GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45730.1

Manuscript received 21 October 2018
Revised manuscript received 31 January 2019
Manuscript accepted 20 February 2019

Published online 11 March 2019

Accommodation- versus supply-dominated systems for sediment partitioning to deep water

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ABSTRACT

Several decades of studies on shelf-margin evolution have led to recognition that both accommodation-dominated and supply-dominated sediment-delivery systems are capable of transporting sediments from the shelf down into deep-water basins. The former case relies on falling sea level and lowstands to move deltas to the shelf edge, whereas the latter depends on well-supplied deltas reaching the shelf edge regardless of sea-level rise. However, it remains unclear how to distinguish between the two sediment-dispersal alternatives, and which of these is more efficient in delivering sediments to deep water. We explore sediment-volume partitioning into deep-water areas by analyzing >1600 runs of a geometric delta model with varying eustatic, shelf-morphologic, and sediment-supply conditions. Previous studies suggest that greenhouse eustatic (low amplitude and frequency) conditions generate lower shelf accommodation, and permit the shoreline to arrive at the shelf edge quickly. Further investigation reveals that (1) this argument works only for the supply-dominated system, and (2) the proportion of total sediment that reaches deep water is not correlated to the frequency of sea-level change, but depends strongly on the shelf width and the amplitude of sea-level change. We suggest a ratio between (1) the product of shelf width and the amplitude of sea-level change and (2) total sediment supply to quantitatively characterize the sediment dispersal system. A ratio of 0.4 forms a good boundary between accommodation- and supply-dominated systems in the modeling results, and in three well-studied ancient systems (the Maastrichtian Washakie Basin, Wyoming, USA; the Pliocene paleo–Orinoco margin, Trinidad and Tobago; and the Miocene New Jersey margin, northeastern USA). This work also suggests that the sediment mass balance becomes more important for continental margin building regardless of sea-level scenarios over the longer term.

INTRODUCTION

Understanding the sediment supply mechanism and sediment distribution of deep-water systems is important for predicting and estimating hydrocarbon resources, deciphering past climatic and tectonic signals, and preventing geohazards. Recent studies have proposed possibilities for driving cross-shelf shoreline transit, thus creating a delta–deep water linkage (Covault and Graham, 2010; Sweet and Blum, 2016; Fig. 1A). In conventional sequence stratigraphy, sea-level fall below the shelf break was considered the only mechanism to drive the shoreline across the shelf, delivering sediments to the preexisting shelf edge and further forming deep-water fans (Vail et al., 1977; we term this the "accommodation-dominated system"). The alternative possibility is that high sediment supply also can push the shoreline to the shelf margin, and that deep-water deposition can ensue regardless of sea-level changes (Burgess and Hovius, 1998; Carvajal and Steel, 2006; we term this the "supply-dominated system"). A shelf-penetrating canyon is another possibility for providing long-lived connections transporting sediments to deep water. In this study, we focus on the first two possibilities. Even though these two end members are widely accepted, it is still not well understood how efficient they each are at delivering sediments to deep water over multiple sea-level cycles. This lack of understanding stems from the limited documentation on sediment-volume partitioning across complete shelf-margin clinoforms (e.g., Carvajal and Steel, 2012). Furthermore, even though there is a tendency to link the frequency and amplitude of eustatic sea-level change with the two types of system (icehouse conditions with accommodation-dominated, and greenhouse conditions with supply-dominated), some cases also demonstrate the importance of additional parameters such as sediment supply and shelf width (e.g., Covault and Graham, 2010). We explore the sediment distribution across numerically modeled shelf-margin clinoforms to (1) compare the efficiency of accommodation- and supply-dominated sediment dispersal systems; (2) understand how upstream and downstream boundary conditions can influence the formation of deep-water fans and continental margin building; and (3) learn how to quantitatively distinguish between these two systems.

METHODOLOGY

We modified the geometric model designed by Kim et al. (2009) (Fig. 1) that was able to accurately estimate the shoreline position in their Experimental EarthScape basin (https://www.safl.umn.edu/facilities/experimental-earthscape-xes-basin) experiments. The conservation of sediment mass is expressed as

$$q_s t = \int_0^L (\eta - b)\,dx, \quad (1)$$

where q_s is the sediment flux (km²/m.y.), t is the simulated model time (m.y.), η is the topographic elevation of the sediment surface (km), b is the elevation of the basement (km), and L denotes total length of the basin (km). A preexisting shelf-margin clinoform is used as the initial basement (Fig. 1). The shoreline position, s, is determined under the prescribed slope conditions for the topset and foreset of deltaic clinoforms that are solved numerically for each time step as

$$\eta = \eta_s + (s - x)\tan(S_t) \text{ if } x < s, \quad (2a)$$

$$\eta = \eta_s - (x - s)\tan(S_f) \text{ if } x > s, \quad (2b)$$

where S_t and S_f are gradients (degrees) of the topset and foreset, respectively. The elevation of the shoreline (η_s) equals sea level (see detailed

CITATION: Zhang, J., Kim, W., Olariu, C., and Steel, R., 2019, Accommodation- versus supply-dominated systems for sediment partitioning to deep water: Geology, v. 47, p. 419–422, https://doi.org/10.1130/G45730.1

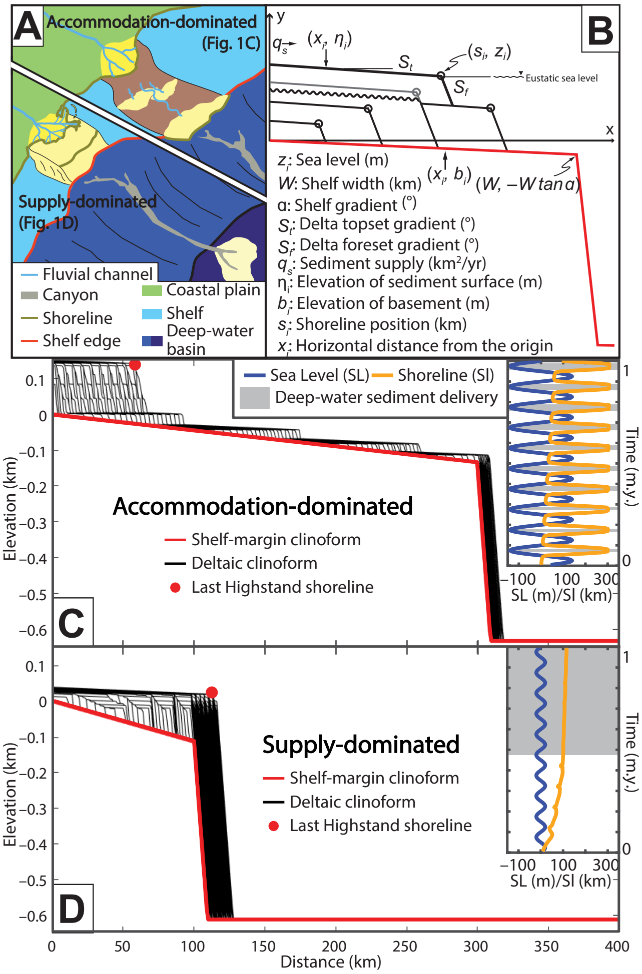

Figure 1. A: Accommodation- and supply-dominated sediment dispersal systems forming shelf-margin clinoforms. B: Two-dimensional geometric model with associated parameters describing shoreline migration across a shelf. Black lines represent deltaic clinoforms, and red lines represent shelf-margin clinoforms. C,D: Final modeled strata with associated shoreline position and sea level taken from one accommodation-dominated system (W = 300 km, A = 140 m, T = 100 k.y.; T—frequency of sea-level change) and one supply-dominated system (W = 100 km, A = 20 m, T = 100 k.y.). See an animation showing shoreline migration in the Data Repository (see footnote 1).

descriptions and limitations in the GSA Data Repository[1]).

We input a wide range of eustatic conditions, shelf width, and magnitude of sediment supply to evaluate the influence of each variable on the partitioning of sediment volumes to the deep-water area. We calculated the ratio of the volume of sediment partitioned beyond the shelf edge to the total sediment budget for each run (Figs. 2 and 3A). Most model runs used q_s = 20 km²/m.y. and a total run time of 1 m.y. (Fig. 2), but q_s = 5–50 km²/m.y. was also tested in some model runs (Fig. 3A). The amplitude of sea-level change varied from 0 to 150 m in 10 m increments. The duration for cycles of sea-level change was from 50 to 500 k.y. in 50 k.y. increments. The shelf width ranged from 20 to 200 km in 20 km increments. We distinguished the accommodation- and supply-dominated systems in the experimental results by their shoreline behavior (Fig. 1; see animations in the Data Repository). In the accommodation-dominated system, shoreline advancement across the entire shelf occurs only when sea level falls below the shelf edge (Fig. 1C). The shoreline in the supply-dominated system, after it arrives at the shelf margin, docks at the shelf edge for the remainder of the simulated model time (Fig. 1D).

SEDIMENT VOLUME PARTITIONING UNDER DIFFERENT EUSTATIC AND SHELF CONDITIONS FOR ACCOMMODATION- AND SUPPLY-DOMINATED SYSTEMS

The proportion of the sediment budget partitioned into deep water, estimated for each run with q_s = 20 km²/m.y., is more sensitive to the shelf width and amplitude of sea-level change than to the frequency of sea-level change (Fig. 2). The deep-water sediment proportion decreases with increasing shelf width (Fig. 2B). For a narrow shelf, the deep-water sediment proportion is high (up to ~90%) and the greenhouse (low-frequency and low-amplitude) and icehouse (high-frequency and high-amplitude) eustatic conditions produce similar results (e.g., <10% differences for 20 km shelf width). For moderately wide shelves, the deep-water sediment proportion in icehouse conditions is maintained, whereas the proportion continuously decreases in greenhouse conditions. For wide shelves, very limited sediments are delivered into deep water in greenhouse conditions. The proportion of sediments transported into deep water is also closely related to the amplitude of sea-level change (Fig. 2C). An increasing amplitude of sea-level change causes the deep-water sediment proportion to decrease and then increase. The deep-water sediment proportion is not closely related to the frequency of sea-level change under certain shelf widths and amplitudes of sea-level change (Figs. 2A and 2D). For an 80 km shelf width under 40 m amplitude of eustatic sea-level change, the deep-water sediment proportion ranges only from 70% to 71% (Fig. 2D).

The modeling results suggest that narrow shelves and a low amplitude of sea-level change favor the formation of supply-dominated systems (Fig. 2). Wider shelves and a higher amplitude of sea-level change produce greater shelf accommodation (Sømme et al., 2009). Therefore, in the supply-dominated system, the deep-water sediment proportion decreases with increasing shelf width and amplitude of sea-level change (Figs. 2B and 2C). When shelf accommodation increases beyond a threshold value, beyond which the sediments cannot fill the space created, the supply-dominated system changes to an accommodation-dominated system. The volume of deep-water sediment in the accommodation-dominated system is decided by how long the shoreline remains at or below the shelf edge (i.e., the amplitude of sea-level change versus the water depth at the shelf edge), rather than by the shelf accommodation. Therefore, the relationship between deep-water sediment proportion and the amplitude of sea-level change is not monotonic. Previous studies argued that longer cycle duration would allow more time for the shoreline to remain at the shelf edge (Porębski and Steel, 2003; Sømme et al., 2009; Zhang et al., 2017). Even though this is true for a single eustatic cycle (~10^1–10^2 k.y.), our results suggest that the influence of the frequency of sea-level change is minor on the long-term deep-water sediment proportion, because the cumulative time for the shoreline to stay below the shelf edge at the million-year time scale is similar despite varying frequencies of sea-level change (see also Harris et al., 2018).

THE ROLE OF SEDIMENT SUPPLY, AND DISTINGUISHING SEDIMENT DISPERSAL SYSTEMS BY THE SHELF ACCOMMODATION/SUPPLY RATIO

To test the role of sediment supply, we use q_s = 5–50 km²/m.y. and a 100-km-wide shelf (Fig. 3A). Higher sediment supply is associated with a higher deep-water sediment proportion, and so a higher chance of the system being supply-dominated. Therefore, icehouse versus greenhouse eustatic conditions do not directly determine sediment dispersal systems. To quantitatively distinguish between

[1]GSA Data Repository item 2019145, additional details on the methodology, animations showing the model runs in Figures 1C and 1D, modeled results of the model runs in Figures. 2B–2D, and inputs of three ancient systems in Figure 3B, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

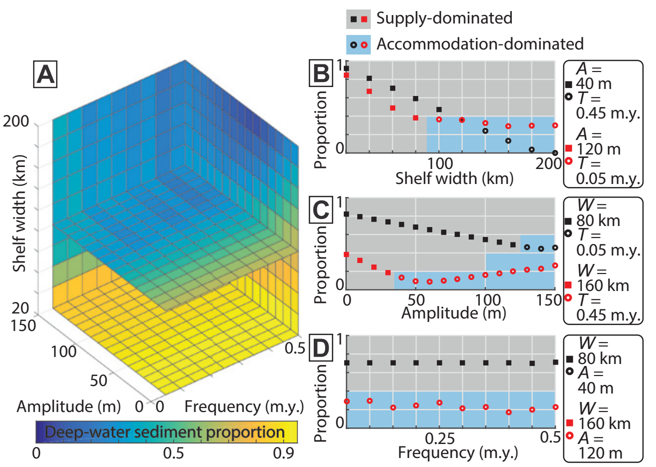

Figure 2. A: Representative slices of three-dimensional volume showing the proportion of total sediment reaching deep water (represented by color) under different shelf widths (*x* axis), as well as the frequency and amplitude of sea-level change (*x* and *y* axes). B–D: Selected examples showing the relationship between deep-water sediment proportion and shelf width *W* (B), amplitude *A* (C), and frequency *T* (D) of eustatic sea-level change. See the modeled results in Figures DR3B–DR3D (see footnote 1).

accommodation- and supply-dominated systems, we propose a simplified shelf-accommodation/supply ratio (SASR), as follows:

$$\mathrm{SASR} = (W \times A)/Q_s, \quad (3)$$

where W is shelf width (km), A is the amplitude of sea-level change (km), and Q_s is total sediment supply (km^2). Even though the simplified shelf accommodation ($W \times A$) does not fully account for real-world accommodation, both shelf width and amplitude of sea-level change are main contributors to shelf accommodation, and their product therefore approximates the bulk of the shelf accommodation. In a rapidly subsiding margin, the amount of subsidence needs to be considered in the model as well. A low SASR predicts a high chance of forming a supply-dominated system. With a high SASR, especially if the SASR >1, the sediment supply may never be able to fill the shelf accommodation and therefore cannot be termed a supply-dominated system. However, deep-water fans can still form in this condition if the sea level falls below the shelf edge. This trend is clear in the modeling results in Figure 3A. The SASRs of supply-dominated systems are mostly <0.4. When the magnitude of sediment supply and the amplitude of sea-level change are small, both sediment dispersal systems fail to work and the deep-water sediment proportion is close to 0.

We test the feasibility of the SASR in 26 shelf-margin clinoforms of three well-studied ancient systems (Carvajal and Steel, 2006; Chen et al., 2016; Hodgson et al., 2018) (Fig. 3B; see the inputs in the Data Repository). The SASRs of eight clinothems of greenhouse Maastrichtian Washakie Basin (Wyoming, United States) are <0.4, indicating that the overall sediment supply outpaced shelf accommodation. This result is consistent with the fact that Washakie deep-water fans formed in every sequence, and that they did so with an overall rising shelf-edge trajectory (Carvajal and Steel, 2006). The SASRs of the icehouse Pliocene Orinoco (Trinidad and Tobago) clinoform sets are generally higher than those of Washakie Basin. Four of the Orinoco clinothems have SASRs between 0.4 and 1, indicating that the sediment supply was less able to fill the entire shelf accommodation, especially considering that some of the sediments were delivered into the deep-water basin during lowstand. Therefore, we suggest that the formation of Orinoco deep-water fans mostly relied on sea-level fall. This is consistent with the reported evidence of forced regression in the onshore Trinidad stratigraphy (Chen et al., 2016). In the case of the deep intra-shelf clinothems developed on the icehouse Miocene New Jersey margin system (northeastern United States; Hodgson et al., 2018), the shorelines did not arrive at the preexisting shelf edge until the Pleistocene (Steckler et al., 1999). The New Jersey SASRs are the highest among the three systems, ranging from 1.2 to 3. The shelf accommodation was always underfilled. In addition, the water depth at the structural shelf edge (100–400 m) likely hampered lowstand sediment delivery, and there are no large-scale deep-water fans in front of the shelf edge (Steckler et al., 1999; Hodgson et al., 2018).

IMPLICATIONS FOR CONTINENTAL SHELF-MARGIN BUILDING

The dominant control of shelf width on the proportion of sediments transported into deep water implies that continental shelf-margin building inevitably tends to slow down at the time scale of several million to tens of millions of years regardless of high-frequency sea-level change, because the shelf becomes very wide. We plot deep-water sediment proportion at 50, 100, 200, and 400 km shelf widths under the full range of sea-level amplitude and frequency over 1 m.y. (Fig. 4A). The results show that even though the deep-water sediment proportion does vary at a certain shelf width due to varying eustatic conditions, its general trend is one of decreasing with a widening shelf. The median of deep-water sediment proportion decreases from 0.68 at 50 km shelf width to 0 at 400 km shelf width. In addition, the sediment dispersal system changes from supply-dominated to accommodation-dominated. At 400 km shelf width, only high-amplitude sea-level fall is able to deliver up to ~20% sediments into the deep-water basin, and in most cases no sediments are deposited in the deep-water basin, indicating that the shelf edge ceases to prograde.

Although the progradation of any shelf margin is decided by multiple controls (not all of which are discussed here) such as basin geometry, water depth in front of the shelf margin, subsidence profile, and magnitude of sediment supply (Helland-Hansen et al., 2012), we suggest that there is commonly a general long-term (several to tens of millions of years) concave-up shelf-edge trajectory during shelf-margin building: progradational shelf building tends to be rapid initially, then slows as the shelf becomes wide, and finally reaches a state where only an accommodation-dominated system with high amplitudes of sea-level change can deliver a small proportion of sediments into the deep-water basin (Fig. 4B). This notion of long-term

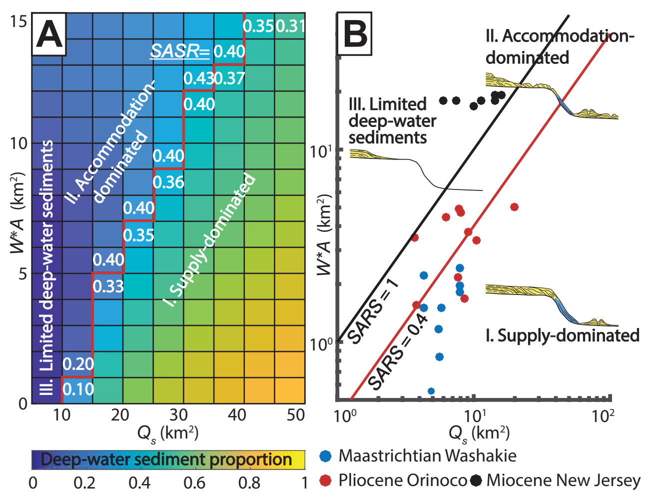

Figure 3. A: Proportion of total sediment reaching deep water with varying shelf accommodation ($W \times A$, where W is shelf width and A is amplitude of sea-level change) and total sediment supply (Q_s). Note that shelf width in this example is 100 km and the frequency of sea-level change is 0.25 m.y. White numbers represent simplified shelf-accommodation/supply ratio (SASR); red line denotes boundary between supply- and accommodation-dominated systems. B: Simplified SASR of 26 shelf-margin clinoforms from three ancient systems (Washakie Basin, Wyoming, USA, Carvajal and Steel, 2006; paleo–Orinoco margin, Trinidad and Tobago, Chen et al., 2016; New Jersey margin, northeastern USA, Hodgson et al., 2018).

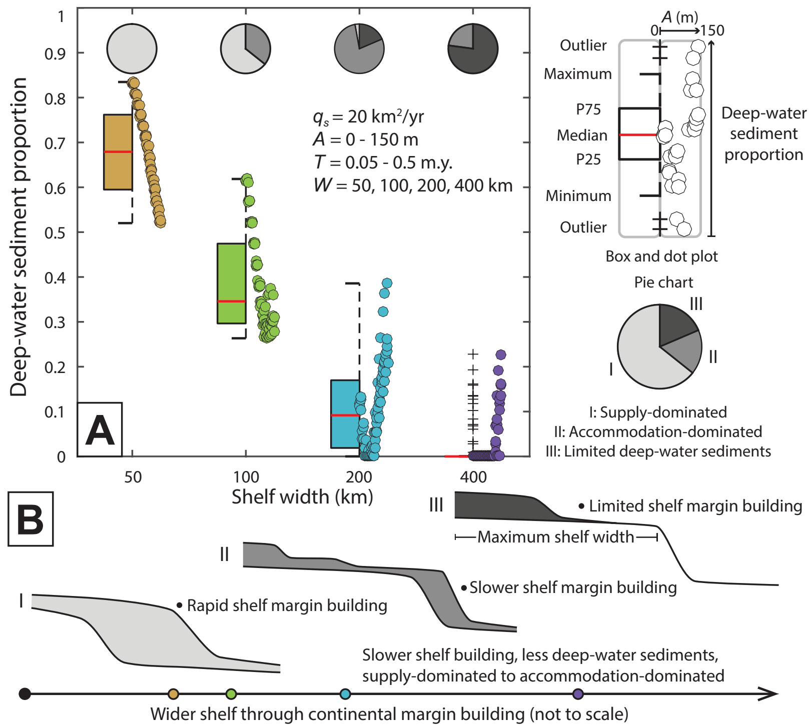

Figure 4. A: Varying deep-water sediment proportion (box and dot plots) and dominant dispersal system (pie charts) with different eustatic and shelf conditions. P25 and P75 are the 25th and 75th percentiles, respectively. q_s—sediment flux; *A*,*T*—amplitude and frequency of sea-level change; *W*—shelf width. B: Sketches showing transitions from a supply-dominated system with rapid shelf-margin building to an accommodation-dominated system with limited shelf-margin building as the shelf becomes wider.

slowdown of progradational shelf-margin growth is borne out by the long-term stacking pattern of clinoforms within many well-known shelf-margin prisms; for example, the Miocene–Quaternary South China Sea shelf margin (Gong et al., 2015) and the early Pliocene to recent New Plymouth margin offshore New Zealand (Salazar et al., 2016). However, this trend can be modified by an upstream catchment reorganization that can either shut down the sediment supply completely or push the fluvial feeder to further progradation.

CONCLUSIONS

Our modeling suggests that (1) the long-term proportion of the sediment budget partitioned into deep water does not relate to the frequency of sea-level change, but is strongly controlled by the shelf width and amplitude of sea-level change; and (2) high amplitudes of sea-level change decrease the deep-water sediment proportion only for supply-dominated systems. In accommodation-dominated systems, higher amplitudes of sea-level change permit a longer time for shorelines to remain docked below the shelf edge, therefore increasing the delivery of deep-water sediments. This complex relationship between deep-water sediment proportion and eustasy emphasizes the importance of determining the type of sediment dispersal system. The ratio between shelf accommodation and sediment supply (SASR) can be used to determine the sediment dispersal system and to help predict the presence of deep-water sand.

ACKNOWLEDGMENTS

We are grateful for funding from the State of Texas Advanced Resource Recovery (STARR) program at the University of Texas at Austin Bureau of Economic Geology, and RioMAR Consortium (http://www.jsg.utexas.edu/riomar/) sponsors ExxonMobil, Shell, Chevron, Eni, Statoil, and Anadarko. The manuscript was greatly improved by comments from Jorge Lorenzo-Trueba, Cristian Carvajal, two anonymous reviewers, and editor Judith Parrish.

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