Department of Energy, Mines, Industry Regulation and Safety
GOVERNMENT OF WESTERN AUSTRALIA

Geological Survey of Western Australia

REPORT 257

SEISMIC INTERPRETATION OF THE KIDSON SUB-BASIN, CROSSLAND PLATFORM, RYAN AND TABLETOP SHELVES OF THE CANNING BASIN, WESTERN AUSTRALIA

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PERTH 2025

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A catalogue record for this book is available from the National Library of Australia

REFERENCE
The recommended reference for this publication is:
Zhan, Y 2025, Seismic interpretation of the Kidson sub-basin, Crossland Platform, Ryan and Tabletop Shelves of the Canning Basin, Western Australia: Geological Survey of Western Australia, Report 2025/257, 35p.

ISBN 978-1-76148-059-1
ISSN 2204-4345

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

Acknowledgement of Country
The Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) respectfully acknowledges Aboriginal peoples as being the traditional custodians of Western Australia. We acknowledge the enduring connection Aboriginal people continue to share with the land, sea and sky through both their ancestral ties and custodianship to Country. We pay our respect to Elders both past and present, and acknowledge the value brought to our department through the collective contribution of Aboriginal and Torres Strait Islander peoples across Western Australia.

Published 2025 by the Geological Survey of Western Australia
This Report is published in digital format (PDF) and is available online at <www.demirs.wa.gov.au/GSWApublications>.

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Cover image The Triwhite Hills on the southwestern margin of the Canning Basin viewed from the route of the Kidson seismic line. Outcrops of Permian Triwhite Sandstone (Liveringa Group) locally capped by Lower Cretaceous Callawa Formation.
Photo courtesy of Peter Haines

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Seismic interpretation of the Kidson Sub-basin, Crossland Platform, Ryan and Tabletop Shelves of the Canning Basin, Western Australia

Y Zhan

Scientific abstract

The subsurface stratigraphy of the southeastern Canning Basin ranges in age from Lower Ordovician to Mesozoic, deposited in environments varying from shallow marine and restricted marginal marine to terrestrial, eolian, fluvial and fluvio-glacial. This study focuses on the structural framework of the Kidson Sub-basin, the Crossland Platform, and the Ryan and Tabletop Shelves, extending the area of previous interpretations to provide comprehensive regional coverage. The current interpretation integrates pre-existing seismic and well data with the 2017–2018 Kidson airborne gravity data; the 2019 18GA–KB1 deep seismic survey; airborne electromagnetic data from 2019–2020; and recently reprocessed seismic data to address structural uncertainties and enhance the understanding of the southern Canning Basin.

Eleven horizons have been interpreted from the top of the Neoproterozoic basement to the base of the Jurassic, with varying levels of confidence due to differing seismic responses and data quality. The top basement maps show that the Kidson Sub-basin and the Crossland Platform form an asymmetric structural entity that deepens sharply from the Tabletop and Ryan Shelves to the sub-basin, and shallows gently towards the Crossland Platform. The depth and thickness of the Ordovician Nambeet, Willara and Goldwyer Formations broadly parallel the basement surface geometry. Two evaporite intervals, the Mallowa and Minjoo Salts of Late Ordovician to early Silurian age, serve as potentially important regional seals over Ordovician reservoir formations, creating exploration opportunities for hydrocarbons, natural hydrogen and helium, as well as for carbon dioxide (CO_2) sequestration and temporary hydrogen storage. The Mallowa Salt is shallower, thicker and more extensive compared to the older Minjoo Salt and was likely fragmented into isolated salt bodies along the periphery of the basin due to salt mobilization and dissolution. The Devonian Tandalgoo Formation is present mainly in the Kidson Sub-basin and the Crossland Platform; whereas, the more widespread underlying formations are found in the Willara Sub-basin and Broome Platform. The restrictive distribution of the Tandalgoo Formation was possibly caused by varying erosion at the bases of the Tandalgoo Formation and the Grant Group. The Base Grant–Reeves unconformity is characterized by deeply incised channels, significant removal of the Devonian in the northwestern area, and erosion of the Lower Ordovician near the basin margins. The Fitzroy Transpression unconformity is interpreted from airborne electromagnetic (AEM) conductivity depth images, revealing a mid-basin high in the central part of the Kidson Sub-basin.

KEYWORDS: Canning Basin, Paleozoic, Mesozoic, seismic interpretation, gravity, structure, isopach maps

Lay abstract

This study uses seismic surveys; gravity and electromagnetic measurements; and drillholes to explore the geology beneath the southeastern Canning Basin and to create detailed maps of the subsurface in areas such as the Kidson Sub-basin, the Crossland Platform, and the Ryan and Tabletop Shelves. The maps include eleven subsurface rock layers formed between about 540 and 145 million years ago in environments that ranged from shallow marine settings to rivers and deserts. The study also highlights major erosion features and changes in rock layers that provide clues about past geological events. These findings help geologists better understand the region's geological history and improve the chances of discovering energy resources and identifying suitable sites for carbon and hydrogen storage in the Canning Basin.

Introduction

Project scope

Although parts of the southern Canning Basin have been previously interpreted and mapped (Zhan, 2018, 2019a), this study focuses on the Kidson Sub-basin, the Crossland Platform, and the Ryan and Tabletop Shelves, expanding upon previous interpretations to provide regional geological context and structural maps (Fig. 1). The southeastern Canning Basin is one of the least explored regions in Western Australia, with only about 10 petroleum wells in an area of over 200 000 km^2 and a limited amount of seismic data acquired mostly from the 1960s to the 1980s.

The latest desktop study from the Canning SEEBASE® interpretation (Frogtech Geoscience, 2017) covered the entire Canning Basin and provided valuable insights, largely based on gravity and magnetic data for the area of this mapping project. Since the SEEBASE study, more geophysical surveys have been acquired, including the Kidson gravity gradiometry; deep crustal Kidson seismic line (18GA-KB1); and airborne electromagnetic surveys from 2017 to 2019. Interpretations (e.g. Southby et al., 2019; Zhan and Haines, 2021; Zhan, 2022) of these surveys indicate that the Kidson Sub-basin forms a broad sag depression flanked by the Munro Arch, the Crossland Platform, and the Ryan and Anketell Shelves. The Kidson seismic survey shows several apparent folds, but these are artefacts caused by acquisition around bends in the road and the sag remains relatively undeformed. Notably, high-angle faults are present in the Lower to Middle Ordovician strata along the eastern and western margins. Moreover, the configuration of the lower succession along these margins suggests that the Kidson Sub-basin originally extended beyond its current boundaries to the west and east. However, uplift and erosion processes have subsequently removed part of the sedimentary sections from these areas, leaving remnants along the edge of the sub-basin, or possible outliers, such as the Cobb Embayment, beyond the main part of the Kidson Sub-basin.

While the well and seismic data are still inadequate for detailed interpretation, particularly the significant data gap to the north of the Kidson seismic survey (Fig. 1b), this study attempts to integrate the best available data to address structural uncertainties and deliver regional maps of the Paleozoic succession in the southeastern Canning Basin. The maps also include the Jurgurra, Mowla and Barbwire Terraces, which are adjacent to the deep Fitzroy Trough and the Gregory Sub-basin, to provide expanded coverage for the southern Canning Basin (Fig. 1a). However, the terraces are more compartmentalized and structurally complex, and include much younger stratigraphy than the rest of the southern Canning Basin. Thus, mapping the terraces requires more detailed interpretation and needs to be updated, in conjunction with the Fitzroy Trough and Gregory Sub-basin in the northern Canning Basin where the stratigraphy is more comparable to the terraces. Areas of the southern Canning Basin which have been interpreted and mapped previously include the southwest (Zhan, 2018), the Willara Sub-basin, the Broome Platform area (Zhan, 2019a), and along the Kidson seismic survey (Zhan and Haines, 2021). This report focuses on the interpretation of the Kidson Sub-basin and the Crossland Platform, as well as peripheral shelves, to provide structural maps that extend to the adjacent elongated terraces and extend the previously interpreted areas (Fig. 1a) to the west coast.

Exploration history

The geology of the interior part of the Canning Basin was first investigated by Talbot (1910a,b), who joined the 1906 Canning Stock Route survey to make geological observations and assess groundwater potential. Within the extensive area of sand dunes along the route, Talbot (1910a,b) described the underlying sandstone and shale as being of the Carboniferous age. The route was later used for a magnetic survey by Kidson in 1914 (Kidson, 1921) to provide scientific data as part of a continental mapping campaign across Australia. The Canning Stock Route was also used for petroleum exploration during a geological reconnaissance by Locke Oil Development Syndicate led by LA Jones in 1922. In 1947, the Zinc Corporation Ltd in conjunction with Vacuum Oil Company Pty Ltd and D'Arcy Exploration Company Ltd flew over the study area during a reconnaissance survey of the Canning Basin, with a few outcrops considered to be of Permian age (Reeves, 1949). In 1954, the Bureau of Mineral Resources (BMR) made an aeromagnetic reconnaissance over part of the area (Quilty, 1960).

A systematic investigation of the regional geology was carried out by Traves et al. (1955) who explored the southern margin of the area over the Tabletop and Anketell Shelves, and concluded that a Tertiary, Mesozoic and Permian succession overlies Proterozoic rocks in the region. In 1957, BMR conducted a combined helicopter geological reconnaissance and gravity survey over a large part of the Canning Basin with geological observations made at Helena Spring, Forebank Hills, Farewell Lakes and Thornton Flat (Veevers and Wells, 1961; Flavelle and Goodspeed, 1962).

The early to middle Paleozoic was unknown in this area until the drilling of Sahara 1 (Singleton, 1965) by the West Australian Petroleum Pty Ltd (WAPET) in the western flank of the Kidson Sub-basin, followed by Kidson 1 which penetrated through the Devonian, Silurian and terminated in the Lower Ordovician (Johnson, 1966) near the middle part of the sub-basin. In the eastern margin, between the sub-basin and Ryan Shelf, Aquitaine Petroleum drilled Wilson Cliffs 1 (Creevey, 1969) and Contention Heights 1 (Brown and Campbell, 1974), showing that the pre-Permian strata become thin and shallow towards the east, with the basement intersected at 3503 m in Wilson Cliffs 1. About 100 km southeast of Kidson 1, Patience 2 was drilled in 2000–2001 by Nerdlihc Company Incorporated and intersected the Mesozoic, Permian, Devonian, Silurian and Ordovician strata, providing a comprehensive stratigraphic section through the Canning Basin (Haines, 2011). The western and northern parts of the sub-basin were explored by New Standard Onshore between 2012 and 2013, with drilling results from Nicolay 1 showing that total organic carbon in the Permian section was less than required for unconventional petroleum resources and too mature to yield wet gas or oil in the marginal area of the Kidson Sub-basin (New Standard Onshore, 2013a, b).

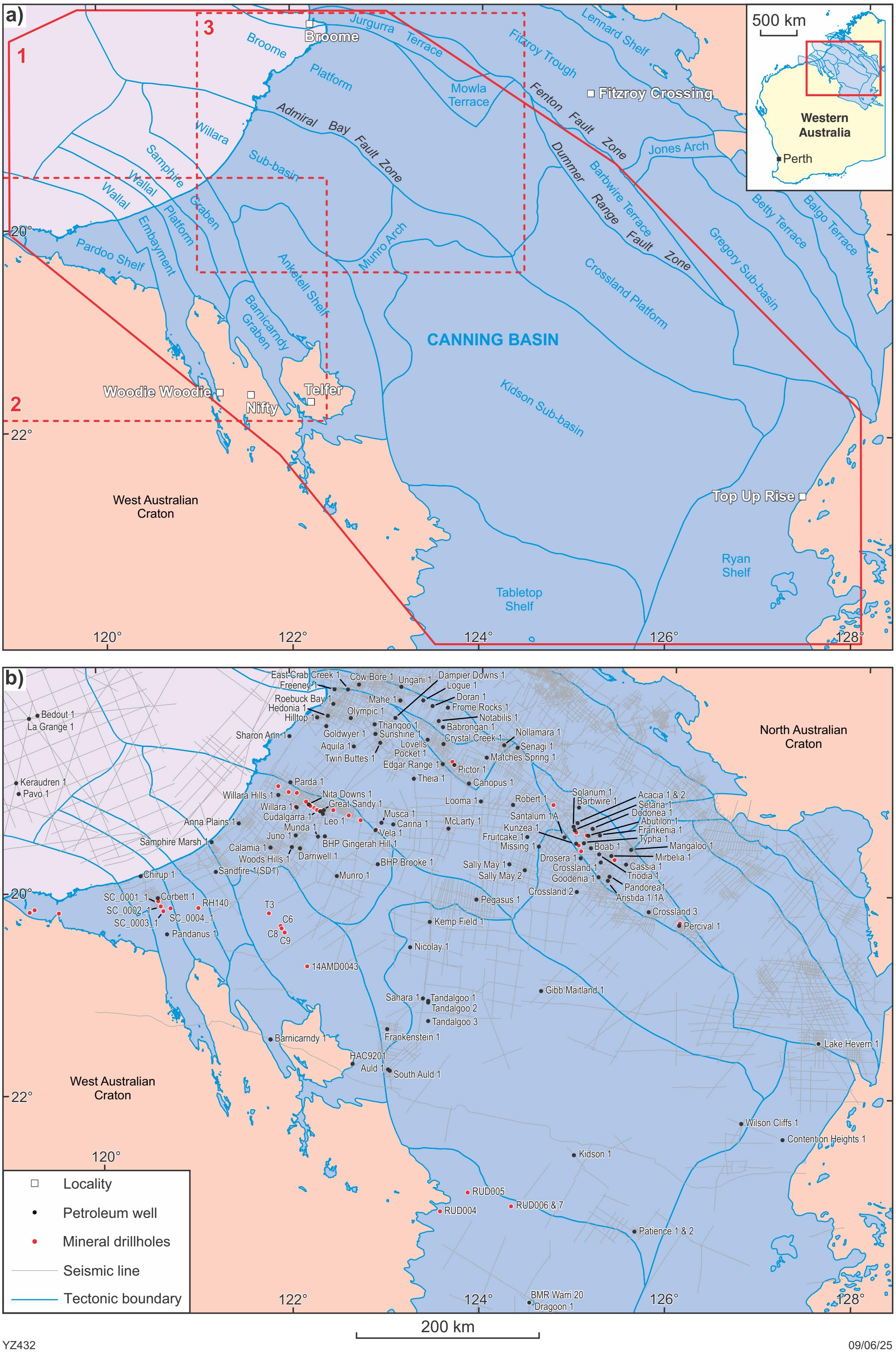

Figure 1. a) Tectonic elements of the southern Canning Basin (GSWA, 2017), 1: the current study area, 2: southwestern area (in Zhan, 2018), 3: Broome Platform and Willara Sub-basin area (in Zhan, 2019a); b) the study area the showing distribution of seismic data and wells

Regional geology

The Canning Basin is a large, mostly onshore intracratonic basin covering a total area of approximately 740 000 km^2 (Fig. 1). The basin infill contains an Ordovician to Cretaceous sedimentary succession that reaches an estimated 15 km in thickness within the Fitzroy Trough (Forman and Wales, 1981; Towner and Gibson, 1983; Brownet al., 1984; Yeatesetal., 1984; Kennard et al., 1994). The basin was initiated in the early Paleozoic as a northwest-oriented intracratonic rift, and later affected by Middle Devonian to Carboniferous extension, middle Carboniferous shortening, and early Permian thermal sag (Yeates et al., 1984; Kennard et al., 1994). The basin onlaps, and is surrounded by, mainly Paleoproterozoic–Neoproterozoic terranes. Offshore, the basin possibly continues below the thick Mesozoic section of the Roebuck Basin and southern Browse Basin in the North West Shelf.

The southern Canning Basin as the primary objective of this mapping project is located south of Broome and extends in a southeasterly direction from offshore northern Western Australia to inland near the Northern Territory border. The onshore area is approximately 310 000 km^2. The southern Canning Basin includes an elongate platform (comprising the Broome and Crossland Platforms), a contiguous northwesterly striking depocentre (comprising the Willara and Kidson Sub-basins), and a series of peripheral elements such as the Barnicarndy Graben, and the Anketell and Ryan Shelves (Fig. 1; Hocking, 1994a, b). The boundaries of these subdivisions are commonly poorly defined and are difficult to locate confidently based on the pre-existing dataset. Adjustments are needed as indicated by the Kidson seismic survey (Zhan and Haines, 2021) and potentially more revisions will be required as data coverage gradually expands. The sedimentary succession of the southern Canning Basin (Fig. 2) is estimated by the SEEBASE study (Frogtech Geoscience, 2017) to have a maximum thickness of 10 km near the boundary between the Kidson Sub-basin and the Ryan Shelf. Most of the succession is of Ordovician to Permian age, with the exact timing of the onset of deposition uncertain in this part of the basin. The SEEBASE study suggested that the Kidson Sub-basin deepens towards its southwestern and southeastern regions. The thickest part of the sedimentary succession was mapped in the southeast region adjacent to the Ryan Shelf (Frogtech Geoscience, 2017), predominantly aligned with low gravity anomalies observed in the area (GSWA, 2020b; Fig. 3).

The stratigraphic framework (Fig. 2) of this study follows that of Haines (2009, 2011), Mory (2010), Mory and Haines (2013), Haines et al., (2013) and Backhouse and Mory (2020). Based on several major angular unconformities, the Phanerozoic sequence in the Canning Basin has been divided into four megasequences, each of which was deposited over 70–100 million years (Fig. 2). The Ordovician to Middle Devonian megasequence includes the succession from the Nambeet Formation to the Mellinjerie Formation and is extensive in the southern part of the basin, although equivalents are only shown in drillholes as locally preserved in the north. The Middle Devonian to Middle Carboniferous megasequence consists of the Devonian reef complexes, the Fairfield Group and the Anderson Formation, each of which is only present in the northern Canning Basin, based on available well intersections. The Middle Carboniferous to Triassic megasequence incorporates the succession from the Reeves Formation and the Grant Group up to the Erskine Sandstone (Fig. 2) and is laterally extensive across the basin. In general, the base of this megasequence is a regional erosional unconformity which cuts down into the Middle Devonian to Middle Carboniferous megasequence in the north, and the Ordovician to Middle Devonian megasequence in the south. The Jurassic to Cretaceous megasequence unconformably overlies the Middle Carboniferous to Triassic megasequence and contains the succession from the Wallal Sandstone to the Anketell Formation. This megasequence has a relatively uniform thickness from north to south, but generally thins from the coast in the west, towards the middle of the basin in the east.

Data description

Geological investigations by government agencies and petroleum and mineral exploration companies in the southern Canning Basin have led to a variety of datasets, including petroleum wells, mineral drillholes, seismic data; as well as gravity, magnetic and airborne electromagnetic surveys. Hydrogeological bores are rare in the Kidson Sub-basin and the Crossland Platform compared to the western coastal area, due to the remoteness. The geological data used in this study are open-file and can be accessed from the data repositories of the Geological Survey of Western Australia (GSWA): WA Petroleum and Geothermal Information Management System (WAPIMS) at https://wapims.dmp.wa.gov.au/wapims); WA Mineral Exploration Reports (WAMEX) at https://geoview.dmp.wa.gov.au/geoview/?Viewer=GeoView&run=WAMEX_Search; and MAGIX at https://magix.dmirs.wa.gov.au/.

Seismic dataset

The Kidson Sub-basin and Crossland Platform are poorly covered by seismic data, most of which were acquired between 1960 and 1987 (Fig. 4a). The Kidson Sub-basin seismic acquisition (18GA-KB1) is one of very few modern surveys which investigates the basin's architecture and basement geology along east–west roads across the area. The total length of the Kidson seismic survey is 872 km and provides good quality data, showing continuous parallel reflectors across the depocentre and faulting near the basin margins. A significant seismic data gap exists north of the Kidson seismic survey, approximately 100 km wide and 300 km long, in the central part of the Kidson Sub-basin.

Overall, the seismic coverage is very sparse and patchy, with several small and coarse grids of seismic lines near the Frankenstein 1, Patience 2, and Wilson Cliffs 1 wells (Fig. 1b, 4a). Compared with the recent Kidson seismic survey, the originally processed versions of the legacy data are generally poor to fair quality, but the quality has been improved via seismic reprocessing by industry and governments in recent times (Fig. 4b). The most recent large-scale reprocessing in the Kidson Sub-basin and the Crossland Platform took place in 2018. GSWA, with funding from the Exploration Incentive Scheme (EIS), selected approximately 30 seismic lines from various vintages to apply modern processing techniques through an external processing company, yielding significant quality improvements (Fig. 5a,b; Bahlol, 2018). However, for some surveys, such improvement by reprocessing is still marginal due to the limitations of the original acquisition settings,

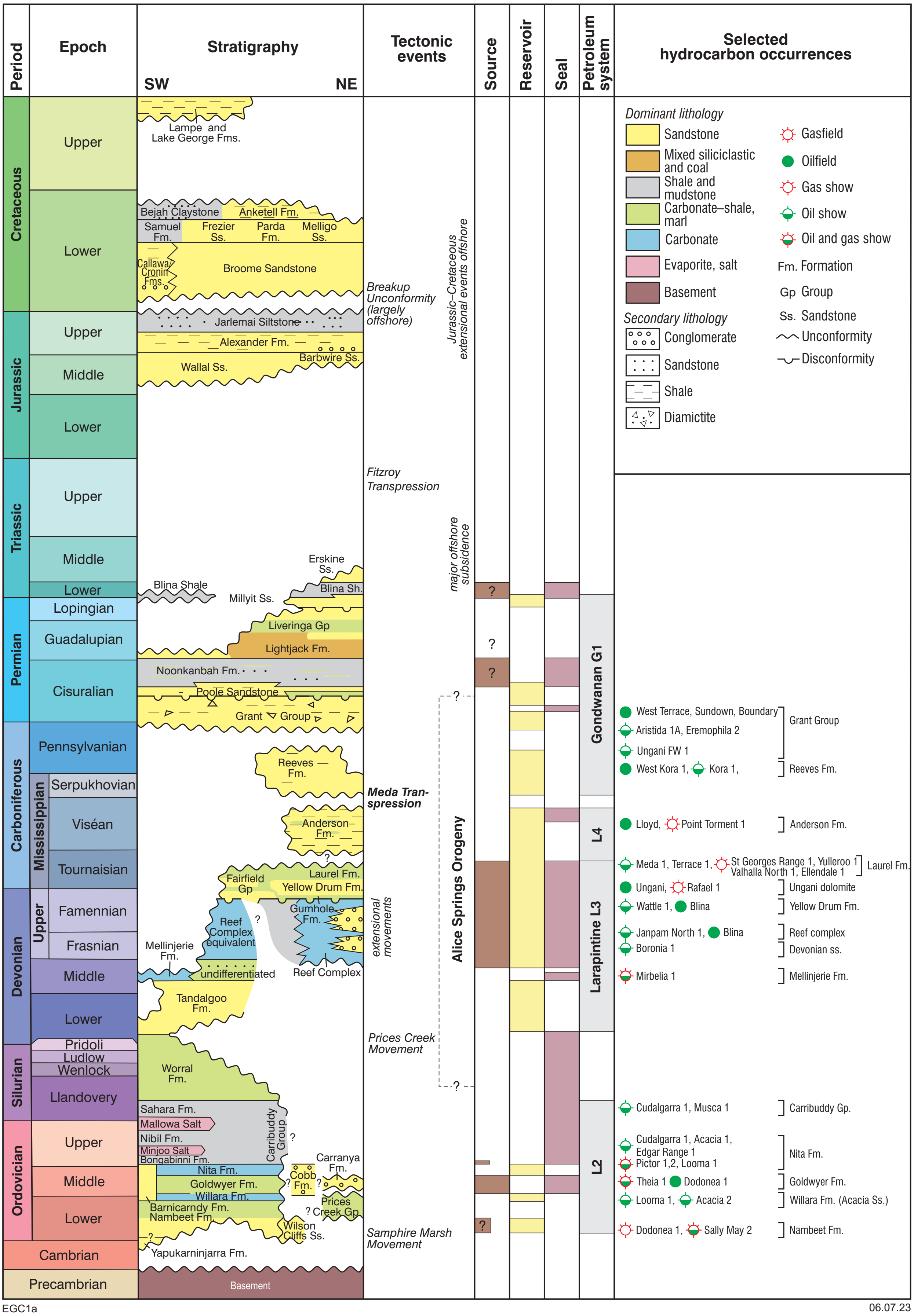

Figure 2. Stratigraphy of the Canning Basin (modified from Haines, 2004, 2009, 2011; Mory 2010; Mory and Haines, 2013; Haines et al., 2013)

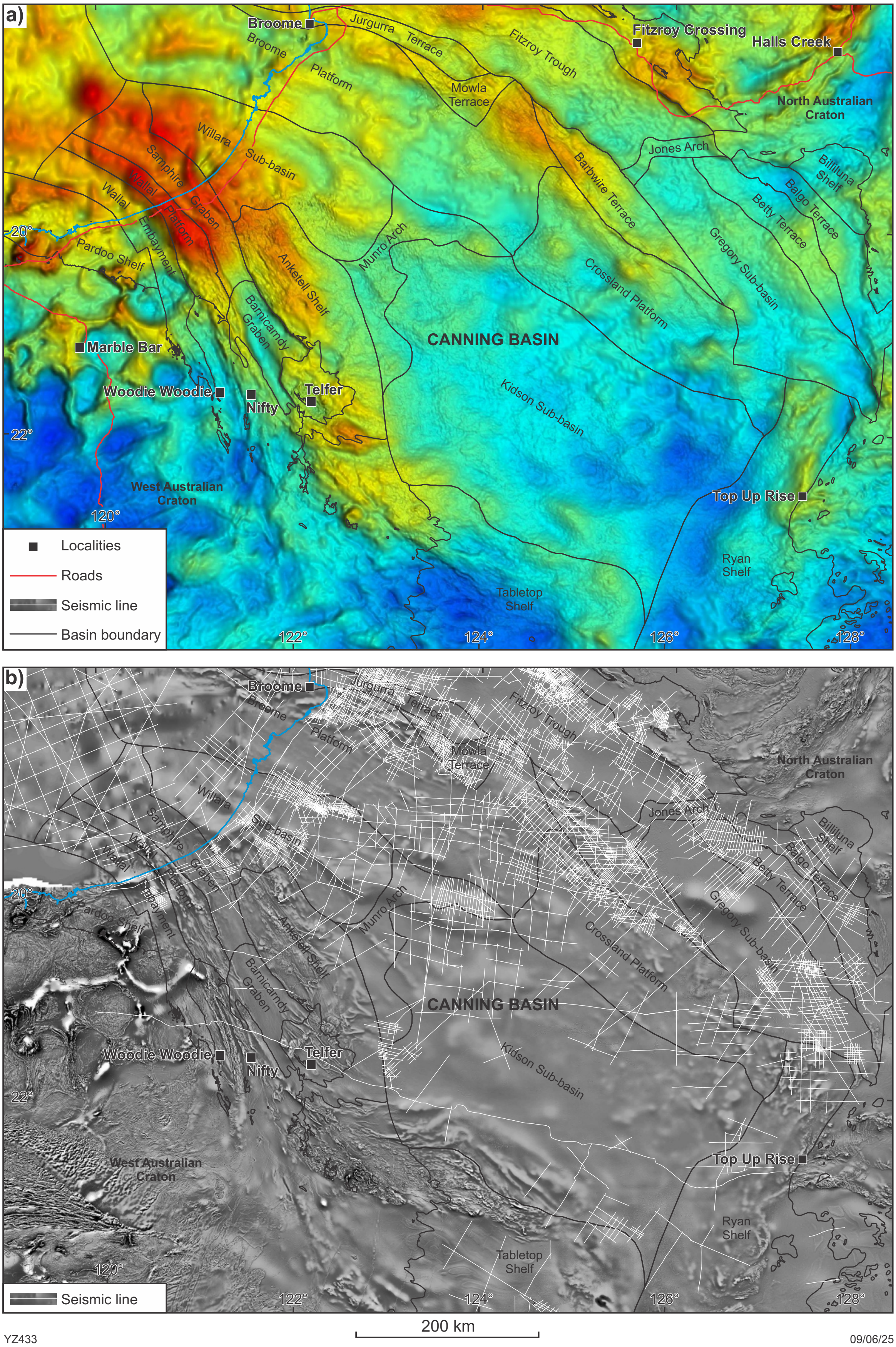

Figure 3. a) Bouguer gravity anomaly; b) first vertical derivative of aeromagnetic data of the southern Canning Basin (GSWA, 2020b,c)

Figure 4. Available seismic data for the study area shown by: a) acquisition vintage; b) data quality

including folds, source energy types, and spread patterns. The limitations also include lack of the raw shot data and/or observation logs, leading to limited work that can be done, other than cleansing of the originally processed stack sections.

The seismic reprocessing provides alternate perspectives to understand the uncertainties in structure and velocity. Some apparent small structural folds on the originally processed sections are absent after reprocessing, indicating artefacts caused by static correction or velocity model in the original processing (Fig. 5a,b). In other words, suspected artificial structures from un-reprocessed seismic lines may require filtering and smoothing when mapping the horizons. Each reprocessing has resulted in substantially different stacking velocities of the same 2D seismic lines (e.g. figure 6 of Zhan, 2019a). This implies that a combination of stacking velocities from different sources will not reflect the true velocity variation. Therefore, well velocity data from both checkshots and sonic logs are considered to be more robust when establishing a velocity field for depth conversion.

The seismic datum differs between surveys and, therefore, requires systematic adjustments before interpretation (Fig. 6a,b). For example, the 2018 processed data of the Kidson seismic survey has a datum of 500 m above mean sea level (AMSL), which was made to preserve the seismic reflections from shallow Mesozoic and Cenozoic strata in elevated areas (Velseis, 2019). Such preservation of seismic reflection data commonly applies to the surveys farther inland where the surface elevation is much higher than MSL. Based on the chosen processing datum and replacement velocity, the variable datums have been corrected in this project to a final datum of MSL to enable a consistent correlation across the study area. This uniform datum can also help identify issues which may be caused by erroneous navigation (Fig. 7a,b) and avoid misinterpretation of structures. However, the datum and replacement velocities were not always available in the corresponding processing reports for the vintage data, and adjustments are only based on visual correlation with other surveys, leading to uncertainties in determining the mis-tie values, especially for isolated seismic lines without nearby profiles for reference.

In general, the seismic quality and interpretation confidence is reasonably good in the Broome Platform, the Willara Sub-basin, the northern Crossland Platform, the strip along the Kidson seismic survey, and part of offshore areas (Figs 4b, 8). Due to the variable quality and quantity of the seismic data, the confidence level of the interpretation and maps is fair in the southeastern Crossland Platform, the northwestern Kidson Sub-basin, and areas near Patience 2 and Nicolay 1. Seismic data is either unavailable or of very low quality in the central parts of the Kidson Sub-basin, the Crossland Platform, the Tabletop and Ryan Shelves, as well as much of the Munro Arch. As a result, the confidence of the interpretation and maps is low in these areas (Fig. 8).

Petroleum wells and mineral drillholes

Petroleum exploration in the Crossland Platform and the Kidson Sub-basin began in 1965 about 10 years after the exploration of the northwest coastal area, with the drilling of Sahara 1 revealing the existence of a Silurian to Devonian sedimentary succession in the western part of the sub-basin (Fig. 1b). The subsequent drilling of Kidson 1 confirmed that an even deeper section included equivalents to the Ordovician Goldwyer Formation that had been recognized in Willara 1 and Goldwyer 1 near the coast. Due to difficult land access and lack of evidence of hydrocarbons in the early wells, petroleum exploration in the area stagnated with a total of fewer than 10 deep wells reaching the pre-Permian section in the vast area of the Kidson Sub-basin and the Crossland Platform.

Mineral exploration drillholes are also minimal in inland areas, including the Kidson Sub-basin and the Crossland Platform, compared to closer to the coast where a cluster of holes have been drilled in the exploration for Mississippi Valley-Type (MVT) Pb-Zn deposits along the Admiral Bay Fault Zone (Fig. 1a). There are a small number of mineral exploration drillholes targeting Precambrian basement rocks near the edge of the southern Canning Basin. These include the Top Up Rise drilling by Border Exploration Pty Ltd and Corazon Mining Limited in the Ryan Shelf and Rudall East drilling by Fortescue Metals Group in the Tabletop Shelf (Fig. 1b). Therefore, these drillholes do not provide much information about the pre-Permian sedimentary section in the central part of the basin, other than confirming much shallower basement along the basin periphery.

Most of the petroleum wells provide downhole velocity profiles and/or sonic logs, which are used to calibrate the horizons between the base of the Jurassic and the top of the basement onto seismic lines, as well as to constrain the velocity field along with seismic stacking velocities for depth conversion. The original formation tops from the well completion reports (e.g. Sahara 1 in Singleton, 1965; Kidson 1 in Johnson, 1966; Wilson Cliffs 1 in Creevey, 1969; Frankenstein 1 in Command Petroleum N.L.,1989; Nicolay 1 in New Standard Onshore, 2013b) were mainly based on lithology and wireline data and, therefore, only provide loose stratigraphic constraints. Since the drilling of these wells, the stratigraphy has been revised to allow a basinwide understanding of the depositional succession (e.g. Haines,2004, 2009, 2011; Mory, 2010; Backhouse and Mory, 2020). The formation tops in this study (Appendix 1) are based on correlations between wells in the basin and integration with biostratigraphic data; thereby, providing a more systematic and coherent stratigraphic interpretation.

Gravity and magnetic data

Gravity and magnetic data have been periodically acquired through ground and airborne surveys throughout the exploration history of the southern Canning Basin. These surveys use passive methodologies with a variety of acquisition parameters, such as station spacing, flight line spacing and heights, and different geophysical sensors. Most ground surveys were conducted primarily along seismic routes before the 1980s and are complemented by modern-day airborne surveys, which significantly increase the spatial resolution.

The Kidson Falcon® airborne gradiometry survey was the latest regional data collection from 2017 to 2018, consisting of a main block of data over the Kidson Sub-basin and the Munro Arch, as well as an extension block of data in the northwestern parts of the Barnicarndy Graben and the Anketell Shelf. This regional survey was flown at 2500 m line spacing and has been processed and amalgamated with other legacy data to provide subsurface geological information (Fig. 3a; GSWA, 2020b) with lateral resolution

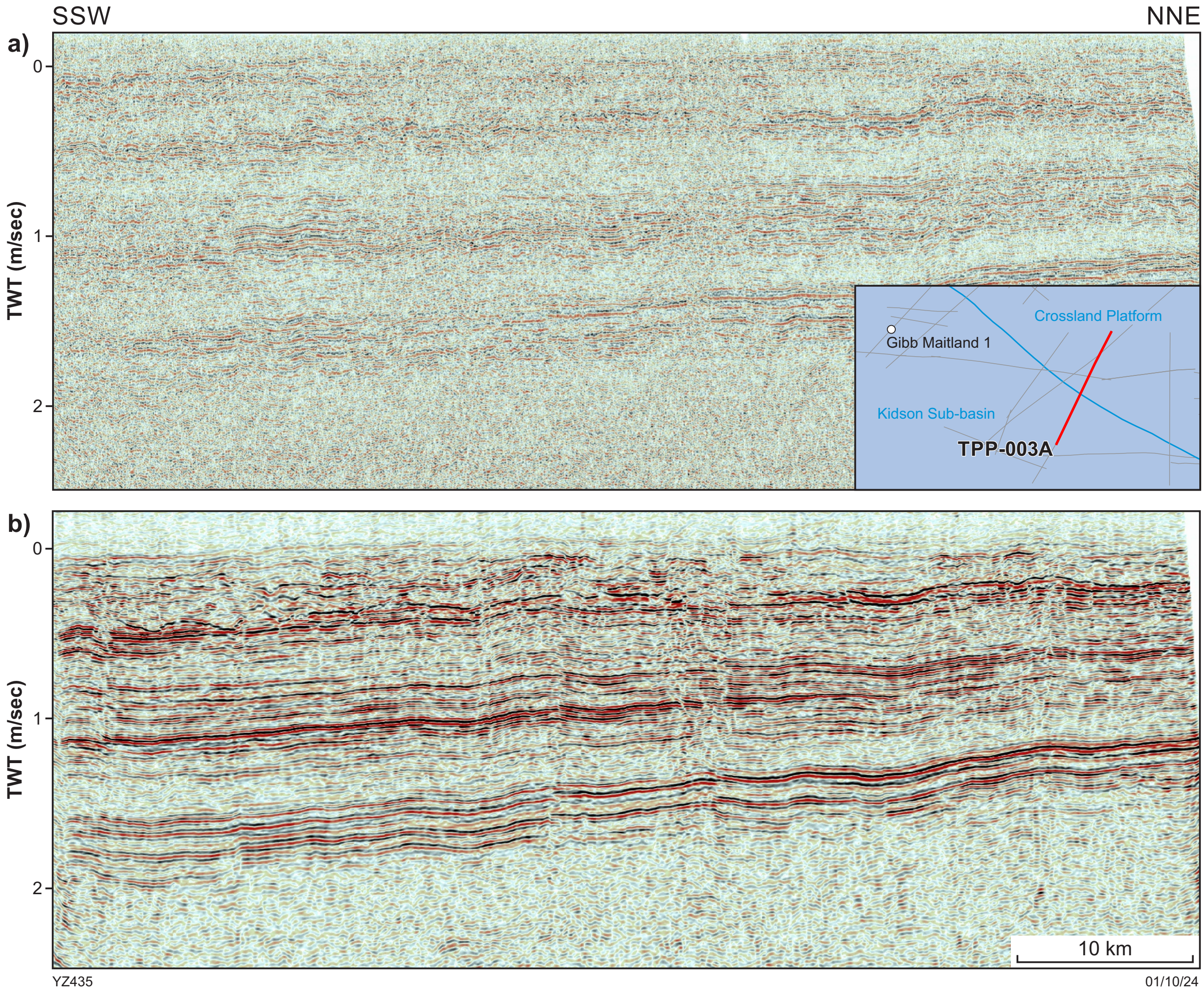

Figure 5. Quality improvement via seismic reprocessing (line TPP-003A) from the Kidson Sub-basin to the Crossland Platform: a) before; b) after reprocessing

of approximately 400 m (0.004167 degrees) in the southern Canning Basin. Similar gradiometry surveys were flown along the Jurgurra Terrace to the Barbwire Terrace by Buru Energy (Rudge et al., 2015), which provided high-resolution data to interpret the basement depth and fault distribution when combined with the seismic data. The aeromagnetic surveys were acquired at reduced spacing between flight lines, and the data has been processed and merged with other magnetic surveys in the area to provide a higher resolution of the magnetic grid, i.e. approximately 40 m (Fig. 3b; GSWA, 2020c).

Airborne electromagnetic survey

The study area is covered by the WA–NT regional airborne electromagnetic survey (figure 1 of Appendix 2; AusAEM 02 in Ley-Cooper, 2020) which extended from the northwest part of the Northern Territory to the western coast of Western Australia in 2019–20. Within the study area, the AusAEM 02 flight lines were west–east oriented and strategically positioned to fly across existing wells at a nominal line spacing of 20 km; thereby, providing data calibrations for the adjacent areas. The AEM survey measures spatial variations in electrical conductivity rather than magnetic properties, despite that term appearing in its compound name. The conductivity contrast is used to image geological boundaries in a similar way to seismic data, but only provides geological information down to 600 m after data inversion by Geoscience Australia. Although the AEM data has a much shallower depth of investigation, the areal coverage is more comprehensive than the seismic data, thus providing better constrains for the interpretation of the shallow Permian strata. The structure in the shallow Permian section might have implication for the deep pre-Permian succession and basement, which is discussed in Zhan (2024) and attached as Appendix 2 to this report.

Tectonic elements

Following previous mapping projects in the southern Canning Basin (Zhan, 2018, 2019; Fig. 1a), this Report focuses on the Kidson Sub-basin, the Crossland Platform, and the Ryan and Tabletop Shelves in the southeastern part of the basin. These subdivisions are mainly oriented in a northwesterly direction, with boundaries being loosely constrained due to a lack of data (Hocking, 1994a, b).

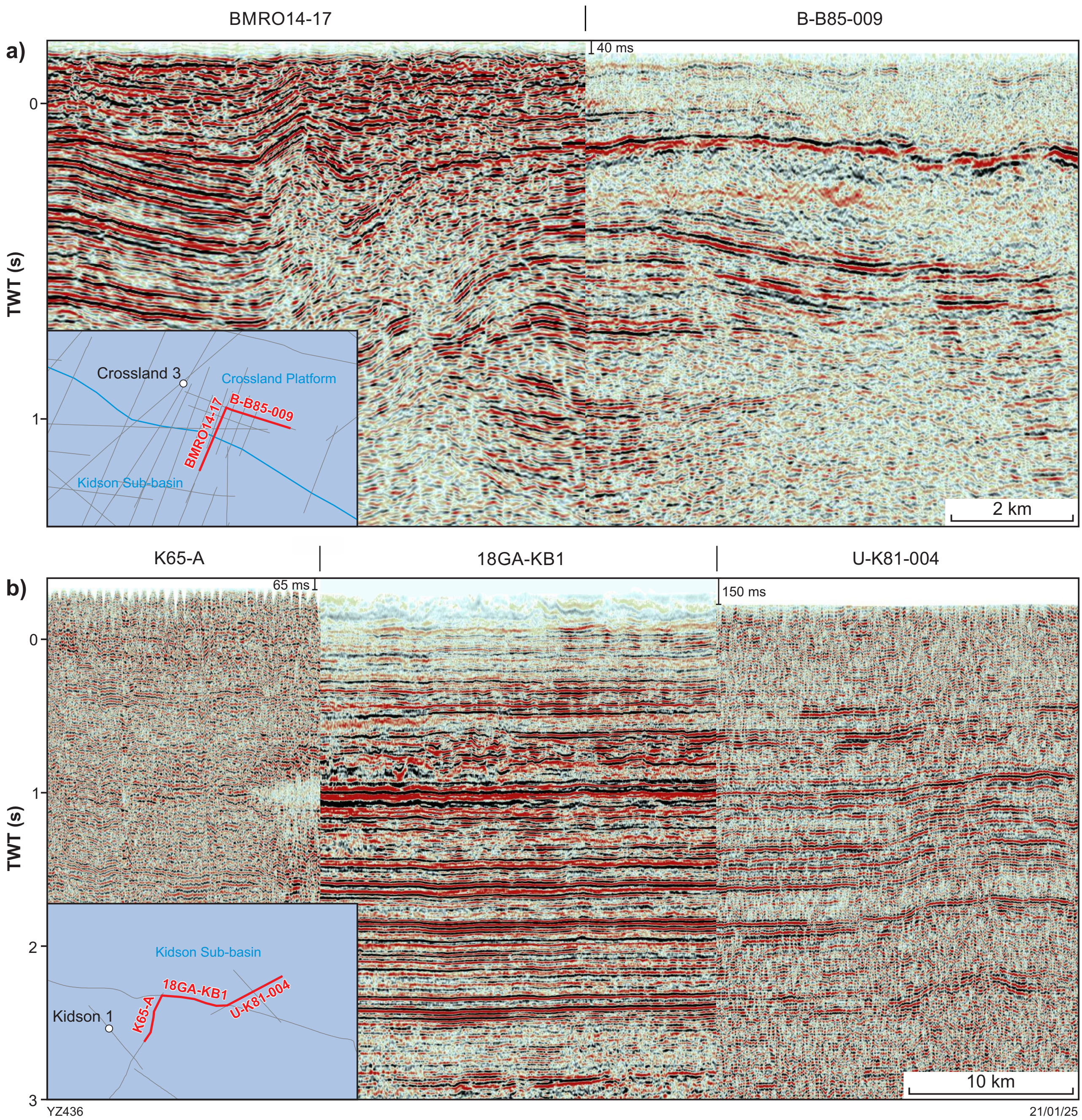

Figure 6. Composite seismic sections showing examples of mis-ties across different seismic surveys

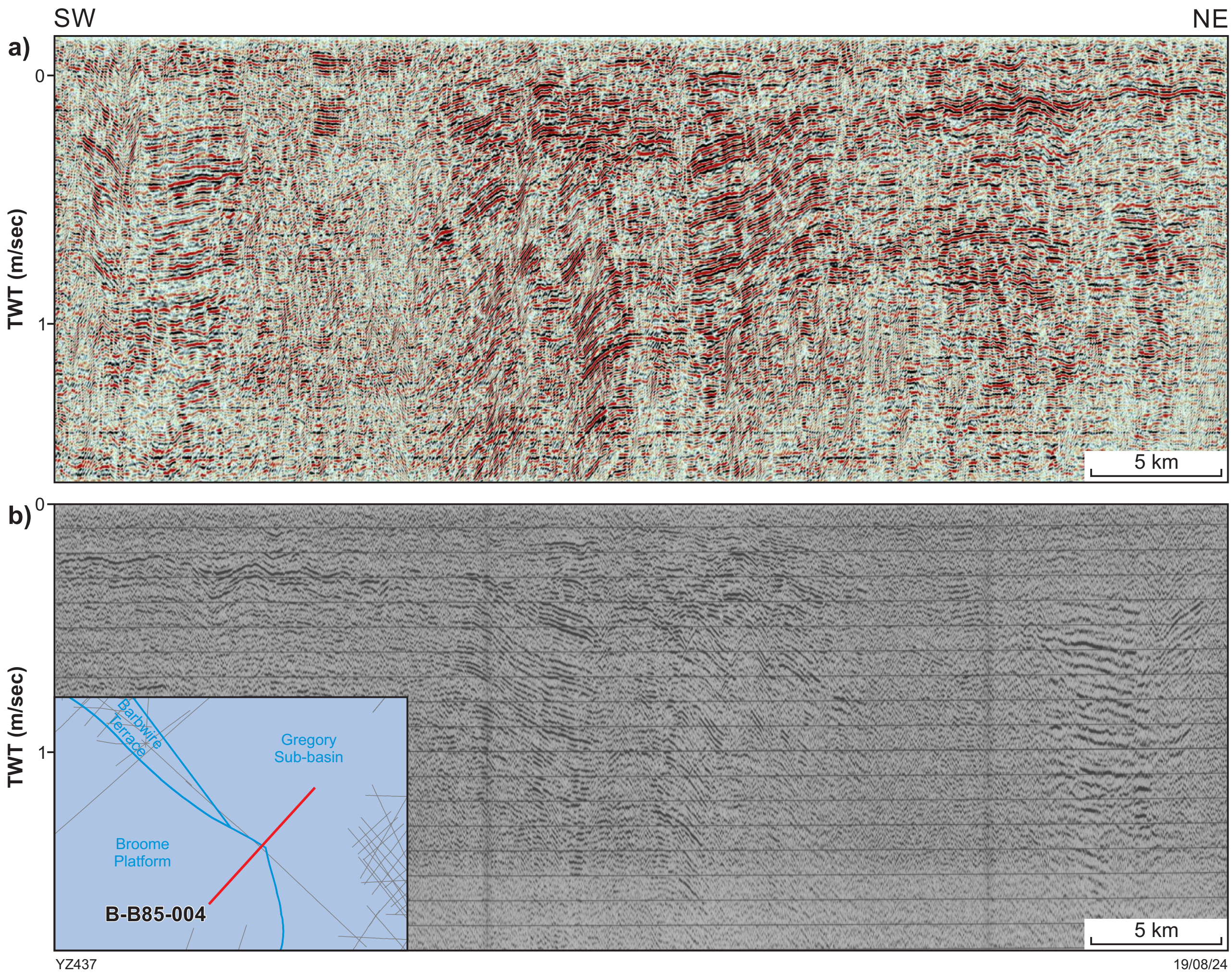

Figure 7. Example of erroneous seismic navigation: a) line B-B85-004 showing strata dipping to the southwest at odds with the regional geology); vs b) original hard-copy data of line B-B85-004 (dipping to the northeast) from the Crossland Platform to the Gregory Sub-basin

Kidson Sub-basin

The Kidson Sub-basin (Fig. 1) is the largest structural component of the Canning Basin, covering approximately 90 000 km^2 and potentially more, considering its arbitrary boundaries. The sub-basin was originally termed the 'Kidson Basin' (e.g. Koop 1966a, b) after the geophysicist Edward Kidson from the general magnetic survey published in 1921. The 'Kidson Basin' was defined with vague boundaries and referred to the broad depression in the north of Western Australia based on early gravity surveys. Later its status was downgraded and defined as a part of the southeast Canning Basin. Compared to the other depocentres of the Canning Basin, such as the Willara Sub-basin and Fitzroy Trough, the Kidson Sub-basin is poorly covered by seismic data and has a limited number of wells, making it one of the least geologically understood provinces with energy potential in onshore Australia.

The Kidson Sub-basin is bound by the Anketell Shelf and the Crossland Platform to the south and north, respectively. Its northern boundary was initially assumed to be the Admiral Bay Fault Zone, but recent seismic interpretation (e.g. Zhan, 2019a) shows that this fault zone does not extend far enough east beyond the northern margins of the Willara and western Kidson Sub-basins. This boundary was set to follow the 1500 millisecond (ms) contour at the top of the Ordovician two-way time (TWT) map (Iasky et al., 1991) along the southwesterly dipping Crossland Platform. The southwestern boundary with the Anketell Shelf was defined on the 600 ms contour at the base of the Grant Group TWT map by Taylor et al. (1991). Historically, the Kidson Sub-basin was inferred to be relatively thin with the basement being about 1500 – 3000 m deep, overlain by marine Ordovician strata that was erosionally truncated by Permian glacial deposits (Koop, 1966b).

The stratigraphic succession was later revealed through petroleum exploration wells, notably Kidson 1 (Johnson, 1966) and Wilson Cliffs 1 (Creevey, 1969), showing that the depression also contains Devonian and Silurian strata above the Ordovician rocks. The sub-basin deepens towards its southwestern and southeastern regions based on gravity, magnetic and marginal seismic data. This deepening trend was interpreted by Frogtech Geoscience (2017) as resulting from overthrusting of the 'Kidson Craton' from the southwest by the Rudall Province and from the east by the 'Gillespie Terrane'. The thickest part of the sedimentary successions was mapped in the southeast region of the sub-basin near the Ryan Shelf (Frogtech Geoscience, 2017), predominantly aligned with low gravity anomalies observed in the area (GSWA, 2020b).

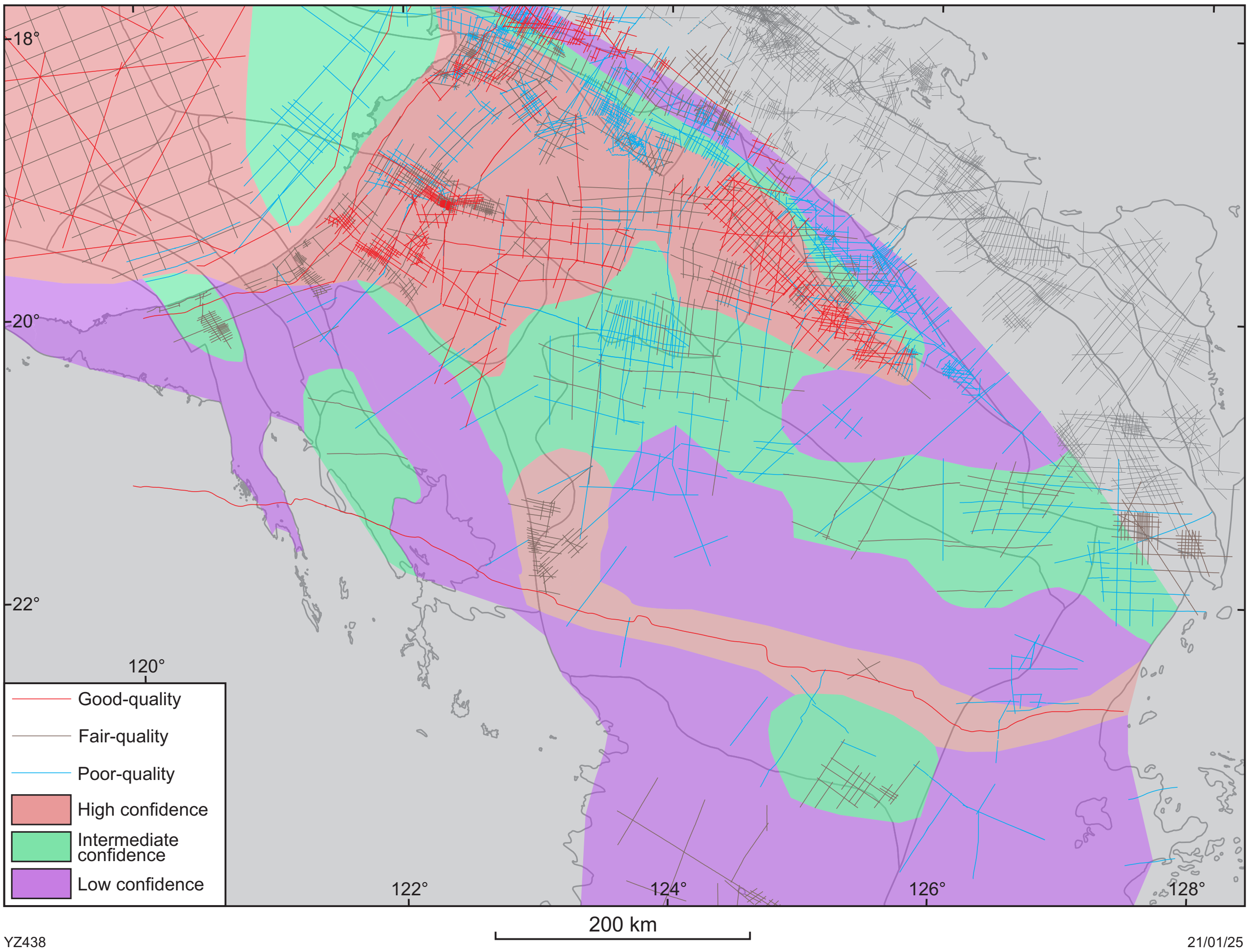

Figure 8. Confidence level for the interpretation in the southern Canning Basin (see Figure 1 for well locations and tectonic units)

Crossland Platform

The Crossland Platform overlies a northwesterly striking basement high in the middle part of the Canning Basin and was previously included in the 'Broome Swell' (Veevers and Wells, 1961; Fig. 1). The separation from the Broome Platform is more geographic than geological, with a loosely defined elevated basement ridge marking the boundary between the two platforms. The southeastern edge, adjoining the Ryan Shelf, is largely arbitrary due to limited data in the area. The Crossland Platform is bound to the northeast by the Barbwire Terrace and the Gregory Sub-basin with the contact defined by the Dummer Range Fault. To the southwest, the Crossland Platform transitions into the Kidson Sub-basin. Its southwestern boundary was determined by Hocking (1994b) to follow a two-way time of roughly 1500 ms to the top of the Ordovician sequence based on the mapping by Iasky et al. (1991). This boundary differs from the contact between the Broome Platform and the Willara Sub-basin that is defined by the Admiral Bay Fault Zone.

Early reconnaissance seismic surveys across the Crossland Platform were oriented in a northeasterly direction and showed that the platform was an upfaulted block with a regional southwesterly dip (WAPET, 1971a, b). Based on this seismic data, the Crossland Platform was considered by Wyborn (1977) as not a true platform in the strictest sense, but rather a shelf, where the sequence of sedimentary deposits is significantly thinner compared to neighbouring tectonic domains. This difference in thickness may be attributed to the likely erosion of some sedimentary layers during the late Middle Devonian to the late lower Carboniferous (Wyborn, 1977).

Four wells have been drilled on the Crossland Platform, all in the northern part. Crossland 2 is situated approximately 29 km south of the platform's northern edge, while the remaining wells (Missing 1, Santalum 1A, and Drosera 1) are located less than 2.5 km from the platform's northern boundary (Fig. 1).

Ryan Shelf

The Ryan Shelf, as described by Gorter et al. (1979; Fig. 1a), encompasses a vast and vaguely defined region along the southeastern margin of the Canning Basin. This region is covered by sedimentary rocks up to 3 km thick, ranging in age from Carboniferous to Mesozoic. Its western contact with the Kidson Sub-basin was originally interpreted as a transitional monocline (Gorter et al., 1979; Hocking, 1994b). To the east it abuts the Amadeus Basin with a fault boundary seen on the Kidson seismic survey (Zhan and Haines, 2021). In some places, the shelf extends beyond the fault to unconformably overlie the Amadeus Basin and older basement domains based on outcrop geology, gravity and magnetic images (GSWA, 2020a–c). The fault was referred to as the Lasseter Shear Zone by Doublier et al. (2020) on the Kidson seismic survey, a feature initially conceptualised from a gravity image by Braun et al. (1991) and used to explain the distribution of Phanerozoic basin depocentres, including the Canning Basin.

The Kidson seismic line confirms the existence of the Ryan Shelf, but reveals it as a much narrower feature, i.e. 30 km wide (Zhan and Haines, 2021) than the previous delineation of 120 km width based on early gravity and magnetic data (Hocking, 1994a). As shown on the seismic data, the Ryan Shelf is better defined as a north-northeast-oriented fault zone, in which the faults are near-vertical and have greatest displacement in the lower part of the basin succession. The faults are assumed to be subparallel to the basin-bounding fault against the Amadeus Basin shown on the gravity and magnetic images. These high-angle faults exhibit reverse and strike-slip components, and some of them have significant vertical displacement (Zhan and Haines, 2021).

Near the eastern edge of the shelf, the stratigraphy was intersected in mineral drillholes at the Top Up Rise prospect where it is limited to a shallow Permian section consisting of a 100–150 m thick sequence of sandstone, siltstone and conglomerate above Proterozoic basement (Marshall, 2013; Marshall and Smith, 2014). Towards the western part of the Ryan Shelf, the Paleozoic succession thickens significantly with a thickness of 745 m of Permian above more than 1 km of Ordovician to Silurian strata in Contention Heights 1. The Kidson seismic line shows two major unconformities within the Permian to Ordovician strata: one at the base of the Permian Grant Group, the other at the base of the Lower Devonian Tandalgoo Formation (Fig. 11a,b).

Tabletop Shelf

The Tabletop Shelf is not as widely adopted as other basin subdivisions such as the Kidson Sub-basin and its boundaries were loosely defined with surrounding tectonic elements. It was historically included as either part of the Anketell Shelf or the Kidson Sub-basin, depending on what subdivisional schemes it followed (e.g. Hocking, 1994; Fig. 1a). The term refers to the southeast extension of the Anketell Shelf (Gorter et al., 1979; GSWA, 2017) covering the area where the thin Permian section unconformably overlies Proterozoic units of the northern part of the Officer Basin. Due to its thin sedimentary cover, the basement underlying the shelf is highlighted as a relatively prominent feature on potential field data, characterized by a northwesterly trending gravity high and high-frequency magnetic anomaly to the southwest of the Kidson Sub-basin (Fig. 3a,b).

Mineral drillholes RUD0002 to 0007 on the Tabletop Shelf have intersected Permian glacial rocks, with RUD0004 and 0007 reaching Proterozoic basement at 243 m and 525.2 m, respectively (Roche, 2017a, b; Backus, 2018). These intersections, combined with the 1570 m of the Permian strata in Kidson 1, suggest that the Tabletop Shelf thickens towards the northeast and is probably structurally similar to the Anketell Shelf. Studies of Permian intersections and outcrops (e.g. Newcrest Mining Ltd, 1993; Hickman and Clarke, 1994; Mory et al., 2008) suggest that the Permian Grant Group onlaps Proterozoic basement to the southwest. The Permian section was commonly referred to as the Paterson Formation in this part of the Canning Basin and over the Officer Basin but has been reassigned to undivided Grant Group by Backhouse and Mory (2020). As previously discussed in Zhan (2018), the pre-Permian section is mostly absent on the Anketell Shelf due to thinning towards basin margins and erosion before the deposition of the Grant Group. The northern limit of direct contact between the Permian and Proterozoic basement on the Tabletop Shelf would be a good criterion to define the northern boundary of the Tabletop Shelf to ensure a consistent definition with the Anketell Shelf.

Seismic interpretation

Regional seismic mapping of the study area was last conducted about 30 years ago, with several key horizons covering the Canning Basin (top Ordovician by Iasky et al., 1991; base Grant Group by Taylor et al., 1991; and depth to base Phanerozoic by Romine et al., 1994 and Copp, 1994). Since then, new datasets have been collected, notably the drilling of the Patience 2, Nicolay 1 and Gibb Maitland 1 wells, and the acquisition of the Kidson seismic survey across the sub-basin. Although the data additions are not as extensive as those in the Willara Sub-basin and the Fitzroy Trough, the incorporation of these data into the study area warrants an update of the regional maps. However, it should be noted that the interpretation is restricted by patchy and poor-quality seismic data and has a varying level of confidence between horizons and geographic regions. Fault correlation is ambiguous in areas of sparse seismic coverage.

Eleven horizons have been tied to wells (e.g. Fig. 9), interpreted and mapped (Appendix 3), including the top of the basement; the tops of the Lower to Middle Ordovician successions; the interfaces of two salt intervals (the Mallowa and Minjoo Salts); and three regional unconformities at the bases of the Devonian Tandalgoo Formation, Permo-Carboniferous Grant Group and the Jurassic successions. The maps for the Kidson Sub-basin and the Crossland Platform have been amalgamated with the previous results in the southwest Canning Basin (Zhan, 2018) and the Broome Platform to Willara Sub-basin (Zhan, 2019a). Within the previous mapped areas where original upper parts of the Ordovician successions were removed, down to the Goldwyer Formation at Hilltop 1, the Willara Formation at Olympic 1, and the Nambeet Formation at Samphire Marsh 1, the mapped Ordovician horizons are combined with the Base Grant–Reeves unconformity to delineate the lateral extent of the remnant sections in those partially eroded areas. This approach is also adopted for the base of the Devonian Tandalgoo Formation, where the horizon is laterally extended following the Base Grant–Reeves unconformity for the calculation of the combined thickness of the Worral Formation, Carribuddy Group and Nita Formation. The horizons of the Mallowa and Minjoo Salts are selected for interpretation, based on their significance as regional seals.

Horizons in TWT are converted to depth domain, mainly through the velocity information from sonic and/or checkshot data recorded in wells. As discussed in the section, *Data description*, the seismic stacking velocity shows drastic differences across surveys, or even between different vintages of the same profiles, as a result of being processed separately and differently (figure 6 in Zhan, 2019a). This suggests that merged stacking velocities from different sources are unlikely to reflect the true velocity variations. The datum of seismic data has been

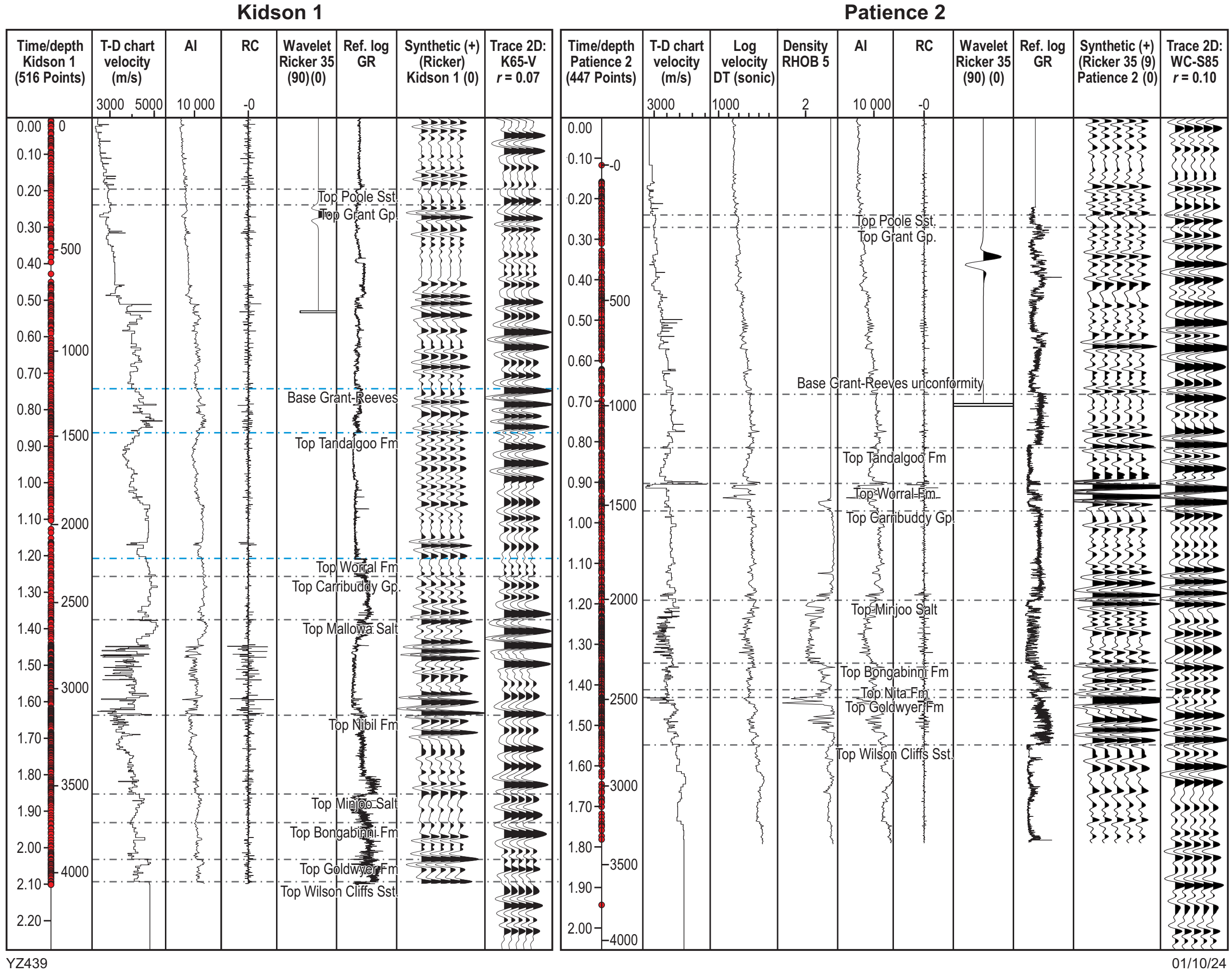

Figure 9. Synthetic seismograms for Kidson 1 and Patience 2 used to calibrate seismic reflection in the Kidson Sub-basin

systematically adjusted to MSL and the surface elevations and bathymetry (Whiteway, 2009) are taken into account for depth conversion (Figs 6, 10).

Top basement (Maps 1–4)

The top basement horizon marks the onset of Canning Basin development during the Phanerozoic and is used to represent the general geometry of the basin in various studies (e.g. Romine et al., 1994; Frogtech Geoscience, 2017). Wells, such as Frankenstein 1 in the west, and Wilson Cliff 1 in the east, intersected basement only in the periphery of the Kidson Sub-basin, (Fig. 11a). Calibration of the basement in these wells indicates a zone of low-amplitude chaotic signatures on seismic sections with few internal structures (Fig. 11b). Where the basement consists of Proterozoic sedimentary or metasedimentary rocks, it can also exhibit some localized parallel internal reflectors below an angular unconformity with the Paleozoic succession (e.g. figure 17 in Zhan and Haines, 2021). By comparison, the overlying Paleozoic strata are characterized by relatively high-amplitude reflections that are more continuous over larger areas. In general, the top basement horizon is a strong contrast that locally induces more than one reflection in its travel path (Fig. 11b). The multiple seismic events add tails to the primary reflection, interfering with the response of the uppermost part of the basement and increasing the uncertainties in the interpretation (e.g. figure 17 of Zhan, 2019a). Thus, the top of the basement is generally tracked along a strong seismic reflection, which may not be the very bottom of the continuous zone of reflectors due to possible reflections from basement beds and multiple reflections.

The Precambrian basement below the Ordovician succession was only intersected at the western and eastern margins of the Kidson Sub-basin in Frankenstein 1 and Wilson Cliffs 1, below 2666 and 3503 m, respectively (Fig. 11a). At the southern margin on the Anketell and Tabletop shelves, mineral drillholes HAC9201 and RUD0007 demonstrated that basement directly underlies the Permian at 419 and 525.5 m, respectively. The basement consists of low-grade metamorphic rocks and is characterized by sharp changes at the basin/basement boundary on the density, acoustic velocity and shallow/deep resistivity logs, indicating increased hardness and reduced porosity. The seismic line that crosses the Frankenstein 1 well location shows that the basement forms a structural dome with its upper part truncated by erosion and is overlain by the Ordovician–Silurian megasequence of the Canning Basin, i.e. below 1.4 s (figure 17 in Zhan and Haines, 2021; Command Petroleum N.L., 1989). This prominent angular unconformity can be tracked further south to the Kidson seismic profile, with a

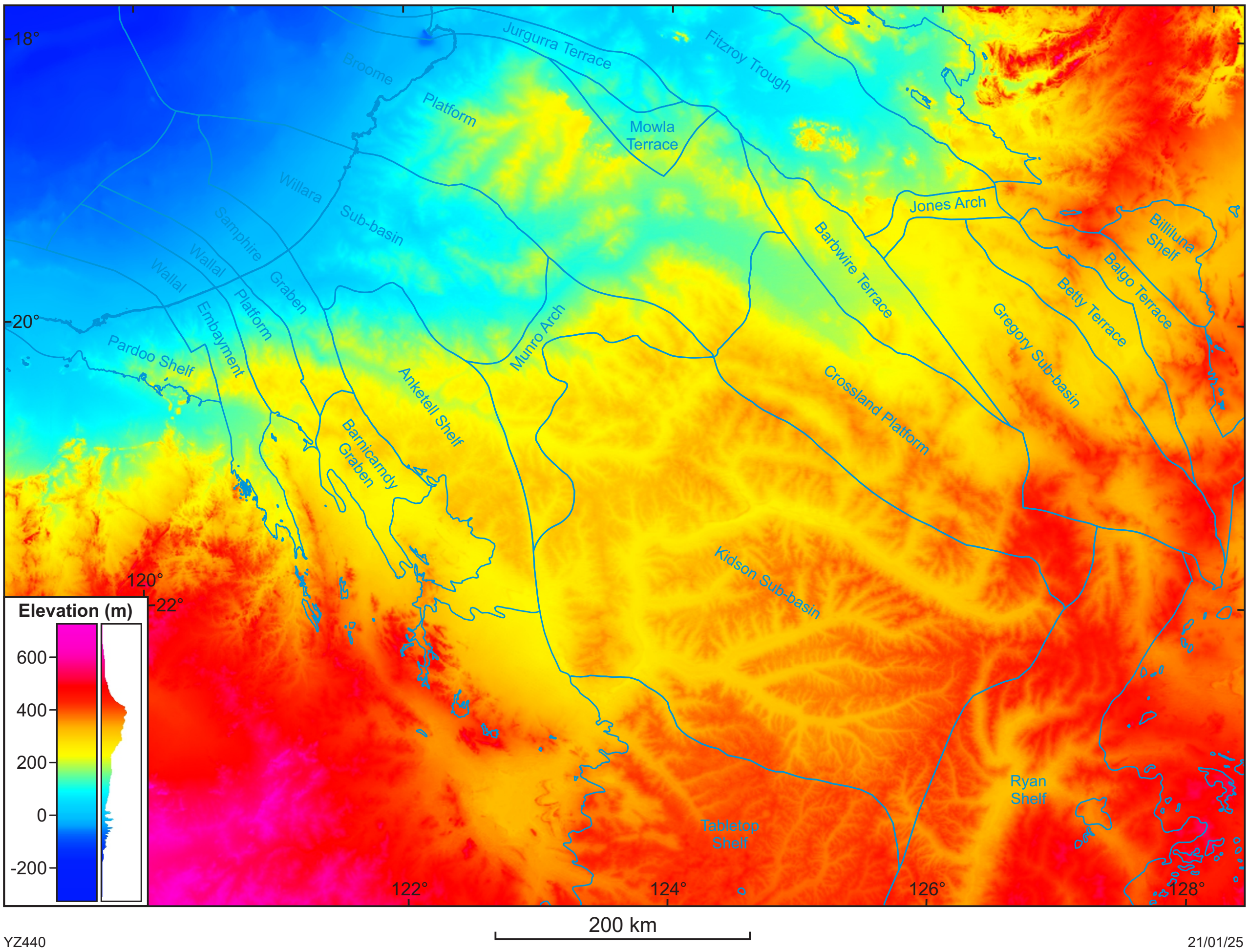

Figure 10. Map of elevation onshore and water depth offshore (Geoscience Australia, 2006; Whiteway, 2009)

relatively high level of confidence across faults (intersection j in figure 11 of Zhan and Haines, 2021). The unconformity deepens steeply to the east, forming a half-graben geometry bounded by the fault (F8) at CDP 49000 (Fig. 11). Following this reflector, the top basement horizon is best interpreted at 1.2 s on the fault's upthrown block to the east, with a significant vertical displacement across the fault.

A fault at the top basement horizon has been observed on reprocessed seismic profiles (Fig. 12) south of Sahara 1, with ~120 ms vertical displacement across the basement and lower Ordovician section. This fault is likely within in a 2.5 km wide fault zone and has a visible gravity signature on the Kidson Falcon® gradiometry data (Fig. 3a; Maps 1–4). The high-resolution gradiometry data was not available for the previous study in this area (Zhan, 2019a), which mapped a fault near the boundary between the Willara Sub-basin and the Anketell Shelf based on vintage seismic data. Since being highlighted in the new gradiometry data, this fault is now extended further into the Munro Arch with evident gravity variations (Fig. 3a). The correlation between the seismic and gradiometry data adds confidence to trace the fault laterally, exhibiting a northwest strike dipping to the southwest. The fault's direction is consistent with others on the Anketell Shelf and the Barnicarndy Graben, suggesting a similar structural event in the southwest of the Kidson Sub-basin.

The deepest parts of the Kidson Sub-basin are in the southern part of the trough and are divided into two depocentres of which a large portion is not covered by seismic or well data. The seismic coverage over the western depocentre of the Kidson Sub-basin is extremely sparse with only two poor-quality lines (S63-D and E) extending towards the depocentre. Seismic coverage is more substantial (though still relatively sparse) in the northwestern side of the sub-basin, between Nicolay 1 and Gibb Maitland 1, where the basement can be interpreted dipping towards the south-southeast to an extrapolated depth of 6300 m in this depocentre, about 100 km southeast of Frankenstein 1 (Maps 3, 4). The area of no seismic coverage is about 100 km by 200 km within the middle part of the sub-basin, and the depth estimation is purely interpolated between the seismic lines to the north and south where basement is shallower. The data interpolation shows that the eastern depocenter could be around 6.6 km deep, about 40 km north of Kidson 1 (Maps 3, 4).

Near the eastern margin of the Kidson Sub-basin, the seismic lines in the vicinity of Wilson Cliff 1 are not good quality but do show a general deepening trend to the west. The basement intersected in Wilson Cliff 1 can be structurally projected to the much better quality Kidson seismic survey (Fig. 11b) by following the strike of boundary faults. With the structural correlation and seismic interpretation, the basement is interpreted to be cut by a set of high-angle faults mostly dipping to the east and the surface deepens steeply from the eastern margin of the

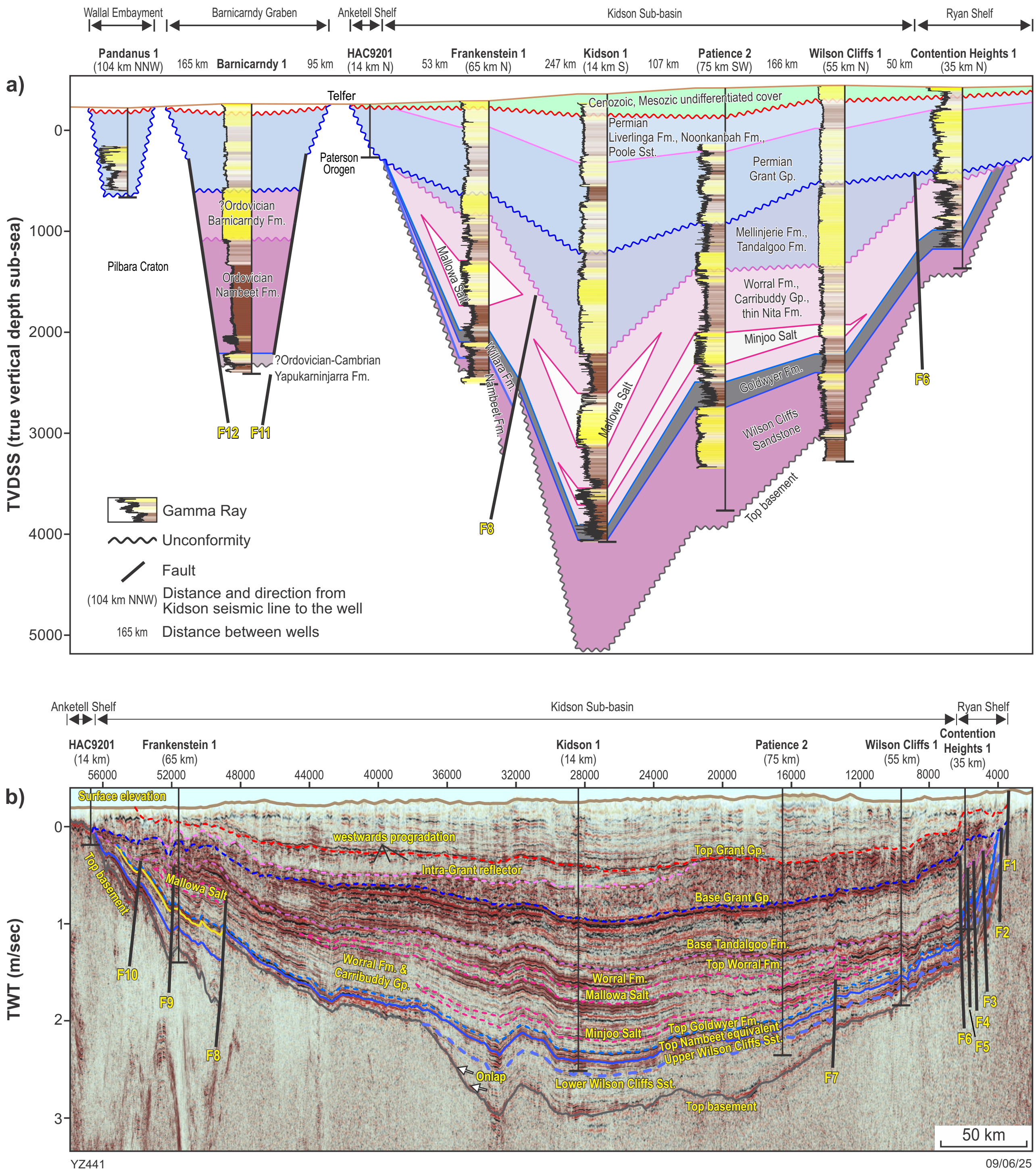

Figure 11. a) West–east well correlation; b) Kidson seismic interpretation. Figures are revised after Zhan and Haines, 2021

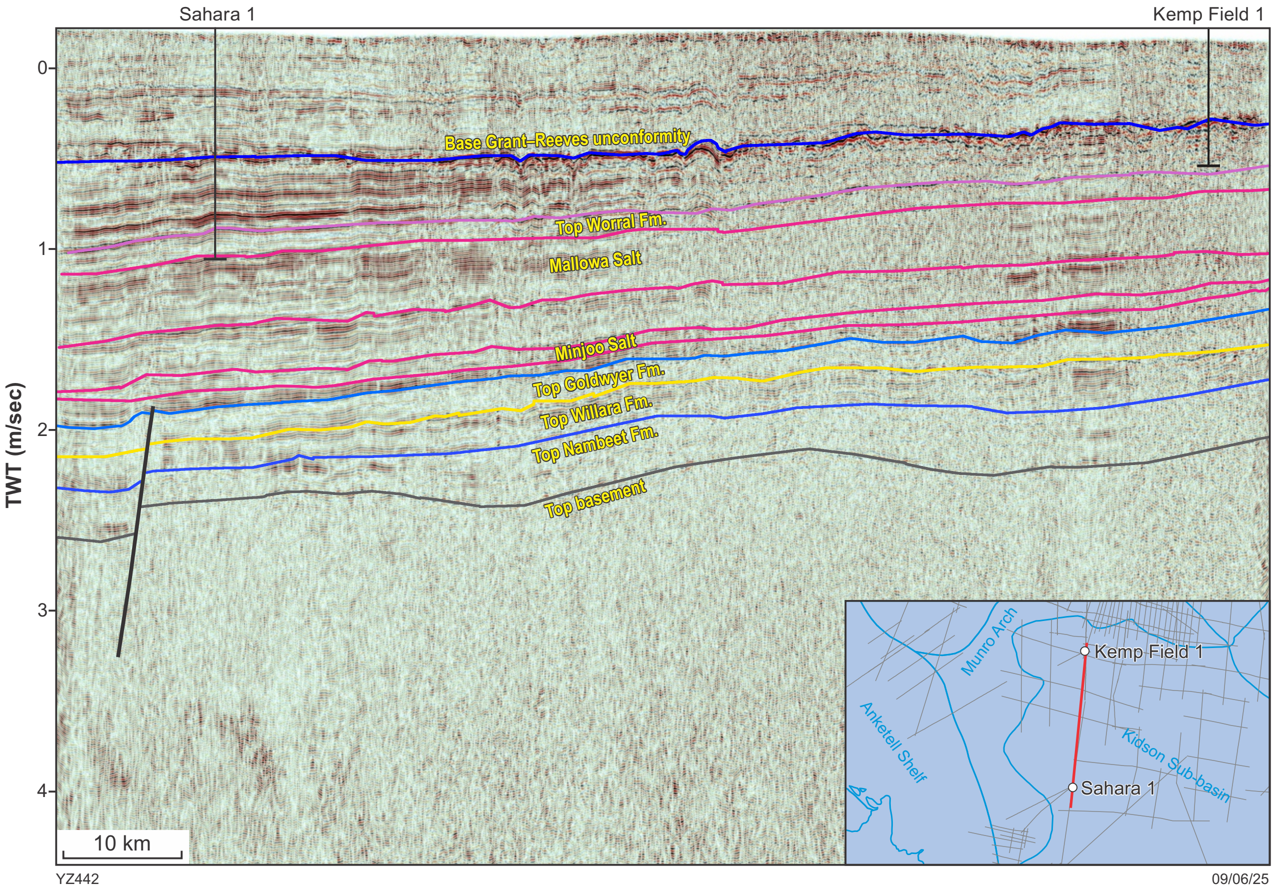

Figure 12. Seismic interpretation near the western margin of the Kidson Sub-basin from Sahara 1 to Kemp Field 1 (TQI-029)

sub-basin towards Contention Heights 1. These near-vertical faults show reverse and strike-slip components across the Ryan Shelf. West of these faults, the basement gently deepens towards the central part of the Kidson Sub-basin, increasing the depth from 4 to 6.6 km within 180 km.

The basement is likely intensely faulted near Patience 2 and the structures appear to be more complex than as seen on the Kidson seismic survey between the sub-basin and the Tabletop Shelf (Maps 1–4). Although a precise interpretation is difficult due to the scarcity of the seismic data, the faults are correlated using seismic displacement and gravity signature to somewhat follow the strike of the gravity, high from the Anketell Shelf to the south of the Ryan Shelf. The depth of the basement was interpreted in the SEEBASE study (Frogtech Geoscience, 2017) to reach around 10 km about 60 km east of Patience 2, as the result of overthrusting of the 'Kidson Craton' from the southwest by the Rudall Province and from the east by the 'Gillespie Terrane'. However, this depth estimate is not supported by subsequent data from the Kidson seismic survey (Fig. 11). The basement in this area is interpreted as slightly deeper than the total depth of Patience 2, based on the indurated lower sandstone package near the bottom of the well, indicated by a significant reduction in the rate of penetration and strong silica cementation described in Haines (2011). The mapped depth to basement ranges from 3700 to 4500 m in the vicinity of Patience 2 and shallows towards the Officer Basin (Fig. 13; Map 4). Based on the seismic signature, it appears that the Neoproterozoic succession of the Officer Basin lies below at least parts of the southeast Canning Basin, with salt pillow-like features below the basement unconformity. The basement horizon is interpreted at the base of the Permian in the southern part of the project area, where the rocks of the Proterozoic Yeneena and Officer Basins mostly underlie the Permian glacial deposits, such as at the intersections in RUD0007, RUD00004, HAC9201, and Dragoon 1 (Fig. 1b; Maps 1 to 4).

A coarse grid of seismic lines across the Crossland Platform shows that the platform joins the Kidson Sub-basin without significant faults (Fig. 14), unlike the separation of the Broome Platform from the Willara Sub-basin by the Admiral Bay Fault Zone to the northwest. Farther inland, these two tectonic units appear to be a single structural entity filled with a Paleozoic succession. The basement under the platform dips gently as compared to that in the southern part of the Kidson Sub-basin. The depth of the basement ranges from 2000 to about 3500 m within the main part of the platform, except the southeastern corner. Within this peripheral area, the seismic, gravity and magnetic data all show that the top basement horizon forms a shallow dome before deepening steeply to the north and northeast into the Gregory Sub-basin (Fig. 15; Zhan, 2022).

Top Nambeet Equivalent (Maps 5–9)

The name Top Nambeet Equivalent horizon was used in the Kidson seismic survey interpretation (Zhan and Haines, 2021) to describe the horizon at the top of the Nambeet Formation in the west and Wilson Cliffs Sandstone in the east of the Kidson Sub-basin. The Lower Ordovician Nambeet Formation is widely intersected in the Willara Sub-basin and the Broome

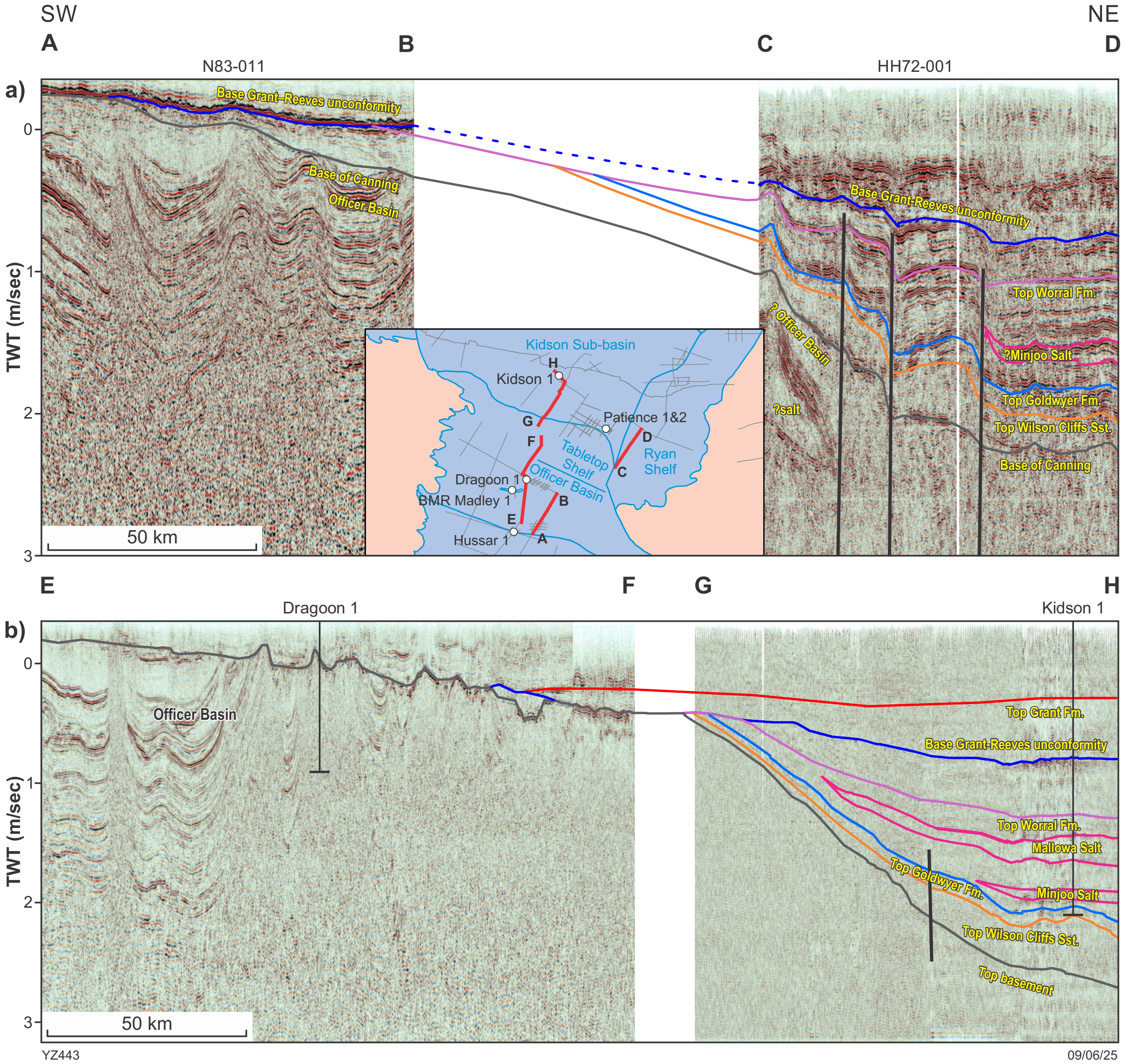

Figure 13. Structural transition from the Officer to Canning Basin in the southeastern area

Platform and is commonly the basal unit of the Canning Basin. It is named after the Nambeet water well less than 5 km southwest from Samphire Marsh 1, where it was first intersected (Playford et al., 1975). The Nambeet Formation in the lower part of Samphire Marsh 1, is a unit of fine- to coarse-grained quartz sandstone and green–grey shale with lesser interbedded limestone, which was nominated as the type section for the formation. A fully cored reference section was proposed in Olympic 1 which contains two formal members: the upper Samphire Marsh Member, dominated by mudstone and carbonate lithologies, and the underlying sandstone-dominated Fly Flat Member (Dent et al., 2021).

The Nambeet Formation has not been intersected east of Nicolay 1 in the Kidson Sub-basin or on the Crossland Platform. The formation is absent in Wilson Cliffs 1, Contention Heights 1 and Patience 2 in the southeast of the Kidson Sub-basin. Instead, those wells intersected the Wilson Cliffs Sandstone which was considered an age-equivalent to the Nambeet Formation based on conodont data from Wilson Cliff 1 (Nicoll, 1993). The Nambeet Formation was intersected in the isolated Barnicarndy Graben, but here it is separated from Proterozoic Yeneena Basin basement by an older Canning Basin unit. This unit, named the Yapukarninjarra Formation, is inferred to be the oldest sedimentary succession thus far intersected in the Canning Basin and may extend down to the upper Cambrian in age (Normore et al., 2023). The Yapukarninjarra Formation consists of red and grey, medium- to coarse-grained quartz arenite with rare mottled bioturbation, local argillaceous sandy siltstone interbeds and poorly sorted arkose at the base (Normore et al., 2023). This formation is restricted to the Barnicarndy Graben and is difficult to correlate with any other sections in the Canning Basin.

The Kidson seismic line exhibits a non-reflective zone above the basement in the middle part of the sub-basin, coinciding

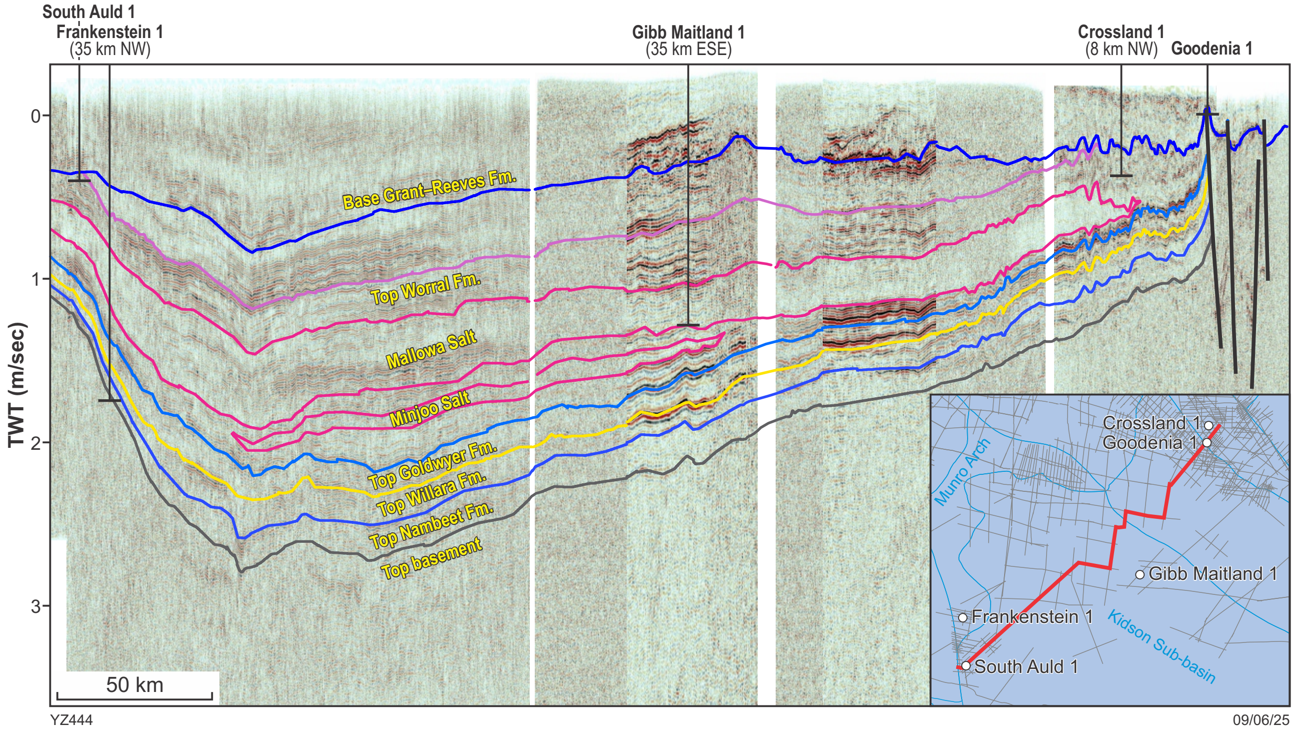

Figure 14. Southwest–northeast seismic interpretation from the Kidson Sub-basin to the Crossland Platform

with several gravity lows about 20 – 50 km wide separated by narrow gravity ridges (Figs 3, 11). This deepest basin unit was interpreted by Carr et al. (2022) as an unknown, possibly Cambrian, section which onlaps the basement in the centre of the basin. This zone is difficult to correlate with any known well intersections in the basin due to the lack of offset lines around the Kidson seismic survey. However, on the reprocessed seismic lines across Patience 2 (Fig. 16), a weak-amplitude zone underneath the reflective section, about 1.5 s, can be calibrated to the basal sandstone package. As the formation identification of this package was ambiguous in the absence of biostratigraphic constrains, Haines (2011) presented three options: an equivalent to the lower Wilson Cliffs Sandstone in Wilson Cliffs 1; a previously unknown unit in the Canning Basin deposited during the earliest phase of basin formation, possibly of Cambrian to earliest Ordovician age; or a pre-Canning Basin ‘basement’ unit, possibly part of the Centralian Superbasin. More recent detrital zircon geochronology results from this unit (Wingate et al., 2019a, b) give a maximum depositional age of c. 493 Ma, indicating that it is not significantly older than the Nambeet Formation or lower Wilson Cliffs Sandstone, and is part of the Lower Ordovician or upper Cambrian succession of the basal Canning Basin. The weak-amplitude zone across Patience 2 is comparable to the lowest part of the basin below the reflective Ordovician section on the Kidson seismic line. Therefore, the weak reflectors directly above the basement can be interpreted as the lower Wilson Cliff Sandstone (Figs 11, 16).

The Nambeet Formation and its equivalent are interpreted to range in depth from 250 to 5750 m below the surface in the southwest part of the Kidson Sub-basin (Map 8). However, the exact location where pre-Permian units begin to emerge beneath the Grant–Reeves unconformity remains highly uncertain along the southwestern margin. This uncertainty affects the assessment of the shallowest occurrence of the Nambeet Formation. The maximum depth of the Nambeet Formation is an extrapolated estimate, situated in the central part of the sub-basin where seismic data are lacking. The isopach map (Map 9) shows thick deposition of the early basinal formations in the Wallal Embayment, the Barnicarndy Graben, the Willara Sub-basin and the southeastern Kidson Sub-basin. On the Crossland Platform, the thickness of the Nambeet Formation and/or Wilson Cliff Sandstone ranges from 200 to 600 m, with a slightly thinning trend towards the Barbwire Terrace. In the Barnicarndy Graben, the Top Nambeet Equivalent horizon is interpreted to be the interface between the Barnicarndy and Nambeet Formations at 1345 m. Thus, the interval isopach between the horizon and the top of the basement in the graben represents the aggregated thickness of the Nambeet and Yapukarninjarra Formations. The isopach in the Wallal Embayment includes all the pre-Permian section, but the interpretation is speculative as no wells have drilled deep enough to intersect the pre-Permian sedimentary succession. Due to the age equivalence to the Nambeet Formation, the upper and lower parts of the Wilson Cliffs Sandstone are included in the same isopach map interval in the eastern Kidson Sub-basin.

Top Willara Equivalent (Maps 10–14)

The stratigraphic interval, directly above the Nambeet Formation in the southern Canning Basin, includes the Willara Formation in the Broome Platform, the Willara Sub-basin, the Goldwyer Formation in the eastern Kidson Sub-basin, and possibly, the Crossland Platform and the Barnicarndy Formation in the eponymous graben.

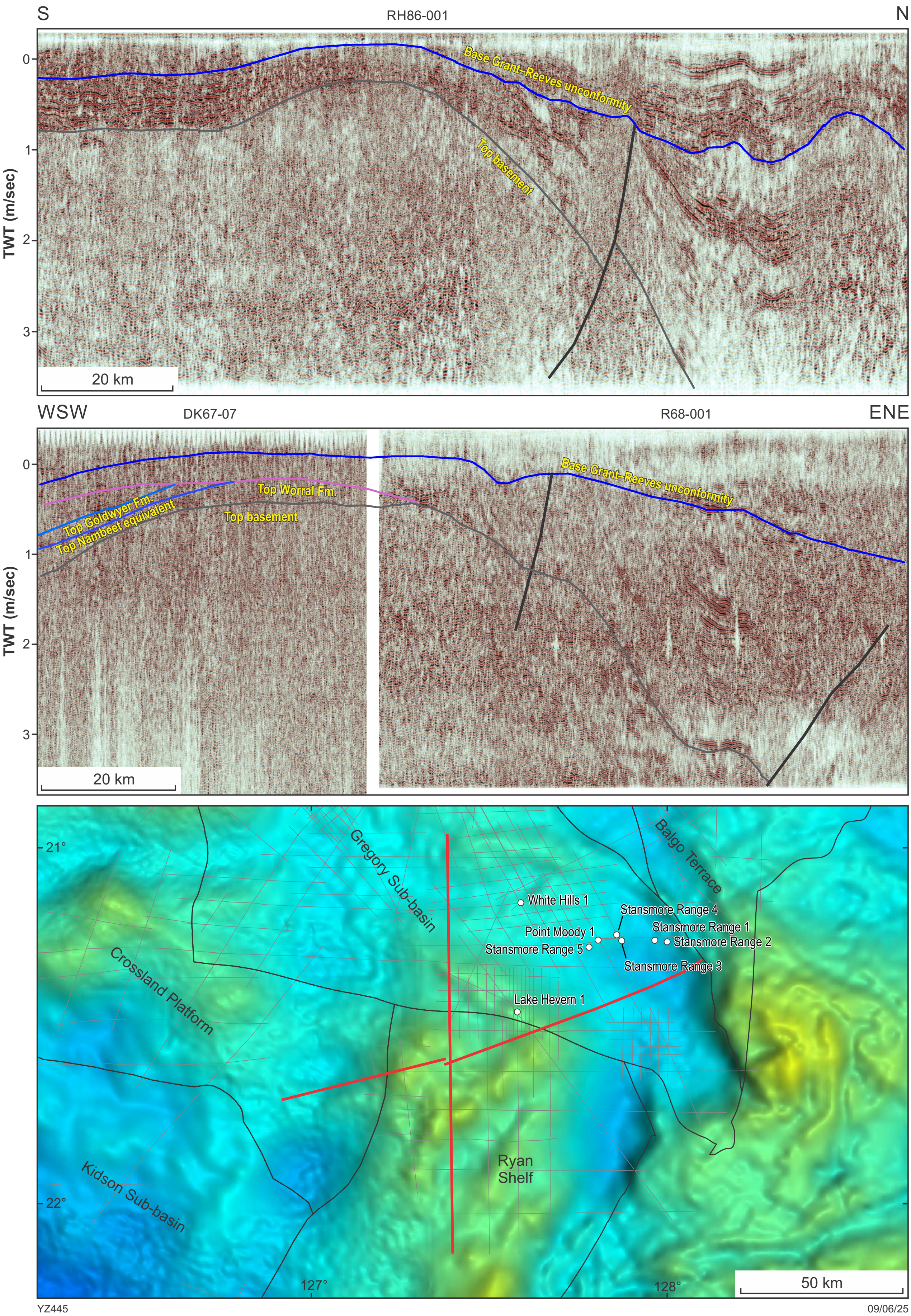

Figure 15. Elevated basement shown on seismic and gravity data in the northern part of the Ryan Shelf

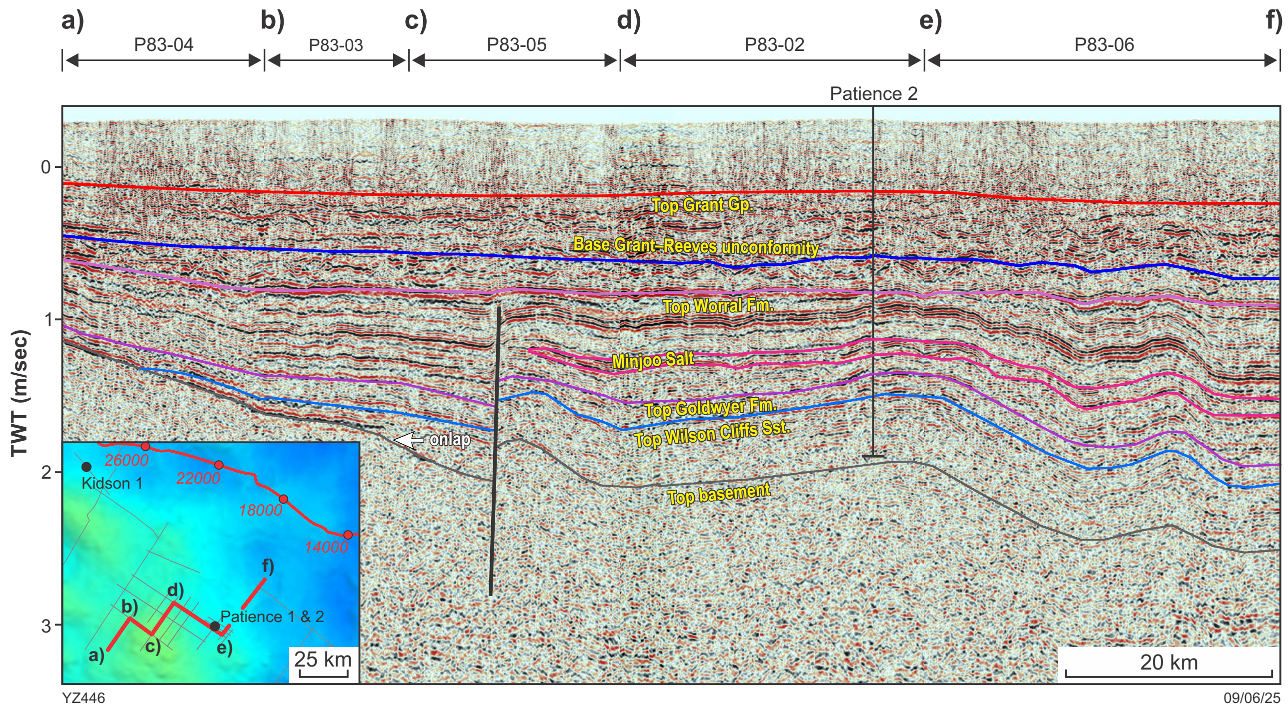

Figure 16. Composite seismic profile across Patience 2 near the southern margin of the Kidson Sub-basin. The Wilson Cliffs Sandstone (i.e. the weak-amplitude zone above total depth) onlaps the basement towards the south and is comparable to the lowest seismic package of the basin on the Kidson seismic profile

The Top Willara Equivalent horizon is defined here as the uppermost boundary of the Willara and Barnicarndy Formations and is marked as absent in the southeastern Kidson Sub-basin where well intersections prove the interval is missing.

The Willara Formation is predominantly limestone, accompanied by lesser amounts of dolomite, mudstone and sandstone, all of which were deposited in shallow marine environments (Haines, 2004). A significant portion of the Willara Formation, if not all, appears to be missing in the southeast of the Kidson Sub-basin, based on the absence of four conodont zones in Wilson Cliffs 1 (Nicoll, 1993). The well intersections in Wilson Cliffs 1, Contention Heights 1, Kidson 1 and Patience 2 show that the Goldwyer Formation directly overlies the Wilson Cliffs Sandstone, suggesting a possible depositional hiatus after the deposition of the Wilson Cliffs Sandstone in the southeast (Fig. 11). TheBarnicarndy Formation in Barnicarndy 1 is composed of 490 m of well-sorted quartz arenite, with the top marked by a major angular unconformity below the Grant Group (Zhan, 2021; Normore et al., 2023). The well completion report indicates that the Barnicarndy Formation is comparable to other Ordovician formations in the Canning Basin based on detrital geochronology and may be a proximal equivalent to the more distal Willara and Goldwyer Formations (Normore et al., 2023).

The presence of the Willara Formation in Frankenstein 1 and Nicolay 1, and its absence in Kidson 1, Wilson Cliffs 1, Contention Heights 1 and Patience 2, confines the southeastern boundary of the formation somewhere between these wells. The Kidson seismic survey shows that a faulted block, F8 at CDP 49000 in Fig. 11b (Zhan and Haines, 2021), in which the Top Willara Formation between CDP 49000 and 55200 is picked on a seismic peak. This strong reflection is a typical signature of the Top Willara Formation as interpreted across the Willara Sub-basin and the Broome Platform (Zhan, 2019a) due to the sharp contrast between the mudstone of the Goldwyer Formation above the high-velocity/high-density material in the Willara Formation. The fault boundary provides a reasonable limit for the extent of the Willara Formation. However, a high level of uncertainty exists as to where and how much of this fault extends into the Kidson Sub-basin. It is likely that the fault propagates to the Crossland Platform in an east-northeast direction and is potentially a major structure as discussed in Zhan (2024; Appendix 2). Without good data coverage, the fault is mapped here as a short splay of the Parallel Range Fault that displaces the Willara Formation at the west-southwest end. The formation onlaps the upper Wilson Cliffs Sandstone and pinches out towards the east-northeast.

The isopach map (Map 14) of the integrated Willara and Barnicarndy Formations show that the thickness varies from 300 to 1000 m in the Willara Sub-basin and the Barnicarndy Graben. The interval rarely exceeds 500 m thick on the Broome Platform. Its presence on the Jurgurra Terrace is highly uncertain due to lack of well penetration and is mapped as relatively thick, ranging from 300 to 700 m, based on the dipping trend of the Lower Ordovician section shown on the Canning Coastal seismic line (Zhan, 2017) near the southwestern boundary of the Jurgurra Terrace. The Willara Formation is possibly thin across the Barbwire Terrace based on intersections of 164 m in Dodonea 1; 243 m in Solanum 1; and 235 m in Acacia 2. This shallow marine deposit thins inland, typically ranging from 200 to 600 m in the northwestern parts of the Crossland Platform and the Kidson Sub-basin before it pinches out to the southeast

Top Goldwyer Formation (Maps 15–19)

The Goldwyer Formation, named after the Goldwyer 1 well, generally overlies the Willara Formation and is widespread in the southern Canning Basin. This unit was mainly deposited in an open marine to intertidal environment (Forman and Wales, 1981; Haines, 2004), and dated as Middle Ordovician based on graptolite and conodont works (Gilbert-Tomlinson, 1961; McTavish and Legg, 1972; Nicoll, 1993; Zhen et al., 2020). The Goldwyer Formation has historically been subdivided into four informal members (Foster et al., 1986, Georgi, 1986; Winchester-Seeto et al., 2000; Haines, 2004), and more recently, three members (Triche and Bahar, 2013; Johnson et al., 2020). Due to high concentrations of marine algae, the Goldwyer Formation has been commonly interpreted to have excellent source rock potential (Foster et al., 1986; Edwards et al., 1997) with a high level of total organic carbon (TOC) – up to 6% on the Barbwire Terrace (Ghori, 2013). Thus, this formation has been intensively studied and was the primary or secondary objective for petroleum exploration. Full core recovery in Theia 1 confirms the lower shale unit of the formation has high porosity (~9.5%) and TOC (~3.8%), good permeability, high wet-mud gas readings, fluorescence and associated hydrocarbon odour (Finder Exploration, 2016).

The Goldwyer Formation consists of predominantly mudstone with intraformational carbonate build-ups observed in exploration wells such as Willara 1 and Thangoo 1A in the Willara Sub-basin and the Broome Platform area, respectively. In the northwest part of the Kidson Sub-basin, Nicolay 1 intersected similar lithologies within the 293 m thick Goldwyer Formation, containing predominantly claystone and minor limestone (New Standard Onshore, 2013b). Towards the southeast, the formation contains less carbonate and becomes sandier. Siltstone and fine-grained sandstone were reported in Kidson 1, Patience 2, Wilson Cliffs 1 and Contention Heights 1. Haines (2004) indicates a broad pattern for the ratio of mudstone to carbonate in which the formation is more mudstone-dominated in deeper basinal regions, while the carbonate percentage generally increases on adjacent platforms and terraces.

The lithological difference between the Goldwyer Formation and overlying carbonate-dominated Nita Formation results in a distinct inflection of both gamma ray and acoustic logs at the top of the formation. The wireline response, aided by biostratigraphic constraints, allows for consistent placement of the Nita–Goldwyer boundary within the southern Canning Basin (Haines, 2004, 2011).

On seismic profiles, the Top Goldwyer Formation is commonly interpreted as an amplitude trough above a relatively thick transparent zone, as opposed to the peak at the Top Willara Equivalent. In the Kidson Sub-basin, the Top Goldwyer Formation is calibrated, via offset seismic lines, to the strong reflectors at 2.35 s and 0.8 s near Kidson 1 and Frankenstein 1, respectively (Fig. 11). This horizon can be consistently tracked between these sites and to the east margin of the sub-basin. However, the thick transparent seismic zone corresponding to the Goldwyer Formation in the Broome Platform and the Willara Sub-basin appears absent in the Kidson Sub-basin and the Crossland Platform (Figs 16, 17). This is probably related to a change of facies and/or reduced thickness, estimated to range from 100 to 250 m in the Kidson Sub-basin. On the Crossland Platform, Santalum 1A and Missing 1 are the only wells that reached the Goldwyer Formation but were drilled near the edge of the Barbwire Terrace and the Broome Platform, respectively. These two wells do not provide sufficient controls for detailed interpretation in this region. Thus, the interpretation in the area relies on the typical signature elsewhere, and the Top Goldwyer Formation is interpreted at a strong reflector above a thick transparent seismic zone (Fig. 18).

The Goldwyer Formation is relatively thick in the southeast of the Kidson Sub-basin and the Broome Platform (Map 19), potentially reaching 800 m or more west of Wilson Cliffs 1 where it coincides with a gravity low. This thickness is comparable to that in the Willara Sub-basin and is inferred to contain significant sandstone and siltstone. The formation maintains a relatively uniform thickness (~300 m) on the northwestern part of the Crossland Platform, and thickens into the Kidson Sub-basin, ranging from 300 to 600 m. The Goldwyer Formation is absent and not mapped in the Barnicarndy Graben based on the drilling result, despite the possible age equivalence of the Barnicarndy Formation to the Willara and Goldwyer Formations. The isopach map of the Goldwyer Formation shows that the formation had been partially or even completely eroded in the northwest Broome Platform, as proven by the Hilltop 1, Hedonia 1, Goldwyer 1 and Olympic 1 results (see erosional boundary on Maps 15–19). The Top Goldwyer Formation horizon is truncated by the Base Grant–Reeves unconformity before dipping towards the Jurgurra Terrace based on the Canning Coastal seismic data. The formation ranges from 100 to 800 m in the southeastern part of the Broome Platform and is potentially thicker farther north with a high level of uncertainty between the Mowla and Barbwire Terraces.

Top and base of the Mallowa and Minjoo Salts (Maps 20–37)

Two evaporate intervals, the Mallowa and Minjoo Salts, have been intersected in the southern Canning Basin and assigned a Late Ordovician to early Silurian age based on biostratigraphic constraints in mudstone interbeds within the Mallowa Salt and stratigraphic relationships within the Carribuddy Group (Haines, 2009). These two salt units have been interpreted and mapped due to their significance as regional seals over the prospective Ordovician section including the Nambeet and Goldwyer Formations. The deposition of the salt is linked to tectonic and sea level changes during the Alice Springs Orogeny initiated in the Late Ordovician (Haines et al., 2001; Zhan, 2019b). Deformation and dissolution of older salt layers might have resulted in brines migrating to the surface, some of which are stranded in restricted inland areas and re-precipitated as modern salt lakes (Zhan, 2019b). The Mallowa Salt of the Carribuddy Group is the upper and generally thicker evaporite interval, with a type section nominated by Lehmann (1984) in Kidson 1 between 2967 and 3501 m that contains mainly halite with minor dolomite, siltstone and claystone. Much thicker intersections were encountered in subsequent wells to the northeast, including at 767 m in McLarty 1, 788.5 m in Pegasus 1 and 800.5 m in BHP Brooke 1. The Minjoo Salt is a lower evaporite interval also defined by Lehmann (1984) from 3905 to 4071 m in Kidson 1 and comprises mainly

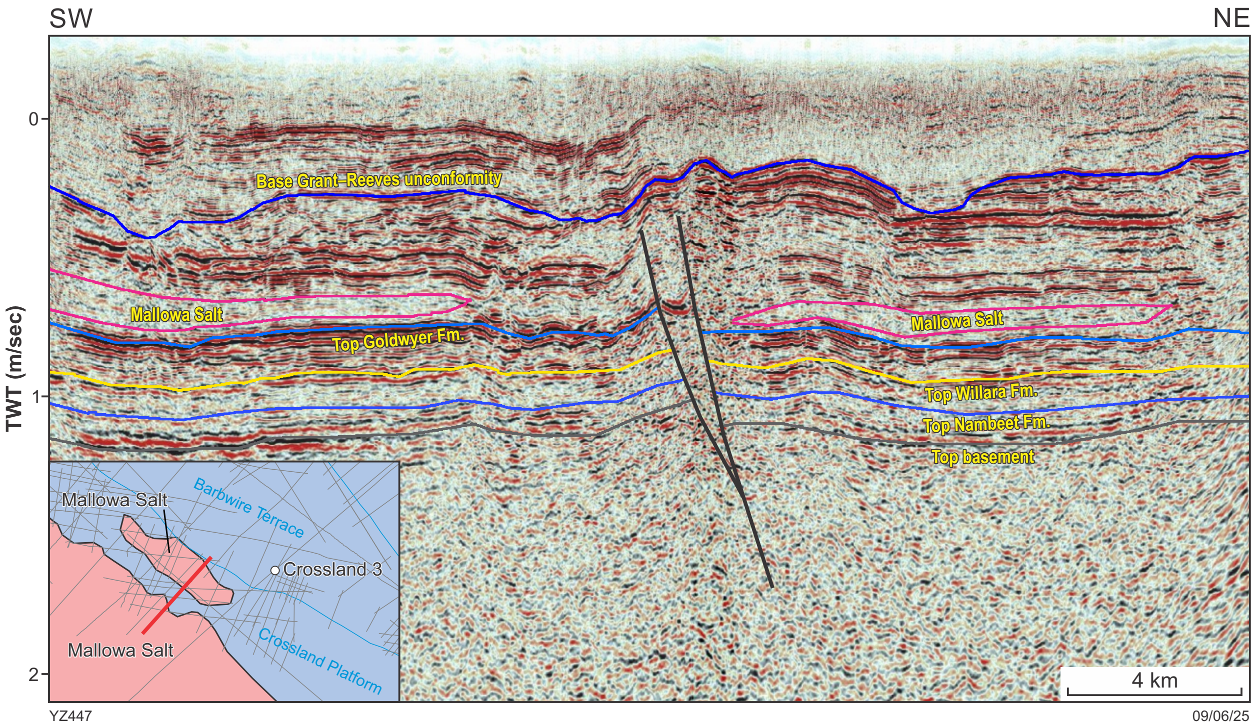

Figure 17. Isolated salt body along the northern margin of the Crossland Platform

halite with a few interbeds of claystone and dolomite, and a minor component of anhydrite. This study follows previous stratigraphic identification in Haines (2009, 2011) to provide details about their distributions based on best available data.

The interpretation of the Mallowa and Minjoo Salts in the Kidson Sub-basin mainly relies on the Kidson seismic survey and small grids of seismic lines near Kidson 1, Patience 2 and Frankenstein 1 to provide key constraints (Fig. 11). These well calibrations are generally consistent with typical seismic signatures of salt in the Willara Sub-basin and southeast of the Broome Platform (figures 13 and 22 in Zhan, 2019a), where the Mallowa Salt generally appears as a thick transparent zone. In some areas, it also corresponds to a package of chaotic weak-amplitude reflections incorporating continuous parallel reflectors on some seismic sections. In the deep parts of the Kidson Sub-basin, the Mallowa Salt is characterized as a mostly thick, continuous, weak-amplitude package, as well as containing some intra-formational reflectors to the west of Kidson 1 (Fig. 11). The formation boundaries of the Mallowa Salt appear to be conformable within the encompassing Ordovician to Silurian succession. Based on well calibration via a composite line, a similar low-amplitude zone in the fault block near Frankenstein 1 is also interpreted as the Mallowa Salt in equivalent seismic stratigraphy (Fig. 11). This bland zone crosses another fault but disappears within 40 km farther west. From the perspective of the 2D seismic section, this may be a separate salt body from the major one in the depocentre; however, these bodies probably connect to each other to the north of the seismic line (Fig. 14).

Due to lack of well penetration on the Crossland Platform, the Mallowa Salt was interpreted empirically based on its typical signature on the Broome Platform (Fig. 14). An isolated salt body probably exists near the northern boundary of the Crossland Platform (Fig. 17), with a northwest-striking fault separating it from the main salt body. The separation might be caused by salt dissolution which is observable in the overlying sections near the fault. To the southeast of this isolated body, the boundary of the main salt unit is difficult to ascertain and generally follows the northwest strike extrapolated from the Broome Platform. For the northwestern part of the Crossland Platform, the boundary of the Mallowa Salt is relatively well controlled based on the dense seismic grid and well penetrations. On the Barbwire Terrace, Mirbelia 1 and 2 intersected another isolated body of Mallowa Salt at 2335 m and 2330 m, respectively, which is shown on seismic profile as a slightly weak reflection interval within the Carribuddy Group. However, this interval is difficult to trace to nearby lines and is tentatively interpreted to be restricted to a northwest-striking fault zone on the terrace.

The Minjoo Salt (Map 28) is relatively thin, mostly less than 100 m in the Willara Sub-basin and the Broome Platform, compared to the younger Mallowa Salt. This thin interval is generally less than one wavelength (120 m) based on an approximate seismic frequency of 35 hertz (Hz) and a velocity of 4200 metres per second (m/s) within the time window of the salt. As a result, the Minjoo Salt does not produce a significant non-reflective seismic zone like the Mallowa Salt. The Minjoo Salt is generally thicker in the Kidson Sub-basin, with a maximum of 313 m in Patience 2, 165 m in Kidson 1, and 115 m in Wilson Cliffs 1, based on well correlations by Haines (2011). These thicker penetrations make the Minjoo Salt relatively more traceable on the Kidson seismic profile compared to elsewhere, but do not necessarily generate a correspondingly thick weak-amplitude reflection due to clastic interbeds in the interval and the large offset between the seismic profile and the wells. The Minjoo Salt is interpreted to be less extensive than the Mallowa Salt (Fig. 11; Map 37). However, it may extend farther southeast than the depositional limit of the Mallowa Salt, across

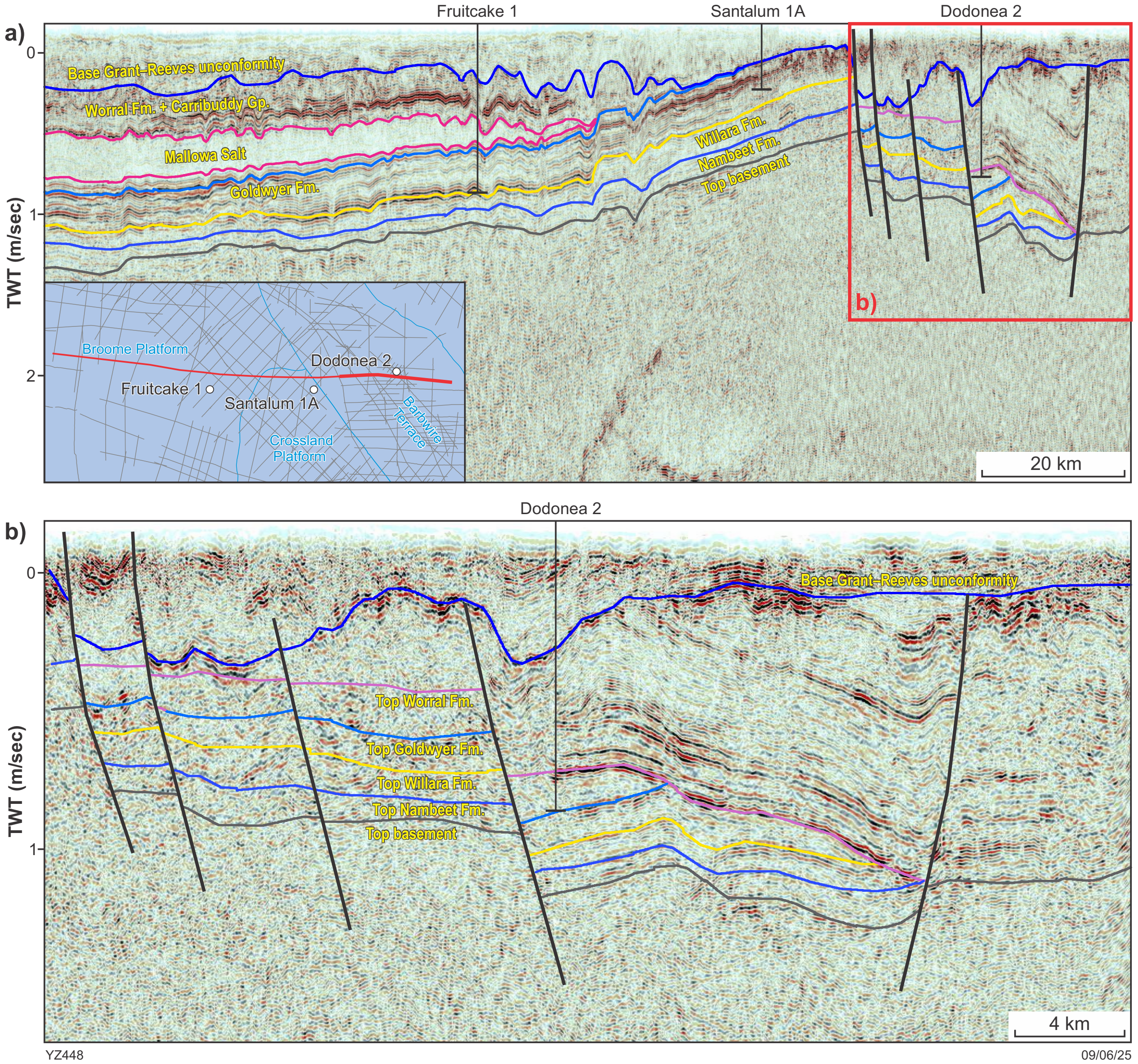

Figure 18. a) Seismic interpretation from the Broome Platform to the Barbwire Terrace; b) enlarged section on the Barbwire Terrace showing the erosion of the Lower Ordovician beneath the Top Worral Formation unconformity

a small-scale fault, and terminate as interpreted on the Kidson seismic line near the structural projection of Wilson Cliff 1, where the weak reflectors pinch out below 1.3 s.

The isopach map of the Mallowa Salt (Map 37) shows that the salt interval generally thickens from the margins to the central part of the southern Canning Basin, with a maximum thickness of 900 m between Frankenstein 1 and Gibb Maitland 1. The two isolated salt bodies on the Crossland Platform and the Barbwire Terrace (Fig. 17) are relatively thin — generally less than 200 m thick. Salt units are absent in the northwestern parts of the Broome Platform and the Willara Sub-basin, as well as the Ryan, Tabletop and Anketell Shelves. The confidence in mapping the Minjoo Salt is considered less than the Mallowa Salt due to the limited well controls, lack of prominent reflectors and very sparse seismic coverage outside of the Kidson seismic survey. It is uncertain whether the Minjoo Salt is continuous from Nicolay 1 across the 300 km gap to Kidson 1. Assuming the salt is present within the gap, as tentatively mapped, the Minjoo Salt still covers much less extent and is thinner, except in the southeast of the Kidson Sub-basin, where it reaches up to 400 m thick between Patience 2 and Wilson Cliffs 1.

Top Worral–Carribuddy unconformity (Maps 38–43)

The Worral Formation was originally assigned to be part of the Devonian – lower Carboniferous megasequence and believed possibly equivalent to the lower Tandalgoo Formation (e.g. Lehmann, 1984, Romine et al. 1994, Kennard et al., 1994., Jones et al., 1998). Detailed examination of drill cores from the Worral Formation by Haines (2009) indicated that the bulk of the Worral Formation is lithologically indistinguishable from the upper part of the Carribuddy Group, indicating a similar marginal marine evaporitic mud flat environment. Reassessment of biostratigraphic constraints suggested that the lower Worral Formation most likely extends in age to at least late Silurian, and it is more suitable to place the formation within the Ordovician–Silurian megasequence along with the underlying Carribuddy Group (Haines, 2009). In addition, a major unconformity was identified lying between the Worral and Tandalgoo Formations in most areas (Warris, 1993; Haines, 2009). This unconformity erodes down to the Lower Ordovician in marginal areas of the southern Canning Basin (Figs 11, 18, 19) and indicates potential as a regional marker for seismic interpretation. However, this contact between the Worral and Tandalgoo Formations may not be valid for the areas where deep erosion occurred, such as in Edgar Range 1, Missing 1, Munro 1, Parda 1. In these areas, the Carribuddy Group unconformably underlies the Permo-Carboniferous section. This study extends the Top Worral Formation unconformity via the top of the Carribuddy Group, mostly towards the northwest in the Broome Platform and the Willara Sub-basin, where the Worral Formation has been eroded (Maps 38–43). The extension of this unconformity can provide a regional coverage for the Ordovician–Silurian megasequence. As the Top Worral–Carribuddy unconformity also marks the base of the Devonian section, this interface is also used to map the extent and thickness of the Devonian section (Map 43).

In the Kidson Sub-basin, the Top Worral–Carribuddy unconformity is marked by a sharp change from massive sandstone in the Tandalgoo Formation above, to an interval of interbedded siltstone, claystone and sandstone below. This horizon is interpreted as a regionally continuous reflector based on calibration with Kidson 1 and correlated to a sinuous reflector at 0.4 s at Frankenstein 1, with the Worral Formation thickness between 100 and 250 m in thickness. Across the eastern boundary fault (F6 in Fig. 11) between the Kidson Sub-basin and the Ryan Shelf, the horizon is shown as an angular unconformity removing much of the Lower to Middle Ordovician section and has significant vertical displacement across the fault. Over the Barbwire Terrace and northeastern part of the study area (Figs 18, 19), the Top Worral–Carribuddy unconformity can be observed dipping towards the northeast and truncates the Lower to Middle Ordovician. The extent and presence of the Worral Formation and Carribuddy Group are uncertain in the deep part of the Fitzroy Trough and the Gregory Sub-basin.

The Carribuddy Group is truncated by the overlying Permo-Carboniferous in the northern part of the Broome Platform (Fig. 14). The Top Worral–Carribuddy unconformity gradually shallows and converges with the Base Grant-Reeves unconformity, which is discussed in the corresponding section below. Based on well intersections in Setaria 1, in which the Worral Formation and Carribuddy Group are both absent, these intervals were probably eroded in a northwest-trending area associated with a structural high between the Barbwire Terrace, and the Broome and Crossland Platforms (Maps 40, 41). In the Willara Sub-basin, the Carribuddy Group extends farther than the preserved extent of the Worral Formation, where the Devonian section is mostly missing. This follows a general tendency within the pre-Permian succession that older units are more expansive than younger ones which recede towards the southeast in the southern Canning Basin. This trend could reflect changes in the depositional extent over time, or removal by erosion beneath the Base Grant–Reeves unconformity.

The Nita Formation (Fig. 2), underlying the Carribuddy Group, ranges in thickness from 0–30 m in the Kidson Sub-basin and reaches about 100 m thick in the northwest. It is difficult to interpret because of the poor seismic resolution and quality. As a result, the base of the Carribuddy Group becomes inseparable from the Top Goldwyer Formation on the seismic data. Therefore, the isopach map related to the Top Worral–Carribuddy unconformity includes the total thickness of the Worral Formation, Carribuddy Group and Nita Formation (Map 42) and covers a larger area than the depth structural maps of the horizon. The aggregated intervals thicken from the Crossland Platform to the central part of the Kidson Sub-basin and reach up to 2900 m between Nicolay 1 and Kidson 1.

The thickness of the overlying Devonian–Carboniferous section (Map 43) is calculated by subtracting the Base Grant–Reeves unconformity from the Top Worral–Carribuddy unconformity. The isopach map shows it is thickest along the Jurgurra to Barbwire Terraces, except for the area of basement, which is high between Matches Springs 1 and Barbwire 1. The interval ranges in thickness from 200 m in the Crossland Platform to approximately 1000 m in the Kidson Sub-basin. A relatively thin Devonian section is mapped from Frankenstein 1 to Gibb Maitland 1 with a low level of confidence due to the lack of good-quality seismic data in the area.

Base Grant–Reeves unconformity (Maps 44–48)

The Base Grant–Reeves unconformity has been widely intersected in petroleum and mineral drillholes and become a major and well-established seismic horizon in the Canning Basin (Mory, 2010). The Reeves Formation and Grant Group are assigned late Carboniferous, and late Carboniferous to early Permian ages, respectively, based on palynomorphs (Mory, 2010; Backhouse and Mory, 2020). This basinwide erosive surface lies either below the Grant Group in the southern Canning Basin, or below the Carboniferous Reeves Formation in the northern Canning Basin (Zhan, 2017). The Reeves Formation does not extend south of the Fitzroy Trough and sections previously interpreted as Reeves Formation in southern areas (Mory, 2010) are now placed within the Grant Group (Backhouse and Mory, 2020). Although the Reeves Formation is not present in the main part of the southern Canning Basin, this study follows the naming conventions of horizons used in previous reports (Zhan, 2017, 2018, 2019a; Zhan and Haines, 2021) to ensure the consistency of basinwide correlation.

In the Kidson Sub-basin, the Base Grant–Reeves unconformity is calibrated to a prominent strong reflector at about 1 s near Kidson 1 and corresponds to a strong undulating reflector at 0.2 s near Frankenstein 1 (Fig. 11). The consistency of this horizon between the two wells increases the confidence when extending interpretations farther east where Patience 2 and Contention Heights 1 can be projected to the seismic profile. The Kidson seismic line shows that the Grant Group in Kidson 1 is expressed as two distinctive intervals. The upper interval is a weak-amplitude zone that thickens and progrades to the west, pinching out about 70 km to the east. The lower interval is a strong-amplitude chaotic zone occupying the whole section of the Grant Group in the east but thinning towards the west. The lower zone consists of medium- to coarse-grained quartz sandstone with variable degrees of sorting and rounding, which was originally included in the now obsolete 'Cuncudgerie Sandstone Member' and 'Braeside

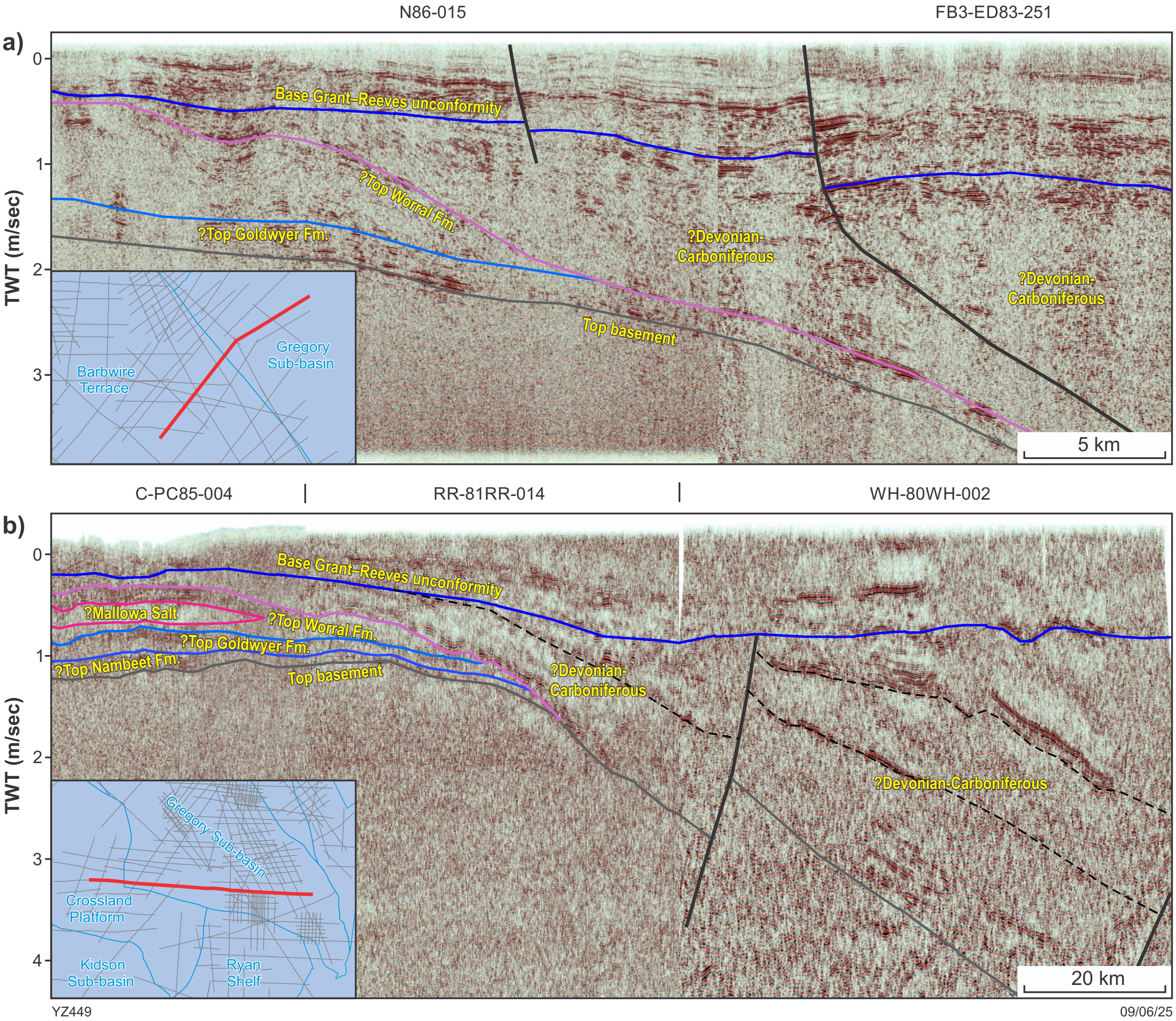

Figure 19. a) Possible truncation of the Lower to Middle Ordovician sections by Top Worral unconformity from the Barbwire Terrace to Gregory Sub-basin; b) from the Crossland Platform to the Gregory Sub-basin

Tillite Member' of the 'Grant Formation' in the Kidson 1 well completion report (Johnson, 1966). In comparison, the upper zone corresponds to a more monotonous sequence of siltstone and fine-grained sandstone. It is possible that the top of the lower sandstone zone might have been eroded in the eastern part of the sub-basin and redeposited in the west as reworked deltaic sediments, based on the westward prograding direction observed in the upper zone between CDP 34000 and CDP 44000.

The Base Grant–Reeves unconformity gradually shallows to the northeast from the Kidson Sub-basin (e.g. 1570 m in Kidson 1; 774 m in Gibb Maitland 1) to the Crossland Platform (e.g. 660 m in Crossland 2). The underlying Devonian section, such as the Tandalgoo and Mellinjerie Formations were completely removed beneath the unconformity in the northwest part of the platform (Fig. 18a,b). Within the Barbwire Terrace, the angular unconformity is prominent between the Grant Group and underlying Devonian section, with a velocity increase of more than 1000 m/s in Crossland 3 indicating that the Devonian section may have experienced a greater burial depth than at the present time (Fig. 20). However, the change of lithology as shown in the gamma ray log would also significantly affect the velocity contrast. Due to the lack of wells on the Crossland Platform, the removal of the Devonian is uncertain, but it is assumed to have been partially eroded towards the Ryan Shelf. In an area with good-quality seismic data, the erosion signature is enhanced by a series of north–south-striking deeply incised channels at the northwestern part of the Crossland Platform (Fig. 21). Buru (2012) interpreted the U-shaped channels to be related to periglacial activity with a northeast transport direction. The morphology and origin of these channels have been analysed in detail by Al-Hinaai and Redfern (2014). These authors consider that the channels were influenced by pre-Grant faulting and salt mobilization, syn-Grant glacial movement, and post-Grant inversion by the Fitzroy Transpression movement.

The isopach map of the Permo-Carboniferous section (Map 48) is calculated for the interval between the Base Grant–Reeves unconformity and the Fitzroy Transpression unconformity discussed below. The thickest deposition in the southern Canning Basin is up to 1700 m in the central part of the Kidson Sub-basin, where the interval aggregates the Grant Group, Poole Sandstone and

Noonkanbah Formation. The section thins towards the Crossland Platform, ranging from 200 to 800 m in that area and containing some localized thick pods within the incised valleys. The Permo-Carboniferous section shallows and pinches out at the outer edges of the Tabletop and Ryan Shelves where it overlies Proterozoic basement.

Fitzroy Transpression unconformity (Maps 49, 50)

The Fitzroy Transpression unconformity was related to a significant tectonic event that shaped the current topography of the onshore Canning Basin. Rattigan (1967) and Smith (1968) identified a series of en echelon, east–west trending anticlines and synclines, as well as numerous north–south trending faults from outcrop in the northern Canning Basin and suggested a tectonic origin by a right-lateral wrenching movement (Fitzroy Transpression of Kennard et al., 1994) during the Mesozoic. The subsequent erosion after wrenching produced an angular unconformity mostly at the base of Middle Jurassic strata (Zhan and Mory, 2013). The stratigraphic gap between the top of the eroded Lower to Middle Triassic sequence and the base of the overlying Middle Jurassic succession is too long to indicate a precise age range for the Mesozoic Fitzroy Transpression wrenching movement. However, data from beyond the Canning Basin may shed light on the timing of the movement. For example, the Canning Basin SEEBASE project (Frogtech Geoscience, 2017) refined the time span to Late Triassic – Early Jurassic based on similar features in three distinct areas:

1. the Browse Basin, where the equivalent movement was from ~228 to ~190 Ma (Struckmeyer et al., 1998)
2. the Petrel Sub-basin, where a similar syn-inversion Malita sequence was dated as Late Triassic to Early Jurassic (Colwell and Kennard, 1996)
3. north of the Woodroffe Thrust, where recent (U-Th)/He thermochronology analysis on zircon suggests an ~215 Ma exhumation event (Quentin de Gromard et al., 2017) that were possibly related to, and propagated from, the Canning Basin.

The wrenching movement might have left a footprint along the terraces in the middle part of the basin. As an example, a sharp change in the seismic reflection indicates the presence of a fault that juxtaposes the Lower Ordovician (Goldwyer, Willara and Nambeet Formations) in the northern part of the Barbwire Terrace (Fig. 22), against a bland seismic zone which is an interval of unknown age. Similar difficulties occur across near-vertical faults near Edgar Range 1 in the Mowla Terrace, where the Grant Group and overlying sections are intensely deformed, as shown on both seismic and AEM sections (Fig. 23). This deformation suggests that the younger strike-slip movement is potentially the cause of the uncorrelatable seismic signature across faults

The Mesozoic section overlying the Fitzroy Transpression unconformity is probably absent on the Crossland Platform where the interpreted bedrock geology (GSWA, 2020a) is shown as Permian. In the Kidson Sub-basin, the unconformity is generally too shallow to be imaged on seismic sections. However, AEM conductivity depth images (CDI), as shown in Figure 23 and figures in Appendix 2, after data inversion by Geoscience Australia provide geophysical information down to 600 m and are suitable for the interpretation of the shallow Fitzroy Transpression unconformity. Based on well calibrations with Frankenstein 1, Wilson Cliffs 1, Contention Heights 1, Kidson 1 and Patience 2, it is evident that a relatively conductive zone corresponds to the Noonkanbah Formation because of its mudstone and siltstone content. The top of the conductive zone approximates the Fitzroy Transpression unconformity, which is mapped via the integration of the wells, bedrock geology and the AEM data.

Based on the data integration, the unconformity generally dips from the surface, about 300 m AMSL in the periphery of the Kidson Sub-basin, to ~30 m AMSL in the centre of the sub-basin which is relatively shallow (~250 m AMSL). The depth of the unconformity highlights a near west–east-trending structural high that divides the sub-basin into north and south structural components (Maps 49, 50). Within the two components, the unconformity lies at ~80 m and ~30 m AMSL, respectively, compared to ~250 m AMSL along the structural high in the central area. This elevated unconformity in the central part of the Kidson Sub-basin may have implication for the Paleozoic succession and basement and is discussed in Appendix 2. Here, the near west–east-trending ridge is mapped as an individual feature only for the Fitzroy Transpression unconformity.

Discussion and conclusion

The subsurface stratigraphy of the southern Canning Basin ranges in age from Lower Ordovician to Mesozoic, deposited in the north-westerly-striking Willara and Kidson Sub-basins, and the Broome and Crossland Platforms as well as in a series of peripheral basin elements. As western parts of this region have been interpreted and mapped previously (Zhan, 2018, 2019; Fig. 1a), this report focuses on the interpretation of the remaining areas, including the Kidson Sub-basin, the Crossland Platform and the Ryan and Tabletop Shelves. The interpretation reveals a more complex and asymmetric structural framework than previously mapped, and refines the spatial extent of key units like the Mallowa Salt, which is now interpreted to be more widespread and thicker in parts of the southern Canning Basin than previously thought. In addition, a regional unconformity at the top of the Worral Formation has been mapped, allowing for better stratigraphic separation and improved assessment of seal–reservoir pairs.

The final maps in Appendix 3 are amalgamated with those from the previously interpreted western part of the basin and extended to cover the elongated terraces and offshore areas in order to provide a regional context of the subsurface geology. However, due to complex geology and limited good-quality seismic data, the interpretation of the extensions to the terraces onshore and offshore are not detailed and are of low confidence; therefore, do not warrant robust interpretation for this project. Detailed interpretation of the terraces would be best incorporated with the northern Canning Basin mapping project, given the similarities of the stratigraphy between them.

Based on the integration of seismic and gravity data, a few faults have been extended, revised, or added in the areas previously mapped in the southwest Canning Basin (Zhan, 2018) and the Broome Platform to the Willara Sub-basin (Zhan, 2019a). These updates are mainly based on

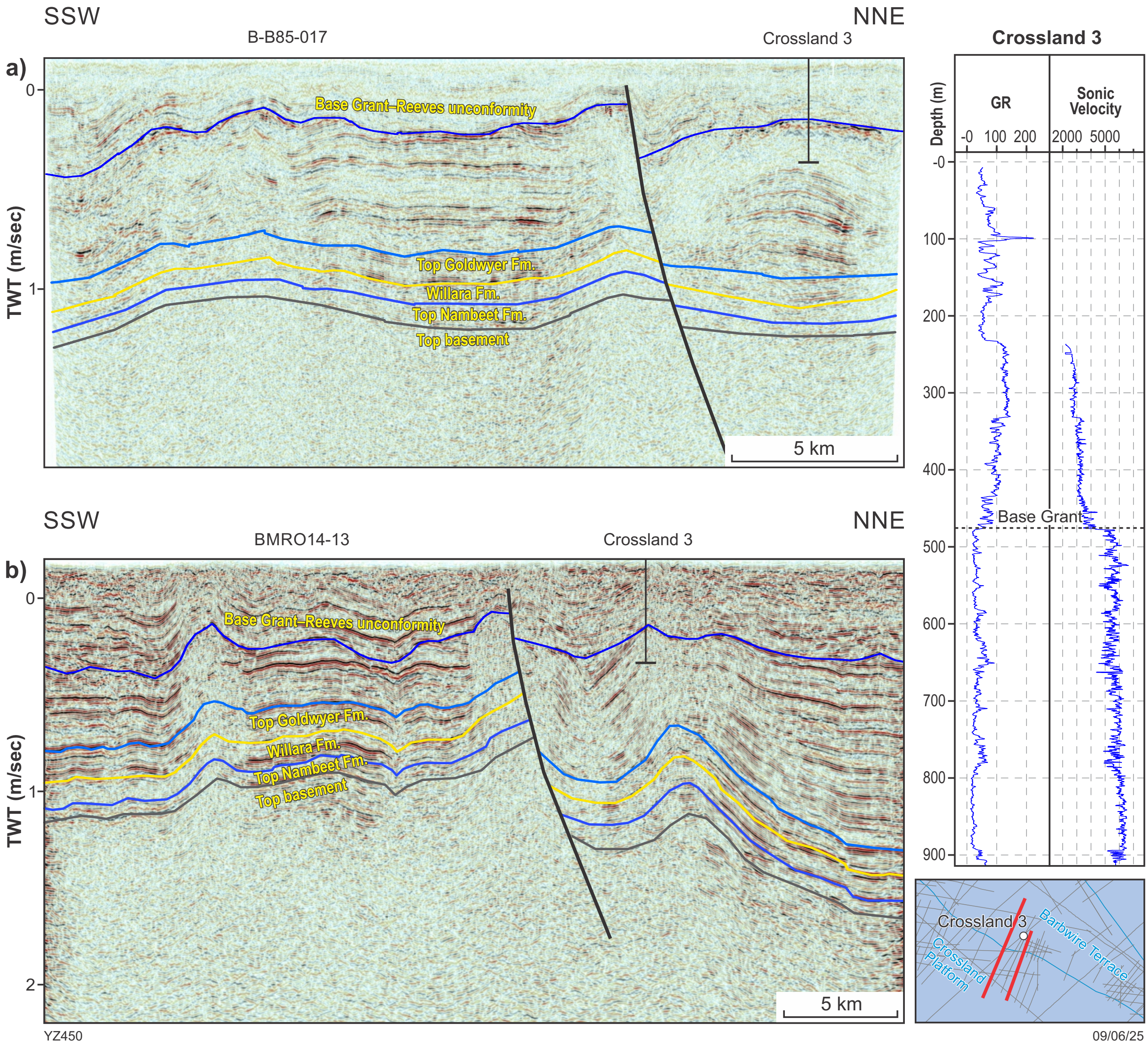

Figure 20. Angular unconformity at the base of the Grant Group on seismic section: a) line B-B85-017; b) line BMRO14-13. Note the sharp increase of velocity by more than 1000 m/s which is associated with erosion and lithology variation in Crossland 3

the Kidson Falcon® airborne gradiometry survey which covers the area from the Kidson Sub-basin to near the coast. This survey provides high-resolution data and enables the interpretation of previously unknown features within seismic gaps, such as those to the west and south of Nicolay 1. Along the Barbwire to Jurgurra Terraces, the faults are interpreted from the integration of the seismic and industry gradiometry data. Although uncertainties persist, the faults can be visualized on the gradiometry data to trend mostly in a north-westerly direction and likely form en echelon patterns along the Dummer Range and Fenton Faults.

In the central part of the Kidson Sub-basin and the Crossland Platform (Figs 11, 14), the faults are difficult to interpret or correlate on seismic or potential field data; thus, most are left unmapped. The lack of faults on the maps is related to the lack of good-quality data rather than the absence of faults. For example, there is the possibility that an elevated basement structure exists in the central part of the Kidson Sub-basin, with the boundary fault initiated before the development of the Canning Basin. The bounding faults of the basement ridge are not delineated in any of the maps in this Report due to the lack of robust supporting evidence. These features are discussed in Appendix 2 because of their potential significance for the prospectivity of resources in the area.

Compared to the previous maps of the Willara Sub-basin and the Broome Platform (Zhan, 2019a), an additional unconformity horizon has been mapped at the top of the Worral Formation, which is merged with the top Carribuddy Group to the northwest where the Worral Formation is absent (Figs 11, 14). This amalgamation of horizons is based on the observation that the Worral Formation is lithologically indistinguishable from the upper part of the Carribuddy Group and both were deposited in similar marginal marine evaporitic mud flat environments. This additional horizon enables separation of the isopach maps of the Devonian from the Upper Ordovician to Silurian interval.

Therefore, eleven horizons have been interpreted within the southern Canning Basin and can be categorized into three groups:

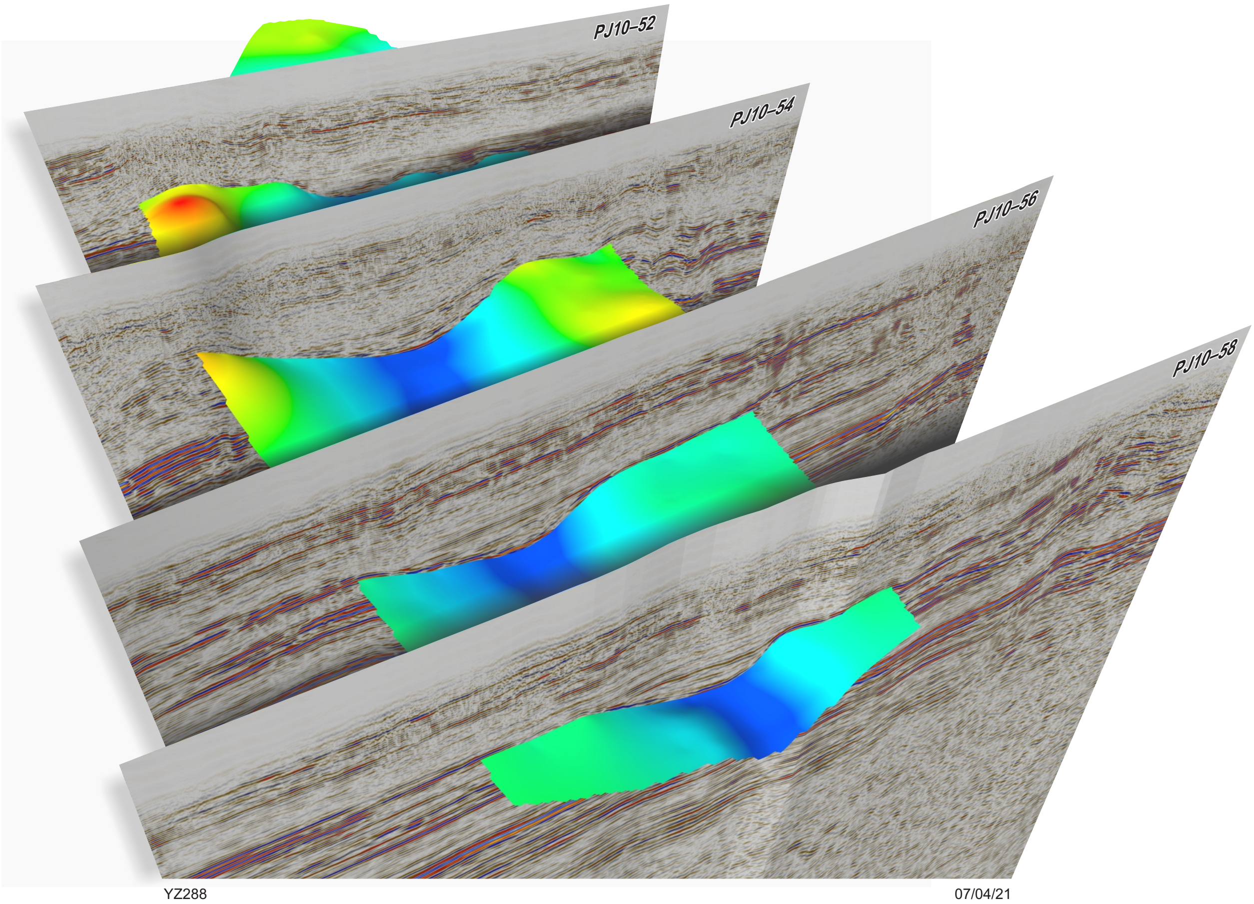

Figure 21. North–south-striking deeply incised channels at the base of the Grant–Reeves unconformity in the northwestern part of the Crossland Platform

1. the top of the basement and the top of the Ordovician units
2. the top and base of the Mallowa and Minjoo Salts
3. angular unconformities at the base of Devonian, Permian and Jurassic strata.

These horizons are selected for interpretation based on reservoir and seal significance for petroleum, helium, natural hydrogen and carbon capture and storage (CCS) prospectivity, and geological implications. The interpretation confidence is highly dependent on the data quality and varies for different horizons. In general, the confidence level of the maps decreases in this order: top of the basement, Base Grant–Reeves unconformity, Top Goldwyer Formation, Top Nambeet and Top Willara Equivalents, Mallowa Salt, Top Worral–Carribuddy unconformity, Minjoo Salt, Fitzroy Transpression unconformity.

Basement and Ordovician units (Maps 1–19)

The depths to the top of the basement, the Nambeet, Willara and Goldwyer Formations, as well as the thickness maps of those formations, provide a broad view of the early phase of basin development (Figs 11, 14). The top basement horizon marks the onset of the Canning Basin's development during the Phanerozoic and is generally marked by a strong seismic contrast with multiple reflections in some places. The basement reaches more than 6.5 km deep near the central part of the Kidson Sub-basin. This estimate is entirely based on mathematical interpolation from the interpretation of data located on the margins of the sub-basin; thus, it differs from an alternative interpretation discussed in Appendix 2. The top of the basement is probably intensely faulted near Patience 2 with complex structures extending towards the Musgrave Province, and gently shallows towards the Crossland Platform without a significant fault displacement, as the Admiral Bay Fault Zone in the northwest does not appear to extend to this area.

The Nambeet Formation shows significant thickness variations across the basin, with thick sections found in the southeast part of the Kidson Sub-basin, Barnicarndy Graben, Wallal Embayment, and the northwest part of the Willara Sub-basin. Within the Kidson Sub-basin, the Nambeet Formation and its age equivalent formations are not dominated by mudstone and carbonate as intersected in the Willara Sub-basin and the Broome Platform. The Top Willara Equivalent is defined as the upper boundary of the Willara and Barnicarndy Formations. In the southeastern Kidson Sub-basin, much of the Willara Formation is missing with the Goldwyer Formation directly overlying the Wilson Cliffs Sandstone, suggesting a depositional hiatus based on the absence of conodont zones in Wilson Cliffs 1. Due to a lack of seismic data in the central part of the Kidson Sub-basin, the southeastern boundary of the Willara Formation cannot be constrained; therefore, it is arbitrarily delineated along a potential basement ridge (discussed in Appendix 2), with fault contact in the southwest and pinching out in the northeast. The Barnicarndy Formation as a proximal age equivalent to the Willara Formation is truncated by the major angular unconformity below the Grant Group. The integrated isopach maps of the Willara and Barnicarndy Formations show thickness variations from 300 to 1000 m in the Willara Sub-basin, similar to the Barnicarndy Graben, but rarely exceeding 500 m on the Broome Platform. As a significant interval for hydrocarbon exploration, the Goldwyer Formation is relatively thick in the Willara and Kidson Sub-basins as well as the Broome Platform, potentially reaching over 800 m based on the isopach map. The variation in its thickness is not as great as for the underlying Willara and Nambeet Formations, suggesting a relatively stable accommodation space and depositional environment with widespread sedimentation.

Both thinning and erosion have been observed near the basin margins for all the Lower to Middle Ordovician intervals (Figs 13, 16, 18, 19). The basement-onlapping patterns within the Nambeet and Willara Formations along the southern margin of the Broome Platform near Parda 1 indicate that the initial phase of basin subsidence was followed by gradual expansion of the accommodation space from the Early to Middle Ordovician (Zhan, 2018). These seismic characteristics echo the interpretation of the geochronological analysis by Haines et al. (2018) that Cambrian magmatism might be the precursor to basin extension, followed by the Early Ordovician sedimentation. Faults with significant throws are present in the northeastern and western parts of the Kidson Sub-basin, as well as the nearshore Samphire Marsh 1 and Admiral Bay Fault Zone, suggesting that the Nambeet Formation was deposited during an active tectonic phase, with rifting and subsidence providing accommodation space for thick sediment accumulation afterwards. Nevertheless, the fact that the Willara and Goldwyer Formations now occupy smaller extents than the underlying succession is likely due to post-depositional erosion near the basin margins.

The erosion, or even complete removal, of the Lower to Middle Ordovician sections can be observed on seismic data beneath the top of the Worral Formation, Base Grant–Reeves unconformity, or possibly the Fitzroy Transpression unconformity. In the eastern part of the Kidson seismic survey, the lower basin strata shallows towards the east, with a relatively constant thickness tilted on the basement and truncated by the Top Worral–Carribuddy unconformity in this marginal area. This geometry differs from a previous perception that the Ordovician sequence onlaps and pinches out against basement to the east (Veevers et al., 1978), suggesting a post-depositional basin inversion as evidenced by Ordovician outliers east of the Canning Basin (Zhan and Haines, 2021; *Ordovician age for the Cobb Embayment* in Haines et al., 2022). The truncation of the Lower Ordovician by the Base Grant–Reeves unconformity is near the Olympic 1 and Samphire Marsh 1 wells and extends to the Anketell to Tabletop Shelves where the Grant Group directly overlies elevated basement and thickens to the northeast. The evidence from seismic data and well intersections is not sufficient to conclude that there is erosion of early basin sections by the Fitzroy Transpression unconformity. The contact between the Mesozoic and Precambrian basement can be interpreted from drillholes in the Pardoo Shelf, where the absence of Paleozoic strata could be the result of either non-deposition or erosion.

Mallowa and Minjoo Salts (Maps 20–37)

The Late Ordovician to early Silurian Mallowa and Minjoo Salts are significant regional seals over prospective Ordovician formations like the Nambeet and Goldwyer Formations in the southern Canning Basin (Figs 11, 14, 17, 18). The two salt intervals separated by the thick Nibil Formation are interpreted as distinct units in this study based on the stratigraphic identification in Haines (2009, 2011).

The shallower Mallowa Salt thickens towards the centre of the southern Canning Basin, with a maximum thickness of 900 m between Frankenstein 1 and Gibb Maitland 1. The lateral extent of the salt has been extended towards the east based on well data in Haines (2009). This is because the Kidson seismic survey (Zhan and Haines, 2021) revealed an eastward shift for the depocentre and it is suitable to place the eastern boundary on the flank of the sag. An isolated salt body is identified from the seismic data on the Crossland Platform, separated from the main salt formation by a northwest-striking fault that potentially caused salt dissolution. The extent of the Mallowa Salt on the Barbwire Terrace is controlled by well data, with Mirbelia 1 and 2 intersecting the formation at 2335 and 2330 m, respectively. However, tracing this interval on nearby seismic lines is challenging, and it is tentatively extended to the northwest-striking fault zone on the terrace.

The Mallowa Salt is absent on the northwest Broome Platform, and the Ryan, Tabletop and Anketell Shelves. The identification of the Mallowa Salt relies on its typical seismic signature observed on the eastern Broome Platform; whereas, the responses from the Minjoo Salt are less prominent on seismic profiles due to being thin and containing clastic interbeds. This lower salt unit has a maximum thickness of 313 m in Patience 2 and 165 m in Kidson 1. It is less extensive and thinner outside the Kidson Sub-basin, and its continuity within the Kidson Sub-basin is uncertain because of large data gaps.

Unconformities at the bases of Devonian, Permo–Carboniferous and Jurassic (Maps 38–50)

Reassessments of the Carribuddy Group and the Worral Formation in the Canning Basin by Haines (2009) suggested that the lower Worral Formation dates from the lower Silurian and is lithologically similar to the upper Carribuddy Group. Haines (2009) inferred a regional unconformity between the Worral and Devonian Tandalgoo Formations, which could serve as a regional marker as confirmed in this study. This horizon should be best developed in the Kidson Sub-basin and Crossland Platform where the base of the Devonian Tandalgoo Formation is traceable on the Kidson seismic survey (Zhan and Haines, 2021). The horizon is shown as a continuous reflector and truncates the Lower Ordovician on the Ryan Shelf. But there is a high level of uncertainty on other seismic data as they are not of good quality. The Devonian Tandalgoo Formation is mainly missing from the Kidson Sub-basin and the Crossland Platform; and the Worral Formation is absent towards the northwest in the Willara Sub-Basin and the Broome Platform.

The unconformity at the base of the Devonian section converges with the Base Grant–Reeves unconformity in some areas like Edgar Range 1 and Munro 1, where the Carribuddy Group is overlain by Permo-Carboniferous deposits. The Base Grant–Reeves unconformity is a prominent erosive horizon across the basin, with consistent characteristics between wells like Kidson 1, Frankenstein 1 and Patience 1 (Figs 11, 14–16). The unconformity shallows from the Kidson Sub-basin to the Crossland Platform, with significant removal of Devonian formations in the northwest Crossland Platform. Deeply incised channels are related to periglacial events and to faulting, salt mobilization, and glacial movement in the northwestern Crossland Platform. The isopach map of the Permo-Carboniferous section aggregates the Grant Group, Poole Sandstone, and Noonkanbah Formation, which are up to 1700 m in combined thickness in the central Kidson Sub-basin, thinning towards the Crossland Platform.

The Fitzroy Transpression unconformity is linked to significant tectonic events during the Mesozoic, creating east–west-trending anticlines, synclines, and possible strike-slip faults along the terraces (Figs 22, 23). This angular unconformity lies mostly at the base of Middle Jurassic strata and is usually too shallow to image on seismic sections in the Kidson Sub-basin and the Broome Platform.

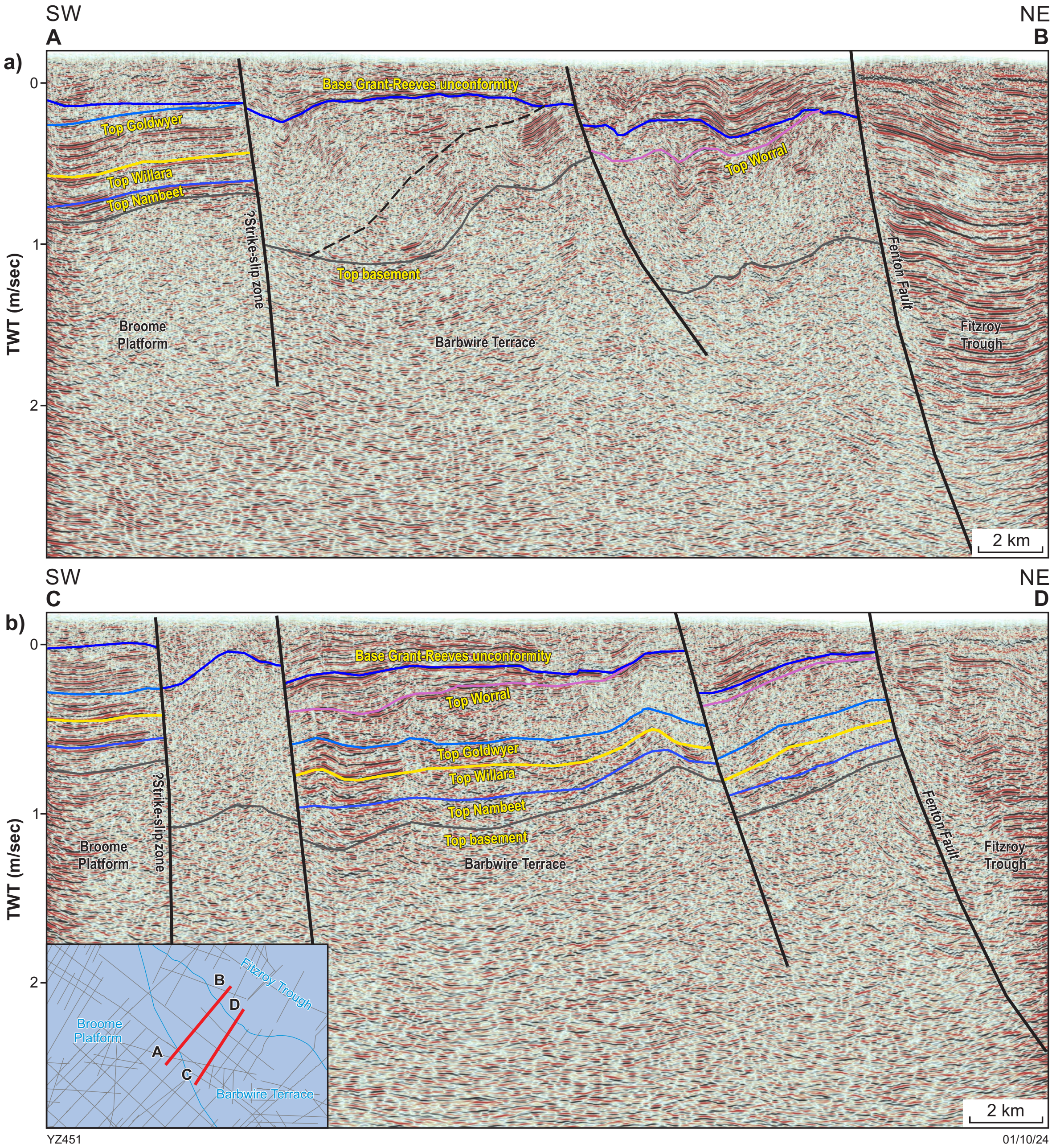

Figure 22. Possible strike-slip movement shown with juxtaposition of reflective Lower Ordovician against bland seismic zones along the Barbwire Terrace

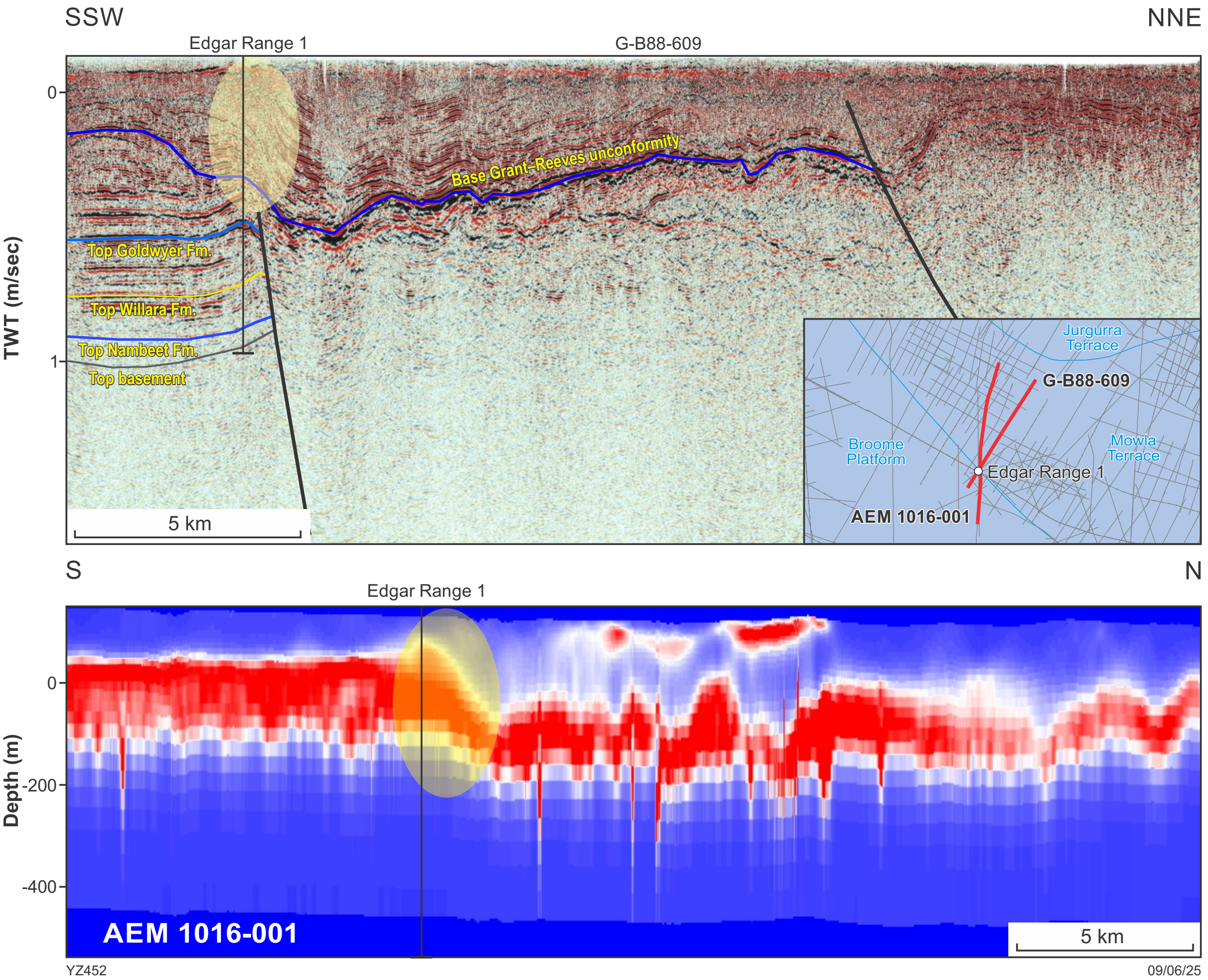

Figure 23. Major structural changes within Permian and Ordovician strata on seismic and AEM profiles, suggesting wrenching movement caused by the Fitzroy Transpression along the southern margin of the Mowla Terrace

However, it can be interpreted from AEM conductivity depth images that show a lithological change corresponding to the top of the Noonkanbah Formation. This unconformity dips from the surface at the sub-basin periphery to about 30 m AMSL in the central area, highlighting a structural high dividing the Kidson Sub-basin into northern and southern components.

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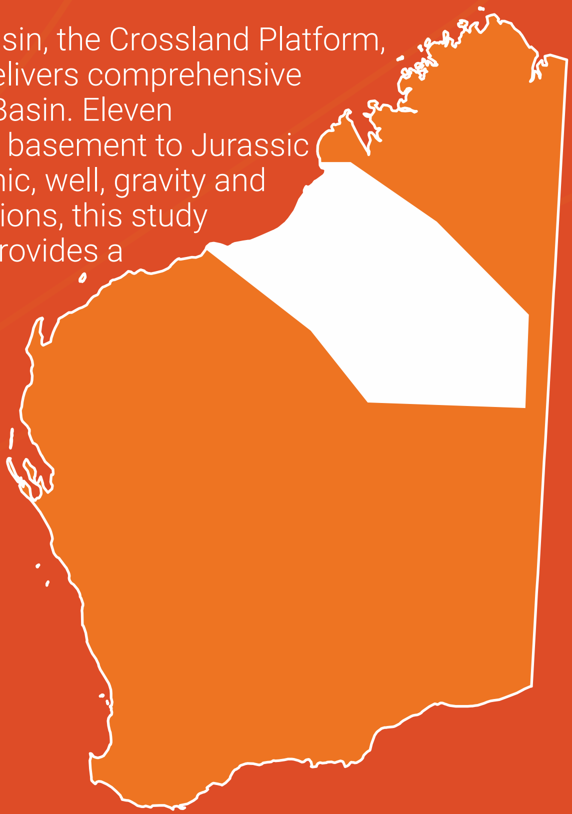
SEISMIC INTERPRETATION OF THE KIDSON SUB-BASIN, CROSSLAND PLATFORM, RYAN AND TABLETOP SHELVES OF THE CANNING BASIN, WESTERN AUSTRALIA

Y ZAHN

This report focuses on the Kidson Sub-basin, the Crossland Platform, and the Ryan and Tabletop Shelves and delivers comprehensive structural maps of the southern Canning Basin. Eleven subsurface horizons from Neoproterozoic basement to Jurassic have been mapped using integrated seismic, well, gravity and electromagnetic data. Despite data limitations, this study enhances geological understanding and provides a foundation for future exploration and geoscientific investigations across the southern Canning Basin.



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