Full-volume interpretation methods: Applications for quantitative seismic stratigraphy and geomorphology of the Lower Barrow Group, Northwest Australia

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SUMMARY

Following decades of technological innovation, geologists have now access to extensive 3D seismic datasets. How these data will help understanding the complexity of the subsurface relies on developing stratigraphic workflows that allow very high-resolution interpretation in a cost-effective timeframe. Here, the use of full-volume, semi-automatic horizon tracking tools allowed interpreting ultra-high resolution seismic sequences (~40,000 yrs duration) within a Cretaceous prograding shelf-margin (Lower Barrow Group; LBG) on the North West Shelf of Australia. Initially, semi-automated horizon tracking allowed mapping key regional unconformities defining 3rd order seismic sequences. In a second step, a very high resolution grid (nodes corresponding to seismic traces) was generated in each 3rd order sequence. An automatic propagation algorithm then linked the nodes based on their similarities, resulting in a very dense network of "proto"-seismic horizons. Volume interpolation resulted in the creation of a Relative Geological Time (RGT) model from which a very high number of chronostratigraphic surfaces were extracted. This allowed a full volume 3D mapping of every clinoform in each 3rd order sequence, from which quantitative data (clinoform height, slope, topset vs bottomset thickness) and seismic attributes (seismic geomorphology) were extracted. This analysis unveiled the high resolution changes in sediment supply and accommodation in time and space in the LBG, and provided new insights on the distribution of shallow and deep marine plays in the basin. This innovative workflow constitutes a new step in sequence stratigraphy as it allows interpreters to map sequences in a true 3D environment hence taking into account the full variability of depositional systems in time and space.

Key words: Sequence stratigraphy; Full-volume seismic interpretation; Barrow Group; Shelf-margin; Quantitative stratigraphy

INTRODUCTION

Since the first breakthrough in seismic stratigraphic interpretation (Mitchum *et al.*, 1977a, 1977b; Vail and Mitchum, 1977), seismic data proved to be the most indispensable tool of petroleum exploration, providing new insights in basin fill and sequence stratigraphy studies (e.g. Posamentier *et al.*, 1988) and pushing forward our comprehension of the subsurface. Over the last few decades, technology innovations allowed geoscientists to have access to extensive and high-quality 3D seismic datasets. Hence, understanding how these data will help unravelling the complexity of the subsurface relies on the development of stratigraphic workflows that allow very high-resolution interpretation in a cost-effective timeframe.

The last few years saw the development of a new generation of full-volume, semi-automatic, seismic interpretation softwares. Those are using advanced algorithms-based methods to autotrack simultaneously horizons throughout the seismic volume and compute geological models (Pauget *et al.*, 2009; Hoyes and Cheret, 2011). This approach constitutes a revolution in seismic interpretation as this method permits to fully appreciate the three dimensionality of the data by comparing several horizons in parallel and potentially providing more accurate solutions than classic manual picking.

In this study, we focus on the Lower Barrow Group (LBG), located in the Northern Carnarvon Basin (North West Shelf, Australia), which was deposited from the latest Tithonian to the Early Valanginian (Fig. 1). Developed during a late syn-rift phase of basin extension, the LBG prograded as a moderately deep-water shelf-margin (~100-500 m high clinoforms), across four main depocentres (Fig. 1; Paumard *et al.*, 2017). At basin-scale, the stratigraphic evolution of the LBG was constrained in six 3rd order seismic sequences (Paumard *et al.*, 2017). Due to the active rift setting, the LBG 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 (Reeve *et al.*, 2016; Paumard *et al.*, 2017). Therefore, standard manual picking of seismic horizons in the LBG falls short in two aspects: (1) the manual seismic interpreter cannot appreciate the complexity of the seismic data and the geology by mapping every shelf-margin clinoform through time and space in an efficient timeframe; and (2) classic sequence stratigraphic interpretation based on a few dip-oriented seismic lines will not take into account the full lateral variability of the sequences.

Here, we use a full-volume, semi-automatic seismic interpretation software (PaleoScan©), to interpret at ultra high-resolution the LBG interval from a high-resolution 3D seismic dataset. Our approach is threefold. Firstly, key regional seismic unconformities are mapped in the 3D volume to define 3rd order seismic sequences (Paumard *et al.*, 2017). Secondly, using the PaleoScan© workflow within each 3rd order seismic sequence, we obtain a Relative Geological Time (RGT) model for each 3rd order sequence where each clinoform is mapped in 3D. Thirdly, using an integrated stratigraphic tool, we identify significant chronostratigraphic surfaces in a true 3D domain. This approach allows a full volume 3D mapping of every clinoform in 3D as well as defining high-order seismic sequences with reduce uncertainty, from which quantitative seismic stratigraphic analysis are conducted to help unravelling at high resolution the controls on shelf-margin architecture of the LBG through time and space, improving the prediction of shallow-marine and deep-water plays in the basin.

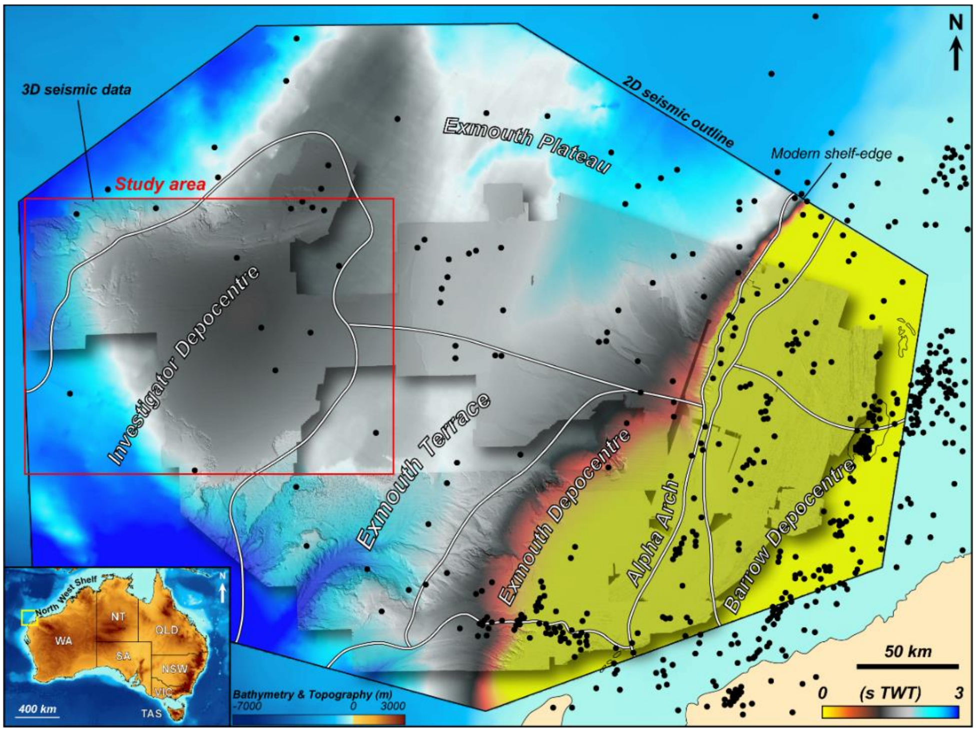

Figure 1: Location map of the study area within the Northern Carnarvon Basin (North West Shelf, Australia). The map corresponds to the seafloor horizon interpreted on both regional 2D and 3D seismic data. The geological provinces indicated on this map correspond to the Lower Barrow Group depocentres interpreted by Paumard *et al.* (2017).

METHOD AND RESULTS

Data

The seismic dataset in the study area consists 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.

Full-volume, semi-automatic seismic interpretation workflow

The seismic analysis on PaleoScan© is threefold. After the import of the seismic volume, a geological model-grid is calculated by establishing links between elementary horizon patches which are based on signal amplitude of neighbouring traces throughout the 3D data (Fig. 2; Pauget *et al.*, 2009). The creation of this grid can be constrained by the user on different parameters (e.g. correlation threshold, resolution). The computation of the similarity of adjacent wavelets and their relative distance in the 3D grid enable the creation of auto-tracked horizons (Fig. 2). The seismic interpreter can intervene at this point to refine the model by checking and modifying the auto-tracked horizons in a seismic stratigraphic framework. The next step consists in calculating a 3D Relative Geological Time (RGT) model (i.e. 3D geomodel), which corresponds to the 3D interpolation of the previous model-grid. A relative geological time is thus assigned to each horizon (Fig. 2). Finally, set of horizons (i.e. horizon stack) can be extracted from the 3D RGT. Thanks to the high-resolution of the interpretation and its full propagation in 3D, the user can scroll up and down through the horizon stacks to conduct stratigraphic and structural analysis. Several seismic attributes can be calculated along those horizons (e.g. RMS amplitude, coherency, spectral decomposition). The 3D seismic horizons corresponding to the main seismic unconformities previously identified on 2D seismic were extracted from the horizon stacks. Time-thickness maps of each seismic sequence were also calculated from the 3D horizons to obtain a better resolution and avoid the 2D gridding artefacts.

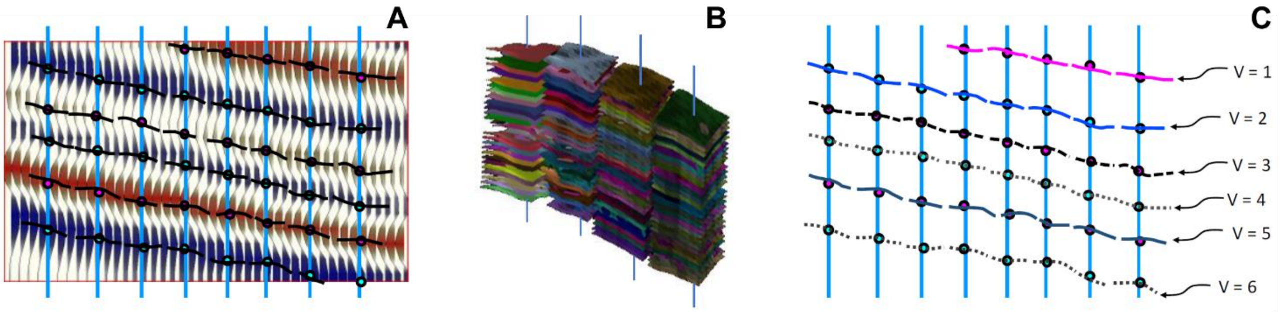

Figure 2: Workflow for full-volume semi-automatic tracking of horizons in Paleoscan©. (A) Creation of a model-grid linking patches to create auto-tracked horizons. (B) 3D view of the patches within the model-grid. (C) A relative geological time is assigned to each horizon. (*after* Pauget and Lacaze, 2017)

High-resolution seismic and sequence stratigraphic interpretation

The resolution of the seismic interpretation from the workflow described above is dependent of the size and number of patches available, as a finite number of patches is distributed within the seismic volume to create the model-grid. For instance, if not enough patches are available to create a model-grid through an entire seismic volume, the interpreter will have to increase the size of the patches, hence decreasing the precision of the interpretation. Therefore, to increase the resolution of our seismic interpretation within the LBG, we decided to apply the PaleoScan© workflow in each of the six 3rd order sequences defined by Paumard *et al.* (2017). Thus, all the patches are distributed in a relatively small interval, allowing to reduce the patch size, hence increasing the precision and resolution of the seismic interpretation. Using this precise workflow, we managed to obtain a very high-resolution 3D geomodel from which horizons can be extracted representing each one of the shelf-margin clinoforms from the LBG, which are now fully mapped in 3D (Fig. 3). In the case of the LBG, the number of horizons generated is over one thousand.

Integrated to the software, sequence stratigraphic tools allows defining sequences based on a standard seismic stratigraphic approach (Mitchum *et al.*, 1977a, 1977b; Vail and Mitchum, 1977). In a "true" 3D domain, by opening multiple seismic inlines and crosslines, we identified seismic unconformities based on the reflection terminations. The interpretation is helped by the calculation of the thinning attribute (based on the RGT) which displays the convergence and divergence of the calculated horizons, hence highlighting the downlap, onlap and toplap surfaces used to recognize seismic unconformities (Fig. 3). Therefore, these seismic unconformities are bounding genetically related strata having the same reflection pattern, here defined as seismic sequences or clinothems (Fig. 3). The 3D navigation throughout the seismic volume helps to define actual 3D seismic sequences, which are not identified from a few dip-oriented seismic lines as in a classic sequence stratigraphic interpretation method. From these sequences, 3D layers, as well as new horizon stacks, can be generated and time-thickness (i.e. isochores) maps calculated. This innovative tool constitutes a new step in sequence stratigraphy analysis as it allows interpreters to map sequences in a true 3D environment hence taking into account the full variability of depositional systems in time and space (Fig. 3).

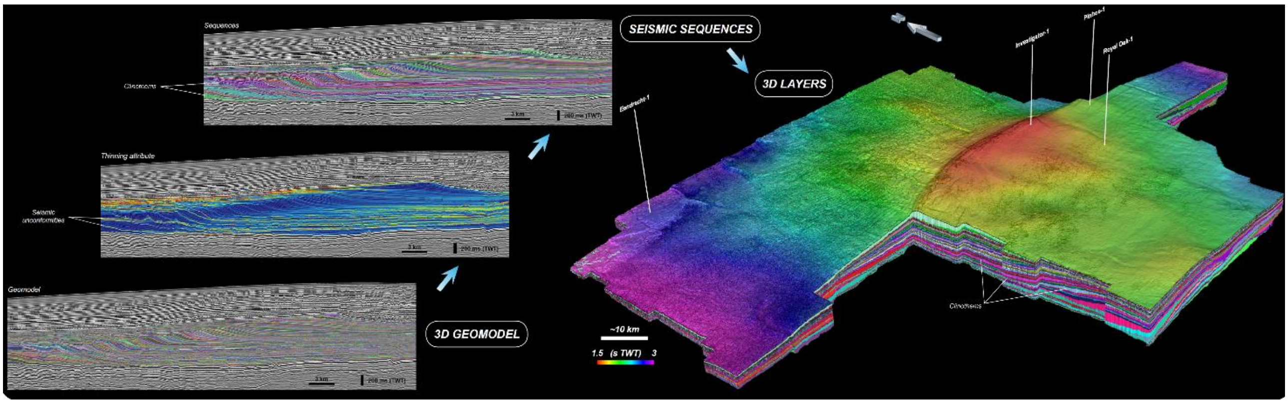

Figure 3: High-resolution sequence stratigraphic interpretation workflow using Paleoscan©. From the 3D geomodel and the thinning attribute, seismic sequences (or clinothems) are identified from which 3D layers can be generated.

Quantitative stratigraphy

This high-resolution seismic stratigraphic interpretation workflow allows identifying 73 seismic sequences or clinothems within the LBG (Fig. 3). Based on biostratigraphic data, we calculate that each clinothem represent a time duration of ~40,000 years. This scale of observation allow conducting high precision quantitative stratigraphic analysis. Within each clinothem, clinoform geometries were measured on 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). Thus, we can interpret at very fine scale the impact of variations in sediment supply and accommodation on the shelf-margin architecture and sediment partitioning between the shelf and the deep-water areas.

In terms of seismic geomorphology, several seismic attributes were calculated within each clinothem, over a time window between ~12 and 15 ms. The attributes presented in this paper include: (1) similarity attribute (equivalent to coherency attribute), which compares trace-to-trace similarities to enhance geological relief and discontinuity surface (e.g. faults); (2) Root Mean Square (RMS) attribute, which represents the measure of reflectivity by allowing the detection of amplitude variations, highlights channels, change in lithology and bright spots; (3) envelope attribute (equivalent to instantaneous amplitude attribute), which is calculated from the trace of seismic data independently of its polarity, emphasizes mostly channelized features (e.g. fluvial and deep-water channels) and amplitude anomalies (e.g. bright spots); and (4) spectral decomposition attribute (i.e. seismic trace based attribute), which decomposes the seismic signal into different frequencies that can be selected and blended in a color-blending (RGB) module to better highlight geological features (e.g. channels, faults) and sub-seismic resolution geological properties (e.g. lateral discontinuities, changes in sediment thickness). These attributes help identifying at high-resolution the shallow-marine features (i.e. fluvial, wave, tidal) and deep-water systems witihn each clinothem, which allows linking the presence of various types of deep-water systems with the different categories of shelf-margin architecture and processes within the LBG.

CONCLUSIONS

Innovative seismic interpretation workflows allowed interpreting 73 ultra-high resolution seismic sequences (~40,000 years duration) within the Lower Barrow Group (LBG; Latest Tithonian – Early Valanginian). This moderately deep-water shelf-margin (~100-500 m high clinoforms) prograded during a syn-rift phase of basin extension. Thus, it 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 at high-resolution.

Using PaleoScan©, a new generation seismic interpretation software, semi-automated horizon tracking allowed mapping key regional seismic unconformities defining 3rd order seismic sequences. In a second step, the PaleoScan© interpretation workflow is applied within each 3rd order seismic sequence, allowing the interpreter to obtain a very high-resolution Relative Geological Time model of the LBG. This permits a full volume 3D seismic mapping of every clinoform within the LBG, from which quantitative data (e.g. slope gradient, shelf-edge trajectory angle) and seismic attributes (e.g. spectral decomposition) were extracted.

This analysis unveiled the high resolution changes in accommodation (A) and sediment supply (S) in time and space within the LBG, and provided new insights on the distribution of shallow and deep marine plays in the basin. The quantitative analysis of the mapped clinothems reveals that low A/S conditions promote bypass of sediments basinward, whereas high A/S conditions increase sediment storage on the shelf. 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 linked to steeper slope clinoforms angles, whereas wave-dominated coastlines are associated with lower-angle slope clinoforms. Also, fluvial-dominated shorelines promote canyon development and formation of tripartite turbidite systems (canyon / slope valley; channel; lobes). Within the LBG, turbidite systems appear mostly as short-lived, vertically / laterally stacked elements fed my multiple small rivers forming linear ramp systems.

This innovative workflow constitutes a new step in sequence stratigraphy as it allows interpreters to map sequences in a 3D environment hence taking into account the full variability of depositional systems in time and space. We show that high-resolution full-volume, semi-automatic, seismic interpretation workflow, associated with quantitative stratigraphic analysis, can constitute a predictive tool in petroleum exploration. Future of seismic interpretation will reside in full-volume analysis of 3D seismic data through semi-automatic methods to obtain "true" 3D seismic and sequence stratigraphic interpretations, which will help in the precise understanding at very fine-scale of the development of clinothems and emphasize the critical aspect of along-strike variability in shelf-margin domains.

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