Shelf-margin architecture and shoreline processes at the shelf-edge: Controls on sediment partitioning and prediction of deep-water deposition style

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SUMMARY

The Lower Barrow Group (LBG; Latest Tithonian – Early Valanginian) is a shelf-margin that prograded during a late phase of rifting under various subsidence regimes and supply-dominated conditions. A 3D semi-automatic, full-volume seismic interpretation method allow identifying high-order clinothems presenting an estimated cyclicity of ~40,000 yrs, in which a quantitative analysis of the shelf-margin architecture and shorelines processes was conducted. Overall, three and four main types of hydrodynamic regimes and deep-water systems were identified, respectively. Falling to flat shelf-edge trajectories are associated with sediment bypass, whereas rising shelf-edge trajectories are linked with increasing sediment storage on the shelf. While fluvial to wave processes can be dominant in all A/S conditions, results show that fluvial-dominated coastlines are associated with steep high-angle slope clinoforms and short to longer run-out turbidites. Conversely, wave-dominated coastlines are linked to low-angle slope clinoforms and poor turbidite system development (occasional sheet sand and MTDs). The short and longer run-out turbidite systems present a tripartite architecture (canyon / slope valley; channel; lobes) which mostly appear as short-lived, vertically / laterally stacked elements fed my multiple small rivers forming linear ramp systems. Due to the shallow configuration of the margin (<500m), the presence of short slopes and overall high sand-to-mud ratio, the turbidite systems are smaller scale (<50 km) and probably shorter lived than most modern turbidite systems (100-1000 km). This study sheds new lights on the significant role of shelf-margin architecture (slope gradient, hydrodynamic regime) in predicting the deep-water sediment delivery behavior (sediment partitioning, type of deep-water system).

Key words: Barrow Group; Shelf-margin; Sediment partitioning; Coastal processes; Deep-water systems

INTRODUCTION

Shelf-margins represent the last interface of source-to-sink systems by driving the sediments from the shoreline-shelf to the slope and basin-floor areas (Helland-Hansen *et al.*, 2016). Studying the evolution of shelf-margin clinoforms can help unravelling how the sediments are partitioned between the shelf and the basin (Helland-Hansen and Hampson, 2009; Henriksen *et al.*, 2009; Prather *et al.*, 2017). The key challenge for geoscientists is to predict how the coarse-grained sediments are delivered from the shelf-edge to the basin-floor (i.e. controls on shelf-edge sands delivery; Gong *et al.*, 2016a, 2016b).

Historically, the occurrence of deep-water sands has been envisaged as a function of accommodation-driven (e.g. Posamentier *et al.*, 1988) and / or supply-driven (e.g. Carvajal *et al.*, 2009) mechanisms. Only recently, attention was given to the process regimes (i.e. fluvial, wave, tidal) occurring at the shoreline (i.e. shelf-edge delta) which can modulate the sand delivery system to deep-water areas (e.g. Dixon *et al.*, 2012; Gong *et al.*, 2016a). Therefore, only a full integrated analysis of the clinoform characteristics, shelf-edge / shoreline trajectories, sediment flux and process dominance at the shelf-edge can help decipher the controls on shelf-margin architecture as a practical tool for predicting the presence or absence of coeval slope and basin-floor fans (Dixon *et al.*, 2012).

The Barrow Group was deposited in the Northern Carnarvon Basin (NCB; North West Shelf, Australia) from the latest Tithonian to the Late Valanginian (Fig. 1). Developed during a syn-rift (Lower Barrow Group; LBG) to post-rift (Upper Barrow Group; UBG) transition, the recent analysis of Reeve *et al.* (2016) and Paumard *et al.* (2018) provided new insights into the linkages between sedimentary systems and late syn-rift to early post-rift tectonics in extensional basins. Prograding as a moderately deep-water shelf-margin (~100-500 m high clinoforms), the stratigraphic evolution of the LBG was constrained in six 3rd order seismic sequences (calibrated to dinocyst zones) across four main depocentres (Paumard *et al.*, 2018). The LBG, mainly developed under supply-dominated conditions, shows significant variations in shelf-margin architecture along-strike due to lateral variations in subsidence regime and shifts in sediment supply that directly impacted the sediment partitioning between the shelf and the deep-water areas (Paumard *et al.*, 2018). Therefore, the LBG constitutes a unique laboratory to study the interplay between accommodation variations (under supply-dominated conditions) and sediment transport regime at the shelf-edge (i.e. shoreline processes) on shelf-margin architecture and deep-water sand delivery.

Here, we use a high-resolution 3D seismic dataset to investigate the relationships between process regime and deep-water systems development along the LBG shelf-margin in combination with a dynamic stratigraphic approach to constrain the interplay of the various controls (accommodation, sediment supply, process regime) on the LBG shelf-margin architecture (Fig. 1). This approach will have direct applications for regional petroleum exploration which allows improving the prediction of shallow- and deep-marine plays in moderately deep-water shelf-margins.

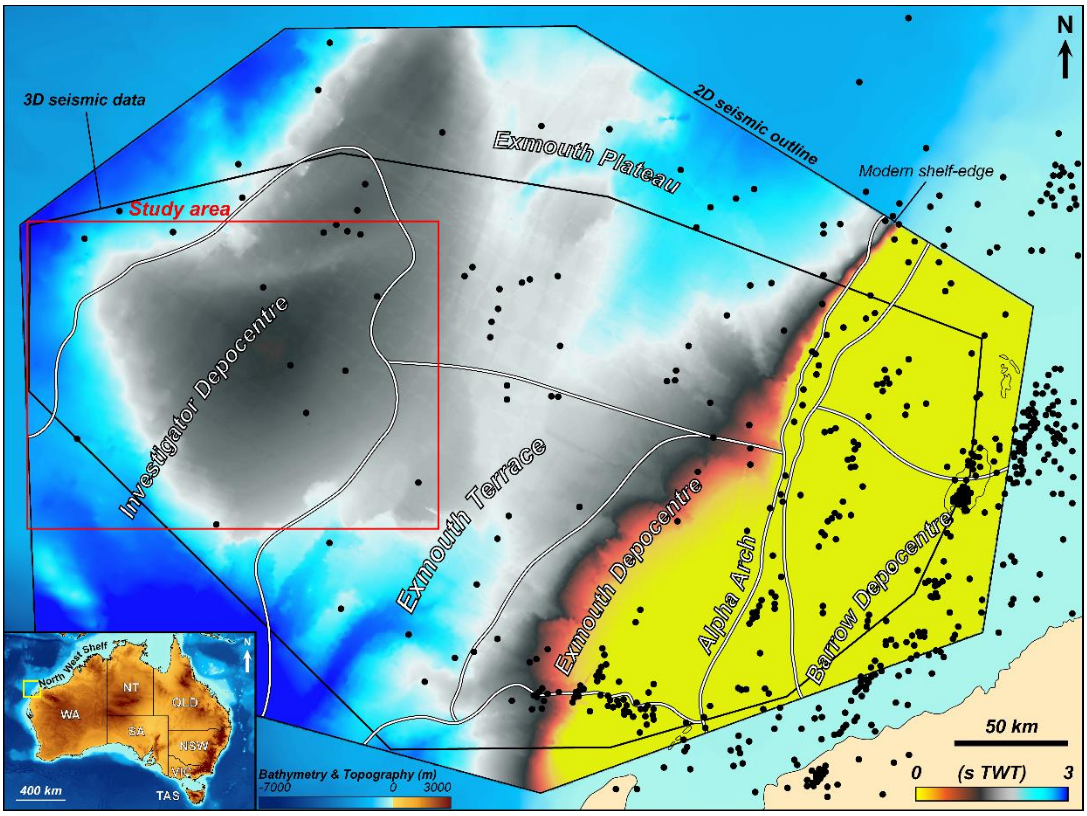

Figure 1: Location map of the study area within the Northern Carnarvon Basin (North West Shelf, Australia). The map corresponds to the seafloor horizon interpreted on regional 2D seismic data. The geological provinces indicated on this map correspond to the Lower Barrow Group depocentres interpreted by Paumard *et al.* (2018).

METHOD AND RESULTS

Data and method

The seismic dataset in the study area consist of two 3D seismic volumes covering an area of approximately 10 000 km^2 (Fig. 1). The first data corresponds to the Mary Rose 3D seismic survey, provided by TGS, and is characterized by a bin spacing of 25 X 18.75 m with a sampling interval of 4 ms. The second data is the Sovereign 3D seismic survey, provided by Geoscience Australia, and comprises a 18.75 X 25 m grid with a 4 ms sample interval. Seismic data was calibrated by three wells (Investigator-1, Royal Oak-1, Pinhoe-1) using velocity (check-shot) survey data available in well completion reports and publicly available well logs and biostratigraphic data. Seismic analysis has been conducted using Paleoscan©, a full-volume, semi-automatic seismic interpretation software. Using a very high resolution seismic interpretation workflow, we managed to extract horizons representing every shelf-margin clinoform of the LBG within the 3D seismic survey. Based on a seismic stratigraphic approach, seismic sequences (i.e. clinothems) were identified. Several seismic attributes were calculated along the horizons extracted, over a time window between ~12 and 15 ms, including similarity, RMS amplitude, envelope and spectral decomposition. Within each clinothem, clinoform geometries were described and measured on four dip-oriented sections at different along-strike locations allowing to calculate various parameters such as: slope gradient, shelf-edge trajectory angle (T_{se}), sediment thickness of topsets (A_t) and bottomsets (A_b). All values were first measured in time and converted in depth using an average velocity of 3100 m/s. In this study, the paleoshorelines of each clinothem have been classified using the process-based shallow-marine classification of Ainsworth *et al.* (2011). To classify the shorelines, the percentage of tide, wave, and fluvial-dominated depositional elements is measured (in % of total areal extent) over a lateral radius of ~5 km from the seismic cross sections used for quantitative analysis within each clinothem. Also based on seismic attribute analysis, we identify and classify different types of deep-water systems downdip the shelf-margin.

Shelf-edge trajectory and sediment partitioning

The high-resolution seismic stratigraphic interpretation allowed identifying 73 seismic sequences (Fig. 2). Based on the shelf-edge trajectory angle and the stratal stacking patterns, four main types of shelf-margins are recognized: falling ($T_{se} < 0°$, progradational pattern), flat ($0° < T_{se} < 1°$, progradational pattern), rising ($T_{se} > 1°$, progradational and aggradational pattern) and backstepping ($T_{se} < 0°$, retrogradational pattern) shelf-margin types. A fifth type of clinothem was identified as "onlapping wedges". These correspond to packages of continuous reflectors onlapping the shelf-margin which were interpreted as mud belts (Fig. 2).

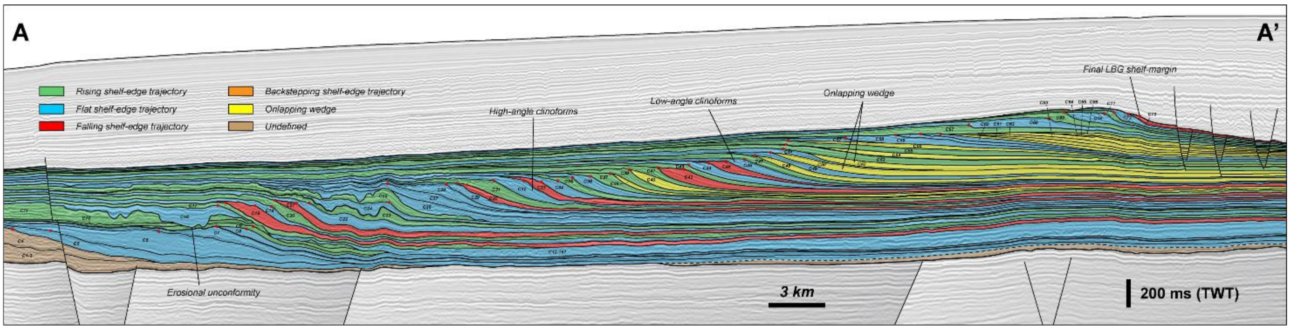

Figure 2: Example of seismic profile from the Investigator Depocentre (see location on Fig. 3) showing the 73 interpreted clinothems with the corresponding types of shelf-margin architecture based on trajectory analysis. Data courtesy of TGS.

To evaluate the sediment partitioning at the shelf-margin following the different types of shelf-edge trajectories, we compare two independent parameters: the shelf-edge trajectory angle (T_{se}) and the differential sedimentation between topsets and bottomsets (A_t/A_b ratio). The falling shelf-edge trajectory types are associated with values of A_t/A_b ratio of 0. In this scenario, all the sediments are bypassed to the basin and no sediments are accumulated on the shelf. Conversely, backstepping shelf-edge trajectory types present values of A_t/A_b ratios between 1 and 3 which indicates that a large amount of sediments in stored on the shelf while little is supplied to the basin. The flat shelf-edge trajectory types show A_t/A_b ratios between 0 and 1, indicating that a large volume of sediments is delivered to the deep-water areas, whereas a smaller amount is stored on the shelf. A part of the rising shelf-edge trajectory types follow a trend where increasing values of T_{se} are linked with increasing values of A_t/A_b ratios between 1 and 3. This means that, as T_{se} increases, more sediments are stored and shelf and less sediments are supplied to the deep-water areas. However, our results show as well that some of the rising shelf-edge trajectory types are located outside of this trend, where increasing values of T_{se} are associated with lower values of A_t/A_b ratios. In this scenario, we suggest that sediments accumulating in the deep-water areas (i.e. bottomset domain) are not supplied directly from the shelf-margin updip but rather by lateral transport of sediments, contributing as well to the deposition of mud belts in some cases.

Seismic geomorphology

To classify the shallow-marine processes along the paleoshorelines within each clinothem, four types of depositional elements were recognized. The first depositional element corresponds to beach ridges, which are interpreted as wave-dominated depositional elements (W process). Appearing as linear to curvi-linear features, they can be laterally continuous on several kilometers. The second depositional element corresponds to fluvial channels which are maximum 100 m wide and 20 ms TWT (~30 m) deep (e.g. Fig. 3). In most cases, the channels are meandering and associated with smaller (~20 m wide) tributaries channels. These depositional elements are interpreted as fluvial-dominated (F process). The third depositional element, which is also fluvial-dominated (F process), corresponds to mouth bars. These depositional features are located at the mouth of fluvial channels and present a lobate to elongate shape. Finally, the fourth type corresponds to “featureless” areas (e.g. Fig. 3). Despite uncertainty, we infer that the featureless areas correspond likely to eroded beach ridges (W process). We identified three main types of shorelines: wave-dominated (W); wave-dominated and fluvial-influence (Wf), where wave-dominated features represent more than 50% of the total mapped area; fluvial-dominated and wave-influenced (Fw), where wave-dominated features represent less than 50% of the total mapped area (in some cases, no wave-dominated features are observed and the shoreline is classified as fluvial-dominated only).

Similarly, four types of deep-water system were identified. The first type corresponds to sheet sands (Fig. 3). Between 2 and 8 km wide, these deposits stand at the base of slope and have run-out distances up to ~5 km. The mass-transport deposits (MTDs) are associated to the type 2 of deep-water systems identified in our study area (Fig. 3). In the upper slope, MTDs are associated with a slump scar. Usually 3-6 km wide, their run-out distance can reach ~10 km. The type 3 consists of short run-out turbidites with a run-out distance between 5 and 10 km (Fig. 3). These systems are composed of ~50-100 m wide slope gullies directly attached to the shelf-edge which are linked basinward with ~1-3 km wide basin floor-fans. Finally, the type 4 is depicted by long run-out turbidites where the run-out distance is about 10 to 60 km (Fig. 3). They present ~200-500 m wide canyons in the upper slope directly linked to basin-floor fans up to ~10 km wide and 60 ms TWT (~90 m) thick.

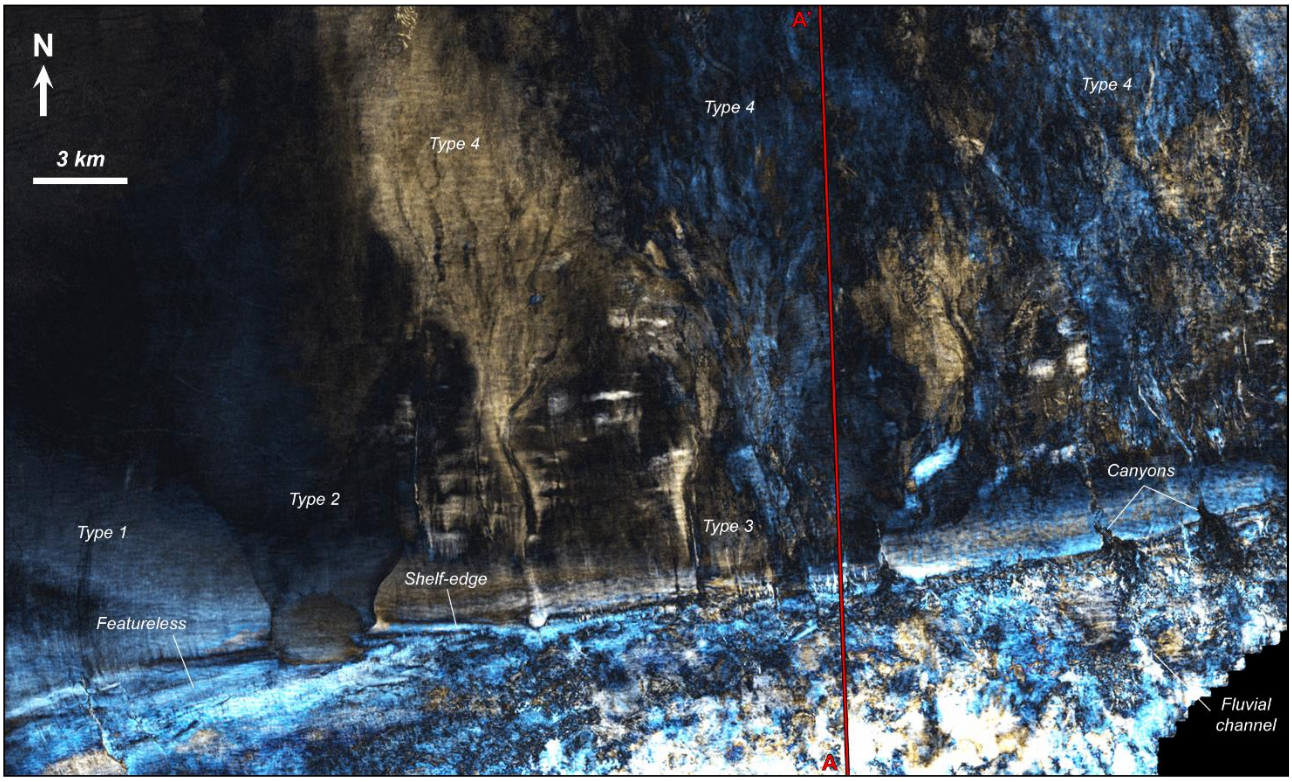

Figure 3: Example of colour-blended (RGB) spectral decomposition map (at 15, 35 and 55 Hz) of one horizon from the clinothem C28 (see Fig. 2) showing interpreted seismic geomorphologies at the shelf-edge (i.e. shallow-marine processes) and the deep-water system types. Data courtesy of TGS.

Link between shelf-margin architecture, shallow-marine processes and deep-water systems

The three categories of shorelines occur in all shelf-edge trajectory types, except for the backstepping shelf-edge trajectory which is only associated with wave-dominated shorelines. In other words, no correlation is observed between the shelf-edge trajectory and the type of shoreline. However, a correlation is observed between the shelf slope gradient and the shoreline type. Using statistical methods to describe the data, we observe that the wave-dominated shorelines are associated with lower gradients (median value of 3.2°), whereas the fluvial-dominated shorelines are linked with higher gradients (median value of 7.4°) suggesting a decrease of the wave dominance as the gradient increases.

Similarly, a strong relationships is observed with the shelf slope gradient and the deep-water system type. The types 1, 2, 3 and 4 are associated with increasing median gradient of 2.5°, 4.6°, 6.6° and 7.6°, respectively.

When comparing the types of shorelines and deep-water systems, we observe that most of the wave-dominated shorelines do not present any attached deep-water system or a few are linked with sheet sands (type 1) and MTDs (type 2). On the other hand, the fluvial-dominated shorelines are mainly linked with long-run out turbidites (type 4), whereas a lower amount is linked with short run-out turbidites (type 3) or MTDs (type 2).

CONCLUSIONS

The Lower Barrow Group (Latest Tithonian – Late Valanginian), is a moderately deep-water shelf-margin (~100-500 m high clinoforms) that prograded during a syn-rift to post-rift transition. Developed during the late syn-rift phase, the Lower Barrow Group constitutes a unique example to study the impact of subsidence variations (under supply-dominated conditions) on shelf-margin architecture, shallow-marine processes and sediment partitioning between the shelf and the deep-water areas.

Three main types of hydrodynamic regimes were identified along the paleoshorelines of the LBG: wave-dominated (W); wave-dominated and fluvial-influenced (Wf); fluvial-dominated and wave-influenced (Fw). Four types of deep-water systems are commonly associated with gullies and canyons which have retrogressively cannibalized the shelf-edge and are directly connected to their fluvial feeder system: sheet sands, MTDs, short run-out and long run-out turbidites.

The quantitative analysis of the mapped clinothems reveals that falling to flat shelf-edge trajectories are associated with sediment bypass and increase in bottomset thicknesses, whereas rising shelf-edge trajectories are linked with sediment storage on the shelf. In other terms, low A/S conditions promote bypass of sediments basinward (low A_t/A_b ratio) whereas high A/S conditions increase sediment storage on the shelf (high A_t/A_b ratio). On the other hand, no clear trend is observed between shelf-edge trajectories and coastal processes: fluvial to wave processes can be dominant in all A/S conditions (falling, flat and rising shelf-edge trajectories). However, results show that fluvial-dominated coastlines are associated with steeper slope clinoforms angles. Conversely, wave-dominated coastlines are linked to lower-angle slope clinoforms.

Fluvial-dominated shorelines are associated with short and longer run-out turbidite systems. Fluvial-dominated shorelines promote canyon development and formation of tripartite turbidite systems (canyon / slope valley; channel; lobes). The short run-out and long run-out turbidite systems appear mostly as short-lived, vertically / laterally stacked elements fed my multiple small rivers forming linear ramp systems. Localized fluvial input promote retrogressive canyon development and direct fluvial-canyon connection which can promote the development of longer-lived fans and thicker turbidite accumulation compared to short run-out turbidite systems. Due to the shallow-configuration of the margin (<500 m), the presence of short slopes, the small and short lives fluvial feeder systems on the coastal plain, and the overall high sand-to-mud ratio, the turbidite systems of the Barrow Group are smaller scale (<50 km) and probably shorter lived than most modern turbidite systems (100-1000 km).

This study sheds new lights on the significant role of the shelf-margin architecture in predicting the deep-water sediment delivery behavior, in term of sediment partitioning (shelf-edge trajectory angle, thickness of topsets and bottomsets) and in term of type of deep-water systems developed (slope gradient), as well as its link with the hydrodynamic regime along the paleoshorelines. We show that integration and quantitative estimation of clinoform trajectories, sediment flux and process dominance at the shelf-edge constitute a predictive tool in petroleum exploration for linked deep-water deposits.

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