Interpretation of Albany–Fraser seismic lines 12GA-AF1, 12GA-AF2 and 12GA-AF3: implications for crustal architecture

by

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Introduction

The aim of this study is to examine the crustal architecture of the Albany–Fraser Orogen, and to examine its relationship to the adjoining Yilgarn Craton by tracking the craton's subsurface extent beneath the orogen. The deep crustal structure of the Albany–Fraser Orogen provides insight into the processes that drove Paleoproterozoic rifting and magmatism along the craton margin, and Mesoproterozoic tectonic assembly. The upper crustal portion of the seismic images show the Mesoproterozoic fold and thrust belt architecture present in the Albany–Fraser Orogen that, although complex, in general terms relates to the tectonic assembly of the West Australian Craton and the South Australian Craton. Commencing in the Yilgarn Craton in the west, and finishing in the Madura Province in the east, the seismic lines provide a complete image and interpreted cross-section of the orogen.

In April to June 2012, 672 line km of vibroseis-source, deep seismic reflection data were acquired along four traverses (12GA-AF1, 158.4 km; 12GA-AF2, 114.04 km; 12GA-AF3, 319.12 km; and 12GA-T1, 80.32 km), collectively referred to as the Albany–Fraser seismic survey. The lines were designed to cross the various tectonic units and major shear zones of the east Albany–Fraser Orogen, and the eastern part of the central Albany–Fraser Orogen (Fig. 1; Plates 1, 2 and 3). The project is, in part, a collaborative project between Geoscience Australia (GA) and the Geological Survey of Western Australia (GSWA), and is part of the ongoing cooperation under the National Geoscience Agreement (NGA). This contribution covers the results and interpretation of seismic lines 12GA-AF1, 12GA-AF2 and 12GA-AF3; 12GA-T1 is presented in Occhipinti et al. (2014), and will not be discussed here.

Details of the acquisition and processing techniques followed for the deep seismic survey are provided in Costelloe et al. (2014). We undertake conversion from two-way travel time (TWT) to depth using an effective P-wave velocity for the crust of 6000 ms^{-1}, so that 1 s TWT is approximately equal to 3 km depth, with the exception of sedimentary rocks in the Eucla Basin and for the Cenozoic regolith, where we assume much slower P-wave velocities of 2500–3800 ms^{-1}.

Acquisition and processing techniques of deep crustal reflection seismic lines are designed to provide images of the crust and uppermost mantle that can be interpreted and shown as two-dimensional (2D) cross-sections of the present-day geological architecture. Although the processed seismic reflection data provide images of reflections to work with, the process of interpretation is analogous to drawing basic structural and lithological cross-sections from mapped surface data, where features that are away from the plane of section are taken into account. This includes analysing their geometrical extent, estimating apparent dip where features are not perpendicular to the line of section, and taking crosscutting relationships into account (i.e. the law of superposition). Because of the 2D nature of the seismic lines, the orientations of structures are apparent dips, and apparent dip directions. While the interpretations presented here have been derived from the seismic reflection images, they have also been guided by interpreted bedrock geology maps (Plates 1, 2, and 3), which in turn are based on field and drillcore relationships, and magnetic and gravity data interpretation compiled between 2008 and 2013. Modelling of the potential field data are presented in Murdie et al. (2014).

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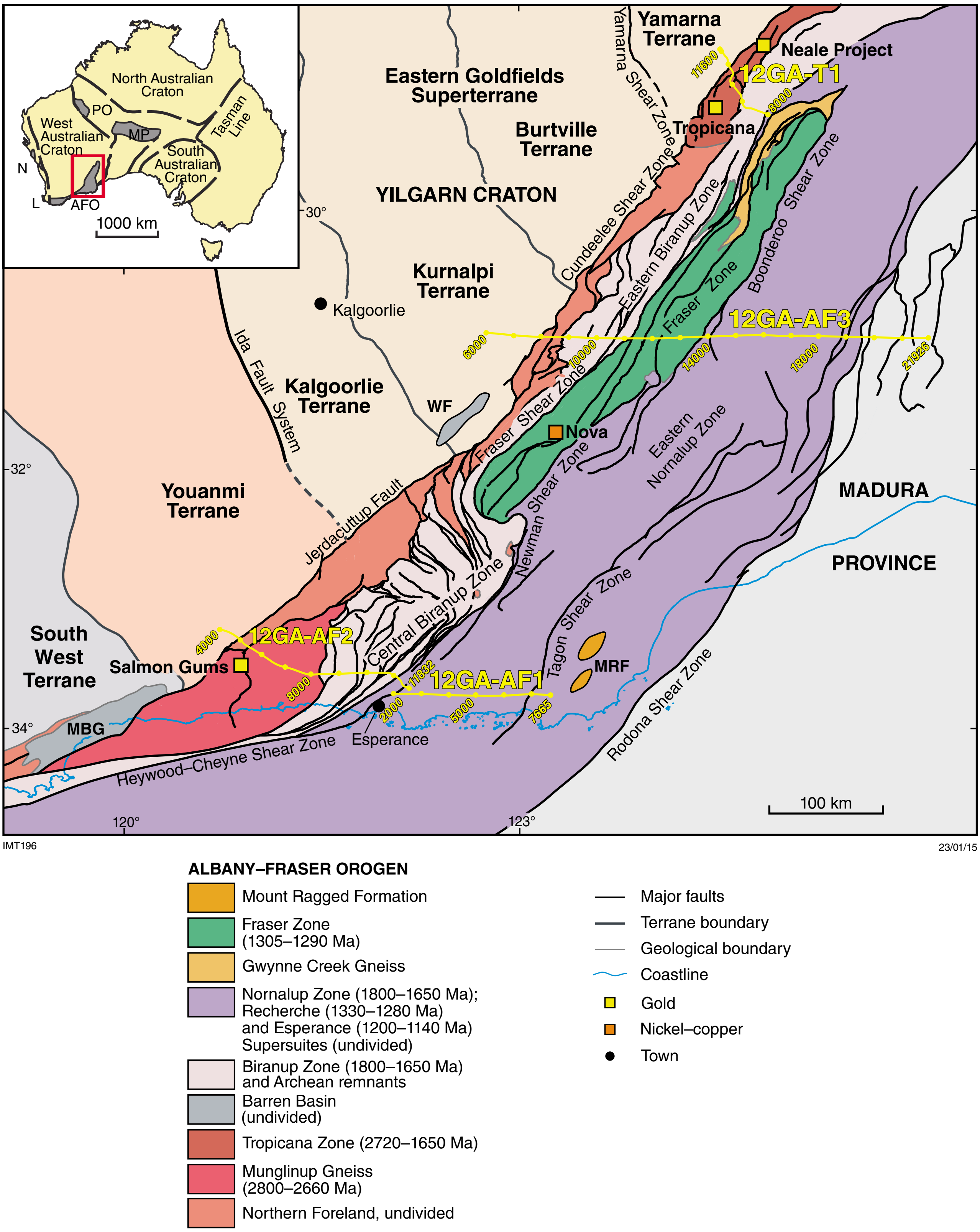

Figure 1. Simplified, pre-Mesozoic interpreted bedrock geology of the Albany–Fraser Orogen and tectonic subdivisions of the Yilgarn Craton (modified from Spaggiari et al., 2014b) showing the location of the Albany–Fraser deep crustal seismic reflection lines; Abbreviations used: MBG – Mount Barren Group; WF – Woodline Formation; MRF – Mount Ragged Formation. Inset: AFO – Albany–Fraser Orogen; MP – Musgrave Province; PO – Paterson Orogen; L – Leeuwin Province; N – Northampton Province

Large areas of the seismic lines cross regions with very sparse outcrop, or regions that are buried by younger cover rocks, such as the Eucla Basin (figure 1, Spaggiari et al., 2012). This has made interpretation difficult, so that there is a high degree of uncertainty in many areas, even near the surface. Other issues include deciding whether reflections are out of plane, and whether they link to other reflections, how far to migrate reflections, and deciding the geological significance of large areas of non-reflectivity. The interpretation methodology includes delineating reflective versus non-reflective zones, which generally corresponds to particular units, marking out the truncations of reflections (usually interpreted as faults or shear zones, or intrusions), and tracking the geometries of reflections, e.g. folded layers. It is important to note that like any other geophysical dataset, not all geological features can be imaged. Only surfaces or packages with different acoustic impedance are detected, so the integration of other datasets is vital. Despite the above, the seismic images have allowed us to track the orientation and extent of major shear zones and the accompanying geology to great depths, permitting interpretations of the underlying geology. In the future, these interpretations will be tested in 3D models that will include passive seismic data (acquisition in progress), and inversions and modelling of potential field data.

The three seismic lines covered by this abstract are described in detail below, from west to east, and also south to north. The images and interpreted sections are shown in Figures 2, 3 and 4, and in greater detail in Plate 4, which also gives the common depth point (CDP) numbers. The lines of section, including the Tropicana line 12GA-T1, are shown in Figure 1, and on three interpreted bedrock geology maps in Plates 1 (line 12GA-T1), Plate 2 (12GA-AF3), and Plate 3 (12GA-AF1 and 12GA-AF2). All four plates accompany this volume. The legend for the lithological units for each section in Figures 2, 3 and 4 is shown in Figure 5. A geological overview of the Albany–Fraser Orogen is given in Spaggiari et al. (2014a) and Kirkland et al. (2014a).

Interpretation of seismic line 12GA-AF2

Seismic line 12GA-AF2 is 114.04 km long and, from west to east, commences in the Youanmi Terrane of the Yilgarn Craton and crosses the central and east Albany–Fraser Orogen to the boundary between the Biranup and Nornalup Zones, just northwest of Esperance (Figs 1 and 2; Plates 3 and 4). From west to east, the line tracks in a southeasterly direction, then turns easterly, before a major bend to the southeast. This line geometry was deliberately chosen to facilitate overlap with the western end of 12GA-AF1. Due to changes in the geometry of geological features related to the bend, the reflections at this eastern end of the line do not match exactly those in the westernmost part of line 12GA-AF1, and should only be interpreted as far east as about CDP 11 600. No magnetotelluric (MT) data was collected along this line because it is located too close to the Southern Ocean.

Yilgarn Craton and Northern Foreland

The westernmost part of 12GA-AF2 has imaged the poorly exposed southern part of the Southern Cross Domain of the Youanmi Terrane. In this region the boundary between the Yilgarn Craton and its reworked counterpart, the Northern Foreland of the Albany–Fraser Orogen, is defined as the southeasterly dipping Jerdacuttup Fault (CDP 4870; Myers, 1990; Witt, 1998), although the seismic image shows a similar fault reaching the surface west of the Jerdacuttup Fault, at CDP 4500. The Northern Foreland is distinguished from the Yilgarn Craton by the degree of Proterozoic deformation in the former. Based on fold geometries in outcrop, and aeromagnetic data interpretation, the Jerdacuttup Fault was previously inferred to mark a major change from Archean northwesterly trending structures to Proterozoic northeasterly trending structures (Myers, 1990; Witt, 1998; Spaggiari et al., 2009). The Jerdacuttup Fault is not exposed, and has been mapped using magnetic imagery. The unnamed fault imaged in the seismic line northwest of the Jerdacuttup Fault is not visible in the magnetic data because this area is heavily overprinted by more than one suite of Proterozoic mafic dykes (see Spaggiari et al., 2009), and is also extensively fractured. Because of the abundance of intrusions and structures the unnamed fault cannot be mapped laterally, so we continue to use the Jerdacuttup Fault as marking the boundary between the Yilgarn Craton and Northern Foreland (Albany–Fraser Orogen) in this region.

From the western end of line 12GA-AF2, east to the Jerdacuttup Fault, the upper crust of the Youanmi Terrane is dominated by granitic rocks and is generally only weakly to moderately reflective. The thickness varies from about 2.0 s TWT (~6 km) at about CDP 4100 to about 3.7 s TWT (~11 km) at about CDP 4500. The Northern Foreland has a similar seismic character as far east as the Cascade Shear Zone, and is of a similar thickness. Two mafic sills of unknown age are interpreted from two sets of very strong subhorizontal reflections in the upper crust at 0.3 – 0.7 s TWT (~1–2 km depth), similar to those imaged on previous seismic lines farther to the north in the Youanmi Terrane (Ivanic et al., 2013). The westernmost sill appears to crosscut the fault west of the Jerdacuttup Fault. 12GA-AF2 crossed a small greenstone belt interpreted from a linear magnetic anomaly at about CDP 5300, but this was not imaged.

Below the Youanmi Terrane, and continuing for the entire length of 12GA-AF2, is a strongly reflective middle to lower crust where the reflections dip gently to the southeast over the western two-thirds of the section, and are subhorizontal in the eastern part. We interpret this as the Yarraquin Seismic Province, which has previously been defined as the moderately to strongly reflective middle to lower crust underlying the Youanmi Terrane farther north (Korsch et al., 2013; Korsch et al., 2014). Hence, the Youanmi Terrane (sensu stricto) is confined to only the upper crust, and its base is defined as the contact with the Yarraquin Seismic Province (Korsch et al., 2013a).

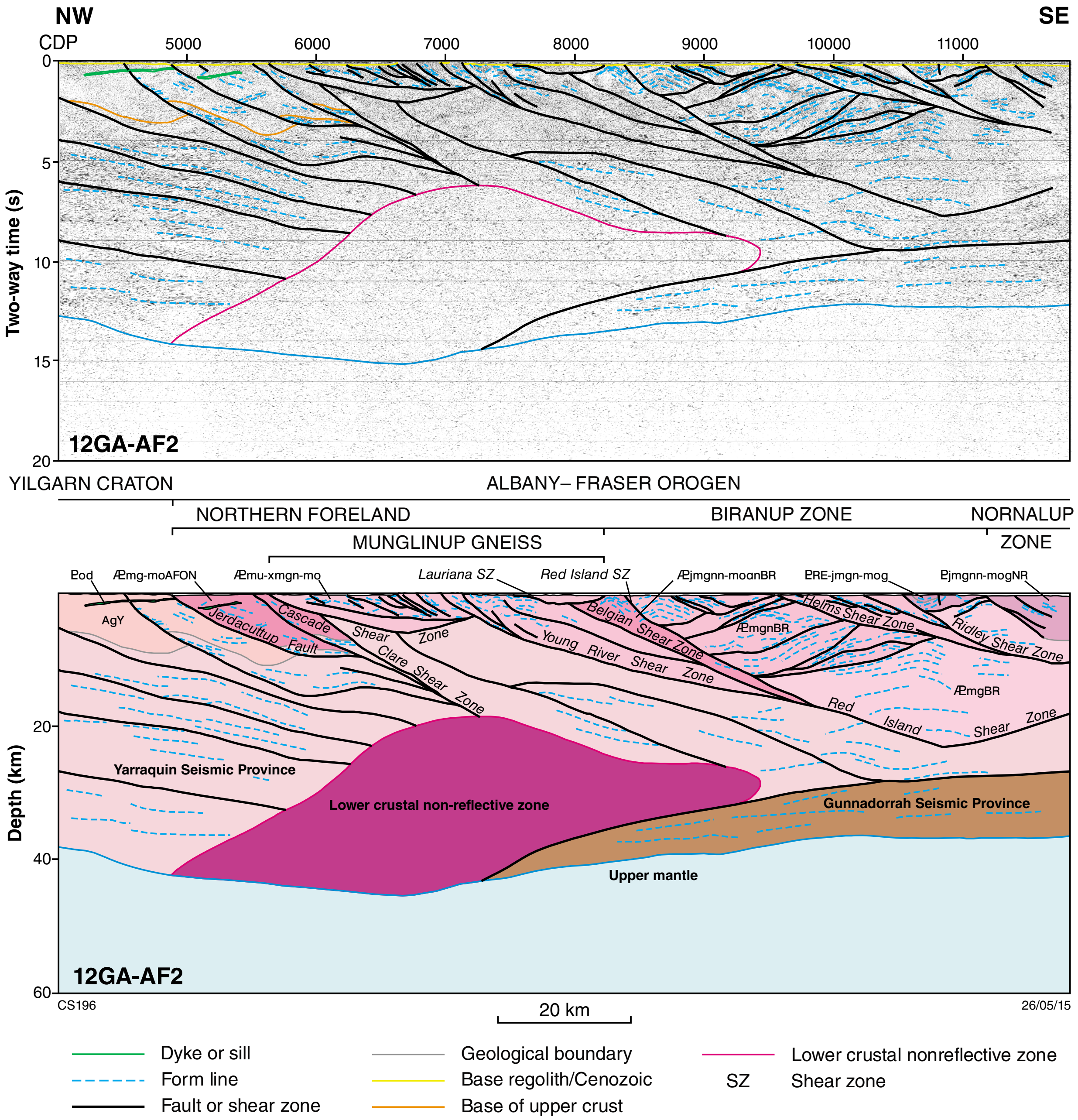

Figure 2. **Migrated section for seismic line 12GA-AF2, showing the seismic image with interpreted linework (upper) and solid geology interpreted section (lower). Display is to 20 s TWT (~60 km) depth, and shows vertical scale equal to the horizontal scale, assuming a crustal velocity of 6000 ms^{-1} for the entire section. See Figure 5 for the units legend.**

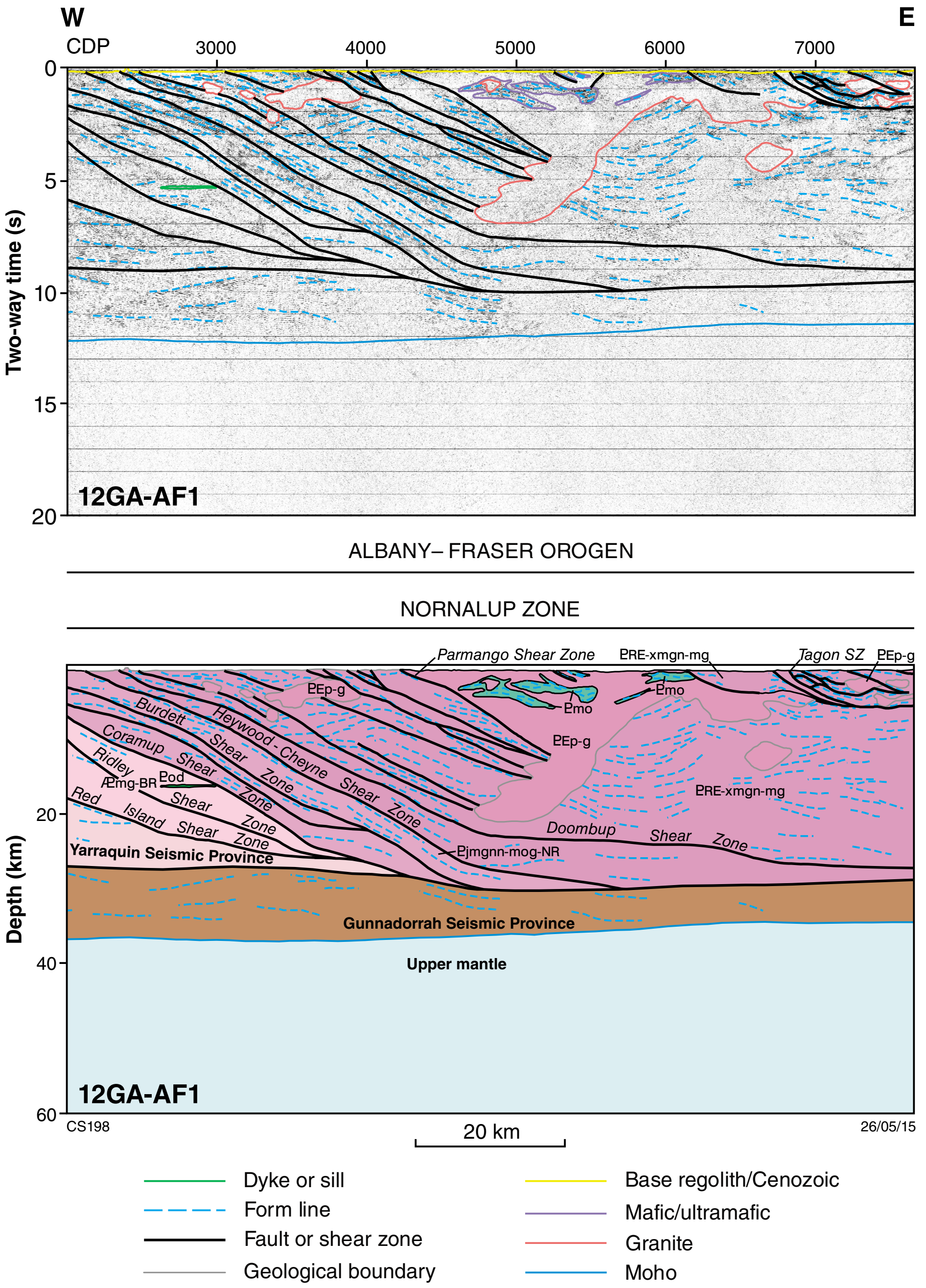

Figure 3. Migrated section for seismic line 12GA-AF1, showing the seismic image with interpreted linework (upper) and solid geology interpreted section (lower). Display is to 20 s TWT (~60 km) depth, and shows vertical scale equal to the horizontal scale, assuming a crustal velocity of 6000 ms^{-1} for the entire section. See Figure 5 for the units legend.

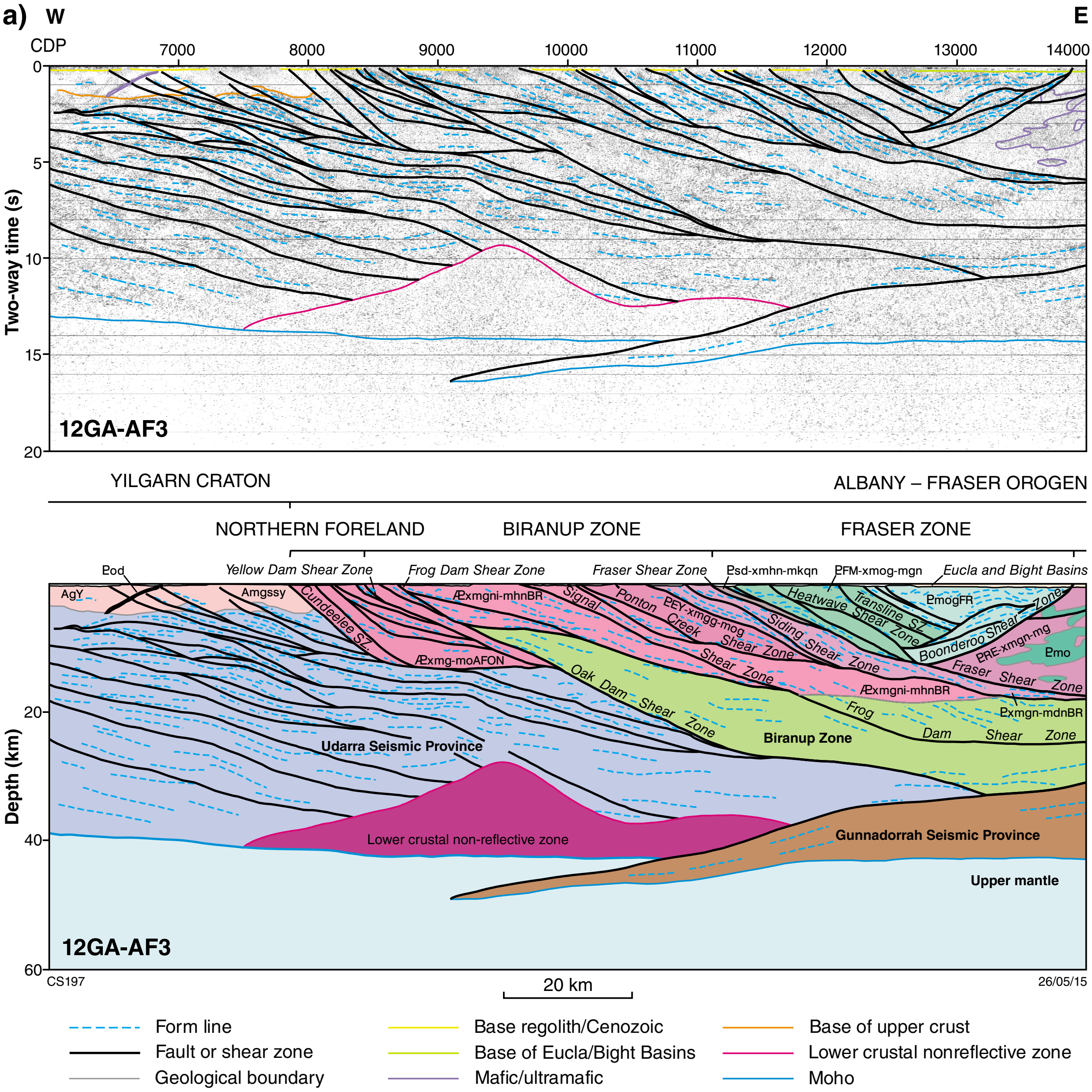

Figure 4. Migrated sections for seismic line 12GA-AF3, showing the seismic image with interpreted linework (upper) and solid geology interpreted section (lower). Display is to 20 s TWT (~60 km) depth, and shows vertical scale equal to the horizontal scale, assuming a crustal velocity of 6000 ms^{-1} for the entire section. The western part of the section is shown in a), and the eastern part in b). See Figure 5 for the units legend.

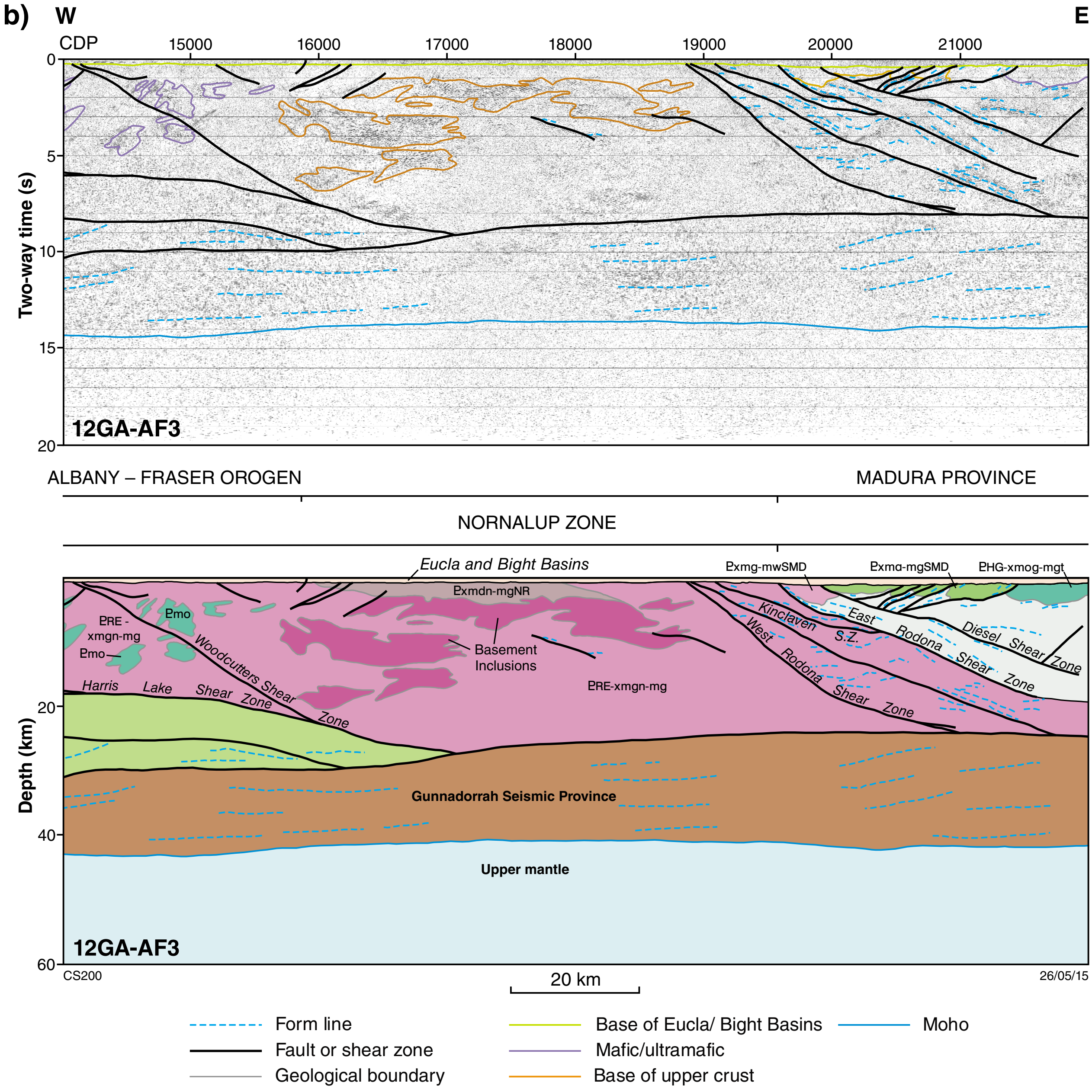

Figure 4. continued

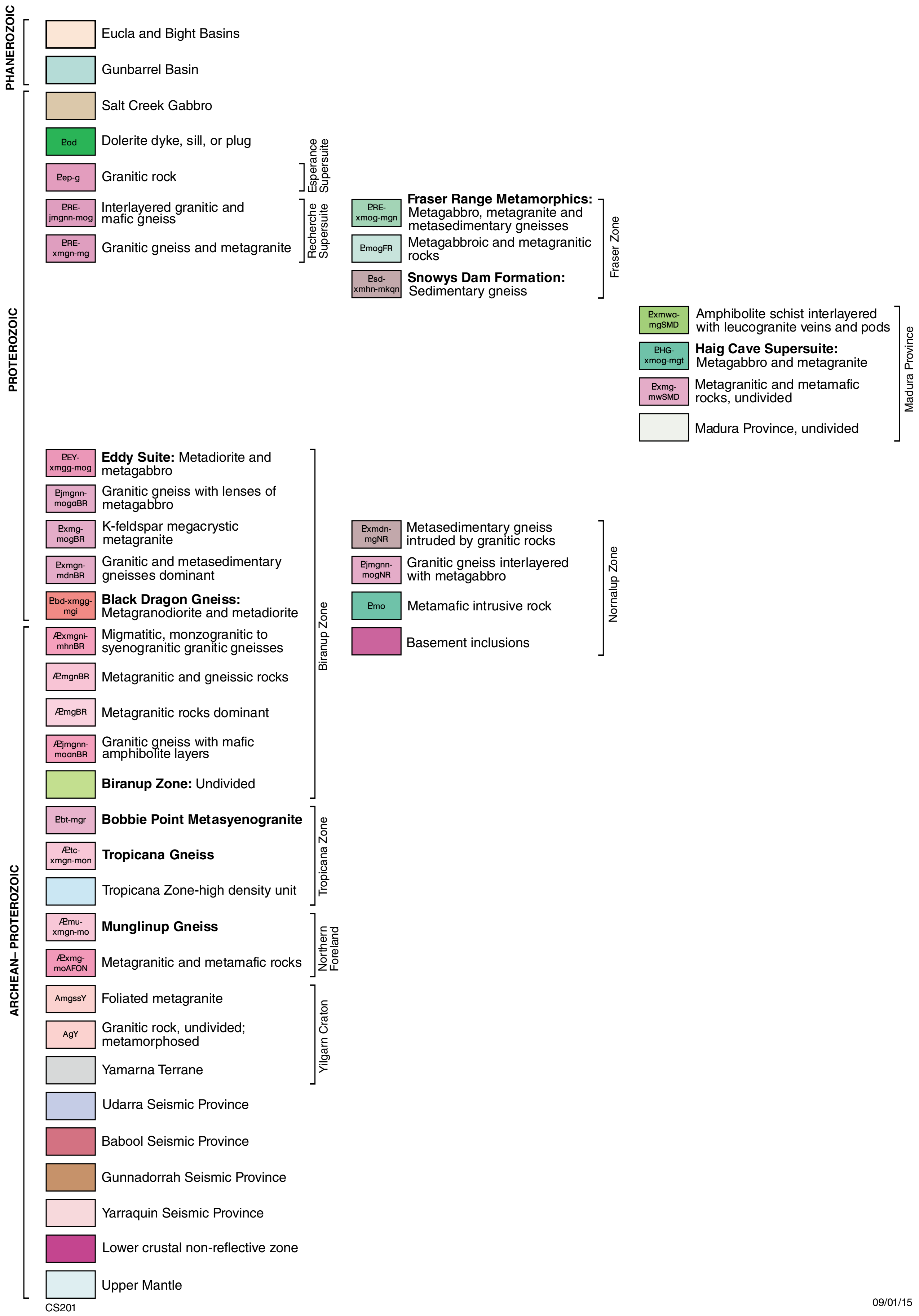

Figure 5. Reference for the units shown in the migrated sections in Figures 2, 3 and 4

Overall there is a predominant southeast dip and listric form to the structures in this part of the Youanmi Terrane and Northern Foreland, and a thrust movement sense is interpreted from the top to the west offsets of the Yarraquin Seismic Province below. This confirms that the Northern Foreland has been thrust over the Youanmi Terrane, as has previously been interpreted (Myers, 1990; Witt, 1998; Spaggiari et al., 2009).

Munglinup Gneiss

Southeast of the Cascade Shear Zone, but still within the Northern Foreland, are fault-bound slices of reworked Yilgarn lithologies at higher metamorphic grade, named the Munglinup Gneiss (in Myers, 1995). The Cascade Shear Zone is interpreted as a thrust with a gentle southeast dip, placing upper amphibolite, Munglinup Gneiss over greenschist facies rocks of the Northern Foreland. The Cascade Shear Zone has a scooped shape and links to the southeasterly dipping Young River Shear Zone to the east at about 1.2 s TWT (~4 km depth) below CDP 7230 (Fig. 6). Above the Cascade Shear Zone is another rather flat-lying shear zone that separates relatively non-reflective Munglinup Gneiss from a more strongly reflective package that contains reflections indicative of an anastomosing and folded fabric, with a predominant southeast dip. The Cascade Shear Zone also truncates major shear zones within the Yarraquin Seismic Province below. East-northeasterly trending, dextral strike-slip faults cut major shear zones in this region, including both the Cascade and Young River Shear Zones (Plate 3).

Farther east, the Munglinup Gneiss occurs within another fault slice between the Young River Shear Zone and the folded Lauriana Shear Zone to CDP 8230 (Fig. 6). In this section are large-scale refolded folds visible in aeromagnetic data (Spaggiari et al., 2009, 2011), which are also visible in the seismic section, particularly just east of the Lort River Shear Zone at CDP 7120 (Fig. 6). The Lauriana Shear Zone is also folded into a broad, northwesterly trending synform between CDPs 7500 and 8230, and overlies the older Belgian Shear Zone, which to the east bounds a slice of Archean Munglinup Gneiss and Paleoproterozoic interlayered granitic and mafic gneiss which includes c. 1800 and 1670 Ma rocks that are part of the Biranup Zone (Hopkinson, 2010; GSWA 192502, Kirkland et al., 2014b; GSWA 192504, preliminary data). The Belgian Shear Zone links to the southeasterly dipping Red Island Shear Zone (named after Red Island off the South Coast, which the shear runs through) at depth, which defines the main boundary between the Northern Foreland (Munglinup Gneiss) and the Biranup Zone (Figs 2 and 7). The Red Island Shear Zone also cuts the folded Lauriana Shear Zone near the surface (Plate 3). Although complex, the crosscutting relationships help constrain the relative timing of movement along these shear zones, with the Belgian Shear Zone preserving the oldest movement, and the Young River and Red Island Shear Zones showing the youngest movement (Plate 3). The fault slice of combined Munglinup Gneiss and Biranup Zone rocks bounded by the Belgian and Red Island Shear Zones is contained within the thrust slice bounded by the Cascade and Red Island Shear Zones (see Plate 3). These relationships, and the presence of both Archean Munglinup Gneiss and Paleoproterozoic Biranup Zone granitic gneiss in the same drillcores at Salmon Gums (Hopkinson, 2010; GSWA 192502, Kirkland et al., 2014b; GSWA 192505, Kirkland et al., 2014c; GSWA 192507, Kirkland et al., 2013a; GSWA 192508, Kirkland et al., 2014d; GSWA 192504, preliminary data), are consistent with the Paleoproterozoic history of magmatic intrusion directly into Yilgarn Craton crust (Spaggiari et al., 2014a; Smithies et al., 2014; Kirkland et al., 2011a,b, 2014a). The relationships show that the Northern Foreland (Munglinup Gneiss) and Biranup Zone are not simply fault-bound entities juxtaposed by major shear zones, but are also autochthonous.

The Munglinup Gneiss is underlain by the Yarraquin Seismic Province, which between CDPs 6330 and 7220 only reaches a maximum thickness of about 6 km (2 s TWT). There is similarity in seismic character between these two units, and given that the Munglinup Gneiss most likely represents deeper slices of reworked Yilgarn Craton (Spaggiari et al., 2009, 2011), it is feasible that in this region it may also have been derived from the Yarraquin Seismic Province. Although dominantly granitic, the Munglinup Gneiss contains distinct layering of felsic and mafic lithologies, which may help define its reflective character. This may also correlate with the upper portion of the Yarraquin Seismic Province.

Biranup Zone

The Red Island Shear Zone marks the main boundary between the Northern Foreland and the dominantly Paleoproterozoic gneissic rocks of the Biranup Zone. In this region the Biranup Zone gneisses are mostly granitic, often garnet rich, and typically interlayered with mafic gneiss. The Biranup Zone not only contains remnants of Yilgarn Craton granite (Kirkland et al., 2011a; Spaggiari et al., 2011), but is also dominated by granitic rocks that were formed by recycling of Archean felsic material that is interpreted as Yilgarn Craton basement (Kirkland et al., 2011b; Smithies et al., 2014). Although in this region the Red Island Shear Zone marks the main boundary of the Biranup Zone, it does not mark the eastern extent of the Yarraquin Seismic Province, which continues below the Biranup Zone, and is consistent with the derivation of Biranup Zone magmatic rocks from Yilgarn Craton basement (Kirkland et al., 2011a,b; Smithies et al., 2014). This suggests that the Biranup Zone was not thrust a substantial distance over the Yarraquin Seismic Province, (i.e. it could not have been displaced a distance greater than extended Yilgarn Craton crust), and/or that the Yarraquin Seismic Province (and inferred Yilgarn heritage) continued a considerable distance to the east and southeast.

The Red Island Shear Zone also marks a distinct change in magnetic character, from a refolded-fold pattern to the northwest, to a linear, shear-related fabric to the southeast. This shear-related fabric extends about 50 km or so across strike as far as the Heywood–Cheyne Shear Zone, and encompasses the boundary between the Biranup and Nornalup Zones, which is described below.

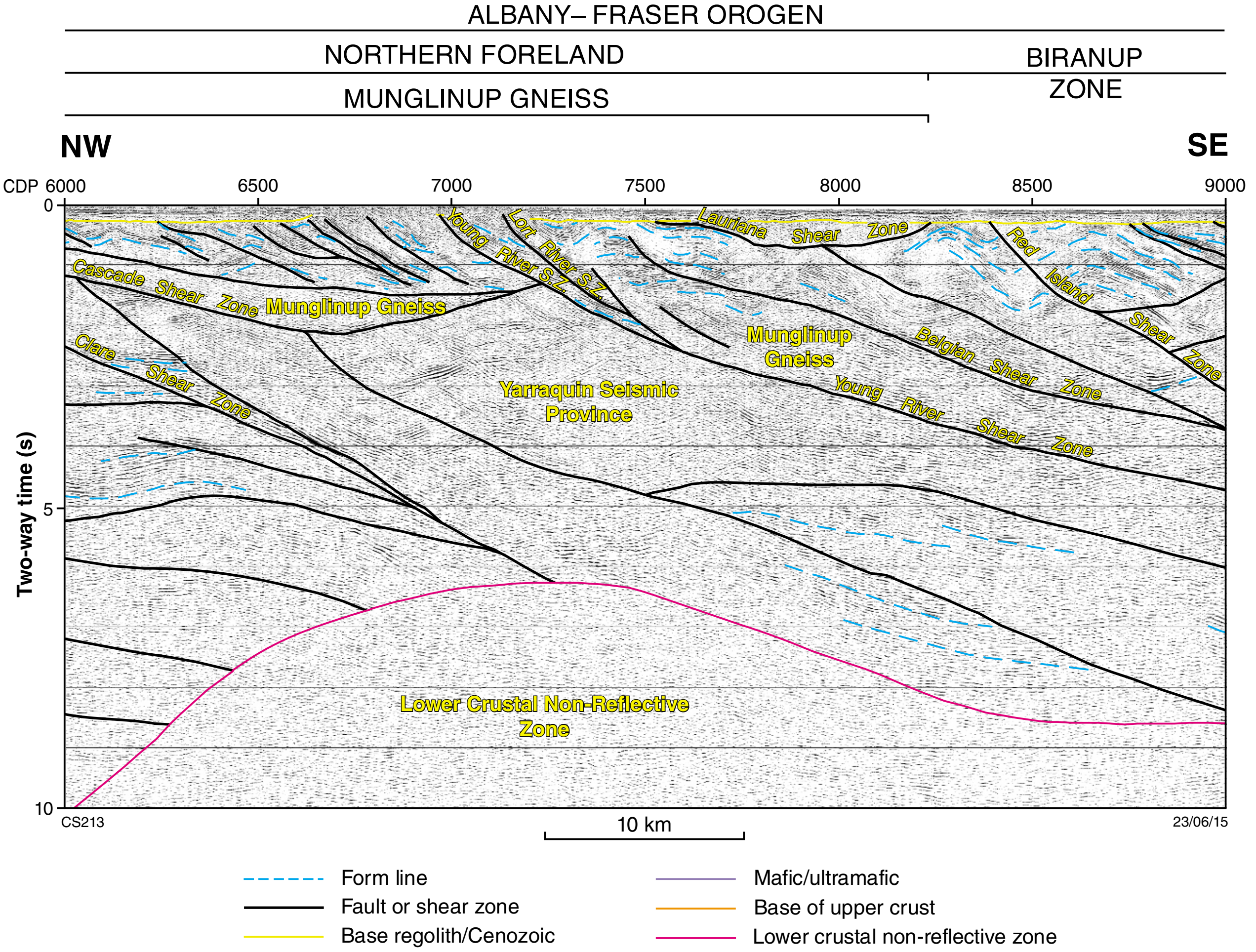

Figure 6. Detail of part of seismic line 12GA-AF2 showing the Munglinup Gneiss in the upper crust

On seismic line 12GA-AF2, the Biranup Zone is dominantly highly reflective, with packages of reflections and shear zones dipping both to the east and west. The westerly dipping shear zones appear to be earlier, and for the most part truncated by the easterly dipping shear zones, such as the Red Island, Helms, Speddingup, Ridley, and Coramup Shear Zones, which all have a moderate easterly to southeasterly dip (Figs 2 and 7). None of the earlier westerly dipping shear zones are exposed at the surface in the vicinity of the seismic line, although one cuts close to the Helms Shear Zone at about CDP 9540. The magnetic data show that the area between the Red Island and Speddingup Shear Zones is dominated by northerly trending folds, and is structurally complex, making 2D interpretation of the seismic image difficult. For example, a doubly plunging antiform is present between the Red Island and Bishops Hat Shear Zones, which is itself folded into a broad synform to the east (Plates 3 and 4). These folds sit above one of the westerly dipping shear zones, and may relate to an earlier deformation event of both folding and shearing, that pre-dates later movement on the large, east to southeasterly dipping shear zones. The Helms Shear Zone also appears to be folded away from the line of section to the south. It is possible that this folding and shearing event was linked to northerly trending folding observed in the adjacent Munglinup Gneiss, although these may also be Archean in age and therefore earlier (Spaggiari et al., 2009). Another possibility is the westerly dipping shear zones may be related to an earlier extensional architecture, representing the tops of tilted blocks. If this were the case, the folded horizons may have formed during inversion processes along the major east to southeasterly dipping shear zones. This would fit with the Paleoproterozoic rift model proposed by Spaggiari et al. (2014b).

East of the Ridley Shear Zone, between CDPs 10 600 and 10 810, is the southern tip of an interpreted sheet of Recherche Supersuite metagranite, truncated by the steeply east-dipping, sinistral strike-slip Jenabillup Shear Zone. The metagranite has been dated to the northeast at Mount Burdett at 1299 ± 18 Ma, which is interpreted as the igneous crystallization age (GSWA 83697, Nelson, 1995). The extent of this metagranite sheet is interpreted from magnetic and gravity data.

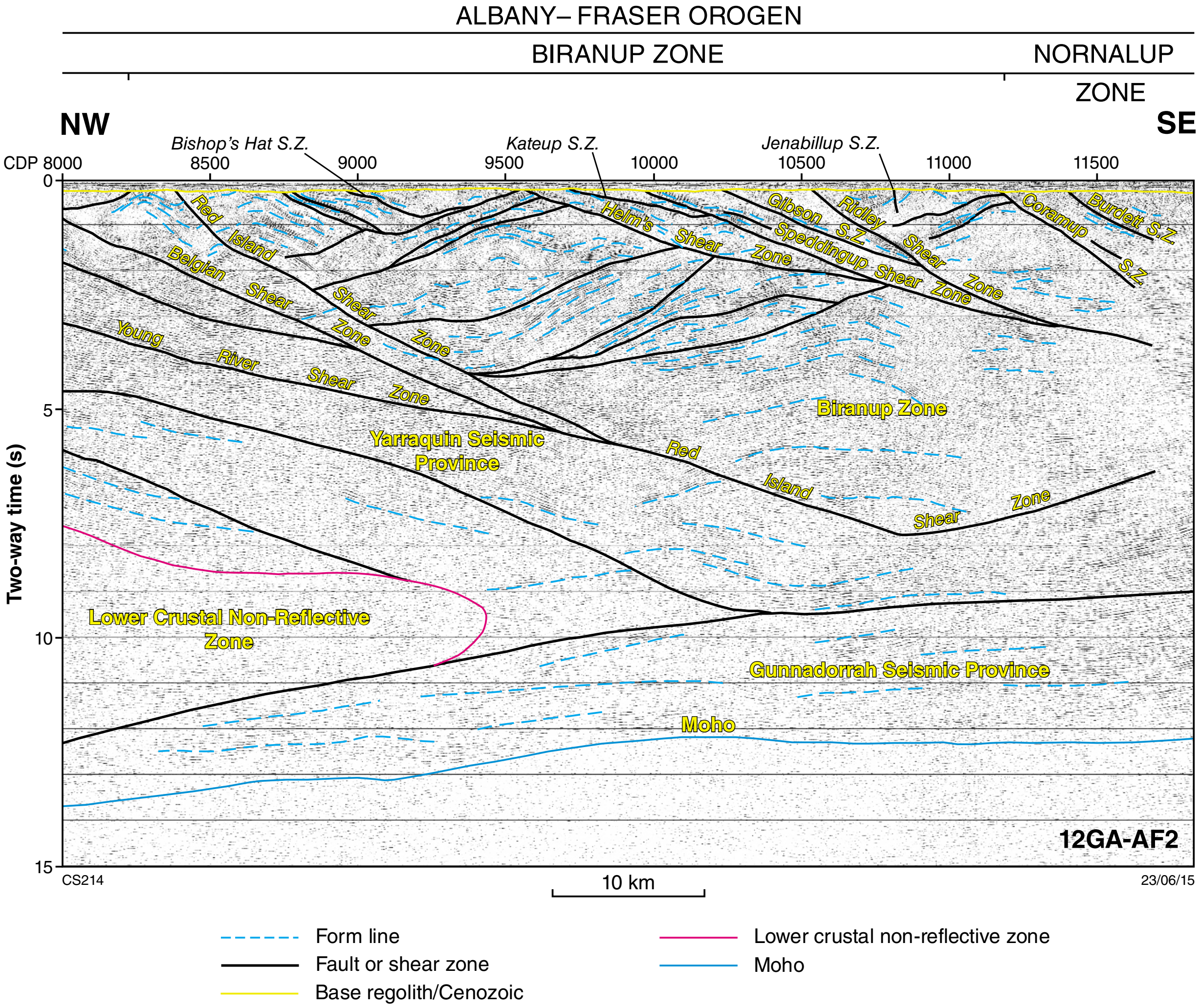

Figure 7. **Detail of part of seismic line 12GA-AF2 showing the Biranup Zone**

Where Biranup Zone rocks cannot be tracked to the surface, and correlated with surface outcrops, we have shown them on the cross-section as Biranup Zone undivided. These terminate against the southeasterly dipping Coramup Shear Zone at the eastern end of line 12GA-AF2.

Coramup Shear Zone

The Coramup Shear Zone is here defined as the main boundary between the Biranup and Nornalup zones, based on interpreted relationships in the seismic images from both 12GA-AF2 and 12GA-AF1, and to some extent, the magnetic data. Previously, the boundary was interpreted as the Heywood–Cheyne Shear Zone (Spaggiari and Pawley, 2012), which marks the easternmost extent of the linear, shear-related fabric in the magnetic data. In any case, the distinction between the Biranup and Nornalup Zones is to some degree blurred, as both contain Paleoproterozoic granitic rocks that are indistinguishable both geochemically and isotopically (Spaggiari et al., 2011), although the data are very sparse in the Nornalup Zone. The Nornalup Zone is also much more thoroughly overprinted by both the Recherche and Esperance Supersuites.

The Coramup Shear Zone contains both metagranitic rocks and metasedimentary rocks of the Barren Basin (Coramup Gneiss) and has been mapped on the coast at Butty Head as a high strain zone. P-T conditions indicate granulite facies metamorphism and range from 850 to 700°C over time, and vary from about 7–10 kbars, and back down to 5–6 kbars (Bodorkos and Clark, 2004a). Early metamorphism and D1 deformation are interpreted to have occurred during Stage I (c. 1290 Ma), and subsequent events during Stage II, of the Albany–Fraser Orogeny (Bodorkos and Clark, 2004a). Detailed structural analysis was interpreted to show reverse movement sense on the southeasterly dipping gneissic foliation (D_1), locally overprinted by intense, northeasterly trending dextral shearing and transpression (D_2), followed by narrow, north-northeasterly trending mylonitic or pseudotachylitic sinistral shear zones (D_3) (Bodorkos and Clark, 2004b). These interpretations are consistent with the seismic and magnetic data. The Burdett Shear Zone crosses line 12GA-AF2 at about CDP 11400, and is another major, southeasterly dipping shear zone subparallel to the Coramup Shear Zone.

Lower crust on 12GA-AF2

A major feature of the lower crust in 12GA-AF2 is a large subhorizontal elongate body, with roughly 90 km maximum width and 25 km maximum thickness defined by its non-reflective seismic character of reduced impedance contrast (Fig. 2; Plate 4). This body truncates southeasterly dipping shear zones and reflections in the Yarraquin Seismic Province, and extends to the Moho, coincident with where the Moho appears to be deepest in this section (15.1 s TWT [~45 km depth]). This body is also coincident with a large, long wavelength positive gravity anomaly which indicates it is made of relatively dense material, such as mafic–ultramafic cumulate (Murdie et al., 2014). Because of the large size, our preferred interpretation of this feature is a former source region for magmatism that contains a combination of crustal melts (or mush), and melt residuals from a magmatic event. These have obliterated the fabrics in the Yarraquin Seismic Province. There are several possibilities for the timing of this magmatism, but the truncations of the shear zones, some of which appear to extend into the Albany–Fraser Orogen above, suggest it was relatively late, and probably during either Stage I or Stage II of the Albany–Fraser Orogeny. One possibility is that it was synchronous with the intrusions of the c. 1210 Ma Gnowangerup – Fraser Dyke Suite that are abundant in this region.

Alternative interpretations of this lower crustal non-reflective zone is that it is a large alteration zone associated with crustal thickening, or a large zone of extensive deformation which has obliterated the earlier seismic fabric. Similar zones of reduced impedance contrast have been observed in mineralized regions; for example, in the lower crust beneath the Olympic Dam deposit in South Australia (Drummond et al., 2006). This was interpreted to be the source-region for the magma of the Hiltaba Suite granite hosting the deposit. All of these interpretations have merit, and the large non-reflective zone may be the result of a combination of these processes, where syndeformation magmatism has released and mobilized fluids.

Interpretation of seismic line 12GA-AF1

Seismic line 12GA-AF1 is 158.4 km long and has minor overlap with the eastern end of line 12GA-AF2. 12GA-AF1 is entirely within the Nornalup Zone and runs parallel to the coast, which is about 20–30 km to the south. At its western end the seismic line crosses the continuation of the approximately 50 km-wide shear zone system (Red Island Shear Zone to Heywood–Cheyne Shear Zone) that contains the Coramup Shear Zone, defined as the boundary between the Biranup and Nornalup Zones (see 'Coramup Shear Zone' section above). No MT data were collected along this line because it is located too close to the Southern Ocean.

Nornalup Zone

The western end of line 12GA-AF1 lies within granitic and mafic gneiss of the eastern Nornalup Zone (Fig. 1). In the field and geophysically, Paleoproterozoic granitic gneiss is indistinguishable from Mesoproterozoic granitic gneiss of the Recherche Supersuite, so their spatial distributions are difficult to map. Because of this, the geological subdivisions on line 12GA-AF1, and also in this region on the geological map (Plate 3), remain very general. Where possible, we have mapped out intrusions of the Esperance Supersuite based on magnetic character and shape (Plate 3), and as non-reflective or weakly reflective zones in the seismic image (Fig. 3; Plate 4). The interpretation of Esperance Supersuite granites as strongly magnetic, ovoid to elongate masses is supported by recent geochronology where homogeneous monzogranite with a locally developed, weak foliation trending 040° was dated at 1172 ± 5 Ma (GSWA 194849, preliminary data). The monzogranite gave high magnetic susceptibility readings in the field, and is located within a large, positive magnetic anomaly (Fig. 8). Small mafic pods and wisps within the monzogranite have even higher magnetic susceptibility readings that range 5000–8000 x 10^{-5} SI. This monzogranite occurs to the east of the southeasterly dipping Parmango Shear Zone (see below).

The western part of line 12GA-AF1 shows the eastern continuation of major shear zones described on line 12GA-AF2 (Red Island, Ridley, Coramup, Burdett, and Heywood–Cheyne Shear Zones) to great depths (Fig. 3). The Red Island Shear Zone continues to dip moderately to the southeast at depth, but flattens slightly before reaching the Coramup Shear Zone, which truncates it. It separates both the Biranup and Nornalup Zones from the underlying Yarraquin Seismic Province, which extends as far east as about CDP 4250. This is about 150 km across strike from the Jerdacuttup Fault, which marks the boundary between the Yilgarn Craton and the Northern Foreland. The Coramup, Burdett, and Heywood–Cheyne Shear Zones also flatten with depth and sole onto the Gunnadorrah Seismic Province (new name, after Gunnadorrah Homestead; Korsch et al., 2014) (Fig. 3). Beyond the Heywood–Cheyne Shear Zone to the east, no distinction between upper and middle crust is possible because there are no obvious differences in reflectivity. It is highly likely, however, that the lower crust, which comprises the Gunnadorrah Seismic Province, is more dense (mafic) and distinct from the middle to upper crust in this region (Murdie et al., 2014).

Between the Heywood–Cheyne and Parmango Shear Zones at CDP 4230, the crust in the seismic image is dominated by easterly dipping, highly reflective packages separated by a series of easterly dipping shear zones. The kinematic history of these shear zones is unknown, but curved reflections in the hanging walls could indicate

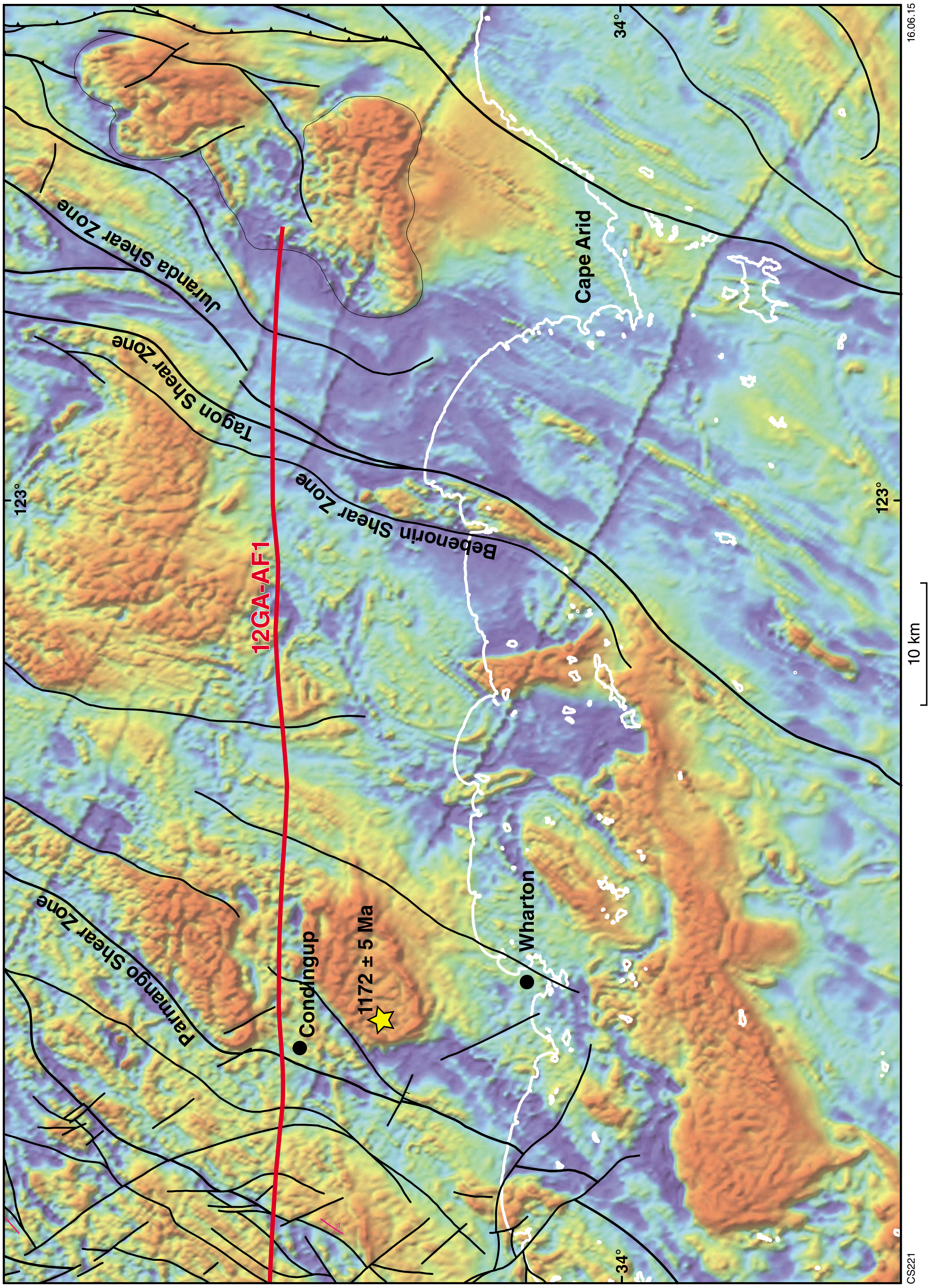

Figure 8. Reduced-to-pole aeromagnetic image of part of the eastern Nornalup Zone, showing the eastern end of line 12GA-AF1, major shear zones, and strongly magnetic (in red) Esperance Supersuite intrusions. The location of dated sample GSWA 194849 (preliminary data), which is coincident with one of these intrusions, is shown.

rollover anticlines and a dominant thrust sense of displacement. Alternatively, the curved reflections could have formed during inversion of extensional shear zones, or they could indicate S–C relationships and a normal movement sense. While shear zones are visible in the magnetic data, it is difficult to determine any shear sense. We have interpreted that this region is dominated by the Recherche Supersuite, which would include remnants of Nornalup Zone basement. The seismic packages, and the shear zones, are interpreted to have been intruded locally by irregularly shaped bodies of Esperance Supersuite granite.

East of the Parmango Shear Zone, stretching approximately 40 km east, is a large, variably reflective to non-reflective zone that appears to crosscut the southeasterly dipping shears, including the Parmango Shear Zone. The variably reflective to non-reflective zone thins at depth, and extends down to the middle crust to 7 s TWT (~21 km). We interpret that this zone is dominated by Esperance Supersuite granitic intrusions, where the deeper portion is inferred to be a residual source region from which magma was injected along several shear zones. An alternative interpretation is that this could be a large alteration zone related to shearing, and/or a conduit, which has obliterated any earlier structures.

The interpretation of the dominantly Esperance Supersuite granitic rocks in this area is consistent with the recently dated monzogranite described above (GSWA 194849, preliminary data) that occurs as a large ovoid, strongly magnetic body in the hangingwall of the Parmango Shear Zone. Rafts of highly reflective material, surrounded by the weakly reflective granitic material, are interpreted to be dominantly mafic in composition. These relationships, as imaged in the seismic line, may be considered large-scale analogues of the outcrops of magmatic rocks along the coast to the south, where phases of mingled granitic and mafic material have been successively intruded and deformed multiple times (Fig. 9). This coastal section runs parallel to the length of Fisheries Road, along which line 12GA-AF1 was acquired (Costelloe et al., 2014), and provides an important constraint on the interpretation. The coastal exposures are interpreted as a magma chamber, where crosscutting relationships of magma mingling textures, fabric formation, and net-veining are indicative of successive pulses of magma injection. The geochemistry of these rocks is consistent with occurrences of Recherche Supersuite intruded by Esperance Supersuite granites (Smithies et al., 2014).

This variably reflective to non-reflective zone ends at about CDP 6710, coincident with the moderately southeasterly dipping Bebenorin Shear Zone, which is just west of and parallel to the Tagon Shear Zone. The Tagon Shear Zone is a major structure that separates a northeasterly trending region of moderately to strongly magnetic granitic rocks to the west, from similar but less magnetic rocks to the east (Plates 2 and 3). In the hangingwall of the Tagon Shear Zone the upper crust is dominated by a series of easterly dipping listric shear zones. Curved reflections and internal shears are interpreted as rollover anticlines, indicating a dominant thrust sense of displacement for both the Tagon Shear Zone and the Juranda Shear Zone, which occurs just to the east. The listric Tagon Shear Zone links onto a flat-lying shear, interpreted as a sole thrust, which has a maximum depth of about 1.8 s TWT (~5 km).

Interpretation of seismic line 12GA-AF3

Seismic line 12GA-AF3 is 319.12 km long and commences in the Kurnalpi Terrane of the Yilgarn Craton from west to east, then crosses the entire east Albany–Fraser Orogen, and ends in the Madura Province to the east (Figs 1 and 4; Plates 2 and 4). The seismic line runs due east, from just east of Karonie through to Haig, following the Trans-Australian Railway. MT data were collected along this line and is currently being processed. The recently acquired Eucla–Gawler seismic line commenced at the eastern end of line 12GA-AF3 and followed the railway line across the border of Western Australia to as far east as the Gawler Craton in South Australia, where it tied to the north–south Gawler–Officer–Musgrave–Arunta (GOMA) seismic line. These data are currently being processed.

Yilgarn Craton and Northern Foreland

The westernmost part of seismic line 12GA-AF3 is broadly similar to the north-westernmost part of line 12GA-AF2, except that here the portion of the Yilgarn Craton that is crossed is the southeastern portion of the Kurnalpi Terrane of the Eastern Goldfields Superterrane. In contrast to line 12GA-AF2, the Northern Foreland on line 12GA-AF3 is only about 16 km wide, and lacks the Munglinup Gneiss (Fig. 4a; Plates 2 and 4). The Kurnalpi Terrane was imaged at the surface between CDP 6002 and the Cundeelee Shear Zone at CDP 7850. In this region, the seismic image shows that the Kurnalpi Terrane consists of a thin upper crust, which in general, is only weakly to moderately reflective, and variable in thickness, ranging from about 0.5 s TWT (~1.5 km) at about CDP 7070 to about 1.5 s TWT (~4.5 km) at about CDP 7900. This region of generally weakly reflective crust is interpreted to be dominated by granitic rocks, cut by northerly trending, east-dipping shear zones (Fig. 4a; Plates 2 and 4). A thin package of strong, moderately west-dipping reflections between CDP 6450 and CDP 6840 at 0.3 – 0.7 s TWT (~1–2 km depth) is interpreted as a mafic sill. This sill crosscuts a major, unnamed shear zone.

Below this upper crustal layer the middle to lower crust is highly reflective, and extends to the Moho. It is dominated by easterly dipping reflections and interpreted shear zones, some of which link to shear zones in the upper crust (Kurnalpi Terrane), showing a thrust sense of displacement of the upper crustal boundary. Because of the distinct change in the seismic character at the boundary between the upper and middle crust, and because we are unable to track the strong reflections in the middle to lower crust to the surface, at this stage we confine the Kurnalpi Terrane (sensu stricto) to only the upper crust, and define its base

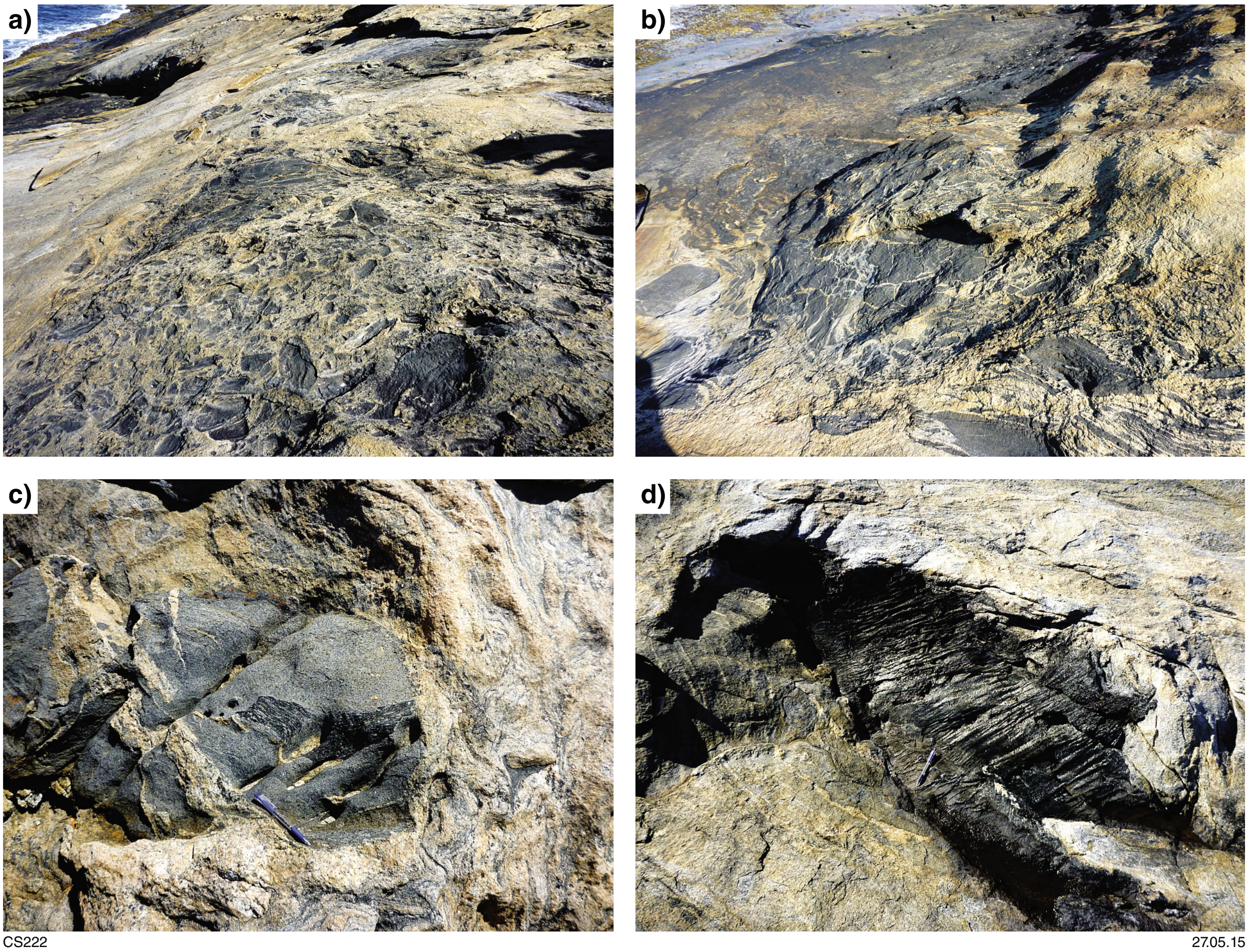

Figure 9. **Photographs of magmatic rocks along the south coast east of Esperance, interpreted to be part of a Mesoproterozoic magma chamber imaged in 12GA-AF1: a) pods of mafic material with variable fabric development entrained in granite; b) net-veined mafic enclaves of variable size in deformed granite and gabbro; c) complex intrusive and fabric relationships in mafic enclaves within felsic magmatic rocks showing early fabric in inner mafic enclave (centre), entrained within a mafic enclave, overprinted by net-veining from the felsic host; d) detail of early crenulated mafic enclave enclosed in younger deformed granite gneiss. Note the difference in fabric orientation.**

as the contact with the Udarra Seismic Province below (new name, after Udarra Soak; Korsch et al., 2014). The Udarra Seismic Province is defined as a discrete package of rocks which forms the current basement to the granite–greenstone rocks of the Kurnalpi Terrane. It extends from the western edge of the seismic section to the boundary with the Gunnadorrah Seismic Province at a depth of about 11 s TWT (~33 km) at about CDP 13 000, a distance of about 140 km. The Gunnadorrah Seismic Province is distinguished by its subhorizontal, moderately reflective and coherent seismic texture.

The moderately southeasterly dipping Cundeelee Shear Zone (CDP 7850) marks the boundary between the Yilgarn Craton and the Northern Foreland (Fig. 4a; Plates 2 and 4), but as described for line 12GA-AF2, this boundary is gradational and attributed to where a major change in deformation intensity can be mapped. The listric Cundeelee Shear Zone is interpreted as a thrust, placing the Northern Foreland over the Kurnalpi Terrane, and at depth it separates the Northern Foreland from the Udarra Seismic Province down to about 4.4 s TWT (~13 km depth). The Northern Foreland is internally deformed, has an east-dipping wedge-shaped geometry, and occurs in the footwall of the moderately to shallowly, east-dipping Frog Dam Shear Zone near the surface. The wedge-shaped geometry could be interpreted as the lower half of a duplex structure. The western half of the Northern Foreland has a similar seismic character to the Kurnalpi Terrane immediately to the west, being a weakly reflective zone. However, east of the Yellow Dam Shear Zone at CDP 8370, the seismic character changes to highly reflective, with a series of strong reflections dipping to the east and subparallel to the bounding Yellow Dam and Frog Dam shear zones. This zone corresponds with patchy, but distinctly linear, northeasterly trending magnetic anomalies that, in part, have defined the Yellow Dam Shear Zone (Plate 2). The Yellow Dam Shear Zone links to the Oak Dam Shear Zone at depth.

The Frog Dam Shear Zone separates the Northern Foreland from the Biranup Zone. It is a major thrust of extensive length, and has placed upper amphibolite to granulite facies Biranup Zone gneissic rocks over greenschist facies rocks of the Northern Foreland. The shear zone is distinct on magnetic imagery as a curvilinear feature, bounding rocks of lower magnetic intensity and fabric to the west from rocks with much more clearly defined magnetic fabric in the east, corresponding to the gneissic fabric in the latter. This interpretation is well supported by age constraints of granitic rocks from this area, which help delineate the boundary between the Northern Foreland and the Biranup Zone (e.g. metamonzogranite from the Northern Foreland dated at 2619 ± 6 Ma, GSWA 194792, preliminary data; metasyenogranite from the Biranup Zone dated at 1670 ± 7 Ma, GSWA 194727, Kirkland et al., 2012a). The Frog Dam Shear Zone appears to flatten at about 2.4 s TWT (~7 km depth), where an interpreted splay, the Signal Shear Zone, commences. At depth, the Frog Dam Shear Zone overrides and truncates the Oak Dam Shear Zone, and the latter becomes the boundary between the Biranup Zone and the underlying Udarra Seismic Province.

Biranup Zone

The Biranup Zone is dominated by highly reflective, easterly dipping reflective packages interpreted to be bound by subparallel shears. In the upper crust, rollover anticlines in the hanging walls of some shear zones indicate a predominant thrust sense of displacement. Major shear zones, such as the Frog Dam and Oak Dam Shear Zones, cut deep into the middle crust to the seismic provinces below. The highly reflective packages in the upper crust correlate with the upper amphibolite to granulite facies, dominantly granitic gneisses that occur in this region. These rocks extend about 50 km to the east, as far as the Fraser Shear Zone (previously named the Fraser Fault; Myers, 1985), which marks the western boundary of the Fraser Zone.

The granitic protoliths in this part of the Biranup Zone have been dated between 1690 and 1660 Ma (Kirkland et al., 2011a). To the west, and north of the Trans-Australian Railway, they include a succession that occurs along Ponton Creek, where granite has intruded psammitic rocks of the Barren Basin, and has been deformed at c. 1680 Ma during the Zanthus Event (Kirkland et al., 2011a). Similar rocks occur to the south of the Trans-Australian Railway. These rocks are in the footwall position to the fault-bound, c. 1665 Ma Eddy Suite (Plate 4; Kirkland et al., 2011a; Spaggiari et al., 2011), which lies between the easterly dipping Ponton Creek and Harris Lake Shear Zones, and forms a wedge that extends to 4.2 s TWT (~12.5 km depth). The Eddy Suite is dominated by mingled gabbroic and granodioritic rocks that have intruded sedimentary rocks of the Barren Basin. These intrusions represent some of the youngest igneous rocks in the Biranup Zone and indicate addition of a more isotopically juvenile, mantle component, mixed with older recycled crust (Kirkland et al., 2011b; Smithies et al., 2014). Where exposed to the south, the Eddy Suite is bound to the east by the Fraser Shear Zone, where it is interpreted to sole onto the Harris Lake Shear Zone at depth (Fig. 4; Plates 2 and 4).

Overall, on line 12GA-AF3, the Biranup Zone is imaged as a long, easterly dipping crustal slice that flattens at depth at about 6 s TWT (~18 km), where it becomes a subhorizontal slice up to about 15 km thick, which passes below the Fraser Zone, and overlies the eastern end of the Udarra Seismic Province and western parts of the Gunnadorrah Seismic Province. Where we cannot make a correlation with the surface geology we have termed the lower portion of the Biranup Zone ‘middle to lower crust Biranup Zone’. We interpret this crust as an extension of the Biranup Zone at depth, although we cannot be certain of this. Another possibility is that it could be reworked Udarra Seismic Province, and include Biranup Zone intrusions. Some major shear zones, such as the Frog Dam Shear Zone, can be traced through to the lower crust as deep as the Gunnadorrah Seismic Province below. To the east, the Harris Lake Shear Zone links to the Fraser Shear Zone at depth, and both pass below the entire width of the Fraser Zone (Fig. 10).

Fraser Zone

The Fraser Zone is a large, Mesoproterozoic, sheeted complex of gabbroic and granitic rocks that have intruded sedimentary rocks of the Arid Basin (Spaggiari et al., 2011; Smithies et al., 2013). In the Fraser Zone, the exposed portion of these rocks that occur to the southwest are defined as the Fraser Range Metamorphics (Spaggiari et al., 2009), but where the metasedimentary component is dominant, such as along the northwestern margin of the Fraser Zone adjacent to the Fraser Shear Zone, they are mapped as the Snowys Dam Formation (Plates 2 and 3; Spaggiari et al., 2014b). No outcrop exists where seismic line 12GA-AF3 crosses the Fraser Zone, due to thick regolith cover over its western side, and the western part of the Eucla Basin to the east, so the interpretation of the units is based on outcrop along strike to the southwest, and gravity and magnetic data.

In seismic line 12GA-AF3, the Fraser Zone is imaged as a distinct V-shaped entity, bound to the west by the Fraser Shear Zone at CDP 11 100, and to the east by the westerly dipping Boonderoo Shear Zone at CDP 13 880, which marks the boundary with the eastern Nornalup Zone (Fig. 10). The maximum depth of the Fraser Zone is imaged at about 4.2 s TWT (~13 km), along the moderately, easterly dipping Fraser Shear Zone. When viewed together with its bounding shear zones, the V-shape becomes a Y-shape, where the tail of the Y is defined by the Fraser Shear Zone. This geometry is consistent with that modelled to the southwest using gravity and magnetic data, where sensitivity testing has shown it to be the most robust geometry (Brisbout et al., 2014). Internally, the V-shaped geometry is subdivided by easterly dipping shear zones in the west (Spy Hill, Heatwave, Transline, and Ballast Shear Zones), and westerly dipping shear zones in the east. Crosscutting relationships of these shear zones are complex, and probably reflect interleaving along strike, rather than simple back-thrusting along the westerly dipping shear zones. A large, broad antiform has been imaged on the eastern side of the Fraser Zone, between CDP 13 000 and CDP 13 400.

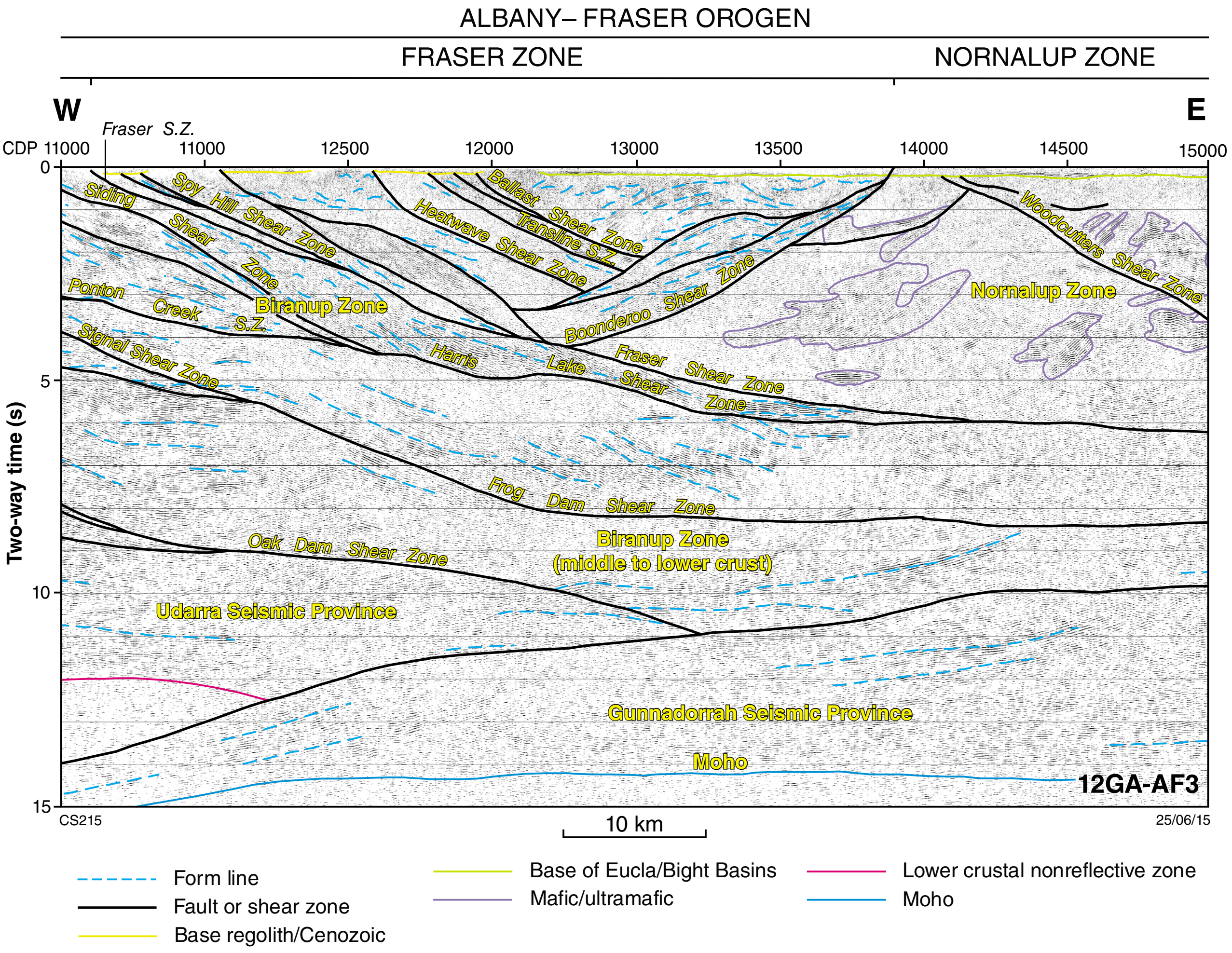

Figure 10. Detail of part of seismic line 12GA-AF3 showing the Fraser Zone

The subdivision in the V-shape is also evident in gravity and magnetic data, and is interpreted to reflect a more voluminous gabbroic package east of the Transline Shear Zone, similar to that on the eastern side of the Fraser Zone where it is exposed in the southwest, but as a separate fault-bounded slice. The western side is interpreted to reflect a greater proportion of metasedimentary material interlayered with metamorphosed gabbro and granite sheets. The strongly linear magnetic texture is interpreted to reflect this layering, but is overprinted by a strong to locally mylonitic fabric, particularly adjacent to the Fraser Shear Zone. These features are observed in outcrop to the southwest, where they show a similar magnetic texture (Spaggiari et al., 2011).

Nornalup Zone

On seismic line 12GA-AF3, the eastern Nornalup Zone lies between the Boonderoo Shear Zone at about CDP 13 880, and the East Rodona Shear Zone at about CDP 19 540 (Fig. 4b; Plates 2 and 3). In this region, the eastern Nornalup Zone is covered by rocks of the Eucla Basin and underlying Bight Basin. The seismic character is similar to the central part of the eastern Nornalup Zone on line 12GA-AF1; it is weakly reflective, and again interpreted to be dominated by granitic material. Because of the weak reflectivity, it has been difficult to map out specific units above the middle to lower crustal Biranup Zone, and Gunnadorrah Seismic Province. Much of the eastern Nornalup Zone in this region has been termed ‘Recherche Supersuite dominant’, although we recognize that the lower crust is possibly more dense and of different composition (Murdie et al., 2014), being a likely source region for much of the magmatic products observed at the surface. Intrusions of the Recherche and Esperance Supersuites appear to have masked much of the original Paleoproterozoic basement features, not only in the seismic data, but also in the magnetic and gravity data. Some of the more recognizable features in the geophysical data are described below.

Within the weakly reflective areas are subhorizontal, irregularly shaped, highly reflective zones interpreted as rafts or lenses within the dominantly granitic material. In the west, these are interpreted to be mafic in composition, based on a stronger gravity signature indicative of denser material. In the east, the reflective material is interpreted as a combination of basement remnants and metasedimentary material. This is based in part on a lower gravity signature compared to the west, and also on the presence of Paleoproterozoic metasedimentary rocks in drillcore from about 80 km to the north of the seismic line that are intruded by both Recherche and Esperance Supersuite granites (Big Red prospect; Spaggiari et al., 2014b).

East of the Fraser Zone, the area of westerly dipping shear zones and reflections are truncated by the easterly dipping Woodcutters Shear Zone at CDP 14 070. This coincides with the western extent of a large, distinct, northwesterly trending gravity ridge and coincident magnetic high that extends as far east as the West Rodona Shear Zone, south of seismic line 12GA-AF3. The magnetic high is strongest in the northwest, and defines a set of tight, northwesterly trending folds that occur in the hangingwall of the Woodcutters Shear Zone.

To the east, between CDP 15 900 and CDP 17 850 on seismic line 12GA-AF3, both the magnetic susceptibility and gravity signature are much lower. This area is interpreted as dominantly Nornalup Zone basement, consisting of metasedimentary gneiss intruded by granitic rocks. The area is also coincident with a distinct change in strike orientation of the magnetic fabric, swinging from the zone of northwesterly trending, tight folding in the west, to an east–west fabric that is visible in the area of lower magnetic susceptibility to the east (Plate 2). This fabric is parallel to the seismic line, so although largely non-reflective and poorly imaged, would show as subhorizontal.

Rodona Shear Zone

The Rodona Shear Zone is an unexposed, major structure that can be traced in magnetic and gravity data along strike for over 500 km (Plates 2 and 3). The southern portion runs offshore around Point Culver, east of Israelite Bay, and the northern extent is deeply buried under the Officer Basin. Although the remainder is entirely under cover of the Eucla Basin, the Rodona Shear Zone is interpreted as the boundary between the eastern Nornalup Zone (and the Albany–Fraser Orogen) and the Madura Province, based on differences in what is known about the geological history from either side (see also Clark et al., 2000; Spaggiari et al., 2012, 2014b; Plates 2 and 3).

In seismic line 12GA-AF3, at CDP 18 810, the weakly reflective, subhorizontal reflections described in the eastern Nornalup Zone are truncated by a series of variable, but dominantly easterly dipping reflections of moderate strength, which define a zone about 14 km wide at the surface, and which extends to the eastern end of the seismic line at depth. This area corresponds with a complex zone of shear-related deformation interpreted in magnetic data, and mapped as the Rodona Shear Zone (Plates 2 and 3). Because of the width of the zone, we have named the western and eastern limits as the West Rodona and East Rodona Shear Zones, respectively (CDP 18 810 to 19 540; Plate 4). The Kinclaven Shear Zone lies within this zone, and links to the East Rodona Shear Zone at depth. The West Rodona Shear Zone extends to the Gunnadorrah Seismic Province at 8 s TWT (~24 km depth), but does not appear to cut through it.

Although unexposed, the unit within the Rodona Shear Zone is interpreted to be dominantly Recherche Supersuite, or at least of Albany–Fraser Orogen affinity, based on similarities in magnetic and gravity data with the adjacent Nornalup Zone. It is highly likely, however, that slices of Madura Province rocks also occur within the Rodona Shear Zone, and recent work suggests the Malcolm Metamorphics, which are exposed on the coast to the south, may be one such example (Plate 3; Spaggiari et al., 2014b).

The only rock record from within the Rodona Shear Zone is from drillcore from the Hannah 1 prospect, located to the south (northeast of Caiguna). This drillhole intersected a coincident magnetic and gravity high that has a boudin-like geometry. The drillcore contains metadiorite dated at 1170 ± 4 Ma (GSWA 182203, Kirkland et al., 2012b), and is part of the Esperance Supersuite. Similar geophysical anomalies occur to the north of this, mainly within the shear zone.

Kinematic history

In the magnetic data, the east–west fabric described between CDP 15 900 and CDP 17 850 on seismic line 12GA-AF3 in the eastern Nornalup Zone (see 'Nornalup Zone' section above) swings to a northeasterly trend adjacent to the northeasterly trending West Rodona Shear Zone. This foliation deflection is interpreted to be indicative of sinistral shear sense. Similar sinistral foliation deflections occur to the south, between the West Rodona and East Rodona Shear Zones. These locally cut interpreted thrusts suggest an earlier phase of thrusting which was responsible for the current easterly dip, overprinted by sinistral, possibly transpressional, shearing. The deformed c. 1170 Ma metadiorite from the Hannah Prospect drillcore indicates that at least the latest phase of deformation was after c. 1170 Ma.

Madura Province

Seismic line 12GA-AF3 crossed the westernmost part of the Madura Province, from the East Rodona Shear Zone at CDP 19 540, to the eastern end of the section. Very little is known about the Madura Province as it lies entirely under cover of the Eucla and Bight Basins, and only eight exploration drillholes have intersected the basement to reasonable depths (summarized in Spaggiari et al., 2012). The best known of these drillcores are those from the Loongana prospect, which lies to the east of the end of the seismic line (Plate 2). The Loongana drillholes are located over a distinct gravity anomaly, and intersected metagabbro, locally with peridotitic cumulate, interlayered with trondhjemitic plagiogranite (Spaggiari et al., 2014b). Both the metagabbro and metagranite have been dated between 1410 and 1400 Ma (see summary in Spaggiari et al., 2014b). The geochemistry and isotopic character of these rocks, and also the metagabbroic rocks from both the Haig and Serpent drillcores nearby (Tillick, 2011; Tillick and Hunt, 2010), are consistent with the formation of an oceanic-arc, with little contribution from continental material, and indicates a largely oceanic setting for this part of the Madura Province at c. 1400 Ma (Spaggiari et al., 2014b). Collectively, these rocks are named the Haig Cave Supersuite (after Haig Cave).

In 2013, GSWA drilled two stratigraphic holes in the Madura Province; MAD002 and MAD014. MAD002 is located about 4 km north of CDP 20 660 (Fig. 11), and intersected basement at 389 m. Here, the basement consists of amphibolite schist interlayered with leucogranite veins and pods that are either parallel to the schistosity, or more locally, transgress it. The drillhole is coincident with a north-northeasterly trending, magnetic fabric of moderate susceptibility. In map view, this magnetic fabric occurs between the westerly dipping Pinto Shear Zone (CDP 20 500) and the westerly dipping Honeymoon Shear Zone (CDP 21 390), which, on the seismic section, overlies the gabbroic rocks of the Haig Cave Supersuite (Figs 4c and 11; Plates 2 and 4). In line 12GA-AF3, drillhole MAD002 occurs in weakly to non-reflective crust, which we have separated from the lower-upper to middle, more reflective crust. Interestingly, the Haig Cave Supersuite does not appear to have strong reflectivity, although, because it occurs at the far eastern edge of the section, it may not have been fully imaged.

The westerly dipping shear zones (Pinto, Anniversary, and Honeymoon Shear Zones (Fig. 11) either sole onto, or are cut by, the easterly dipping Diesel Shear Zone, which lies parallel to the East Rodona Shear Zone, and is probably related to that structure. In the magnetic data, the Honeymoon Shear Zone appears to be folded into two, along-strike antiforms cored by the Haig Cave Supersuite, but now cut by the unconformity of the overlying Bight Basin (Plate 2). One possibility is that the westerly dip of the reflectors and shear zones in this area may represent the western limb of a large, antiformal structure that has been truncated by the Rodona Shear Zone.

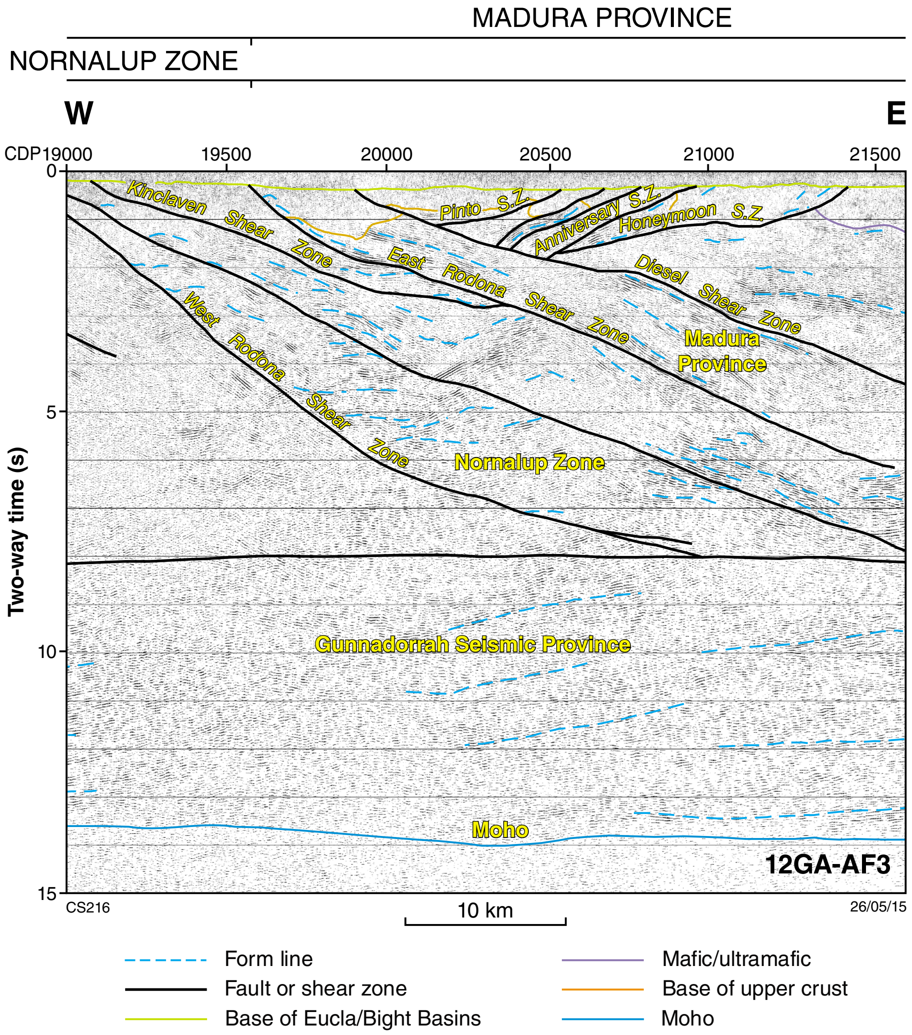

Figure 11. Detail of part of seismic line 12GA-AF3 showing the Madura Province

Lower crust on 12GA-AF3

The long length of 12GA-AF3 (319.12 km) has provided an image of the lower crust across the entire Albany–Fraser Orogen. Much of the lower crust, from beneath the Biranup Zone through to the eastern end of the section, is characterized by subhorizontal reflections with moderate to strong reflectivity, which is substantially different from the middle crust above it. Because of the difference in seismic character, this lower crustal zone is defined as the Gunnadorrah Seismic Province (Korsch et al., 2014). This seismic province is up to 5.5 s TWT (~16 km) thick at the eastern end, and gradually tapers to a thin wedge in the west.

The tapered western end of the Gunnadorrah Seismic Province lies beneath an interpreted low-angle, westerly dipping thrust at about CDP 10 650, which is also interpreted to cut through the Moho (Fig. 4a; Plate 4). The vertical displacement is estimated to be 2.3 s TWT (~7 km). An alternative interpretation is that the Moho is not faulted, but that the crust thickens considerably from about 13 s TWT (~39 km) at the western end of the line to about 16.3 s TWT (~49 km) centred below CDP 10 650, and then shallows eastwards to a depth of about 14 s TWT (~42 km) (Kennett, 2014).

Interestingly, this complication in the Moho coincides with another large zone of reduced impedance contrast (relatively non-reflective zone) of similar size to that interpreted on line 12GA-AF2. As in 12GA-AF2, the non-reflective zone occurs where the crust is thickest. However, there is no large, long wavelength gravity anomaly associated with the non-reflective zone on 12GA-AF3, and the modelling suggests a much less dense composition (Murdie et al., 2014). Nevertheless, as in 12GA-AF2, we have interpreted this non-reflective zone as a zone of crustal melt and melt residuals, which here can be interpreted as having a more felsic composition. Alternatively, as described above for 12GA-AF2, the non-reflectivity may be due to alteration, perhaps associated with magmatism and/or deformation.

Discussion

Crustal architecture and kinematics

The three seismic lines described above (12GA-AF2, 12GA-AF1 and 12GA-AF3) all show a series of structures with a predominant, moderate, easterly or southeasterly dip, particularly in the middle to upper crust. Most of these structures are interpreted as shear zones that show a thrust sense of displacement. This interpretation is consistent with mapped structures, both in magnetic data and in outcrop. As discussed below, however, it is highly likely that many of the thrusts are inverted, extensional structures. The truncated, westerly dipping shear zones in the Biranup Zone in seismic line 12GA-AF2 (Figs 2 and 7) could be interpreted as earlier extensional features representing the tops of tilted blocks. This would fit with a model of Paleoproterozoic extension and rifting (Spaggiari et al., 2014b). Seismic line 12GA-AF3 does not appear to preserve the same, early west-dipping structures in the Biranup Zone, perhaps because of the effects of the c. 1680 Ma Zanthus Event that has been recognized in this area (Kirkland et al., 2011a).

The prevalence of Albany–Fraser Orogeny, Stage II metamorphic dates throughout the east Albany–Fraser Orogen (e.g. Kirkland et al., 2011a, 2014a) is likely to reflect the formation of the present day crustal architecture imaged by the seismic data. These metamorphic dates are likely to constrain the timing of crustal thickening during folding and thrusting under relatively high temperature conditions (upper amphibolite to granulite facies), although more work is required to establish this. Thrusting during Stage II is supported by a recent study of the Mount Ragged Formation (Plate 3), which was deposited either during the late stages of, or after, Stage I of the Albany–Fraser Orogeny, and is interpreted to have a fold and thrust architecture (Waddell, 2014).

Thrusts have also been mapped in the central and west Albany–Fraser Orogen, particularly in relation to northwest-vergent folding in coastal exposures. At Bremer Bay, Paleoproterozoic Biranup Zone gneisses show large-scale, northwest-vergent, c. 1180 Ma F_3 folding, which is bracketed by two phases of boudinage (Spaggiari et al., 2009; Barquero-Molina, 2009). Northwest-vergent, asymmetric folding has also been mapped in the Mount Barren Group (see also Witt, 1998), and dates of xenotime and monazite of 1206 ± 6 and 1194 ± 8 Ma, respectively, were interpreted to record static overprinting of peak D_2 assemblages that were assumed to have formed during Stage I of the Albany–Fraser Orogeny (Dawson et al., 2003). However, given that no Stage I dates have been recorded in the Mount Barren Group, it is likely that these Stage II dates record both deformation and metamorphism during Stage II. Similar, northwest-vergent, asymmetric folds within the Biranup Zone were also mapped along the Pallinup River (Central Domain, Beeson et al., 1988), but these structures have not been dated. All of these areas have a similarity in the dominant northwest-vergent fold style, and the available geochronology suggests that this folding may have occurred more or less synchronously during Stage II of the Albany–Fraser Orogeny. Although largely unconstrained in timing, northwest-vergent folding is also commonly observed in the east Albany–Fraser Orogen, particularly in the Northern Foreland and Biranup Zone (Spaggiari et al., 2011).

Even though the Stage II timing is prevalent, at least one phase of thrusting may also have occurred during Stage I. For example, the folding and pop-up architecture of the Fraser Zone suggests a period of compression (see below), and the lack of Stage II dates within the Fraser Zone, coupled with the metamorphic Stage I dates (Clark et al., 2014), indicate that some exhumation and folding occurred during this time. Stage I metamorphism has also been recorded in the far northeast in the Gwynne Creek Gneiss (Plate 1), which contains refolded folds (Spaggiari et al., 2011).

Strike-slip shearing is also a feature of at least the late stages of the structural evolution of the Albany–Fraser Orogen, and is largely interpreted from magnetic data. It appears to be more prevalent towards the east, from between the Red Island and Heywood–Cheyne Shear Zones to the Rodona Shear Zone. In the latter, some thrusts appear to be cut by sinistral strike-slip shear zones (Plate 3). It is not clear whether these strike-slip shear zones are simply not imaged in the seismic data, or whether they have moderate dips, and may be transpressional structures. The seismic reflection technique can only image dips of structures up to about 60°. Overall, it is clear that much more work, particularly detailed fieldwork, is required to unravel the details of the timing and kinematics of the major shear zones throughout the Albany–Fraser Orogen, and their relationships with magmatism.

Structural emplacement of the Fraser Zone

In seismic line 12GA-AF3, the Fraser Zone is interpreted as a distinct V-shaped entity (Figs 4 and 10; Plate 4). The maximum depth of the Fraser Zone is imaged at about 4.2 s TWT (~13 km), along the moderately, easterly dipping Fraser Shear Zone. When combined with the V-shape of the Fraser Zone, the Fraser Shear Zone can be interpreted to form the tail of a Y-shape.

There are several ways the Y-shaped geometry could be interpreted to have formed, so it is relevant to provide a brief overview of the structures observed in the Fraser Range Metamorphics to the southwest. These rocks are dominated by a well-developed, northeasterly trending, predominantly steeply southeast-dipping, gneissic foliation. In general, this foliation is axial planar to tight to isoclinal, northeasterly trending folds of the layering, which are, in turn, cut by thrusts and shear zones. Deformation under high temperature conditions up to 850º C took place shortly after intrusion of the gabbroic and granitic sheets between about 1305 and 1290 Ma (Spaggiari et al., 2013; Clark et al., 2014). Evidence for this is provided by the dating of late, metagranitic veins containing large euhedral garnets that crosscut the foliation, dated at 1283 ± 8 Ma (Stage I; GSWA 194780, Kirkland et al., 2013b).

Major shear zones such as the Coramup and Heywood–Cheyne Shear Zones that occur to the southwest of the Fraser Zone (see sections 12GA-AF2 and 12GA-AF1) are interpreted to have an early history related to Paleoproterozoic extension. These large, crustal-scale shears are interpreted to have been utilized by the intrusion of the Fraser Zone sheeted complex during Stage I of the Albany–Fraser Orogeny (Spaggiari et al., 2014b), prior to the formation of the current bounding shear zones (Fraser, Newman, and Boonderoo Shear Zones). The relatively short time between intrusion and deformation and metamorphism suggests the stress field may have rapidly switched from extensional or transtensional (accommodating Mesoproterozoic magma emplacement) to contractional or transpressional (Spaggiari et al., 2013). This switch probably drove the first period of exhumation of the Fraser Zone along the bounding shear zones, possibly resulting in the formation of a pop-up architecture between the Biranup and Nornalup Zones (Spaggiari et al., 2013). This could account for the Y-shaped geometry, with initial formation of the Fraser and Harris Lake Shear Zones acting as the main floor thrusts during emplacement of the Fraser Zone over the Biranup Zone. At the same time, the formation of the Boonderoo and Newman Shear Zones as westerly dipping shear zones was probably accommodated by synmagmatic intrusions of the Recherche Supersuite into the eastern Nornalup Zone, softening and weakening the crust on the eastern side of the Fraser Zone.

Subsequent translational deformation, probably during Stage II of the Albany–Fraser Orogeny, is interpreted to have brought the Fraser Zone to its current location. This is indicated by lower temperature shear zone fabrics and the kinematics in the bounding shear zones to the southwest. These include discrete L-tectonites and L–S tectonites along the Newman Shear Zone, indicative of both vertical movement (southeast side up), and sinistral strike-slip movement. In contrast, mylonitic fabrics along the Fraser Shear Zone are all indicative of dextral shear (Spaggiari et al., 2011, 2013). The differential kinematics have been interpreted as wholesale southwestward translation of the Fraser Zone, contributing to the formation of the ‘S-bend’ termination (see Spaggiari et al., 2011). If correct, this implies that the initial intrusion and emplacement of the Fraser Zone during Stage I took place an unknown distance to the northeast.

Influence of magmatic processes on crustal architecture

Both seismic lines 12GA-AF1 and 12GA-AF3 show large areas of weak to non-reflective crust, within the eastern Nornalup Zone. We have interpreted the crust in these areas to have been heavily intruded by dominantly granitic rocks of the Recherche and Esperance Supersuites, as is evident from outcrop along the South Coast, east of Esperance (Plate 3). These areas, particularly those on 12GA-AF1, truncate dipping reflections and easterly dipping shear zones. Although more work is needed to constrain the interaction between deformation and magmatic emplacement processes, based on the relationships of fabrics within meta-igneous rocks that show repeated intrusion and deformation (Fig. 9), it is highly likely that the emplacement of these magmatic rocks was facilitated by shear zone development during deformation. The high temperature conditions and variable orientations of these sheeted intrusions have probably not produced coherent, linear, layered areas that would equate to well-defined, coherent reflections in the seismic data, perhaps with the exception of some of the rafts or large enclaves interpreted in 12GA-AF3. Hence, it is possible that these non-reflective zones may not always equate to the youngest intrusions, but may simply be areas dominated by variably oriented magmatic fabrics that do not produce coherent reflections in the seismic image.

Magmatic processes have played a significant role throughout the entire history of the Albany–Fraser Orogen, and all major tectonic events have been accompanied by voluminous magmatism (Spaggiari et al., 2014b; Smithies et al., 2014). This has no doubt left its mark on the structural fabric of the orogen.

Middle to lower crust

The middle to lower crust is dominated by easterly dipping reflections and interpreted shear zones that are generally shallow at depth and are truncated by, or sole onto the top of, the Gunnadorrah Seismic Province. These are punctuated by weakly reflective to non-reflective zones, some of which may relate to magmatic and/or alteration processes, as discussed above. Two of these features are distinct in the western part of the lower crust, one in line 12GA-AF2 and one in line 12GA-AF3. One interpretation of these non-reflective zones is that they are areas of crustal melt and melt residuals that do not contain coherent fabrics that can be imaged. They may also be large zones of alteration, possibly driven by magmatic processes linked to upper mantle heat. As discussed above, it is not clear whether these non-reflective zones are relatively early or late features, because, although in the 2D images they appear to be crosscut various shear zones, this may simply be because they do not contain fabrics or layers that image as coherent reflections.

Interpreting the middle to lower crust is problematic for many reasons, such as whether it is viable to extrapolate large, individual shear zones evident near the surface or in the upper crust downwards to the middle or lower crust. The question arises, how might the crust be partitioned vertically? In many localities the seismic images certainly do show consistent packages of reflections that can be traced long distances, but it is important to recognize that the interpretation of individual structures is simplistic and limited to 2D, and more likely reflects zones of particular rock packages in particular orientations. This means that caution should be exercized in extrapolating known structural relationships from the surface to the middle or lower crust.

Following on from this, the middle to lower crust contains regions of seismic character that cannot be correlated with the upper crust — the Yarraquin, Udarra, and Gunnadorrah Seismic Provinces. The age and origin of these seismic provinces are unknown, although both the Yarraquin and Udarra Seismic Provinces have also been interpreted below the Youanmi and Kurnalpi Terranes, respectively, which suggests they are likely to have an affinity with the Yilgarn Craton. Although the amount of craton-vergent, thrust-related displacement cannot be measured, this suggests that previous interpretations of isotopic and geochemical data, and models of extension and rifting (Kirkland et al., 2011a,b, 2014a; Smithies et al., 2013; Spaggiari et al., 2014b; Smithies et al., 2014), are consistent with the seismic interpretations presented here.

The Albany–Fraser Orogen has often been regarded as a Mesoproterozoic Grenvillian collisional orogen, but when the basin history and magmatic evolution are taken into account, it is clear that the orogen has been dominated by extensional processes throughout much of its history, particularly during the Paleoproterozoic (Clark et al., 2014; Spaggiari et al., 2014b; Smithies et al., 2014). The geometry of the listric or shallowly dipping to subhorizontal structures in the middle to lower crust are consistent with an extensional architecture, and are interpreted as inverted structures. Although speculative, the flat-lying geometry of the Gunnadorrah Seismic Province could indicate that this seismic province represents highly attenuated and modified Yilgarn Craton crust. However, the interpreted low-angle westerly dipping thrust that offsets the Moho in seismic line 12GA-AF3, is at odds with this. If the thrust was originally extensional, it would be expected to dip the other way, as most of the thrusts dip to the east or southeast. An extensional regime or detachment could, however, produce tilting of the Gunnadorrah Seismic Province to the west, although it is unclear how this might manifest itself in the lower crust or along the Moho. Alternatively, the inferred thrust could reflect subhorizontal wedging of the lower crust during compression, or, as indicated by Kennett (2014), the thrust may not exist, and there is simply a bulge in the Moho in this region. In addition, it is not clear whether the Rodona Shear Zone, which marks the eastern edge of the Albany–Fraser Orogen, truncates the Gunnadorrah Seismic Province, or soles onto it. Future work on the continuation of seismic line 12GA-AF3, the Eucla–Gawler line, should help clarify this.

Conclusions

The interpretation of the three seismic lines, 12GA-AF2, 12GA-AF1 and 12GA-AF3, described here has provided a 2D cross-section of the entire crust of the east Albany–Fraser Orogen. The interpretations show that the orogen has a dominantly east- to southeast-dip, that generally shallows or flattens at depth. Major shear zones are either truncated by, or sole onto, the Yarraquin, Udarra, or Gunnadorrah Seismic Provinces at depth.

The Coramup Shear Zone separates the Biranup Zone from the eastern Nornalup Zone, and although this shear zone and several subparallel major shear zones form one of the most significant shear zone systems in the orogen, it is not interpreted as a suture zone. This is because of the similarities in the geological evolution of the Biranup and Nornalup Zones, which together, form part of the Kepa Kurl Booya Province. Furthermore, in seismic line 12GA-AF3, the along-strike continuation of that boundary, here represented by the bounding shear zones of the Fraser Zone in the upper crust, shows the Biranup–Nornalup boundary as flat-lying beneath the Fraser Zone, and extending to the top of the Gunnadorrah Seismic Province to the east (Fraser and Harris Lake Shear Zones).

The middle to lower crust contains regions of seismic character that cannot be correlated with the upper crust — the Yarraquin, Udarra, and Gunnadorrah Seismic Provinces. The age and origin of these seismic provinces are unknown, although both the Yarraquin and Udarra Seismic Provinces have also been interpreted below the

Youanmi and Kurnalpi Terranes, respectively, which suggests they are likely to have an affinity with the Yilgarn Craton. This suggests that the Yilgarn Craton can be tracked under the Albany–Fraser Orogen at least as far as under the Fraser Zone in line 12GA-AF3, and at least halfway under the eastern Nornalup Zone in line 12GA-AF1, but beneath interpreted Biranup Zone. Although the amount of craton-vergent, thrust-related displacement cannot be measured, it is highly likely that this portion of the Yilgarn Craton was significantly extended and thinned during the Proterozoic, and, therefore, the generally listric to flat-lying structures represent an inverted, extensional architecture. This is consistent with the history of basin formation and magmatism in the orogen.

The seismic images also show large areas of weakly to non-reflective crust, where structures are interpreted to be masked by magmatic processes of deformation-related intrusion. This is consistent with the repeated history of voluminous magmatism in the orogen, leading to partial melting of the crust. An excellent example of this is the preservation of an interpreted magma chamber that is exposed on the South Coast east of Esperance, which may correlate with the variably reflective to non-reflective broad zone imaged in line 12GA-AF1.

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