UPPER EOCENE - LOWER OLIGOCENE STRATIGRAPHIC PLAYS IN THE CASWELL SUB-BASIN, BROWSE BASIN (AUSTRALIA). AN ATTEMPT TO IDENTIFY NEW HYDROCARBON RESERVES IN A MATURE PETROLEUM PROVINCE

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Abstract. The Browse Basin, now part of Australia`s North West Shelf passive margin, was formed through six major tectonic events, from the Paleozoic to the Miocene, and is a gas and condensate rich province in north-west Australia. In this study we focused on Eocene-Oligocene stratigraphic plays in order to extend the basin`s resources by proposing new prospects that could include reservoirs with both liquid and gaseous hydrocarbons. Lithologic descriptions from wells, structural and depth maps, along with seismic attributes (GSD and RMS Amplitude), were integrated to create a sedimentological model for the evolution of the Prion Fm. We highlighted the fact that the distal zones of the upper part of the Upper Eocene – Lower Oligocene sequence host multiple individual, disconnected, submarine fan systems that create the proper framework for the exploration activity. An interesting prospect was proposed in this project, one that might yield recoverable resources of around 31 MMbbl of oil and 236 BCF of gas (solution gas and free gas cumulated) (P_{mean} values for volumetric estimates). This is an attempt to unlock oil reserves that currently lack throughout the region.

Key words: seismic attributes, petroleum play, prospects, risk

1. INTRODUCTION

Passive margins are one of the most important tectono-stratigraphic settings in the oil and gas industry. They represented the starting point for the early studies and notions of seismic sequence stratigraphy (Vail *et al.*, 1977; Van Wagoner *et al.*, 1988) and contributed over time to the deep understanding of petroleum plays and systems. Even now, after decades of exploration, passive margins are some of the most sought after petroleum regions on the planet. This is the case for Australia`s North West passive margin system, which has been a major exploration target in the last few decades (Le Poidevin *et al.*, 2015).

The Browse Basin is a premiere hydrocarbon province located in Australia`s North West Shelf that hosts over 41 TCF of gas, 1214 MMbbl of condensate and 33 MMbbl of oil (Geoscience Australia, 2018). The basin includes four major Mesozoic petroleum systems that make the oil fields in the region functional (Blevin *et al.*, 1998b): a Lower-Mid Jurassic, thermogenic, dry gas prone system that has a regional extent in the basin (Westralian 1) (sourced in the Plover Fm.) and three Upper Jurassic-Lower Cretaceous thermogenic systems that generate both oil and gas, which are emplaced exclusively in the Caswell sub-basin (Westralian 1+2 Central-Jurassic; Westralian 1+2 Heywood - Jurassic; Westralian 3 - Early Cretaceous). The interaction and mixing between the

Jurassic hydrocarbons produced by continental source-rocks (type III kerogen mostly) and Upper Jurassic marine source rocks (both type II and type III kerogen) has led to a couple of hybrid systems in the central part of the Caswell sub-basin and in the Heywood Graben that have been termed Westralian 1+2 (Westralian 1+2 Central - Jurassic; Westralian 1+2 Heywood - Jurassic) (Blevin *et al.*, 1998a; Blevin *et al.*, 1998b; Edwards *et al.*, 2014; Nexus Energy Ltd, 2014; Le Poidevin, 2015). Recent studies, carried by Rollet *et al.* (2016), led to a reclassification of the petroleum systems, indicating the presence of a hybrid petroleum system formed through the interaction of hydrocarbons generated by Upper Jurassic (Tithonian) and Lower Cretaceous source rocks in the central part of the Caswell sub-basin, different from the Westralian 1+2 system that was proposed earlier.

In this study we intend, using a 2828 km^2 seismic survey and data from 8 wells, to decipher the unknown potential of younger, more subtle, stratigraphic plays emplaced in the Upper Eocene-Lower Oligocene sedimentary succession of the Prion Fm. from the Caswell sub-basin, Browse Basin`s most important depocenter. The goal is to see if there is any potential left in this mature petroleum province and to define new prospects.

2. GEOLOGICAL SETTING

The Browse Basin is a passive margin, located on the northwest coast of Australia (Fig. 1), that covers nearly 218.000 km^2 of continental shelf and slope. It generally follows a Northeast-Southwest structural trend and includes a thick Permian-Holocene sedimentary succession that reaches even up to 15 km in the major depocenters (Le Poidevin *et al.*, 2015). The Browse Basin belongs to a group of extensional basins that form the Westralian Superbasin, whose evolution commenced during the late Paleozoic (Yeates *et al.*, 1987). Thereby, the Browse Basin is bounded to the south and southwest by the Roebuck and Offshore Caning basins and extends toward the north and northeast to the tectonic contact with the Bonaparte Basin (Fig.1). It develops westward to the Argo Abyssal Plain and is bordered by the Kimberley Paleoproterozoic Basin in the east (Symonds *et al.*, 1994).

In a tectono-stratigraphic framework, the Browse Basin can be divided into five major sub-basins/units (Fig.1): the Yampi and Leveque shelves, two shallow basement elements that delineate the eastern and south-eastern extent of the basin; the central region includes the Barcoo and Caswell sub-basins (the major depocenters) and the deep water part of the basin comprises the Seringapatam sub-basin and the Scott Plateau (Willis, 1988; Elliot, 1990; O`Brien *et al.*, 1993; Hocking *et al.*, 1994; Symonds *et al.*, 1994; Struckmeyer *et al.*, 1998).

The tectonic evolution of the Browse Basin started in the Carboniferous and comprises six main deformation pulses (Allen *et al.*, 1978; Struckmeyer *et al.*, 1998) (Fig. 2):

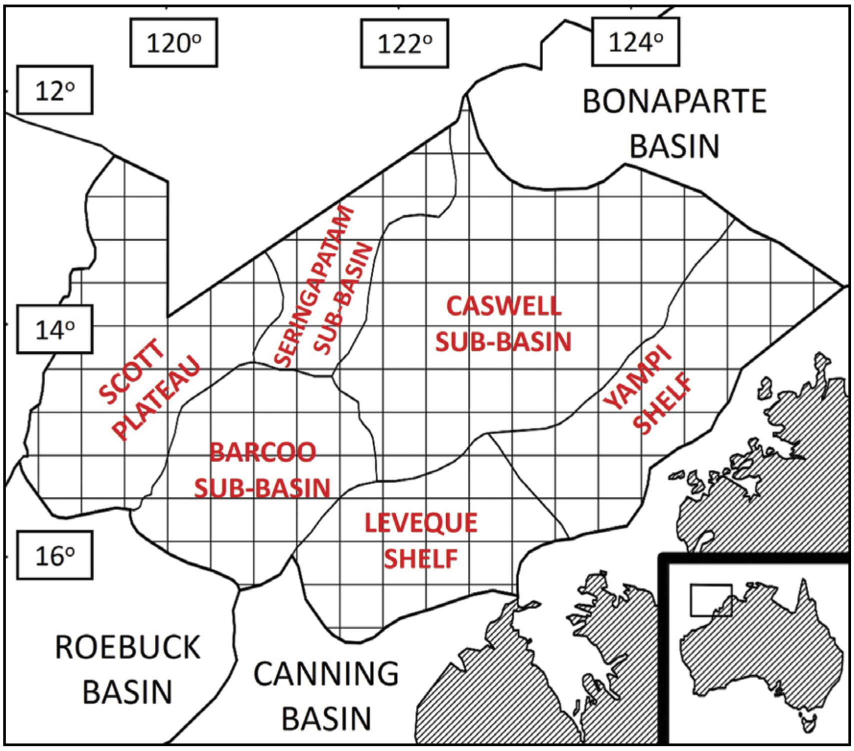

Fig. 1. Location and distribution of the Browse Basin along with the main tectono-stratigraphic units and the surrounding basins (after Rollet *et al.*, 2016).

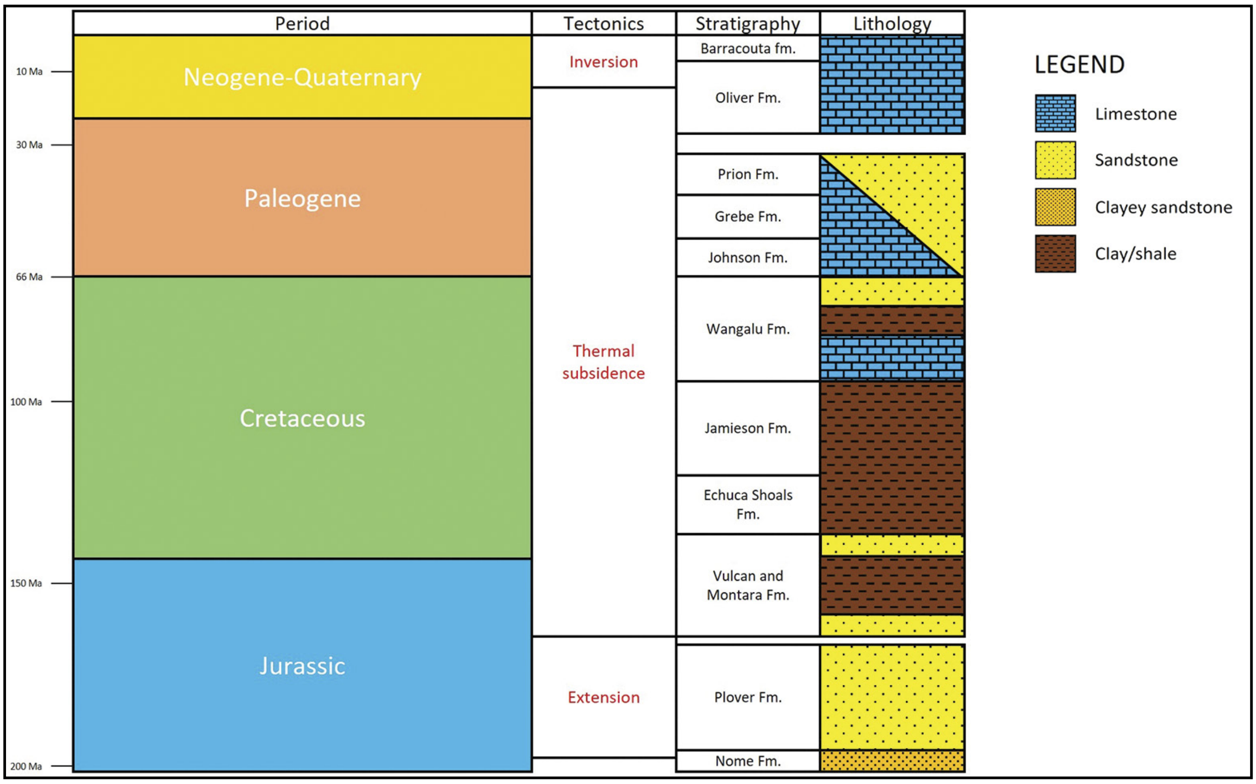

Fig. 2. Tectono-stratigraphic chart for the Browse Basin (Caswell sub-basin) (after Geoscience Australia, 2022).

(1) Lithospheric extension (Mississipian-Cisuralian);
(2) Thermal subsidence (Cisuralian-Late Triassic);
(3) Inversion (Late Triassic-Early Jurassic);
(4) Lithospheric extension (Early-Middle Jurassic);
(5) Thermal subsidence (Late Jurassic-Middle Miocene);
(6) Inversion (Middle-Late Miocene).

The early stages of lithospheric extension and thermal subsidence in the Paleozoic are related to the rifting and separation of the Sibumasu continental block from the Australian Plate and the opening of the Neo-Tethys (Veevers *et al.*, 1991). During this time intracratonic half-graben structures were formed, creating sufficient accommodation space for the deposition of a thick sedimentary succession comprising fluvio-deltaic and marine deposits (Symonds *et al.*, 1994). Afterwards, inversion occurred in the region, leading to the development of anticlines and synclines in the hanging walls of the former normal faults (Etheridge & O`Brien, 1994).

The next tectonic cycle commenced in the Early Jurassic with lithospheric extension, permitting a regional development of the fluvio-deltaic depositional environments identified in the Plover Fm. (Le Poidevin *et al.*, 2015). Complete continental break-up and sea floor spreading occurred during the Callovian, promoting the transition to a passive margin status (Le Poidevin *et al.*, 2015). This was followed by a major transgressive event during the Early Cretaceous that marked the onset of deep marine sedimentation in the basin, forming a thick pile of shales from the Upper Vulcan Fm., Echuca Shoals Fm. and Jamieson Fm. (Blevin et al, 1998a).

The Late Cretaceous was characterized by a progradational, regressive, cycle that led to the deposition of significant submarine fan systems and to the continuous migration of the shelf margin to the northwest (Benson *et al.*, 2004).

The Paleocene is distinguished by the growth of a large, sandy, inner shelf and the outburst of carbonate sedimentation in the northern sector of the basin. Pronounced subsidence during the Eocene leads to a rise in sea-level, marking another transgressive cycle in the history of the depocenter (Le Poidevin *et al.*, 2015). The process is interrupted later during the Oligocene by a short-lived regression that is linked with the general drop in the eustatic level at a global scale (Haq *et al.*, 1988).

Marine conditions returned during the Miocene (Le Poidevin *et al.*, 2015) and continue to the present day, leading almost entirely to the deposition of carbonate rocks. Changes in the tectonic configuration, as a result of convergence between the Australia-India Plate and the Eurasian Plate, initiated an inversion during the Miocene (Shuster *et al.*, 1998).

3. DATASET AND METHODOLOGY

The dataset for this project consisted of a seismic survey and eight boreholes with log data, tops, cores and well site lithology descriptions (Fig. 3).

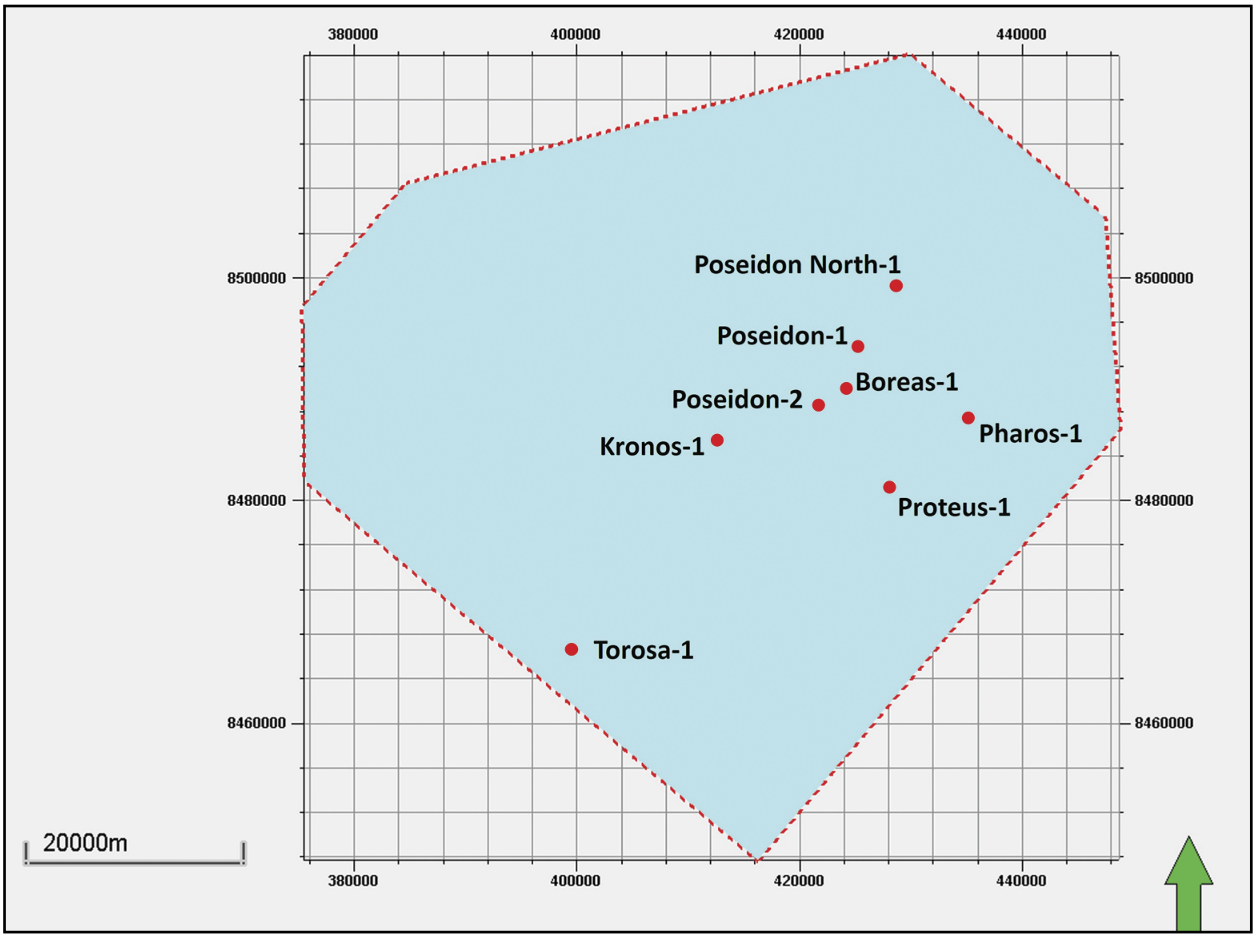

Fig. 3. Location of the Poseidon 3D seismic survey and the position of the available wells that were used in this project.

The Poseidon 3D (TWT) was acquired and processed by CGGVeritas in an exploration block operated by ConocoPhillips during the October 2009 - September 2010 period, covering an area of 2828 km2 (Conoco Phillips, 2012).

The entire workflow of the project was represented by the following phases:

- Creating the project and loading the seismic and well data in the Petrel software from SLB;
- Carrying the structural and stratigraphic interpretation using the principles of seismic (sequence) stratigraphy;
- Generating structural maps in time (TWT);
- Time-depth conversion using a layer cake velocity model;
- Generating structural maps in depth after conversion and calculating the vertical thickness for each formation;
- Applying seismic attributes (Generalized Spectral Decomposition – GSD and RMS Amplitude) on the original seismic in order to delineate the distribution of reservoirs. The volumes were flattened at the tops of key formations. Frequencies of 18 (red), 28 (green) and 43 Hz (blue) were used for GSD;
- Establishing plays, prospects and the associated risk;
- Carrying volumetric calculations in the Peter Ross software using the Area x Net Pay method (the input consisted of the following parameters: area, depth of the target, Net Pay thickness, oil proportion, porosity, oil formation volume factor – Bo, gas formation volume factor – Bg, the recovery efficiency, Gas-Oil ratio – GOR and the saturation in hydrocarbons – Sh) (Table 1).

Table 1. Input data for the volumetric calculations: area, depth of the target, Net Pay thickness, oil proportion, porosity, oil formation volume factor – Bo, gas formation volume factor – Bg, the recovery efficiency, Gas-Oil ratio – GOR and the saturation in hydrocarbons – Sh.

Area (km^2)	Depth (m)	Prospect (target)	Net Pay (m)	Oil Proportion (%)	Porosity (%)	Bo	Bg	Oil Recovery Efficiency (%)	Gas Recovery Efficiency (%)	GOR	Sh
25.6	2800	Prometheus	30-80	70	7-10	1.36	210	12.5	85	500	70

4. RESULTS AND DISCUSSIONS

In the study area within the Caswell sub-basin, based on the structural-stratigraphic interpretation, several petroleum plays were identified (Fig. 4):

1. Plays with anticline structures and tilted blocks that include Triassic and Jurassic fluvio-deltaic reservoirs with thermogenic gas (proven play throughout the Browse Basin in the syn-rift Plover Fm., including the Poseidon field that is located in the study area);
2. Plays with monocline structures that include Triassic and Jurassic fluvio-deltaic reservoirs with thermogenic gas (an extension to the north of the play that defines the Poseidon field);
3. Plays with stratigraphic traps (and minor structural element) in Upper Cretaceous oil and gas-bearing deltaic reservoirs (there have been several discoveries in Upper Cretaceous reservoirs from the Browse basin) (Le Poidevin *et al.*, 2015);
4. Plays with stratigraphic traps in Upper Eocene-Lower Oligocene oil and gas-bearing turbidite reservoirs (not proven yet).

The focus of this study is on the latter play, within Upper Eocene-Lower Oligocene basin floor and slope fans of the Prion Fm. The formation is characterized lithologically, in the existing wells, mostly by calcarenite and calcilutite with minor chert and loose sands. Thereby it can be considered that in the Southern and North-eastern parts of the study area deposition occurred during periods of high stand in a carbonate dominated shelf. However, the top of the succession deepens (Fig. 5) and the thickness increases (Fig. 6) to the North-west, indicating the development of a low stand prograding system (Fig. 7). The rare presence of sands in the wells could mark the bypass of siliciclastic input from the continent all the way to the distal zones, in a slope-basin floor depositional environment. In the upper part of the Prion Fm. we identified a regime in which individual submarine fans evolve completely separate one from another, with no visible amalgamation between lobes in the basin floor. The size of 10-15 km and the morpholgy of the submarine fans corresponds mud/sand rich systems that are characterized by a channel-levee architecture on the slope and channelized lobes on the basin floor (in accordance to the classification of Reading and Richards, 1994) (Fig. 8; Fig. 9; Fig. 10).

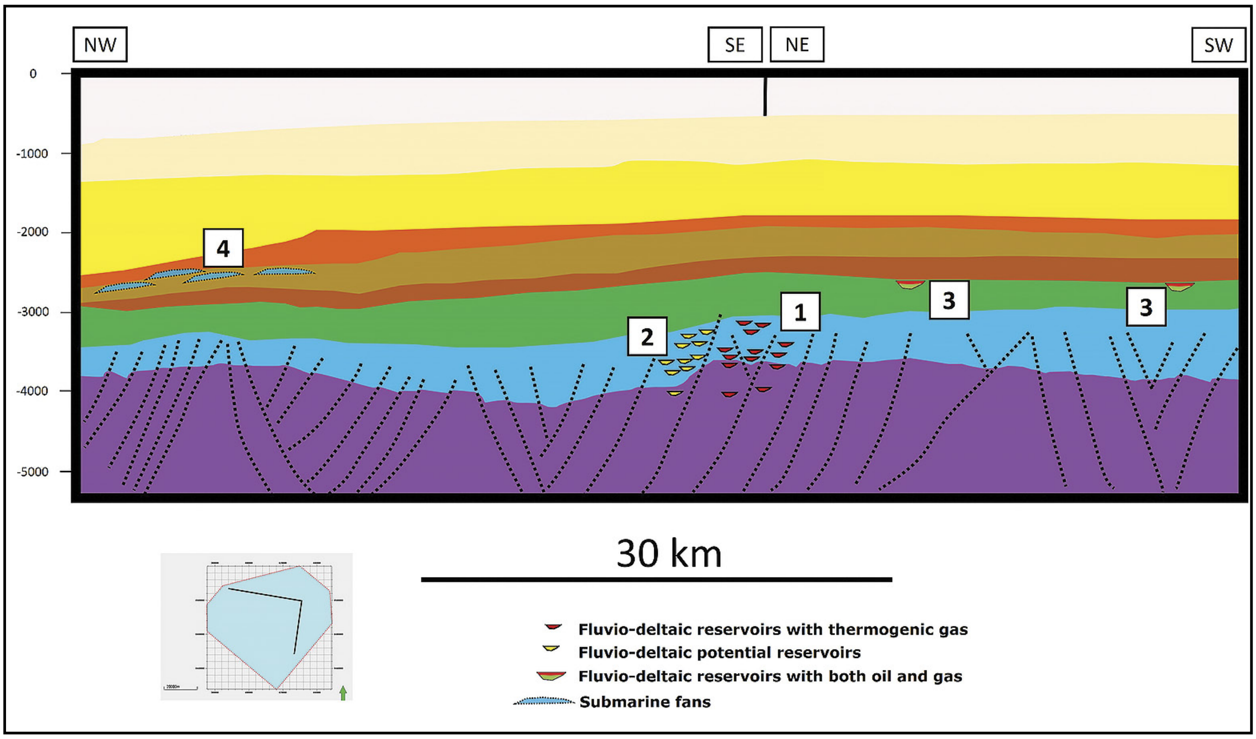

Fig. 4. Regional TWT (ms) cross section along the study area showing the stratigraphy and the main petroleum plays that were identified: **1**) Plays with anticline structures and tilted blocks that include Triassic and Jurassic fluvio-deltaic reservoirs with thermogenic gas (proven play throughout the Browse Basin in the syn-rift Plover Fm., including the Poseidon field that is located in the study area); **2**) Plays with monocline structures that include Triassic and Jurassic fluvio-deltaic reservoirs with thermogenic gas (an extension to the north of the play that defines the Poseidon field); **3**) Plays with stratigraphic traps (and minor structural element) in upper Cretaceous oil and gas-bearing deltaic reservoirs (there have been several discoveries in upper Cretaceous reservoirs from the Browse basin); **4**) Plays with stratigraphic traps in upper Eocene-lower Oligocene oil and gas-bearing turbidite reservoirs (not proven yet).

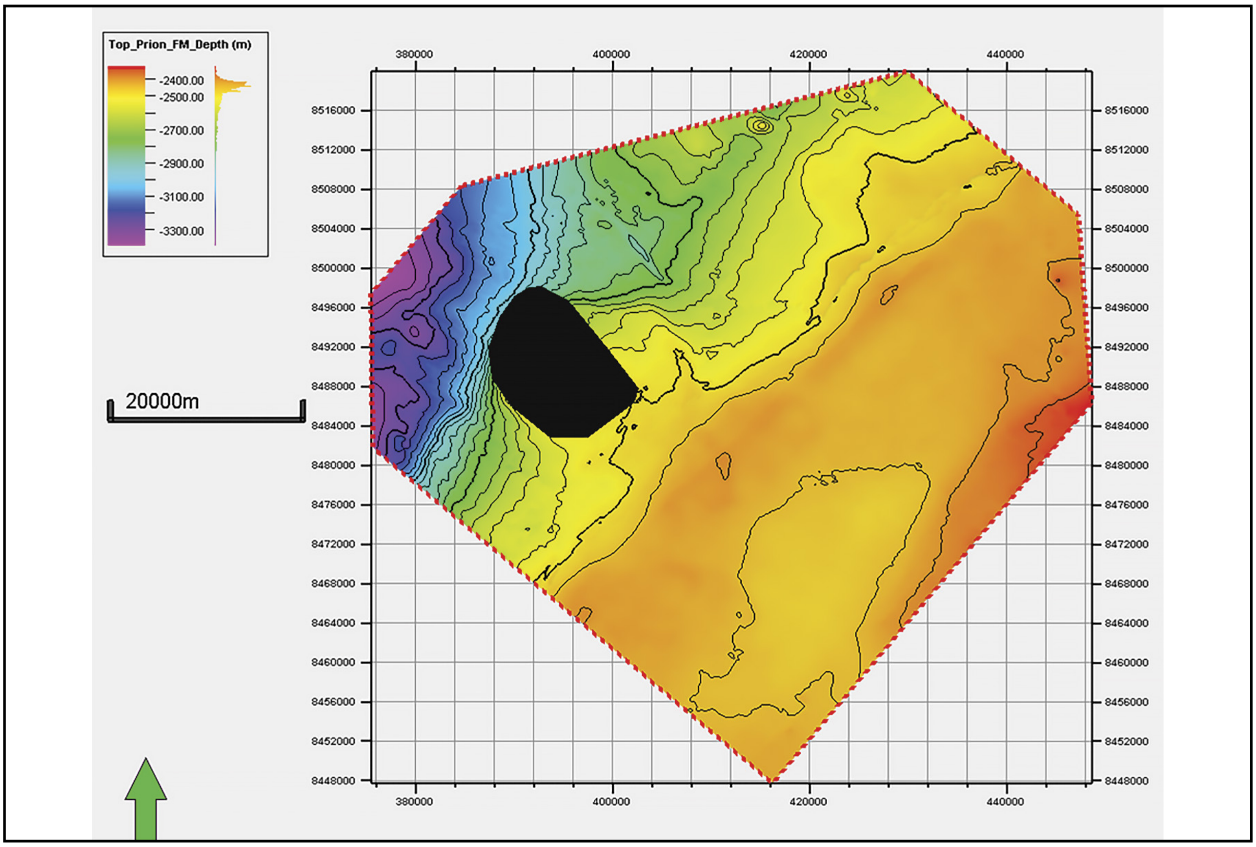

Fig. 5. Structural depth map for the top of the Prion Fm. It reflects that the succession deepens toward the North-West.

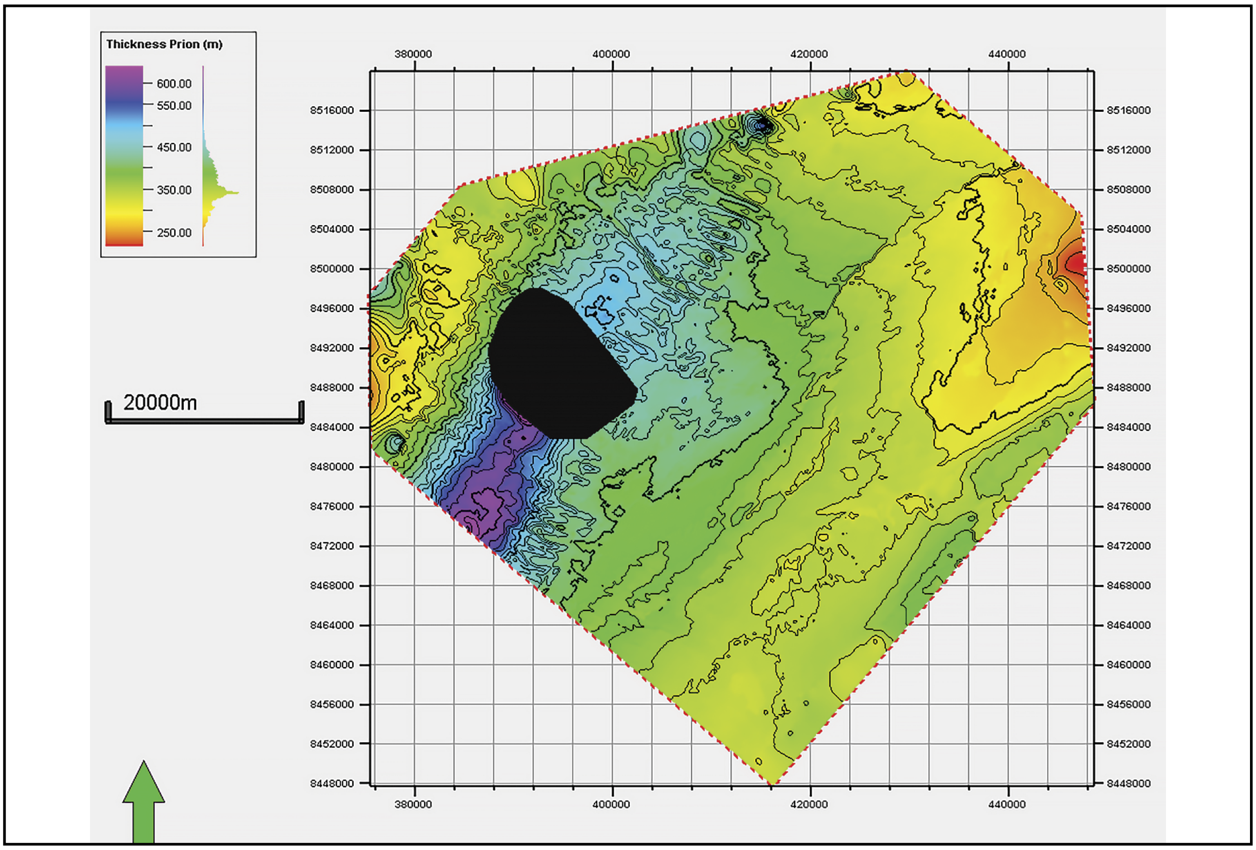

Fig. 6. Thickness map for the Prion Fm. showing a partial increase in vertical thickness to the North-West.

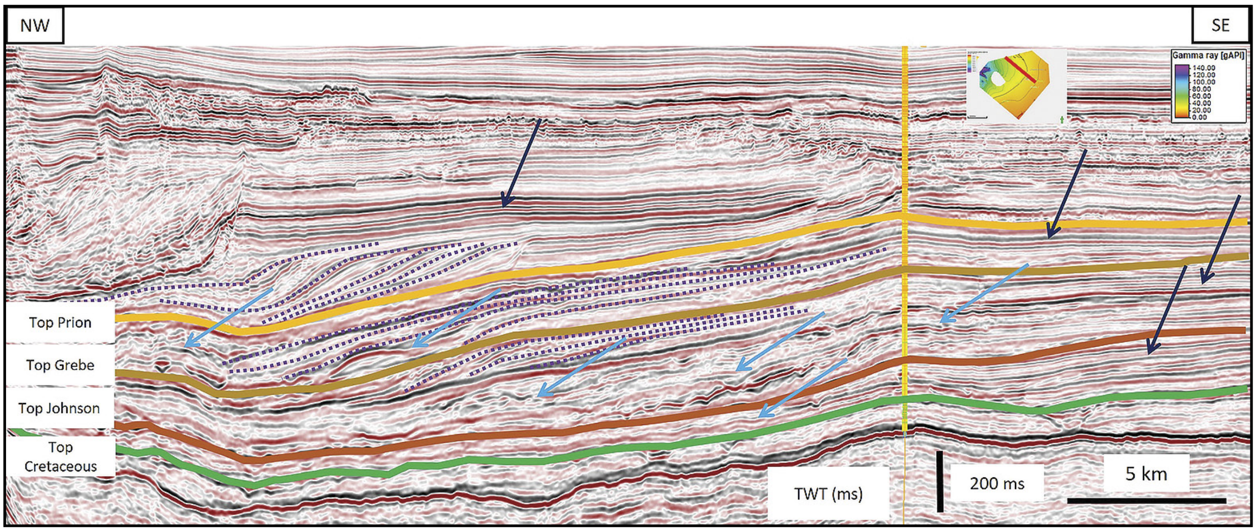

Fig. 7. Seismic profile (TWT) showing the Paleogene prograding systems (dotted purple lines) and the typical facies for shelf environments (parallel reflectors – dark blue arrows) and submarine fans (chaotic reflectors – light blue arrows).

In this way it was possible to delineate an interesting prospect (named Prometheus), since each lobe-channel complex could be evaluated independently (Fig. 8; Fig. 9; Fig. 10). We considered that the reservoir, which is represented by mixed turbidites with carbonate and siliclastic sediments, is charged with both liquid and gaseous hydrocarbons by lower Cretaceous source rocks from the Upper Vulcan Fm., Echuca Shoals Fm. and Jamieson Fm. that form the Westralian 3 petroleum system (Blevin *et al.*, 1998b). This petroleum system is completely functional in the region so it was deemed that there is no risk associated with the source rocks. However, one issue for this prospect is related to the ability of hydrocarbons to successfully migrate along the post-rift sedimentary succession in the absence of a major fault system that could directly feed the reservoirs. Even if the migration problem could be solved, there are still a couple of question marks left, related to the competence of the seal (how effective are the intra-formational seals is unknown), the reservoir performance (if there is a carbonate component in the turbidites then it would lead to porosity and permeability issues) and the closure of the interpretation (since the edge zone of the seismic survey has a doubtful quality).

The overall geological chance of success (Table 2) for this prospect was estimated at 19%, but with all the associated risks it is worth taking a shot at since the turbidite system could yield recoverable resources of 31 MMbbl of oil, 88 BCF of solution gas and 148 BCF of free gas (at a P_{mean} statistic parameter) (Table 3). If a discovery is made in this Eocene-Oligocene petroleum play it could mark the onset of future important discoveries of oil resources, which at the moment lack overall in the Browse Basin.

Table 2. Risk factors for the Prometheus prospect and the chance of geologic success (Final Pg).

Risk Factors	Pg (%) Prometheus
Source	100
Timing and migration	70
Reservoir	70
Closure / Trap	80
Seal	50
Final Pg	**19**

Table 3. In place and recoverable resources from the Prometheus prospect based on P_{mean} statistic values.

PROMETHEUS PROSPECT					
HYDROCARBON RESOURCES					
IN PLACE			RECOVERABLE		
OOIIP (MMbbl)	SGIIP (BCF)	GIIP (BCF)	Recoverable Oil (MMbbl)	Recoverable SG (BCF)	Recoverable Gas (BCF)
	P_{mean} values			P_{mean} values	
252	713	174	31	88	148

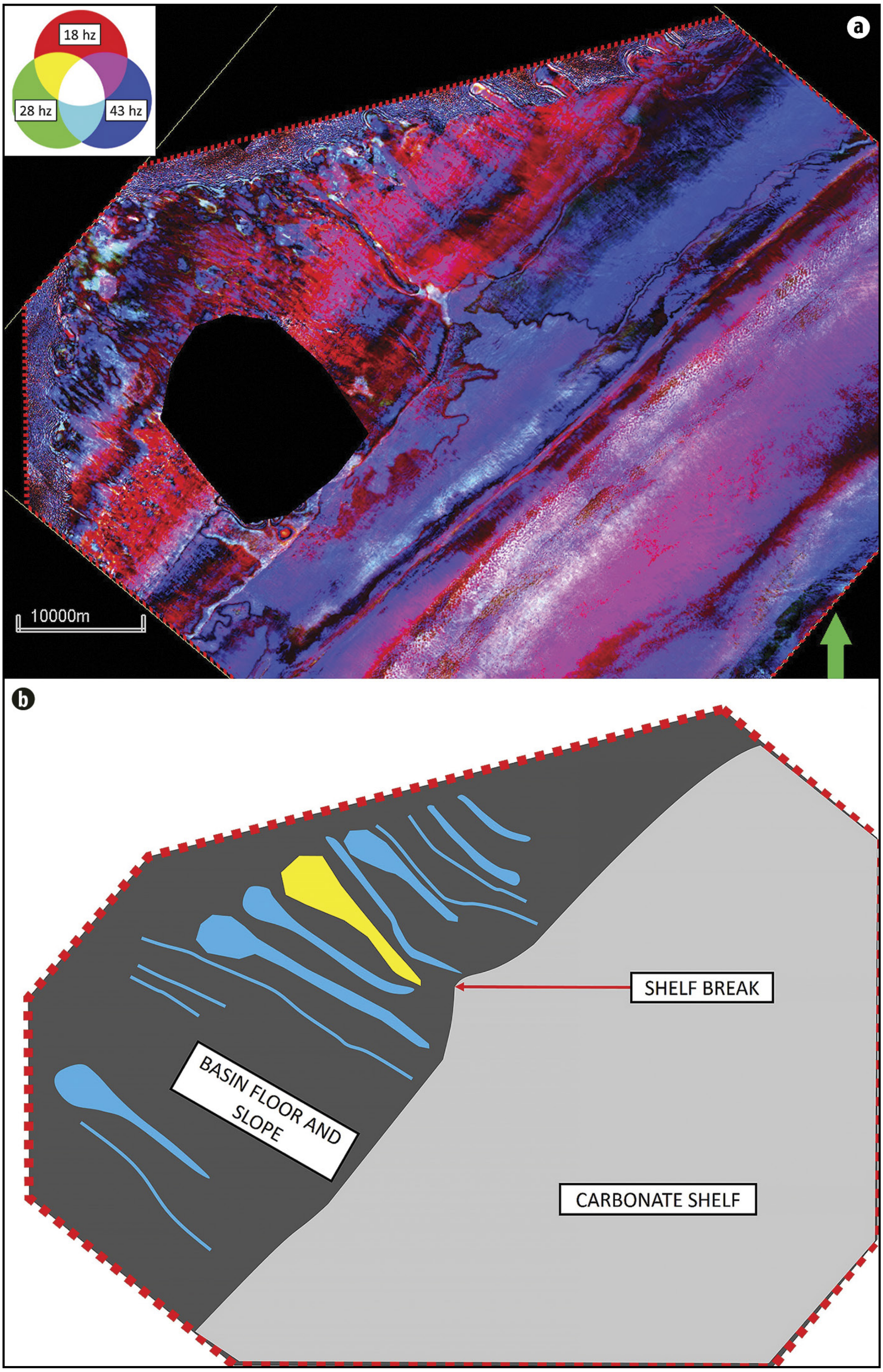

Fig. 8. Time slice at -2488 ms from the GSD volume flattened at the top of the Prion Fm. (**a**) that was used to build the stratigraphic model for the sedimentological evolution of the Prion Fm. in the deep water environments. (**b**) The yellow submarine fan system represents the Prometheus prospect.

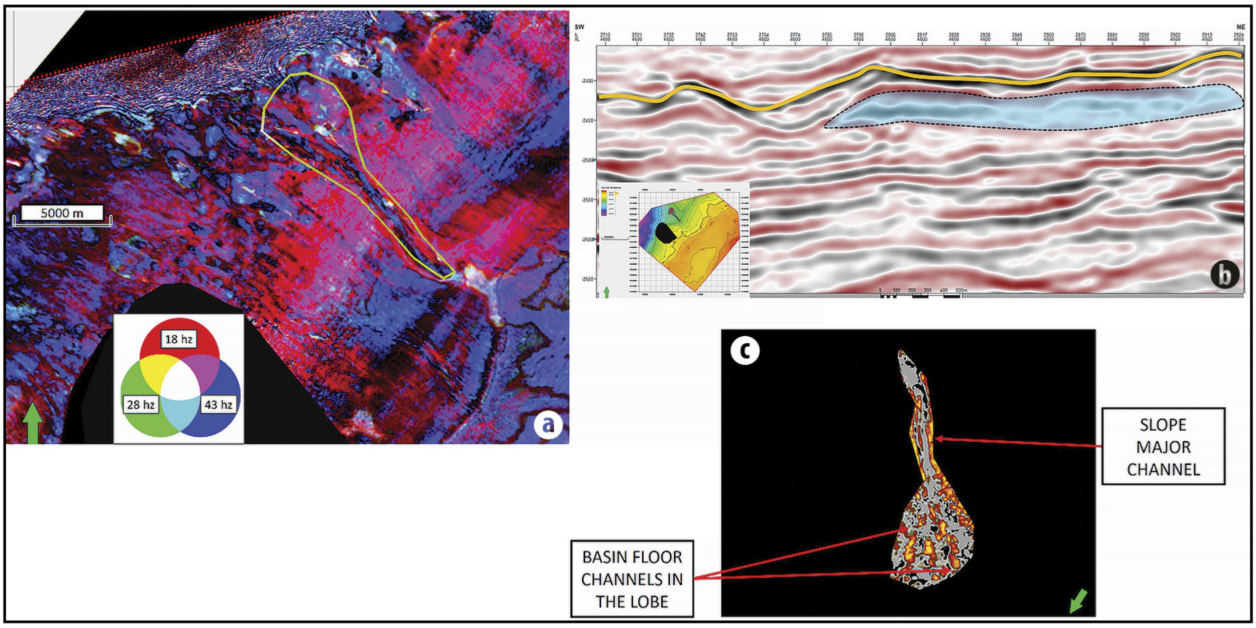

Fig. 9. A closer look at the GSD time slice that was used to delineate the submarine fan system of the Prometheus prospect, (**a**) along with a seismic section were the specific lobe morphology was identified (the position of the profile is figured on the map). (**b**) The RMS Amplitude volume shows specific morfosedimentary features of the turbidite: (**c**) slope major feeder channel and basin floor lobe channels.

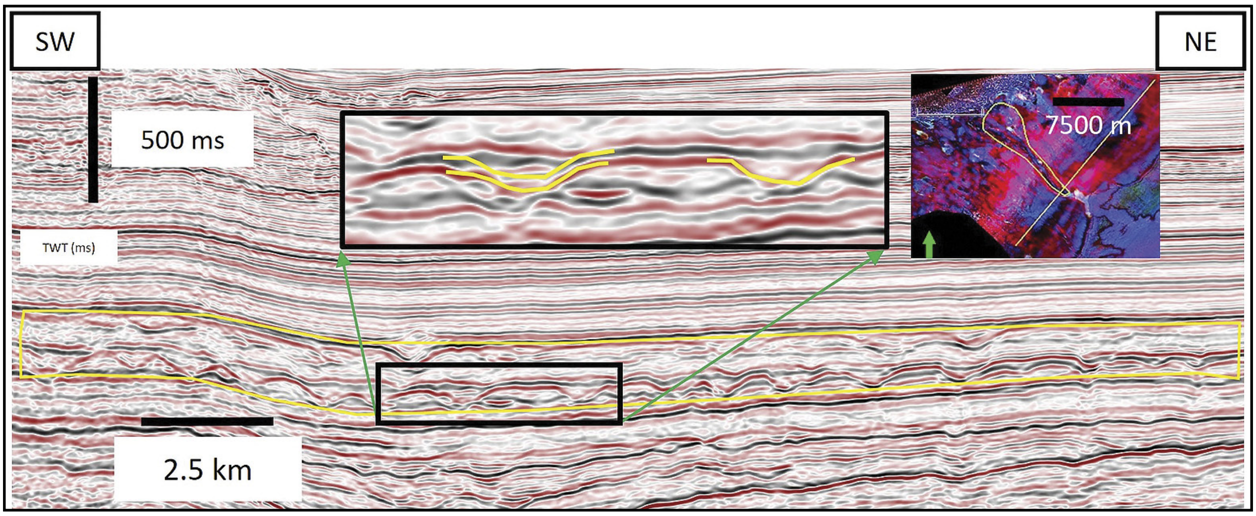

Fig. 10. Seismic profile revealing the channel-levee systems that are included in the submarine fans.

5. CONCLUSIONS

This study shows that there is plenty of unlocked hydrocarbon potential in the Browse Basin (Caswell sub-basin) from Australia`s North West Shelf. Using an integrated study, based on borehole data, classic seismic interpretation and seismic attributes (Generalized Spectral Decomposition) we unveiled a new stratigraphic play in the basin, characterized by slope to basin floor submarine fan systems in the Prion Fm. (Upper Eocene-Lower Oligocene).

Lithologic descriptions from wells show that the Prion Fm. is represented mostly by carbonate sequences (calcarenite and calcilutite usually) in the southern and north-eastern segments of the seismic coverage area, developed most likely in a shelf depositional environment. But very little is known about the sedimentological evolution of the succession in the northern and north-western zones. The structural and thickness maps that were created in this project indicate that the succession deepens and becomes thicker towards the north-west, marking the presence of a progradational wedge that includes probably mixed, carbonate-siliciclastic, turbidite systems fed by rivers that carried siliciclastic material from the mainland and carbonate sediments from the exposed shelf all the way to the abyssal zones. The interpretation is further validated by our attribute maps that highlight individual, disconnected and non-amalgamated, submarine fan systems in a slope to basin floor setting for the upper part of the formation.

Using this stratigraphic model we were able to delineate a prospect, named Prometheus, with a 19% chance of geologic success that might host recoverable resources of 31 MMbbl of oil, 88 BCF of solution gas and 148 BCF of free gas (P_{mean} values).

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