# Interpretation of a Permian conjugate basin margin preserved on the outer Northwest Shelf of Australia

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## SUMMARY

The Northwest Shelf (NWS) of Australia is characterized as a series of northeast-southwest trending Mesozoic offshore depocenters which both juxtapose and partially overprint a series of onshore, northwest-southeast trending Palaeozoic basins. An integrated interpretation of well bore data, regional seismic data and plate tectonic models suggests that the Palaeozoic section is also present below the Mesozoic depocenter. Referred to as the East Gondwana Interior Rift, the primary rift axis is oriented in a (present day) NE-SW direction, with orthogonal marginal rift basins such as the onshore Canning and Southern Carnarvon basins.

While precise age dating for the formation and stratigraphy of the axial rift is speculative, our integrated interpretation suggests that a significant portion of the pre-existing rift was modified by a Mid-Permian extensional event, forming the Northern Carnarvon basin. Interpretation of recently acquired 3D reflection seismic data suggests that the conjugate basin margin from this Permian rifting event is preserved, and is visible below the Mesozoic section. A series of back-stepping, Late Permian carbonate ramps and banks is interpreted to form on a thermally subsiding rift flank. Our interpretation of these carbonate banks is based primarily on seismic geometries, and is supported by area well control and regional paleogeographic models.

This interpretation suggests that a deep marine intra-continental basin bisected the NWS in the Late Permian. Shallow marine conditions then persisted across the conjugate margin through the Triassic and into the Jurassic. After Late Jurassic rifting associated with Gondwanan break-up, the region subsided into deep water.

**Key words:** Northwest Shelf, East Gondwana Interior Rift, Intracratonic Basin, Late Permian, Carbonate Margin, Carbonate Banks

## INTRODUCTION

Decades of offshore exploration on the NWS of Australia have resulted in the discovery of significant quantities of commercial hydrocarbons, both oil and gas. As known plays mature and discovery size decreases, industry continues to assess and explore new plays or previously overlooked plays. These efforts include pushing play concepts further towards basin edges, into deeper present day water depths. These efforts could also include exploring for deeper objectives in sections previously considered too risky or non-commercial. Both the advancement in seismic technology and the proliferation of 3D reflection seismic as an exploration tool, allows industry to image deeper in the section and build interpretations for previously undescribed or poorly described portions of the sedimentary section.

In this study, we describe aspects of the Late Palaeozoic stratigraphy within a sub-region of the greater NWS of Australia. The area of interest crosses the boundaries of many of the familiar Westralian basin names, and thus cannot succinctly be described as residing in any one basin (Figure 1). Unfortunately, the commonly used basin names frequently derive from Cainozoic to recent physiography, or from Mesozoic structural domains, and thus do not effectively describe the deep Palaeozoic section. Here we describe a Permian basin configuration which extends beyond, and is largely unrelated to, the basin boundaries shown in Figure 1.

Many authors have cited the existence of Palaeozoic stratigraphy (Figure 2) across the northwest margin of Australia (Etheridge and Obrien, 1994, Lipski, 1994, O'Brien et al., 1994, Symonds et al., 1994). Borehole penetrations of Palaeozoic rocks and outcropping stratigraphy onshore have been coupled with regional reflection 2D seismic surveys to interpret this section below the >10km thick Mesozoic depocenter of the NWS (Lipski, 1994, Ramsay and Exon, 1994, Stagg and Colwell, 1994). Harrowfield et al. (2005), Vachard et al. (2014), and Haig et al. (2017) interpreted the Late Palaeozoic section across the NWS to be a portion of the East Gondwana Interior Rift (Figure 3), which continued for thousands of kilometres from the Panthalassic Ocean to southern Africa. This Carboniferous –Permian intracontinental rift preceded and was located in the approximate locations of the Jurassic to Cretaceous rift margin which separated Australia from various poorly constrained Asian terranes, Greater India, and India, respectively.

Consistent with the interpretation of Belgarde et al. (2015), this intracontinental rift was structurally modified by later middle Permian extension. This event, which formed what would become the Northern Carnarvon basin, was roughly contemporaneous with the middle Permian separation of Gondwana with the Sibumasu terrane (Metcalfe, 2011, 2013, Zhang et al. 2013). Recent long offset, long record, 2D multiclient surveys as described by Belgarde et al. (2015) and Bellingham et al. (2015) were key datasets for this age interpretation. This middle Permian aged intracratonic basin separated continental Australia from the relatively smaller continental crust supported terranes which would eventually rift in the Jurassic and accrete to Eurasia in the Cretaceous (Hall 2012, Metcalfe 2013, Heine and Muller 2005, Zahirovic et al., 2014).

By integrating borehole information, seismic interpretation from both 2D and 3D datasets, basin evolution concepts, and plate tectonic models, we interpret a modified intracratonic basin with a preserved conjugate margin to continental Australia. Regional observations of Late Permian stratigraphy are coupled with local seismic observations to support a carbonate dominated model for the region. A series of carbonate banks and ramps are interpreted on multiple 3D datasets, including the licensed Capreolus 3D survey and the open-file Naranco and Curt 3D surveys. We observe diachronous relationships between the carbonate banks and interpret a (present day) south to north back-stepping relationship. Thermal subsidence on the flanks of the Middle Permian basin is interpreted as the mechanism for south to north relative transgression. Portions of the conjugate margin within the study area remained in shallow water conditions, beyond the influence of Australia derived clastic deposition until the Middle Triassic, when Carnian aged prodelta deposits are confirmed by the research boreholes ODP-759B and ODP-760A/B (Ito et al., 1992). This entire Permo-Triassic section is severely deformed during Jurassic extension and rifting. Lesser terranes such as Argoland and Banda (Hall 2012) are rifted away from the Australian margin but relicts of the Permian conjugate margin remain, below the Late Jurassic to modern passive margin sedimentary section.

## MATERIAL AND METHOD

This study integrates stratigraphic and structural observations from a combination of both open file and proprietary multidisciplinary datasets. These include industry and research derived borehole data, open file and proprietary licensed 2D and 3D reflection seismic data, and proprietary plate tectonic models.

### Material

The seismic database used for this work supports both regional exploration efforts as well as focused mapping which is specific to individual work programs. The database includes all open file 2D surveys in the area of interest (Figure 1). Some of these data are several decades old, with varying quality and relatively short record length (e.g. 5sec two-way time). These data are complemented by multi-client licensed 2D seismic datasets which variously include both reprocessed products and more recent, long offset, long record length (Belgarde et al., 2015; Bellingham et al., 2015). Also used was the proprietary Naranco 3D and all publically available 3D seismic surveys within the area of interest. The Curt 3D survey, acquired on behalf of Woodside Energy Ltd in 2012 and made public in December 2015, is noted as particularly important to the study as this was the first 3D survey in the outer Rowley basin. The study also uses multi-client, licensed 3D datasets. These include the Capreolus 3D survey, acquired by Polarcus in 2015. The 12 second record length and the broadband Pre-SDM workflow significantly improved the imaging of the pre-Mesozoic section.

All publically available borehole data within the area of interest were included in the study. During the course of the work, additional well data was released (e.g. Anhalt-1) and these were integrated into the chronostratigraphic framework and the depositional model. We focused our efforts on offshore exploration, and thus, a comprehensive onshore well database was not incorporated in the work. Mory (2010) and Parra-Garcia et al., (2014) provide comprehensive summaries of the onshore stratigraphy of the Canning Basin. Due to the absence of Palaeozoic well penetration in the study area, we included additional well data with Palaeozoic information from across the NWS. Distances to these ranged from several 100's of kilometres (e.g. Poissoinier-1) to greater than 2000 km (e.g. Kelp Deep-1 ST2).

We modified and updated the BHP proprietary plate model during this study. We leveraged legacy versions of the model which are consistent with the Mesozoic plate architecture and motion described by Hall (2012), Metcalfe (2013), and Gibbons (2013). The model was updated with our interpretation of Late Palaeozoic plate configuration in East Gondwana (Figure 3). The geographic extent includes the entire Australian northwest margin and all associated Gondwana derived terranes. Also included are the India/Greater India continental landmasses with their formerly adjacent terranes (e.g. Lhasa and Qiangtang). Plate configurations from the Carboniferous-Permian boundary (299 Ma) to the present day are included in the model.

### Method

The plate model was then modified after an integration of mega-regional seismic interpretations with high resolution 3D seismic mapping from surveys such as the Naranco 3D, Curt3D and the Capreolus 3D. The chronostratigraphic framework (Figure 2) builds upon previous proprietary mapping of both the crustal architecture (Belgarde et al., 2015) and from the Mesozoic section. Top of crystalline crust (Belgarde et al., 2015) was used as a proxy for the base of the Palaeozoic section. Early Palaeozoic age interpretations were not attempted due to considerable uncertainty and very limited information. The horizons mapped at the mega-regional scale include top of crystalline crust, a middle Permian unconformity surface, and a top of Permian surface (Figure 2). Our basin evolution model was informed by additional Triassic through Cainozoic interpretations, but these are not discussed here in detail.

The 3D surveys in the study area were interpreted at a higher resolution than was done for the megaregional framework surfaces. Multiple Triassic and younger surfaces were interpreted across the Naranco 3D, Capreolus3D, Curt3D, and other 3D surveys in the study area. No well control existed to correlate the top of the Permian on the above mentioned surveys, so long distance (100's of km) seismic correlations are required to interpret the Late Palaeozoic section. In addition a shallower, Early Triassic marker (Cossigny Formation equivalent) was correlated to in-board wells. Since the interval immediately below this marker corresponds to a period in Earth's history were carbonate bank or reef building organisms do not exist, or are extremely rare (Pruss and Bottjer, 2005, Baud et al., 2007), this supports the interpretation that the observed banks are most likely end Permian features.

The 3D interpretation includes a Top of Permian surface and multiple additional surfaces, presumed to be within the late Permian. These are not correlated to any surfaces from the megaregional mapping. The 3D work also includes a late Permian unconformity surface and this is correlated to the megaregional middle Permian unconformity surface.

In parallel with the megaregional seismic interpretations, we constructed a Late Palaeozoic through present day plate model to provide megaregional context for our interpretation of basin evolution and stratigraphic environments. As new seismic data revealed higher quality images of the pre-Mesozoic section, the model was updated to incorporate the thick (>10 km) Palaeozoic basin interpreted from megaregional seismic mapping. The span of geologic time represented in the plate model was extended to include the entire Permian Period.

Detailed analysis of the structural timing of this Palaeozoic depocenter is beyond the scope of the study; our plate model does not include any movement of Gondwanan terranes before the middle Permian. The model and plate restorations include the middle Permian extension that forms the Northern Carnarvon basin (Belgarde et al., 2015). After the Permian event, a region of thinned continental crust is separated from Australia by several 100's of kilometres. This thinned continental crust is still attached to terranes such as Argoland and Banda on its western edge. The result is the formation of an intracratonic basin positioned between Australia and the Argoland terrane. Continental crust thinned by Permian extension exists on both margins of this Permian basin. Following the Permian extensional event, the plate positions remain relatively unchanged until the Early Jurassic. Jurassic to Cretaceous rifting associated with Gondwana breakup is included in our model but is not discussed here.

## DISCUSSION

### Seismic Interpretation Discussion

After initial recognition of the carbonate shelf edge geometries (Gartner et al., 2005) on the Curt 3D it was possible to follow similar bank edge geometries through to the adjacent 3D Surveys (Figures 4 and 5). Furthermore, it was evident that these features were stratigraphic in origin as they show no sign of contemporaneous faulting and are often cross cut by the younger stages of faulting (Figure 5). In some areas, though, the edge of the carbonate platform is observed to act as a locus for younger faulting (Figure 4 and 5) with the younger faulting detaching into the thick, Early Triassic high-stand shales that flooded the carbonates after the end Permian extinction event.

The licensed Capreolus 3D survey was critical to expanding the team's interpretation of multiple carbonate ramp edges. A 3D perspective view (Figure 5) demonstrates the geometry of these ramp edges. As seen on the Curt 3D (Figure 4), the ramp edges on the Capreolus 3D are dominantly south facing, suggesting deeper water to the south and shallower, photic zone conditions to the north. Figure 5 differentiates the interpreted Late Permian aged ramp edges from the Jurassic extensional faults which overprint the region. Subregional seismic correlations across 3D and 2D data suggest that the Permian ramps seen in Figure 5 are the oldest of all the ramps identified. Absolute ages for the ramps identified in the above mentioned seismic surveys are highly uncertain and are beyond the scope of this study. Regional seismic ties and well control constrain our interpretation only to the Late Permian (Figure 4).

### Plate Model Discussion

Restorations of the Palaeozoic and early Mesozoic plate models are highly uncertain due to the loss of constraining oceanic crust in subduction zones. Burrett (2014) effectively summarizes the variability in published Palaeozoic plate models and their inherent uncertainly. The Carboniferous to Permian boundary (299 Ma) plate restoration (Figure 3) is modified from the above authors and is consistent with Metcalfe (2013). The East Gondwanan Interior Rift system is schematically represented in Figure 3, consistent with Harrowfield et al (2005), Vachard et al (2014) and Haig et al (2017). The rift basin is immediately adjacent to known Palaeozoic depocentres on the Australian margin, such as the offshore Petrel sub-basin, the onshore Canning and the southern Carnarvon basins. Extending known Palaeozoic stratigraphy from these basins to the north and northwest allows us to interpret the thickness and orientation of the axial rift basin below the Mesozoic. Palaeozoic marginal basins that may occur on the Argoland and Banda terranes which eventually accrete to Eurasia are highly speculative. We observe relatively thin Palaeozoic section in the present area occupied by the Northern Carnarvon Basin. This is consistent with our model for basin evolution with the Northern Carnarvon forming in the mid Permian due to intracratonic extension. The mapped thickness is interpreted as Late Permian deep marine deposition.

A schematic diagram for this interpretation (Figure 6) represents the Gross Depositional Environment (GDE) for the Late Permian (Guadalupian - Lopingian) across the study area. Shallow marine carbonate environments can are interpreted near the Australian continent (MacNeill and Marshall, 2015) as well as on the conjugate margin to a middle Permian intracratonic basin. Blue dashed lines represent the edges of carbonate banks which back-step from south (Figure 5) to north (Figure 4).

The Late Permian section is present further to the north, in a crustal domain defined as thinned continental crust (Figure 3). This region of thinned continental crust would form on the conjugate margin to Australia following the Permian extension. Areas of increased crustal thickness in isostatic equilibrium would be expected to be in decreasing water depth. Our interpretation of a carbonate bank is consistent with this integrated interpretation of a region with shallow water depths. The reflections internal to the carbonate bank identified on the Curt 3D also prograde from the north to the south. This suggests that water depths increases to the south, which is consistent with the interpretation of a deep marine intracratonic basin present at this time to the south. The shallow marine carbonate environment continues to the north, at least as far as the location of Jurassic rifting. The depositional environment across the Argoland terrane is highly speculative. We interpret this terrane as extremely distal to Australian derived sediment and, thus, likely to be dominantly carbonate. The Late Permian water depth across Argoland is highly speculative and uncertain. We use the carbonate environment interpreted in the Curt 3D as an analogue for the environment across Argoland.

The progressive Jurassic and Cretaceous rifting that results in the present day NWS morphology was localised to the northwest of where we interpret Permian carbonate banks. The paleo crustal boundary between thinned Australian continental crust and the crust supporting the Argoland terrane was rifted, leaving the thinned continental crust domain on the Australian plate. Thus the region which was once a conjugate margin during Permian extension is now on the proximal margin from the Jurassic rifting event.

## CONCLUSIONS

The Late Palaeozoic East Gondwana Interior Rift can be identified below the Mesozoic depocenter across much of the Australian NWS. Regional 2D and 3D seismic interpretation reveals the NE-SW oriented (present day) axial rift basin which locally reaches thicknesses in excess of 18km. 2D regional mapping also shows two of the coeval NW-SE oriented marginal basins which crop out in the onshore Canning and Southern Carnarvon basins. The absolute age interpretation of the sediments within the basin are highly speculative due the requirement of long distance well ties, and due to limited high quality seismic images. Extending the geographic area of interest for this study to the northeast, closer to the distal equivalent of the Palaeozoic Petrel sub-basin would be desirable to increase confidence in the age interpretation and the greater basin geometry.

The East Gondwana intracratonic rift was structurally modified during the middle Permian by extensional forces that created the greater Northern Carnarvon basin. The incipient Palaeozoic basin was rifted away from the stable Australian craton, resulting in little to no Palaeozoic section as this was a new basin. Previous authors have interpreted oceanic crust or exhumed lithospheric mantle flooring this basin. Arguments for or against a specified crustal composition below this basin are beyond the scope of this study, but we agree with the interpretation that the Northern Carnarvon Basin began in the middle Permian as a deep intracratonic basin with access to marine waters.

The conjugate margin to Australia that was formed during this extensional event is identified using recently acquired 3D seismic datasets such as the Naranco, Capreolus and Curt 3D surveys. The Late Permian section on this conjugate margin is predominantly a carbonate environment, with multiple, steep carbonate banks and ramps back-stepping from south to north away from the intracratonic basin center. This stratigraphic interpretation is consistent with a carbonate lithologies that are observed along the Australian proximal margin for several hundreds of kilometres both the northeast and to the southwest. Our findings are also consistent with the work of other authors who interpret a robust Late Permian carbonate platform immediately to the south (present day) of the back stepping ramps described here.

Robust carbonate production ceases with the end-Permian mass extinction event and Triassic clastic progradation from south to north, filling the Northern Carnarvon basin. Identifying shelf edges which indicate shallow marine conditions along the conjugate margin becomes increasingly uncertain during the middle to early Late Triassic. Carnian prodelta deposits in local ODP wells provide age control for the prograding clastic system reaching the location of the ancient conjugate margin, and ending its existence as a bathymetric feature. Multiple kilometres of Late Triassic to Middle Jurassic clastic deposition continue to bury the Permian margin, obscuring its precise geometry. Jurassic extensional tectonics deform the region, increasing the uncertainty of the nature of the Palaeozoic section. Still, the Jurassic rifted margin is to the north and the northwest of the observed Permian shelf edges, indicating that the Permian conjugate margin 'survived' Jurassic extension, and remains with the Australian plate, on the Jurassic to modern proximal margin.

We use seismic geometries and facies as principle lines of evidence for the interpretations of carbonate banks and ramps and we acknowledge the lack of wellbore penetrations that would serve as confirmation. Well penetrations of Late Permian carbonates, while rare, can be found to the southeast towards the Southern Carnarvon basin and to the northeast in the Bonaparte Basin. We recognize that these long distance correlations introduce uncertainty for the age interpretation. Observations made from seismic geometries and seismic facies are integrated with regional age correlations and megaregional models for NWS basin evolution to form the basis for these conclusions. As additional seismic and borehole data continues to be made available to industry, additional observations will undoubtedly be made to further understanding of the enigmatic Palaeozoic history of the Northwest Shelf of Australia.

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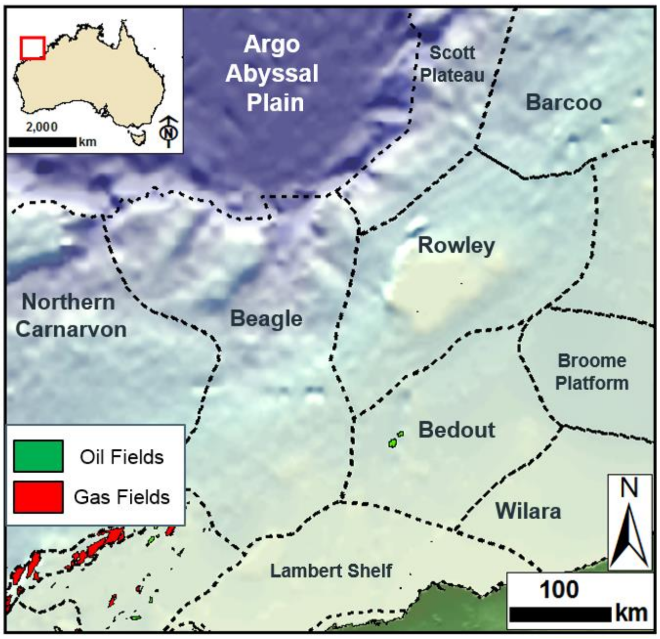



**Figure 1: Base map of area of study. Commonly used basin and sub-basin bounded by dashed lines and annotated.**

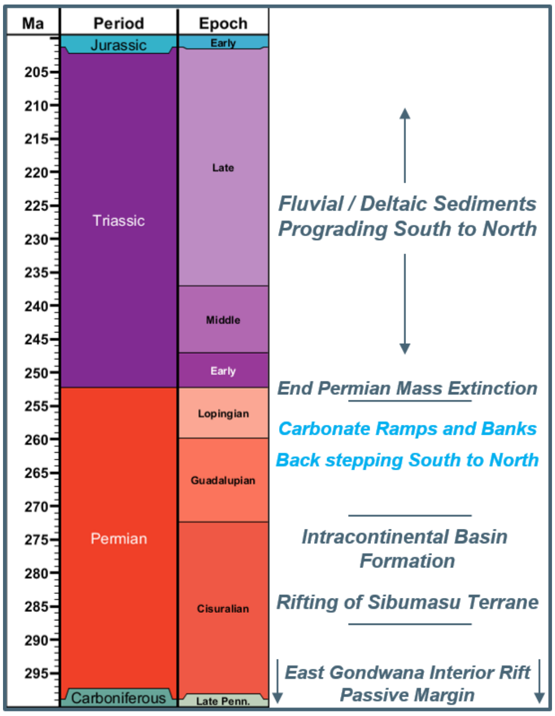



**Figure 2: Permian-Triassic time scale (GTS 2012) with key basin evolution and depositional events.**

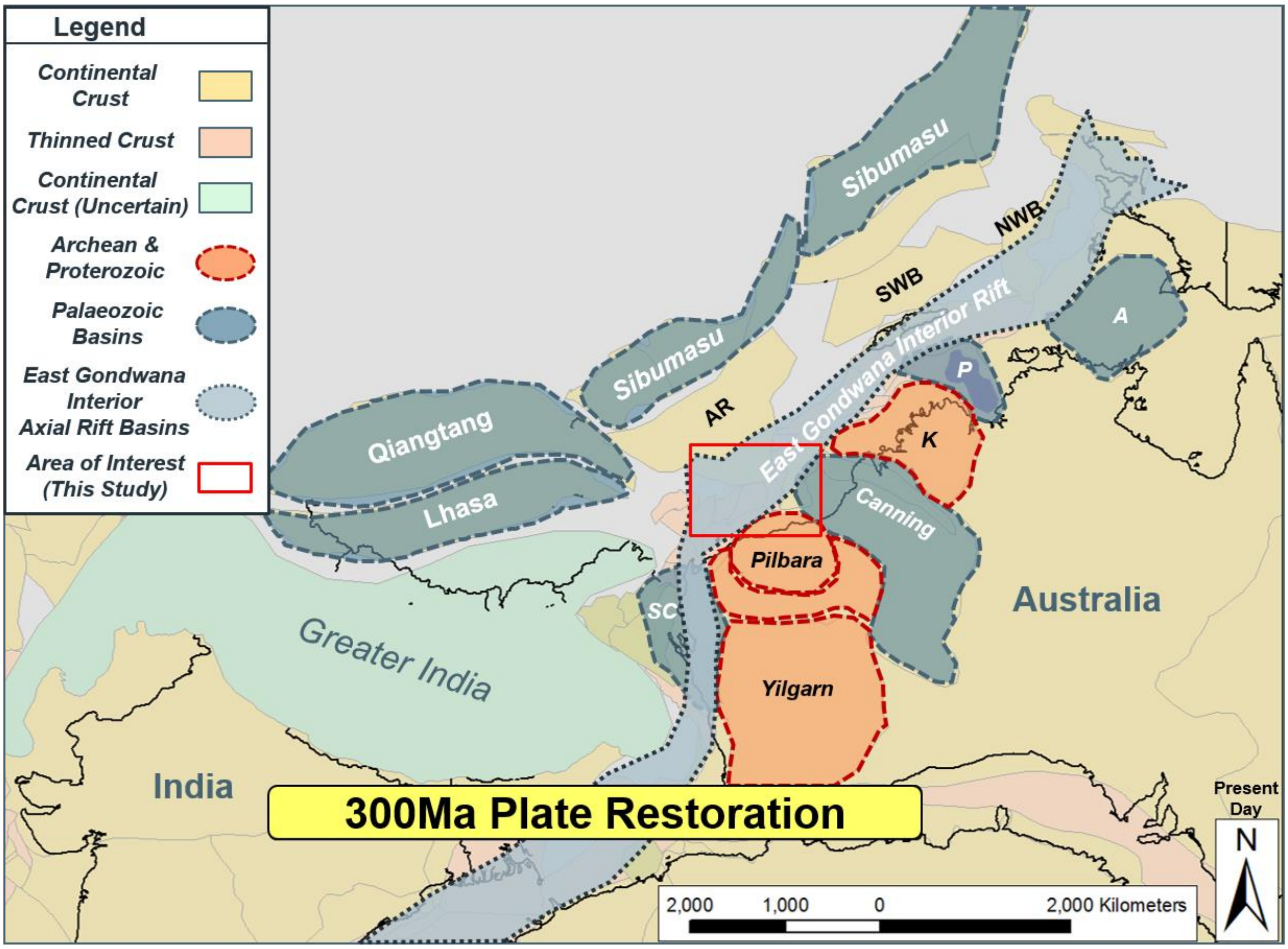



**Figure 3: Schematic plate reconstruction east Gondwana at Carboniferous /Permian boundary (299Ma). Area of study is highlighted with an inset box. Additional terranes and basins K: Kimberley, AR: Argoland, SWB: Southwest Borneo, NWB: Northwest Borneo, SC: Southern Carnarvon, P: Petrel, A: Arafura.**

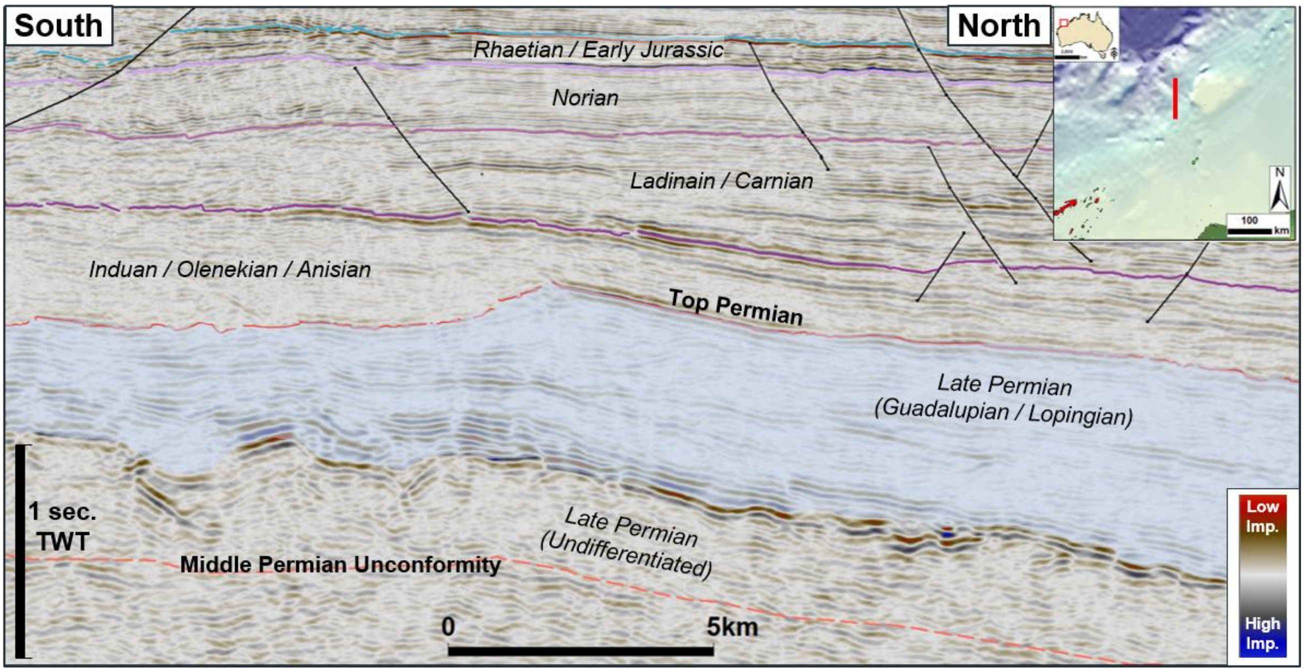



**Figure 4: North South oriented seismic cross section (TWT) from the open-file Curt 3D seismic survey. Age interpretation from 2D and 3D regional seismic correlations. Late Permian carbonate bank exhibits internal geometries which prograde from north to south, increasing in slope angle.**

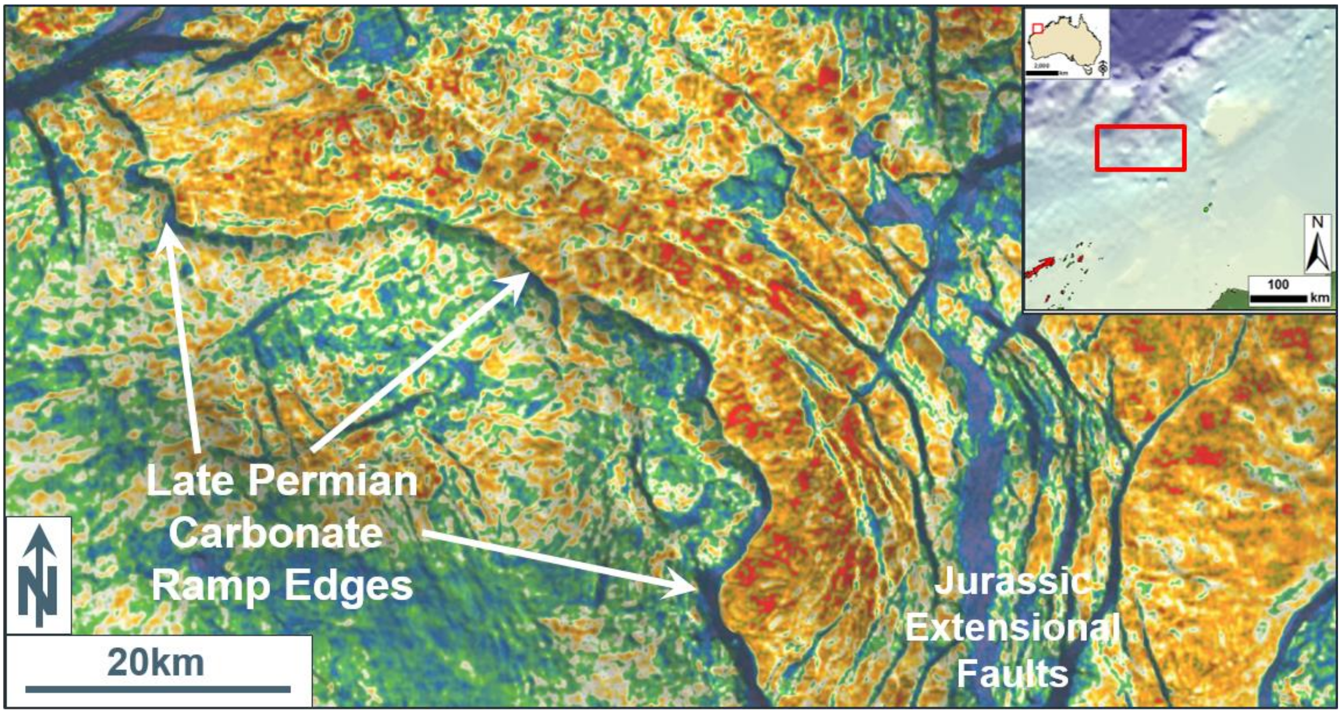
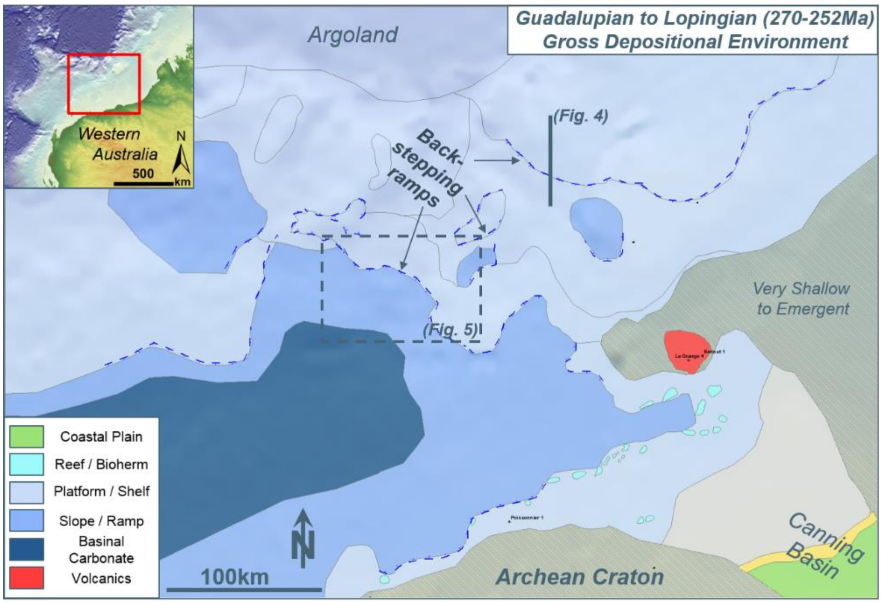



**Figure 5: Perspective view of Late Permian carbonate bank environment interpreted on licensed Capreolus 3D seismic survey. Image usage courtesy of Polarcus.**



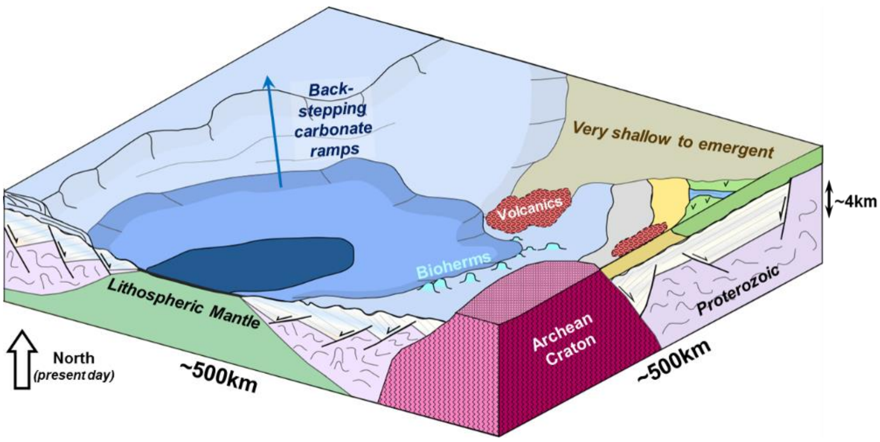




**Figure 6: Late Permian Gross Depositional Environment and block diagram. The line of section (Figure 4) and map area (Figure 5) are posted on the GDE map. The schematic block diagram**