light blue highlight. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Record section for a portion of the east–west line 08-G1, across the Eyre peninsula in the Gawler craton in South Australia. A preliminary interpretation is presented in [22].
OD1 (CDP 3000–4000) there is a more diffuse zone of basal reflectivity between 12.5 s and 14 s two-way-time, which Drummond et al. [23] interpreted as a Moho transition zone. In between, from CDP 5000–8000, there is a distinct lack of significant reflectivity below 6 s two-way-time, which lies below the host rocks for the deposit. This relatively bland zone is also distinct on the perpendicular line OD2, and in the east–west direction is not much more than 20 km across. The processes that allowed ~1000 °C magma to come up through the crust to form the concentrated ore deposit at around 1600 Ma have reworked the lower crust in the neighborhood of a junction of different crustal types and eliminated any clearly identifiable reflection Moho feature.

2.3.3. Line 08-C1
The Proterozoic Curnamona province lies to the northeast of the Gawler province, with surface exposure of metasedimentary rocks.
of deposit around 1700 Ma. To the north, Neoproterozoic rocks (around 830 Ma) overlie the older material. The 2008 north–south reflection profile 08-C1 crossed this Curnamona province, linking with east–west profiles [24]. The profile lies across a region with thin sedimentary cover that thickens to the north of the profile. The nature of the Moho on this profile is very distinctive, as can be seen in Fig. 10, with dipping structures that reach to or through the general trend of the base of crustal reflectivity. These reflectors might represent crustal slices assembled in a ‘thick-skinned’ tectonic style, as in the southern Arunta block (Goleby et al. [17]).

Cook et al. [4] note similar features in the Proterozoic portion of the north–south Western Superior transect undertaken by Litho-probe in Canada, and also in the Thorsby area of the central Alberta transect where the crustal basement is also likely to be Paleoproterozoic. In all such cases the possibility exists that the features are generated by three-dimensional effects, so that out of plane reflections are superimposed on near vertical arrivals in the two-dimensional sections. But, for the Canadian examples, Cook et al. [4] point out that the evidence is in favour of the crossing reflections being real.

2.4. Northern Queensland

The Proterozoic Mt Isa province with multiple phases of deformation up to 1600 Ma hosts a variety of different mineral systems [18]. The province has been a target for a number of reflection profiles, as indicated in the map displayed in Fig. 11. The profiles in 1994, across the area of outcrop, were carried out with explosive sources, and showed little sign of the base of the crust. At the time, the acquisition configuration was questioned, since the Moho was found in refraction work in the same area [25]. Subsequent reflection profiles using multiple vibrator sources have confirmed that the very weak reflectivity at the base of the crust is a feature of a major corridor through the Mt. Isa belt, where there is evidence for a broad transition in seismic velocities between crust and mantle. Later reflection profiles have focussed on the portions of the Mt. Isa province with less surface exposure (Fig. 11), and the link to the Georgetown Inlier to the east, which has similar deformational ages (Korsch et al. [26]).

2.4.1. Lines 06-M4, 06-M5

Fig. 12 illustrates portions of the intersecting profiles M4 and M5, acquired in 2006, on the edge of the exposed Mt. Isa province that both show a fade in reflectivity with depth rather than any very distinctive Moho. In Fig. 12 both profiles are oriented so that the northern end of the profiles lie on the right. There is good consistency of character is the neighbourhood of the crossing point (M4 – cdp 9200, M5 – cdp 15,000) with a strong band of reflectivity in the upper to middle crust, but with only weak and fragmentary reflections below. Although this style of behaviour is sustained across most of line M5, we note that on line M4 towards the north and west as the line enters the core of the Mt. Isa block we increasingly pick up diffuse reflectivity throughout the crust. A similar behaviour is seen on much of the east–west line M6, particularly
in the zone due south of the northern portion of line M4. This behaviour suggests the possibility of widespread mafic underplating or intrusion (Thybo and Artiemieva [27]), an idea which is supported by a the character of the seismic wavespeeds at the base of the crust (Drummond et al. [25]). The diffuse lower crustal reflectivity in a zone of rather thick crust is similar to that seen on the Proterozoic segments of FIRE profiles 1, 2 and 3 across southern Finland [6], where the crust is also very thick with little surface topography.

2.4.2. Line 07-IG1

The distinctive nature of the Mt. Isa block, and the way in which the reflection character of the crust can change completely in just a few kilometres, is dramatically illustrated on the 2007 profile IG1, displayed in Fig. 14. This reflection profile starts in the Mt. Isa block and then traverses toward the northeast into a region with very little outcrop, finally reaching the Georgetown inlier near the Croydon gold fields. The edge of the structures related to Mt. Isa is very clear in the line 07-IG1, as can be seen in the upper panel of Fig. 14. At the southwestern end of the line, the Moho is at first just the base of a diffuse zone of reflectors at around 17 s two-way-time with a similar character to that seen on line M4 but perhaps a slightly more evident base. Within 30 km the reflection Moho begins to emerge as a distinct band of short reflectors at 14 s two-way-time. The surface outcrop of the Mt. Isa block ceases by CDP 4000, but the nature of the reflection records indicate this class of rocks continues to CDP 6000.

Beyond CDP 6000 there is a dramatic change in crustal character with a largely transparent upper crust and strong lower crustal reflectivity terminating in a distinct reflection Moho at 12–13 s two-way-time. This bold lower crustal character is sustained for nearly 200 km (middle and lower panels, Fig. 13). But, close to CDP 17,000 there is a sharp increase in the depth of the Moho associated with distinctive dipping reflectors in the mantle (lower panel – Fig. 13). This feature has been interpreted by Korsch et al. [26] as a fossil subduction zone, based on analogies with other examples, e.g., in Canada [4,28], and in the BABEL survey [5]. A similar configuration can be seen in the Alcudia reflection profile in central Spain [5], arising from the impact of Africa and Europe though in this case the dip opposes the direction of convergence.

Beyond the Moho step a slightly different style of crustal reflectivity, with again a distinct reflection Moho base is sustained into and through the Georgetown inlier, as is seen on the east–west line 07-IG2.

2.4.3. Line 07-A1

Another reflection profile that shows significant steps in the reflection Moho, formed part of the same 2007 suite of reflection profiles. Line A1 was designed to cross the Palmerville fault, which has been identified as the surface manifestation of the Tasman Line marking the exposed eastern limit of Paleoproterozoic and Mesoproterozoic rocks (e.g., Korsch et al. [26]). Profile A1 illustrated in Fig. 14 shows two distinct steps in the reflection Moho thinning towards the northeast. The first step at CDP 9300 raises the Moho by a couple of seconds in two-way-time. The second step is close to CDP 7500 which is the surface outcrop of the Palmerville fault, with at least a second of shallowing in the base of crustal reflectivity. The reflection Moho is very clear throughout so the steps...
are very evident. The interpretation of the reflection section presented by Korsch et al. [26] has the Palmerville fault dipping to the east so that there would be no causal relation between the tectonic boundary and the step in the Moho.

2.5. Southeastern Australia

2.5.1. Lines 09-SD1, 09-SD2

The first group of reflection profiles we present from southeastern Australia come from the Delamarian orogen, which couples the Lachlan Fold Belt to the older structures linked to the South Australian craton. Funding from the AuScope national infrastructure project supported the acquisition of nearly 200 km of reflection profile in this area. The main reflection line 09-SD1 starts in South Australia in the west and after about 75 km crosses into Victoria across a zone with no bed-rock exposure. The cross line 09-SD2 provides 3-D control and links to older reflection work carried out with explosive sources along the border between the States. Limestones in the west of the region had presented considerable problems with the older low fold procedures, but very high quality data was obtained with the vibrator sources in 2009. To the west the main reflection profile SD1 linked to the 2006 Victorian transect (Cayley et al. [29]).

The results from this South Delamarian experiment are striking, as shown in Fig. 15. On the east–west line 09-SD1 the crust thickens from 10 s two-way-time in the east to 14 s at the western end.
of the profile, with a distinct Moho except at the extreme west. The surprise was the presence of the distinct reflector at 14 s that is suggestive of an imbricate Moho. By pure chance, since the 14 s feature was unsuspected, the cross line 09-SD2 at about 70° inclination to SD1, also captures the deeper reflector. The cross line provides 3-D control on the deep reflection feature, which deepens to the south and west. However, this control is not at the point of maximum clarity of the reflection near 14 s two-way time.
The Delamarian material in the west is likely to be Proterozoic, with the younger Lachlan Fold Belt material on top. On both lines 09-SD1, 09-SD2 in Fig. 15 we see similar fade in lower crustal reflectivity on the western side to that seen in the 07-IG1 section as it comes off the Mt. Isa block (upper panel of Fig. 13).

2.5.2. Line 06-VT2

To the east, the VT2 segment of the 2006 Victorian transect in the western Lachlan Fold Belt shows clear mid crustal reflections, which are inferred to be associated with the Proterozoic Selwyn Block (Cayley et al. [29]). The reflection section is of high quality.
with clear thrust connection to surface ophiolites at CDP 8200 (Fig. 16), linked to the edge of the Selwyn Block. Even though mid-crustal reflectivity is strong, the precise location of the reflection Moho is rather difficult to determine, and can be classified as class C, at best. There is a band of reflectivity around 12\,s two-way-time, but below that there is partially continuous weak reflections to around 14\,s. Limited receiver function results from the general area would be compatible with the shallower surface being identified with the Moho, but also suggest the presence of a gradient zone in the crust–mantle transition.

3. Summary of Moho character across Australia

In Fig. 17 we summarize the character of the Moho across Australia from the full range of recent reflection profiling, by displaying the class of the pick from the reflection records, using the classification described in the Introduction, together with information from receiver function studies. Because the nature of the reflection pick is subject to the quality of the data acquisition, we have restricted the data set to just the data collected using vibrator sources since 1999, and a few earlier high quality lines using explosive sources with lower fold of cover, rather than using all surveys to 2011 as in Fig. 4 of Kennett et al. [2]. In the same figure we also display the nature of the crust–mantle transition inferred from receiver function studies of distant earthquakes at passive seismic sites, using results collated for the construction of the crustal component of the Australian Seismological Reference Model, AuSREM (Salmon et al. [30]). The classification used is based on an estimate of the thickness of the transition between the crust and mantle with T: < 2\,km, U: 2–4\,km, V: 4–8\,km, W: > 8\,km.

Class A reflections with a sharp base to crustal reflectivity are prominent in Archean regions, e.g., line 10-YU2, shown in Fig. 3. The more common situation (Class B) is that there is a distinct change in the character of the crustal reflectors with depth, so that the location of the Moho is well controlled, usually better than 0.5\,s in two-way time, but the actual base of reflectivity is less distinct as e.g., at the western end of line 05-T1 in Fig. 6. In a number of localities the crustal reflectivity reduces with increasing reflection time so that although the crust can be distinguished from the much less reflective mantle, but the base of the crustal reflectivity is not at all easy to pick. A good example of this Class C behaviour is provided by line 06-VT2 shown in Fig. 16. For Class D there are no clear reflections in the vicinity of the Moho, as in much of the Mt. Isa inlier.

In some cases there is a sharp transition in character along a profile so that a clear Moho can rapidly disappear and be replaced by a very different style of reflectivity at the base of the crust. This occurs on both the 05-T1 and 09-GA profiles in Central Australia, where the precise configuration of the Moho in the zone of crustal thickening cannot be determined, and unfortunately there is no control on the seismic wave speeds in these zones of highly localised crustal thickening.

As noted by Kennett et al. [2], there is generally a good correlation between the class assigned to the reflection character of the Moho and the thickness of the crust–mantle transition estimated from receiver function studies. Though unlike the scenario in north-western India [7], we rarely see a distinct band of basal reflectivity that might correspond directly to a gradient zone. A possible example has been seen in the western Gawler craton on an east–west reflection profile completed in early 2014. In the western Superior province, White et al. [31] have interpreted such a band of basal crustal reflections in terms of accreted oceanic crust with seismic P wave speeds in the range 7.0–7.4\,km/s – rather fast for the crust.

Class A for the reflection Moho corresponds to a sharp end to crustal reflectivity and ties well with Class T receiver function results. A broad gradient between crustal and mantle seismic wave speeds (V, W), normally produces an indistinct base of reflectivity (Classes C, D). Such gradient zones are common in Proterozoic terranes in Australia. Often reflection Class B ties with a modest thickness of crust–mantle transition as in case U: 2–4\,km.

In both the reflection and receiver function results we see considerable variability in the character of the transition between the crust and mantle over moderate distance scales. The major changes occur at the transition between lithospheric blocks, but even within areas that are thought to have a common geological history there can be noticeable contrasts.

The extensive set of high quality information across the Australian continent reveals a complex geometry at the base of the crust. Distinct jumps in the depth to Moho are often as large as 8–10\,km. On occasion these link to reflections that project through the Moho (e.g. line 08-CT, Fig. 10). In several places we have evidence for an imbricated structure with one crustal block apparently pushed under another and two distinct Moho boundaries preserved. A particularly striking example is shown in Fig. 15 for line 09-SD, where a doublet Moho structure has been captured in 3-D, with two crossing lines fortuitously placed, since the existence of the structure was anticipated. For 09-SD, the older material to the west appears to be pushed beneath younger crust to the east. Whereas in the two West Australian examples (10-CP3, 11-YOM) it is the younger Proterozoic material that is thicker and lies beneath the Archean.

4. Age relations?

Cawood and Korsch [18] provide a succinct account of the assembly of the Australian continent during the Proterozoic, building on Archean cores in the cratons. As can be seen from Fig. 1, the sampling of the continent by reflection profiles is extensive. However, it is worth noting that the locations of the profiles have generally been chosen because of potential economic interest, modulated by available logistics, and may not therefore provide an unbiased sample of the whole continent.

Nevertheless, the examples show the diversity of interrelations between crust and mantle across the Australian continent No systematic pattern that can be linked to crustal age emerges from the illustrated examples or indeed the broader range of available profiles. Most examples of very thick crust are found in Proterozoic regions, and then there is generally no distinct base to crustal reflectivity (e.g., Figs. 12 and 13), possibly due to magmatic under-plating. But, very thick crust is also found in the region affected by the Alice Springs orogeny (500–300 Ma) as in lines 05-T1 (Fig. 6) and 09-GA (Fig. 7). There are a number of cases where the crust thickens at the edge of recognised cratons, this zone of thickening may be accomplished through underthrusting (e.g. 10-CP3, Fig. 4) or a downwarp of the base of the crust often accompanied by a lack of clarity in the reflection Moho, linked to an asymmetric suture.

Across a region of a craton with a common initial age and tectonic history, such as the Youanmi province of the Yilgarn craton (Fig. 3), the character of the Moho is relatively coherent with modest changes in depth and clarity. Elsewhere, as we have seen in the examples there can be significant change including steps in the reflection Moho of several kilometres, even within a zone with similar material at the surface.

The examples show the diversity of crustal reflectivity seen across the Precambrian areas of Australia and their immediate margins. In some cases the nature of the basal reflectivity differs from that at shallow levels (e.g. Figs. 3, 5, 8, 12, 16). In others the Moho marks the base of a zone with similar character over an extensive depth range (e.g. Figs. 6, 10, 13 – lower panel, Fig. 15 – eastern end). The differences in character transcend crustal age and show little immediate link to tectonic history. The diversity
of behaviour, and lack of relation to crustal age, is similar to that revealed in the Lithoprobe program in Canada (Cook et al. [4]), where again there was little indication of significant reflectivity in the mantle except for a few features hypothesised to be linked to ancient subduction.

The style of basal crustal reflectivity seen in Archean terranes across the globe shows considerable similarities. Sections from the Canadian Shield (Superior and Slave provinces) [4] and from Profile 4 of FIRE in Finland [6] share a clear Moho base with the Australian examples from the Yilgarn craton, yet show distinct patterns of reflectivity in the crust. Proterozoic domains with considerable crustal thickness show a relatively diffuse base to the crust as in the Mt. Isa block and much of southern Finland [6]. But, there is no simple characterisation of Proterozoic crust. Some of the clearest examples of a mid-crustal discontinuity in Australia in northern Queensland, and in the recent work across the Eucla basin, occur in assumed Proterozoic crust (though not directly dated). However, we also have distinct mid-crustal features in southern Queensland where the surface materials are certainly Paleozoic. It is likely that similarities of crustal reflection style emerge through exposure of the crust to comparable processes, rather than carrying forward some initial imprint on the contrasts in seismic wavspeed and density.

5. Discussion and conclusions

The character of the reflection Moho reflects the geological fabric at the base of the crust and can be expected to be influenced by the rheological properties of the lower crust and upper mantle and the transition zone between them. It is not just current day rheology that needs to be taken into account, but that prevailing at the time of the last major tectonic processes in the region. Most models of rheology have a significant contrast in yield between the base of the crust and the upper mantle [32] for Shields, and this is likely to have prevailed even in the hotter environment of the earlier Earth. Strong reflectivity would be expected if a strongly sheared fabric remains in place at the base of the crust.

Nevertheless, in Australia, we find strong Moho reflectivity in a variety of tectonic environments. The nature of the reflection character at the base of the crust is not an effective indicator to be used to discriminate past tectonic processes.

The differences in seismic reflectivity between the crust and the upper mantle is likely to be related to the configuration of seismic contrasts. These in turn will be controlled by rheology. A stiff upper mantle will retain structure over long periods of time, with relatively slow rates of change of seismic properties, and it will not be easy for contrasts to be annealed. In contrast, a more mobile basal crustal rheology could allow the formation of much smaller scale heterogeneity, and its modification by subsequent geological processes.

On the northern and eastern margins of the Yilgarn craton, there is evidence for an imbricated Moho with the younger Proterozoic belts pushed under the craton. In this way the Proterozoic material is locked into place against the craton margin, and the configuration appears to have been preserved since the last orogenic activity at about 1400 Ma. The undisturbed Moho in the Yilgarn craton may well be much older, preserving its reflectivity orogenic activity at about 1400 Ma. The undisturbed Moho in the Yilgarn craton may well be much older, preserving its reflectivity and the configuration appears to have been preserved since the last major tectonic processes in the region.

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