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# Reconciling the onshore/offshore stratigraphy of the Canning Basin and implications for petroleum prospectivity

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**ABSTRACT**

The Canning Basin is a prospective hydrocarbon frontier basin and is unusual for having limited offshore seismic and well data in comparison with its onshore extent. In this study, seismic mapping was conducted to better resolve the continuity of 13 key stratigraphic units from onshore to offshore to delineate prospective offshore hydrocarbon-bearing units, and better understand the distribution of mafic igneous units that can compartmentalise migration pathways and influence heat flow. The offshore Canning Basin strata are poorly constrained in six wells with limited seismic coverage; hence data availability was bolstered by integrating data from the onshore portion of the basin and adjacent basins into a single 3D seismic stratigraphic model. This model integrates over 10 000 km of historical 2D seismic data and 23 exploration wells to allow mapping of key stratal surfaces. Mapped seismic horizons were used to construct isochores and regional cross-sections. Seven of the 13 units were mapped offshore for the first time, revealing that the onshore and offshore stratigraphy are similar, albeit with some minor differences, and mafic igneous units are more interconnected than previously documented whereby they may constitute a mafic magmatic province. These basin-scale maps provide a framework for future research and resource exploration in the Canning Basin. To better understand the basin's geological evolution, tectonic history and petroleum prospectivity, additional well data are needed in the offshore Canning Basin where Ordovician strata have yet to be sampled.

**KEY POINTS**

1. Coastlines act as barriers that can prevent parity of stratigraphic interpretations and geoscience data acquisition for adjacent onshore, offshore areas.
2. This study features seismic stratigraphic mapping of 13 key units in the Canning Basin coastal area, including seven units mapped continuously from onshore to offshore for the first time.
3. This research delivers a framework for future exploration and a better understanding of the Canning Basin's geological history.

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Seismic; stratigraphy; geophysics; Canning Basin; North West Shelf; 3D modelling; prospectivity; igneous

## Introduction

The geologically complex Paleozoic Canning Basin spans some 530 000 km$^2$, with its offshore component extending onto the North West Shelf in Western Australia (Figure 1; Backhouse & Mory, 2020; DMIRS, 2017; Hashimoto *et al.*, 2018; Mory, 2010; Totterdell *et al.*, 2014). The basin preserves one of the deepest (∼18 km) and relatively most continuous packages of Ordovician to Permian strata in Australia (Mory & Haines, 2013) and was subject to a series of continental break-up events (Keep *et al.*, 2007; Li *et al.*, 2008; Li & Powell, 2001; Matthews *et al.*, 2016; Metcalfe, 2006; Müller *et al.*, 2005; Yeates *et al.*, 1984). This study focusses on the near coastal regions, which are divided into two major depocentres: the Fitzroy Trough and its offshore equivalent the Oobagooma Sub-basin, and the Willara Sub-basin, which are separated by the Broome Platform.

The Canning Basin is one of the Earth's most underexplored Paleozoic basins with an average of six wells per 10 000 km$^2$ compared with the most explored U.S. Paleozoic basins that have an average of 500 wells per 10 000 km$^2$ (DMIRS, 2017) and so remains poorly understood in its entirety (Cadman *et al.*, 1993; DMIRS, 2017; Haines, 2009; Middleton, 1990). Nevertheless, the onshore part of the basin has proven conventional and potential unconventional

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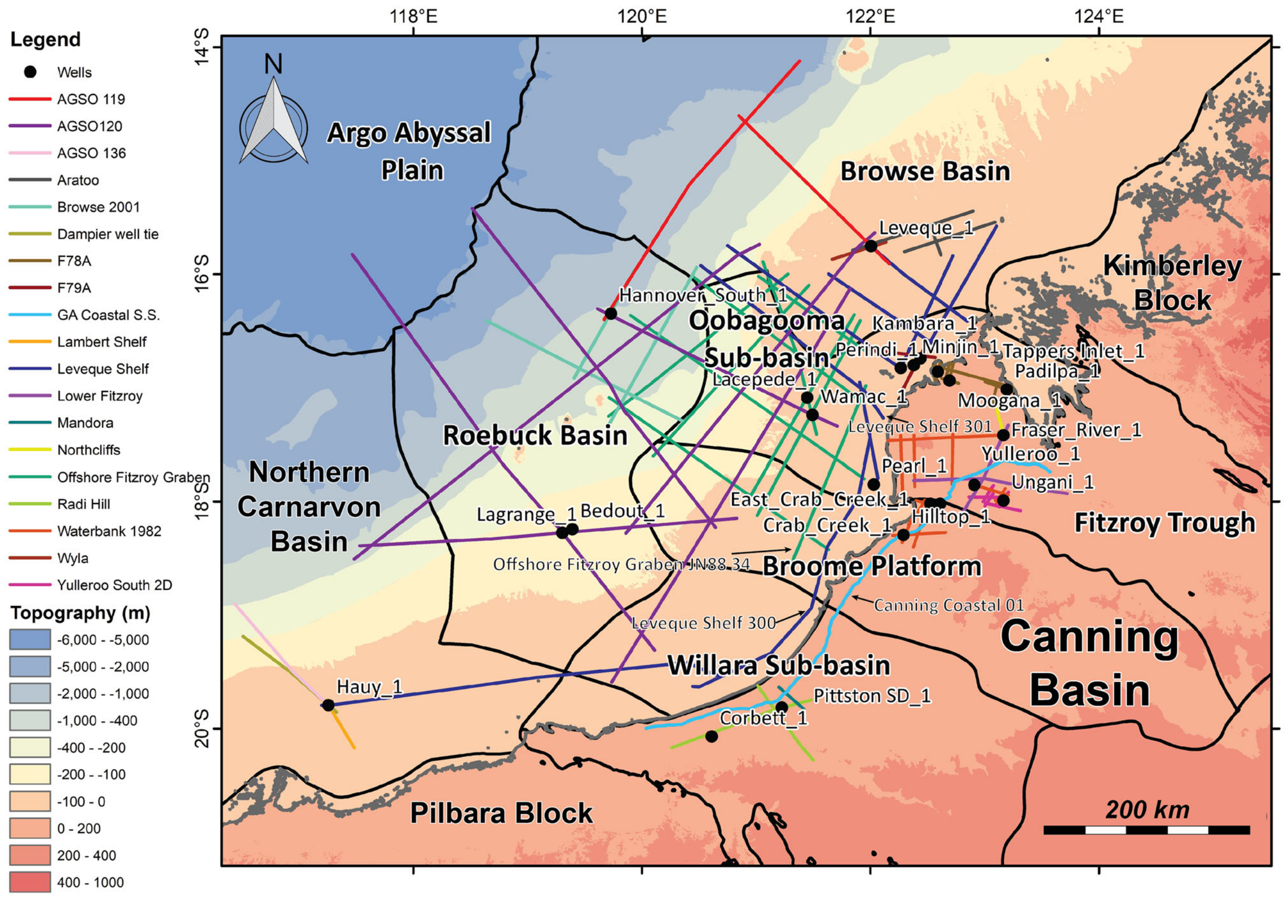


**Figure 1.** Topographic map of the study area with terrestrial and marine topography. Seismic and well data displayed in this map are incorporated into a seamless 3D model used for basin-scale seismic stratigraphic mapping.

hydrocarbon prospectivity derived from lower Carboniferous source rocks located in and along the margins of the Fitzroy Trough (Kingsley & Streitberg, 2013; Murray *et al.*, 2018; Triche & Bahar, 2013). However, a hydrocarbon accumulation has yet to be discovered in the Oobagooma Sub-basin, although hydrocarbon indications are present in some wells (*i.e.* Perindi 1 oil, Minjin 1 gas). In the Kidson Sub-basin, large unconventional shale gas resources have been evaluated for the Ordovician Goldwyer Formation (Triche & Bahar, 2013), whereas its extension into the neighbouring onshore–offshore Willara Sub-basin warrants further study.

The Canning Basin is different from nearby Phanerozoic basins because petroleum systems are only known from Paleozoic strata, rather than in Mesozoic strata of the offshore Roebuck (Bedout Sub-basin) (Thompson, 2020), Northern Carnarvon (Totterdell *et al.*, 2014) and Browse (Rollet, Abbott, *et al.*, 2016; Rollet, Grosjean, *et al.*, 2016) basins. Despite nearly 100 years of onshore petroleum exploration, only small commercial accumulations have been identified in the Canning Basin (Cadman *et al.*, 1993; Jonasson, 2001; Purcell, 1984) with more recent production from the Ungani oil field since its discovery in 2011 (Edwards & Streitberg, 2013; Long *et al.*, 2018). Exploration is continuing to prove up the Paleozoic tight wet gas resources along the margins of the Fitzroy Trough (*e.g.* Valhalla, Black Mountain Energy, 2022; Yulleroo and Rafael 1, Buru, 2022).

The Canning Basin has significant stratigraphic variability between its onshore and offshore components (Figure 1). Historically, these two parts of the basin have been investigated as separate entities owing to differences in data acquisition, quality and accessibility for the onshore and offshore sectors, which has resulted in different stratigraphic terminology on either side of the coastline (Hackney *et al.*, 2015; Totterdell *et al.*, 2014), although Smith *et al.* (2013) attempted some unification. These differing stratigraphic histories and levels of understanding are the result of limited geological investigation, especially offshore where data from only six wells and vintage seismic data from the 1970s through to 2014 (Figure 1) are available. Currently, there are no continuous seismic and stratigraphic correlations of the basin's major stratigraphic units across the coastline. Mapping strata from onshore to offshore in basins globally is commonly problematic owing to data scarcity, lack of data

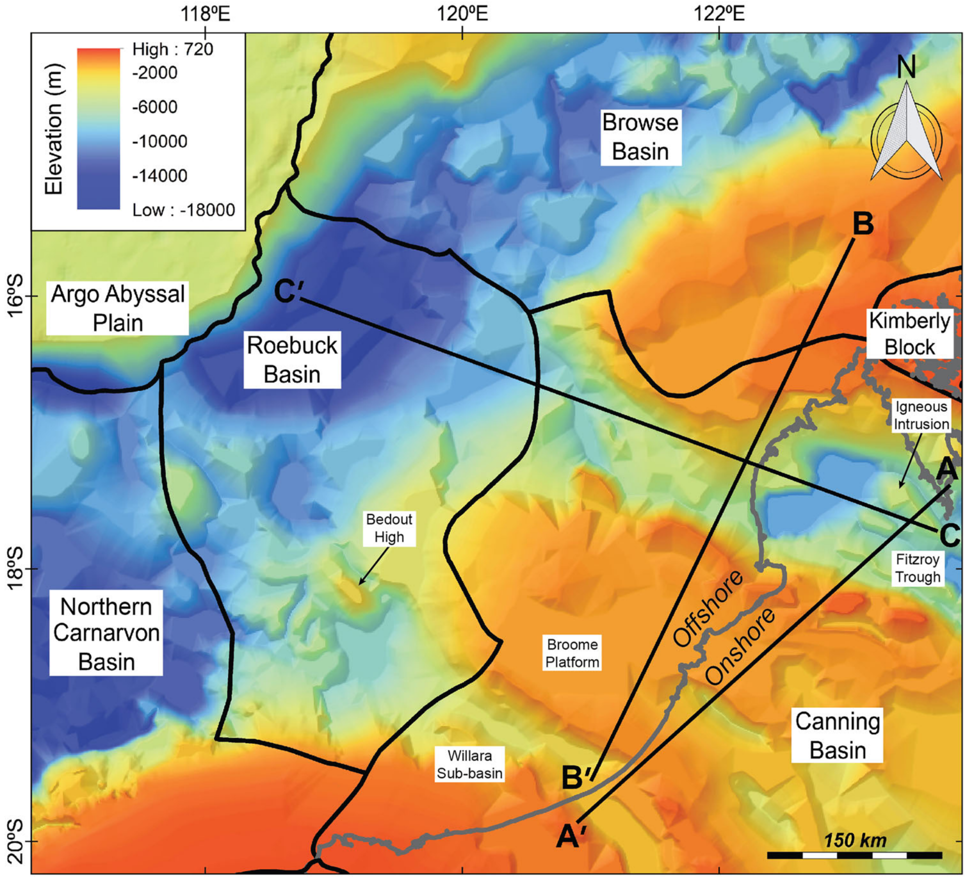


**Figure 2.** Basement map of the study area and location of basin-scale cross-sections. The SEEBASE dataset used to create this map was developed by Frogtech (2014) by combining geophysical and geological data (de Vries *et al.*, 2007). Basement geometry of the study area significantly differs from surface topography. Cross-sections are displayed in Figure 5.

near coastlines and focussed study areas (Breivik *et al.*, 2005; Duin *et al.*, 2006; Sopher & Juhlin, 2013). The consequence for not mapping the Canning Basin onshore–offshore transition is that many stratigraphic intervals have not been identified offshore, making the overall stratigraphy ambiguous.

There are several key questions that mapping of the Canning Basin onshore–offshore transition can answer, which include:

1. Reconciliation of the Paleozoic stratigraphic relationships on either side of the onshore–offshore transition (Totterdell *et al.*, 2014).
2. Mapping the offshore extent and depth of potentially prospective Paleozoic petroleum systems.
3. Mapping the distribution of mafic igneous units and assessing their impact on stratigraphy and petroleum systems.

To answer these questions, this study focussed primarily on correlating the onshore and offshore depocentres (Figure 2) to synchronise the stratigraphy across the basin and establishing a holistic view of the geology. Although the hypothesis that the stratigraphy of the offshore Canning Basin generally matches that of the coastal onshore region, it remains to be convincingly demonstrated with the sparse data available.

Improving the onshore–offshore stratigraphy of the Canning Basin is important because it has the most comprehensive record of Ordovician and, to a lesser extent, Silurian strata in Western Australia, ambiguous volcanism, one of Australia's thickest depocentres, and it possesses significant hydrocarbon potential.

## Geological background

### *Recent studies*

Exploration of the onshore Canning Basin has continued for nearly 100 years (Purcell, 1984), but the offshore component is less understood (Abbott et al., 2019; Orlov *et al.*, 2019; Rollet, Grosjean, *et al.*, 2019). Up to the late 1990s, much of the offshore Canning Basin stratigraphy was unnamed and not well defined (Sayers *et al.*, 1995). An updated stratigraphic chart has improved this, but recognition of Paleozoic strata is still incomplete compared with the onshore stratigraphy (Smith *et al.*, 2013). Recently, Triassic strata have been the main exploration target in the offshore Roebuck Basin (Thompson *et al.*, 2018, 2019), but the Paleozoic systems of the Oobagooma Sub-basin are still poorly understood owing to a lack of wells and seismic data. This lack of data may have resulted in the petroleum systems in the offshore Canning Basin being overlooked; however, integration of onshore and offshore data has proven to enhance the understanding of the offshore stratigraphy (Amiribesheli & Weller, 2019; Yule & Spandler, 2022). This includes linking the onshore–offshore uppermost Mesozoic unconformity (labelled top Mesozoic) from this study with the offshore Triassic mapping from Rollet, Grosjean, *et al.* (2019) and available well data.

Recent studies have highlighted the presence of igneous material across the Roebuck and Canning basins, which presents exploration uncertainty (Orlov *et al.*, 2019; Rollet, Grosjean, *et al.*, 2019; Yule *et al.*, 2022). Intrusions can either destroy petroleum systems or mature reservoirs and can act as either pathways or barriers to fluid migration (Kumar *et al.*, 2022). Prospectivity of this region is tied to the understanding of mafic igneous rocks and their relationship with surrounding strata (Abbott *et al.*, 2019). Once this is better clarified with additional data, the offshore Canning Basin could host several Paleozoic petroleum systems and commercial quantities of hydrocarbons (Ghori, 2018; Orlov *et al.*, 2019; Rollet, Grosjean, *et al.*, 2019).

### Tectonic history

The Canning Basin was initiated by rifting of the Tarim Block from the North West Shelf during the Cambrian, which formed crustal weaknesses and initiated an extensional tectonic regime (Keep *et al.*, 2007; Li *et al.*, 2008; Li & Powell, 2001). Further extension, referred to as the Carribuddy Sag, continued from the Ordovician through to the late Carboniferous when new accommodation space was generated for sediment deposition in the Canning Basin (Laurie *et al.*, 2016; Purcell, 1984; Totterdell *et al.*, 2014). On a larger scale, deformation associated with the Devonian Rodingan Movement, which resulted in extension from the initiation of the Gondwanaland break-up, caused minor folding coupled with regional uplift and erosion in the Canning Basin (Craig *et al.*, 1984; Keep *et al.*, 2007). The second continental rifting event involved the break-up of the Cimmerian Block from the North West Shelf during the early Permian to create a triple junction and formation of the Bedout High (Figure 2; Li & Powell, 2001; Matthews et al., 2016; Müller *et al.*, 2005). The Bedout High formed from basin-scale uplift, faulting and volcanism in the Canning Basin and adjacent basins (Müller *et al.*, 2005). Prior to the Middle Triassic, the dominant tectonic regime in the Canning Basin was extensional; the basin was subsequently deformed owing to compression associated with the Fitzroy Movement, which caused reverse faults, fault inversion, strike-slip movements and 1–3 km of uplift that accelerated erosion in the Canning Basin (Laurie *et al.*, 2016; Totterdell *et al.*, 2014; Yeates *et al.*, 1984). Finally, early Jurassic rifting of the Mawgyi Terrane from the North West Shelf formed the Argo Abyssal Plain and resulted in the current geometry of the North West Shelf (Matthews *et al.*, 2016; Metcalfe, 2006; Müller *et al.*, 2005; Yeates *et al.*, 1984).

Rifting of the Cimmerian Block along the edge of the Northwest Shelf around the Permian–Triassic boundary may have caused rift rebound across the North West Shelf, allowing the continental crust to rise in elevation when lithostatic loading from the rifted continent is removed. Elevated crust is more susceptible to erosion, so continental rifting can leave erosional unconformities as recorded in the stratigraphy (Houseman, 1991; Pirajno & Santosh, 2015; Zeyen *et al.*, 1997). Rifting of the Cimmerian Block left a regional unconformity that can be identified across the Canning Basin as the top Paleozoic boundary (Hashimoto *et al.*, 2018). Sea-level variation can be ruled out as an explanation for the Permian–Triassic unconformity because global sea-level was stable during this period. Following the rebound, subsidence from rifting and emplaced igneous units provided Cenozoic and Mesozoic units the accommodation space to make thicker deposits offshore. The thickening of Cenozoic strata could be related to the northwest tilting of the Australian continent, where eroded onshore sediments are deposited offshore (Craig *et al.*, 1984; DiCaprio *et al.*, 2009).

### Petroleum potential of depocentres

This study focuses on the two coastal sub-basins of the Canning Basin; the Fitzroy Trough–Oobagooma Sub-basin and the Willara Sub-basin, which are separated by the Broome Platform (Figure 1). The Fitzroy Trough and its offshore equivalent, the Oobagooma Sub-basin (Figure 1), contain one of Australia's largest depocentres at ∼18 km thick (Figure 2). These sub-basins host Ordovician to Triassic strata with many unconformities (Yeates *et al.*, 1984) and owing to immense depths, many of the petroleum systems are overmature. However, onshore petroleum systems along the margins of the Fitzroy Trough are shallower and oil generative, with fault bounded structural traps (Brown *et al.*, 1984). The Oobagooma Sub-basin is not as well studied as the Fitzroy Trough, but limited data show that Devonian reef complexes drilled offshore could potentially act as stratigraphic traps (Totterdell *et al.*, 2014). Petroleum prospectivity of these sub-basins is made complex with abundant igneous intrusions that could impact petroleum system quality (Smith *et al.*, 1999; Totterdell *et al.*, 2014).

The Broome Platform is located in the centre of the study area and extends onshore and offshore (Figure 1). It is a 600 km-long and 150 km-wide section of uplifted basement orientated NW–SE (Figure 2; Yeates *et al.*, 1984). It has the shallowest sedimentary package in the Canning Basin with thicknesses of the Ordovician, Devonian and Permian strata ranging from 1 to 2 km (Figure 2; Totterdell *et al.*, 2014). The Broome Platform is unique compared with the rest of the Canning Basin because despite a long history of extension, subsidence and tectonism in the adjacent sub-basins, it has been minimally deformed (Yeates *et al.*, 1984). A *ca* 150 Ma unconformity separates the Ordovician from the Permian units on the Broome Platform (Smith *et al.*, 2013) as a result of uplift and erosion from the Rodingan Movement in the Devonian (Craig *et al.*, 1984). There are several petroleum plays of varying quality on the Broome Platform. Ordovician petroleum systems likely have the most potential as there are known source, reservoir and trap elements, which are shallower on the Broome Platform than in neighbouring sub-basins (Bentley, 1984).

The Willara Sub-basin is the southernmost depocentre of the coastal Canning Basin region and is present onshore and offshore, although little is known about the offshore component owing to sparse seismic data and no well data (Figure 1). Maximum depocentre thickness is estimated to be ∼3 km where it is dominated by Paleozoic strata (Totterdell *et al.*, 2014). The offshore Willara Sub-basin has hydrocarbon potential owing to the identification of an Ordovician succession in the seismic data (Totterdell *et al.*, 2014). However, like much of the onshore Canning Basin, there are not enough data to confirm an effective petroleum system (Totterdell *et al.*, 2014).

### *Petroleum systems*

Ordovician sedimentary rocks that have organic-rich units intersected in onshore wells include the Tremadocian–Floian Nambeet, Dapingian–Darriwilian Goldwyer, and Sandbian Bongabinni formations (Ghori, 2018; Hashimoto *et al.*, 2018), where oil and gas shows are most widely attributed to the Goldwyer Formation (Edwards *et al.*, 2013). Mapping from this study presents the possibility of extending this onshore petroleum system farther offshore on the Broome Platform where the top of the Goldwyer Formation is ∼1500 m. However, more seismic and well data are needed to determine the geometry of the Goldwyer Formation in the offshore Willara Sub-basin, but it is likely to deepen from the Broome Platform towards the centre of the Willara Sub-basin depocentre. The Nambeet Formation has source potential throughout the Canning Basin, where many samples are interpreted to be within the upper oil window (Dent & Normore, 2017). Although gas shows have not yet been typed to the Nambeet Formation, gas has been detected in fluid inclusions within this formation in onshore wells (Boreham *et al.*, 2020). Therefore, the Nambeet Formation warrants further research, including in the coastal study region. Proven source rocks in the Bongabinni Formation are restricted to the Admiral Fault Bay region on the northern edge of the onshore Willara Sub-basin (Haines & Ghori, 2006), and as yet there is no new evidence to support this petroleum system extending offshore.

Oil has been produced from the onshore Blina field where it presumably originates from Devonian marine marls within the northern margin of the Fitzroy Trough (Edwards *et al.*, 2013), and hence there is the potential for this petroleum system to extend offshore. The offshore well Minjin 1 encountered a small gas (mainly methane) anomaly in the Pillara Limestone beneath the Grant Group and intruded dolerite. The total organic carbon content of three samples from the Pillara Limestone ranges from 1.5 to 2 wt%, but the formation is thermally immature (vitrinite reflectance = 0.4–0.45%) and unlikely to have generated hydrocarbons at this location (Powis, 1984). Hence, the source of gas for Minjin 1 is unconstrained but mostly likely Devonian or older.

Effective source rocks within the lower Carboniferous (Tournaisian) Laurel Formation of the Fairfield Group, have generated oil and gas within upper Carboniferous and Permian reservoirs on the Lennard Shelf and Fitzroy Trough. Recovery from these oil fields was most productive throughout the mid-1980s and 1990s, and has been declining ever since, with Ungani being the only recent field to come into production (Long *et al.*, 2018). Numerous tight wet gas accumulations (*e.g.* Valhalla, Yulleroo) are associated with an unconventional basin-centred gas system within the Fitzroy Trough (Kingsley & Streitberg, 2013). Hydrocarbon indications within the offshore well Perindi 1 provides evidence that this lower Carboniferous (and potentially other) petroleum systems extend offshore at this location. Perindi 1 intersected oil indications in the Pool Sandstone (833–877 mKB), oil indications and bitumen in the Grant Group to Laurel Formation (1771–1778 mKB), and bitumen and minor gas in the Pillara Limestone (1778–1801 mKB) (Reeckmann & Mebberson, 1984). The geochemistry of these hydrocarbons is variable in their compositions (Esso Australia Limited, 1984); however, some of these hydrocarbons are similar to other Carboniferous-sourced oils in the Canning Basin. Notably, these formations are separated by a doleritic intrusion between 1379 and 1535 mKB in the Grant Group. As measured in both Perindi 1 and Minjin 1, contact metamorphism is localised to the section immediately above the intrusions; however, increases in regional heat production from cone sheets associated with the mafic magmatic province (Yule & Spandler, 2022) could have thermally matured any organic-rich rocks in the Laurel Formation and older Paleozoic rocks (Kennard *et al.*, 1994a, 1994b; Yule *et al.*, 2022).

In the onshore Canning Basin, the mid-Cisuralian Noonkanbah Formation contains organic-rich mudstones that are marginally mature for hydrocarbon generation in the Fitzroy and Gregory sub-basins, whereas mudstones and coals in the Roadian–Changhsingian Liveringa Group are immature, as is the Lower Triassic (Induan–Olenekian) Blina Shale (Mory & Hocking, 2011). Given that the Noonkanbah Formation is more deeply buried under the westward thickening Mesozoic succession beyond Kambara 1 and Minjin 1 (Figure 6), there is the potential for Permian sourced hydrocarbons to have been generated in the offshore Canning Basin. Evidence that these petroleum systems are viable on the western margin of Australia comes from gas/condensates derived from Permian source units within the Petrel Sub-basin, Bonaparte Basin and Perth Basin (Edwards *et al.*, 2013).

### *Stratigraphic history*

Sedimentation in the Canning Basin probably began in the Ordovician where it was deposited directly onto Archean basement (Yeates *et al.*, 1984), although the recent drilling of the Barnicarndy 1 well in the Barnicarndy Graben hints at the possibility of older, perhaps Cambrian, sedimentary rocks overlie a Proterozoic Yeneena Basin basement (Forbes *et al.*, 2020; Normore *et al.*, 2021). The Canning Basin underwent near continuous Ordovician–Cenozoic deposition within the main Fitzroy Trough depocentre, which hosts up to ~18 km of strata (Yeates *et al.*, 1984).

The distribution of Paleozoic units in the Canning Basin can be better understood, especially offshore where Paleozoic strata are deeply buried under Mesozoic cover (DMIRS, 2017; Haines, 2009; Laurie *et al.*, 2016; Lewis & Sircombe, 2013; Middleton, 1990; Mory & Haines, 2013; Mory & Hocking, 2011). Uncertainties associated with the biostratigraphy (Hilbert-Wolf *et al.*, 2017; Mory & Haines, 2013) of Paleozoic sections include: reliance on fossils endemic to Western Australia make it difficult to correlate with global datasets, contradictory fossil interpretations, inconsistent distribution of fossils, with large age error margins, and sparse well coverage (Mory & Haines, 2013). Radiometric ages for some Canning Basin units are available (Laurie *et al.*, 2016; Lewis & Sircombe, 2013; Mory & Haines, 2013); however, additional sampling and seismic stratigraphic mapping are required to better resolve the temporal and spatial distribution of strata within the offshore part of the basin.

Mafic igneous units can be found throughout the Canning Basin, but few have been sampled, and their extents have only recently been mapped as part of this study (Yule & Spandler, 2022). Igneous intrusions are known to influence the development and functioning of petroleum systems (Augland *et al.*, 2019; Black & Gibson, 2019). Ordovician, Carboniferous, and Permian strata in the Oobagooma Sub-basin host igneous intrusions that may have impacted local petroleum systems by over-maturation, bringing immature source material into the oil window and compartmentalising petroleum systems by blocking migration pathways. These intrusions are a critical risk to petroleum systems, but their temporal distribution and extent is unknown, so their impact remains speculative (Holford *et al.*, 2013; Reeckmann & Mebberson, 1984; Smith *et al.*, 1999; Totterdell *et al.*, 2014). Recent studies have highlighted that the mafic igneous units across the onshore and offshore Canning Basin could be interconnected and represent a magmatic province, which could have had a significant impact on Paleozoic petroleum systems (Rollet, Shi, *et al.*, 2019; Yule & Spandler, 2022).

## Methods

To answer this study's research questions, we conducted seismic stratigraphic mapping across the Canning Basin onshore–offshore transition to develop a 3D seismic stratigraphic model. A model was developed from existing 2D seismic data (>10 000 km line length) with stratigraphic well ($n = 23$; Table 1) data acquired across the Canning Basin and adjacent basins. To account for the paucity of offshore data, the model was supplemented with well data from the onshore Canning Basin and well data from adjacent basins to better constrain the seismic interpretations. Prominent seismic reflectors were identified and matched to well logs to assign a common stratigraphic terminology for key units from onshore to offshore (Figure 3) using top horizon picks. Additionally, stratigraphic nomenclature was checked against the Australian Stratigraphic Units Database (ASUD, 2022), to ensure names and time periods for each unit are formalised and up to date. Seismic horizon picks were interpolated into continuous 3D sheets representing the location and depth of the stratigraphic units, which were then made into maps and regional cross-sections (Figures 2 and 4–6).

The 3D seismic stratigraphic model was developed from numerous datasets including 23 wells and over 10 000 km of onshore and offshore 2D seismic data (Table 1) collected over the last few decades and archived in the publicly available National Offshore Petroleum Information Management System (NOPIMS, 2022) and Western Australian Petroleum and Geothermal Information Management System (WAPIMS, 2022) databases. All the wells within the offshore Canning Basin were selected for use in this study; however, many well datasets could not be incorporated into the 3D model because they were either not available prior to 2018 at the initiation of the project, or they had either incomplete or missing data (such as depth–time models and velocity profiles) (Table 1). Seismic lines were visually checked for quality control (resolvable reflectors, minimal artefacts, positioning), then those that directly intersected wells and linked between wells, and provide reasonable coverage across the study area were chosen (Table 1). These seismic surveys have been previously reprocessed multiple times since their acquisition and as such, no further reprocessing was undertaken, and all surveys were brought into the same coordinate system (UTM 51 S) compatible with OpendTect (an open-source 3D data visualisation and seismic horizon mapping tool) using RadExPro. Once all the seismic and well data were imported into OpendTect, the 'Tie Well to Seismic' function was used to correlate the well data to the seismic data. This function uses sonic and density well logs to generate a synthetic seismic trace for the well, which was then aligned to the nearest seismic trace, thereby

**Table 1.** List of seismic surveys and wells used in this study with their respective year of acquisition.

| Seismic surveys | Year | Wells | Year |
|---|---|---|---|
| AGSO 119 M.S.S. | 1993 | Barlee 1 | 1960 |
| AGSO 120 M.S.S. | 1993 | Bedout 1 | 1971 |
| AGSO 136 M.S.S. | 1994 | Corbett 1 | 1994 |
| Aratoo M.S.S. | 1997 | Crab Creek 1 | 1987 |
| Browse 2001 M.S.S. | 2001 | East Crab Creek 1 | 1984 |
| L205 Canning Coastal S.S. | 2014 | Fraser River 1 | 1956 |
| Dampier Well Tie M.S.S. | 1995 | Hannover South 1 | 2014 |
| F78A S.S. | 1979 | Hauy 1 | 1972 |
| F79A M.S.S. | 1979 | Hilltop 1 | 1987 |
| Lambert Shelf M.S.S. | 1980 | Kambara 1 | 1982 |
| Leveque Shelf M.S.S. | 1998 | Lacapede 1 | 1970 |
| Lower Fitzroy S.S. | 1967 | Lagrange 1 | 1983 |
| Mandora S.S. | 1970 | Leveque 1 | 1970 |
| Northcliffs S.S. | 1974 | Minjin 1 | 1984 |
| Offshore Fitzroy Graben M.S.S. | 1988 | Moogana 1 | 1980 |
| Radii Hill S.S. | 1985 | Padilpa 1 | 1987 |
| Waterbank S.S. | 1982 | Pearl 1 | 1983 |
| Wyla M.S.S. | 2001 | Perindi 1 | 1983 |
| Yulleroo South S.S. | 2010 | Pittston SD 1 | 1992 |
| Zeester M.S.S. | 2012 | Tappers Inlet 1 | 1971 |
| | | Ungani 1 | 2011 |
| | | Wamac 1 | 1973 |
| | | Yulleroo | 1967 |

shifting the length of the well more reliably than an isolated depth–time model.

Interpreted seismic horizons were interpolated across the study area using a minimum curvature spline with a tension factor of 0.75 (Smith & Wessel, 1990). Interpolation produced a series of horizons that displayed the approximate location and depth of strata continuously across the Canning Basin onshore–offshore transition. Interpolated surfaces were bound by the seismic picks they were derived from, which ensures the surfaces do not appear in areas with no data. Interpolation was especially useful for areas that lacked sufficient seismic and well data for seismic stratigraphic mapping, but the interpolations in these areas are less accurate. Interpolated horizon depths are reported in two-way travel time (TWT) as a time–depth conversion would introduce errors owing to the large size of the study area and comparatively sparse distribution of wells. The stratigraphy was summarised from regional cross-sections that intersected key horizons along the onshore and offshore Canning Basin and from the onshore Fitzroy Trough through to the edge of the Roebuck Basin. Paleozoic stratigraphic units examined in this study include the Ordovician Nambeet Formation, Willara Formation, Goldwyer Formation, Ordovician–Silurian Carribuddy Group, Devonian Reef Complex, Carboniferous Fairfield Group, Anderson Formation and Reeves Formation, and the Permian Grant Group, Noonkanbah Formation and Liveringa Group (Smith *et al.*, 2013). Mafic igneous unit distribution and the top Mesozoic horizon were also examined.

## Seismic mapping results

Seismic horizons include the conformable and unconformable tops of each unit to show their shallowest presence and for more data-rich interpolations. The interpolated 2D seismic horizon picks are presented as continuous surfaces on a series of maps for each stratigraphic unit (Figures 4–7). Included with the interpolated horizons are the top well intersection depths to provide context for unit depths in metres (Table 2). The results are presented in stratigraphic order from oldest to youngest with the North West Shelf mafic magmatic province (MMP) appearing last. The stratigraphy is summarised in three regional cross-sections that run NE–SW onshore and offshore, and NW–SE across the onshore–offshore transition (Figure 2 and 5). Full extents of the mapped units can be found in the online data (https://doi.org/10.5281/zenodo.7336274; Yule *et al.*, 2022).

### Ordovician units

#### Nambeet Formation (Tremadocian–Dapingian)

The Nambeet Formation is the lowest stratigraphic unit in this study and is predominantly sandstone with shale and carbonate. It was mapped in the onshore Canning Basin along the coastline (Figure 4a) with time ranges of 963–6215 ms in TWT, with the shallowest sections on the Broome Platform and Willara Sub-basin and deepest section in the Fitzroy Trough. Trends include along-strike horizon deepening from the Broome Platform into the Fitzroy Trough, flattening in the middle of the Fitzroy Trough, then becomes shallower along strike towards the Kimberly Block (Figure 5a). When imaged, the Nambeet Formation has a relatively strong seismic signal compared with other Ordovician units (Figure 3a), but it was difficult to map owing to thick cover, well data being absent offshore and poor seismic quality in some areas. Hence, the limited coverage across the study area.

This unit was interpreted in the well 'Tappers Inlet 1'; however, adjacent wells do not suggest the presence of Ordovician units at drilled depths at the well location (Figure 10). Additionally, the Tappers Inlet 1 Destructive Analysis report (Nicoll, 1971) states that 11 Ordovician aged conodonts were identified across three sections of the well but stipulates 'the conodonts recovered are not stratigraphically diagnostic and no refinement of the accepted ages of the rock units can be made'. Therefore, we are not confident with the Nambeet Formation interpretation for this well without quantitative geochronological data for verification.

The bottom of this unit was differentiated from crystalline basement using previous interpretations (AGSO, 2001; Hashimoto *et al.*, 2018), the basement map (Figure 2) and identification of deeper reflectors (Figure 3a), but the limited coverage prevents reliable thickness estimates. Owing to the lack of well data and quality of offshore seismic data, the crystalline basement could not be reliably mapped in seismic data, but the basement map (Figure 2) provides an estimate of its geometry.

#### Willara Formation (Floian–Dapingian)

For the first time, the carbonate dominated Willara Formation was mapped across the onshore–offshore

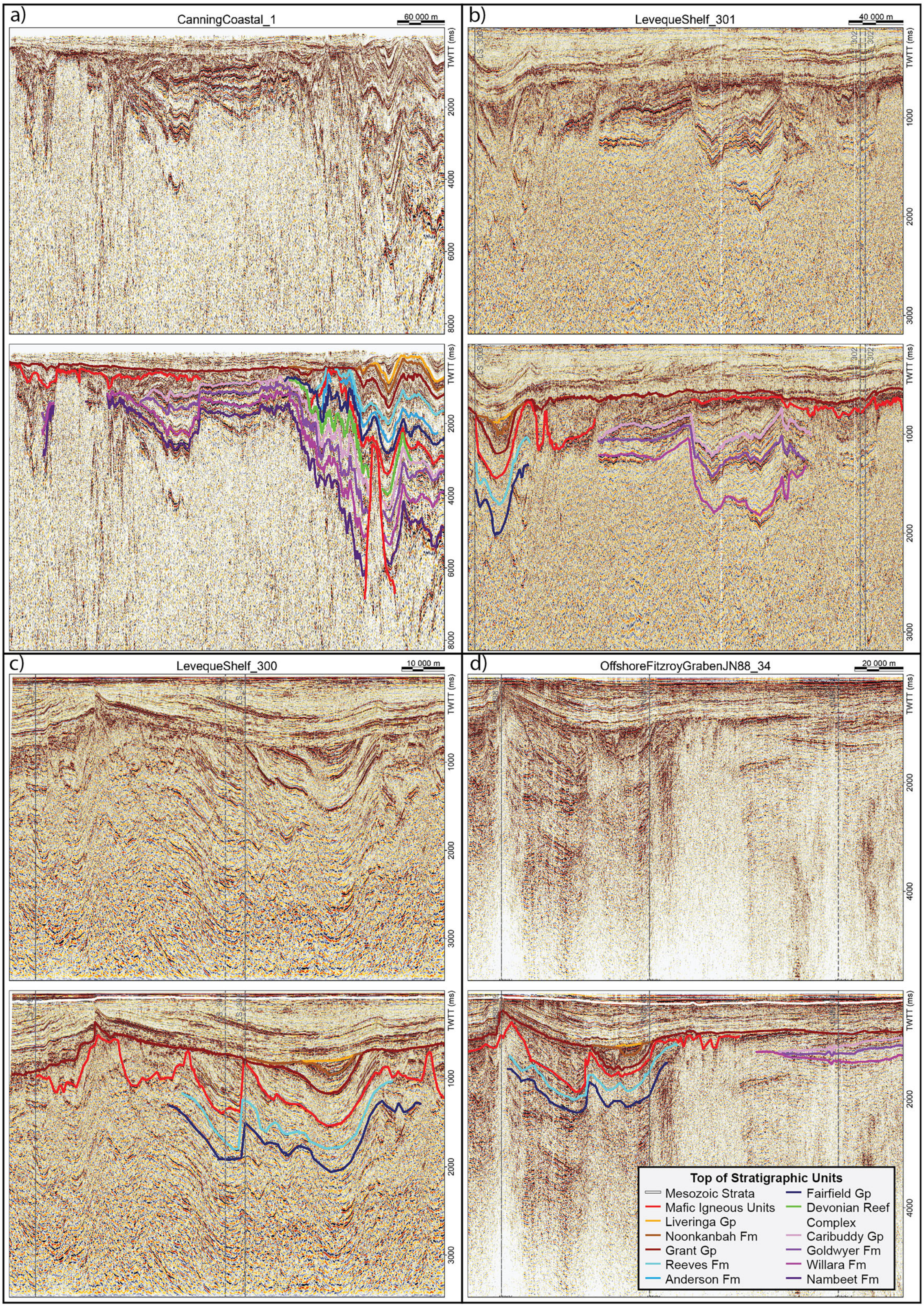


**Figure 3.** Some of the seismic interpretations used to make interpolated horizons. The horizons represent the top pick for each unit and are guided by well and seismic data. These seismic lines are labelled in Figure 1. All interpretations and full resolution seismic lines can be found in https://doi.org/10.5281/zenodo.5091392.

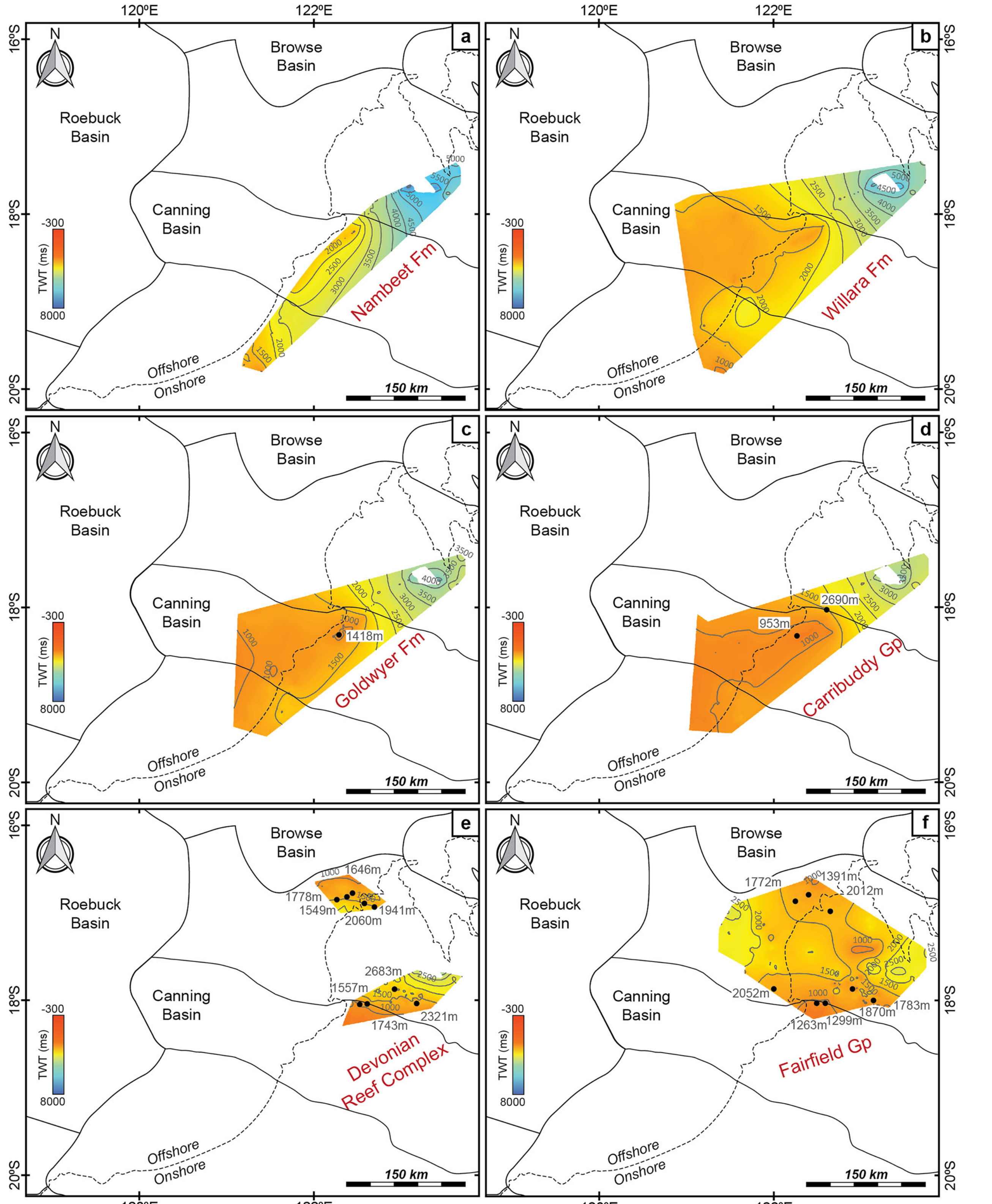


**Figure 4.** Interpolated horizons with well intersections of the: (a) Nambeet Formation; (b) Willara Formation; (c) Goldwyer Formation; (d) Carribuddy Group; (e) Devonian Reef Complex; and (f) Fairfield Group. Contours display elevation changes every 500 ms in two-way travel time (TWT) and well depths are in metres. Contours and well depths display the top intersections of each respective unit. These horizons represent the mapped extent of each unit, not the entire extent across the basin.

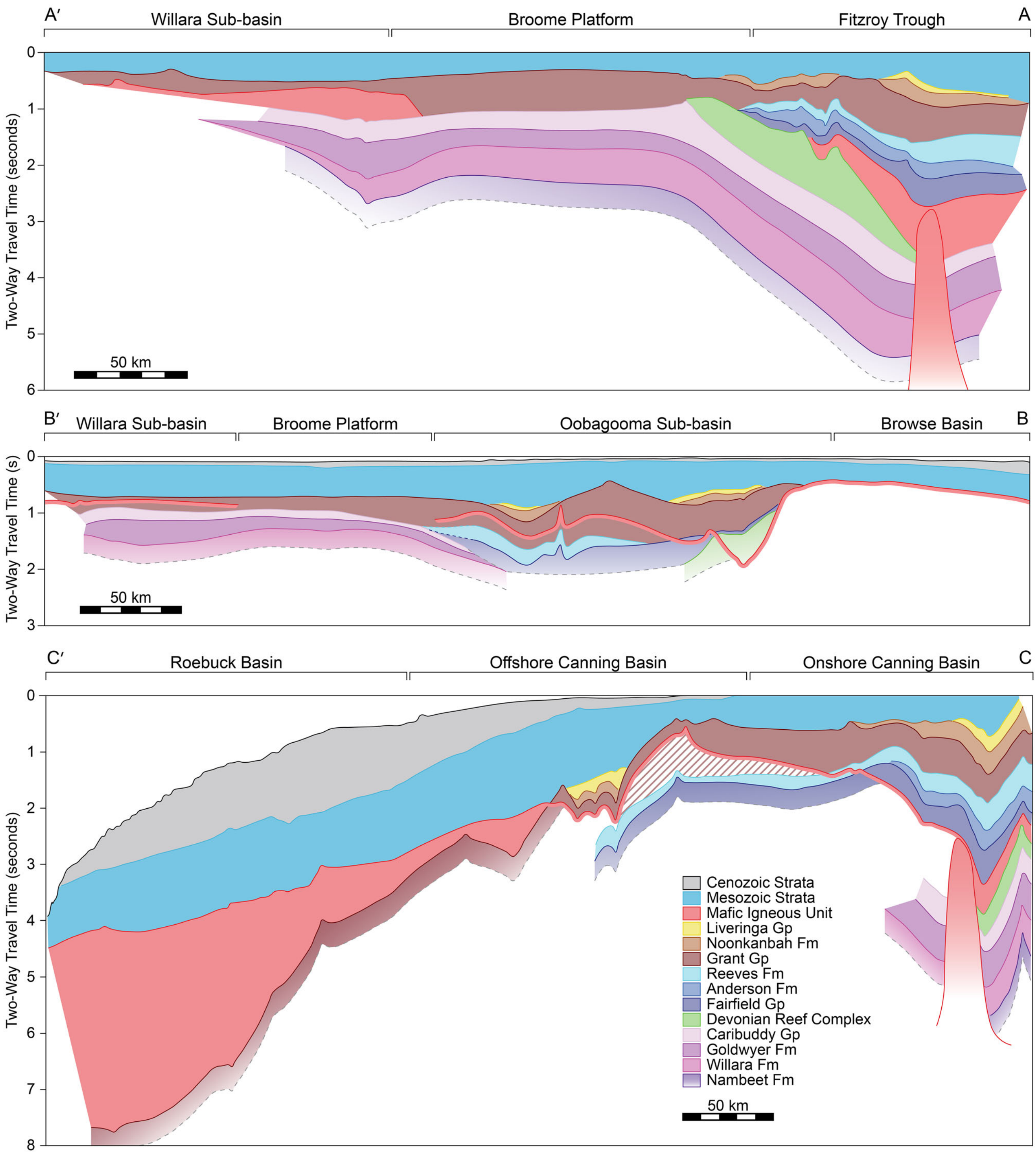


**Figure 5.** Regional cross-sections of the study area developed from interpolated horizons. The hatched pattern represents the potential location of the Grant Group where attenuation from the mafic igneous unit has impacted imaging. The vertical axis is consistent across all three cross-sections. Cross-section locations are displayed in Figure 2.

transition in the Canning Basin (Figure 4b; Yule & Spandler, 2022; supplementary material A: OffshoreFitzroy GrabenJN88_01). Time ranges are 754–5365 ms (TWT) with the shallowest and deepest portion in the offshore Canning Basin and Fitzroy Trough, respectively. This formation is the most widespread Ordovician unit and appears flat in the offshore Canning Basin and Broome Platform, but rapidly steepens along strike into the Fitzroy Trough. Onshore, it has a uniform thickness of ∼500 ms (TWT) but rapidly thins towards the centre of the Willara Sub-basin (Figure 5a). There is not enough offshore coverage to determine thickness trends because the crystalline basement and Nambeet Formation are not properly imaged.

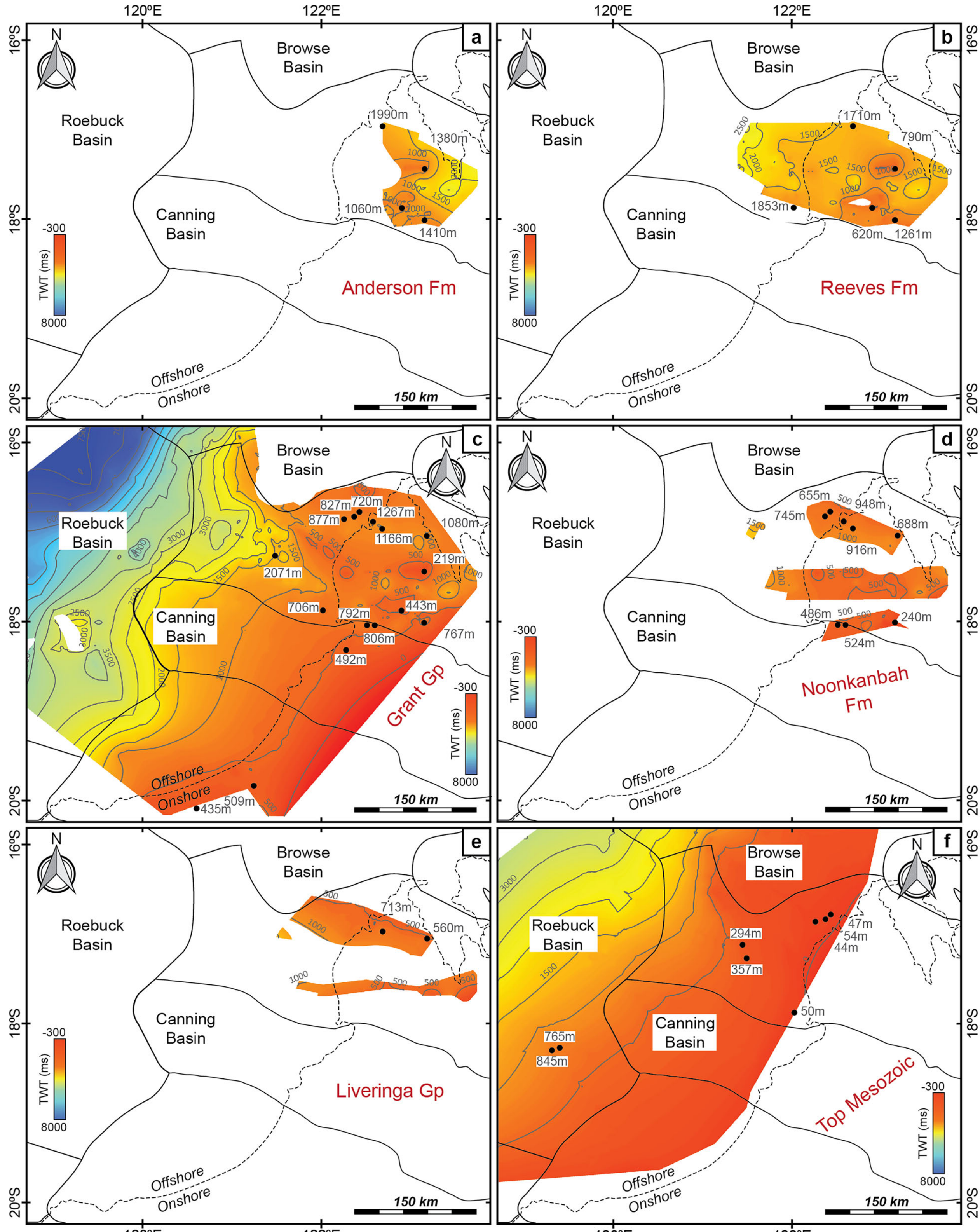


Figure 6. Interpolated horizons with well intersections of: (a) Anderson Formation; (b) Reeves Formation; (c) Grant Group; (d) Noonkanbah Formation; (e) Liveringa Group; and (f) Top Mesozoic. Contours display elevation changes every 500 ms in two-way travel time (TWT), and well depths are in metres. Contours and well depths display the top intersections of each respective unit. These horizons represent the mapped extent of each unit, not the entire extent across the basin.

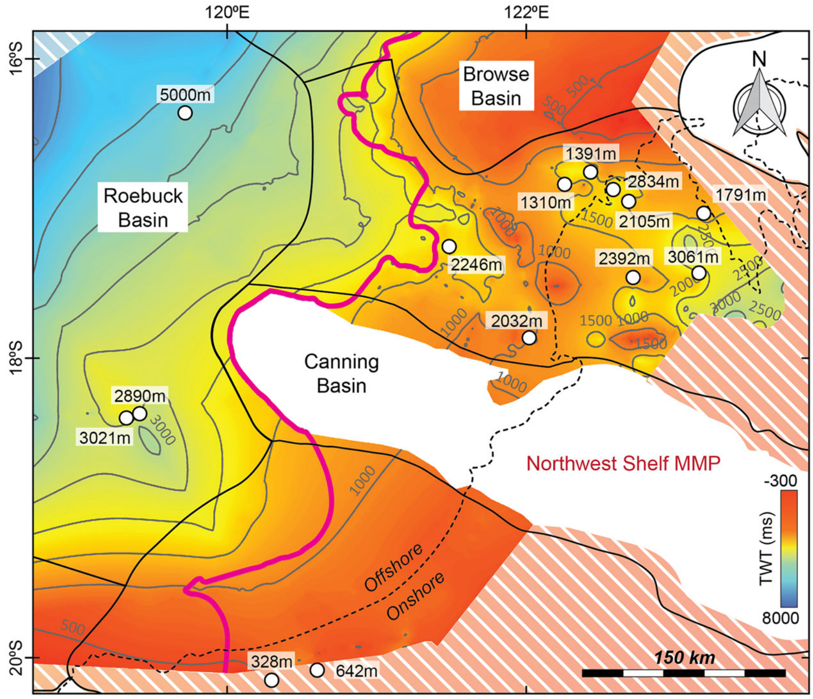


Figure 7. Interpolated horizon of the North West Shelf mafic magmatic province displaying its depth (Yule & Spandler, 2022). Contours display elevation changes every 500 ms in two-way travel time (TWT) and well depths are in metres. The purple line represents the transition from intrusive dolerites in the Canning Basin to extrusive basalts in adjacent basins. Contours and well depths display the top intersections of each respective unit.

### *Goldwyer Formation (Darriwilian)*

Another unit mapped from onshore to offshore in the Canning Basin for the first time is the mixed siliciclastic–carbonate Goldwyer Formation (Figure 4c). The Goldwyer Formation time range is 850–4702 ms (TWT), shallowest in the offshore Canning Basin and deepest in the Fitzroy Trough. It has similar seismic characteristics, dip and geometry to the Willara Formation except that it is shallower, covers a smaller extent and is thinner with a mostly consistent onshore thickness of ~350 ms (TWT) (Figure 5a).

### *Carribuddy Group (Darriwilian–Rhuddanian)*

The Carribuddy Group is the uppermost Ordovician unit and was mapped offshore for the first time during this study (Figure 4d). It consists of halite, mudstone and dolostone facies. The mapped time ranges for this unit are 673–4356 ms (TWT), with the shallowest part in the offshore Broome Platform and deepest in the Fitzroy Trough. The mapped extent, seismic characteristics, thickness (~350 ms TWT) and dip of the Carribuddy Group are very similar to the Goldwyer Formation but is a little shallower (Figure 5a).

### *Devonian Reef Complex (Frasnian–Famennian)*

This Devonian Reef Complex unit is an aggregation of all the limestone and carbonate units deposited during the Devonian, which is now mapped across the Canning Basin onshore–offshore transition (Figure 4e). The units that make up the Devonian Reef Complex include the Mellinjerie Limestone, Gogo Formation, Sadler Limestone, Pillara Limestone and Nullara Limestone. These units were aggregated together because they were not distinguishable in the seismic data. The time range for the top of the Devonian Reef Complex is 687–3966 ms (TWT), with the shallowest parts on the flanks of the Fitzroy Trough and is deepest within the Fitzroy Trough. In this study area, the Devonian Reef Complex is only found near the boundary of the Fitzroy Trough and the northern Oobagooma Sub-basin, but not in the centre of the Fitzroy Trough. The distribution of the Devonian Reef Complex splits this unit into northern and southern depocentres that have differing spatial trends. The southern component sharply deepens along strike into the Fitzroy Trough and both depocentres appear flat farther away from the Fitzroy Trough. The thickness of this unit is highly variable with a maximum thickness of ~1100 ms (TWT) in the southern part of Fitzroy Trough (Figure 5a). The Devonian Reef Complex also has unique seismic characteristics including high-amplitude reflectors relative to surrounding siliciclastic rocks and the appearance of large carbonate mounds (Yule & Spandler, 2022; supplementary material A: F78A_02).

## *Carboniferous units*

### *Fairfield Group (Famennian–Tournaisian)*

The Fairfield Group is the lowermost Carboniferous unit in the study area and is mapped across the Fitzroy Trough and Oobagooma Sub-basin (Figure 4f). It consists of units

**Table 2.** Well intersection depths for each stratigraphic unit pick generated in this study.

| Stratigraphic unit | Well | Depth (m) |
|---|---|---|
| Goldwyer Formation | Hilltop 1 | 1418 |
| Caribuddy Group | East Crab Creek 1 | 2690 |
| | Hilltop 1 | 953 |
| Devonian Reef Complex | Crab Creek 1 | 1557 |
| | East Crab Creek 1 | 1743 |
| | Kambara 1 | 1646 |
| | Minjin 1 | 1549 |
| | Moogana 1 | 2060 |
| | Perindi 1 | 1778 |
| | Tappers Inlet 1 | 1941 |
| | Ungani 1 | 2321 |
| | Yulleroo 1 | 2683 |
| Fairfield Group | Crab Creek 1 | 1263 |
| | East Crab Creek 1 | 1299 |
| | Kambara 1 | 1391 |
| | Moogana 1 | 2012 |
| | Pearl 1 | 2052 |
| | Perindi 1 | 1772 |
| | Ungani 1 | 1783 |
| | Yulleroo 1 | 1870 |
| Anderson Formation | Fraser River 1 | 1380 |
| | Moogana 1 | 1990 |
| | Ungani 1 | 1410 |
| | Yulleroo 1 | 1060 |
| Reeves Formation | Fraser River 1 | 790 |
| | Moogana 1 | 1710 |
| | Pearl 1 | 1853 |
| | Ungani 1 | 1261 |
| | Yulleroo 1 | 620 |
| Grant Group | Corbett 1 | 435 |
| | Crab Creek 1 | 792 |
| | East Crab Creek 1 | 806 |
| | Fraser River 1 | 219 |
| | Hilltop 1 | 492 |
| | Kambara 1 | 720 |
| | Minjin 1 | 827 |
| | Moogana 1 | 1166 |
| | Padilpa 1 | 1080 |
| | Pearl 1 | 706 |
| | Perindi 1 | 877 |
| | Pittston SD 1 | 509 |
| | Tappers Inlet 1 | 1267 |
| | Ungani 1 | 767 |
| | WAMAC 1 | 2071 |
| | Yulleroo 1 | 443 |
| Noonkanbah Formation | Crab Creek 1 | 486 |
| | East Crab Creek 1 | 524 |
| | Kambara 1 | 655 |
| | Minjin 1 | 745 |
| | Moogana 1 | 916 |
| | Padilpa 1 | 688 |
| | Tappers Inlet 1 | 948 |
| | Ungani 1 | 240 |
| Liveringa Group | Moogana 1 | 713 |
| | Padilpa 1 | 560 |
| Top Mesozoic | Bedout 1 | 845 |
| | Hauy 1 | 462 |
| | Kambara 1 | 47 |
| | Lacapede 1 | 294 |
| | Lagrange 1 | 765 |
| | Leveque 1 | 335 |
| | Minjin 1 | 54 |
| | Pearl 1 | 50 |
| | Perindi 1 | 44 |
| | WAMAC 1 | 357 |
| North West Shelf MMP | Barlee 1 | 2392 |
| | Bedout 1 | 3021 |
| | Corbett 1 | 328 |
| | Fraser River 1 | 3061 |
| | Hannover South 1 | 5000 |

(*Continued*)

Table 2. (*Continued*).

| Stratigraphic unit | Well | Depth (m) |
|---|---|---|
| | Hauy 1 | 805 |
| | Lagrange 1 | 2890 |
| | Leveque 1 | 896 |
| | Minjin 1 | 1391 |
| | Moogana 1 | 2105 |
| | Padilpa 1 | 1791 |
| | Pearl 1 | 2032 |
| | Perindi 1 | 1310 |
| | Pittston SD 1 | 642 |
| | Tappers Inlet 1 | 2834 |
| | WAMAC 1 | 2246 |

with mixed siliciclastic–carbonate composition. Its time ranges from 688 to 3062 ms (TWT) where it is shallowest on the boundary of the Fitzroy Trough and deepest on the eastern most section of the Fitzroy Trough and western most section of the Oobagooma Sub-basin. The Fairfield Group is generally deeper along the axis of the Fitzroy Trough but there is a shallow anomaly <1000 m depth that disrupts this trend (Figure 4f) and has a maximum thickness of ∼500 ms (TWT) but is varied (Figure 5a). It also does not have the most prominent seismic reflectors with lower-amplitude signals than other units (Figure 3c), hence interpretations were supported by well data.

### *Anderson Formation (Tournaisian–Serpukhovian)*

The Anderson Formation is a mixed siliciclastic–carbonate unit with a higher proportion of sandstone, siltstone and shale, and was found only within the Fitzroy Trough of the onshore Canning Basin (Figure 6a). It has a time range of 549–2511 ms (TWT) with the shallowest part on the southern end of the Fitzroy Trough and deepest part on the east section of the Fitzroy Trough. The mapped extent of the Anderson Formation is small compared with some of the other units in this study, but the general trend of this unit is that it deepens up-dip in the Fitzroy Trough. It has a maximum thickness ∼350 ms (TWT) but is generally thinner (Figure 5a). This unit was difficult to identify owing to its weak seismic signal (Figure 3a) and it may be present in other areas of the Canning Basin.

### *Reeves Formation (Serpukhovian–Bashkirian)*

Identified across the onshore–offshore transition (Figure 6b), the sandstone dominated Reeves Formation is the uppermost Carboniferous unit in this study. With a time range of 435–2684 ms (TWT), the shallow areas are in the southern Fitzroy Trough, and the deep areas are in the Oobagooma Sub-basin. The Reeves Formation gently deepens downdip onshore, but steeply deepens downdip into the offshore Canning Basin. It has a maximum thickness of ∼550 ms (TWT) on the northeastern end of the Fitzroy Trough but rapidly thins towards the Broome Platform (Figure 5a). Similar to the Anderson Formation, the Reeves Formation has weak seismic reflectors (Yule & Spandler, 2022; supplementary material A: YullerooSouth_11) that made mapping difficult, but the offshore well Pearl 1 made it possible for offshore mapping.

## Permian units

### Grant Group (Gzhelian–Asselian)

By far the thickest unit in this study, the Grant Group is mapped across the onshore Canning, offshore Canning, Browse, Roebuck and Northern Carnarvon basins (Figure 6c). It consists of several units composed of sandstone, siltstone, mudstone, diamictite and minor conglomerate. The Grant Group has a large time range where the top of the unit varies between −278 and –8074 ms (TWT), where it is above sea-level farther inland of the Canning Basin and deepest in the Roebuck Basin near the Argo Abyssal Plain. It is also thick, reaching up to ∼1000 ms (TWT); however, it may be thicker in the Roebuck Basin, but the lower boundary is unclear (Figure 5c). The Grant Group displays shallow dips in the Canning Basin, whereas it is steeply dipping in the Browse and Roebuck basins. There are more subtle trends including being found deeper in the Fitzroy Trough than in the rest of the Canning Basin and an anomaly in a depocentre southeast of the Bedout High. The Grant Group is not present where the Bedout High is prominent and on shallower parts of the Browse Basin. The Grant Group can be easily identifiable in seismic data because of its strong reflectors, and the top boundary is commonly marked by a regional-scale unconformity where it is unconformably overlain by Mesozoic strata (Figure 3a).

### Noonkanbah Formation (Sakmarian–Kungurian)

The Noonkanbah Formation is a siliciclastic unit with grain-size varying from conglomerate to mudstone. It has not previously been mapped offshore but is now mapped across the Fitzroy Trough and Oobagooma Sub-basin (Figure 6e). The top of this unit has a time range between 65 and 1734 ms (TWT) where it is shallowest south of the Fitzroy Trough and deepest in the Oobagooma Sub-basin. The maximum thickness reaches ∼350 ms (TWT) but is highly variable and commonly much thinner (Figure 5c). The Noonkanbah Formation is split into three major parts and a minor part in a small depocentre offshore (Figure 6e). This formation is relatively flat but is steeper downdip in the southernmost part. The Noonkanbah Formation does not have the strongest reflectors but has been drilled by several wells, which has assisted mapping. It is generally absent above the Grant Group (Yule & Spandler, 2022; supplementary material A: LowerFitzroy04), which is likely due to erosion as marked by a regional unconformity (Figure 5).

### Liveringa Group (Roadian–Changhsingian)

Similar to the Noonkanbah Formation, the Liveringa Group is now mapped offshore across the Fitzroy Trough and Oobagooma Sub-basin (Figure 6e). The Liveringa Group is compositionally a little different from the Noonkanbah Formation, consisting of sandstone, siltstone and shale. The Liveringa Group is slightly shallower at 118–1569 ms (TWT) time where it is shallowest at the boundary of the Fitzroy Trough and deepest towards the centre of the Oobagooma Sub-basin. The maximum thickness is ∼300 ms (TWT) but it is commonly much thinner (Figure 5c). Erosional unconformities (Figure 5a, b) and a small depocentre offshore (Figure 5c), has split this unit into two major parts that gradually become deeper downdip towards the centre of the Oobagooma Sub-basin (Figure 6e). The seismic characteristics and trends of the Liveringa Group are similar to those of the Noonkanbah Formation, but it is not found on the southern Fitzroy Trough.

## Mesozoic

The top Mesozoic horizon is found across the offshore Canning, Browse, Roebuck and Northern Carnarvon basins and represents the surface of the coastal onshore Canning Basin (Figure 6f). It is shallowest near the coastline and deepest towards the Argo Abyssal Plain with a time range of −71.6–4353 ms (TWT). The top Mesozoic horizon has a very low dip in the downdip direction in the offshore Canning Basin and southern Browse Basin, but the dip increases at a consistent rate farther offshore (Figure 5c). Offshore, the top Mesozoic horizon is identifiable from high amplitude reflectors and unconformities and because it is shallow, the reflector is higher resolution than lower units (Yule & Spandler, 2022; supplementary material A: AGSO119_12). Intersections of several offshore wells greatly assisted with mapping (Figure 6f). The maximum thickness measured in this study is ∼1500 ms (TWT). This large thickness value is due to the addition of the many Mesozoic strata that comprise this unit. Strata above the Mesozoic horizon are Cenozoic and found exclusively offshore because it is likely Cenozoic strata were eroded from the onshore Canning Basin and deposited offshore.

## Mafic igneous units

A suite of mafic igneous rocks consisting of several units, comprise the North West Shelf MMP. These igneous rocks have age ranges from 336 ± 2 Ma to 163 ± 13 Ma derived from a variety of geochronological techniques (Yule & Spandler, 2022). The aggregation of mafic igneous units were mapped across the onshore Canning, offshore Canning, Browse, Roebuck and Northern Carnarvon basins (Figure 7). The time range of the North West Shelf MMP is 172–5865 ms (TWT) where it is shallowest on the southern Browse Basin and northeast Northern Carnarvon Basin and deepest towards the Argo Abyssal Plain. The maximum thickness of the mafic lava delta system in the Roebuck Basin is ∼3700 ms (TWT) (Figure 5c). This thickness is consistent with other studies including MacNeill *et al.* (2018) and Rollet, Shi, *et al.* (2019). The thickest section that has

Table 3. Summary of top well depths for each unit in this study and the maximum thickness of each unit as described in the Australian Stratigraphic Units Database (ASUD, 2022).

| Unit | Min top well depth (m) | Max top well depth (m) | Max thickness (m) | Smith *et al.* (2013) | This study |
|---|---|---|---|---|---|
| Nambeet Formation | – | – | 800 | Unknown | Unknown |
| Willara Formation | – | – | 838 | Unknown | Identified |
| Goldwyer Formation | – | 1418 | 750 | Unknown | Identified |
| Carribuddy Group | 953 | 2690 | 1591 | Unknown | Identified |
| Devonian Reef Complex | 1549 | 2683 | ~1800 | Identified | Identified |
| Fairfield Group | 1263 | 2052 | 900 | Identified | Identified |
| Anderson Formation | 1060 | 1990 | 1800 | Unknown | Unknown |
| Reeves Formation | 620 | 1853 | 2000 | Unknown | Identified |
| Grant Group | 219 | 2071 | 2500 | Identified | Identified |
| Noonkanbah Formation | 240 | 948 | 650 | Unknown | Identified |
| Liveringa Group | 560 | 713 | 435 | Unknown | Identified |
| Mesozoic | 44 | 845 | – | Identified | Identified |
| Mafic Igneous Units | 328 | 5000 | Up to 10 000 | Identified | Identified |

Smith *et al.* (2013) and This study columns show whether the unit was identified or unknown in the offshore Canning Basin.

been drilled is ~500 m in Hannover South 1 and Anhalt 1 in the Roebuck Basin where they have been broadly described as 'weathered volcanics' in the well completion reports. Samples of mafic igneous units across the study area confirm that these rocks are either intrusive dolerites or extrusive basalts and mostly consist of plagioclase, pyroxene and magnetite (Yule & Spandler, 2022). Generally, the North West Shelf MMP is flat onshore and near the coastline, and the dip steepens downdip. However, it is anomalously deeper in the Fitzroy Trough (which hosts a ~3.5 second [TWT] thick and ~40 km wide intrusion; Figure 5a, c), shallower on the Bedout High, and absent on the Broome Platform. Mafic igneous units are easily identifiable from seismic reflectors that are generally much stronger than the surrounding sedimentary rocks and feature strong signal attenuation below (Figure 3; Yule *et al.*, 2022).

## Discussion

### *Stratigraphy*

Of the 13 units mapped in this study, only four have been previously mapped offshore (Smith *et al.*, 2013). This study includes the first offshore mapping for seven of these units in published literature, totalling 11 units mapped offshore and leaving only two units unidentified in the offshore domain (Table 3). The apparent absence of Paleozoic strata offshore (Smith *et al.*, 2013) gave the impression that the Canning Basin offshore stratigraphy differs significantly from the onshore stratigraphy. Regional stratigraphic changes from onshore to offshore are summarised in Figures 8 and 9 from the regional mapping. From these results, we demonstrate the stratigraphy across the Canning Basin onshore–offshore transition is similar (Figures 4–9), but there are some differences. Generally, strata offshore are deeper than they are onshore (Figures 4, 5a and 6). Offshore, Ordovician units are found on the Broome Platform, but they are absent in the Oobagooma Sub-basin (Figure 4), whereas all of the younger units (except the Anderson Formation) are interpreted in the Oobagooma Sub-basin, but are mostly absent from the Broome Platform (except for the Grant Group and Top Mesozoic units) (Figures 4 and 6). Onshore in the Fitzroy Trough, most sedimentary sequences from the Ordovician through to the Cretaceous are visible in the Coastal Canning Basin Deep Reflection Seismic Survey (Figure 3a). However, offshore Ordovician–Devonian units are mostly absent (Figure 5b), which could be due to attenuation by thick mafic igneous units (Yule *et al.*, 2022), tectonism or the quality of the offshore seismic data (Figures 4–6). Higher-quality seismic data are needed to better confirm the positioning of strata more extensively across the offshore Canning Basin. With the data available and results presented herein, we discuss notable stratigraphic features, changes and trends across the study area ordered from oldest units to youngest.

Ordovician units are laterally continuous across the onshore Canning Basin as seismic stratigraphic mapping from this study indicates (Figures 3a and 5a). Previous studies have not differentiated Ordovician units in the Fitzroy Trough (Figure 8; Hashimoto *et al.*, 2018; Mory & Hocking, 2011; Smith *et al.*, 2013; Yeates *et al.* 1984). This study provides the first maps of Ordovician units found in the offshore Canning Basin (Figures 4 and 5b). Ordovician units in the offshore Willara Sub-basin and Broome Platform near the coastline are thin and disappear towards the Oobagooma Sub-basin (Figure 4a–d). These trends could be a result of a variety of factors including: an unconformity that eroded Ordovician strata, poor seismic data quality that fails to image Ordovician units in deep depocentres such as the Oobagooma Sub-basin (Figures 5b and 9) or strong seismic signal attenuation caused by overlying mafic igneous units that prevents deeper imaging (Cortez & Cetale Santos, 2016; Eide *et al.*, 2017; Sun *et al.*, 2010). It is likely a combination of poor seismic data quality and attenuation from mafic igneous units have prevented further mapping of Ordovician strata. Seismic surveys such as the Coastal Canning Basin Deep Reflection Seismic Survey (Figure 3a) were acquired to image deep strata at high resolution

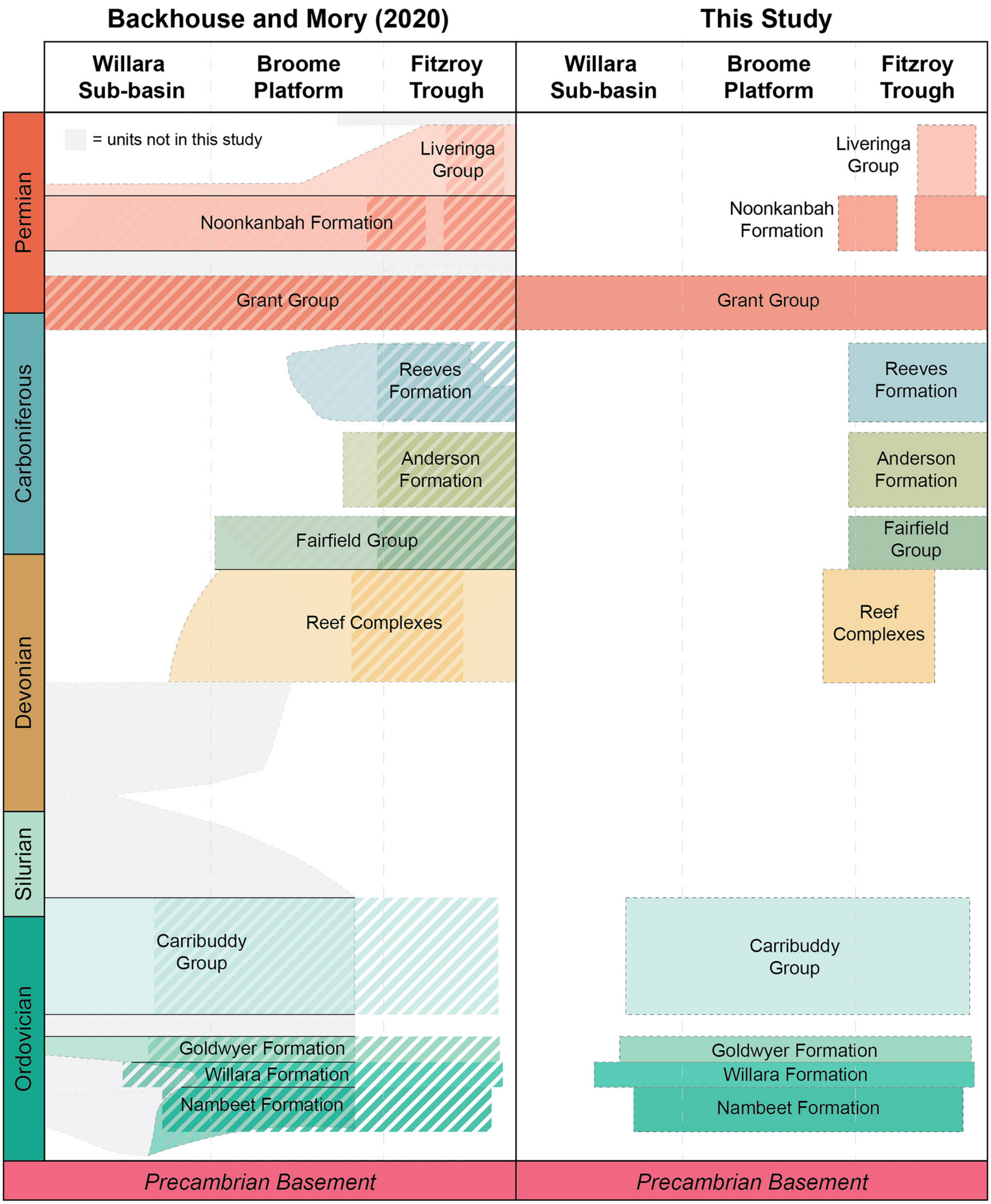


**Figure 8.** Comparison of basin-scale Paleozoic chronostratigraphy of Backhouse and Mory (2020) with the onshore cross-section presented in this study (Figures 2 and 5a). The highlight is the addition of Ordovician units within the Fitzroy Trough. The grey Paleozoic units were not mapped in this study because they were not resolvable in seismic data, they appeared in enough well logs or they were prominent in other mapping studies. Mapping results from this study are not to replace existing basin stratigraphy, but rather to add to geological understanding of the Canning Basin.

and successfully imaged Ordovician units in the study area. Thus, Ordovician units may be present in the Oobagooma Sub-basin and other parts of the Canning Basin but have yet to be imaged or drilled.

The Canning Basin is famous for its Devonian reef systems and there are many carbonate units, including the Mellinjerie Limestone, Luluigi Formation, Clanmeyer Siltstone, Gogo Formation, Pillara Sequence, Virgin Hills

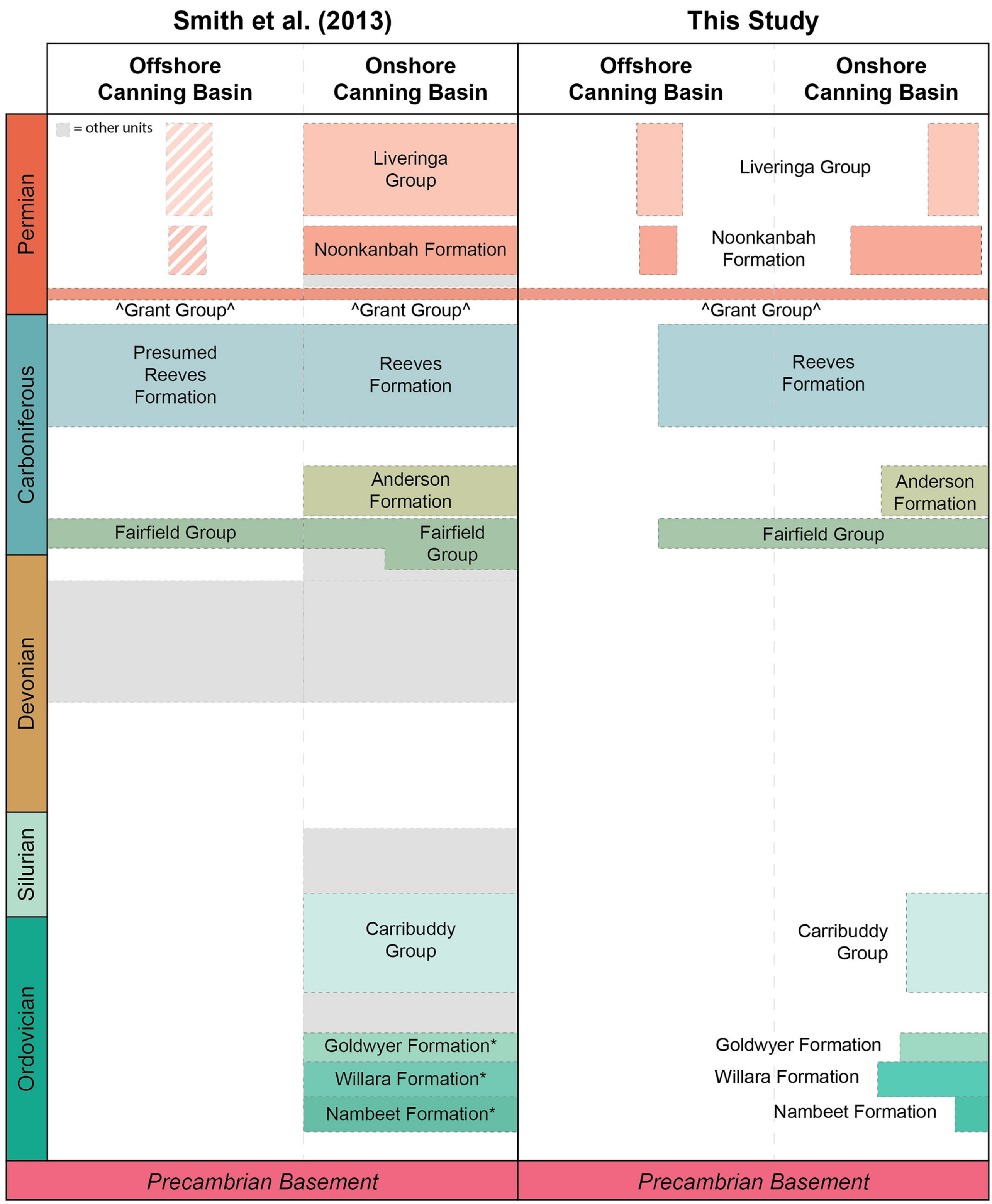


**Figure 9.** Comparison of basin scale onshore–offshore Paleozoic chronostratigraphy of Smith *et al.* (2013) with the onshore–offshore cross-section presented in this study (Figures 2 and 5c). The grey Paleozoic units were not mapped in this study because they were not resolvable in seismic data, they appeared in enough well logs or they were prominent in other mapping studies. *Possible strata location.

Formation and Nullara Sequence (Smith *et al.*, 2013). For simplification, these units were grouped together and mapped as the 'Devonian Reef Complex' in this study. The Devonian Reef Complex is present throughout the Fitzroy Trough but appears to pinch out with shallowing basement near the coastline in the Oobagooma Sub-basin (Figures 4e and 5c) and towards the Broome Platform (Figures 4e and 5a). The Devonian Reef Complex is bounded by major

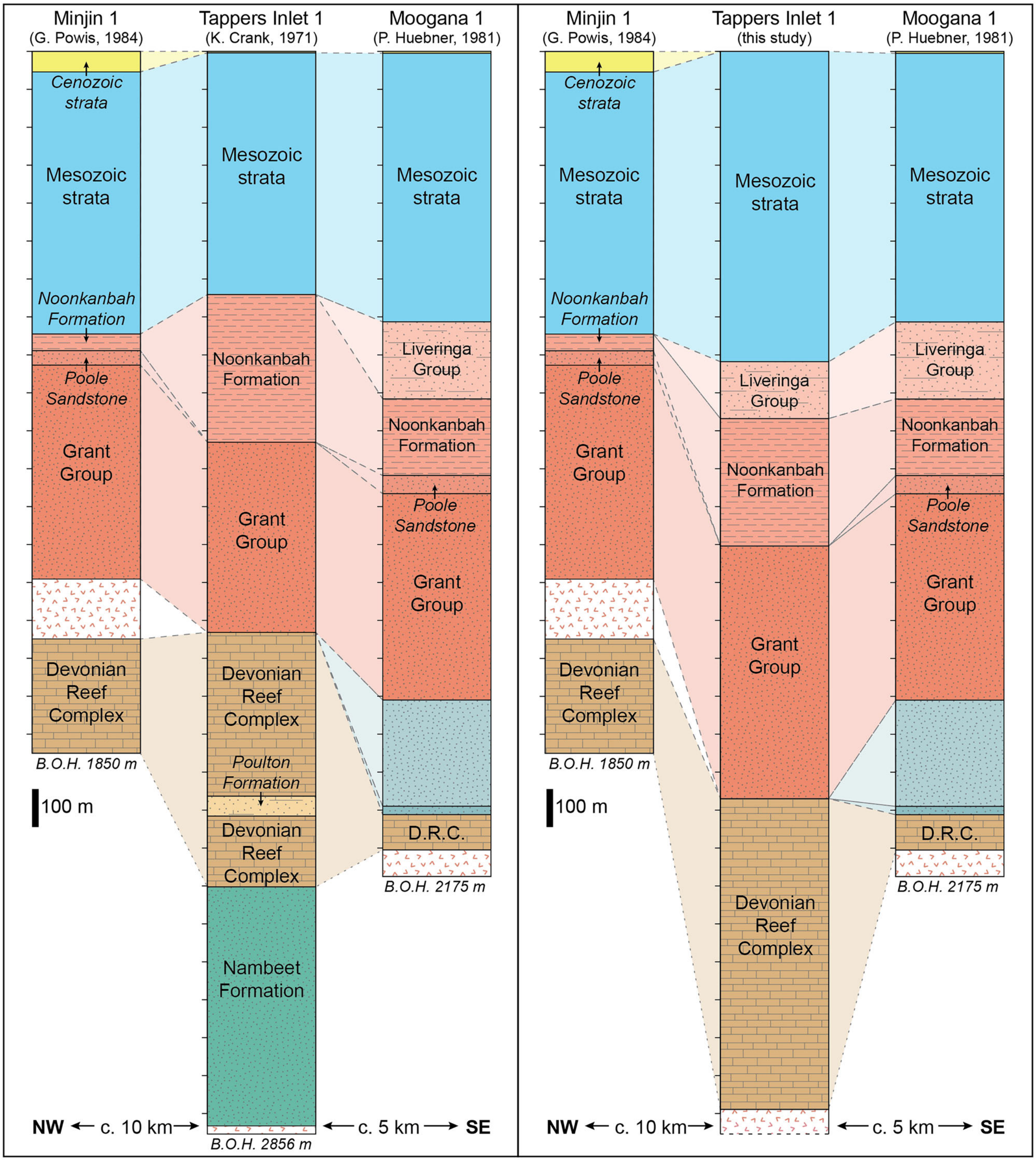


**Figure 10.** Lithostratigraphic representation of lithological logs from wells Minjin 1, Tappers Inlet 1 and Moogana 1. The left side is what was originally recorded in the well lithological logs, and the right side includes adjustments for Tappers Inlet 1 based on seismic stratigraphic interpretations from this study (Yule & Spandler, 2022; supplementary material A: F78A_02). Formation picks may differ from those of other studies (Backhouse & Mory, 2020; Mory, 2010) because this study combines seismic mapping results with well lithological logs.

unconformities on both upper and lower boundaries in the Willara Sub-basin and Broome Platform (Figures 4–6; Smith *et al.*, 2013). This is likely due to the Rodingan Movement (Craig *et al.*, 1984; Keep *et al.*, 2007) and Cimmerian Block rifting (Li & Powell, 2001; Matthews et al., 2016; Müller *et al.*, 2005) tectonic events preceding and following deposition, respectively. From stratigraphic relationships surrounding the Devonian Reef Complex, three broad Paleozoic mega sequences can be delineated into Ordovician, Devonian and Carboniferous–Permian groupings derived from regional-scale unconformities.

Carboniferous units, including the Fairfield Group, Anderson Formation and Reeves Formation, are only present in the Fitzroy Trough and Oobagooma Sub-basin

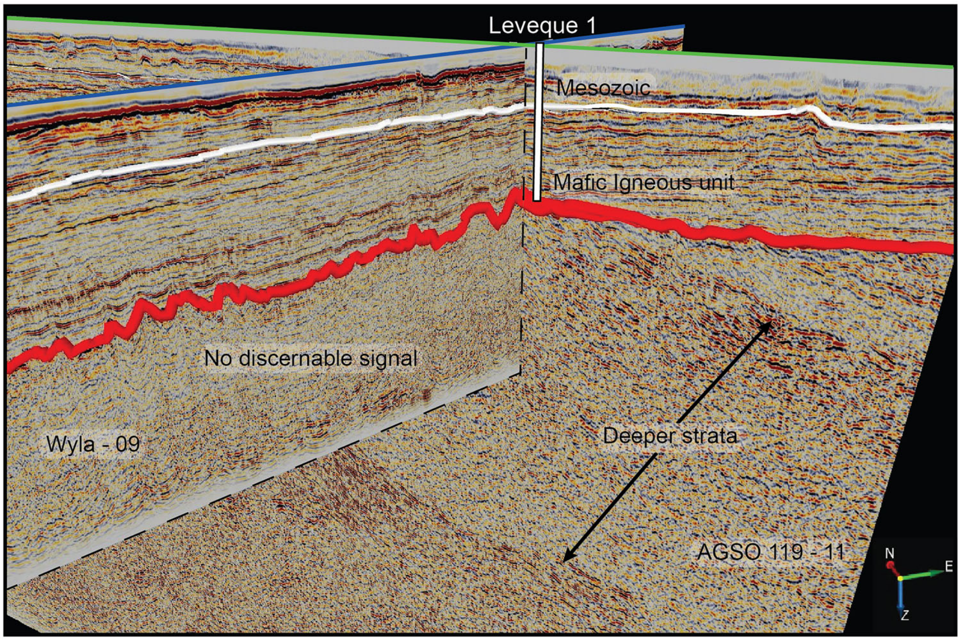


**Figure 11.** Leveque 1 well intersecting a mafic igneous unit in the AGSO 119 and Wyla 2D seismic surveys. The well report suggests the mafic igneous unit is basement. However, the AGSO survey reveals sedimentary horizons below the mafic igneous unit.

(Figures 4f and 6a, b). This is a consequence of sag subsidence that deepened the basement of these areas to create accommodation space for these units to deposit and erosion that caused unconformities outside the Fitzroy Trough (Keep *et al.*, 2007). Carboniferous units are bound by unconformities at the edges of the Fitzroy Trough and Oobagooma Sub-basin (Figure 5a, b), but owing to poor seismic quality offshore, it is unclear how these units interact with other strata towards the Roebuck Basin (Figure 5c).

The Permian Grant Group is the only stratigraphic unit present throughout the entire study area (Figure 6c). Mapping of the Grant Group demonstrates the continuity of strata across the onshore and offshore Canning Basin. The lower boundary of the Grant Group has a consistent unconformity across the Canning Basin that ranges from *ca* 80 Ma to *ca* 7 Ma (Smith *et al.*, 2013) likely due to erosion caused by the Cimmerian Block rift (Li & Powell, 2001; Matthews et al., 2016; Müller *et al.*, 2005). Stratigraphically higher Permian units mapped in this study, the Noonkanbah Formation (Figure 6d) and Liveringa Group (Figure 6e), are only found in the Fitzroy Trough and Oobagooma Sub-basin. These two units are preserved in sag structures, and the upper boundary appears to be strongly eroded by the Permian–Triassic unconformity caused by the Fitzroy Movement (Figure 5; Laurie *et al.*, 2016; Totterdell *et al.*, 2014; Yeates *et al.*, 1984).

Cenozoic and Mesozoic strata thicken from the coastline outboard towards the continental shelf edge (Figure 5c). Onshore Mesozoic strata are typically ∼300 ms (TWT) thick (Figure 5a) but thicken up to ∼1500 ms (TWT) on the continental shelf edge in the Roebuck Basin (Figure 5c). The Roebuck Basin initiated from late Carboniferous to early Permian extension, which led to the rifting of the Cimmerian Block in the late Permian (Smith *et al.*, 1999). Hence, no Ordovician to mid-Carboniferous strata were identified in the Roebuck Basin (Figure 4), but it hosts more Mesozoic and Cenozoic strata than the Canning Basin (Figure 6f).

Owing to widely spaced, regional-scale 2D seismic mapping, it was not in the scope of this project to map individual petroleum system elements, such as source, seal and reservoir units, and detail barriers to migration pathways from depocentres. Rather, inferences are drawn from the available geological data as to the likelihood of source rocks being present in the mapped extents of the 13 units. From this work, it is postulated that seven of these Paleozoic units may contain some hydrocarbon potential in the onshore–offshore transition including the Nambeet Formation, Goldwyer Formation, Devonian Reef Complex, Fairfield Group, Noonkanbah Formation and Liveringa Group. Having said this, it is difficult to ascertain the hydrocarbon potential of these units owing to the lack of well data and mapped source rock quality, which are prerequisites to defining an effective petroleum system.

### *Regional cross-sections*

Regional cross-sections illustrate the relationships between units and provide an accessible summary of the stratigraphy (Figure 5). Generally, the deepest depocentres have the greatest number of mappable units, which is particularly true for the Fitzroy Trough, Oobagooma Sub-basin and Roebuck Basin (Figures 2 and 5a, c). However, the lack of seismic and well data in deep, frontier areas like the Willara Sub-basin has prevented detailed seismic stratigraphic mapping, which is why fewer units are mapped in this depocentre, and their coverage is missing from Figures 4 and 6. All units featured in this study were mappable in the Fitzroy Trough but were not as apparent and mappable in the connecting Oobagooma Sub-basin (Figures 3 and 4), which may be due to offshore data quality (Figure 6a, c). Regional stratigraphic changes from onshore to offshore are well imaged and mappable above the Grant Group but tend to be poorly imaged below this level owing to reduction in seismic signal quality (Figure 5b, c). One such change successfully mapped regionally from onshore to offshore is the thickening of Mesozoic and Cenozoic strata from the Canning Basin to the Roebuck Basin, until they terminate against the continental slope (Figure 5c).

There is a significant unconformity between the Carribuddy Group and Grant Group on the Broome Platform (Figures 5a, b and 8). This unconformity represents a *ca* 150 Ma time gap (Smith *et al.*, 2013) owing to erosion on the Broome Platform (which has a shallower basement) as a result of the Rodingan Movement, which uplifted strata in the Devonian (Craig *et al.*, 1984). The Grant Group records another unconformity, but on its upper boundary with Mesozoic strata. This unconformity is regionally extensive (Figure 5) with a varying time gap depending on the depocentre. The Permian–Mesozoic unconformity on the Broome Platform has the maximum time gap representing *ca* 135 Ma (Smith *et al.*, 2013), which is similar to the Ordovician–Permian unconformity in the same depocentre. Additionally, the same unconformity has a lower time gap of *ca* 55 Ma (Smith *et al.*, 2013) in the Oobagooma Sub-basin where there is a larger depocentre to host more strata (Figure 2). This Permian–Mesozoic unconformity may have developed from the Fitzroy Movement, which caused regional uplift (Totterdell *et al.*, 2014). There are several other instances of unconformities such as Devonian and Carboniferous strata onlapping the Broome Platform (Figure 5a, b), the Noonkanbah Formation and Liveringa Group onlapping and downlapping the Grant Group (Figure 5), and non-conformities caused by igneous intrusions and volcanics throughout the study area (Figures 5 and 7).

The mafic igneous units have distinct spatial trends compared with sedimentary units. The igneous units transition from intrusive in the Canning Basin to extrusive in adjacent basins (Yule & Spandler, 2022; Figures 5 and 7). The intrusive units are always either underneath or within the Grant Group, cut across strata and much thinner than the extrusive mafic units, which always cover the Grant Group (Figure 5) and rapidly thicken towards the Argo Abyssal Plain (Figure 5c). There is also a ~3.5 second (TWT) thick and ~40 km wide intrusion in the Fitzroy Trough that cross-cuts Ordovician and Devonian units (Figure 5a, c) that is expressed in the basement map (Figure 2) and gravity and magnetic geophysical datasets (Yule, 2021).

### *Well correlations*

Ordovician units such as the Nambeet and Willara formations were difficult to map because they have never been drilled in this study area (Hashimoto *et al.*, 2018; Totterdell *et al.*, 2014). The other Ordovician units in this study, the Goldwyer Formation and Carribuddy Group, have been intersected by Hilltop 1, which provides significantly more mapping confidence than the lower Ordovician units.

Seismic stratigraphic mapping reveals that some wells used to ground truth the 3D model contain errors in the lithological logs. This was determined by using adjacent wells, seismic data, previous interpretations (*e.g.* Hashimoto *et al.*, 2018; Totterdell *et al.*, 2014) and the stratigraphic columns of Mory and Hocking (2011) and Smith *et al.* (2013). The lithological log from Tappers Inlet 1 does not match the logs from the nearby Padilpa 1, Moogana 1, Minjin 1, Kambara 1 and Perindi 1 wells, as indicated by seismic horizon mapping (Figure 10). Tappers Inlet 1 appears to have the greatest discrepancy where the lithological log has interpreted Ordovician units, and yet these are not intersected in the nearby wells, the stratigraphic column of Smith *et al.* (2013) makes no mention of in this area, and there is no mechanism for a potential unconformity of this scale. Tappers Inlet 1 was drilled in 1971 when data were limited, and only small samples/wall plugs were taken. In this study, we updated the lithological log for Tappers Inlet 1 from our seismic interpretations, which better reflect the geology (Figure 10). For example, we interpret the Grant Group to be ~274 m deeper than originally picked and the Nambeet Formation no longer in this well.

Thorough seismic stratigraphic mapping and analysis of well data revealed that well use is most effective when directly intersecting a seismic line. Whereas stratigraphy can vary significantly across distances of ~10 km as illustrated in Figure 10. It is industry practice to apply well data to seismic interpretations from >10 km away (Hashimoto *et al.*, 2018). The approach adopted in this study was to ensure each well was intersected by a seismic line (Figure 1) to facilitate direct interpretations.

### *Mafic igneous units*

The mafic igneous units are more continuous and widespread than previously suggested (Yule & Spandler, 2022). Our initial interpretation from this study hypothesised a widespread sheeted sill complex with dykes intruding into onshore and offshore Canning Basin strata. These intrusions may be part of a Large Igneous Province (LIP) plumbing system that would likely have formed during the rifting of the Cimmerian Block (Rollet, Shi, *et al.*, 2019; Yule & Spandler, 2022). An older LIP such as this would have had the surface basalts eroded away, leaving only a regional-scale unconformity and intrusions as evidence of the LIP (Ernst *et al.*, 2005; Wingate *et al.*, 2004; Xu *et al.*, 2014).

However, there is insufficient evidence to classify these observed mafic igneous units as an LIP, but rather anMMP (Yule & Spandler, 2022).

Widespread mafic igneous units, such as those from anMMP, can severely impact seismic imaging (Yule *et al.*, 2022; Yule & Spandler, 2022). The Canning Basin SEEBASE basement map (de Vries *et al.*, 2007; Frogtech, 2014) indicates the presence of significant sediment depocentres within the Browse Basin and Oobagooma Sub-basin (Figure 2) below mafic igneous units (Yule *et al.*, 2022). However, historical seismic datasets have not adequately imaged these systems (Figure 11). Mafic igneous units are known to be up to 500 m thick from drill core in the neighbouring Roebuck Basin, as drilled by Hannover South 1 (and Anhalt 1, which was not included in this study because it lacked the velocity data to include in the 3D model) and ∼10 000 m thick from geophysical data (MacNeill *et al.*, 2018; Rollet, Shi, *et al.*, 2019) and, as a result, have the potential to cause significant seismic signal attenuation owing to their relatively high acoustic impedance (Maresh *et al.*, 2006). Modern seismic reflection surveys may improve sub-igneous rock imaging, which could reveal hidden depocentres (Yule *et al.*, 2022). This could include imaging of Ordovician and Devonian units that could not be mapped with the historical regional seismic datasets, but which contain effective petroleum systems in the onshore Canning Basin (Figure 3).

Mafic igneous units in the offshore Browse, Roebuck and Northern Carnarvon basins are generally simple to trace in seismic data because they have continuous, strong reflectors with a consistent dip and downdip direction (Figure 7). Previous seismic interpretations (AGSO, 2001: latest Permian horizon representing some of the igneous units) suggest that strata above igneous units are largely parallel with the igneous units, which highlights a basin-wide unconformity where strata below the igneous units dip at a different angle offshore (Figure 5c). Compared with the aforementioned basins, seismic horizon mapping of igneous units in the Canning Basin was more difficult because of more chaotic seismic signals (Figures 3 and 7); however, collating seismic and well data into an integrated 3D model produced robust, large-scale interpretations across the onshore–offshore transition.

Minjin 1, Perindi 1 and Tappers Inlet 1 all intersected doleritic intrusions within a large carbonate mound composed of Devonian reef, but such intrusions are not emplaced within Mesozoic strata (Yule & Spandler, 2022; supplementary material A: F79A_22, LevequeShelf_111 and F78A_02) and so must be older than the Mesozoic. Additionally, all dolerite intrusions appear to be found either within or below the Grant Group (Figure 3). Typically, carbonate units such as the Devonian Reef Complex attenuate seismic reflection data (Kosa *et al.*, 2015; Schlager, 1981), but in this case, adjacent wells and seismic data confirm the presence of mafic igneous material below carbonates.

Interpretations of igneous units (consisting of the North West Shelf MMP) are consistent across the onshore–offshore transition as there is a prominent reflector from a disconformity that many of the wells signify the top of a mafic igneous unit (Figure 7). There is a clear distinction in the wells between true basement and the mafic unit, as the well BMR 04 A Mandora has intersected a granitic gneiss that was determined to be Precambrian (NOPIMS, 2022). Prominent seismic reflectors below mafic igneous units may be basement. For consistency, it is also important to consider where mafic igneous units are absent. Analysis of seismic and well data, including thermal maturation profiles, showed that mafic igneous rocks are not present on the Broome Platform (Yule & Spandler, 2022); however, further drilling and seismic acquisition are needed to better understand the location, geometry and composition of mafic igneous rocks across the Canning and Roebuck basins (Yule *et al.*, 2022).

## Conclusion

Seismic stratigraphic mapping, basin-scale maps and regional cross-sections were utilised to identify key strata across the Canning Basin onshore–offshore transition. Connecting strata across the onshore–offshore transition assists in de-risking frontier basins, delivers a framework for future exploration and provides a better understanding of the Canning Basin's geological history. Key results from this study are:

1. Seven units were mapped offshore for the first time, meaning 11 out of the 13 units mapped in this study are now identified offshore.
2. Additional mapping of poorly understood Ordovician strata from this study can assist with the prospectivity and exploration potential of associated petroleum systems both onshore and offshore.
3. Mafic igneous units found throughout the study area are more interconnected than previously thought and are understood to make up the North West Shelf MMP. The North West Shelf MMP has broad implications for basin evolution, petroleum prospectivity and the geological history of the Canning Basin.
4. Lastly, seismic stratigraphic mapping of 13 key strata has shown many similarities between the onshore and offshore domains, but offshore strata are generally deeper. Further mapping with new data is needed to correlate more units across the North West Shelf.

The results in this study can be used to refine petroleum prospectivity by using the interpolated horizons as a guide for the location and depth of petroleum systems elements. To improve the results presented in this study, new seismic data capable of imaging beneath mafic igneous units, well data with core samples for stratigraphic correlation and radioisotope geochronology for temporal correlation, are needed to better constrain interpretations and improve our understanding of the Canning Basin.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement

Supplementary material including scripts, raw data, images and additional sample information are available through Dryad and Zenodo online repositories under a GNU GPLv3 licence (https://doi.org/10.5281/zenodo.7336274; https://doi.org/10.5061/dryad.1c59zw3vx). The authors publish with the permission of the CEO, Geoscience Australia, Commonwealth of Australia (Geoscience Australia) 2022.

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