Can sediment-supply variations create sequences? Insights from stratigraphic forward modelling

Jinyu Zhang[1, 2], Peter M. Burgess[3], Didier Granjeon[4] and Ronald Steel[2]

1. Bureau of Economic Geology, Jackson School of Geosciences, the University of Texas at Austin
2. Department of Geological Sciences, Jackson School of Geosciences, the University of Texas at Austin
3. School of Environmental Sciences, University of Liverpool
4. Department of Geology-Geophysics-Geochemistry, IFP Energies Nouvelles

Correspondence: Jinyu Zhang, Bureau of Economic Geology, Jackson School of Geosciences, the University of Texas at Austin, 10100 Burnet Road, Austin, Texas, USA. Email: Jinyu.zhang@utexas.edu

ABSTRACT

Classic sequence stratigraphy suggests depositional sequences can form due to changes in accommodation and due to changes in sediment supply. Accommodation-dominated sequences are problematic to define rigorously, but are commonly interpreted from outcrop and subsurface data. In contrast, supply-dominated sequences are much less commonly identified. We employ numerical stratigraphic forward modelling to compare stratal geometries forced by cyclic changes in relative sea level with stratal geometries forced by sediment discharge and water discharge changes. Our quantitative results suggest that both relative sea-level oscillations and variations in sediment/water discharge ratio are able to form sequence-bounding unconformities independently, confirming previous qualitative sequences definitions. In some of the experiments, the two types of sequence share several characteristics, such as an absence of coastal-plain topset deposits and stratal offlap, something typically interpreted as the result of falling relative sea level. However, the stratal geometries differ when variations in amplitude and frequency of relative sea-level change, sediment/water discharge ratio, transport diffusion coefficient, and initial bathymetry are applied. We propose that the supply-dominated sequences could be recognized in outcrop or in the subsurface if the observations of stratal offlap and the absence of coastal-plain topset can be made without any strong evidence of relative sea level fall (e.g., descending shoreline trajectory). These quantitative results suggest that both supply-dominated and accommodation-dominated sequences are likely to occur in the ancient record, as a consequence of multiple, possibly complex, controls.

INTRODUCTION

Definitions have evolved since the first introduction of sequence stratigraphic nomenclature by Sloss (1949) (Table 1). We summarized two key characteristics from the definitions in Table 1, the surface bounding sequences (i.e., unconformities) and the cyclic controls on the sequence development, which are present repetitively in these definitions. Initial definitions emphasized that a sequence is bounded top and base by unconformities that represent significant time gaps (Table 1; Fig. 1). More recent definitions emphasized controls, such as relative sea level and sediment supply, on cyclic sequence development (Table 1). Posamentier and Vail (1988) and Catuneanu (2006) highlighted changes in relative sea level as the main controlling factor, and more recently Catuneanu et al. (2009) defined a sequence as ‘a succession of strata deposited during a full cycle of change in accommodation or sediment supply’. Despite both relative sea level and sediment supply being included in the definitions, fewer studies invoke time-variable sediment supply as the dominant driver of sequence development (Porebski and Steel, 2003). For example, subaerial erosion surfaces, forming sequence-bounding unconformities, have been interpreted almost exclusively as products of relative sea-level fall, due to fluvial incision of subaerially exposed topset strata (e.g., Posamentier et al., 1988). The roles of sediment supply have largely been ignored, even though several modelling studies have documented the significant impact of time-variable sediment supply on fluvial morphodynamics and continental stratigraphy (e.g., Sun et al., 2002; Van Saparoea and Postma, 2008; Powell et al., 2012; Simpson and Castelltort, 2012). Recent field and experimental studies also suggest that a complex interaction of sediment supply and accommodation is the most realistic explanation for most sequence development, for several reasons. Firstly, it has been demonstrated that erosion surfaces below fluvial valleys are resulted from repeated erosion and deposition throughout relative sea-level cycle (Blum and Price, 1998; Holbrook et al., 2006; Strong and Paola, 2008; Holbrook and Bhattacharya, 2012; Li and Bhattacharya, 2013). Secondly, when the ratio between sediment discharge and water discharge is high or the marine shelf gradient is low, topset aggradation can occur without unconformity formation during relative sea-level fall (Swenson and Muto, 2007; Prince and Burgess, 2013;

Nijhuis et al., 2015). Rivers do not simply incise costal deposits during relative sea-level fall. Instead, they tend to undergo autogenic cycles of deltaic lobe deposition, incision, and abandonment (Muto and Steel, 2004, Swenson and Muto, 2007, Petter and Muto, 2008). Thirdly, sequence boundaries can also form due to variable sediment erosion and transport rates, without relative sea-level fall (Burgess and Prince, 2015). This complexity of process and control, and the relative simplicity of many existing models, suggests that our understanding of sequence geometries and what controls them requires further investigation (Heller et al., 1993; Hampson, 2016; Burgess and Steel, 2017; Zhang et al., 2017). We approach these problems by studying the forward modelled sequences generated by full cycles of change in relative sea level or sediment supply. The three-dimensional numerical stratigraphic forward modelling is employed to study the influences of external controls (relative sea level, sediment discharge, and water discharge), as it is difficult to extract the signal of each forcing from sedimentary record. We aim to use the modelling results to 1) understand the consequences of supply and accommodation control of strata; 2) compare and contrast the sedimentological and stratigraphic characteristics of accommodation-dominated cycles and supply-dominated cycles to understand their similarities and differences.

METHODOLOGY

We employ DionisosFlow, a three-dimensional numerical stratigraphic forward model, to simulate shoreline migrations over the shelf in response to supply and relative sea-level change. The model assumes sediment transport by diffusion, with a relatively low-rate slope-only component, and a higher-rate water-discharge and slope-driven component (Granjeon, 1997; Granjeon and Joseph, 1999; Granjeon, 2014). For each time step, DionisosFlow calculates relative sea-level change (eustasy and subsidence), sediment supply (sediment discharge and water discharge), erosion, sediment transport, and sediment deposition. Modelling this combination of processes allows experimental simulation of stratal geometries developed on basin scale over geological time scale.

We designed two sets of model experiments (i.e., accommodation-dominated and supply-dominated), each spanning 2 million years, with 0.1 million-year time steps, both representing the same modeled basin configuration (Figs. 2; 3). All input parameters of two sets of model experiments (e.g. shelf width, shelf gradient, water discharge, sediment discharge, subsidence rate, and eustatic sea-level change) are selected within the natural range of equivalent parameters observed in modern environment or interpreted from ancient strata (Fig. 4; Table 2). The model setup and input parameters are introduced below and summarized in Table 2.

Basin geometry and subsidence

The modeled basin is 200 km wide and 250 km long, with a single sediment input point on the basin axis (Fig. 2). The initial shoreline is 50 km from the sediment input point. The initial shelf gradient is ~0.06° leading to 200 m water depth at the shelf edge (Fig. 2). Values of both shelf width and shelf gradient are in the range of modern shelves (Fig. 4A). The subsidence profile has a hinge line with a maximum subsidence rate of 10 m/My at the shelf edge (Fig. 2), which is relatively low within the natural range of subsidence rates (Fig. 4C). The subsidence at the initial shoreline is 2 m for 1 My cycle duration (Fig. 2), much smaller than the eustatic sea-level change. Therefore, the relative sea-level change is mainly contributed by the eustatic sea-level change in the designed models.

Accommodation and sediment supply

The two model sets have different relative sea level and sediment supply scenarios, one dominated by variations in eustasy causing relative sea-level oscillations, and the other dominated by changes in sediment-supply sediment/water discharge ratio (Fig. 3). Note that in terms of sediment/water discharge ratio, an increase in water discharge is equivalent to a decrease in sediment discharge, and vice-versa, so supply variation may occur due to changes in either. Here we keep same sediment discharge but only change water discharge for the convenience of comparison between all model results. Each model set has two full 1 My cycles of sediment supply or eustatic sea-level change (Fig. 3). Two model sets includes 420 individual models runs in total, with parameters values varying to cover a range of eustatic sea-level oscillation amplitudes and sediment/water discharge ratios (Fig. 2). The eustatic sea-level change results from water-volume changes in the ocean. The frequency and amplitude of their changes are controlled by various geological mechanisms including growth and decay of continental ice sheets, desiccation and inundation of marginal seas, and variations in sea-floor spreading rates (Miller et al., 2005). The sediment and water discharge are also controlled by multiple tectonic and climatic parameters (Syvitski and Milliman, 2007), which change at different time scales (thousands to millions of years) (Blum and Hattier-Womack, 2009).

The accommodation-dominated model set has changing eustatic sea level, constant sediment discharge, and constant water discharge over the 2 My model duration. Amplitude of eustatic sea-level change ranges from 5-100 m (Fig. 3), similar to rates commonly interpreted in the eustatic sea-level models (Miller et al., 2005; Fig. 4D). Sediment discharge in all model runs is 500 km^3/My. The water discharge of each model run ranges from 50-1000 m^3/s, so the resulting sediment/water discharge ratio range is consistent with data from modern rivers which span three orders of magnitude (Fig. 4B).

Note that issues with a meaningful definition of accommodation in real, non-model strata and depositional systems, were raised by Muto and Steel (2000). They redefined the term 'accommodation' as 'the thickness, measured at a specified site and time, of a space which becomes filled with sediments during a specified time interval' but pointed out that this will be very difficult to apply interpreting ancient strata, where information on volumes and time are likely incomplete. We are able to use this definition here in our numerical modelling study because we have the requisite complete information about volume of supply and the thickness that it can fill through time. The practical use of the term accommodation in when considering real strata remains debatable.

For the supply-dominated model set, eustatic sea level is constant at 0 m through each model run (Fig. 3). The sediment/water discharge ratio is varied by changing water discharge. Sediment discharge is held at 500 km^3/My, for the convenience to compare two types of model sets. Amplitude of water discharge cycles ranges from 10-1000 m^3/s between each model (Fig. 4B). The average water discharge in wet cycles is a few times bigger than that in dry cycles. For example, if a $1.67*10^4$ km^2 catchment transits from arid (0-100 mm/yr runoff) to semi-arid (100-250 mm/yr runoff) (Milliman and Farnsworth, 2013; Eide et al., 2018), its water discharge ranges from 0-500 m^3/s to 500-1250 m^3/s.

Sediment transport diffusion coefficient

Determining realistic diffusion coefficients from ancient or even modern sediment transport system remains difficult. Continental and marine diffusion coefficients used here (Table 2) are within the range of values in other applications of diffusion based modelling (Kenyon and Turcotte, 1985; Gvirtzman et al., 2014; Csato et al., 2014; Harris et al., 2016). Perhaps more importantly, the modeled results suggest the selected diffusion coefficients are reasonable because resulting stratal geometries form over a realistic time span, and topset gradient of modeled deltaic clinoform ranges from 0.003-0.06°, close to both present-day and ancient examples (Patruno et al., 2015).

RESULTS

Model Set 1: accommodation-dominated sequences

To explore the possible range of accommodation-dominated sequences geometries, we present two end-members of accommodation-dominated cycles below (Figs. 5-8). Model 1.1 is characterized by high amplitude of eustatic sea-level change (80 m), and a relatively low sediment/water discharge ratio (sediment discharge=500 km^3/My; water discharge=500 m^3/s) (Fig. 5). Model 1.2 is forced by eustatic sea-level oscillations with an amplitude of 20 m, and a high sediment/water discharge ratio (sediment discharge=500 km^3/My; water discharge=100 m^3/s) (Fig. 5). For the convenience of discussion, the 2-million-year elapsed model time is divided into eight units (Units 1-8) evenly (Fig. 7). Each cycle is composed of four units.

The relatively high amplitude of eustatic sea-level change (80 m) and a relatively low sediment/water discharge ratio (sediment discharge=500 km^3/My; water discharge=500 m^3/s) in Model 1.1 force shoreline regression and transgression over a long distance (>150 km) (Fig. 8A). Fluvial erosion occurs throughout relative sea-level falls (Fig. 6A) and leads to significant bypass of coarse sediment and a basinward shift (Fig. 7A). The fluvial erosion occurs at the basin axis initially (0.5 My in Fig. 6A) then bifurcates into two channels (0.75 My in Fig. 6A). Significant fluvial erosion juxtaposes younger fluvial strata atop older marine strata, with an abrupt facies transition across a subaerial hiatus surface (Figs. 8A). The initial highstand strata (Units 1 and 5) within the fluvial valley are totally eroded (Figs. 7A). Detached marine strata formed during falling relative sea level (Units 2, 3, 6, and 7) lack topset deposits and show clear offlapping geometry, with a descending shoreline trajectory (Fig. 7A). Offlap includes both toplap and erosional truncation, which is mainly caused by the removal of previously deposited sediment (Christie-Blick, 1991; Plint and Nummedal, 2000). The shoreline backsteps and backfills the valleys during subsequent relative sea-level rise (Fig. 6A). The transgressive strata are mostly within the valley, underlain by younger highstand strata (Figs. 6A, and 7A).

Model 1.2 is forced by relatively low amplitude of eustatic sea-level change (20m) and a relatively high sediment/water discharge ratio (sediment discharge=500 km^3/My; water discharge=100 m^3/s) (Fig. 5). The shoreline in Model 1.2 shows much less migration distance, compared to that in Model 1.1 (Fig. 8B). Regression distance decreases from 45 km in the first cycle to 25 km in the second cycle because of widening topset (Fig. 8B). Subaerial erosion occurs only within the area <50 km from coeval shoreline (Figs. 6 and 8B). No subaerial hiatus is directly atop marine strata (Fig. 8B). Contrary to Model 1.1, during falling relative sea level (Units 2, 3, 6, and 7), topset strata are preserved and mostly detached from coeval foreset deposits with descending shoreline trajectory and offlapping stratal geometry (Fig. 7B). The transgression distance is only 10 km (Fig. 8B). The transgressive deposits sometimes onlap on the previous deposits (Fig. 7B). The stratigraphic geometry are similar along depositional strike (Fig. 7B).

Model Set 2: supply-dominated sequences

Supply-dominated cycles with variable amplitude of water discharge change force stratal geometries that share several elements with accommodation-dominated sequences. To explore supply-dominated sequence formation, we ran Model 2.1 with 500 m^3/s amplitude of water discharge change and Model 2.2 with 100 m^3/s amplitude of water discharge change (Figs. 5 and 8).

The shoreline in Model 2.1 is purely progradational (Fig. 8C). Its progradation rate increases with increasing water discharge because higher water discharge would bring higher diffusion of the sediment, enhancing the distal sedimentation. The shoreline trajectory is almost flat due to the constant eustatic sea level and minor subsidence. Onset of erosion is synchronous with increasing water discharge (Fig. 6). The topset strata at the basin axis are destroyed with increasing water discharge, creating an offlapping deltaic clinoform geometry (Figs. 7Ca and 7Cb). Parts of the topset strata away from the river mouth are preserved (e.g., Units 2 and 6 in Figs 7Cc and 7Cd). Shoreline prograde slower and sometimes aggradate with decreasing water discharge (Fig. 8C). Topset deposition during decreasing water discharge is aggradational and sometimes onlaps to the previous strata (Fig. 7C). When water discharge is at the lowest (within the range), parts of the shelf are sediment starved (Fig. 8C).

The stratal geometry in Model 2.2 is very similar to that in Model 2.1. The shoreline is purely progradational. It progrades 70 km from the initial shoreline, slightly less than the shoreline progradation in Model 2.1. Topset deposition at the basin axis is restricted to periods of increasing water discharge (Figs. 7Da and 7Db). Deltaic clinoforms show an offlapping geometry (e.g., Unit 3). Those further away from the river mouth are completely preserved (Figs. 7Dc and 7Dd). Similar to Model 2.1, erosion occurs as water discharge increases. However, the chronostratigraphic diagram shows that both spatial (along depositional-dip) and temporal (vertical) extent of the hiatus is far less than that in Model 2.1 (Fig. 8D)**.** It is mostly restricted in the proximal area. With decreasing water discharge, tospet strata completely drape previous deposits (Fig. 7D).

DISCUSSION

How do sediment supply ratio cycles generate sequences?

Sequence definitions (Table 1) have emphasized (1) presence of an unconformity, which represents significant amount of missing time (Sloss et al., 1949; Sloss, 1963; Mitchum, 1977; Posamentier and Vail, 1988; Catuneanu et al., 2017) and (2) a full cycle of sediment supply or accommodation change (Posamentier and Vail, 1988; Catuneanu, 2006; Catuneanu et al., 2009). In the present study, both model sets include full cycles of unsteady forcing by either sediment supply or relative sea-level oscillations. To quantify missing time on the unconformity surfaces, we calculate stratigraphic completeness from chronostratigraphic diagrams using the proportion of the 2-My elapsed model time that is non-depositional or erosional in three dimensions. Higher hiatus proportion (lower stratigraphic completeness) indicates (1) a longer hiatus between overlying and underlying strata, and possibly (2) a higher volume of erosion and sediment bypass (Wheeler, 1958). To explore how development of sequence-bounding unconformities varies with different allogenic controls, we run 400 accommodation-dominated models where water discharge varies from 50-1000 m^3/s and the amplitude of eustatic sea-level change varies from 5-100 m, and 20 supplied-dominated models where water discharge ranges from 50-1000 m^3/s. To ensure other model parameters such as time step and grid size are not the major controls on the hiatus proportion, we compare the hiatus proportion of different model configurations for Model 1.1. When the grid size is 10, 5, 2.5, and 1 km, the hiatus proportion is 20.4%, 21.1%, 21.7%, and 21.9% respectively.

When the time step is 0.05, 0.01, and 0.005 My, the hiatus proportion is 20.4%, 22.7%, and 23.1% respectively. These results confirm that these model grid and time step parameters do not influence the hiatus proportion significantly. However, it should be noted that other boundary conditions such as basin geometry and shelf setting, which may also influence the hiatus proportion, are not tested in the current study.

The hiatus proportion from each model is calculated and plotted in Fig. 9. In general, the three-dimensional hiatus proportion in accommodation-dominated cycles is positively correlated to amplitude of eustatic sea-level change and magnitude of water discharge (Fig. 9A). The hiatus proportion reaches 24% when amplitude of relative sea-level change and water discharge are highest. However, with low water discharge and low amplitude of eustatic sea-level change, the hiatus proportion is as low as 2%. In the supply-dominated cycles, the hiatus proportion is also positively correlated to water discharge ranging from 6%-23% (Fig. 9B). These model results suggest that both accommodation-dominated and supply-dominated sequences are likely to be bounded by significant unconformities.

Relative sea-level fall forces the shoreline basinward and downward, which modifies sediment transport distribution, triggering subaerial erosion that forms an unconformity (Fig. 10). Similarly, variation in sediment/water discharge ratio also triggers topset erosion. Higher water discharge decreases topset gradient, truncating underlying strata, forming an unconformity surface. Hiatus proportion metrics demonstrate that unconformities of both accommodation-dominated and supply-dominated cycles represent significant missing time. Therefore, accommodation-dominated Model Set 1 and supply-dominated Model Set 2, both with full but different cycles of allogenic change, have unconformities that show, on a large scale at least, a key characteristic of traditionally-defined sequences. Note, however, that even in this simple numerical forward model depiction of strata in three-dimensions rather than the more typical two-dimensional depictions used in many sequence stratigraphic conceptual models, suggesting that many of those conceptual models are perhaps over-simplistic representations of a more complex reality (see discussion in Burgess, 2016).

Implications of comparison between accommodation-dominated and supply-dominated sequences

The most obvious and most significant difference between accommodation-dominated sequences and supply-dominated sequences is the shoreline trajectory (Table 3) (Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009). A descending shoreline trajectory indicates falling relative sea level while an ascending trajectory presents rising relative sea level (Fig. 7). However, it should be noted that the low-angle shoreline trajectory, which is common in non-glacier environments, is difficult to measure with confidence especially if differential compaction occurs (e.g., Prince and Burgess, 2013). The presence of maximum flooding surface and transgressive marine deposits overlying the terrestrial deposits are also good indicators of relative sea-level rise (Fig. 7).

However, some other sedimentological and stratigraphic characteristics, long considered as indicators of relative sea-level fall, are not helpful to distinguish accommodation-dominated sequences and supply-dominated sequences (Table 3). Firstly, some characteristics such as absence of topset strata and deltaic clinoform offlap can occur in both types of sequences (Table 3). More importantly, they are not always present in the accommodation-dominated sequences. For example, topset aggradation within the period of falling sea level is also observed in Model

1.2. Similar observations have been made in various mathematical modelling and flume experiments (Swenson and Muto, 2007; Petter and Muto, 2008; Prince and Burgess, 2013) and also from study of Holocene strata (Nijhuis et al., 2015; Dietrich et al., 2017). The time and length scale of the topset aggradation during falling relative sea level is affected by rate of relative sea-level change, sediment discharge, water discharge, and shelf gradient (Swenson and Muto, 2007). Topset geometry may also vary along depositional-strike, decided by its distance to the river mouth (Fig. 7). Secondly, some characteristics such as shallower clinoforms from proximal to distal zones, foreshortened stratigraphic succession, separation between successive shoreface deposits, long-distance regression, and grainsize increase from proximal to distal zones depends on the conditions of sediment supply, relative sea-level change, shelf settings, and sediment transport rates. They are not always present in the accommodation-dominated sequences (Table 3). For example, decreasing proximal-to-distal deltaic clinoform height and decreasing foreset thickness, which were considered as important stratal architecture of forced regression (Posamentier and Morris, 2000), are determined not only by amplitude of relative sea-level fall but also by the bathymetric profile onto which the clinoforms prograde. Bathymetry with a 0.06° gradient across 50-km shelf gives a water depth increase of 52 m. If relative sea-level fall is less than 52 m, deltaic clinoform foreset height will not decrease but will be maintained and will increase as it progrades to the shelf edge. Similarly, detached shoreface strata (Fig. 6Ad), present in Model 1.1, can only be used to detect high amplitude relative sea-level change. Shoreline migration distance is also decided by several factors, including amplitude of relative sea-level change, sediment discharge, water discharge, and sediment transport rates. The rapid relative sea-level rise in Model 1.1 re-establishes deltaic deposition (Unit 5) at the former highstand shoreline, separated from previous shelf-edge deltas by backstepped shoreface deposits (Unit 3). However, long distance shoreline regression would not occur in this case without sufficient sediment supply and sediment transport rates. Low amplitude of relative sea-level change and high sediment/water discharge ratio in Model 1.2 lead to low magnitudes of erosion and low volumes of sediment bypass. Consequently Model 1.2 lacks the basinward grain size increase and the separation between successive terrestrial deposits seen in Model 1.1.

In summary, shoreline trajectories as well as the presence of transgressive deposits and associated maximum flooding surfaces are likely to be the best properties to differentiate the accommodation-dominated and supply-dominated sequences (Table 3). Other sedimentological and stratigraphic characteristics are likely to be non-unique, shared by both types of sequences or decided by multiple parameters.

Calculation or estimation of sediment/water discharge ratio in both accommodation-dominated and supply-dominated sequences is probably necessary in future sequence stratigraphic studies; the magnitude of both sediment discharge and water discharge from supplied rivers is a key control on strata, and just as important as the amplitude of relative sea-level oscillations. This significance of sediment supply variations is increasingly recognized (Chen et al., 2018), and various techniques now exist to estimate both sediment discharge (e.g., Allen et al., 2013; Holbrook and Wanas, 2014; Zhang et al., 2018) and water discharge (e.g., Eide et al, 2017) for the ancient systems. Another implication of this work is that maximum flooding surfaces are likely more useful for stratigraphic correlation compared to valley base surfaces (i.e., sequence boundary) (Galloway et al., 1989). As demonstrated in Model Set 2, the variations in sediment/water discharge ratio, which could be climatically controlled and occur at high-frequency time scale (Holbrook et al., 2006; Blum and Womack, 2009), is able to create an erosional surface at the base of fluvial strata and complicate the correlation. The interaction between the sediment/water discharge variation, amplitude and frequency of relative sea-level change, sediment transport rate, and initial bathymetry make it difficult to define the exact controls on sequence development in most cases. Therefore, we suggest sequence definition should contain only the basic observational elements, emphasizing the traditional concept of unconformity bounded packages, and not including interpreted forcing mechanisms.

CONCLUSIONS

1. Numerical stratigraphic forward modelling experiments demonstrate both differences and similarities in the characteristic stratal geometries forced by variations in accommodation, versus strata forced by sediment/water discharge ratio change. Both types of forcing can create sequences, packages of genetically-related strata bounded by unconformities, and their correlative conformable strata. With constant sediment discharge, both a relative sea-level fall and a water discharge increase can drive fluvial incision of topset strata, and so create subaerial unconformities. Unconformity duration in the accommodation-dominated sequences ranges from 2% to 24% of elapsed model time. Relatively slow relative sea-level fall with high sediment/water discharge ratio tends to create less extensive subaerial erosion (<5% of elapsed model time). In supply-dominated strata, 6%-23% of elapsed model time is recorded on erosion surfaces across the range of water discharge modeled.
2. If sediment/water discharge ratio, amplitude and frequency of the relative sea-level change, sediment transport rate, and initial bathymetry can all vary, it remains challenging to differentiate accommodation-dominated sequences and supply-dominated sequences. Traditionally defined diagnostic characteristics of forced regressive system tract (Table 3) do not work well to distinguish the accommodation-dominated sequences because most of

these characteristics are controlled by multiple parameters (e.g., long regression distance) and some of them occur in both accommodation-dominated and supply-dominated sequences (e.g., absence of coastal plain topset; stratal offlap). Among these characteristics, the shoreline trajectory is the most reliable way to recognize the accommodation-dominated and supply-dominated sequences, even though it may be difficult to accurately determine in outcrop or subsurface strata, for example due to differential compaction effects (Price and Burgess, 2013; Kominz and Pekar, 2001). Therefore, only a combination of factors should be considered diagnostic of an accommodation-dominated sequence, for example, a descending and then ascending shoreline trajectory, combined with transgressive deposits and associated maximum flooding surface, is a more convincing indicator of accommodation-dominated sequences. The observation of stratal offlap and absence of coastal plain topset without any strong evidence on the relative sea-level change is a reasonable indicator of a supply-dominated sequence.

3. These results emphasize the importance of sediment discharge and water discharge on sequence development. Magnitude of sediment discharge and water discharge in ancient depositional systems can often be estimated from catchment or trunk channel parameters (e.g., Holbrook and Wanas, 2014; Eide et al., 2017; Zhang et al., 2018). However, future work could improve both precision and accuracy of these estimates and improve understanding of how they vary at shorter time scales (<1 My).
4. Future work should also focus on understanding the probability of occurrence of accommodation-dominated and supply-dominated sequences (e.g., Heller et al., 1993; Burgess and Steel, 2017), particularly under different tectonic, climatic, and eustatic conditions, and taking into account possible interactions between autogenic processes and

allogenic controls (Muto et al., 2016; Hajek and Straub, 2017). Perhaps many existing interpretations of accommodation-dominated sequences need to be revisited, assessed, and possibly revised.

ACKNOWLEDGEMENTS

We are grateful for the academic licenses of DionisosFlow, provided by Beicip-Franlab. JZ wants to thank Poe Chen (Bureau of Economic Geology) for IT support and the State of Texas Advanced Oil and Gas Resource Recovery (STARR) program for funding. JZ also wants to thank Ronald K. DeFord Field Scholarship to support his visit to University of Liverpool. RJS acknowledges support from the RioMAR consortium (http://www.jsg.utexas.edu/riomar). We are thankful for the thoughtful and constructive comments from Reviewers Christian Haug Eide and Tetsuji Muto and Editor Atle Rotevatn.

REFERENCES

BLUM, M. D. & PRICE, D. M. (1998) Quaternary alluvial plain construction in response to glacio eustatic and climatic controls Texas Gulf coastal plain. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative role of eustasy, climate and tectonism in continental rocks: SEPM Special Publication, 59, pp. 31-48.

BLUM, M. D. & Hattier-Womack, J. (2009) Climate change, sea-level change, and fluvial sediment supply to deepwater depositional systems. *External Controls on Deep Water Depositional Systems: SEPM*, *Special Publication*, *92*, 15-39.

Burgess, P.M., (2016) The future of the sequence stratigraphy paradigm: Dealing with a variable third dimension, Geology, 44, 335–336.

BURGESS, P. M. & PRINCE, G. D. (2015) Non-unique stratal geometries: implications for sequence stratigraphic interpretations. Basin Research, 1 6, 27(3), pp. 351-365.

BURGESS, P. M. & STEEL, R. J. (2017) How To Interpret, Understand, and Predict Stratal Geometries Using Stratal-Control Spaces and Stratal-Control-Space Trajectories. Journal of Sedimentary Research, 4 4, 87(4), pp. 325-337.

CSATO, I., CATUNEANU, O. & GRANJEON, D. (2014). Millennial-scale sequence stratigraphy: Numerical simulation with Dionisos. Journal of Sedimentary Research, 84, 394-406.

CATUNEANU, O., WILLIS, A. J., & MIALL, A. D. (1998). Temporal significance of sequence boundaries. *Sedimentary Geology*, *121*(3-4), 157-178.

CATUNEANU, O. (2006) Principles of sequence stratigraphy. Elsevier, Amsterdam. 375 pp.

CATUNEANU, O. (2017) Sequence Stratigraphy: Guidelines for a Standard Methodology. In Stratigraphy & Timescales (Vol. 2, pp. 1-57). Academic Press.

CATUNEANU, O. ET AL. (2009) Towards the standardization of sequence stratigraphy. Earth-Science Reviews, 1, 92(1-2), pp. 1-33.

CHRISTIE-BLICK, N. (1991). Onlap, offlap, and the origin of unconformity-bounded depositional sequences. *Marine Geology*, *97*(1-2), 35-56.

CHEN, S., STEEL, R., OLARIU, C. AND ZHANG, J. (2018). Clinoform Drivers of the Late Miocene to Pliocene Paleo-Orinoco Delta. In *EGU General Assembly Conference Abstracts*, Vol. 20, p. 7910.

DIETRICH, P., GHIENNE, J.F., SCHUSTER, M., LAJEUNESSE, P., NUTZ, A., DESCHAMPS, R., ROQUIN, C. & DURINGER, P. (2017) From outwash to coastal systems in the Portneuf–Forestville deltaic complex (Québec North Shore): Anatomy of a forced regressive deglacial sequence. *Sedimentology*, *64*(4), pp.1044-1078.

EIDE, C. H., MÜLLER, R., & HELLAND-HANSEN, W. (2018) Using climate to relate water discharge and area in modern and ancient catchments. *Sedimentology*, *65*(4), 1378-1389.

FIELDING, C. R. (2015) Anatomy of falling-stage deltas in the Turonian Ferron Sandstone of the western Henry Mountains Syncline, Utah: Growth faults, slope failures and mass transport complexes. Sedimentology, 1 1, 62(1), pp. 1-26.

GALLOWAY, W. E. (1989) Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. *AAPG bulletin*, *73*(2), 125-142.

GRANJEON, D. (1996) Modélisation stratigraphique déterministe: Conception et applications d'un modèle diffusif 3D multilithologique. (Doctoral dissertation, Université Rennes 1).

GRANJEON, D. (2014) 3D forward modelling of the impact of sediment transport and base level cycles on continental margins and incised valleys. In: From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin. Chichester, UK: John Wiley & Sons, Ltd, pp. 453-472.

GRANJEON, D. & JOSEPH, P. (1999) Concepts and applications of a 3-D multiple lithology, diffusive model in stratigraphic modelling. SEPM Special Publication No. 62, pp. 197-210.

GVIRTZMAN, Z., CSATO, I. & GRANJEON, D. (2014) Constraining sediment transport to deep marine basins through submarine channels: The Levant margin in the Late Cenozoic. Marine Geology, 347, 12-26.

HAJEK, E. A., & STRAUB, K. M. (2017) Autogenic sedimentation in clastic stratigraphy. *Annual Review of Earth and Planetary Sciences*, *45*, 681-709.

HAMPSON, G. J. (2016). Towards a sequence stratigraphic solution set for autogenic processes and allogenic controls: Upper Cretaceous strata, Book Cliffs, Utah, USA. *Journal of the Geological Society*, *173*(5), 817-836.

HARRIS, A., COVAULT, J., MADOF, A., SUN, T., SYLVESTER, Z. & GRANJEON, D. (2016). Three-dimensional numerical modelling of eustatic control on continental-margin sand distribution. Journal of Sedimentary Research, 86, 1434-1443.

HELLAND-HANSEN, W. & HAMPSON, G. (2009). Trajectory analysis: concepts and applications. Basin Research, 21(5), 454-483.

HELLER, P. L., BURNS, B. A., & MARZO, M. (1993). Stratigraphic solution sets for determining the roles of sediment supply, subsidence, and sea level on transgressions and regressions. *Geology*, *21*(8), 747-750.

HOLBROOK, J., & BHATTACHARYA, J. (2012). Reappraisal of the sequence boundary in time and space: Case and considerations for an SU (subaerial unconformity) that is not a sediment bypass surface, a time barrier, or an unconformity. Earth-Science Reviews, 113(3-4), 271-302.

HOLBROOK, J., SCOTT, R. W. & OBOH-IKUENOBE, F. E. (2006) Base-Level Buffers and Buttresses: A Model for Upstream Versus Downstream Control on Fluvial Geometry and Architecture Within Sequences. Journal of Sedimentary Research, 1 1, 76(1), pp. 162-174.

HOLBROOK, J., & WANAS, H. (2014). A fulcrum approach to assessing source-to-sink mass balance using channel paleohydrologic paramaters derivable from common fluvial data sets with an example from the Cretaceous of Egypt. *Journal of Sedimentary Research*, *84*(5), 349-372.

KENYON, P., & TURCOTTE, D. (1985). Morphology of a delta prograding by bulk sediment transport. Geological Society of America Bulletin, 96(11), 1457.

KOMINZ, M., & PEKAR, S. (2001) Oligocene eustasy from two-dimensional sequence stratigraphic backstripping. Geological Society of America Bulletin, 113(3), 291-304.

LI, Y. & BHATTACHARYA, J. P. (2013) Facies-Architecture Study of A Stepped, Forced Regressvie Compound Incised Valley In the Ferron Notom Delta, Southern Central Utah, U.S.A. Journal of Sedimentary Research, Volume 83, pp. 206-225.

MITCHUM, R. M. (1977) Seismic Stratigraphy and Global Changes of Sea Level: Part 11. Glossary of Terms used in Seismic Stratigraphy: Section 2. Application of Seismic Reflection Configuration to Stratigraphic Interpretation. Volume 165, pp. 205-212.

MILLER, K. G. ET AL. (2005) The Phanerozoic record of global sea-level change.. Science (New York, N.Y.), 310(5752), pp. 1293-1298.

MILLIMAN, J. D., & FARNSWORTH, K. L. (2013). *River discharge to the coastal ocean: a global synthesis*. Cambridge University Press.

MUTO, T., STEEL, R. J., & BURGESS, P. M. (2016) Contributions to sequence stratigraphy from analogue and numerical experiments. *Journal of the Geological Society*, *173*(5), 837-844.

MUTO, T. & STEEL, R. J. (2004) Autogenic response of fluvial deltas to steady sea-level fall: implications from flume-tank experiments. *Geology*, *32*(5), 401-404.

MUTO, T., & STEEL, R. J. (2000) The accommodation concept in sequence stratigraphy: some dimensional problems and possible redefinition. *Sedimentary Geology*, *130*(1-2), 1-10.

NIJHUIS, A. G., EDMONDS, R.L., CALDWELL, J.A., SLINGERLAND, R.L., BEST, J.L., PARSONS, D.R. & ROBINSON, R.A.J. (2015) Fluvio-deltaic avulsions during relative sea-level fall. Geology, 43(8), 719-722.

PATRUNO, S., HAMPSON, G. J. & JACKSON, C. (2015) Quantitative characterisation of deltaic and subaqueous clinoforms. Earth-Science Reviews, Volume 142, pp. 79-119.

PETTER, A. L., & MUTO, T. (2008) Sustained alluvial aggradation and autogenic detachment of the alluvial river from the shoreline in response to steady fall of relative sea level. *Journal of Sedimentary Research*, *78*(2), 98-111.

PLINT, A. G., & NUMMEDAL, D. (2000). The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. *Geological Society, London, Special Publications*, *172*(1), 1-17.

POSAMENTIER, H. W., JERVEY, M. T. & VAIL, P. R. (1988) Eustatic Controls on Clastic Deposition I—conceptual Framework.

POSAMENTIER, H. W. & MORRIS, W. R. (2000) Aspects of the stratal architecture of forced regressive deposits. Geological Society, London, Special Publications, 1 1, 172(1), pp. 19-46.

POSAMENTIER, H. W. & VAIL, P. R. (1988) Eustatic Controls on Clastic Deposition II—sequence and Systems Tract Models.

POWELL, E. J., KIM, W., & MUTO, T. (2012). Varying discharge controls on timescales of autogenic storage and release processes in fluvio‐deltaic environments: Tank experiments. *Journal of Geophysical Research: Earth Surface*, *117*(F2).

PRINCE, G. D. & BURGESS, P. M. (2013) Numerical Modelling of Falling-Stage Topset Aggradation: Implications for Distinguishing Between Forced and Unforced Regressions In the Geological Record. Journal of Sedimentary Research, 22 8, 83(9), pp. 767-781.

SIMPSON, G. & CASTELLTORT, S. (2012) Model shows that rivers transmit high-frequency climate cycles to the sedimentary record. Geology, 40(12), pp. 1131-1134.

SLOSS, L. L., KRUMBEIN, W. C. & DAPPLES, E. C. (1949) INTEGRATED FACIES ANALYSIS 1. In Sedimentary facies in geologic history: conference at meeting of the Geological Society of America held in New York, New York, November 11, 1948 (Vol. 39, p. 91). Geological Society of America.

SLOSS, L.L. (1963) Sequences in the cratonic interior of North America. *Geological Society of America Bulletin*, *74*(2), pp.93-114.

STRONG, N. & PAOLA, C. (2008) Valleys that never were: Time surfaces versus stratigraphic surfaces. Journal of Sedimentary Research, Volume 78, pp. 579-593.

SUN, T., PAOLA, C., PARKER, G. & MEAKIN, P. (2002) Fluvial fan deltas: Linking channel processes with large-scale morphodynamics. Water Resources Research, 8, 38(8), pp. 26-1-26-10.

SWENSON, J. B. & MUTO, T. (2007) Response of coastal plain rivers to falling relative sea-level: allogenic controls on the aggradational phase. Sedimentology, 1 2, 54(1), pp. 207-221.

VAN DEN BERG SAPAROEA, V. & POSTMA, G. (2008) Control of climate change on the yield of river systems. SEPM Special Publication, 90.

WHEELER, H.E. (1958) Time-stratigraphy. *AAPG Bulletin*, *42*(5), pp.1047-1063.

ZHANG, J., STEEL, R., & OLARIU, C. (2017). What conditions are required for deltas to reach the shelf edge during rising sea level?. *Geology*, *45*(12), 1107-1110.

ZHANG, J., COVAULT, J., PYRCZ, M., SHARMAN, G. R., CARVAJAL, C., & MILLIKEN, K. (2018) Quantifying sediment supply to continental margins: Application to the Paleogene Wilcox Group, Gulf of Mexico. *AAPG Bulletin*, (20,180,220).

CAPTION

Figure 1. (A) and (B) Depositional-dip cross-section and chronostratigraphic diagram illustrating the early view on space-time relationship of the subaerial unconformity (after Catuneanu et al., 1998)

Figure 2. Initial bathymetry in map view (top) and cross-section (below). Map view shows the position of the sediment supply entry point at the proximal side of the grid and the location of Fig. 7. Spatial distribution of subsidence is indicated on the cross section. V.E. =Vertical exaggeration.

Figure 3. Inputs parameters of two model sets. Accommodation-dominated model sets with variable eustasy and constant sediment discharge and water discharge. Supply-dominated model sets have constant eustasy, constant sediment discharge, and variable water discharge. Q_s=Sediment discharge; Q_w=Water discharge.

Figure 4. The range of inputs (shelf width, shelf gradient, sediment discharge, water discharge, subsidence, and eustatic sea-level change) shown in the red lines and blocks and their comparison with rates from natural systems. Modern shelf width and related shelf gradient database are summarized from Cornel and Steel (2009) and Somme et al., (2009). Sediment discharge and water discharge of modern rivers are summarized from Milliman and Syvitski (1992). The subsidence and eustatic sea-level change data are modified after Burgess and Steel (2017).

Figure 5. Inputs parameters of Models 1.1, 1.2, 2.1, and 2.2. Q_s: sediment discharge; Q_w: water discharge.

Figure 6. Sedimentation rates from accommodation-dominated models 1.1 and 1.2 as well as supply-dominated models 2.1 and 2.2 at 0.25, 0.5, 0.75, and 1 My elapsed model time. Yellow, red, and white represent depositional, erosional, and non-depositional/bypassed, respectively.

Figure 7. 2-D stratigraphic cross-section of Models 1.1 (A), 1.2 (B), 2.1 (C), and 2.2 (D) at basin axis (a and b) and basin margin (c and d). The cross-sections are colour coded by time (a and c) or facies (b and d). The 2-million-year simulated interval is divided into 8 units from 1-8. Sl: shoreline.

Figure 8. Chronostratigraphic diagrams with facies attribute of Models 1.1, 1.2, 2.1, and 2.2. Pie charts show the proportion of different facies in 3-Dimension.

Figure 9. Hiatus proportion in accommodation-dominated sequences (A) and supply-dominated sequences (B). The colour bar indicates the value of hiatus proportion. The hiatus proportion of Models 1.1, 1.2, 2.1 and 2.2 are present in black blocks. The water discharge varies from 50-1000 m^3/s and the

amplitude of eustatic sea-level change varies from 5-100 m in accommodation-dominated model set. The water discharge ranges from 50-1000 m^3/s in supply-dominated model set. M: Model; n: Model runs.

Figure 10. Sequence development of accommodation-dominated and supply-dominated cycles. Note that both relative sea-level change and variation in sediment/water discharge ratio are able to create sequence-bounding unconformities. RSL: relative sea level.

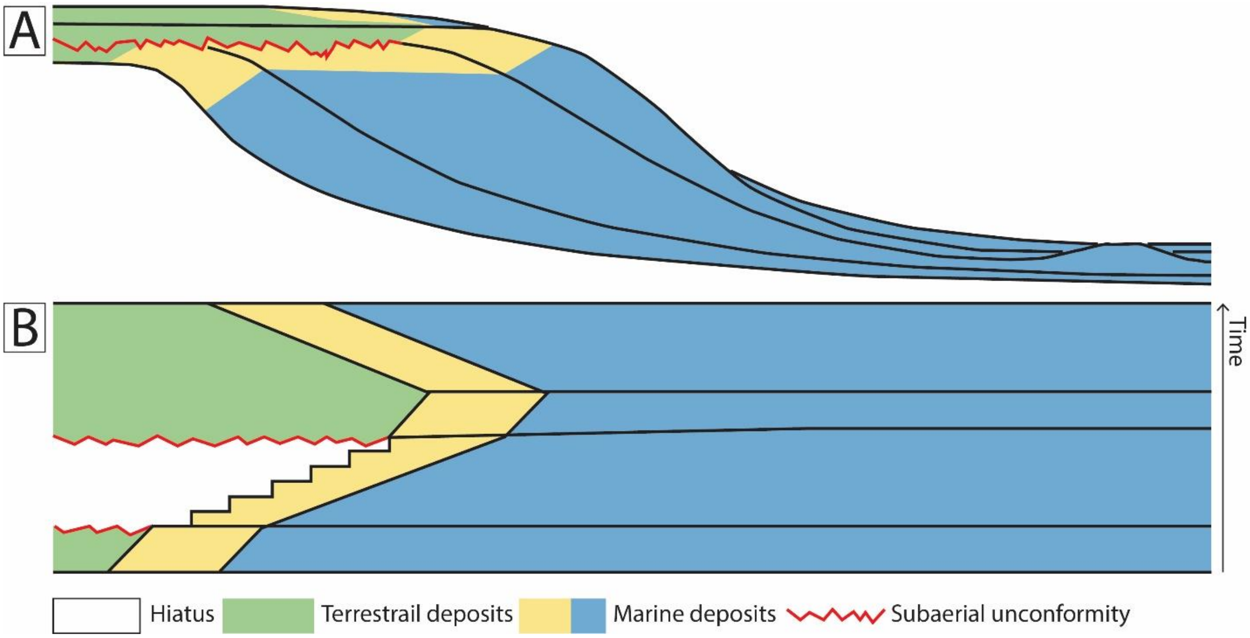

Figure 1. (A) and (B) Depositional-dip cross-section and chronostratigraphic diagram illustrating the early view on space-time relationship of the subaerial unconformity (after Catuneanu et al., 1998)

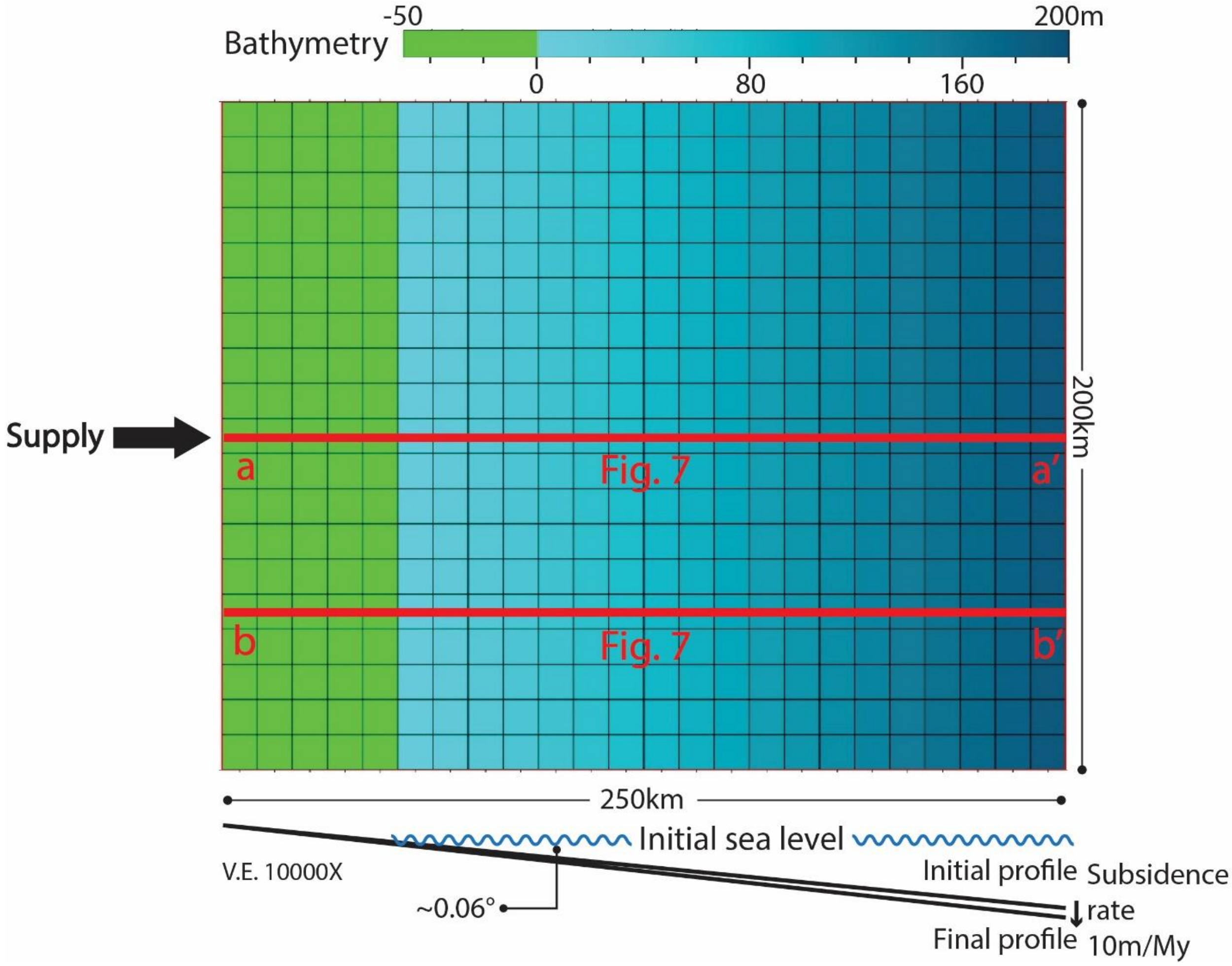

Figure 2. Initial bathymetry in map view (top) and cross-section (below). Map view shows the position of the sediment supply entry point at the proximal side of the grid and the location of Fig. 7. Spatial distribution of subsidence is indicated on the cross section. V.E.=Vertical exaggeration.

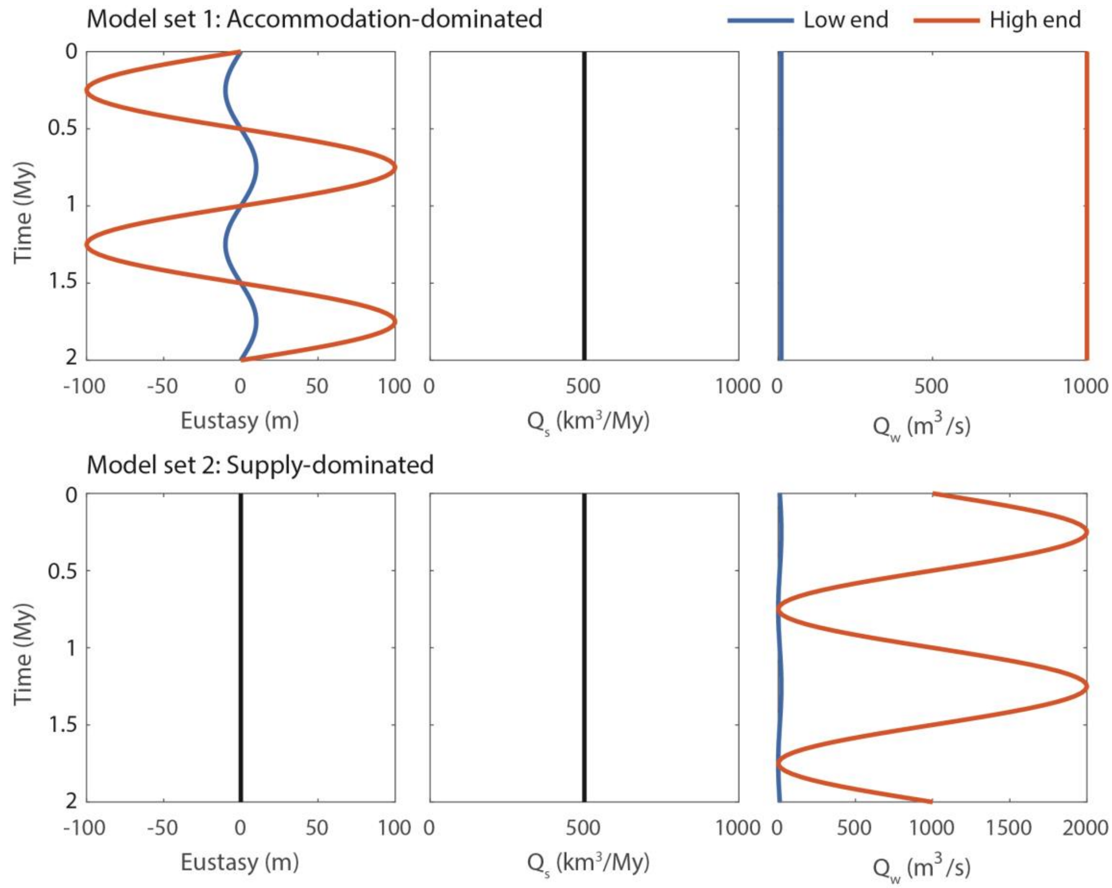

Figure 3. Inputs parameters of two model sets. Accommodation-dominated model sets with variable eustasy and constant sediment discharge and water discharge. Supply-dominated model sets have constant eustasy, constant sediment discharge, and variable water discharge. Q_s=Sediment discharge; Q_w=Water discharge.

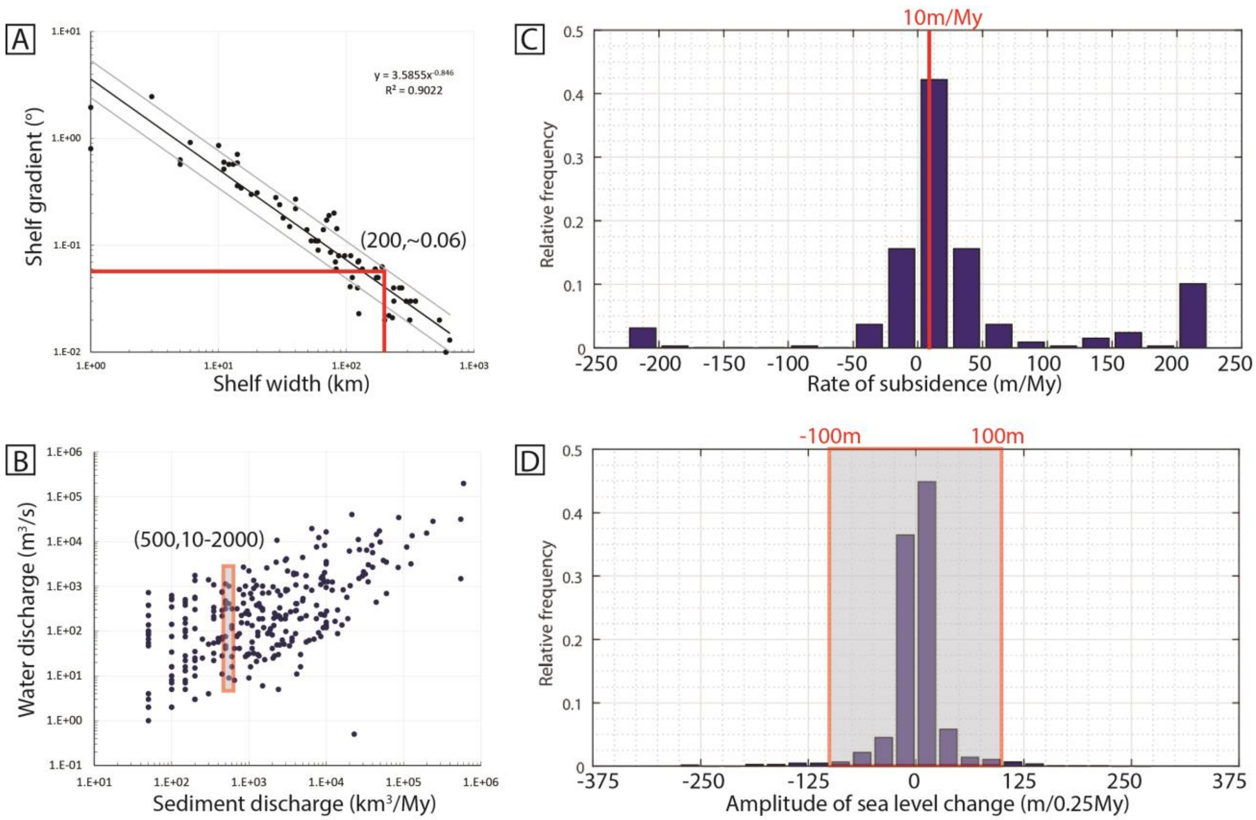

Figure 4. The range of inputs (shelf width, shelf gradient, sediment discharge, water discharge, subsidence, and eustatic sea-level change) shown in the red lines and blocks and their comparison with rates from natural systems. Modern shelf width and related shelf gradient database are summarized from Cornel and Steel (2009) and Somme et al., (2009). Sediment discharge and water discharge of modern rivers are summarized from Milliman and Syvitski (1992). The subsidence and eustatic sea-level change data are modified after Burgess and Steel (2017).

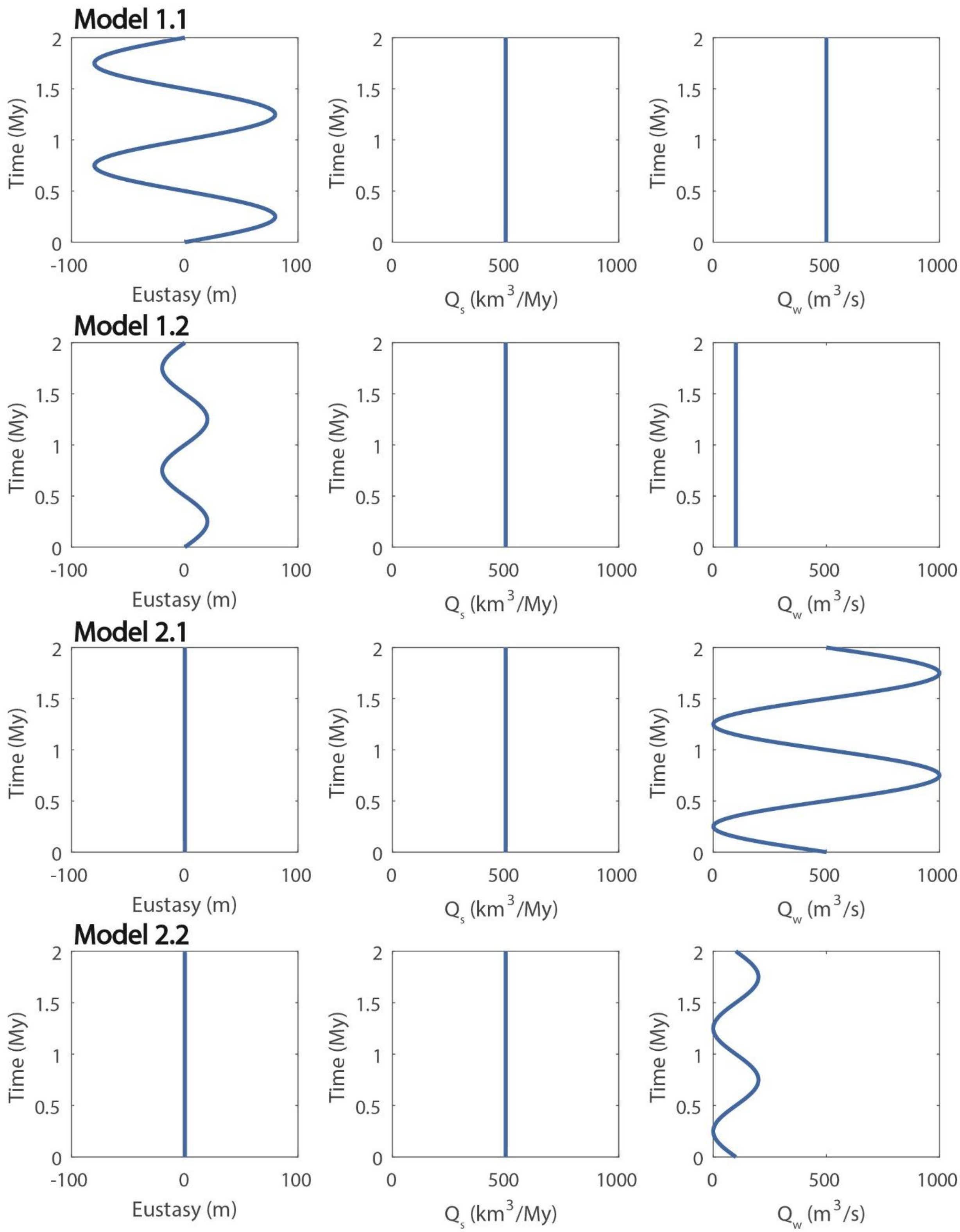

Figure 5. Inputs parameters of Models 1.1, 1.2, 2.1, and 2.2. Q_s: sediment discharge; Q_w: water discharge.

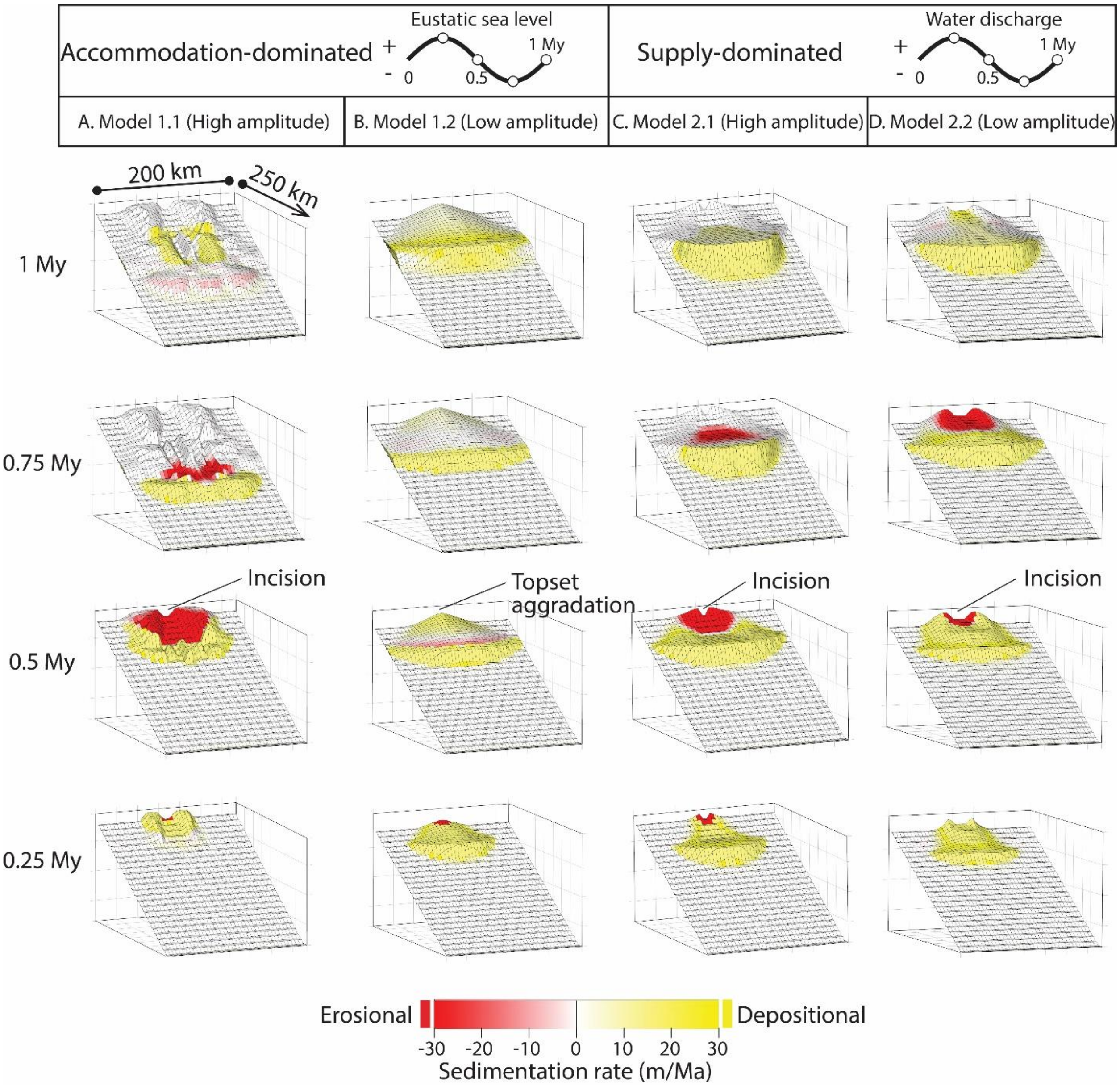

Figure 6. Sedimentation rates from accommodation-dominated models 1.1 and 1.2 as well as supply-dominated models 2.1 and 2.2 at 0.25, 0.5, 0.75, and 1 My elapsed model time. Yellow, red, and white represent depositional, erosional, and non-depositional/bypassed, respectively.

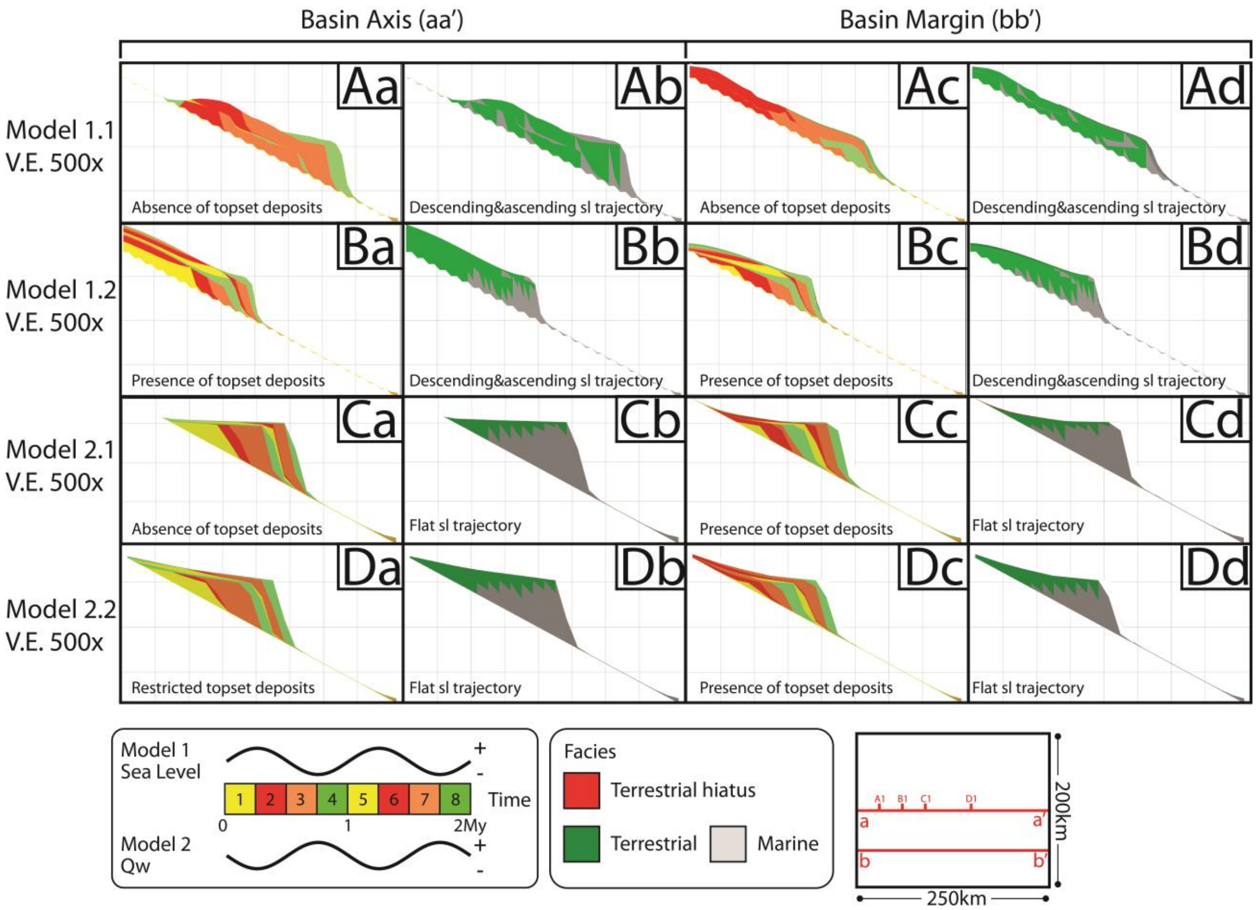

Figure 7. 2-D stratigraphic cross-section of Models 1.1 (A), 1.2 (B), 2.1 (C), and 2.2 (D) at basin axis (a and b) and basin margin (c and d). The cross-sections are colour coded by time (a and c) or facies (b and d). The 2-million-year simulated interval is divided into 8 units from 1-8. Sl: shoreline.

Figure 8. Chronostratigraphic diagrams with facies attribute of Models 1.1, 1.2, 2.1, and 2.2. Pie charts show the proportion of different facies in 3-Dimension.

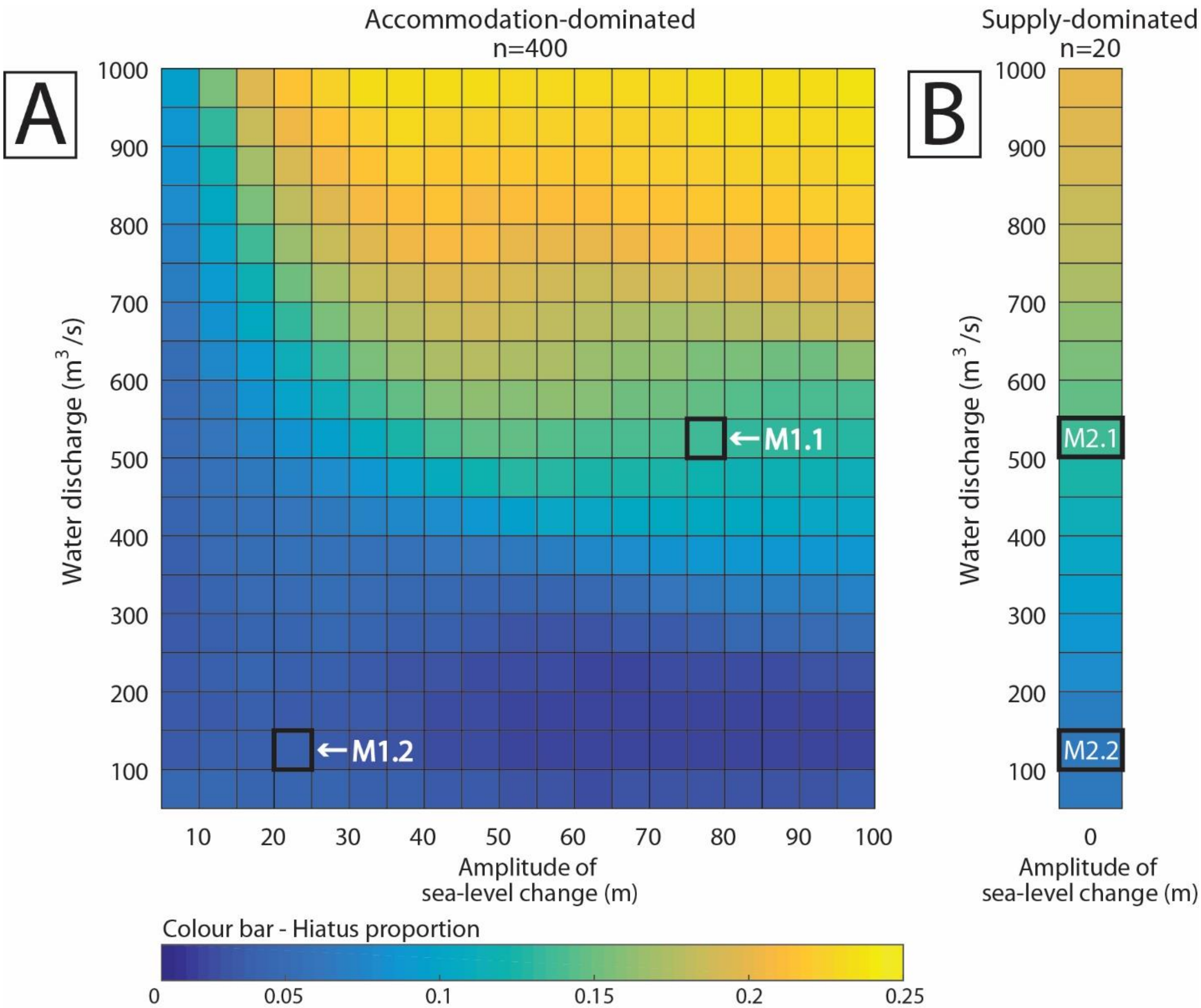

Figure 9. Hiatus proportion in accommodation-dominated sequences (A) and supply-dominated sequences (B). The colour bar indicates the value of hiatus proportion. The hiatus proportion of Models 1.1, 1.2, 2.1 and 2.2 are present in black blocks. The water discharge varies from 50-1000 m^3/s and the amplitude of eustatic sea-level change varies from 5-100 m in accommodation-dominated model set. The water discharge ranges from 50-1000 m^3/s in supply-dominated model set. M: Model; n: Model runs.

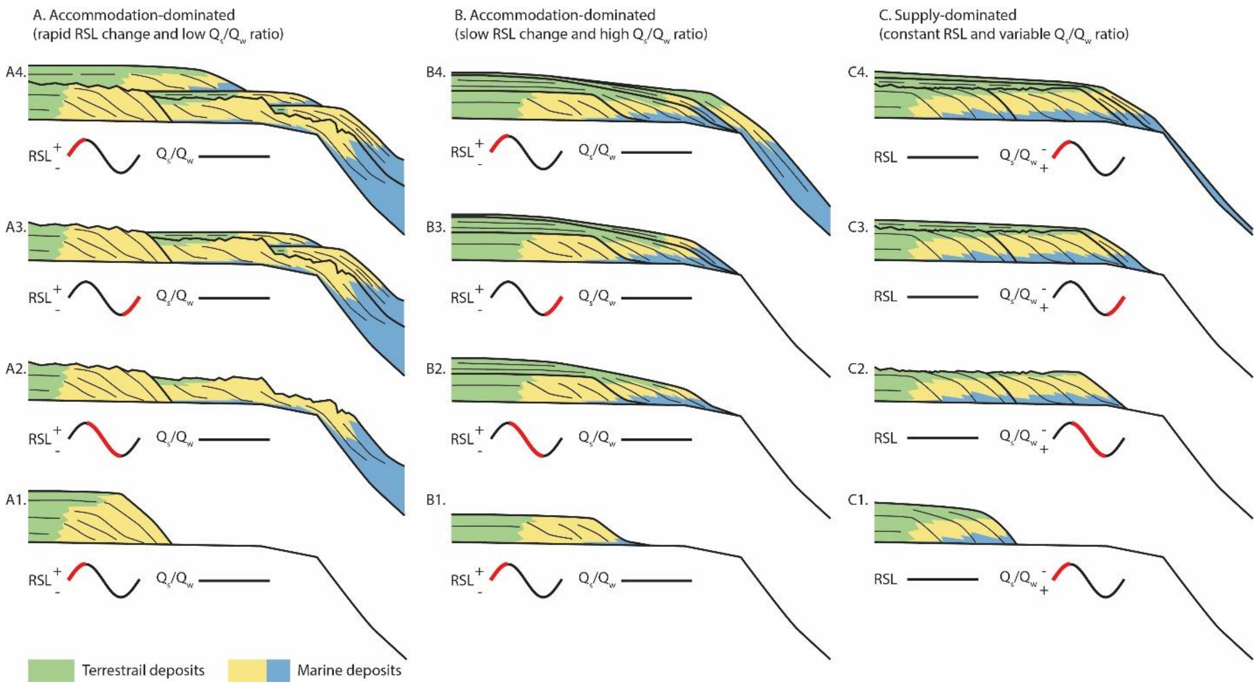

Figure 10. Sequence development of accommodation-dominated and supply-dominated cycles. Note that both relative sea-level change and variation in Q_s/Q_w ratio are able to create sequence-bounding unconformities. RSL: relative sea level.

Sloss et al, 1949	The strata which are included between objective, recognizable horizons, and are without specific time significance since their limits do not coincide with time lines and may include rocks of different ages in various area
Sloss, 1963	Rock-stratigraphic units of higher rank than group, megagroup, or supergroup, traceable over major areas of a continent and bounded by unconformities of interregional scope
Mitchum, 1977	A relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities
Posamentier and Vail, 1988	Composed of genetically related sediments bounded by unconformities or their correlative conformities and are related to cycles of eustatic change
Catuneanu, 2006	The ‘sequence’ is the fundamental stratal unit of sequence stratigraphy, and it corresponds to the depositional product of a full cycle of base-level changes or shoreline shifts depending on the sequence model that is being employed
Catuneanu et al., 2009	A succession of strata deposited during a full cycle of change in accommodation or sediment supply
Catuneanu et al., 2017	A cycle of change in stratal stacking patterns defined by the recurrence of sequence stratigraphic surfaces in the rock record

Table 1. Definitions of sequence.

Parameter	Value
Domain length (x axis) (km)	250
Domain length (y axis) (km)	200
Grid spacing (km)	5
Run period (Ma)	2-0
Time Steps (My)	0.1
Sediment discharge (km^3/My)	500; see Fig. 3
Water discharge (m^3/s)	Up to 1000; see Fig. 3
Amplitude and period of eustatic sea-level change (m/yr)	10-100m/1Ma; see Fig. 3
Gradient of initial shelf (degrees)	~0.06
Gravity-driven terrestrial diffusion for mud (km^2/kyr)	0.05
Gravity-driven terrestrial diffusion for sand (km^2/kyr)	0.1
Gravity-driven marine diffusion for mud (km^2/kyr)	0.005
Gravity-driven marine diffusion for sand (km^2/kyr)	0.05
Water-driven terrestrial diffusion for mud (km^2/kyr)	50
Water-driven terrestrial diffusion for sand (km^2/kyr)	100
Water-driven marine diffusion for mud (km^2/kyr)	0.01
Water-driven marine diffusion for sand (km^2/kyr)	0.1
Maximum erosion rate of sediment (m/My)	100

Table 2. Input parameters in each model

Criterion	Accommodation-dominated sequence		Supply-dominated sequence	
	High amplitude of relative sea-level change; Low Q_s/Q_w ratio	Low amplitude of relative sea-level change; High Q_s/Q_w ratio	High amplitude of water-discharge change	Low amplitude of water-discharge change
Shoreline trajectory	Descending	Descending	Almost flat	Almost flat
Stratal offlap	Yes	Yes	Yes	Yes
Absence of coastal plain topset	Yes	No	Yes	Partially
Shallower clinoforms from proximal to distal zones; Foreshortened stratigraphic successions	Possible, also decided by shelf profile		No	No
Separation between successive shoreface deposits	Yes	No	No	No
Long-distance regression	Possible, also decided by sediment discharge, water discharge, and transport diffusion coefficient			
Grainsize increase from proximal to distal zones	Yes	No	Yes	Yes

Table 3. Characteristics of sediments formed during falling relative sea level (after Fielding, 2015) or increasing water discharge