Shelf-to-basin sediment transfer mechanisms in contrasted tectonic settings: Insights from quantitative 3D seismic stratigraphy

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SUMMARY

With ~15% of siliciclastic hydrocarbon reservoirs located in deep-water basins, a key challenge is to predict when and where sands are bypassed to deep-water areas, and how they are architecturally organized.
Quantitative 3D seismic stratigraphy (QSS) aims at investigating the linkages between hydrodynamic regime along paleoshorelines, shelf-margin architecture and the development of coeval deep-water systems in a variety of tectonic and climatic settings. This approach is underpinned by state-of-the-art, full-volume 3D seismic interpretation methods that enable high-resolution seismic stratigraphic analysis.
Results obtained from shelf margins developed in late syn-rift (Northern Carnarvon Basin, Australia), post-rift (Porcupine Basin, Ireland) and foreland fold and thrust belts (NW Borneo) settings will be presented.
Statistical analysis of these data reveals that overall, fluvial-dominated shorelines are typically associated with: (1) slope gradients twice steeper than the wave-dominated shorelines; and (2) longer run-out turbidite systems. However, these relationships become less clear in basins where the slopes are highly affected by tectonics (i.e., ponded slopes) and/or the inherited paleotopography of the basin. Additionally, the turbidite systems developed in NW Borneo present a significant longer run-out distance because the shelf-margin clinoforms are merging with the continental margin clinoforms, thus promoting the development of architecturally more mature turbidite systems along higher and longer slopes.
These results highlight that variations from fluvial- to wave-dominated systems represent first-order controls on the coeval development of deep-water systems. However, while shelf-to-basin sediment transfer mechanisms influence slope gradients, inherited paleotopography and tectonics have a direct impact on shelf-margin architecture and associated turbidite systems.
By integrating advanced tools in seismic interpretation, quantitative 3D seismic stratigraphy represents a novel approach in assessing at high resolution the controls on deep-water sand delivery, and potentially predicting the type and location of reservoirs in deep-water areas based on shelf-margin architecture and depositional process regime.

Key words: Quantitative 3D seismic stratigraphy; Shelf margin; Deltaic process regime; Deep-water; Tectonics

INTRODUCTION

Shelf margins are key areas of source-to-sink systems (Pellegrini et al., 2020). The delivery of reservoir quality sands at and beyond the shelf edge results from the complex interplay between accommodation and sediment supply, which are directly influenced by tectonics (e.g., subsidence, uplift) and climate (e.g., eustasy, rainfall). Therefore, studying quantitatively the architecture of shelf-margin clinoforms is crucial to decipher these controls and better understand sediment partitioning between the shelf and the basin (e.g., Steel and Olsen, 2002; Carvajal and Steel, 2009; Patruno and Helland-Hansen, 2018).

Traditional models predict that deep-water sand delivery to the basin is promoted by the development of shelf-edge deltas, which are developed during periods of relative sea-level fall associated with reduced accommodation and shelf emersion (e.g., Posamentier et al., 1988; Porebski and Steel, 2003), Subsequently, it was also envisaged that deep-water sand delivery can be promoted at all sea-level stands where narrow shelves and/or supply-dominated conditions are present (e.g., Carvajal and Steel, 2006; Carvajal et al., 2009). In both cases, deltas (i.e., shoreline) need to reach the shelf edge to initiate deep-water sediment transfer. However, recent studies have demonstrated that hydrodynamic regime (i.e., coastal processes) play an equally, if not more important, role on shelf-to-basin sediment transfer mechanisms (e.g., Dixon et al., 2012; Gong et al., 2016; Cosgrove et al., 2018; Paumard et al., 2020). These studies highlight that deep-water sand delivery is promoted by fluvial-dominated shorelines. At different stratigraphic orders, both climate and tectonics can modulate these parameters (i.e., accommodation, sediment supply and deltaic process regime).

Therefore, it is critical to conduct integrated studies considering these various aspects to better constrain the full range of controls on deep-water sand delivery in various tectonic and climatic settings. Nowadays, 3D seismic data have the advantage to cover extensive parts of depositional systems within sedimentary basins (e.g., Paumard et al., 2019c), and thus constitute a unique opportunity to conduct this type of analysis. However, to be able to compare different types of margins, a consistent approach is needed to make reasonable conclusions. The quantitative 3D seismic stratigraphy (QSS) workflow was developed in this context.

METHODS AND RESULTS

Quantitative seismic stratigraphy

The QSS workflow is underpinned by the use of innovative seismic interpretation tools that are able to semi-automatically interpret full 3D seismic volumes and extract the information contained in these data at an unprecedented resolution and in a relatively short timeframe. The QSS approach is fourfold: (1) full-volume seismic interpretation; (2) geometric attribute calculation; (3) high-resolution seismic stratigraphy; and (4) quantitative analysis (Fig. 1; Paumard et al., 2019a).

First, the software PaleoScan^{TM} is used. In short, the software compare trace-to-trace the seismic data, creates elementary horizon patches and link them following their similarities, thus creating proto-seismic horizons within a *Model-Grid*, which can be manually refined. It is then possible to interpolate the *Model-Grid* in 3D to obtain a *Relative Geological Time Model*, also called a *3D Geomodel*. In complex structural areas, fault interpretation and integration in the *Model-Grid* are necessary, although more time is needed for refinement. From this *3D Geomodel*, an unlimited number of 3D seismic horizons can be extracted in *Horizon Stacks*, along which a variety of seismic attributes can be calculated.

The second and third steps involve the calculation of a *Thinning* attribute and the definition of a high-resolution seismic stratigraphic framework, respectively. The *Thinning* attribute, which highlights convergence and divergence of seismic reflections, used in conjunction with direct observations of reflections terminations, help to identify seismic unconformities (*sensu* Mitchum et al., 1977a, 1977b; Posamentier et al., 2022). By opening several dip-oriented and strike-oriented seismic cross-sections, and navigating throughout the 3D seismic volume, it is possible to pick at high resolution these seismic unconformities taking into account the full variability of shelf-margin depositional systems contained within the 3D seismic data.

The fourth step consists in the quantitative analysis of shelf-margin clinoforms and clinothems (i.e., seismic sequences previously identified). A series of parameters can be measured and calculated (e.g., shelf-edge trajectory angle, slope gradient). These measurements are conducted along key dip-oriented seismic lines and populated in a database. This workflow also includes the quantitative characterization of depositional environments in map view using the principles of seismic geomorphology (Posamentier et al., 2022). Paleoshorelines within each clinothem are classified using the process-based shallow-marine (WAVE) classification (Ainsworth et al., 2011; Vakarelov and Ainsworth, 2013). Similarly, coeval deep-water systems are identified and characterized.

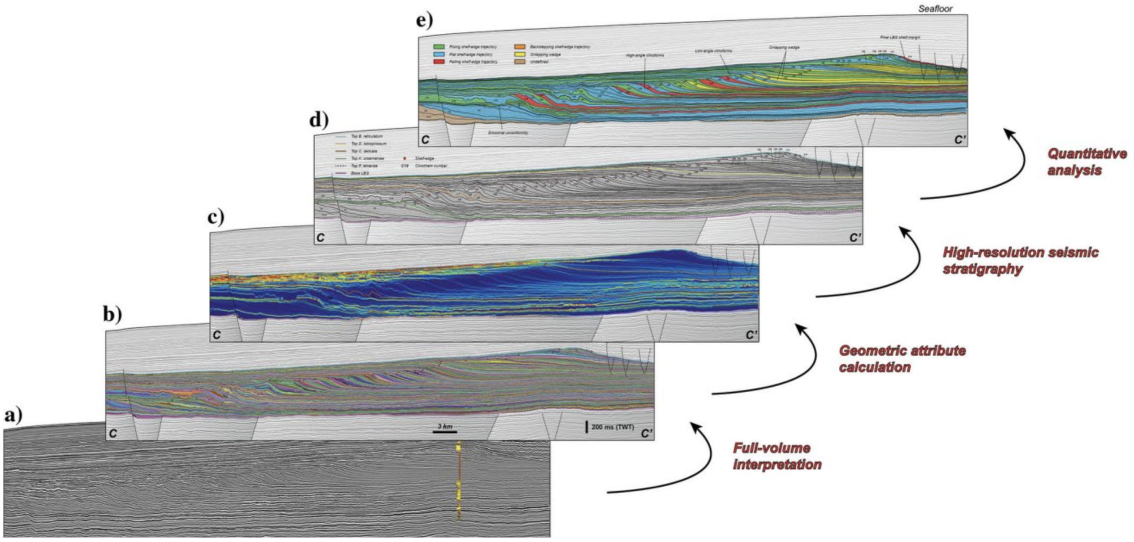

Figure 1. Quantitative seismic stratigraphy workflow (after Paumard et al., 2019a).

Lower Barrow Group (North West Shelf, Australia)

The Lower Barrow Group (LBG) corresponds to a shelf margin (i.e., clinoforms ~ 100-500 m high) that prograded in the Northern Carnarvon Basin (NCB; North West Shelf, Australia) from the latest Tithonian to the Early Valanginian under syn-rift conditions. Thus, the evolution of this shelf margin was affected by along-strike variations in subsidence and lateral shifts in sediment supply directly impacting the sediment partitioning between the shelf and deep-water areas (Paumard, 2018). Therefore, the LBG constitutes a natural laboratory to study the interplay between shelf-margin architecture, process regime along paleoshorelines, and controls on deep-water sand delivery (Paumard et al., 2019b; Ainsworth et al., 2020). Being an Early Cretaceous depositional system, the LBG was developed under greenhouse climatic conditions. The LBG is also a sand-rich system characterized by a strong sediment supply (Paumard et al., 2018).

Variations from fluvial- to wave-dominated systems resulted in significant lateral changes for deep-water sand delivery, which also impacted shelf-margin architecture (i.e., slope gradients; Paumard et al., 2020). Wave-dominated shorelines are associated with gentle slope gradients, whereas fluvial-dominated shorelines are linked with slope gradients twice steeper (Fig. 2). From wave-dominated to fluvial-dominated shorelines, there is an overall increase in the architectural maturity of deep-water systems (i.e., from no turbidite systems to long run-out turbidite systems; Fig. 2).

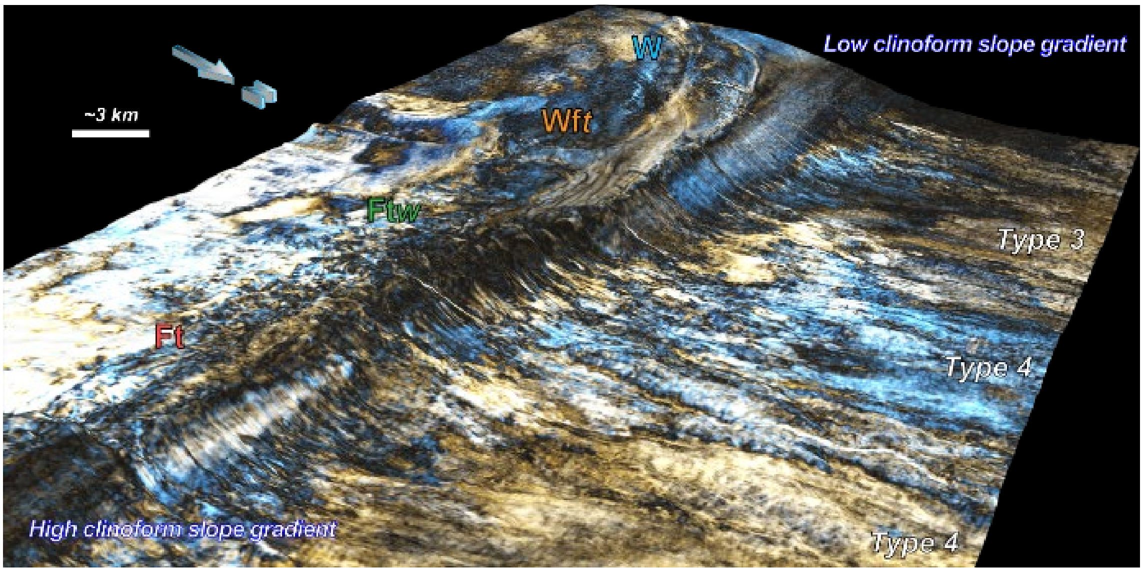

Figure 2. Color-blended (RGB) spectral decomposition attribute in three-dimensional view showing the LBG shelf-margin. W/w/w = Wave; F/f/f = Fluvial; T/t/t = Tidal; Type 3 = short run-out turbidite systems; Type 4 = long run-out turbidite systems.

North West Borneo

The North West Borneo margin can be characterised as an underfilled foreland basin that has been located in an active convergent margin setting since the late Eocene. Early Miocene to present day fluvio-deltaic sediments built out over a deeply buried foreland fold-thrust belt, the latter interpreted to be comprised of Oligocene to Early Miocene deep-water deposits (Ingram et al., 2004; Morley, 2007; Gartrell et al., 2011; Torres et al., 2011; Morley et al., 2021). The combination of high sediment supply and high subsidence rates in the foreland basin resulted in a very thick deltaic sedimentary pile (6-8 km). The interval of interest corresponds to the Pleistocene (~2 Ma) to present-day interval, selected because it contains relatively well imaged clinoforms and it is less deformed. These shelf-margin clinoforms prograded in an active tectonic setting during the later stages of a syn-orogenic pulse, as indicated by thickening/thinning and onlap relationships in the vicinity of the thrust ridges and inboard inversion structures, under icehouse climatic conditions. The complex interplay between structurally controlled subsidence and uplift with eustatic sea-level changes, strongly impacted the architecture of the margin and its variability through time and space (Gartrell et al., 2011; Torres et al., 2011).

Similarly to the LBG, seismic attribute analysis reveals that long run-out turbidite systems are observed where fluvial-dominated coastal processes are active at the shelf margin. The fluvial-dominated shorelines are highlighted by the presence of large channel belts and sometimes distributary channels. In other areas, mixed-process shorelines are linked with short run-out turbidite systems. While similar types of deep-water systems than in the LBG are observed along the NW Borneo margin (i.e., sheet sands, MTDs, short and long run-out turbidite systems), run-out distances are significantly longer (e.g., the shorter run-out turbidite systems have a run-out distance between 15 and 50 km, whereas long run-out turbidite systems have run-out distance up to 140 km). Indeed, shelf-margin clinoforms are merging with continental margin clinoforms, hence the longer and higher slopes promote longer run-out distances. In some cases, more complex shorelines are observed because of the growth faulting that creates local accommodation space along the shelf margin (e.g., presence of lagoons and bayhead deltas), which can hinder deep-water sand delivery.

Porcupine Basin (offshore Ireland)

The north-south oriented Porcupine Basin has known a complex tectono-stratigraphic history, with several phases of rifting over a ~200 Myrs period (e.g., Reston et al., 2004; Bulois et al., 2018). An intense Late Jurassic rifting event formed a hyperextended continental crust towards the south, likely responsible for the “V” shape of the basin (Tate, 1993; O’Reilly et al., 2006; Prada et al., 2017; Whiting et al., 2021). Post-rift thermal subsidence during the Late Cretaceous and Cenozoic led to the development of a thermal sag basin. During this time, up to 9 km of sediments are accumulated in the centre of the basin, which thins towards the flanks of the basin. Large-scale shelf-margin clinoforms, prograding towards the south, are developed during the Late Paleocene to Mid-Eocene. These siliciclastic sediments are sourced from platform highs in the north. Thus, the Porcupine Basin offers the opportunity to study the evolution of shelf-margin clinoforms developed in a passive rift basin under greenhouse climatic conditions. Regionally, the margin presents a convex-southwards shelf-edge physiography, flanked with paleotopographic highs situated to the northwest and east of the basin. This configuration results in clinoforms prograding concomitantly from several directions.

Overall, most of the shelf-margin is wave-dominated during its evolution, which may explain the lack of architecturally mature turbidite systems in deep-water areas. The lack of fluvial dominance, together with low sediment supply and the presence of longshore drift currents, likely hindered deep-water sand bypass to the basin. However, where steep slope gradients are observed, slope instability triggers the development of MTDs. Unlike previous case studies, these steeper slope gradients are not linked to the location of fluvial feeder systems and coeval turbidite systems, but are rather inherited from the basin paleotopography. This depositional system can be described as a combined structural-sedimentary shelf, where shelf-margin architecture is partly structurally controlled (i.e., inherited topography).

CONCLUSIONS

By integrating advanced tools in seismic interpretation, quantitative 3D seismic stratigraphy represents a novel approach in assessing at high resolution the controls on deep-water sand delivery, and potentially predicting the type and location of reservoirs in deep water based on the shelf-margin architecture and depositional process regime, in different climatic and tectonic settings. Case studies presented here include: (1) late syn-rift (Northern Carnarvon Basin, Australia); (2) post-rift (Porcupine Basin, Ireland); and (3) foreland fold and thrust belts (NW Borneo) settings.

Overall, variations from fluvial- to wave-dominated systems represent a first-order control on the coeval development of deep-water systems. Fluvial-dominated shorelines tend to be associated with steeper slope gradients and longer run-out turbidite systems. However, while shelf-to-basin sediment transfer mechanisms influence slope gradients, inherited paleotopography and tectonics have also a direct impact on shelf-margin architecture and associated turbidite systems, which may overprint these relationships.

Therefore, this study demonstrates that deep-water sand delivery results from a complex interplay between different parameters at various stratigraphic orders, in different climatic and tectonic settings. While there is no simple relationships, it seems that the tectonic context is critical in establishing the set of rules that may apply to a particular shelf margin and associated deep-water sediment transfer mechanisms.

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