REPORT 216

KIDSON SUB-BASIN SEISMIC SURVEY – A PANORAMA OF THE SOUTHERN CANNING BASIN

by

Y Zhan and PW Haines

Australian Government
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Government of Western Australia
Department of Mines, Industry Regulation and Safety

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Cover image: A combination of a drone photo of the seismic acquisition on the Kiwirrkurra Road and the Kidson seismic profile

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Plate

1. Geological interpretation of the southern Canning Basin along the Kidson Sub-basin seismic survey 18GA-KS1

Kidson Sub-basin Seismic Survey — a panorama of the southern Canning Basin

by

Y Zhan and PW Haines

Abstract

The west–east oriented Kidson Sub-basin seismic survey covers the southern part of the Canning Basin from the Wallal Embayment to the Ryan Shelf, also extending 103 km into the Pilbara Craton and 14 km into the Amadeus Basin at the western and eastern ends of the survey, respectively. The survey is of good quality and shows continuous highly reflective zones and fault displacement across the sedimentary rocks in the basin. Preliminary interpretation of the line was integrated with offset seismic profiles, drillhole data, and gravity and magnetic images to analyse subsurface stratigraphy and structure. The seismic profile reveals two major angular unconformities, the base Grant Group (Permian) and top Worral Formation (Silurian) horizons, which divide the Palaeozoic strata of the Canning Basin into three mega-sequences in the southern Canning Basin.

The Kidson Sub-basin, along with the Ryan and Anketell Shelves, forms a broad sag depression that is relatively undeformed. A few apparent folds are observed near the acquisition bends. These structural artefacts are caused by the crooked geometry of the line over the northerly dipping strata in the southern flank of the basin. Some high-angle faults are present in the lower part of the basin fill near the eastern and western margins, but appear not to be controlling factors for regional basin deposition. These faults indicate a complex tectonic history with normal, reverse and strike-slip movements during the basin's development. The lowermost package in the Kidson Sub-basin is interpreted as upper Cambrian to Lower Ordovician and probably equivalent to the Nambeet Formation, based on its onlapping relationship to basement highs, which are comparable to that in the coastal area near Parda 1, shown on the Canning Coastal seismic profile. These onlaps in different areas indicate that the basin was initiated as several discrete depocentres in the Early Ordovician, then gradually expanded to allow the deposition of the Middle Ordovician strata over basement highs.

The regional seismic line crosses the southern ends of the Barnicarndy Graben and Wallal Embayment obliquely on the periphery of the basin. It shows that the deep Barnicarndy Graben is bounded by high-angle faults, one of which (F11/ F8) swings back through the seismic profile and shows significant displacement in the Kidson Sub-basin. Based on this fault connection and anomalous velocity profile in Barnicarndy 1, the Barnicarndy Graben and Anketell Shelf were more deeply buried than present-day, then uplifted with partial removal of the Permian section during the Fitzroy Transpression movement. The exhumation was likely concurrent with basaltic intrusion and extrusion near the coastal area during the Late Triassic.

KEYWORDS: Canning Basin, Kidson Sub-basin, seismic, Western Australia

Introduction

Southern Canning Basin

The southern Canning Basin is located south of Broome and extends in a southeasterly direction from the offshore northern Western Australia to inland near the Northern Territory border. The onshore area is approximately 240 000 km^2. The southern part of the 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 Barnicarndy Graben, Anketell and Ryan Shelves (Fig. 1; Hocking, 1994a,b). The subdivision's boundaries are commonly poorly defined and are difficult to locate confidently based on the pre-existing dataset. Some adjustments are needed as the data coverage gradually expands. The sedimentary succession of the southern Canning Basin (Fig. 2) is estimated to have a maximum thickness of 10 km near the boundary between the Kidson Sub-basin and the Ryan Shelf, based on the recent SEEBASE study (Frogtech, 2017). Most of the succession is of Ordovician to Permian age, with uncertainties around the timing of the onset of deposition in this part of the basin.

Kidson Sub-basin seismic survey

Within the southern Canning Basin, the Kidson Sub-basin is a major structural component covering approximately 90 000 km^2, and potentially more considering its arbitrary boundaries. Compared to the other parts of the Canning

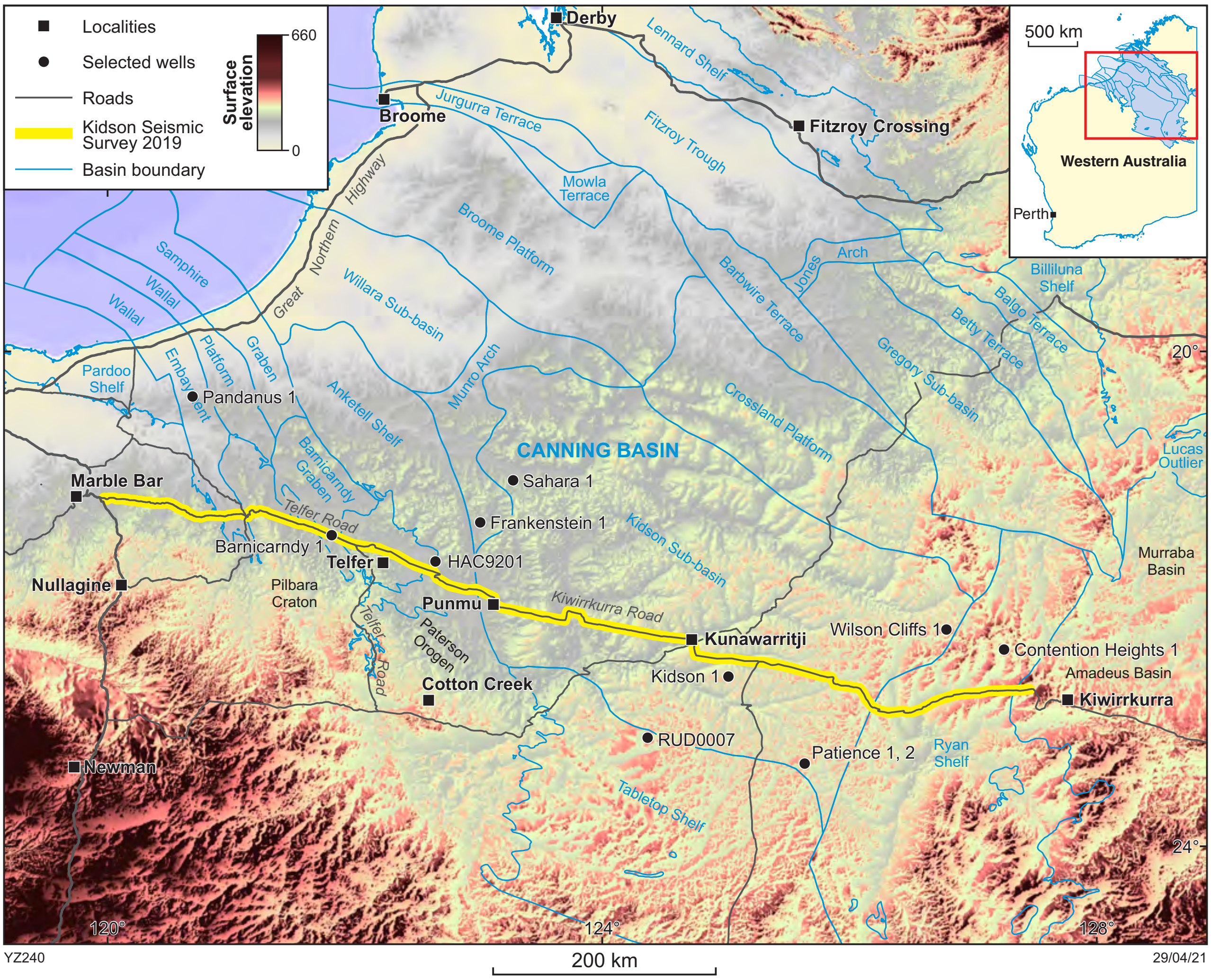

Figure 1. Location map of the Kidson Sub-basin seismic survey draped over surface elevation imagery, with road networks, habitation and tectonic elements (GSWA, 2017a) of the Canning Basin

Basin, the Kidson Sub-basin is poorly covered by seismic data and has a limited number of wells, thus it is one of the least geologically understood provinces with hydrocarbon potential in onshore Australia. The Kidson Sub-basin seismic survey (18GA-KS1) was conducted in 2018 to investigate the basin's architecture and basement geology across this area. The survey was a joint project sponsored by Geoscience Australia and the Geological Survey of Western Australia, under the Exploring for the Future initiative (EFTF) of Australian Government and the Exploration Incentive Scheme (EIS) of the Western Australian State Government.

The total length of the Kidson Sub-basin seismic survey is 872 km and records reflection data to 20 s two-way time (TWT). The survey crosses the southern region of the Canning Basin from approximately 30 km west of the Kiwirrkurra community near the Western Australian/Northern Territory border to about 20 km east of the Marble Bar township in the eastern Pilbara region (Fig. 1). The seismic survey was titled 'Kidson Sub-basin' as this is the most extensive tectonic element along the route, but it also covers the following areas: the western edge of the Amadeus Basin and underlying Arunta Orogen; the Ryan and Anketell Shelves; the Barnicarndy Graben and Wallal Embayment; and the Precambrian basement elements, including the Paterson Orogen, Fortescue and Hamersley Basins, and the Pilbara Craton. As the survey title exclusively refers to the Kidson Sub-basin, this Report uses other terms interchangeably, such as Kidson seismic profile and Kidson seismic line, to avoid the confusion when interpreting other structural units.

The final survey data is of good quality, particularly in the Kidson Sub-basin, showing continuous parallel reflectors across the depocentre and faulting near the basin margins (Plate 1). The seismic data is constrained by the offset petroleum exploration well Kidson 1, as well as projections from more distant wells, including Frankenstein 1, Patience 2, Wilson Cliffs 1 and Contention Heights 1. The integration of new data with wells sheds light on the depositional history and structural evolution of the southeast Canning Basin.

Interpretation of basin subdivisions

The Kidson Sub-basin seismic survey was processed with a minimum phase and recording polarity for the final trace polarity (Velseis, 2019). The final seismic datum was placed at 500 m above mean sea level, which is beyond the highest

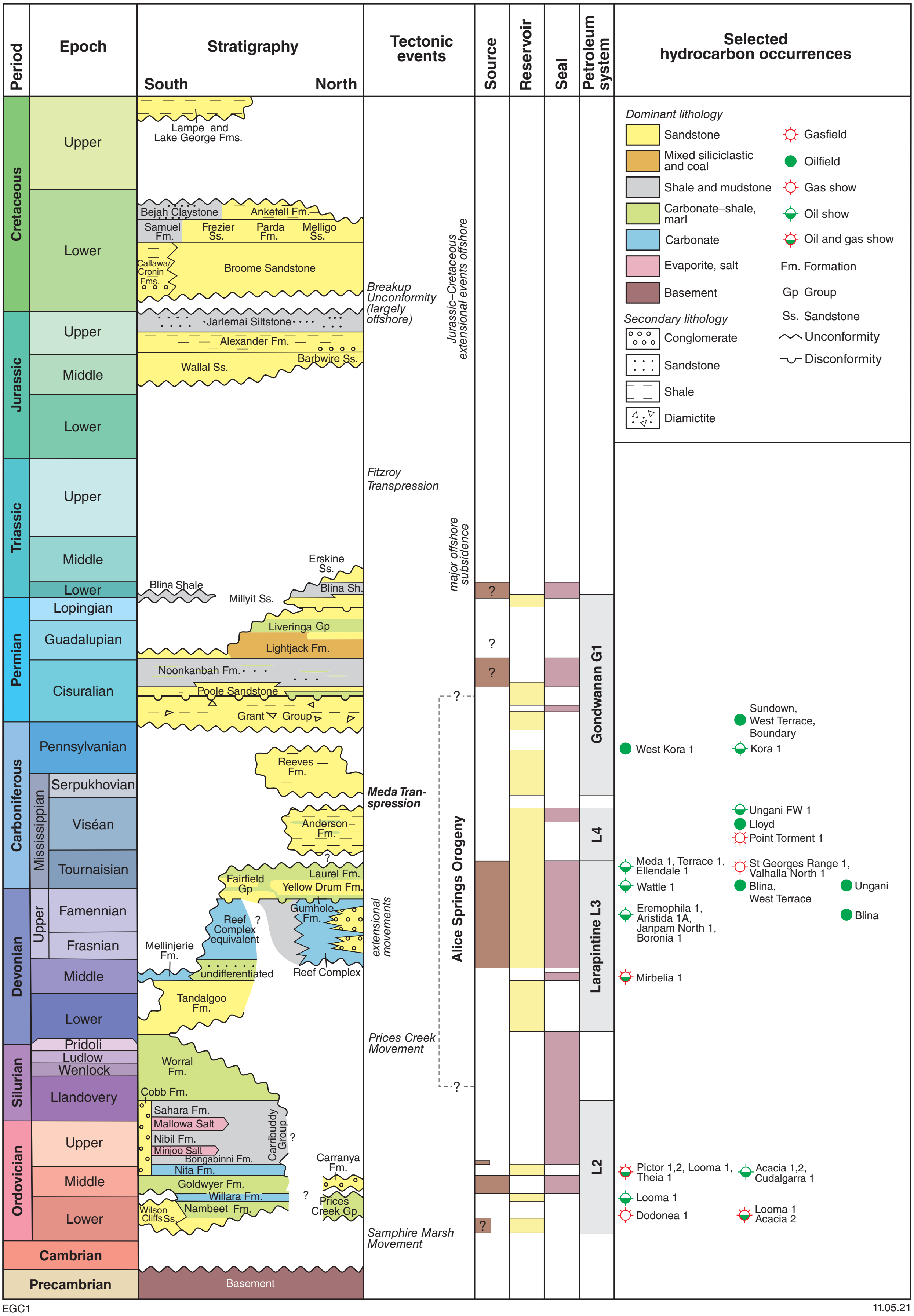

Figure 2. Stratigraphy of the Canning Basin, modified from Haines (2009), Haines et al. (2013), Backhouse and Mory (2020)

surface elevation (480 m), in order to preserve the data in the elevated areas. Static corrections were applied to the seismic data to compensate for the effects of variations in elevation, weathering zone thickness, weathering zone velocity and reference to the processing datum. A replacement velocity of 2500 m/s was used between the near-weathering zone floating datum and the final datum.

The current interpretation of the seismic profile is integrated with drillhole information, nearby seismic profiles, gravity and aeromagnetic data, and surface geological maps, focusing on the Paleozoic section in the Canning Basin. The current tectonic subdivisions of the Canning Basin (GSWA, 2017a) are broadly consistent with the geometry that is shown on the Kidson seismic survey, with the Kidson Sub-basin flanked by shallow shelves on each side. However, the current subdivision boundaries do not coincide with appropriate seismic features identified in the Kidson seismic survey, and thus need to be updated. In this Report the numbers of common depth point (CDP) at current boundaries are indicated in the header of each section, which then provides alternative CDP locations of the proposed boundary revisions that better correspond to the seismic profile.

As an essential precursor to the seismic interpretation, well-ties derived from sonic data and/or velocity profiles of exploration wells were used to calibrate the stratigraphy that had been previously intersected. However, most of the wells have large offsets from the seismic profile, creating difficulties in orthogonal projection of the wells for the calibration. Because the strata is commonly gently dipping with lateral changes in unit thicknesses, some adjustments are needed to allow for the uncertainties over the projection distance between the wells and the seismic profile.

Western Amadeus Basin (CDP 2000 to 3300; proposed boundary from CDP 2000 to 3400)

The acquisition of the Kidson Sub-basin seismic survey started in the east over the western edge of the Amadeus Basin, 13 km to the east of the Canning Basin (Fig. 3). The western edge of the Amadeus Basin is positioned at the major fault (F1 at CDP 3400; Lasseter Shear Zone in Doublier et al., 2020) across which the Canning Basin thickens considerably towards the west. The Kidson seismic survey covers the western side of a regional north–south striking gravity ridge, with the basement deepening to the west (Fig. 4). The eastern side of the ridge in the south (HH72-004, Fig. 5) shows that the shallow bright reflectors possibly correlate to the thin Permian of the Canning Basin covering the Amadeus Basin. The deep reflectors dipping towards the east below 2 s likely correspond to the basement. Thus, the reflections with opposite directions of deepening westwards on the Kidson seismic profile (Fig. 3) versus eastwards on HH72-004 line (Fig. 5) may indicate a dome structure in the basement along the regional gravity ridge.

Within the gravity ridge, a major structural lineament runs parallel to the strike of the ridge with a total length of about 200 km. The lineament has a similarly prominent signature on the first vertical derivative magnetic image (Fig. 4a,b), confirming that a Precambrian basement feature runs along the outcrop boundary between the Canning and Amadeus Basins (thick black line in Fig. 4). The Kidson seismic profile shows that the gravity lineament is correlated to a deeply seated near-vertical fault (F1) that separates the basements under the Canning and Amadeus Basin at CDP 3400 (Fig. 3). Based on the gravity and magnetic data, this fault extends to the northern limit of the Ryan Shelf (Fig. 4), and beyond to the eastern Gregory Sub-basin, where the fault is bounded by a wedge-shaped depression in the Canning Basin against the Neoproterozoic Murraba Basin to the east (Fig. 6). The stratigraphy in the wedge is constrained by Lake Hevern 1 that yielded Devonian palynomorphs near total depth, and has a potential correlation to a Late Devonian sandstone-dominated package in Ngalti 1, about 179 km to the north (Haines, 2020, written comm.). The internal reflectors of the Devonian package show a converging trend from a faulted anticlinal structure at Lake Hevern 1 to the F1 boundary fault with an angular unconformity (Base Grant) at the base of Permian package (Fig. 6). The converging internal reflectors in the wedge do not indicate a syndepositional rifting during the Devonian in the northern Canning Basin. Instead, they suggest that postdepositional movements more likely occurred along the fault with a compressional or strike-slip component near the eastern margin of the Canning Basin.

The Permian succession appears to be thin near the eastern boundary of the Canning Basin, and is absent over the Amadeus Basin east of the fault (F1 in Fig. 3). This Permian succession is probably equivalent to that drilled in the nearest mineral drillholes about 15 km north of the seismic survey at the Top Up Rise Prospect (Fig. 4; Marshall, 2013; Marshall and Smith, 2014). The drilling reports interpreted a shallow Permian section consisting of a 100–150 m thick sequence sandstone, siltstone and conglomerate beneath 1–4 m of red dune sands below the surface.

Ryan Shelf (CDP 3300 to 15750; proposed boundary from CDP 3400 to 6150)

Due to the lack of good-quality seismic data along the eastern margin of the Canning Basin, the Ryan Shelf was previously a poorly-defined tectonic element, about 120 km wide between CDP 3300 and 15750 along the seismic route (Fig. 3) (Hocking, 1994a; GSWA, 2017a). The shelf was originally interpreted to have a transitional monoclinal boundary on its western side (Gorter et al., 1979; Hocking, 1994b). In the east it abuts the Amadeus Basin with a fault defined from outcrop geology, gravity and magnetic images (GSWA, 2017b, 2018). Doublier et al. (2020) refer to the fault as the Lasseter Shear Zone, which was conceptualized from a gravity image and was used to explain the distribution of Phanerozoic basin depocentres, including the Canning Basin by Braun et al. (1991).

The Kidson seismic profile confirms the existence of the Ryan Shelf, but as a narrower feature with a different structural configuration from previous interpretations. As revised here, the Ryan Shelf is restricted to a fault zone (F2–6 in Fig. 3), with the western boundary defined by F6 at CDP 6150. The fault zone encompassed by the shelf is about 30 km wide along the seismic profile, which is about 90 km narrower than the previous delineation. Within the zone, the faults are near vertical and have greatest displacement in the lower part of the basin succession. The orientation of these faults is assumed to be sub-parallel to the basin-bounding fault (F1 in Fig. 3; Lasseter Shear Zone in Doublier et al., 2020)

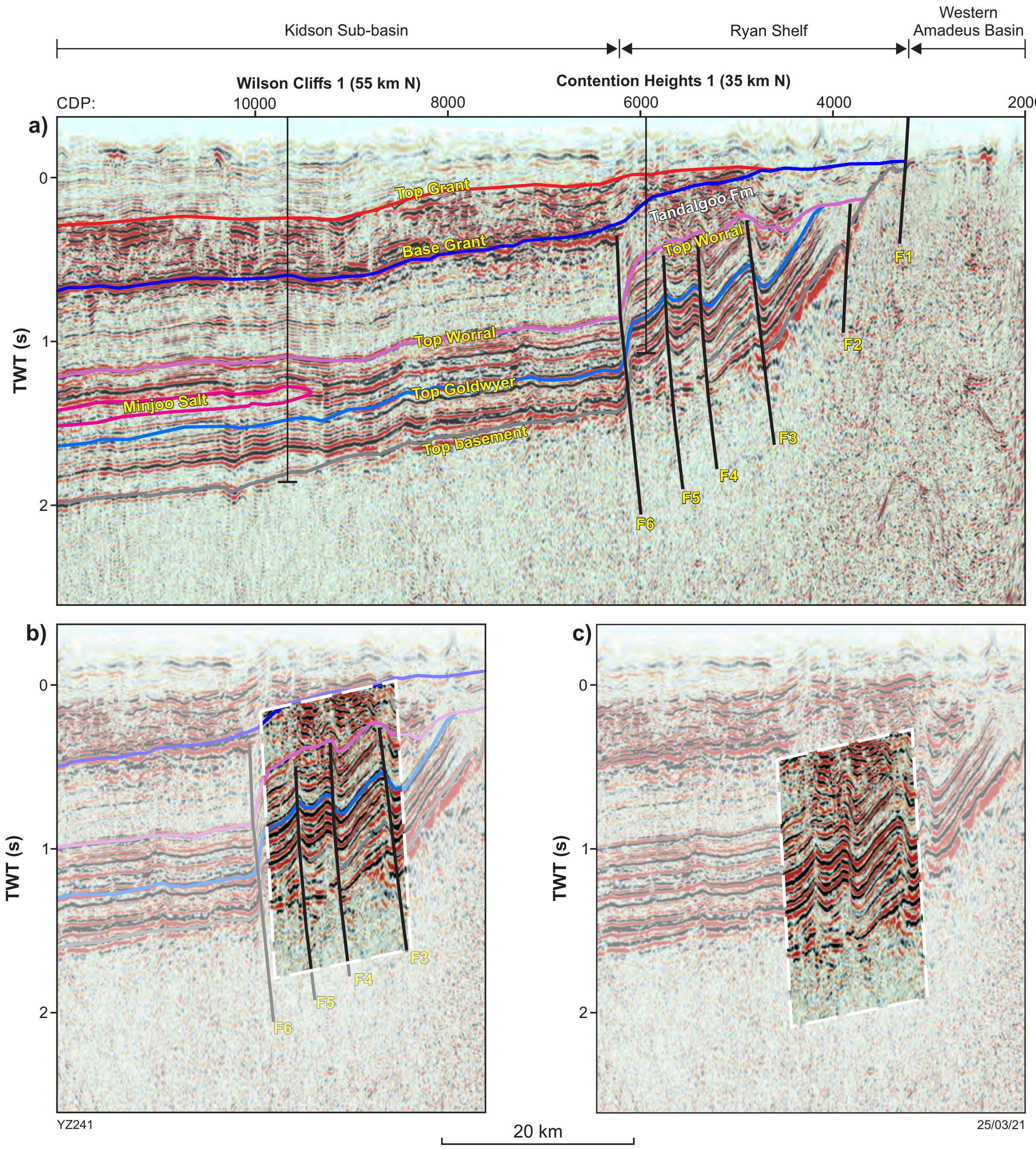

Figure 3. Seismic profiles in the eastern margin of the Canning Basin: a) interpreted seismic section from CDP 2000 to 12000, see Figure 4 for profile location; b) seismic reflection and interpretation of the western fault zone of the Ryan Shelf (highlighted in white dashed box); c) comparison of seismic reflection between the fault zone (white dashed box shifted across the boundary F6 fault) and adjacent Kidson Sub-basin, showing the continuity and similarity of the Lower Ordovician strata

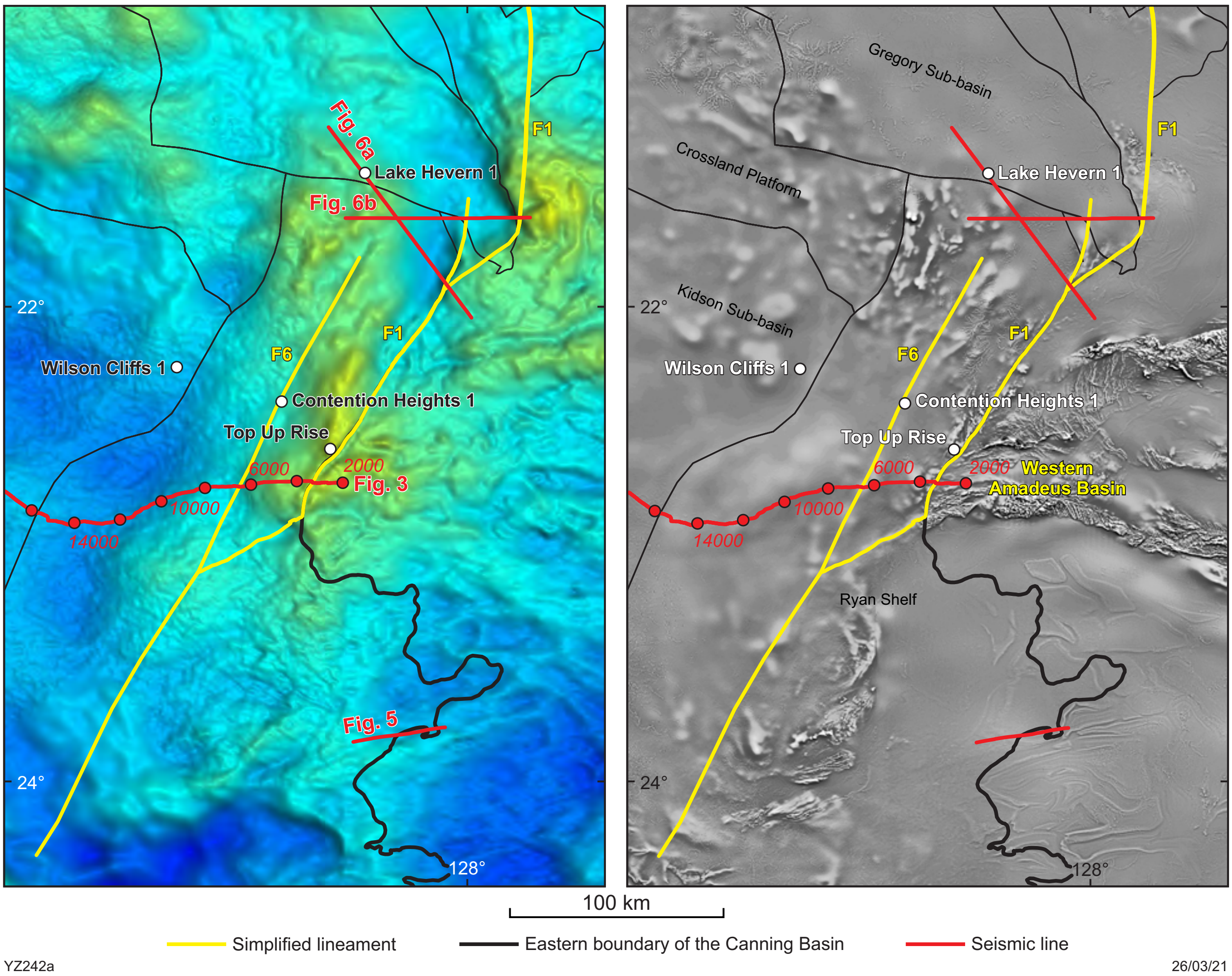

Figure 4. Geophysical images of the eastern margin of the Canning Basin: a) gravity map with blue representing deep basement (GSWA, 2017b); b) first vertical derivative of aeromagnetic data (GSWA, 2018)

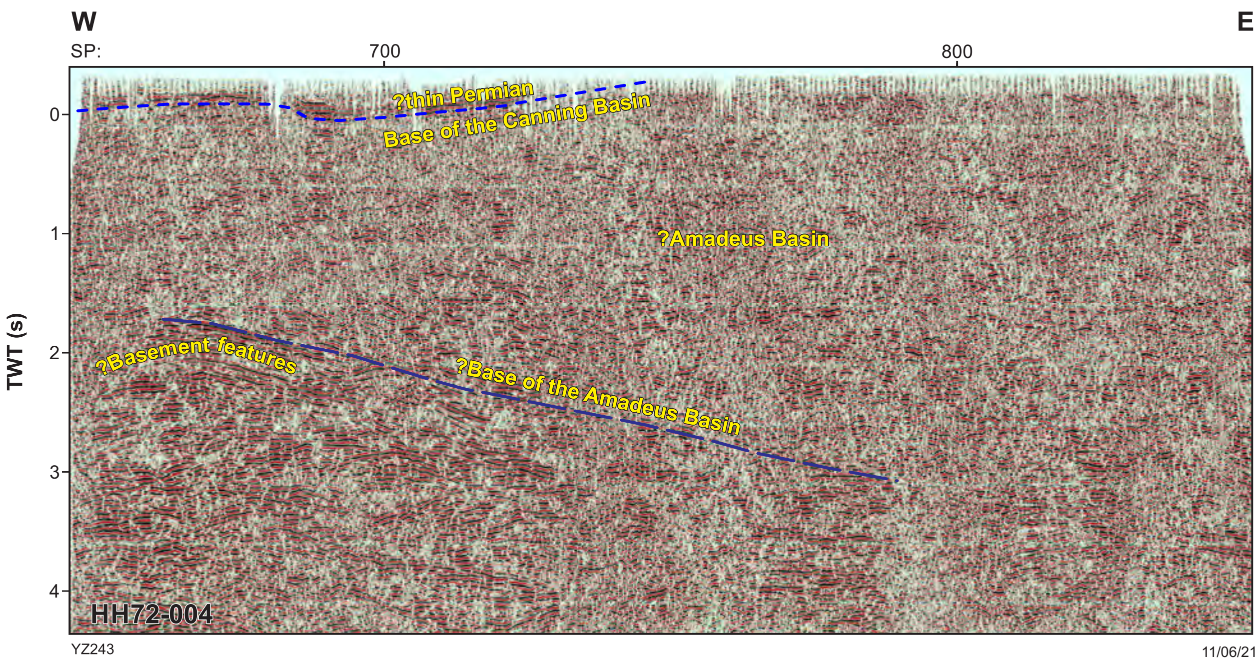

Figure 5. Seismic profile (HH72-004) to the east of the Canning Basin, showing basement dips towards the east, see Figure 4 for profile location

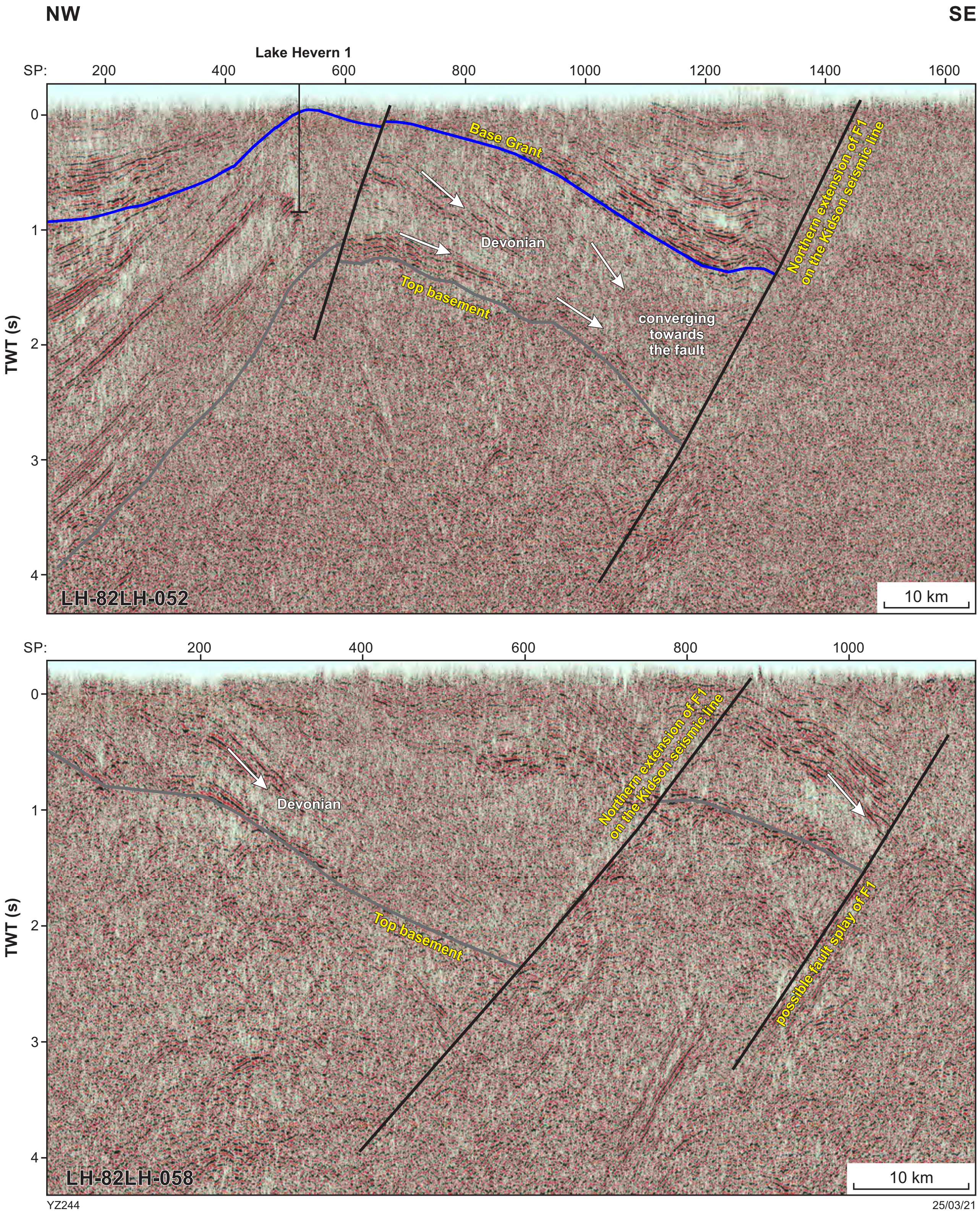

Figure 6. Seismic profiles across the regional boundary F1 fault at: a) the northern end of the Ryan Shelf (LH-82LH-052); b) the southeastern end of the Gregory Sub-basin (LH-82LH-058), showing that the Devonian reflectors converge towards the faults (white arrows) within the wedge-shaped depression. See Figure 4 for locations

against the Amadeus Basin shown on the gravity and magnetic images (Fig. 4). These high-angle faults (F2–6) exhibit reverse and strike-slip components, and some of them have significant vertical displacement (Fig. 3).

Drillhole Contention Heights 1, 35 km to the north, is structurally projected to the profile by following the strike of the boundary faults (Figs 1, 3, 4). If this projection is valid, it indicates that the reflective sedimentary package ranging from surface to 1.5 s at the projection point (Fig. 3) correlates to the Permian–Ordovician. Within the package, the profile shows two major unconformities: one at the base of the Permian Grant Group, and the other at the base of the Lower Devonian Tandalgoo Formation. The Permian strata is characterized by mostly strong amplitude but chaotic reflectors, and shows less displacement by the near-vertical faults than the underlying formations. The lower basin strata in the profile are correlated to the Lower Ordovician in Contention Heights 1 and are truncated by the Tandalgoo Formation through erosion (represented by the top Worral pick) in this marginal area. This section shallows towards the east, with a relatively unchanged thickness tilted on the basement. Such geometry is different from a previous perception that the Ordovician sequence onlaps and pinches out against basement to the east (Veevers et al., 1978). The Ordovician at CDP 5730 shows a sharp juxtaposition against a near vertical fault (F5 in Fig. 3) with either side becoming shallower to form a tight deformation. The fault extends up into the Worral Formation but with a diminished tightness of deformation. The change in the deformational magnitude takes place near the top of Goldwyer Formation (Fig. 7).

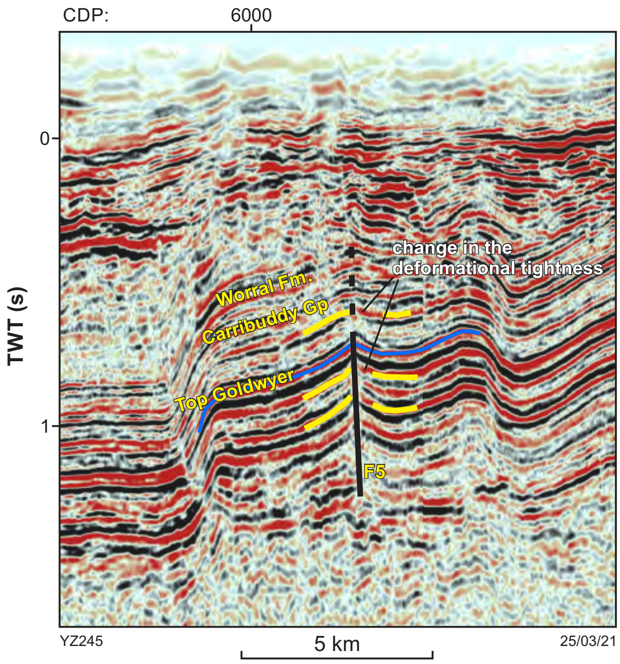

Figure 7. Deformational signature on the Ryan Shelf, showing a sharp juxtaposition or tight fold against a high-angle fault with its tightness reducing above the Goldwyer Formation

Kidson Sub-basin (CDP 15750 to 52160; proposed boundary from CDP 6150 to 56650)

The Kidson Sub-basin was originally termed the 'Kidson Basin' (e.g. Koop 1966), referring to the broad depression in the north of Western Australia based on early gravity surveys. At that time this basin was inferred to be relatively shallow with the basement being around 1500 to 3000 m deep, overlain by marine Ordovician strata and truncated by Permian glacial deposits (Koop, 1966). The stratigraphic succession was later revealed through petroleum exploration wells, notably Kidson 1 (Johnson, 1966) and Wilson Cliffs 1 (Creevey, 1969), revealing that the depression also contains Devonian and Silurian strata above the Ordovician rocks. With the limited coverage of seismic data, the boundaries of the Kidson Sub-basin were considered arbitrary, as explained by Hocking (1994a). Its southwestern boundary with the Anketell Shelf was defined on the 600 ms contour at the base of the Grant Group shown by Taylor et al. (1990). The northern boundary, against the Crossland Platform, is based on the 1500 ms contour at the top of the Ordovician (Iasky et al., 1991).

The Kidson Sub-basin is shown on the seismic profile as a sag depression with the Paleozoic section gradually thickening towards the centre near Kidson 1 (Fig. 8). The laterally continuous reflectors inside the sag are generally parallel or subparallel, with apparent small-scale folds near CDP 35000 and 29000. These artefacts are caused by the route bend and strata dipping to the northeast in the western part of the sub-basin. Kidson 1 was drilled in the interior of the Kidson Sub-basin as a stratigraphic well to determine the structural configuration and stratigraphic sequence of the area, with the nearest pre-existing well Sahara 1 (Fig. 1) situated about 240 km to the northwest (Johnson, 1966). Kidson 1 (Fig. 9) intersected 189 m of Cretaceous sediments and 1358 m of Permian succession, followed by nearly 1000 m of mainly Lower Devonian and a 1700 m evaporitic sequence of Ordovician to Silurian age, terminating 155 m into the Ordovician Goldwyer Formation. The Phanerozoic succession in the peripheral parts of the sub-basin, as intersected in Frankenstein 1 and Wilson Cliffs 1, comprises similar stratigraphy from Cretaceous to Ordovician age with variable thicknesses for each interval. Both Frankenstein 1 and Wilson Cliffs 1 reached basement below the Lower Ordovician section, indicating that the basement shallows to the west and east away from the Kidson 1 area. The basin's most southerly well, Patience 2, 75 km south of the line, potentially intersected the complete basin succession with oil and gas shows in its Ordovician section (Haines, 2011). The stratigraphy in Patience 2 is comparable to other wells, but also includes a greater thickness of the Ordovician sandstone above the total depth (Haines, 2018). Despite the great distance between the well and the seismic line, the homogeneous sandstone in Patience 2 may provide some insight onto the lower non-reflective zone observed across the Kidson Sub-basin on the seismic profile (Fig. 10).

Previous basin-wide well correlations in the Canning Basin (Haines, 2004, 2009, 2011 and Mory 2010) were based on wireline logs and biostratigraphic control. They revealed several erosive surfaces in the Kidson Sub-basin (Fig. 9), including at the base of the Permo-Carboniferous Grant Group and at the top of the upper Silurian to Lower Devonian Worral Formation. Sections previously included in the Reeves Formation by Mory (2010) south of the Fitzroy Trough are now placed within the Grant Group (Backhouse and Mory, 2020). The unconformity at the top of the Tandalgoo Formation is marked by the sudden change of the gamma ray characteristic from low to high upwards, and a noticeably angular contact on the seismic image near the

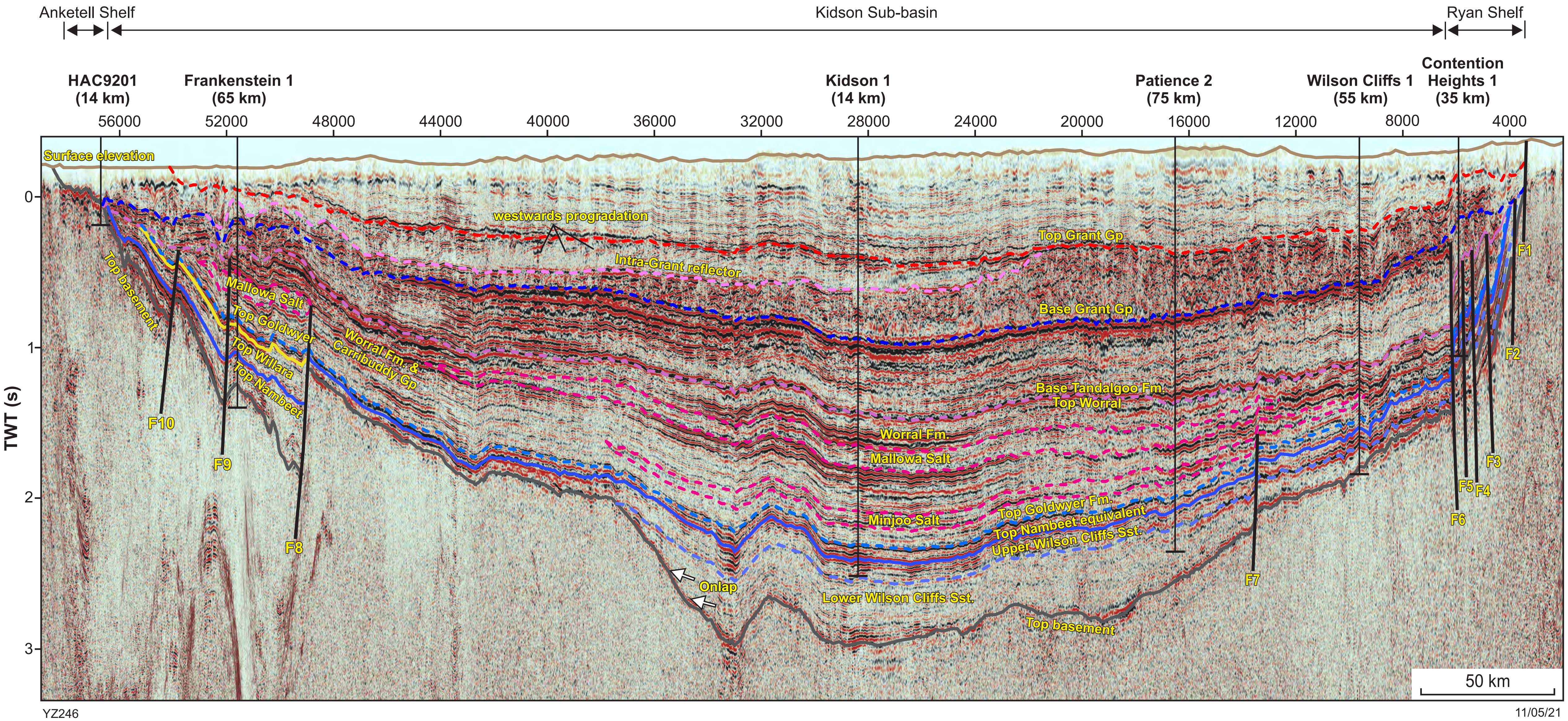

Figure 8. Seismic interpretation of the extended Kidson Sub-basin, showing a relatively undeformed sag with a series of faults near the margins

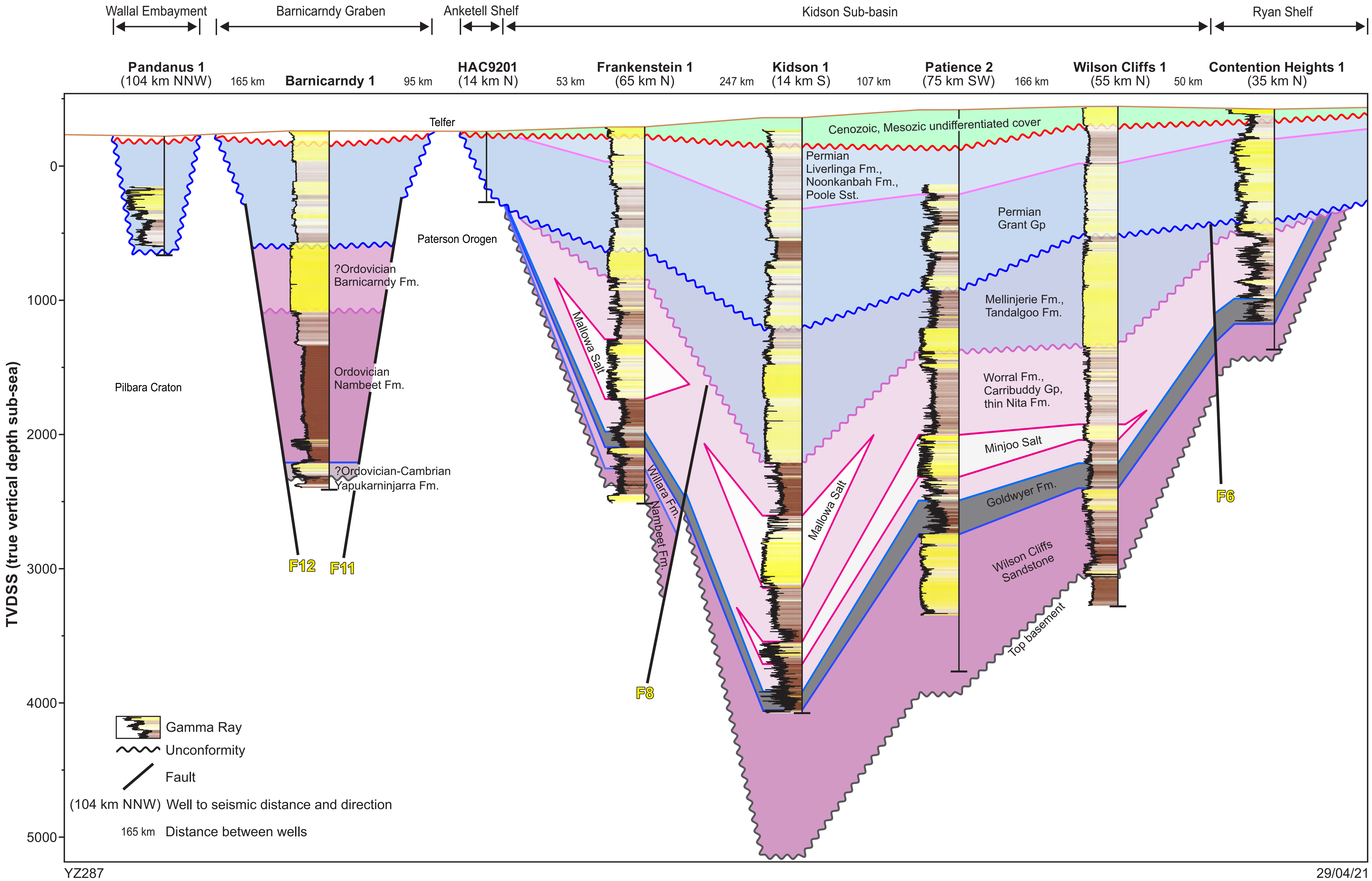

Figure 9. Well correlation from Pandanus 1 to Contention Heights 1 along the Kidson seismic survey. The formation tops are based on Haines (2011) and Normore et al. (2021). See Figure 1 for well locations

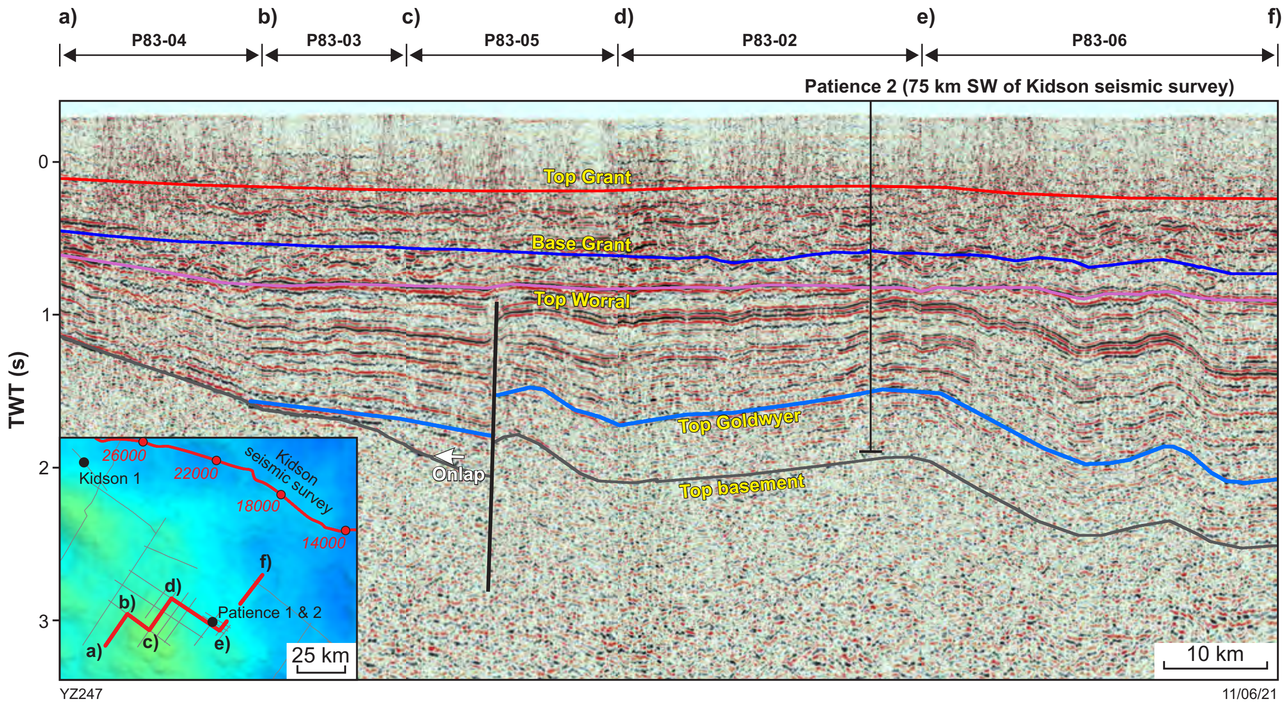

Figure 10. Composite seismic profile across Patience 2 near the southern margin of the Kidson Sub-basin. The lower sandstone package (weak-amplitude zone above total depth) onlaps the basement towards the south and is comparable to the lowest part of the basin on the Kidson seismic profile

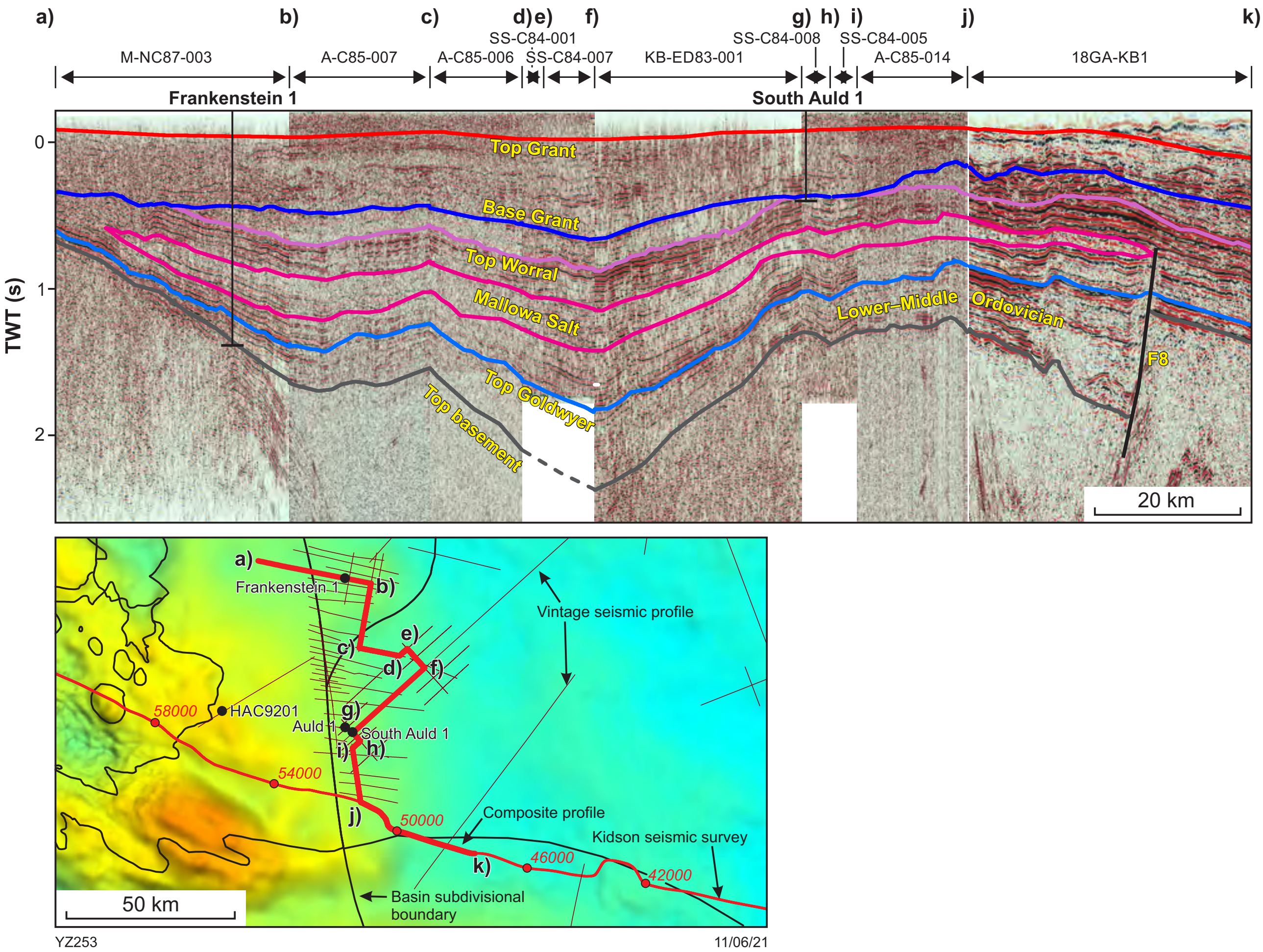

Figure 11. Composite seismic line connecting Frankenstein 1 to the Kidson seismic profile, showing that the faulted wedge is probably filled with Lower Ordovician strata. Note that the undulating horizons are related to the route of the composite profile and do not indicate folding in the area

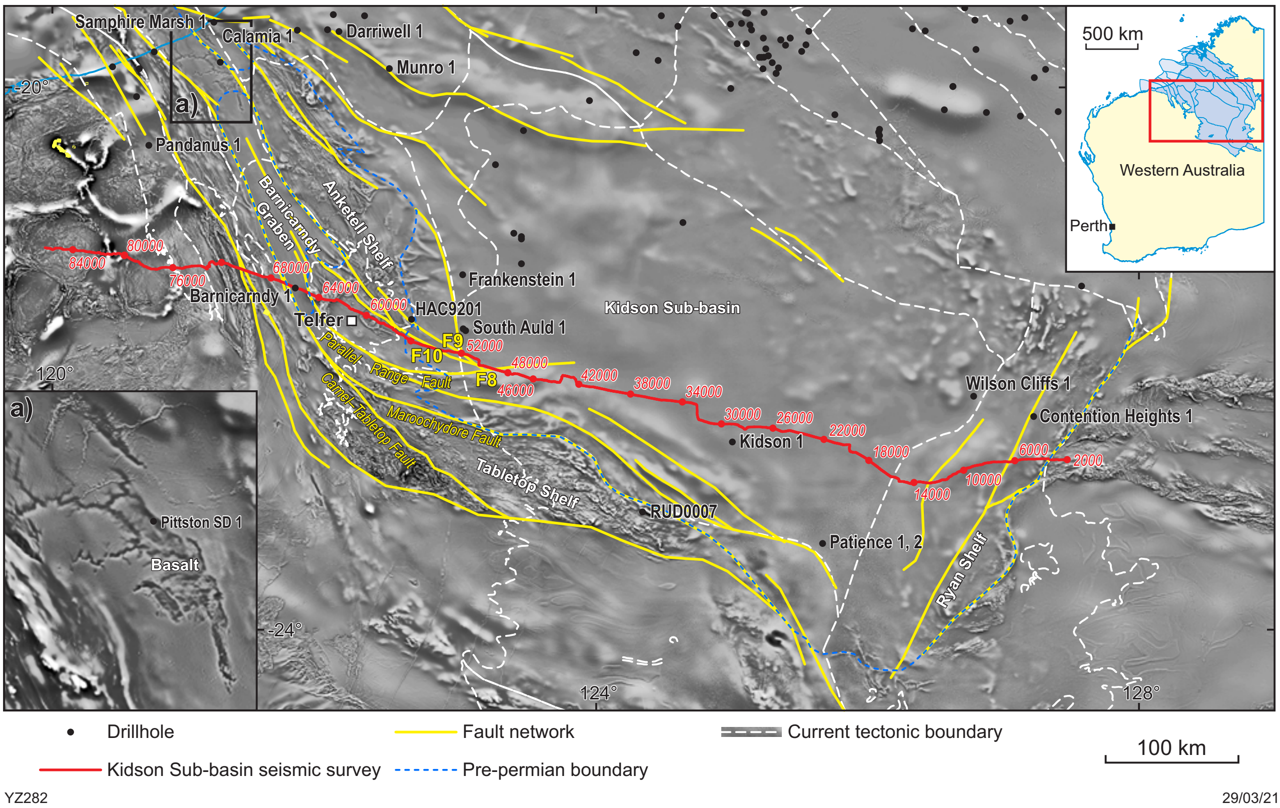

Figure 12. First vertical derivative of aeromagnetic data of the southern Canning Basin, overlain with linear structures (yellow) from GSWA (2017a), Zhan (2018, 2019a) and the current study. The dark blue dashed line indicates the extent of the pre-Permian strata in the Barnicarndy Graben, and the southern boundary of the strata in the Willara–Kidson Sub-basins. The figure insert a) shows the basaltic occurrences, which were likely related the tectonic reactivation along the faults during the Fitzroy Transpression

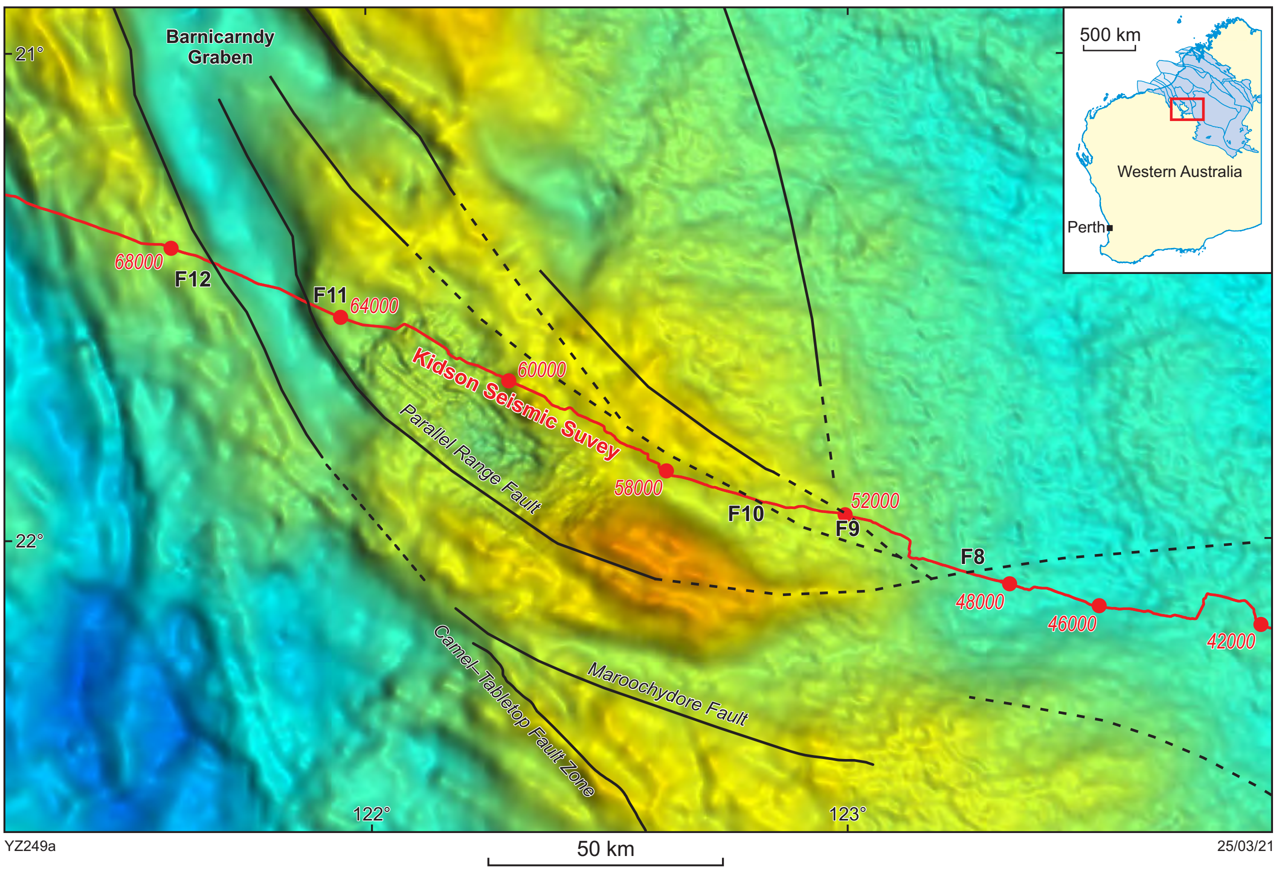

Figure 13. Gravity image between the Kidson Sub-basin and Barnicarndy Graben. See Figures 8 and 15 for positions of faults (F8 to F12) on the Kidson seismic profile

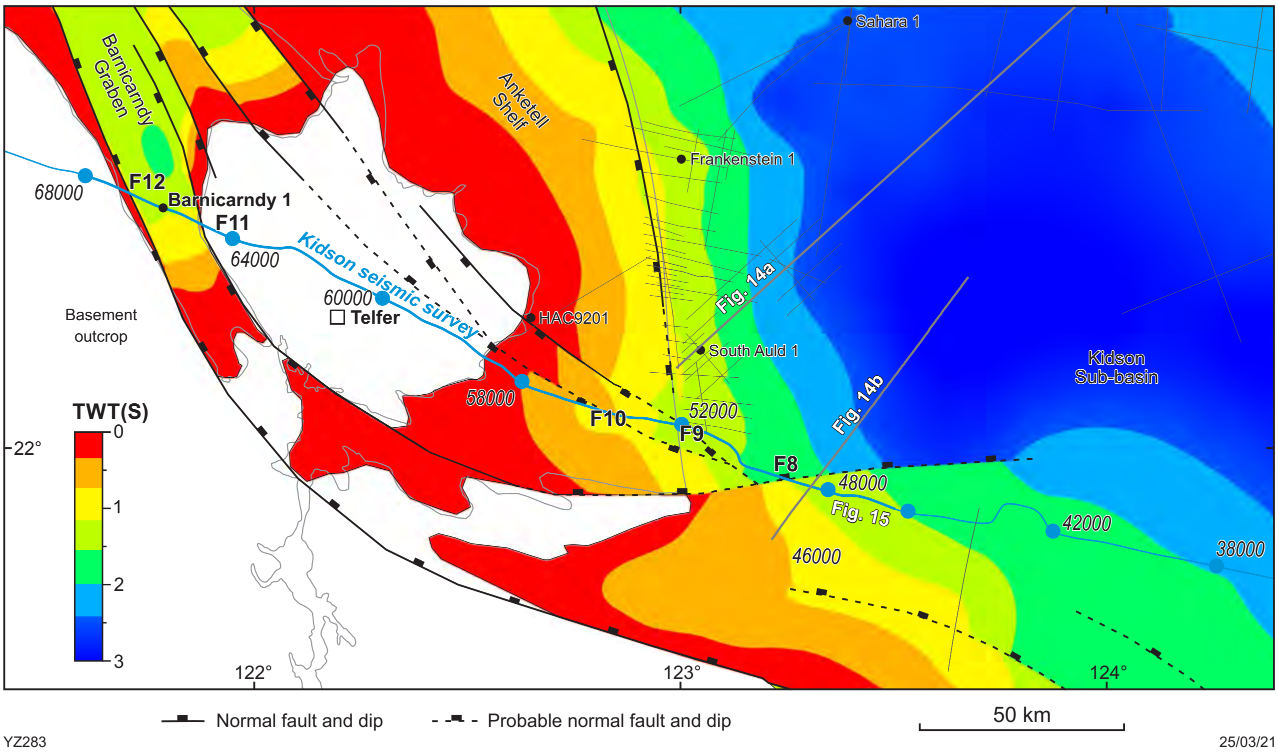

Figure 14. Two-way time map of the top basement from the Barnicarndy Graben to Kidson Sub-basin, showing fault correlation along the Kidson seismic profile

Patience 1 and 2 wells (Haines, 2011). Due to the variation in the thickness of Mellinjerie and Tandalgoo Formations (Fig. 2; plate 1 in Haines, 2011), this study amalgamates these two formations and only interprets the base of the Tandalgoo Formation as a regional marker on the Kidson seismic survey. The top of the Worral Formation is a low angle unconformity that has removed the upper part of the formation in Kidson 1, Patience 2 and Contention Heights 1 (Fig. 9) in the southern Canning Basin. These regional unconformities form prominent markers in calibrating the geology with the seismic reflection (Fig. 8).

Frankenstein 1, near the western margin of the sub-basin, can be correlated to the Kidson seismic survey via offset seismic lines (Fig. 11). The Lower Ordovician in Frankenstein 1 is interpreted to extend towards the southeast and fill the faulted block (F8 in Fig. 11) along the seismic profile. The presence of the Ordovician in this area suggests that the Kidson Sub-basin is better revised to include the fault blocks from CDP 49000 to 56650 (Fig. 8). This boundary revision will avoid the pre-Permian wedge being included in the Anketell Shelf, which elsewhere is typically restricted to a thin Permian succession overlying Proterozoic basement (Hocking, 1994a; Arunachalam and Rehna, 2013; Gregory and Fitzgerald, 2014; Zhan, 2018).

It is difficult to laterally correlate the boundary fault of the wedge at CDP 49000 (F8 in Figs 12–14; referred to as Triwhite Hills Fault in Doublier et al., 2020). The fault displaces the top basement horizon by about 600 ms. If the fault is parallel to the strike of the Anketell Shelf and dips to the southwest, it should be observed with significant fault displacement and similar dip direction on offset lines northwest of the Kidson seismic survey. But no such fault is obvious on seismic lines near South Auld 1 and Frankenstein 1 (Fig. 15a; KB-ED83-001). Instead, another nearby profile (Fig. 15b; TT70-B) shows a set of reflectors below 1.5 s in its northeast part, as opposed to the shallow basement in the southwest. This potential displacement makes it feasible to interpret the fault to strike west–east. This direction is at odds with the north-northwest boundary of the Anketell Shelf, but matches the trend of magnetic and gravity anomalies along the Parallel Range Fault (Figs 12, 13; GSWA, 2017a).

Tracing the F8 fault away from the Kidson seismic survey is hindered by the sparse grid of the offset seismic lines. Instead, surface geology and potential field data are largely used to determine the fault strike and scale. Based on the magnetic and gravity anomalies, two west-northwest trending faults (F9 and F10 in Figs 12–14) are interpreted to obliquely cross the Kidson seismic survey and converge with the major fault (F8) towards the east-southeast. As a result of the obliqueness of the seismic line to the fault orientations, these faults are expressed with irregular geometry in the seismic plane and are interpreted to follow the top of the strong reflectors within the basement under the western margin of the Kidson Sub-basin (Fig. 16).

Based on the surface geology (GSWA, 2016) and geophysical images, the major fault (F8 in Figs 12–14) is interpreted to be part of the Parallel Range Fault that changes strike from westerly in the Kidson Sub-basin to north-northwesterly along the eastern margin of the southern Barnicarndy Graben. The fault swings back and re-intersects the Kidson seismic profile at CDP 64900 with a change in dip direction along strike. The Parallel Range Fault (F8 and F11 in Fig. 16) becomes invisible on the seismic profile between the Barnicarndy Graben and Anketell Shelf due to its distance from the survey. Based on the continuity of the Paleozoic reflectors, it is unlikely

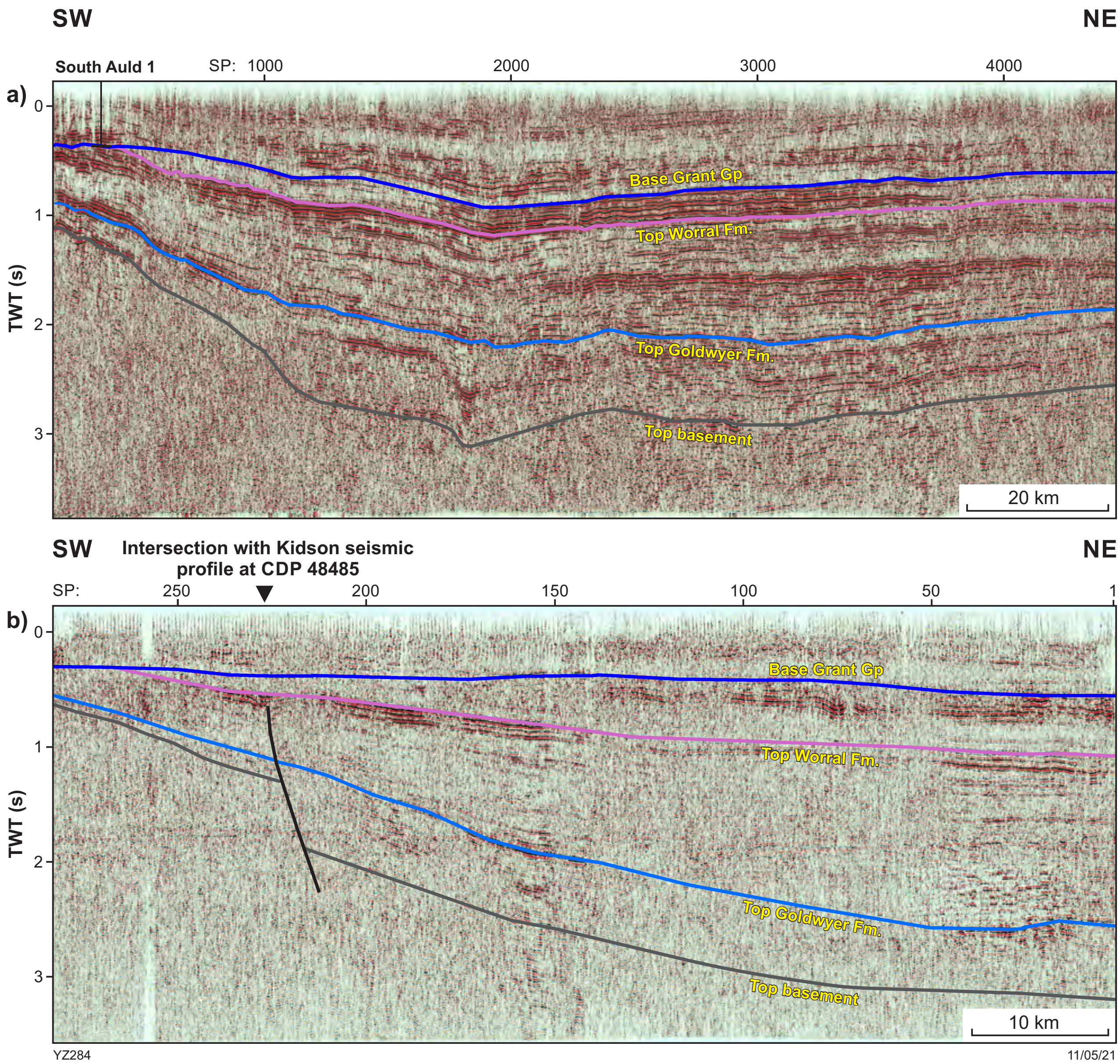

Figure 15. Interpreted offset seismic profile in the western margin of the extended Kidson Sub-basin: a) KB-ED83-001; b) TT70-B. Fault correlation between the Kidson seismic section and TT70-B indicates a west-east strike for the major fault (F8). See Figure 13 for profile locations

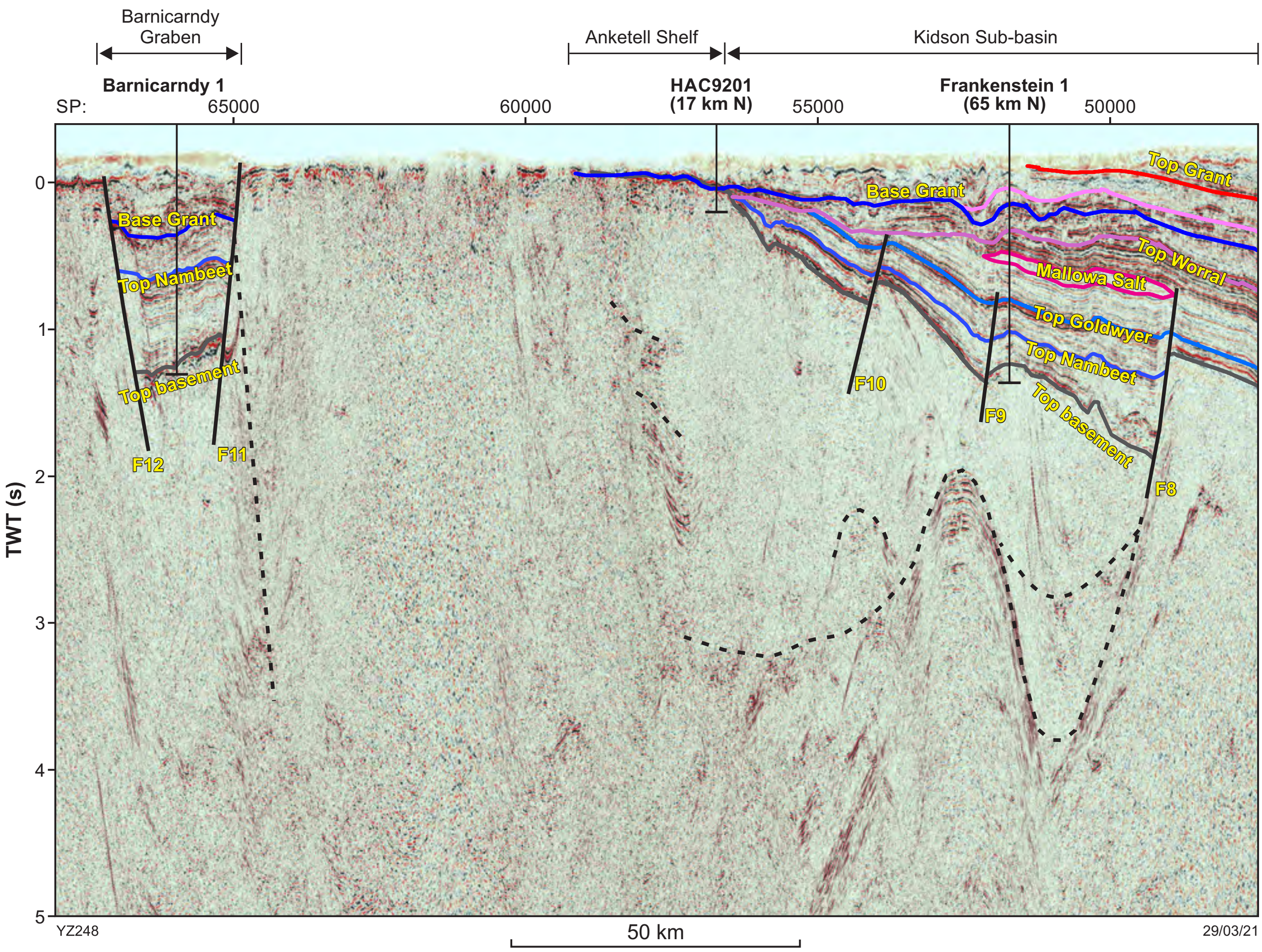

Figure 16. Interpreted seismic profile from the Kidson Sub-basin to Barnicarndy Graben. Dashed lines indicate a possible intersection of the Parallel Range Fault with the seismic plane. See Figure 13 for profile location

that the fault (F8) curves back to the south to again intersect the Kidson seismic profile between CDP 40000 and 42000 (as implied by the bedrock structure line in GSWA, 2016). If the fault does follow the basement structure trends interpreted from the potential field data (GSWA, 2016) and does swing to the south to intersect the seismic profile, then the only possible location is an oblique crossing between CDP 32000 and 37000 that only affects the basal reflectors of the basin (Plate 1). As no low-angle fault plane is evident between CDP 37000 and 49000, this alternative interpretation of the fault is not plausible.

The prominent fold-like shape in the basement (Fig. 16) with concave upwards between CDP 49000 and 52500 and downwards between CDP 51000 and 54000 was interpreted by Doublier et al. (2020) as an amphibolite unit of the Neoproterozoic Yeneena Basin. This was based on the amphibolite cored at the bottom of Frankenstein 1, where the well intersected the basement and the top of a similar package of concave-up reflectors (refer to the anticlinal feature under Frankenstein 1 in Fig. 11). Whereas Doublier et al. (2020) inferred a continuous anticlinal axis between the two areas, the Precambrian structure beneath Frankenstein 1 is more likely a localized dome (Fig. 17) that does not extend towards the south or link to the Kidson seismic profile at CDP 52500. The prominent antiformal structure between CDP 51000 and 54000 on the Kidson seismic profile is more likely to be related to the fault planes (F8, F9, F10 in Figs 14, 16) intersecting the seismic plane with variable distance and dips between them. The major fault plane (F8) would intersect the seismic profile at deeper position, if the fault deeps more steeply and/or diverges away from the seismic line.

Anketell Shelf (CDP 52160 to 57200; proposed boundary from CDP 56650 to 59000)

The Anketell Shelf (Anketell Ridge in Koop, 1966; Gorter et al., 1979) is generally considered to form the southern margin of the Willara and Kidson Sub-basins, where it onlaps the Precambrian Yeneena and Officer Basins. In general, the Anketell Shelf is a northwesterly oriented basement high (GSWA, 2020; Zhan, 2020), and the structural trend was possibly inherited from the pre-existing Precambrian structural framework. Due to extremely sparse seismic coverage, the location and nature of the northeastern boundary against deeper sub-basins is poorly defined, and

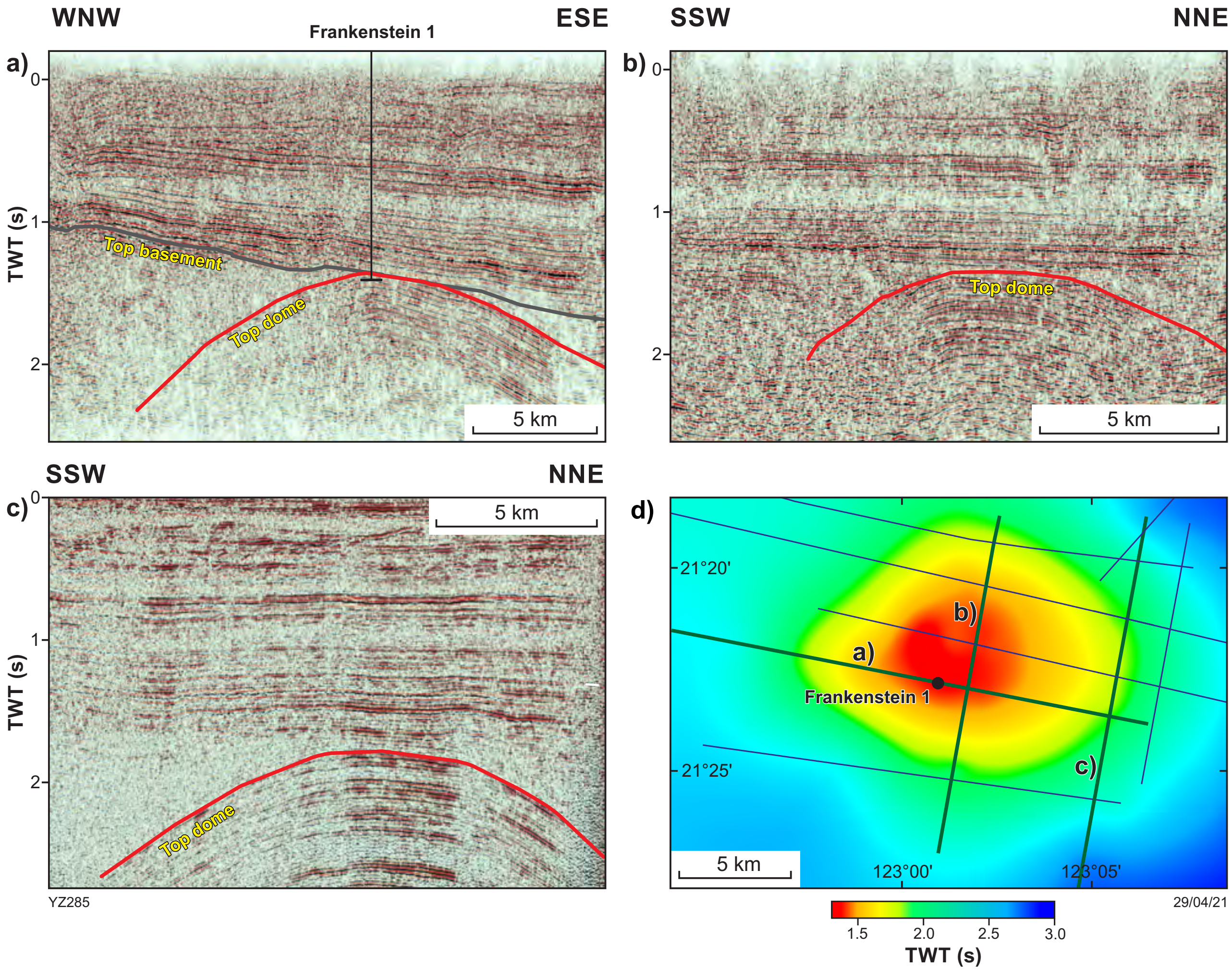

Figure 17. Interpreted seismic profiles around Frankenstein 1 and two-way time map of the top of the basement dome below the Canning Basin

placed approximately by Hocking (1994a,b) on the 3 km depth to basement contour shown by Forman and Wales (1981, plate 33).

About 100 km north of the Kidson seismic survey on the Anketell Shelf, multiple mineral drillholes (e.g. Venus T3, C6, and Antipa 14AMD00043) have penetrated Permian strata directly overlying Precambrian basement. These intersections, combined with outcrop studies (e.g. Newcrest Mining Ltd, 1993; Hickman and Clarke, 1994; Mory et al., 2008), suggest that the Permian Grant Group, or equivalent Paterson Formation and overlying Mesozoic, onlaps Precambrian basement to the southwest. Near the Kidson seismic profile, mineral drillhole HAC 9201, drilled to 528 m in search of Telfer-style gold mineralization, penetrated through Permian glaciofluvial sediments before intersecting Proterozoic metasedimentary rocks at 419 m (Fig. 16; Henderson, 1993; Backhouse, 1993).

The stratigraphy in the aforementioned mineral drillholes suggests that the Anketell Shelf is better defined as a tectonic element overlying a basement high, containing only Permian to Mesozoic strata (Hocking, 1994a; Zhan, 2018). Thus the eastern boundary of the shelf needs to be revised from the current position at CDP 52160 to 56650, where the Ordovician pinches out at the margin of the Kidson Sub-basin (Figs 8, 16). This revision can avoid the pre-Permian wedge being included in the Anketell Shelf. The western boundary of the shelf is placed where basement outcrops near the Telfer area at CDP 59000. The stark contrast in basement depth between HAC9201 (419 m) and Frankenstein 1 (2666 m) over 54 km indicates a considerable northeasterly dip of the basement unconformity surface from the Anketell Shelf into to the Kidson Sub-basin. This suggests that the Ordovician succession likely extends some distance to the southwest of Frankenstein 1, with the boundary of the Anketell Shelf tentatively moving westwards to exclude areas with significant pre-Permian section from the shelf, shown as the dashed blue line in Figure 12.

Barnicarndy Graben (CDP 64900 to 67000)

The Kidson seismic line crosses the Barnicarndy Graben, a structural sub-division that was previously known as the Waukarlycarly Embayment. It is distinctly separated by faults from the main depocentres (Willara and Kidson Sub-basins) in the southern peripheral area of the Canning Basin. It was first identified through Bouguer gravity images, which show a localized gravity low within a regional north-northwesterly trending gravity high (the Anketell Regional Gravity Ridge of Fraser, 1976 or Warri Gravity Ridge of Iasky, 1990). The localized gravity low implies the presence of a basinal depression between the

Pilbara Craton and the main Canning Basin. The elongated gravity low is about 25–50 km wide and 150 km long, and subparallel to the nearby Precambrian structural trends in the Paterson Orogen. The graben configuration was later confirmed by seismic profiles, which show that the graben is fault-bounded to the nearby tectonic units (GSWA, 2020; Zhan, 2020), including the Paterson Orogen and Anketell Shelf. The bounding faults have displaced most of the sedimentary fill with a deepening trend towards the west shown on the Kidson seismic profile (Fig. 16). The surface geology (GSWA, 2016) and potential field data (Figs 12, 13) show that the western boundary fault (F12) of the graben possibly extends to the south and connects with either the Camel-Tabletop Fault or Maroochydore Fault. The eastern boundary fault (F11), as discussed in the Kidson Sub-basin section, is correlated to the Parallel Range Fault that swings back to the Kidson seismic profile at CDP 49000 as the major fault (F8) with a change in its dip along the strike.

The Barnicarndy 1 stratigraphic well was drilled in the south-southeast extension of the Barnicarndy Graben and penetrated a different package of sedimentary rocks from the rest of the Canning Basin, especially for the pre-Permian succession. The pre-Permian succession consists of about 530 m thick porous sandstone, about 900 m massive claystone, and about 300 m sandstone above an angular contact with dolomite basement at 2585 m (Normore and Rapaic, 2020). The age of the pre-Permian succession is currently under investigation, and only two formation boundaries can be confidently determined based on core features and wireline logs, which are the base Permian Grant Group at 858 m and the top basement 2585 m.

Vertical seismic profile (VSP) shows that the top basement at 2585 m corresponds to a two-way travel time of 1.7 s, which sits in the middle of a non-reflective zone and has no corresponding reflector on the Kidson seismic profile (Fig. 16). Moreover, it is difficult to correlate the seismic trace across the well with synthetic seismograms using VSP, sonic and density logs. Detailed correlation with the seismic section suggests that the VSP time-depth pairs require a systematic 215 ms shift upwards, due to an unknown delay from VSP sensors (Zhan, 2021, in prep.). The synthetic–seismic discrepancy in the lower sandstone and basement below 2290 m indicates that an out-of-plane issue occurs in this basin marginal area. Here, the seismic section images a shallow basement (2455 m) reflected from further south, rather than that from vertically below the survey route. This reflection issue requires an additional 55 ms upwards shift to reconcile the discrepancy between the synthetic and seismic section.

With the quantitative analysis and synthetic shifts, the top basement is calibrated to a high-amplitude reflector above the non-reflective zone, and has a significant vertical displacement across the boundary faults (Fig. 16). The Kidson seismic line shows that the basement appears to gently shallow towards the northeastern boundary fault; however, this apparent updip is probably related to the obliqueness of the line to the strike of the graben. The base Permian (base Grant Group) is interpreted at the angular unconformity from 0.55 to 0.65s that truncates the reflectors underneath. The unconformity is uneven, possibly due to Permian glacial or fluvial incision. The uppermost strong reflector at about 0.2 s probably corresponds to an intra-formational boundary within the Permian section at 210 m, which extends smoothly across the boundary faults of the graben to onlap the Paterson Orogen.

Post-drilling well analysis indicates that the well has an anomalous velocity profile and does not follow the expected trend of velocity with depth along most of the well trajectory (Zhan, 2021, in prep.). The well reaches unexpectedly high velocity in shallow sections, such as about 3000 m/s at 210 m (upmost logging point; ~50 m AMSL), 3500 m/s at 450 m and 4200 m/s at 858 m in Permian diamictite and underlying sandstone of uncertain age, with possibilities of high velocity immediately below the weathering layer (96 m). Those velocities are approximately 500 to 1000 m/s faster than other wells in the southern Canning Basin, such as Calamia 1, Munro 1 and Frankenstein 1, at equivalent depths. The sections from 210 m to 1600 m in Barnicarndy 1, containing the Permian and underlying sandstone and claystone sections, resemble the Permian to Devonian sections in Kidson 1 (800–2200 m) in terms of the velocity range and seismic reflection (Fig. 18).

If the boundary faults of the Barnicarndy Graben (F11 and F12 in Fig. 13) are correlated to the Parallel Range and Maroochydore Faults, respectively, then the graben might have been interconnected with the Kidson Sub-basin, and they underwent similar tectonic movements. These faults were possibly reactivated after Permian deposition and led to different amounts of uplift, exhumation and erosion along the fault zone, including in the Barnicarndy Graben, Telfer mining area, Anketell Shelf and Kidson Sub-basin (Fig. 14). If post-depositional tectonic movement did occur, it may explain a gas show in RUD0007 at 460 m above the basement (see well location in Figs 1, 12; Roche, 2017) in the southern margin of the Kidson Sub-basin. That is possibly because the Permian section in this area was originally more deeply buried than at the present time, and potentially reached maturation at its original maximum burial depth. However, the shallow gas occurrence may also be related to lateral migration from a deeper part of the Kidson Sub-basin. Nevertheless, the anomalous velocity range in Barnicarndy 1, its similarity to Kidson 1 in terms of velocity and reflection, as well as the possible tectonic connection with the Kidson Sub-basin, indicates that the Permian section in the Barnicarndy Graben might have been more deeply buried and a large amount of overlying section could have been eroded after the Permian.

The boundary faults of the Barnicarndy Graben constitute a deeply seated north-northwesterly trending fault network that potentially extends to the coastal area, where subsurface basaltic rocks occur within the Canning Basin and are imaged by aeromagnetic data (image insert in Fig. 12). The basalts were intersected in a mineral drillhole SD 1 (Pittston Sandfire SD1; 643–714 m in Douglas McKenna & Partners, 1992) where they form sills intruding Permian strata. These sills have a Late Triassic age based on Ar–Ar dating (Mory et al., 2017). The dendritic shape of magnetic anomaly suggests that the basaltic magma also formed surface flows away from a fault onto the Permian section (Mory et al., 2017). If the magmatic activity were coincident with the tectonic movement, then the Late Triassic age may indicate the timing of the uplift movement with significant amount of erosion in the graben and surrounding areas.

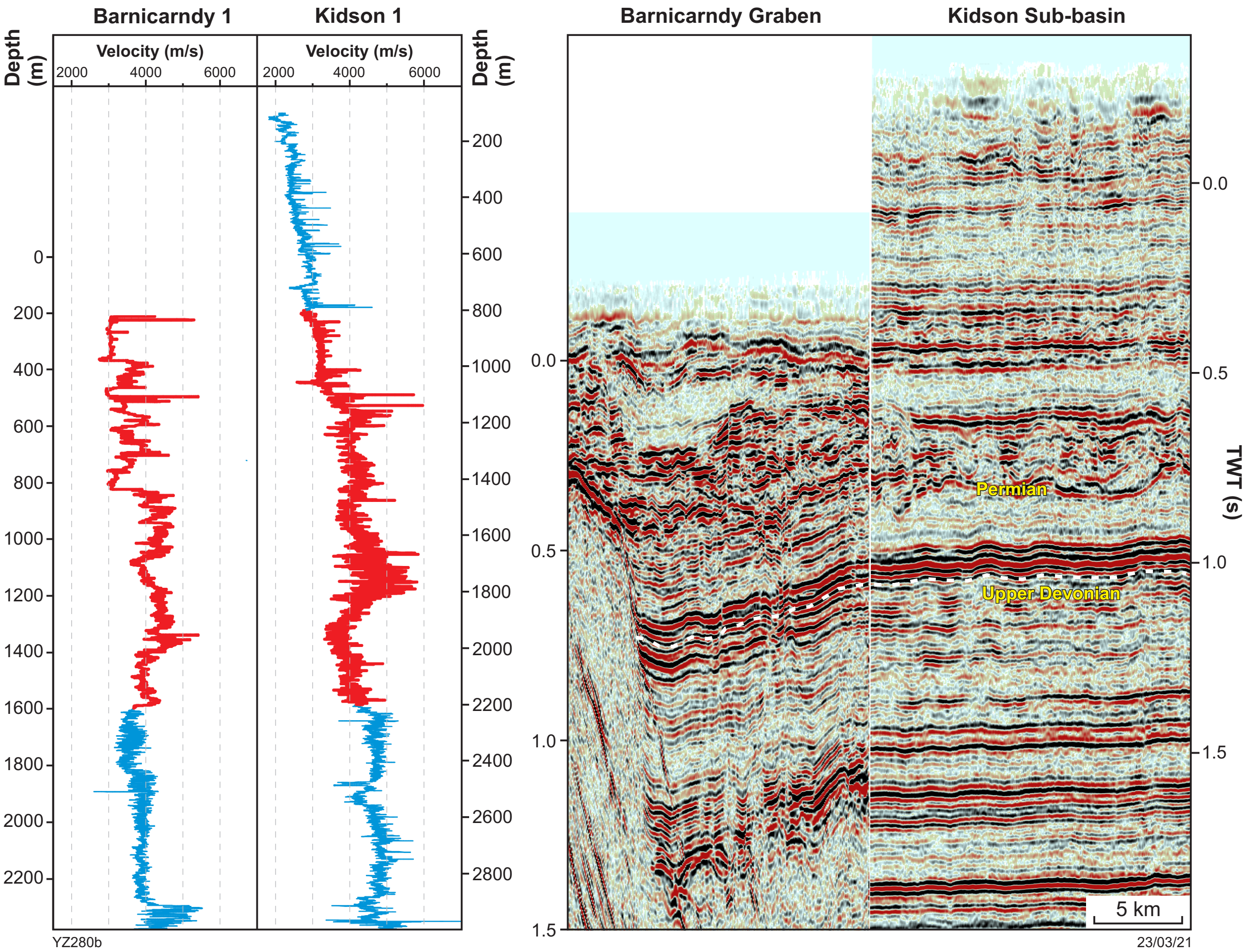

Figure 18. Comparison of sonic velocity and seismic reflection between Barnicarndy 1 and Kidson 1. The velocity range and seismic reflection shows similarity between the upper half of Barnicarndy 1 (210–1600 m; Zhan, 2021, in prep.), including the Permian and underlying sandstone and claystone sections, and the Permian to Devonian sections in Kidson 1 (800–2200 m)

Wallal Embayment (CDP 73700–76100)

Based on pre-existing geophysical data near the Canning coastal area, the Wallal Embayment (Fig. 1) was defined as fault-bounded against the Pardoo Shelf to the south (Geophysical Service International Party 852, 1967; Hocking, 1994a,b). The Kidson seismic profile covers the southernmost extension of the Wallal Embayment, where it lies between the Pilbara Craton and Paterson Orogen. Investigations of surface geology in this area (Traves et al., 1956) indicated a glaciofluvial deposit of pebble beds, sandstone, mudstone and shale overlying the Precambrian basement. These rocks were correlated to the Permian Paterson Formation based on glacial striations on clasts and palynological interpretation of shallow drillcore samples (Hickman, 1975).

Drillhole data are not available near the Kidson seismic profile, and the closest well, Pandanus 1, is about 100 km to the north-northwest of the seismic line along the strike of the Wallal Embayment (Figs. 1, 19; GSWA, 2020; Zhan, 2020). The well intersected green to dark-grey quartzite at 854 m, which resembles rocks found in the Mesoproterozoic to Neoproterozoic sedimentary successions of the Eel Creek Formation and Tarcunyah Group, respectively, overlying the Pilbara Craton (Williams, 2003). Such remote well data are not particularly meaningful for interpretation at the line location, except for suggesting an even shallower basement to the south-southeast near the seismic line.

The Phanerozoic divisions of the Wallal Embayment are difficult to interpret in detail on the Kidson seismic profile, and it is likely to be filled mostly by Permian strata (GSWA, 2020; Zhan, 2020). The top basement interpretation in the Wallal Embayment is largely constrained by surface geology (Fig. 19; Williams and Trendall, 1998; GSWA, 2016), showing that the Neoarchean Carawine Dolomite and Jeerinah Formation, Neoarchean to Mesoproterozoic Pinjian Chert Breccia, and Neoproterozoic Waltha Woora Formation outcrop in the vicinity of the seismic line. The Neoarchean Carawine Dolomite exposed 1.5 km to the south of CDP 74500 is projected to correspond to a chaotic weak reflection zone, which deepens to the west underneath the embayment. This indicates that the underlying bright parallel reflections probably correspond to the Archean succession. The bottom of the inferred Wallal embayment is interpreted at the strong reflector near 100 ms above the weak zone with its eastern boundary set at CDP 74800. To the west, the Wallal Embayment is bounded by the Neoarchean Jeerinah Formation of the Pilbara Craton at CDP 76000. The embayment is most likely displaced by a steeply easterly dipping fault at CDP 75600 (F13 in Fig. 19), which extends down into the Archean upper crust shown on the seismic profile.

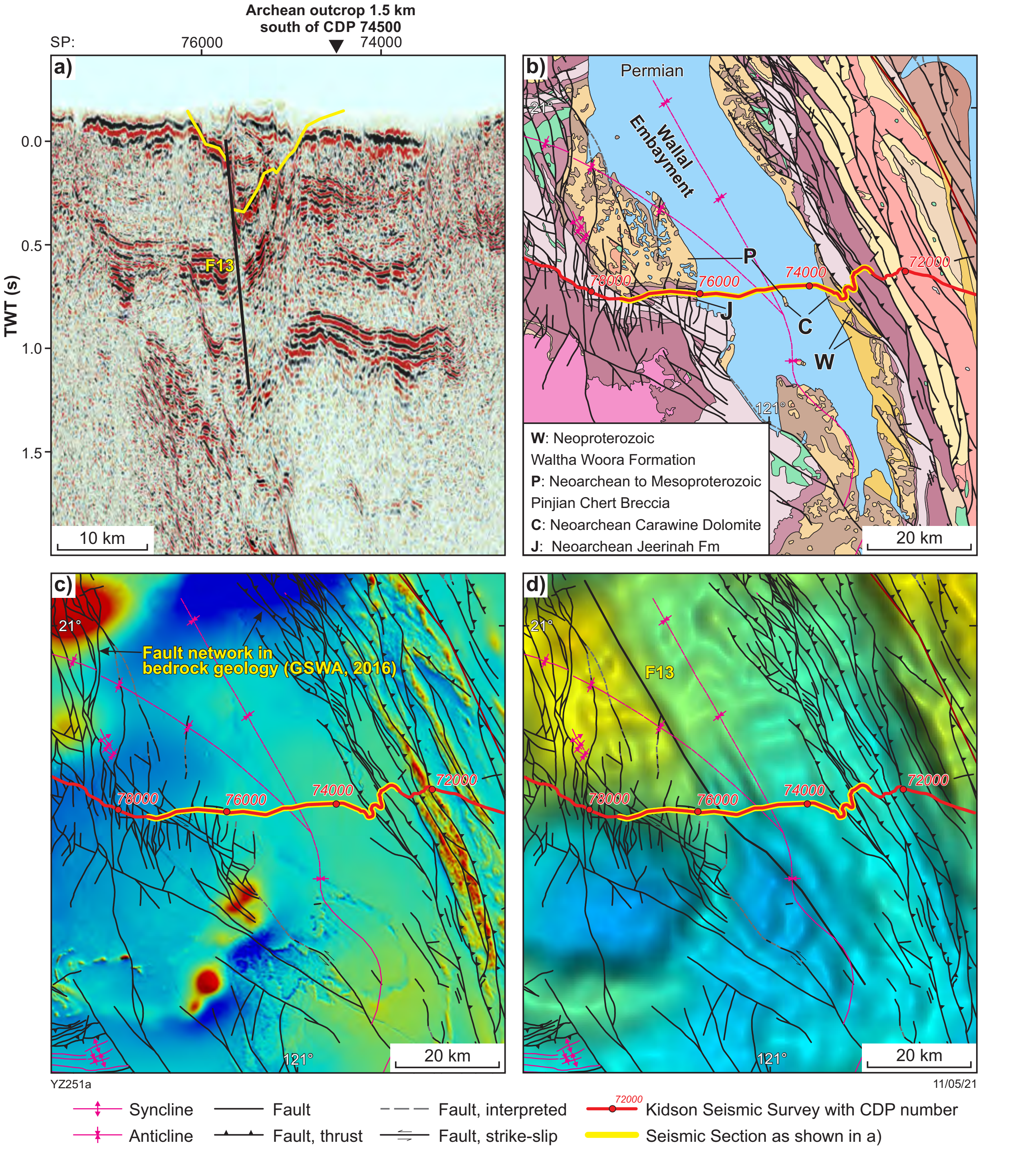

Figure 19. Interpretation across the Wallal Embayment: a) Seismic profile across the southern extension of the Wallal Embayment; b) surface geology; c) aeromagnetic; d) gravity images

Horizon interpretation of the extended Kidson Sub-basin

The Kidson Sub-basin and adjacent Ryan and Anketell Shelves form a large sag depression. The currently defined boundaries between these tectonic subdivisions are poorly defined. Thus, the depression between CDP 3400 and 59000 on the Kidson seismic survey is referred to here as the extended Kidson Sub-basin. This chapter focuses on the interpretation of horizons from the base of the Canning Basin to the top of the Permian Grant Group within this extended sub-basin.

The two factors affecting direct correlation of well synthetic seismograms with the Kidson seismic profiles are large offset and lateral strata variation. Based on the checkshot velocity survey of Kidson 1, its intersection of 4432 m of strata can be calibrated onto the seismic profile at CDP 28400, but with poor correlation of formation boundaries between the drill site and the profile. As the synthetic trace bears little resemblance to the actual seismic profile, most of the significant formation boundaries, such as the base Grant Group and Top Worral Formation, are in the middle of non-reflective zones. The reason for this mismatch is the offset, and because the strata dips from the well towards seismic profile, preventing a direct calibration between them. A composite seismic profile (Fig. 20) is drawn from the Kidson seismic line via K65-MercuryB and K65-VenusB lines, the latter of which crosses the well location. Section K65-A shows that the Kidson Sub-basin deepens northwards, leading to about 600 m vertical difference in 15 km with a dip angle estimated at about 2 degrees. Further to the west along the Kidson seismic profile, a composite line (Fig. 11) is also required to connect Frankenstein 1 to the Kidson seismic line to avoid mismatch due to the large offset.

Top and base of Grant Group

Based on the formation constraints from Kidson 1, the top Grant Group (Fig. 2) is placed onto the trough reflector at 0.4 s TWT at CDP 28400 (Figs 8, 20). This interface lies directly below a strong continuous peak caused by a stark lithological contrast between the shaly Noonkanbah Formation and the Poole Sandstone. This interface extends to the northern Canning Basin as a typical seismic marker (Apak and Backhouse, 1998; Zhan and Mory, 2013; Dent, 2016). The base Grant Group is calibrated to a prominent strong reflector at about 1 s near Kidson 1, and corresponds to a strong reflector with undulated surface at 0.2 s near Frankenstein 1. 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 profile (Fig. 8) shows that the Grant Group in Kidson 1 is expressed as two distinctive intervals: an upper weak-amplitude zone that thickens and progrades to the west, and pinches out about 70 km to the east; and a lower strong-amplitude chaotic zone occupying the whole section of the Grant Group in the east and thinning towards the west. The lower zone consists of sandstones with loose, medium to coarse quartz grains and variable degrees of sorting and rounding, which was originally included in the now obsolete 'Cuncudgerie Sandstone Member' and 'Braeside 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 line and re-deposited in the west as reworked deltaic sediments, based on the westward prograding direction observed in the upper zone between CDP 34000 and 44000.

Top Worral Formation

The Middle to Lower Devonian units were intersected below the Grant Group in the extended Kidson Sub-basin (Haines, 2011). These units include Mellinjerie and Tandalgoo Formations (Fig. 2), and vary greatly in their thicknesses from Frankenstein 1 to Contention Heights 1 (plate 1 in Haines, 2011). The current study groups these units together and uses the unconformable contact with the underlying Worral Formation as a regional marker to interpret the Kidson seismic survey. The top Worral Formation (base Tandalgoo Formation) interface 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 can be interpreted as a regionally continuous reflector based on the calibration with Kidson 1, and correlated to a deformed reflector at 0.4 s at Frankenstein 1, with the formation thickness ranging from 100 m to 250 m.

The top Worral Formation is subparallel to the base Grant Group across the majority of the sub-basin. Across the eastern boundary fault (F6 in Fig. 8) into the Ryan Shelf, the horizon can be interpreted as an angular unconformity at much shallower position due to significant vertical displacement (Fig. 3). Both the top Worral Formation and the base Grant Group can be consistently interpreted from Frankenstein 1 to Kidson 1, and can be used as anchor points to shift the time-depth pairs of these two wells for approximate correlation of the underlying formations.

The base Grant Group and top Worral Formation horizons gradually shallow and converge to the west of Kidson 1, forming angular contacts near Frankenstein 1 where folds can be observed along the two horizons. The folds are similar to features described near Carribuddy Group salt margins elsewhere in the basin (Zhan, 2019a,b) and indicate post-depositional deformation related to salt movement.

Top and base of Mallowa and Minjoo Salts

The top Carribuddy Group horizon was not interpreted on the seismic profile, because as reassessed by Haines (2009), the bulk of the Worral Formation is similar in lithology and depositional environment to the upper part of the Carribuddy Group (Fig. 2). Both intervals should belong to the Ordovician–Silurian megasequence based on biostratigraphic constraints and stratigraphic relationships (Haines, 2009). Although the top boundary of the Carribuddy Group is difficult to differentiate from the overlying Worral Formation, its two internal salt units (Mallowa and Minjoo) were interpreted due to their significance as regional seals over prospective Ordovician formations underneath.

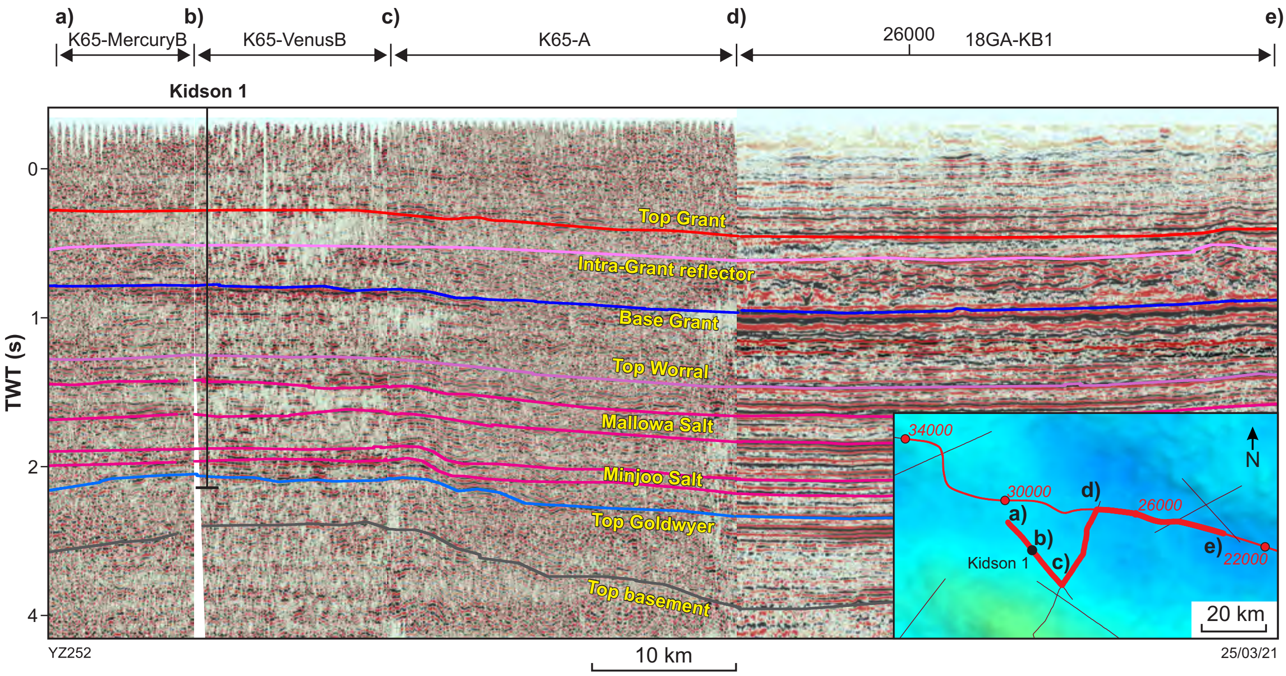

Figure 20. Composite seismic line connecting Kidson 1 to the regional profile, showing a northwards dipping trend of the Paleozoic horizons

Previous interpretation in the southern Canning Basin (Zhan, 2019b) showed that the Mallowa Salt generally appears as a thick transparent zone that separates the Lower to Middle Ordovician strata from the overlying Silurian to Devonian section. In some areas, it also corresponds to a package of chaotic weak-amplitude reflection (Zhan, 2019b) with a series of continuous parallel reflectors occurring sporadically on seismic sections. These typical signatures of the Mallowa Salt also apply to the interpretation of the Kidson seismic profile. The salt is characterized as a mostly thick, continuous, weak-amplitude package within the deep part of the Kidson Sub-basin, as well as containing some intra-formational reflectors to the west of Kidson 1 (Fig. 8). The stratigraphic contacts of the Mallowa Salt appear to be conformable within the encompassing Ordovician to Silurian succession.

A similar low-amplitude zone near Frankenstein 1 is also interpreted as the Mallowa Salt in an equivalent seismic stratigraphy in the fault block (Fig. 8). This bland zone crosses another fault but disappears within 40 km farther west. From the perspective of the 2D seismic section, it appears to be a separate salt body from the major one in the depocentre; however, these bodies possibly connect to each other to the north of the seismic line.

Compared to the thick low-amplitude Mallowa Salt, the relatively thin Minjoo Salt generally does not produce a significant non-reflective seismic zone. The lack of reported Minjoo Salt in some deep wells may be related to: non-deposition; salt dissolution and mobilization; or failure to recover salt in cuttings where the salt interval is very thin, disseminated or dissolved due to use of unsaturated drilling mud. Assuming the limited reported intersections of the Minjoo Salt provide a true indication of its distribution, the extent of this unit is limited both laterally and in thickness (mostly less than 100 m) compared to the Mallowa Salt. These thin intervals in general will be less than one seismic wavelength (120 m) based on an approximate seismic frequency of 35 Hz and velocity of 4200 m/s within the time window of the salt. Therefore, even though the Minjoo Salt is within the seismic resolution (30 m as a quarter of the wavelength), seismic profiles cannot image it as a thick transparent zone such as the Mallowa Salt.

In the Kidson Sub-basin, variable thicknesses of the Minjoo Salt have been intersected, 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 thick penetrations make the Minjoo Salt relatively traceable on the Kidson seismic profile compared to elsewhere, but do not warrant a correspondingly thick weak-amplitude reflection due to clastic interbeds in the interval and the large offset between the seismic and wells. The thickest Minjoo Salt, characterized by weak-amplitude reflectors, is interpreted near the projection of Patience 2, gradually thinning to the west, but to a lesser extent than the Mallowa Salt (Fig. 8). Towards the east, the Minjoo Salt appears to extend across a small-scale fault, but it becomes difficult to identify by CDP 9000 before reaching the projection of Wilson Cliffs 1.

The top and base horizons of both Mallowa and Minjoo Salts are interpreted to follow the trend of the base Grant Group and top Worral Formation (base Tandalgoo Formation). The edges of the salt units remain loosely constrained on the seismic line, and are placed at wedge-like points where the salt appears to pinch out, including CDP 12600 and 44400 for the Mallowa Salt, and CDP 9400 and 37600 for the Minjoo Salt (Fig. 8).

Top Goldwyer Formation

The Nita Formation underlying the Carribuddy Group ranges in thickness from 0 to 30 m in the Kidson Sub-basin, and is thus of negligible thickness in terms of the seismic resolution. Instead, the base of the Carribuddy Group can be substituted by the top of the Goldwyer Formation (Fig. 2), which has been widely drilled in the basin due to its petroleum prospectivity. The source rock potential in this formation is highlighted by a full core recovery in Theia 1, with average total organic carbon at about 3.8%, high wet mud gas readings, fluorescence and associated hydrocarbon odour in its lower shale unit (Finder Exploration, 2016; Normore et al., 2018).

The Goldwyer Formation contains predominantly dark-grey calcareous shale in its upper unit in the southern Canning Basin, whereas the overlying Nita Formation is dominated by carbonates interbedded with lesser amounts of mudstone (Haines, 2004). This lithological variation at formation scale leads to a distinct wireline inflection at the top of the formation. This is marked in both gamma ray and acoustic logs from low readings in the lower part of the overlying Nita Formation to high readings in the upper Goldwyer Formation.

The changes in wireline log characteristics correspond to a prominent seismic reflector above a relatively thick transparent zone at the top of the Goldwyer Formation (Fig. 8). This strong reflector is a regional marker in the Broome Platform, Willara Sub-basin and Munro Arch (Zhan, 2019a). 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. These reflectors can be consistently tracked between these sites, and are also readily extended to the east margin of the sub-basin. However, the thick transparent seismic zone corresponding to the Goldwyer Formation in the Broome Platform and Willara Sub-basin appears absent in the Kidson Sub-basin. This is probably related to its change of facies and/or reduced thickness, estimated to range from 100 m to 250 m in the Kidson Sub-basin.

Top Willara Formation

The stratigraphy underneath the Goldwyer Formation varies from the combination of carbonate and sandstone of the Willara Formation in Frankenstein 1 to the Wilson Cliffs Sandstone in Patience 2 near the margin of the extended Kidson Sub-basin (Fig. 8). In the depocentre, Kidson 1 intersected about 20 m of sandstone above the total depth. It is unclear if this sandstone unit is age equivalent to the Willara Formation or the Wilson Cliffs Sandstone. The current study tentatively places this sandstone within the upper part of the Wilson Cliffs Sandstone, and interprets that the Willara Formation is present only in the faulted blocks where Frankenstein 1 can be projected along the Kidson seismic profile. The top Willara Formation between CDP 49000 and 55200 is picked empirically on a seismic peak reflector (Fig. 8), which is a typical signature interpreted across the Willara Sub-basin and Broome Platform (Zhan, 2019a). Its strong reflection supposedly correlates to the interface between the mudstone of Goldwyer Formation and the high velocity/density material in the Willara Formation.

Top Nambeet Equivalent

The Nambeet Formation is the basal unit of the Canning Basin in most wells in the Willara Sub-basin, the Broome Platform and terraces farther north and east (Fig. 2). This unit was interpreted by Haines (2011) to be age equivalent to the Wilson Cliffs Sandstone of parts of the Kidson Sub-basin based on conodont data from Wilson Cliffs 1. The top horizon of both Nambeet Formation and Wilson Cliffs Sandstone is named Top Nambeet Equivalent here, and covers most of the extended Kidson Sub-basin. The Nambeet Formation is interpreted to be present only in the faulted blocks between CDP 49000 and 56650 and is truncated by the Lower Devonian Tandalgoo Formation near the western margin. The Wilson Cliffs Sandstone is overlain by the Goldwyer Formation across the majority of the sub-basin from CDP 49000 to 4000, but is overlain by the Tandalgoo Formation with an angular unconformity farther east (Figs 3, 8).

Haines (2011) identified a different sandstone package underlying the upper part of the Wilson Cliffs Sandstone in Patience 2 from 3322 m to total depth. This was based on the sharp break in wireline logs, a significant reduction in the rate of penetration and strong silica cementation reported from cuttings. As the formation identification of this package was ambiguous in the absence of biostratigraphic constrains, Haines (2011) presented three options: 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.

It is difficult to directly correlate the lower package of sandstone in Patience 2 with the Kidson seismic profile due to the lack of offset lines connecting to the well. However, on the recently reprocessed profiles across Patience 2 (Fig. 10), the lower Wilson Cliffs Sandstone package corresponds to the weak-amplitude zone underneath the reflective section below about 1.5 s, and onlaps the basement towards the south. Such weak seismic characteristics are comparable to the lowest part of the basin below the reflective Ordovician section on the Kidson seismic profile. The presence of this section within the central part of the sub-basin coincides with several gravity lows about 20 to 50 km wide separated by narrow gravity ridges.

The lower Wilson Cliffs Sandstone package can also be tracked from the eastern edge to CDP 37400 but is absent between CDP 37400 and 49000, a distance of over about 100 km near the southwest margin of the Kidson Sub-basin (Fig. 8). This package gradually thins towards the eastern edge of the sub-basin (Fig. 8) and appears to onlap the basement slope from CDP 33000 to CDP 37000 (Fig. 21a). The western onlap geometry, as well as the missing Nambeet Equivalent package, mimics the seismic signature of the Nambeet Formation between Parda 1 and Sharon Ann 1, shown on the Canning Coastal seismic profile (Fig. 21b; Zhan, 2017, 2019a). Both profiles indicate that the Nambeet Formation, or the Nambeet Equivalent package, was restricted to thicker, earlier-formed parts of the basin, with a lack of deposition across basement highs during the earliest phase of the basin development.

Top basement

Precambrian basement consisting of low-grade metamorphic rocks were intersected in Frankenstein 1 and Wilson Cliffs 1 below 2666 m and 3503 m, respectively, at the western and eastern margins of the Kidson Sub-basin (Fig. 8). The basement boundaries in both wells are characterized by sharp downward changes on the density, acoustic velocity and shallow/deep resistivity logs, indicating an increased hardness and reduced porosity below the boundaries. The seismic profile across Frankenstein 1 shows that the basement forms a structural dome with its upper part truncated by the Ordovician–Silurian megasequence of the Canning Basin (below 1.4 s in Fig. 17a, b; Command Petroleum N.L., 1989). This prominent angular unconformity can be tracked along the composite line, with a relatively high level of confidence across faults, to about 1.3 s at CDP 51600 on the Kidson seismic profile (intersection j in Fig. 11). The seismic signature deepens sharply to the east, forming a half-graben geometry bounded by the fault (F8) at CDP 49000 (Fig. 8). 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 (Figs 8, 11).

To the east of the fault the top basement horizon dips towards the middle of the sub-basin, reaching a maximum depth of about 3 s (equivalent to ~7 km; Fig. 8) near the projected position of Kidson 1. However, this estimate does not provide a maximum thickness for the Kidson Sub-basin, as the seismic profile sits on the southern flank of the sub-basin. The depocentre of the sub-basin is possibly up to 10 km deep about 20–40 km to the north of the line, based on gravity data and offset lines such as Tabletop 70-B (Fig. 15), which show a north-eastward deepening trending from the Kidson seismic line.

Discussion

The recently acquired regional Kidson seismic survey provides an overview of two deep depressions in the southern Canning Basin: the extended Kidson Sub-basin and Barnicarndy Graben, as well as the southern extension of the shallower Wallal Embayment, which consists mostly of the Permian section. The current tectonic subdivisions of the Canning Basin (GSWA, 2017a) are broadly consistent with what can be observed from the Kidson seismic survey, but need to be revised to match with the seismic features at the boundaries. A hierarchical system of the tectonic elements may need to be adopted to further subdivide the extended Kidson Sub-basin. Within the extended depression, the Ryan Shelf and the currently defined Kidson Sub-basin are considered as the interior elements based on their similar stratigraphy.

The Kidson seismic survey shows that the Ryan Shelf is intensely faulted (F2 to F6) in Fig. 3) and was uplifted after the deposition of the Ordovician strata. The location of its western boundary on the seismic profile needs to be revised to CDP 6150 (Fig. 8) from a previous interpretation locating it at about CDP 15750 (GSWA, 2017a), to remove structural inconsistencies. This boundary shift redefines the eastern edge of the Kidson Sub-basin by including the thicker, relatively undeformed succession in the western part of the original Ryan Shelf. The western boundary of the Kidson Sub-basin is more difficult to determine. Use of the F8 fault at CDP 49000 is hampered due to the uncertainty in extrapolating this fault further to the east or south. This fault will likely serve as a boundary of a different tectonic unit when it can be regionally mapped with more data collected in this area. The current study temporarily includes the faulted wedges between faults F8, F9 and F10 (Fig. 8) within the Kidson Sub-basin, and places its western boundary at the truncation point of the pre-Permian strata (CDP 56650). The truncation has an irregular outline shown as the blue dashed line in Figure 11, compared with the relatively straight line of the sub-basin's eastern boundary (fault at CDP 6150). The Anketell Shelf is revised to be restricted to an area containing only the Permian strata from CDP 56650 to 59000 (Fig. 12).

The majority of the extended Kidson Sub-basin is a relatively undeformed sag, with a series of high-angle faults near the eastern and western margins. The Barnicarndy Graben is fault-bounded to the nearby tectonic units, including the Wallal Platform, Anketell Shelf and the Paterson Orogen. The two deep depressions contain thick Paleozoic successions and are interpreted to have undergone several depositional phases during the development of the basin.

Early to Middle Ordovician phase

The earliest deposits intersected in the southern Canning Basin are the Lower Ordovician Nambeet Formation or the age-equivalent lower package of the Wilson Cliffs Sandstone, which was identified in Wilson Cliffs 1 and possibly correlates to the bottom package of sandstone in Patience 2 (Haines, 2011; Wingate et al., 2018a,b). The seismic profile across Patience 2 shows that the package corresponds to the weak-amplitude zone below a thick continuous reflective section (Fig. 10), and can be tentatively jump-correlated to the lowest transparent zone above the strong continuous top basement reflector on the Kidson seismic profile.

The seismic interpretation (Fig. 21) shows that the lowermost Ordovician strata thins away from the sub-basin depocentre, and becomes absent between CDP 37400 and 49000 over about 100 km near the southwest margin of the Kidson Sub-basin. Its onlapping patterns over the basement and eventual absence towards the west (Fig. 21) resembles the seismic signature of the Nambeet Formation between Parda 1 and Sharon Ann 1 in the Canning coastal area (Zhan, 2017, 2019a). Both the Kidson seismic profile and the Canning coastal profile indicate that the Nambeet Formation, or its equivalent, was restricted to the discrete depocentres of the Canning basin and was not deposited across basement highs during the earliest phase of basin development. The restricted deposition may also apply to the lowest package of sandstone in Barnicarndy 1, between 2290 and 2585 m. The age of this lowest sandstone package is yet to be determined. Interpretation will be subject to the ongoing analysis; however, it may be older than the Nambeet Formation. These lowest sandstones in Barnicarndy 1 may have also been emplaced into the graben by the tectonic activities along the swinging fault, labelled as F8 and F11 in Figure 14, if strike-slip movements occurred after the deposition.

Some normal faulting also occurred in response to this Early to Middle Ordovician phase of basin subsidence, shown on the Kidson seismic profile at CDP 49000, 52000 and 54000 (Fig. 8). These faults (F8, F9 and F10; Fig. 8) are interpreted to strike westerly to northwesterly, and are similar to the faults near Munro 1 and the Admiral Bay Fault Zone (Zhan, 2019a).

They all exhibit a thickening of the lower unit within the hanging-wall towards the fault, implying syndepositional movement during the Early Ordovician. However, none of these faults appear to have had significant control over deposition in the extended depression, given its overall sag morphology and the relatively small scale of the faults.

The initial sag phase of basin subsidence was followed by gradual expansion of the accommodation space from the Early to Middle Ordovician, allowing the deposition of the Wilson Cliffs Sandstone and Goldwyer Formations over the previous basement highs between CDP 37000 and 49000 (Fig. 8). While the onlapping features of these formations are obscured on the Kidson seismic profile, it is still comparable to the coastal area near Parda 1 where the Willara Formation onlaps the basement (Fig. 21).

Underlying the Top Goldwyer horizon, the Lower to Middle Ordovician section shallows towards the east on the Ryan Shelf but its thickness above the basement remains relatively unchanged (Fig. 3). A similar configuration is also observed over the western margin of the sub-basin, where the Lower to Middle Ordovician succession is truncated by the Lower Devonian Tandalgoo Formation (Fig. 8). This geometry of the lower succession along both margins suggest that the Kidson Sub-basin originally extended farther to the west and east beyond the current margins, but basin succession originally deposited in these areas was subsequently uplifted and eroded from the periphery of the sub-basin.

Middle Ordovician to Middle Devonian phase

The Middle Ordovician to Early Devonian succession consists of the Carribuddy Group and Worral Formation. The stratigraphic contacts within this succession appear to be conformable; however, the package is truncated by the overlying Lower to Middle Devonian Tandalgoo Formation on the Ryan and Anketell Shelves (Fig. 8). Truncation and erosion of the Lower to Middle Ordovician succession in these areas is probably related to regional post-depositional compression. This tectonic event also led to the movement of the near-vertical faults (Fig. 3), which show reverse and strike-slip components across the Ryan Shelf between CDP 4000 and 6200. At CDP 5730 (Fig. 7), the Lower to Middle Ordovician succession, under the Top Goldwyer horizon, exhibits a sharp juxtaposition against a high-angle fault that extends up into the Carribuddy Group and Worral Formation. The sharp contact becomes much reduced above the Goldwyer Formation. The change in deformational magnitude from the Goldwyer to Worral Formation indicates that the movement was initiated after the Middle Ordovician, and was possibly reactivated in the Early Devonian to produce distortion in the Worral Formation.

The Mallowa and Minjoo Salts of the Carribuddy Group, and concurrent similar deposits in the eastern Amadeus, Bonaparte and Southern Carnarvon Basins, are coeval with a global glaciation event and associated sea-level fall during the Late Ordovician to Silurian (Zhan, 2019b; Haines, written comm., 2020). In addition to the change in climate, the tectonic movement after the Middle Ordovician discussed above may have also contributed to salt deposition in the Canning Basin. The regional structural event caused uplift in the southern Canning Basin, including the Ryan–Anketell Shelves, Jurgurra–Barbwire terraces and northern margin of the Broome–Crossland platforms, as well as the present-day nearshore portions of the Broome Platform–Willara Sub-basin during the deposition of the Upper Ordovician to Silurian succession. The different amounts of tectonic uplift may have created a barrier that isolated the southern Canning Basin from open marine realm, resulting in evaporite deposition (Zhan, 2019b). This tectonic movement is interpreted to be the result of the regional Alice Springs Orogeny (Dunlap et al., 1995; Haines et al., 2001), as the timing of the start of the orogeny is coincident with the salt deposition in the Canning Basin. Shortening from the regional orogeny propagated throughout the Kidson and Willara sub-basins with evidence of reverse and strike-slip faults along the basin margins.

Overlying the Worral Formation, the post-evaporative Lower to Middle Devonian succession consists of the Tandalgoo Formation, which includes porous sandstones in the Kidson and Willara Sub-basins, and Barbwire Terrace, overlain by the Mellinjerie Limestone and lateral equivalents. Koop (1966) suggested that the Tandalgoo Formation and Carribuddy Group were both deposited during a tectonically induced regressive cycle. The post-evaporative sediments were deposited in eolian to fluvial environments with minor marine influence (Lehmann, 1984). The Kidson seismic survey shows that this interval has a package of continuous parallel reflectors but is truncated by the overlying Grant Group at the margins of the southern Canning Basin (Fig. 8). It is possible that reactivation of the Alice Springs Orogeny during the Lower to Middle Devonian created further tectonic uplift in the southern part of the basin to allow deposition of only shallow-water to eolian facies (e.g. 'Tandalgoo red beds' of interval 2 of Forman and Wales, 1981).

Late Devonian to Carboniferous phase

The Upper Devonian to Carboniferous succession is mainly confined to the northern Canning Basin and does not extend to the southern area imaged by the Kidson seismic profile. This suggests that there was either a depositional hiatus of the order of 80 million years in the south, or a differential erosion between the northern and southern Canning Basin during the Late Devonian to Carboniferous period.

The eastern boundary fault (F1, Figs 3, 8) of the Canning Basin at CDP 3400 on the Kidson seismic profile is correlated to the north with the fault separating the wedge-shaped graben east of Lake Hevern 1 from the Murraba Basin (Figs 4, 6). Within the wedge, the Upper Devonian to Carboniferous section thins towards the boundary fault and constitute a faulted anticline at Lake Hevern 1. This post-depositional structural style indicates a compressional or strike-slip movement along the boundary fault near the eastern margin of the Canning Basin. This movement was most likely a reactivation of the compression regime initiated in the middle Ordovician, and created a sharp tectonic boundary along this edge of the Canning Basin, particularly for its pre-Permian succession.

Permian to Mesozoic phase

The Permian succession (above Base Grant) is widespread across the Canning Basin and directly overlies the Precambrian basement in some areas along the seismic profile (e.g. the Wallal Embayment, Plate 1). It is possible that the widespread Permian section has been more deeply buried within the southwestern margin of the Canning Basin,

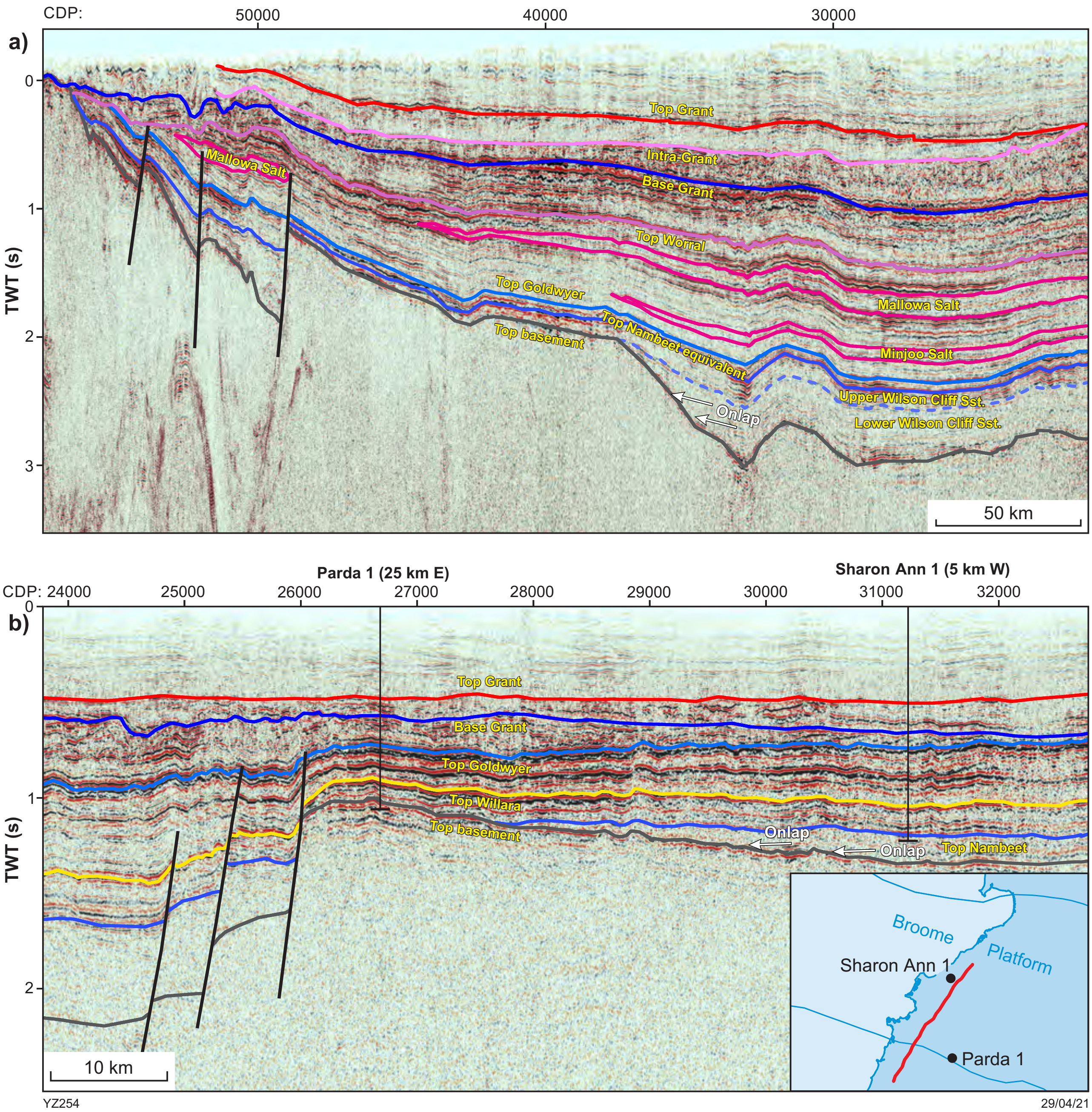

Figure 21. Comparison of the lower part of the basin fill between the Kidson a) and Canning coastal b) and seismic profiles, showing that the Nambeet Formation, or its equivalent, was restricted to thicker, early formed parts of the basin. Inset map shows the location of the Canning coastal seismic profile and nearby Parda 1 well

than at present, based on the anomalous velocity profile in Barnicarndy 1 and the structural connection to the Kidson Sub-basin. Due to regional tectonism and fault reactivation, the thick Permian section possibly underwent different amounts of uplift and erosion, such as complete removal in the Telfer mining area, but only partial erosion in Anketell Shelf and Barnicarndy Graben areas (Fig. 12). This tectonic movement possibly had a regional impact and may have been associated with the Late Triassic basaltic intrusion and extrusion near Pittston SD 1 to the north-northeast of the Barnicarndy Graben near the coastal area (Fig. 12 inset). If this timing is correct it indicates that the fault reactivation was associated with the regional Fitzroy Transpression movement (Rattigan, 1967; Zhan and Mory, 2013).

During the deposition of the Permian section, the Canning Basin underwent a regional extension, which was possibly responsible for a series of northwest–southeast oriented faults, and an episode of salt dissolution and withdrawal in the southern Canning Basin (Zhan, 2019b). This is shown by the geometrical irregularities at the base of the Grant Group near the salt margins between CDP 51000 and 53000 (Fig. 8). The deformation around and beyond the present-day salt boundary indicates the salt deposits originally covered a larger area in the southern Canning Basin, which has been reduced by withdrawal and dissolution around the rim during subsequent burial, with residual salt pillows possibly present after the salt mobilization.

Conclusion

The west–east oriented Kidson Sub-basin seismic survey was acquired from about 30 km west of the Kiwirrkurra community to approximately 20 km east of Marble Bar. The survey is 872 km long, and images the southern Canning Basin and surrounding basement domains. The data is of good quality, particularly in the extended Kidson Sub-basin, where it shows continuous parallel reflectors across the depocentre and fault displacements near the basin margins.

The Kidson seismic profile shows that the boundaries of previous tectonic subdivisions (GSWA, 2017a) did not coincide with seismically defined features around the margins of the Kidson Sub-basin presented here. The Ryan and Anketell Shelf boundaries have been revised to more geologically meaningful positions. As a result, the extent of the Kidson sub-basin has been expanded into areas formally classified as shelves. The hangingwall and footwall of the major fault (F8) at CDP 49000 are both now included in the Kidson Sub-basin because the fault is difficult to correlate with limited data. This fault could be used to separate a new tectonic unit from the Kidson Sub-basin, when more data become available.

The Canning Basin is bounded to the east by a deeply seated near-vertical fault (F1) against the Amadeus Basin and underlying Arunta Orogen. This boundary fault can be traced along its gravity signature to the north where it separates a wedge-shaped depression of the Gregory Sub-basin from the Murraba Basin. The movement of this regional boundary fault is interpreted to be post-deposition of the wedge with a compressional or strike-slip component along the eastern margin of the Canning Basin. The lower part of the basin on the Ryan Shelf is correlated to be Lower Ordovician and is truncated by the Tandalgoo Formation. The Ordovician succession becomes shallower towards the east, with internal reflectors parallel to the top basement surface. This geometry, specifically the constant thickness, contrasts with 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 and the possibility that Ordovician outliers may be present to the east of the Canning Basin. The Ordovician succession near CDP 5800 shows a sharp juxtaposition against a near vertical fault (F5) that extends up into the Worral Formation but with much reduced deformation. The change in deformational magnitude from the Goldwyer to Worral Formation indicates that the basin inversion was initiated after the Middle Ordovician and reactivated in the Devonian after the deposition of the Worral Formation.

The extended Kidson Sub-basin, including the Ryan and Anketell Shelves, forms a relatively undeformed sag depression, with several apparent folds caused by the combination of route bends and the northeast dip of the strata. With the inclusion of well calibration and offset seismic profiles, eleven horizons are interpreted from the top basement to the top Grant Group. The top basement horizon deepens towards the central part of the Kidson Sub-basin, reaching about 3 s (equivalent to ~7 km) below the projected position of Kidson 1 in the seismic plane. As the profile images the southern flank of the sub-basin, its depocentre about 20–40 km north of the line is estimated to be about 10 km deep based on the strata dip measured through an offset seismic line.

The lowermost package of the basin fill onlaps the sloping basement surface from CDP 33000 to CDP 37000 in the Kidson Sub-basin, and is comparable to the lower part of the Wilson Cliffs Sandstone in Patience 2. The onlap geometry mirrors the seismic signatures, in the Canning coastal seismic profile, of the Nambeet Formation between Parda 1 and Sharon Ann 1 (Zhan, 2017, 2019a). Thus the bottom package is interpreted to be equivalent to the Nambeet Formation or the lower part of the Wilson Cliffs Sandstone in Patience 2. Both units belong to the Lower Ordovician succession that was probably restricted to discrete depocentres during the earliest phase of the deposition within the Canning Basin.

The basin gradually expanded from the Early to Middle Ordovician, allowing the deposition of the Willara and Goldwyer Formations over previous basement highs. Syndepositional movement occurred (e.g. on faults F8, F9, F10) in response to the basin subsidence, but did not control deposition of the Kidson Sub-basin as a whole given its overall sag morphology and the relatively small scale of the faults. The nature of the Lower to Middle Ordovician strata along both margins suggests that at that time the basin extended farther to the west and east beyond the current preserved limits, but this extended deposition was subsequently uplifted and eroded around the peripheral of the sub-basin.

The Middle Ordovician to Middle Devonian phase includes the Mallowa and Minjoo Salts of the Carribuddy Group, as well as the Worral Formation. The timing of the evaporitic deposition is consistent with the early stage of the Alice Springs Orogeny, suggesting a propagation of the compressional stress field into the Kidson Sub-basin. The overall compression probably had a long duration that can be inferred from the shallow-water to eolian environment of the later Tandalgoo Formation, and the compressional/wrenching movement near the eastern margin of the Canning Basin.

The widespread Permian section might have been more deeply buried than at the present time, based on the anomalous velocity profile in Barnicarndy 1 and the structural connection to the Kidson Sub-basin. This indicates that the thick Permian section possibly underwent different amounts of uplift and erosion caused by tectonic movement. This movement was possibly coeval with the Late Triassic basaltic intrusion and extrusion near Pittston SD 1 to the north-northeast along the boundary fault of the Barnicarndy Graben. If correct, it indicates that the fault reactivation and uplift movement were likely associated with the regional Fitzroy Transpression movement (Rattigan, 1967; Zhan and Mory, 2013).

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The Kidson Sub-basin seismic survey has a total length of 872 km, starting just west of Kiwirrkurra near the Western Australia/Northern Territory border, crossing the southern Canning Basin, and nearly reaching Marble Bar in the eastern Pilbara Craton. The survey is of good quality and shows continuous highly reflective zones and fault displacement across the sedimentary rocks in the basin. A few apparent folds are structural artefacts caused by the crooked geometry of the line over the northerly dipping strata on the southern flank of the basin. The extended Kidson Sub-basin, including the Ryan and Anketell Shelves, forms a relatively undeformed sag depression, with the lowermost package interpreted as upper Cambrian to Lower Ordovician succession. Eleven horizons in the extended sub-basin are interpreted from the top basement to the top Grant Group, based on well calibration and offset seismic profiles. The Barnicarndy Graben and adjacent areas were more deeply buried than present-day, then uplifted with partial removal of the Permian section during the Fitzroy Transpression movement.

Further details of geoscience products are available from:

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