

# Prospectivity of the Triassic successions of the North West Shelf of Australia: New insights from a regional integrated geoscience study

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## Abstract

The North West Shelf (NWS) of Australia is a prolific hydrocarbon province hosting significant volumes of hydrocarbons, primarily derived from Jurassic and Cretaceous targets. A new regional, integrated geoscience study has been undertaken to develop insights into the paleogeography and petroleum systems of Late Permian to Triassic successions, which have been underexplored historically in favor of Jurassic to Cretaceous targets. Within the NWS study area, graben and half-graben depocenters developed in response to intracratonic rifting that preceded later fragmentation and northward rifting of small continental blocks. This, coupled with contemporaneous cycles of rising sea levels, brought about the development of large embayments and shallow, epeiric seas between the Australian continental landmass and outlying continental fragments in the early stages of divergence. Key elements of the study results discussed herein include the study methodology, the paleogeographic and gross depositional environment mapping, and the reservoir and source kitchen modeling. The study results highlight the presence of depocenters that developed within oblique rift zones due to regional Permo-Triassic strike-slip tectonics that bear compelling similarities to modern-day analogues. These intracratonic rift zones are well-known and prominent tectonic features resulting from mantle upwelling and weakening of overlying lithospheric crust, initiating the development of divergent intraplate depocenters. The comprehensive analysis of these depocenters from a paleogeographic and petroleum system perspective provides a basin evaluation tool for Triassic prospectivity.

associated with the breakup of the Gondwana Margin, commenced in the Norian, affecting the sedimentary basins of the NWS (Metcalf, 2013; Zahirovic et al., 2016).

More than 70 of the discoveries made in the NWS, with total gas reserves approaching 150 TCF, are within Middle to Late Triassic reservoirs, mostly in the fluvio-deltaic sandstones of the Mungaroo Formation and its equivalents. The recent Dorado oil discovery in Middle Triassic reservoirs within the Bedout subsbasin has sparked new interest in the hydrocarbon potential of the

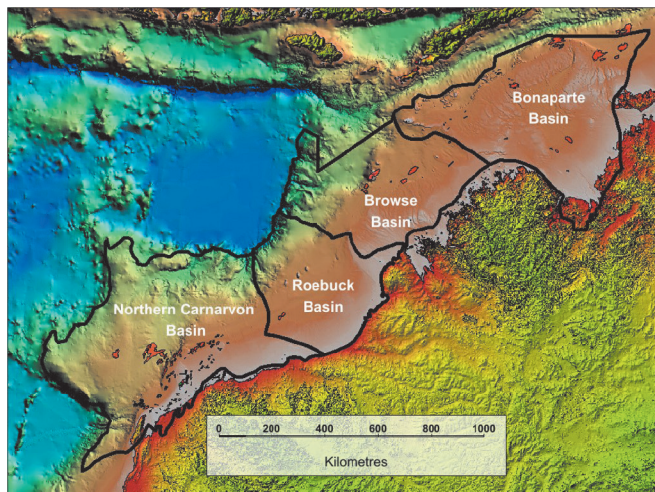


Figure 1. NWS Triassic study coverage area, including the four major basins.

## Introduction

The North West Shelf (NWS) is located along the northwest coast of Australia covering an area of 720,000 km<sup>2</sup>, which developed contemporaneously with breakup along the eastern margin of Gondwana, with proven petroleum systems ranging in age from Paleozoic to Mesozoic (Purcell and Purcell, 1988) (Figure 1). Throughout the Triassic, the NWS was located at the southern margin of the Tethys Ocean. Depositional systems of the four sedimentary basins are a function of eustatic sea level changes and thermal subsidence following the opening of the Tethys ocean basins (Figure 2). Renewed tectonic activity,

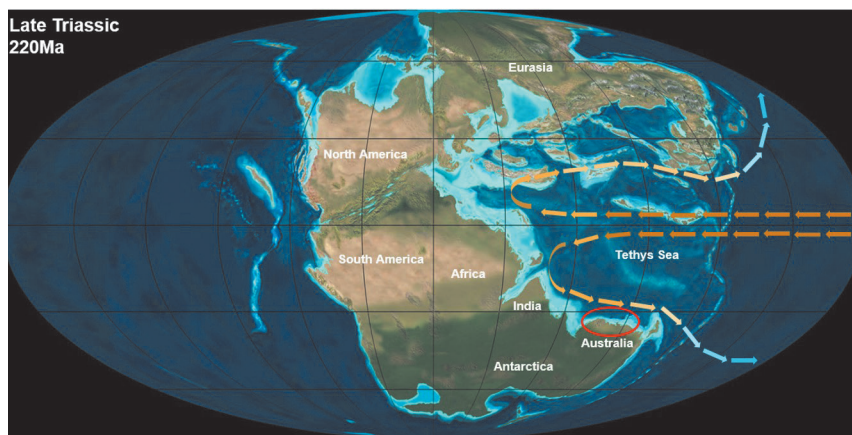


Figure 2. Late Triassic continental configuration (Tethys Sea), with warm ocean-current circulation.

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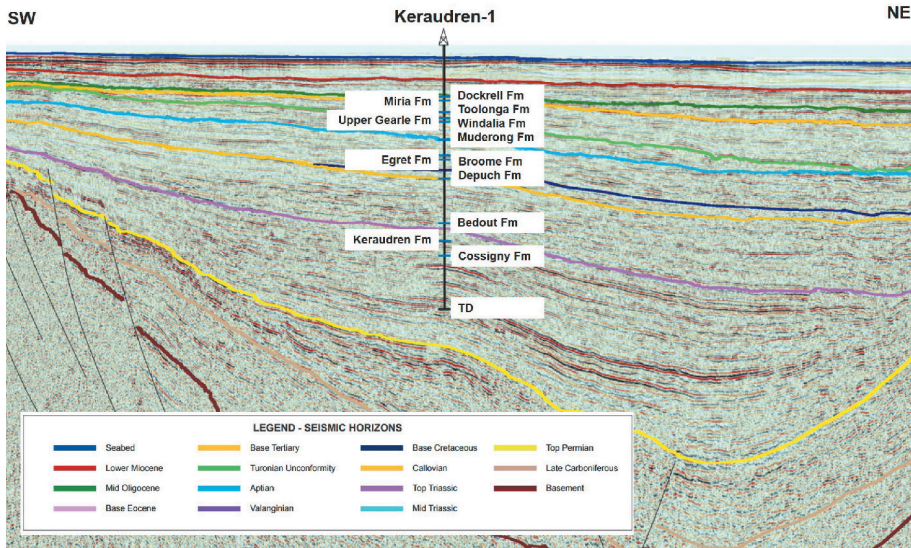


Figure 3. AGSO 2D seismic line S110r07 in the Bedout subbasin, with Keraudren-1 well and interpreted horizons.

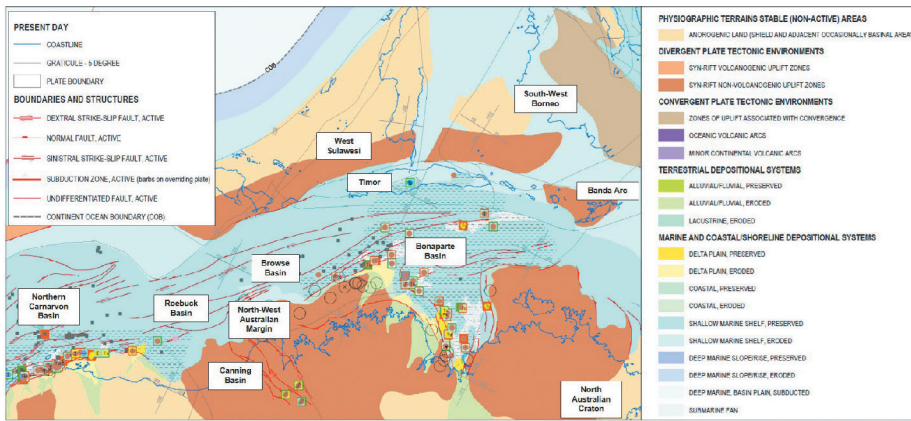


Figure 4. Early Triassic GDE map illustrating intracratonic depositional environment (CGG Plate Kinematics).

Triassic sediments within the NWS. The Dorado discovery was reported to hold 2C gross resource of 344 MMBOE (Carnarvon Petroleum, 2019). The Keraudren-1 well, located in close proximity to the Dorado discovery and included on the seismic line in Figure 3, can be seen to intersect the Middle Triassic Keraudren Formation, which is the primary reservoir for the recent discovery in the Bedout subbasin. Other factors, such as the seismic identification and drilling confirmation of Late Triassic reefs in multiple settings and the improving knowledge of active Triassic source rocks in Timor-Leste, point to new plays and potential within the Triassic successions.

The four basins of the NWS represent the area for a new multidisciplinary study undertaken by CGG, the main aims of which were to:

- enhance understanding of the prospectivity of NWS Triassic petroleum systems
- construct a database of key wells, hydrocarbon field data, and seismic data
- develop a reliable Triassic stratigraphy, including the Late Triassic carbonates, and present it on a series of chronostratigraphic summary charts

- create a tectonostratigraphic model by relating the chronostratigraphy to the evolving tectonic development of the NWS
- define the regional geohistory through the Triassic and illustrate this on a series of NWS-wide gross depositional environment (GDE) maps, showing the factors controlling the distribution of source, reservoir, and seal
- interpret a regional seismic grid to prepare top and base Triassic depth maps and a regional Triassic isopach

The results from the paleogeographic and petroleum systems analysis of the study highlight new insights into the relationship between the intracratonic rift environments and associated petroleum system development for Permo-Triassic sediments of Gondwanan-Westralian origin (Bradshaw et al., 1994). Of particular relevance to the topics discussed herein is the recognition that the intracratonic depositional environments were developing within an oblique rift setting for much of the Permo-Triassic, as evidenced by trans-tensional features identified through comprehensive interpretation of the data (Figure 4). This evidence underpins the new understanding of implications for petroleum development discussed herein. The Mesozoic (Gondwanan)

petroleum systems of the NWS make up the primary focus for the topics discussed herein (Loutit et al., 1997).

### Geologic development

Initial development of the NWS basins occurred as a result of crustal extension along the eastern Gondwana Margin in the Paleozoic (Borel and Stampfli, 2002). In the Proterozoic, the primary structural complexes of the Australian Plate, the West Australian and North Australian cratons, were located in southern latitudes as part of the supercontinent Rodinia. Current plate-modeling knowledge based on the Robertson Plate Kinematics model, as well as Metcalfe (2013) and Torsvik et al. (2012), indicates that the NWS area was located in a continental setting from the Ordovician onward. In the Carboniferous, the NWS was located within the northeastern part of Gondwana, which was composed of Western Australia (including the NWS) and neighboring terranes, including Sibumasu, Qiantang, Lhasa, Northwest Borneo, and East Java/West Sulawesi. Commencing in the Devonian, these terranes progressively rifted away from Gondwana in consecutive tectonic phases. In the Triassic, the NWS was located in an intracontinental plate setting (East Gondwana Interior Rift; Haig et al. [2017]) and was subject to

far-field stresses as a consequence of dynamic supraregional plate tectonics. In this context, the progressive breakup of the Gondwana continent provided an overriding set of controls on the evolution of the NWS depositional environments. Despite this complex tectonic evolution, the development of the petroleum systems of the NWS has a unifying tectonic theme of polyphase deformation on a basin scale that can be used to constrain the geologic record. The present-day configuration of the NWS comprises four main northeast-trending basins, located predominantly within a passive margin setting. These are the Northern Carnarvon, Offshore Canning/Roebuck, Browse, and Bonaparte basins from southwest to northeast, respectively.

Specific reference is made here to the wrench faulting and normal faulting during the Triassic–Middle Jurassic synrift phases and the effects on depositional processes throughout the NWS basins. The present-day configuration of the NWS comprises four main northeast-trending basins, located predominantly within a passive margin setting. These are the Northern Carnarvon, Offshore Canning/Roebuck, Browse, and Bonaparte basins from southwest to northeast, respectively.

### Study methodology

The study was undertaken within a multidisciplinary framework to yield new information from available data for the NWS. The data analyzed included regional 2D and 3D seismic data for basin-scale interpretation, physical well samples for core description and cuttings sample analyses, well reports, and existing biostratigraphic data. The study combined material from Commonwealth and State open-file databases with the comprehensive publications catalog of Petroleum Exploration Society of Australia and Australian Petroleum Production and Exploration Association publications.

The study database includes samples and logs from 238 wells, as well as outcrop samples, including 28 from Timor-Leste. An extensive data set of paleoenvironment control points was also compiled for GDE mapping, some of which were inherited from precursor CGG data sets (Robertson Predictions, 2017). In addition, there are 35 new paleobiology paleoenvironment outcrop sites. Fourteen key wells were selected for the study: Barcoo-1, Brecknock-1, Central Gorgon-1, Jupiter-1, Lynher-1, Maple-1, North Rankin-5, Observation-1, Phoenix-2, Scott Reef-1, Thebe-2, Tiberius-1, Vinck-1, and Yampi-1.

The key multidisciplinary elements of the study included structural geology and basin evaluation; dynamic plate modeling and paleogeographic reconstruction; petroleum system analyses, including organic geochemistry and basin modeling; sedimentology, biostratigraphy, and palynology; and detailed core description and sample analyses including petrography and automated mineralogy. Two-dimensional and one-dimensional basin modeling was used to establish the distribution of source kitchens and the timing of hydrocarbon charge for both the new play concepts and the established plays. The resulting analytical results and interpretation formed the basis for new paleogeographic maps; tectonic models; GDE maps; schematic depositional models for key intervals; source rock and reservoir quality and distribution maps; and prospectivity summary maps.

Permian, Triassic, and Jurassic source rock quality and maturity were analyzed in each of the NWS basins and then combined with reservoir distribution and quality maps to derive play fairways and overall prospectivity trends.

### Results and discussion

**Clastic and carbonate reservoir sedimentology.** More than 70 fields have their reservoir within fluvial and deltaic clastics within the Middle-to-Late Triassic Mungaroo Formation (and equivalents). This study has identified and documented additional clastic reservoirs within the Triassic, including: the Mount Goodwin Subgroup/Cape Londonderry Formation, consisting of shallow marine clastics, coastal clastics, and submarine fans; the Lower Keraudren Formation, consisting of fluvial and deltaic clastics; the Locker Shale formed of fluvial-deltaic clastics, shallow marine clastics, submarine fan sand bodies, and basal transgressive sandstone; and the Early to Middle Triassic submarine fans and canyons around the Candace Terrace in the Northern Carnarvon Basin. In addition, the paleospace-oriented GDE mapping has led to the identification of several potential new play fairways, including subbasins where Bedout-analogue plays may have developed. Additionally, Early Triassic northerly sourced submarine fans on the Sahul Platform in the Bonaparte Basin, and Mungaroo/Brigadier Formation equivalent shallow marine clastics derived from the north (not the south, as usually predicted) in the Northern Carnarvon Basin have been identified.

**Carbonate reservoirs.** Three extensive Triassic reefal complexes, mapped on seismic in the Northern Carnarvon and Browse basins and informally named the Logan, Collins, and Tierchert reef complexes, provide promising new exploration targets (Figure 5). Another two have previously been identified and drilled in the Northern Carnarvon Basin, namely Playford and Wombat (Figure 5). The Tiberius-1 well was drilled in a bioherm and intersected 330 m of Late Triassic carbonate material, consistent with an isolated reef buildup, with wireline log evaluation indicating average porosity of 13% and higher porosity zones. Massive circulation losses in the well confirm well-developed, vuggy porosity related to subaerial exposure and karstification (Grain et al., 2013). The Late Triassic reef targets of the NWS have yet

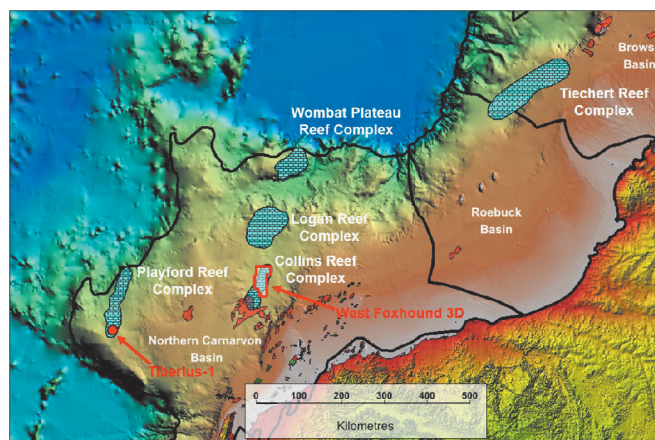


Figure 5. Late Triassic reef complexes, Tiberius-1 well location, and West Foxhound 3D. (Modified from Grahame et al., 2019).

to yield any discoveries. However, their widespread distribution, as identified on seismic data, provides encouragement for potential as a new play where they can be identified in close proximity to effective migration from underlying source rock (Figure 6).

The CGG West Foxhound 3D survey provides good seismic coverage of the inboard Collins reef complex as can be seen in Figure 5. The interpretation of the West Foxhound 3D represents a key seismic focus area for the NWS Triassic Study. The interpretation included attribute volume generation and analysis to better define the size and distribution of the carbonate buildups in the context of a depositional setting. Figure 7, which shows a spectral decomposition image example, highlights compelling similarities both in scale and depositional features with a modern-day analogue, the Alacran Reef in the Gulf of Mexico. The spectral decomposition image is detailed enough to identify reefal connectivity within the smaller buildups that would correspond to the shallower reef areas, as well as larger more isolated buildups in the deeper lagoonal areas.

Areas have been identified where the carbonate complexes are overlain by Jurassic and Cretaceous sediments, providing potential seal/source units. The GDE mapping points to potential for similar carbonate development in other areas of the study basins.

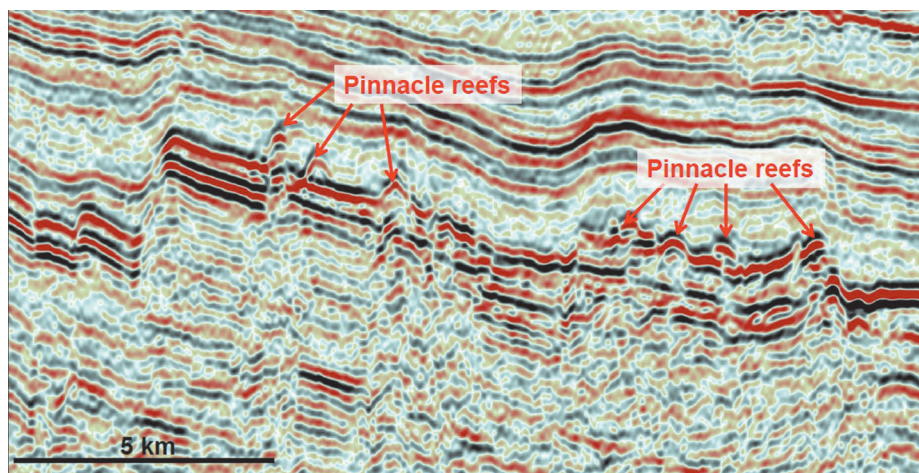


Figure 6. Interpreted Late Triassic pinnacle reefs on seismic line HB78-34.

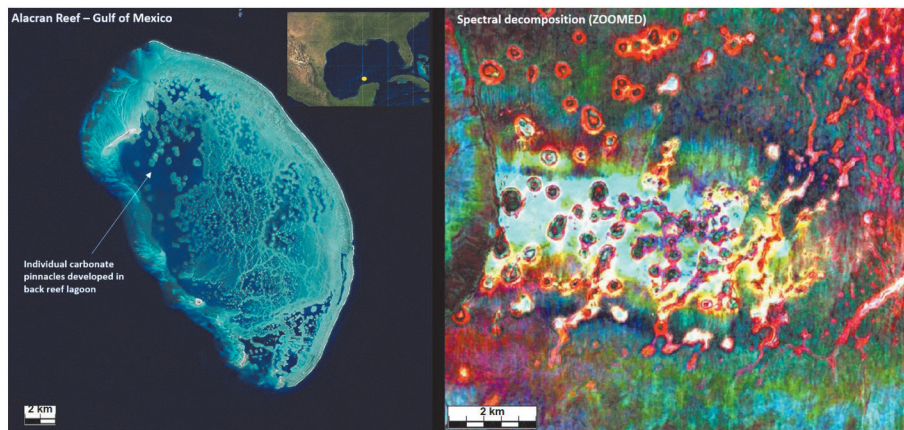


Figure 7. Late Triassic pinnacle reef complex (West Foxhound 3D). Spectral decomposition results compared with modern-day analogue (Alacran Reef, Gulf of Mexico). (Modified from Grahame et al., 2019).

**Paleogeography.** The main paleogeographic conclusions from this study are presented as a series of 10 regional GDE maps (see Figure 4 example). These maps were constructed using CGG Robertson Plate Kinematics 2017 base maps and display the data in “paleospace” — that is, with the correct latitude and orientation. The results leading up to and including the Triassic depositional environments from the GDE mapping can be summarized as follows.

In the Late Permian, Southwest Borneo, West Sulawesi, and East Java formed partly emerged areas of continental crust that intervened between what is now the NWS and the Meso-Tethys Ocean (Figure 2). The NWS formed a broad (300–500 km wide) intracontinental seaway that extended for almost 3000 km from Lhasa in the west to a subduction-related uplift zone in the area that is now New Guinea in the east. This paleogeographic scheme represents the dominant set of controls on sedimentation through the Triassic.

In the Early Triassic, extensional deformation between Lhasa and Greater India led to the development of a deep marine trough and was responsible for the onset of extensional and strike-slip deformation within the NWS. While the paleogeography established in the Permian persisted, the onshore Canning Basin was

inverted around this time, and erosion of the Paleozoic basin fill commenced (Zhan and Mory, 2013). Extensional deformation between Lhasa and Greater India was responsible for the development of a deep marine trough here and for the onset of extensional and strike-slip deformation in the NWS. In the Middle Triassic, the pattern and history of the hinterland uplift and basin subsidence regimes established in the Olenekian persisted into the Anisian, but the characteristics of the sediments preserved at the southern margin of the NWS basins indicate that the rate of both the uplift in sediment source areas and the subsidence in the basins increased. At this time, the deepwater trough between Lhasa and Greater India probably propagated southeastward. Fluvio-deltaic depositional systems prograded at the southern margins of the NWS basins, and canyon-like features imaged on 3D seismic data at the southern margin of the Carnarvon Basin (McGee et al., 2017) are indicative of accelerated rates of subsidence.

The Ladinian, Carnian, and Norian GDEs share a set of common characteristics associated with increased rates of clastic sediment supply from rivers draining the Australian craton. Fluvio-deltaic depositional systems were sites for the accumulation of good reservoir-quality

sand bodies. Coal swamps were an integral feature of the delta plain systems and, together with carbonaceous overbank and interdistributary bay mudstones, formed gas-prone source facies. The theme of increasing rates of clastic sediment supply continued into the Late Triassic. The rate of progradation of fluvio-deltaic systems increased in the Late Triassic such that Carnian deltas are significantly more extensive than their Anisian–Ladinian precursors. The fluvio-deltaic system that occupied the India/Australia Rift probably coalesced with the Mungaroo system at this time to form an extensive sand-prone reservoir tract in the Northern Carnarvon Basin. In the Carnian, the rate of clastic sediment supply to smaller systems at the northern margin of the NWS basins also may have increased.

In the Norian, the deepwater trough between Lhasa and Greater India continued to propagate southeastward. For this time slice, numerous data points indicate deep, off-shelf environments and facies, including deep marine cherts. These environments were a precursor to the emplacement, prior to the Rhaetian, of oceanic crust. Extensional deformation was probably part of the mechanism driving both clastic sediment supply from uplifted hinterlands and basin subsidence. The deltaic depositional systems at the southern margins of the NWS basins reached their maximum progradational extent at this time. Reefal carbonates started to accumulate in the warm waters of the NWS in the Norian and are well represented in the shallow waters of an archipelago interpreted at the southern flank of the Timor landmass. Deltaic depositional systems reached their maximum extent in the Late Triassic (Norian). The rate of clastic sediment supply to smaller systems at the northern margin of the NWS basins also may have increased at this time. The latest Triassic was marked by a change in subsidence style and rising sea levels in the Rhaetian that were responsible for a change from fluvio-deltaic clastic-dominated depositional systems to shallow marine environments including reefal reservoir facies. The emplacement of new oceanic crust between Lhasa and Greater India was coincident with this change in the characteristics of the sediments accumulating on NWS and represented a new set of tectonic controls. A series of fault blocks hosting the Late Triassic reef systems were formed, creating an additional reservoir facies. The fault blocks persisted into the Early Jurassic when subaerial emergence was responsible for the creation of paleokarst porosity. The deeper-water environments were probably sediment traps that limited the extent of clastic sediments supplied from the fluvio-deltaic systems that persisted into the latest Triassic. In the warm shallow waters, on the crestal parts of the fault blocks, reefal carbonates accumulated and provide a record of a range of reef, lagoon, and reef talus environments

**Geochemistry.** Geochemical analyses were undertaken on organic-rich mudstone, claystone, and shale sections from the Triassic interval in 14 key study wells. The results demonstrate the presence of multiple source rock intervals in the NWS. The source rock quality and richness observed in the study wells was used to generate four time slices to show the source rock quality and distribution through the Late Permian to Middle Jurassic intervals (Grahame et al., 2019). The source rock richness is defined according to the criteria in Table 1.

In addition to the analysis undertaken for the 14 key study wells, a field sampling program was undertaken on Timor-Leste

Table 1. Source rock richness.

Quality	Richness criteria (value)
Poor	< 100 kt HC/km <sup>2</sup>
Fair	Between 100 and 1000 kt HC/km <sup>2</sup>
Good	Between 1000 and 10,000 kt HC/km <sup>2</sup>
Excellent	> 10,000 kt HC/km <sup>2</sup>

with the purpose of collecting source rock and live oil seep samples for geochemical analyses. The results show that there is evidence of a carbonate source rock in the Middle–Late Triassic in Timor-Leste that may provide an analogue to potential Triassic carbonates across the NWS. This includes geochemical evaluation on two Triassic source rock samples (Babulu Formation) and 12 oils/seep samples from Timor-Leste (Robertson, 2017). The results show that the oils/seeps suggest three types of source rocks. Eleven of the oils/seeps are typed to two Jurassic source rocks (both inferred as Wai Luli Formation). These represent a gas-prone Type III source rock and a mixed gas-oil Type II-III source rock. The twelfth sample is typed to a Late Triassic marine carbonate source rock (inferred as Aitutu Formation). The results on the extraction of the two Triassic source rock field samples (Middle to Late Triassic Babulu Formation) differ from the oils/seeps results, and therefore suggests an additional potential fourth source rock. The presence and quality of these source rocks provides compelling evidence that Triassic source rocks can provide charge for Middle to Late Triassic reservoirs.

## Conclusions

The conclusions of this integrated study regarding the prospectivity of the Triassic section on the NWS can be summarized as follows:

- There is significant potential for well-developed reservoir facies derived from Triassic clastic depositional environments. More than 70 known fields have their reservoir within fluvial and deltaic clastics, primarily within the Triassic Mungaroo Formation. The recent discovery of oil within the Keraudren Formation in the Bedout subbasin attests to more widespread distribution of these clastic reservoirs. The GDE mapping has led to identification of several potential new play fairways where Bedout subbasin analogue plays may have developed. These include Early Triassic northerly sourced submarine fans on the Sahul Platform in the Bonaparte Basin and Mungaroo/Brigadier Formation equivalent shallow marine clastics derived from the north in the Northern Carnarvon Basin.
- In addition to the clastic potential, the Late Triassic carbonate reef complexes, as identified in this study and previously mapped, have been shown to have widespread distribution and well-developed secondary porosity as evidenced by the drilling of the Tiberius-1 well in the outer Exmouth Plateau. With the exception of Tiberius-1, the Late Triassic reef complexes remain undrilled and represent a new and emerging exploration play where they can be found in close proximity to active Permo-Triassic source rocks.

- The paleogeographic results highlight the presence of intracratonic, mixed marine terrestrial depositional environments throughout the Permo-Triassic. The implications for source rock development have been shown to be favorable within the Permo-Triassic. The geochemistry results have provided fresh insights and compelling evidence for active oil-prone Triassic source rocks as evidenced by NWS equivalent source rocks that have been correlated on Timor-Leste. The basin and source kitchen modeling have shown potential for widespread distribution of good- to fair-quality source rock development throughout a number of areas for the NWS basins.
- The integrated approach and methodology, leveraging extensive geoscience resources, has shown to be successful in developing new play concepts, identifying key areas for source rock and reservoir presence and quality, and generating fresh insights into the prospectivity of Triassic successions within the NWS. ■■

### Data and materials availability

Data associated with this research are confidential and cannot be released.

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