# Non-unique stratal geometries: implications for sequence stratigraphic interpretations

**Peter M. Burgess and Guy Prince**

## ABSTRACT

There is now strong evidence that stratal geometries on basin margins are most likely a consequence of multiple controls, not just variations in accommodation. Consequently correct sequence stratigraphic interpretation of stratal geometries requires an understanding of how multiple different controls may generate similar geometries. Using a simple numerical stratigraphic forward model we explore the impact of time variable sediment supply and different sediment transport rates on stratal geometries. We demonstrate how four common types of stratal geometry can form by more than one set of controlling parameter values and are thus likely to be non-unique, meaning that there may be several sets of controlling factors that can plausibly explain their formation. For example, a maximum transgressive surface can occur in the model due to an increase in rate of relative sea-level rise during constant sediment supply, and due to a reduction in rate of sediment supply during a constant rate of relative sea-level rise. Sequence boundaries, topset aggradation and shoreline trajectories are also examples of non-unique stratal geometries. If the model simulations in this work are sufficiently realistic, then the modelled stratal geometries are important examples of non-uniqueness, suggesting the need for a shift towards sequence stratigraphic methods based on constructing and evaluating multiple hypotheses and scenarios.

## INTRODUCTION

Large-scale (10s of metres to kilometers thick) stratal geometries formed on basin margins are a consequence of the interplay of changes in accommodation and supply (e.g. Schlager 1993; Helland-Hansen and Gjelberg 1994; Carvajal et al. 2009), sediment transport rates (e.g., Meijer 2002; Burgess and Steel 2008; Prince and Burgess 2013), and basin-margin topography (e.g., Schumm 1993; Leeder and Stewart 1996; Ulicny et al. 2002; Petter and Muto 2008). This influence of multiple controls is increasingly well understood, and yet many interpretations of such strata, at various scales in outcrop and in subsurface data, are still made following a sequence stratigraphic model that assumes dominant control by variations in accommodation (e.g., Posamentier et al. 1988; Van Wagoner et al. 1990; Plint and Nummedal 2000; Neal & Abreu 2009). Assuming dominant control by accommodation variations is no longer tenable, as has been known for some time (Schlager 2003), but work still needs to be done to fully explore the implications of this for sequence stratigraphic interpretations. More recent presentations of the sequence stratigraphic method and model (Catuneanu 2006; Catuneanu et al. 2009) do acknowledge the importance of additional controls, for example time-variable sediment supply, but still emphasize the concept of an idealised base-level cycle (Helland-Hansen 2009) and do little to explore what variable sediment supply and other controls might mean for the application of the models.

Investigation of multiple controls on stratal geometries should begin with a consideration of non-uniqueness. A unique stratal geometry must be demonstrably different from other stratal geometries and must, by definition, result from only one set of controlling processes with specific parameter values. Non-unique stratal geometries, in contrast, are not demonstrably different from one another, and can occur as a consequence of different parameter values for controlling processes, or from entirely different controlling processes. If various controls aside from just variations in accommodation can control stratal geometry it seems likely that several different controlling processes, or combinations of controlling processes, may create similar stratal geometries, meaning that non-unique stratal geometries could be common in the ancient record.

Previous theoretical and forward modeling work has suggested that non-unique stratal geometries exist and that their existence is a serious issue in the application of the sequence stratigraphic model. For example, Burton et al. (1987) modelled similar stratal geometries from different combinations (their “family of solutions”) of parameter values for sedimentation, eustacy and tectonic subsidence/uplift. They suggested that true inversion of stratigraphic data is not possible due to lack of sufficient information to enable separation of effects of individual controlling processes. Cross and Lessenger (1999) took a more optimistic view of this problem based on an automated method for inversion of stratigraphic data with a forward model and discussed some issues of non-uniqueness. Heller et al. (1993) also discussed non-uniqueness in this context and proposed the idea of a stratigraphic solution set to represent the various possible parameter explanation for any specific stratal geometry. Other work has explored non-uniqueness related to specific stratal geometries. Flemings and Grotzinger (1996) demonstrated that sequence bounding unconformities may be non-unique, created either via changes in accommodation or by variations in sediment supply through time. Both analogue and numerical experiments have demonstrated how topset aggradation can occur at various stages on a sea-level curve (Burgess and Allen, 1996; Swenson and Muto, 2007; Prince and Burgess, 2013), suggesting that geometries typically interpreted to be highstand systems tracts may be non-unique and also form during the falling stage of a relative sea-level curve.

### ***Aim of this work***

This work revisits some examples of non-unique stratal geometries, and demonstrates a new example. In both cases the purpose is to examine in more detail how non-unique stratal geometries occur, and to further consider their significance for the sequence stratigraphic model and method. Four common types of stratal geometry are investigated, including (i) maximum transgressive surface (MTS) (*sensu* Hellend-Hansen 2009), (ii) sequence boundaries, (iii) aggradational topset strata and (iv) shoreline trajectories. We compare modelled stratal geometries generated by different parameter values of controlling processes using stratigraphic forward model cross sections, chronostratigraphic charts, synthetic well log correlations and shoreline trajectory plots.

## MODELLING METHODS

Dionisos is a stratigraphic forward model of basin-scale stratal architectures developed on geological time-scales (Granjeon and Joseph 1999). The model consists of a two or three dimensional grid of cells. It simulates basin-scale sediment transport on geological time scales using a finite difference solution to a modified version of the classic diffusion equation. This mathematical approach allows calculation of erosion, transport, and deposition for a range of sediment grain sizes at rates determined by topographic slope, water flow and terrestrial and marine diffusion coefficients. Similar diffusional approaches have been applied in other models (Begin et al. 1981; Flemings and Jordan 1989; Jordan and Flemings 1991; Sinclair et al. 1991; Kaufman, et al. 1991; Paola et al. 1992; Heller and Paola 1992) and a justification for the use of diffusional approach for modelling of basin-margin strata on long time scale was given in Paola et al. (1999) based on modelling of a simple field-scale example of a fluvial fan-delta system.

As well as sediment transport, Dionisos also represents many other stratigraphic processes essential to generate typical large-scale basin margin stratal geometries. Accommodation variations are modelled by combining spatially and temporally variable total subsidence with sinusoidal eustatic sea-level curves to create both simple and more complex relative sea-level histories. Sediment supply can be constant through a model run, or can vary through time. In 3D models sediment supply rate can also vary spatially, for example along a modelled basin margin.

Stratal geometries are investigated in this work using both individual and multiple model runs that investigate the consequences of particular combinations of accommodation, supply and sediment transport parameters. Single runs are relatively complex two- or three-dimensional model runs addressing a specific question that can be addressed by analysis and comparison of a small number of modelled stratal geometries. In other cases analysis of more models is required and in these cases several hundred simple two-dimensional model runs are executed, analyzed using a quantitative metric that describes an aspect of the stratal geometry, and the results presented using some example model cross sections and plotted as parameter space plots (Williams et al. 2011). All the models and the model sets used below are summarized in Table 1.

## MAXIMUM TRANSGRESSIVE SURFACES

Transgressive surfaces and MTSs are almost exclusively interpreted in sedimentary geology literature as a consequence of variations in the rate of accommodation creation (e.g. Van Wagoner et al. 1990; Catuneanu 2006; Catuneanu et al. 2009). However, it is clear that accommodation variations are not the only possible mechanism to create transgressive surfaces (e.g. Flemings and Grotzinger 1996; Schlager 2003). We investigate the dual control of accommodation and supply and the consequent non-uniqueness of transgressive surfaces with cross sections and chronostratigraphic diagrams from two stratal geometries generated after 2 My of elapsed model time (EMT) (Figure 1). Model parameter values used to generate both stratal geometries are listed in Table 2. The accommodation and sediment supply controls, which differ for the two modeled stratal geometries, are shown in Figure 1. Correlated well sections (Fig. 1e and g) from stratal geometry 1 (SG1) and stratal geometry 2 (SG2) are displayed for comparison.

***Stratal Geometry 1: Accommodation-driven MTS***

SG1 was generated with constant sediment supply, constant rates of sediment transport for the various grain sizes and environments (Table 1), and a time-varying rate of RSL rise (Fig. 1a). The rate of RSL rise is initially 100 m My$^{-1}$, a typical rate for an early postrift stage passive margin. After initial progradation to around 200 km from the proximal edge of the model, the shoreline stacking pattern becomes aggradational at 0.5 My EMT (Figs. 1b and e), representing a period of balanced supply and accommodation creation. At 0.9 My EMT, rate of accommodation creation increases due to an increase in the rate of RSL from 100 m My$^{-1}$ to 400 m My$^{-1}$. (Fig. 1a) and the stacking pattern becomes retrogradational. Retrogradational stacking continues until 1 My EMT, at which time the shoreline has transgressed back to approximately 50 km and created a transgressive surface more than 100 km in lateral extent (Fig. 1b, 1c and 1e). Note that this transgressive surface generated in SG1 is similar to the conformable downlapped MTS described in sequence stratigraphic literature (e.g. Catuneanu 2006). From 1 to 1.35 My EMT the rate of RSL rise drops to 25 m My$^{-1}$ before returning to the initial rate of 100 m My$^{-1}$. These changes in the rate of accommodation end the retrogradation phase, and cause progradation of the shoreline and downlap of clinoforms onto the transgressive surface. By the end of the model run at 2 My EMT the shoreline has reached its previous most distal position.

***Stratal Geometry 2: Supply-driven MTS***

In contrast to SG1, SG2 was generated with a constant rate of RSL rise and a time varying rate of sediment supply. From 0.75 to 1 My EMT sediment supply drops from 1200 to 250 km$^3$ My$^{-1}$. At 1 My EMT sediment supply returns to 1200 km$^3$ My$^{-1}$. All other model parameters are the same as values used to generate SG1 (Table 2).

Despite generation with different accommodation and sediment supply histories, SG2 is similar to SG1. For example, as with SG1, after initial supply driven progradation, the stacking pattern in SG2 becomes retrogradational; compare Fig. 1b with Fig. 1f, Fig. 1d with

Fig. 1h and Fig. 1c with Fig. 1g. However, unlike shoreline transgression in SG1, which is driven by a change in rate of accommodation creation, shoreline transgression in SG2 is driven by a reduction in rate of sediment supply during constant rate of RSL rise (compare Fig. 1a with Fig. 1e). The shoreline reaches maximum landward extent at approximately 50 km at 1 My EMT, creating a MTS, which is preserved and downlapped by progradational strata that forms when sediment supply returns to its previous rate.

### ***Comparison of Stratal Geometries 1 and 2***

MTSs generated in SG1 and SG2 exhibit several diagnostic characteristics that correspond to MTS described in the various sequence stratigraphic depositional models (e.g. Catuneanu 2006). For example, in both SG1 and SG2, the stacking pattern below and above the MTS is retrogradational and progradational, respectively. In both modeled cases (Fig. 1) the MTS is downlapped by the overlying progradational strata. Wells intersecting the MTSs observed in SG1 and SG2 (Fig. 1c, B1 to D1 and Fig 1h, B2 to D2) display a sharp facies transition from fluvial to shallow marine strata. Finally, the MTS in both SG1 and SG2 shows a marine hiatus on the outer shelf lasting between 0.5 and 1My EMT. Despite their similarities, the two MTSs were clearly generated by two quite different controlling processes (Fig. 1a & 1e). This demonstrates that a MTS can be a non-unique stratal geometry, generated either by changes in the rate of accommodation creation during steady sediment supply, or by changes in the rate of supply during a steady rate of accommodation creation.

### ***Stratal Geometry 3: Implications of along-strike sediment supply variations for MTS correlation***

SG1 and SG2 show how MTSs are non-unique. Catuneanu et al. (2009) mentioned how along-strike variations in sediment supply can cause an MTS surface to be diachronous, but the impact of time-variable sediment supply leading to non-uniqueness leads to problems more serious than just diachronous surfaces. Non-uniqueness is a significant challenge for sequence stratigraphic correlations using MTSs because MTS formed by reductions in sediment supply may be indistinguishable in form from and therefore correlated with accommodation-driven MTSs (e.g., Wehr 1993), even though they are unlikely to be contemporaneous. To illustrate this potential correlation problem SG3 (Figure 2) shows how MTS can form at different times on a basin margin due to local variations in sediment supply (Fig. 2 a, b, c) during steady RSL rise (Fig. 2a). Shut-down of sediment supply occurs at various times on this modelled margin (Fig. 2a) and as a result transgressive surfaces form along the margin at different times. Wells or vertical sections from points A, B and C (Fig. 2e) each show three transgressive surfaces which can be correlated. If it was assumed, as it commonly is, that variations in the rate of accommodation creation were controlling formation of these surfaces, the correlation would probably be considered chronostratigraphically significant because the surfaces would be assumed to be isochronous. The correlation panel (Fig 2e) shows the actual position of the time lines in the model. Comparison between the MTS correlation lines and the time lines shows that the correlation lines are diachronous across up to 1.9 My. There is no reason why this mis-correlation could not be greater. In any case where MTSs are correlated based on an assumption of regional, basin-wide or even global accommodation control this kind of mis-correlation is likely to occur unless accommodation driven and supply driven MTSs can be reliably distinguished. A key question that arises from this possibility of miscorrelation is how sediment supply varies in time and space. Over what kind of spatial and temporal scale, if any, is it reasonable to assume constant sediment supply? More work is required to address this question (e.g. Allen et al. 2013; Forzoni et al. 2014).

## SEQUENCE BOUNDING UNCONFORMITIES

Subaerial erosion surfaces forming sequence bounding unconformities are a key element in most sequence stratigraphic models and almost exclusively interpreted to be a consequence of relative sea-level fall driving fluvial incision (e.g. Posamentier et al. 1988; Posamentier 2001; Catuneanu 2006; Catuneanu et al. 2009). However, modelling studies have started to explore this element of the model (Strong and Paola, 2008; Tomer et al., 2011) and some important observations and modelling results cast serious doubts on this assumption (e.g. Schumm, 1993; Best and Ashworth, 1997; Martin et al., 2011). To investigate how sequence bounding unconformities generated by fluvial incision may be the non-unique consequences of a combination of RSL change, variable sediment supply and variable rates of sediment transport, we have run two example models and generated two stratal geometries, SG4 and SG5. Cross sections, chronostratigraphic diagrams and vertical stratigraphic sections from the two different stratal geometries generated after 3 My of EMT are shown in Figure 3. The history of time-variable RSL and terrestrial diffusion coefficients are also shown for each model (Fig. 3a and 3e)

### *Stratal Geometry 4: Accommodation controlled sequence boundary*

SG4 was initiated with 1 My of constant sediment supply and constant RSL (Fig. 3A), generating an initial phase of progradation and topset aggradation (Fig 3B and 3d). Sediment supply and sediment transport rates remain constant throughout this model, but after 1 My EMT relative sea-level falls by 50 m My$^{-1}$ for 1 My (Fig. 3A), and this causes fluvial erosion and bypass which removes some of the underlying topset strata, and generates an erosional sequence boundary that extends basinward during forced regression during falling RSL, and reaches its maximum extent at the end of RSL fall at 2 My EMT (Fig. 3B and 3C). Correlated well sections (Fig 3c) show that between 1 and 2 My EMT only marine foreset strata are deposited, reflecting sediment bypass across the shelf and deposition into deep-water deposystems. From 2 My EMT to the end of the model run at 3 My EMT RSL rises again by 50 m My$^{-1}$, leading to rapid onlap and burial of the sequence boundary surface below aggradational terrestrial topset strata (Fig. 3B and 3d). This stratal geometry is similar to classic sequence geometries described, for example, by Catuneanu (2006) and forms due to changes in the rate of accommodation creation, as is typically expected to be the case.

### *Stratal Geometry 5: High sediment transport rate sequence boundary*

In contrast to SG4, SG5 is generated without any relative fall in sea-level, and with variable sediment transport rates caused by variable terrestrial diffusion coefficient. RSL is constant until 2 My EMT, at which point it rises at 50m My$^{-1}$. Sediment transport rates are initially relatively low (diffusion coefficient are 50 km$^2$ky$^{-1}$ for sand and 100 km$^2$ky$^{-1}$ for mud) but then increase by a factor of four at 1 My EMT (Fig. 3E). As with SG4, SG5 was initiated with 1 My of constant sediment supply and no relative change in sea-level (Fig. 3E), generating an initial phase of progradation and topset aggradation (Fig 3F and 3h). The increase in sediment transport rates at 1My triggers fluvial erosion and sediment bypass, leading to formation of an erosional sequence boundary that, for the next 1 Myr, extends basinward. In contrast to the sequence boundary in SG4, in SG5 topset aggradation occurs across the outer topset region between approximately 1.1 and 2 My EMT. However, the cross-section and well C2 indicate that the amount of aggradation was less than 2 m (stacked timelines 1 to 2 My EMT in well C2, Fig. 3g), and the majority of sediment bypasses the topset region between 1 and 2 My EMT. The unconformity surface reaches its maximum extent at 2 My EMT, at which point relative sea-level begins to rise, triggering topset aggradation that buries the unconformity surface.

### *Comparison of Stratal Geometries 4 and 5*

SG5 demonstrates how increased sediment transport rates in the terrestrial topset environment could lead to sediment bypass and erosion during steady RSL. SG4 and SG5 are very similar. Both have a sequence boundary formed by an unconformity surface of similar duration and lateral extent that truncates strata below and is onlapped by overlying strata. This demonstrates how sequence bounding unconformities could be non-unique features, generated either by fluvial incision during RSL fall, or by fluvial incision driven by an increase in the discharge rate, carrying capacity and sediment transport rate within the fluvial channels. Considering the variability of modern drainage systems (Hovius 1998) such changes may be caused by both external forcing (e.g. changes in rainfall volume and frequency in the drainage basin), by autogenic mechanisms such as avulsion or reorganization of drainage systems, or by complex combinations of both, but maybe with substantial buffering in larger drainage systems (e.g. Castelltort and Van Den Driessche, 2003). Only the details of the shoreline trajectory distinguish SG4 and SG5. In SG4 the shoreline trajectory between 1 and 2 My EMT is descending regressive due to RSL fall. In contrast, for the same interval in SG5 the shoreline trajectory is horizontal, indicating unchanging RSL. However, it would not be straight forward to distinguish these two shoreline trajectories in ancient strata that have undergone differential compaction (Prince and Burgess, 2013) or where a reliable regional palaeohorizontal datum is difficult to define (Hellend-Hanson and Hampson, 2009).

### ***Implications of non-unique sequence boundaries for sand bypass predictions***

Predicting sediment partitioning across a basin margin is a key aim of siliciclastic sequence stratigraphic models. For example, standard sequence models predict that deep-marine sand deposition occurs primarily during RSL lowstands due to fluvial incision and sediment bypass (Catuneanu et al. 2009). This prediction and the assumptions behind it have already been shown to be an oversimplification; it is now clear that significant sand bypass into deep-marine settings can occur at any point on a relative sea-level cycle (e.g. Helland-Hansen and Gjelberg 1994; Burgess and Hovius 1998; Carvajal and Steel 2006; Covault and Graham 2010). Given this, it is interesting to consider the implications of unconformity formation in SG5 for sand bypass into deep-marine settings. SG4 and SG5 are composed of 80% mud and 20% sand, and the sand fraction is partitioned according to the terrestrial and marine diffusion coefficients used in the models to calculate sediment transport rates. Comparison of cross sections and vertical sections from SG4 and SG5 colour coded by percentage of sand content shows that the sand partitioning in the two cases is similar.

During unconformity formation due to either relative sea-level fall (SG4) or steady RSL but increased fluvial discharge (SG5), most of the sand is located in the top of the foresets (Fig. 4C, D, E and F) with only minor volumes reaching the deep-water toeset strata in both cases (Fig. 4G). During subsequent RSL rise in both models the sand-rich strata are restricted to the proximal topset. Similar sand distribution in SG4 and SG5 shows that the non-uniqueness extends to the grain size distribution, suggesting that sequence boundaries formed by RSL fall and by increased fluvial discharge may have similar consequences for sand partitioning.

## NON-UNIQUE TOPSET AGGRADATION

An implicit assumption in many sequence stratigraphic interpretations is that topset aggradation represents rising relative sea-level (e.g. Posamentier et al. 1988; Catuneanu 2006). From this assumption it follows that when topset aggradation is observed, this is likely a consequence of rising relative sea-level, and on this basis, the strata would probably be interpreted to be part of a highstand system tract (Catuneanu 2006). However, this is only a valid approach if there is evidence to show that topset aggradation is a unique product of increasing accommodation during rising relative sea-level. Swenson and Muto (2007) and Prince and Burgess (2013) used physical and numerical modelling to show that topset aggradation is controlled not just by accommodation creation, but also by fluvial discharge and sediment supply rates, and as a consequence topset strata may also form during falling relative sea-level. If this is the case, distinguishing highstand and falling stage systems tract strata becomes more complicated, as does reconstruction of relative sea-level histories. To build on the work of Swenson and Muto (2007), Muto et al. (2007), Petter and Muto (2008) and Prince and Burgess (2013), and further investigate controls on topset aggradation we have executed 399 Dionisos models with a range of amplitudes of relative sea-level fall and rise and a range of sediment transport rates to investigate how topset aggradation is non-unique for different combinations of sediment transport rate and relative sea-level change.

### *Model set one: Topset aggradation during rising, steady and falling relative sea-level*

As defined in Prince and Burgess (2013) a topset/foreset ratio (t/f ratio) summarizes the proportion of topset strata relative to foreset strata in an individual stratal geometry. When no topset strata are present the t/f ratio is 0, otherwise t/f ratio > 0. The t/f ratios calculated from 399 different model runs are displayed in a parameter space plot (Fig. 5a). Model runs span a range of amplitudes of RSL change from -100 to 100 m in 10 m increments. Amplitudes and the durations of RSL fall and rise span a range based on amplitudes of RSL fluctuation implied by Phanerozoic eustatic curves (Miller et al. 2005). For each amplitude of RSL change a range of terrestrial diffusion coefficients for sand and mud from 20 to 200 $km^2kyr^{-1}$ and 40 to 400$km^2kyr^{-1}$ respectively are also tested. This range is representative of small- to medium-sized delta systems (Kenyon and Turcotte 1985). Additional model parameters, such as sediment supply and river discharge rate, are listed in Table 2.

A t/f ratio can be calculated for each model run across the range of RSL and diffusion co-efficient values described above, and the calculated t/f ratios plotted against the value of RSL change and diffusion coefficient that generated each model (Figure 5a). Selected cross sections from the model runs are shown in Figure 5b, with their t/f ratio and parameter values, and the position of each profile in the parameter space is indicated on Figure 5a with a label. Topset aggradation is best developed in models with low rates of sediment transport and high amplitudes of relative sea-level rise. For example, model profile 1, Figure 5b, which has the highest t/f ratio of all the models, was generated with RSL rise of 100 m and a terrestrial diffusion coefficient of 20$km^2kyr^{-1}$ for sand, and plots in the top left corner of the parameter space shown in Figure 5a. Topset aggradation decreases at the magnitude of RSL rise decreases, and also decreases as the rate of sediment transport increases, as represented by higher diffusion coefficient values (Figure 5a). Note however that when sediment transport rates are low, significant topset aggradation occurs even with a large magnitude RSL fall e.g. model profile 3A, figure 5a and 5b. For higher rates of sediment transport, t/f ratio decreases with decreasing magnitude of RSL rise, and goes to zero as the magnitude of RSL fall increases (Figure 5a). At the point at which t/f ratio is zero and no erosion occurs, the fluvial profile in the model can be said to be at grade, with exactly the right transport capacity to move all of the sediment supply into the foresets with no aggradation or degradation of the fluvial profile (fluvial grade line indicated in Figure 5a).

A key feature of the strata generated with this range of RSL and sediment transport rate parameters is that the same t/f ratio occurs at many points in the parameter space. In other words, stratal geometries with a very similar proportion of topset strata occur for quite different magnitudes of RSL change and sediment transport rates. For example, model profiles 3A to D all have a t/f ratio of 0.32, but represent a range of RSL change from -70m to +60m, and an order of magnitude change in sediment transport rate. In terms of gross stratigraphic architecture, as represented by the t/f ratio at least, this is a striking example of non-uniqueness. A similar pattern of non-unique stratal geometries occur in other parts of the parameter space, for example model profiles 2A and B, and model profiles 4A to D. Non-unique topset aggradation has serious implications for application of basic sequence stratigraphic methods such as definition of different systems tracts, as well as for recognition and reconstruction of RSL histories from ancient strata. As in previous examples (SG4 and SG5), the only feature that would allow an observer to distinguish these geometries is the shoreline trajectory, but analysis of the shoreline trajectory may itself be a non-trivial process with differential compaction and without a well-defined regional datum.

## NON-UNIQUE SHORELINE TRAJECTORIES

Shoreline trajectory analysis and other similar constructs such as shelf-margin trajectories, have many advantages over other elements of the sequence stratigraphic method because, in general, they are more directly based on observation and require fewer *apriori* assumptions to apply (Hellend-Hansen and Hampson, 2009). However, results presented above suggest that non-uniqueness may also be a significant issue with the analysis of shoreline trajectories. We investigate the non-uniqueness of shoreline trajectories using four model runs SG1, SG2, SG6 and SG7 that generate similar shoreline trajectories with different RSL and sediment supply histories.

The RSL curve, sediment supply history and marine diffusion coefficients used to generate stratal geometries 1, 2, 6 and 7 (Figs. 1, 6 and 7) are illustrated along with calculated shoreline trajectories plotted as chronostratigraphic shoreline charts (Fig. 6a and Fig. 7a) and simple shoreline position plots (Figs 6d and 7f). Stratal geometries 6 and 7 result from 3 My duration model runs (Fig. 6), whereas stratal geometries 1 and 2 result from 2 My duration model runs (Figs. 1 and 7).

### *Progradational to retrogradational shoreline trajectories*

Stratal geometry 6 (SG6) was generated with a constant rate of sediment supply and two rates of rising RSL (Fig. 6a). From 0 to 2 My EMT, RSL rose at a rate of 50 $mMy^{-1}$ generating a progradational, ascending shoreline trajectory (Fig 6a, b and d). Rate of progradation gradually decreases as the height and length of the foresets increase, and by 1.5My the shoreline is retrogradational due to autoretreat (Muto and Steel 2002). From 2 to 3My EMT RSL rose at 100mMy$^{-1}$ and this increase in the rate of accommodation creation causes an increase in the rate of retrogradation of the shoreline, leading to a retrogradational ascending trajectory for the last 1My of EMT.

Comparing the shoreline trajectory calculated from SG6 with the shoreline trajectory calculated from SG7 is illuminating. Despite different accommodation and supply histories (Figure 6a), the shoreline trajectories look very similar (Figure 6b, c and d). For the first 1My EMT, the shoreline trajectory in SG7 shows an ascending progradational trend much like the trajectory observed in SG6. However, for the first 1My EMT, SG7 was generated with a higher and more complex history of sediment supply to compensate for a rate of RSL rise of 100mMy$^{-1}$, double the rate of RSL rise for the same period in SG6 (Figure 6a). In SG7 retrogradation starts at about the same time as in SG6, after 1.5My EMT, and persists for the rest of the SG7 model run. Unlike the SG6 transgression initiated by delta autoretreat, shoreline transgression in SG7 is also driven by a reduction in sediment supply during rising RSL.

Comparison of SG6 and SG7 demonstrates that different rates of RSL rise can lead to very similar shoreline trajectories if the history of sediment supply compensates for differences in the RSL history to lead to a similar overall history of accommodation change. This is another example of a non-unique stratal geometry, in this case demonstrating that, at least for simple regressive-transgressive cycles, there may be a substantial problem determining a unique set of controlling parameters from any particular regressive-transgressive shoreline trajectory.

### ***Non-unique shoreline trajectories from SG1 and SG2***

SG1 and SG2 were described above in terms of several diagnostic characteristics that correspond to MTS. They demonstrates that a MTS can be a non-unique stratal geometry, generated either by changes in the rate of accommodation creation during steady sediment supply, or by changes in the rate of supply during a steady rate of accommodation creation. Shoreline trajectories from SG1 and SG2 also have similar overall geometries (Figure 7) and can be considered non-unique. This demonstrates that a shoreline trajectory analysis is unlikely to offer solution to the problems of interpretation raised by the non-uniqueness of the MTS in SG1 and SG2.

## DISCUSSION

A question that is sometimes asked of numerical stratigraphic forward models is what do they tell us that is not already obvious? Non-uniqueness is, arguably, an example of non-obvious behavior, not least because this behavior can only be properly explored via multiple runs of quantitative models. Non-unique stratal geometries are similar arrangements of strata that can occur as a consequence of different parameter values for controlling processes, or from entirely different controlling processes. The seven stratal geometries modelled in this work are examples of non-uniqueness because for each type of surface, stacking pattern or shoreline trajectory, similar stratal geometries have been generated by more than one set of parameter values. A MTS was generated by an increase in the rate of accommodation creation during constant sediment supply (SG1) but also a shut-down in sediment supply during a constant rate of accommodation creation (SG2). A sequence boundary was generated by a fall in RSL with a ‘mid case’ rate of terrestrial sediment transport (Kenyon and Turcotte 1985) (SG4) but also by a ‘high case’ rate of terrestrial sediment transport during constant RSL (SG5). Multiple model runs in Model Set One demonstrated that topset aggradation can be non-unique in the sense that, for different rates of terrestrial sediment transport, the same volume of topset aggradation can occur in strata generated by falling, steady and rising RSL. Finally, geometrically similar pairs of shoreline trajectories were generated in the numerical model with distinctly different accommodation and sediment supply histories (SG6 to SG7).

A limitation of this analysis of non-unique stratal geometries is that all of the geometries shown are produced by a numerical model Dionisos that is a much simplified representation of a real sedimentary system. Dionisos is based on various assumptions about how such sedimentary systems behave. Williams et al. (2011) and Prince and Burgess (2013) discussed the various simplifications and assumptions involved in this type of model, and the points they raised and addressed regarding the applicability of diffusion to sediment transport, the issues with finding realistic diffusion coefficients for different settings, and 2D versus 3D models apply to the results presented here too. Perhaps the best way to summarize this is a well-known quote from Box (1979) who said “all models are wrong, but some are useful”. This quote applies just as much (possibly more so?) to sequence stratigraphic models supported only by cartoons, but applied to the numerical model results presented here, it suggests that these results are best treated as  a working hypothesis; if these model results are realistic, non-uniqueness is an issue, as described above. However, if the models are considered too simplistic to generate insight about how real stratal geometries form, then we need to create, test and explore more complex analogue and numerical models that better represent the complexity of Earth-surface systems. A key thing to discover about these models would be to what degree simplicity and complexity, including non-uniqueness, emerge from their operation, as well as to what degree they can match stratal geometries known from outcrop and subsurface examples where external controlling factors can be independently constrained (e.g. in Holocene systems where the RSL curve and supply history is well known compared to more ancient examples).

If for the moment we accept that the numerical model results presented above are on some level valid representations of how basin margin strata can form, these four examples of non-uniqueness are important in the context of sequence stratigraphy because they show how various controls aside from just variations in accommodation may control stratal geometry. This would mean that several different controlling processes, or combinations of controlling processes, may create similar stratal geometries. Such non-unique stratal geometries are a challenge to our assumed ability to uniquely determine the history of controlling factors responsible for any particular strata. This has been pointed out several times before (e.g. Burton et al., 1987; Burgess and Allen, 1996; Heller et al., 1993; Burgess et al. 2006; Charvin et al. 2009) but the problem has remained largely ignored in the mainstream sequence stratigraphic method. Note that this can be considered an example of the contrasting approaches to sequence stratigraphy, which where summarized by Miall and Miall (2004) as the global eustasy paradigm versus the complexity paradigm. A proper consideration of non-uniqueness would certainly fall in the complexity paradigm, and while a step forward in moving away from an emphasis on eutasy, even recent attempts to summarize and standardize developments in sequence stratigraphy (e.g. Catuneanu et al., 2009) arguably still tend to over-simplify.

Catuneanu et al. (2009) is a key recent paper in the recent development of sequence stratigraphy, representing an attempt to define a common, model-independent methodology and terminology. Given this, it is useful to consider how the issue of non-uniqueness highlighted above might impact on the latest version of the sequence stratigraphic model and method. Catuneanu et al. (2009) do acknowledge the importance of departures from the standard accommodation-forced geometries, for example by variable sediment supply in controlling stratal geometries. They say "It is this high degree of variability in the precise expression of sequence stratigraphic units and bounding surfaces that requires the adoption of a methodology that is sufficiently flexible that it can accommodate the range of likely expressions" However, there is still an assumption that accommodation is the key underlying control; even the choice of system tract names ("forced regressive, lowstand and highstand normal regressive, transgressive") demonstrates an assumption of dominant control by relative sea-level. This may yet turn out to be correct, but even if relative sea-level oscillations are a dominant control, this still does not adequately consider non-uniqueness as a limitation in the proposed method. The following examples demonstrate why this matters.

The first example relates to a statement from Catuneanu et al. (2009) "In contrast, sequence stratigraphic surfaces that form in relation to changes in the direction of base-level shift at the coastline, and so in essence independently of sediment supply … are more suitable for building a chronostratigraphic framework." This statement contains many implicit assumptions (see Thorne (1992) for an analysis of implicit assumptions in sequence stratigraphic models and methods), but a key assumption is that it is possible to distinguish between surfaces generated by a change in sediment supply, and surfaces generated by some change in base level. The seven stratal geometries presented above demonstrate why this is a poor assumption. RSL, sediment supply and sediment transport rate variations all control stratal geometries, and consequently significant surfaces such as MTS and sequence bounding surfaces are likely to be non-unique. This means that stratal geometries and surfaces formed by quite different processes may be indistinguishable from one another, and therefore how, especially with incomplete and often ambiguous data, should one choose which examples are of chronostratigraphic significance and which are not? How would one know that the surfaces chosen to correlate are the best, or indeed valid, choices?

The second example relates to assumptions made by the original sequence stratigraphic models regarding the relationship between sequence boundary formation and sediment bypass to deep-marine systems during lowstands (e.g. Posamentier and Kolla, 2003; Catuneanu et al., 2009). Most of these assumptions have been shown to be often inappropriate simplifications (e.g. Kolla and Perlmutter, 1993; Hellend-Hansen and Gjelberg, 1994; Burgess and Hovius, 1998; Porebski and Steel, 2006; Boyd et al. 2008; Carvajal and Steel, 2006; Covault et al. 2007; Covault and Graham 2010). Even in cases where sediment bypass on a sequence boundary surface is considered key to formation of sand-prone deep-marine strata, the non-uniqueness of sequence boundaries, if demonstrated in real strata, would further complicate application of the simple lowstand model. For example, does prediction of likely sand-supply to more distal parts of the depositional system require an ability to distinguish a sequence bounding surface formed by base level fall from a similar surface formed by an increase in fluvial discharge and transport capacity?

All of the questions listed above require further work to address, but perhaps two key outstanding issues are 1) how much does the sequence stratigraphic model and method need to change to properly account for controls on strata that are more complex than relative sea-level oscillations and the related issue of non-uniqueness, and 2) how much does sediment supply vary in time and space and what are the consequences of this? The requirement for modification of the model has been recognized for a while (e.g. Posamentier and Allen, 1993; Helland-Hansen, 2009) and methods incorporating numerical modelling are being developed that incorporate more complex controls and can make predictions that begin to take into account non-uniqueness (Cross & Lessinger, 1999; Burgess et al. 2006; Charvin et al. 2009a; 2009b; Falivene et al. in press). Incorporating these numerical modelling techniques as an integral part of a standard sequence stratigraphic method would be an important step forward. More data and information on spatial and temporal variations in sediment supply is emerging (e.g. Allen et al. 2013; Forzoni et al. 2014), and this will be useful in further developing models to understand and predict basin margin stratal geometries.

## CONCLUSIONS

1. The numerical stratigraphic forward modelling results presented here show how a maximum transgressive surface, an erosive sequence bounding unconformity, topset aggradation and cycles of progradational and retrogradational shoreline trajectory are all non-unique stratal geometries that can be created in each case by more than one set of controlling processes or parameter values. MTSs are generated due to an increase in rate of RSL rise during constant sediment supply or a decrease in rate of sediment supply during steady rise in RSL. Sequence boundaries are generated due to falling RSL with relatively low rates of sediment transport and steady RSL with an increase in the rate of

sediment transport. Similar volumes of topset strata are generated in model runs with a range of amplitudes of rising and falling RSL, depending on the sediment transport rate. Similar shoreline trajectories occur for a range of different accommodation and supply histories.

2. Non-uniqueness of key stratal geometries is a serious issue for the sequence stratigraphic method and model because it challenges assumed ability to identify a single explanation or history for a given stratal geometry, for example when attempting to explain and understand sediment bypass and RSL histories, and it also makes it more difficult to assign chronostratigraphic significance to stratal surfaces, with implications for our ability to correlate strata.
3. Non-uniqueness of stratal geometries requires a shift towards stratigraphic methods more weighted towards constructing and evaluating multiple hypotheses and scenarios. This is perhaps best done by incorporating newly developed methods in numerical forward modelling into existing sequence stratigraphic methods.

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Table 1: A summary of the models used in the paper

| **Model Name** | **Stratal Geometry investigated** | **Number of model runs** | **Model run duration** | **Time-variable parameters** |
|---|---|---|---|---|
| SG1 | Maximum transgressive surface | 1 | 2 My | RSL |
| SG2 | Maximum transgressive surface | 1 | 2 My | Sediment supply |
| SG3 | Maximum transgressive surface | 1 | 6 My | Sediment supply |
| Model Set 1 | Topset aggradation | 399 | 2 My | RSL, terrestrial *k* |
| SG4 | Sequence boundary | 1 | 3 My | RSL |
| SG5 | Sequence boundary | 1 | 3 My | RSL, terrestrial *k* |
| SG6 | Progradation-retrogradational shoreline trajectory | 1 | 3 My | RSL |
| SG7 | Progradation-retrogradational shoreline trajectory | 1 | 3 My | RSL, sediment supply |

Table 2: Dionisos default model parameters.

| **Parameter** | **2D value** |
|---|---|
| Grid length (*x* axis) (km) | 500 |

| | |
|---|---|
| Grid length (*y* axis) (km) | 40 |
| Grid Point Spacing (km) | 20 |
| River discharge (km$^3$My$^{-1}$) | 6.31 x 10$^{12}$ |
| Gravity weathering rate (m My$^{-1}$) | 1 |
| Water weathering rate (m My$^{-1}$) | 100 |
| Composition of sediment supply (sand, mud) (%) | 20, 80 |
| Gravity-driven terrestrial diffusion coefficient for sand (km$^2$ky$^{-1}$) | 4 |
| Gravity-driven terrestrial diffusion coefficient for mud (km$^2$ky$^{-1}$) | 8 |
| Gravity-driven marine diffusion coefficient for sand (km$^2$ky$^{-1}$) | 0.05 |
| Gravity-driven marine diffusion coefficient for mud (km$^2$ky$^{-1}$) | 0.1 |

## FIGURE CAPTIONS:

**Figure 1**

Stratal geometry 1 (SG1) and stratal geometry 2 (SG2) shown in cross section (d and h), as chronostrat digarams (b and f) and as correlated vertical sections (c and g) have similar maximum transgressive surfaces (MTS) despite being generated with different relative sea-level and sediment supply curves (a and e).

**Figure 2**

Selected input parameters and output from the three-dimensional SG3 model run showing how variable sediment supply histories (a) at multiple point sources (b, d) lead to strongly diachronous maximum transgressive surfaces that can be mistaken for a single correlative chronostratigraphic surface (e). The model run has constant rising RSL (c) but sediment supply varies through time (a) and each sediment input point has a different sediment supply history (b).

**Figure 3**

Stratal Geometry 4 (SG4) and Stratal Geometry 5 (SG5) have similar sequence boundaries shown in cross section (d and h), in chronostratigraphic diagrams (b and f) and as correlated vertical sections (c and g) despite being generated with different parameter values for RSL and sediment transport rates (a and e). Note that differences in the most distal part of the sequence bounding unconformity between the two cases are more significant in time than in thickness; approximately 1 My of EMT in SG5 (f) is represented by only 2m of preserved sediment thickness (h and g) meaning that SG4 and SG5 are very similar in both cross section (b and h) and in vertical sections (c and g).

**Figure 4**

Stratal geometry 4 (SG4) and stratal geometry 5 (SG5) shown with strata colour coded for proportion of sand content in cross section (c and d) and vertical sections (e, f and g). Although the overall stratal geometries are very similar (see also figure 3) there are some subtle differences in sand content of the strata. Sand content is higher in SG5 in the proximal coastal plain (d) leading to less sand bypass and slightly lower sand proportion in deep-water toeset strata (g).

**Figure 5**

(a) Nearly 400 models from Model Set 1 plotted as colour-coded values of the t/f ratio in a sediment transport rate and relative sea-level amplitude parameter space plot. High t/f ratios represent models with topset strata approaching the same volume as forest strata. Low to zero t/f ratio occurs for higher rates of sediment transport or for high amplitudes of RSL fall. The fluvial grade line indicates the points in the parameter space where models develop fluvial profiles that are at grade, with neither accumulation or erosion of strata, just bypass of all sediment to the shoreline (b) Cross sections from a subset of model runs are shown with shoreline trajectory, t/f ratio, terrestrial diffusion coefficient value (*k*) and RSL amplitude labeled. The position of each cross section is labelled on the parameter space plot in (a). Note that cross sections with the same number label are considered non-unique sets with similar geometries yet generated by different RSL and terrestrial diffusion coefficient parameter values.

**Figure 6**

Stratal Geometry 6 (SG6) and Stratal Geometry 7 (SG7) have similar shoreline trajectories (b, c and d) generated with different RSL and sediment supply histories (a).

**Figure 7**

Relative sea-level and sediment supply curves (a) for SG1 and SG2 that generate similar shoreline trajectories in time (b) and in elevation (c).

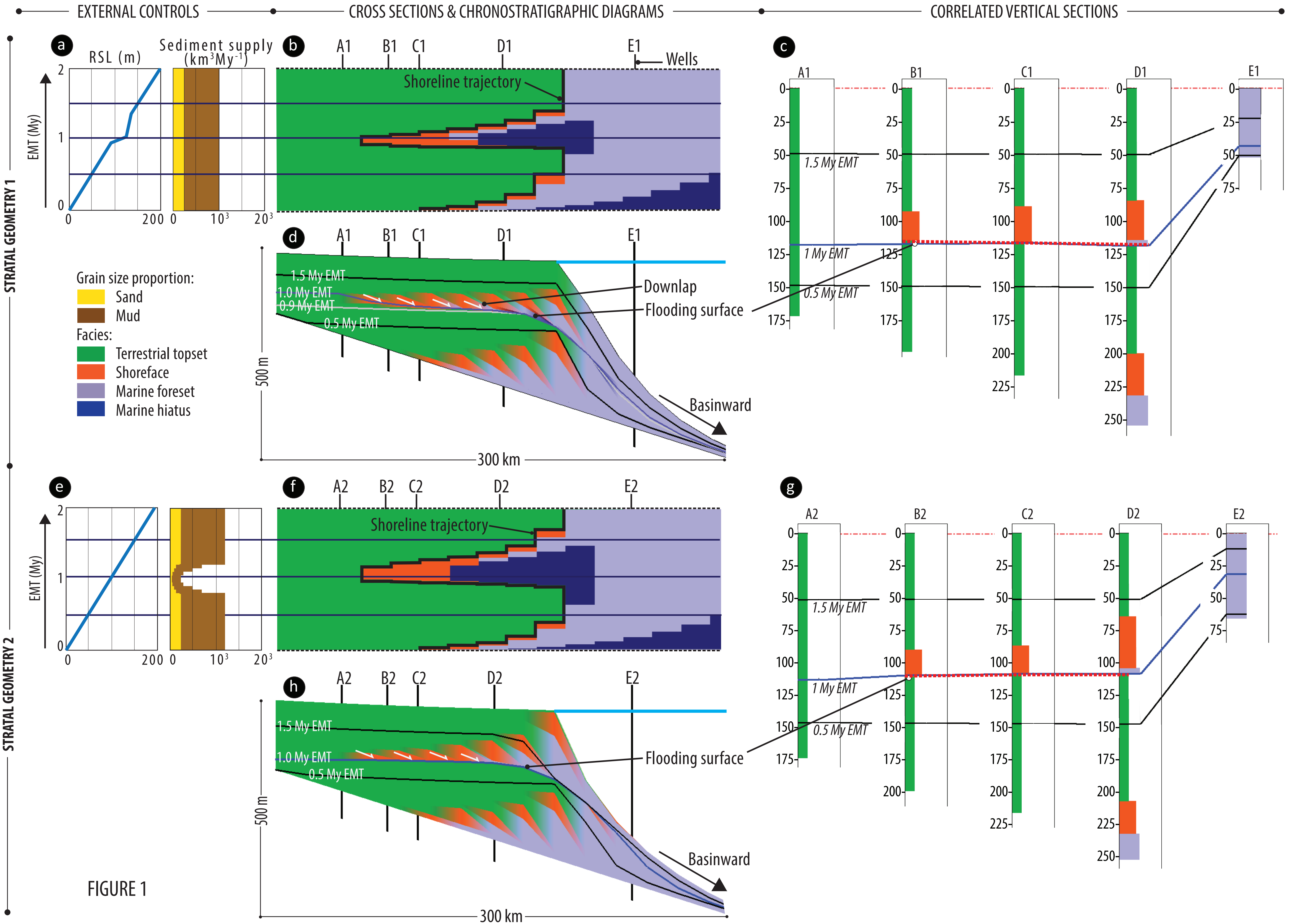
EXTERNAL CONTROLS
CROSS SECTIONS & CHRONOSTRATIGRAPHIC DIAGRAMS
CORRELATED VERTICAL SECTIONS
STRATAL GEOMETRY 1
STRATAL GEOMETRY 2
a
RSL (m)
Sediment supply (km³My⁻¹)
EMT (My)
0
1
2
0
200
0
10³
20³
b
A1
B1
C1
D1
E1
Wells
Shoreline trajectory
c
A1
B1
C1
D1
E1
0
25
50
75
100
125
150
175
200
225
250
1.5 My EMT
1 My EMT
0.5 My EMT
d
1.5 My EMT
1.0 My EMT
0.9 My EMT
0.5 My EMT
Downlap
Flooding surface
500 m
300 km
Basinward
Grain size proportion:
🟨 Sand
🟫 Mud
Facies:
🟩 Terrestrial topset
🟧 Shoreface
🟪 Marine foreset
🟦 Marine hiatus
e
EMT (My)
0
1
2
0
200
0
10³
20³
f
A2
B2
C2
D2
E2
Shoreline trajectory
g
A2
B2
C2
D2
E2
0
25
50
75
100
125
150
175
200
225
250
1.5 My EMT
1 My EMT
0.5 My EMT
h
A2
B2
C2
D2
E2
1.5 My EMT
1.0 My EMT
0.5 My EMT
Flooding surface
500 m
300 km
Basinward

FIGURE 1

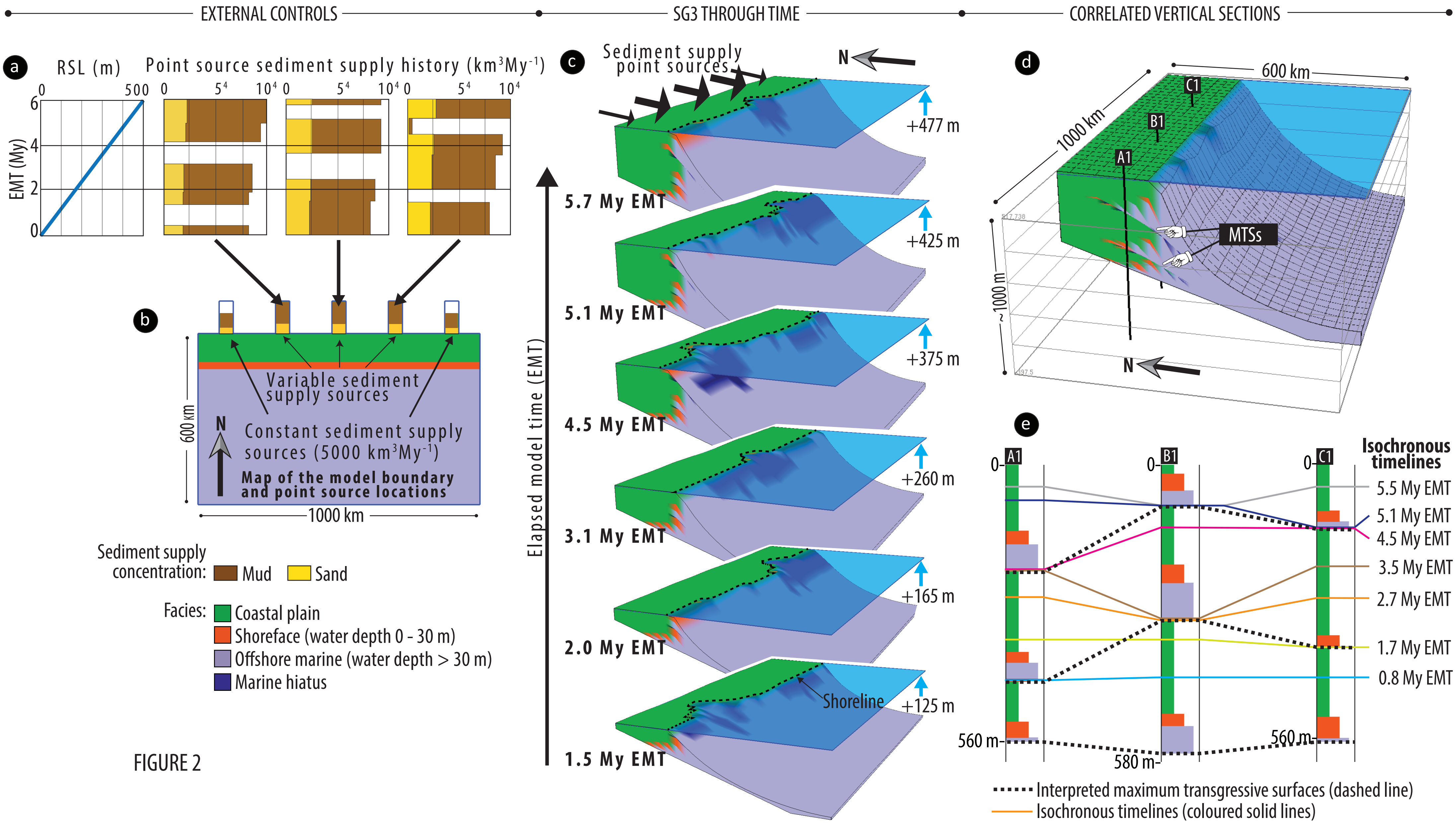
EXTERNAL CONTROLS
SG3 THROUGH TIME
CORRELATED VERTICAL SECTIONS
a
RSL (m)
Point source sediment supply history (km³My⁻¹)
0
500
5⁴
10⁴
EMT (My)
6
4
2
0
b
Variable sediment supply sources
N
Constant sediment supply sources (5000 km³My⁻¹)
Map of the model boundary and point source locations
600 km
1000 km
Sediment supply concentration:
Mud
Sand
Facies:
Coastal plain
Shoreface (water depth 0 - 30 m)
Offshore marine (water depth > 30 m)
Marine hiatus
c
Sediment supply point sources
N
Elapsed model time (EMT)
5.7 My EMT
+477 m
5.1 My EMT
+425 m
4.5 My EMT
+375 m
3.1 My EMT
+260 m
2.0 My EMT
+165 m
1.5 My EMT
Shoreline
+125 m
d
600 km
1000 km
C1
B1
A1
MTSs
1000 m
N
e
A1
B1
C1
0
Isochronous timelines
5.5 My EMT
5.1 My EMT
4.5 My EMT
3.5 My EMT
2.7 My EMT
1.7 My EMT
0.8 My EMT
560 m
580 m
560 m
Interpreted maximum transgressive surfaces (dashed line)
Isochronous timelines (coloured solid lines)

FIGURE 2

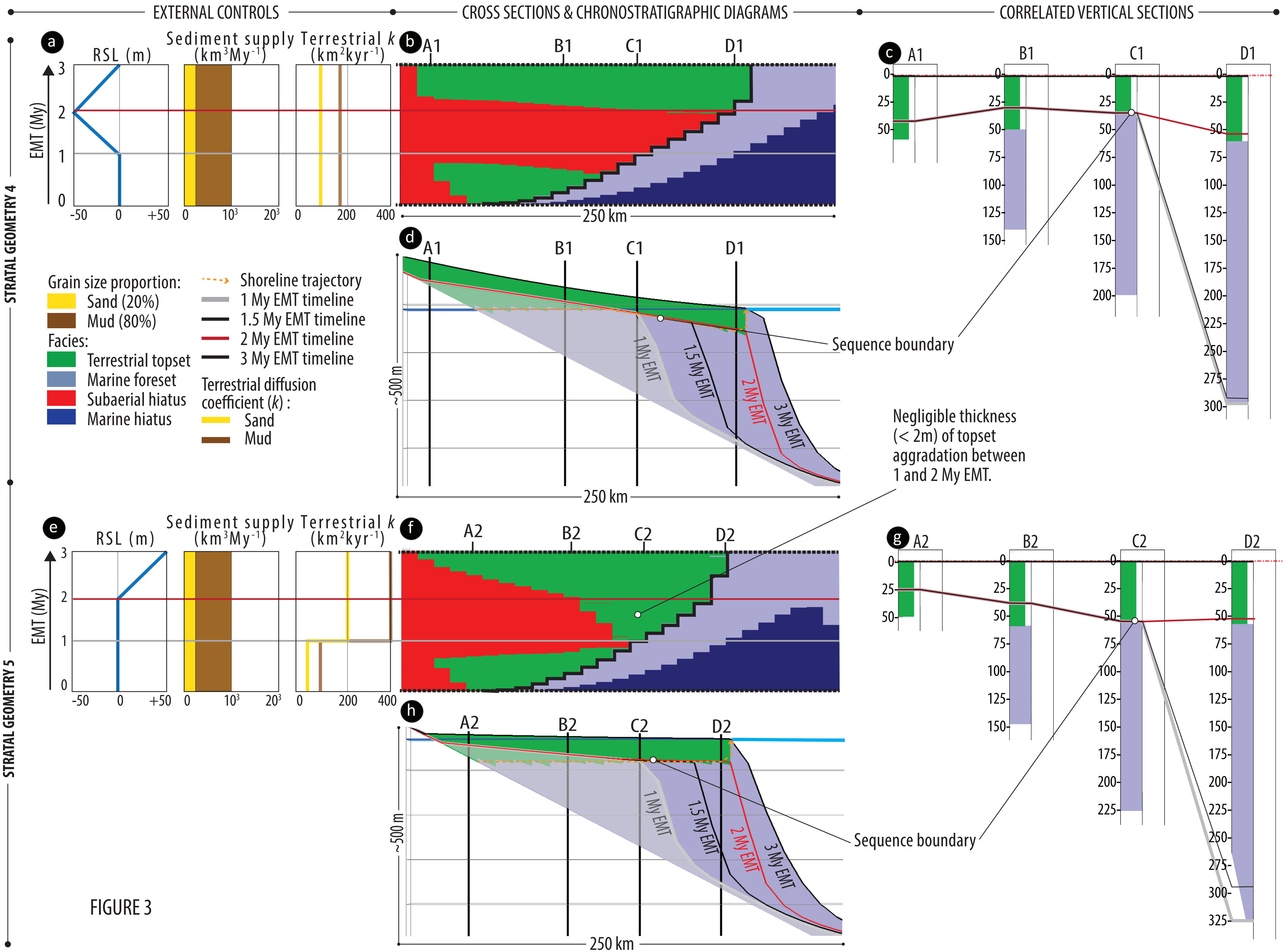
EXTERNAL CONTROLS
CROSS SECTIONS & CHRONOSTRATIGRAPHIC DIAGRAMS
CORRELATED VERTICAL SECTIONS
STRATAL GEOMETRY 4
STRATAL GEOMETRY 5
a
RSL (m)
Sediment supply ($km^3My^{-1}$)
Terrestrial k ($km^2kyr^{-1}$)
EMT (My)
3
2
1
0
-50
0
+50
0
$10^3$
$20^3$
0
200
400
b
A1
B1
C1
D1
250 km
c
A1
B1
C1
D1
0
25
50
75
100
125
150
175
200
225
250
275
300
d
A1
B1
C1
D1
~500 m
1 My EMT
1.5 My EMT
2 My EMT
3 My EMT
250 km
Sequence boundary
Grain size proportion:
🟨 Sand (20%)
🟫 Mud (80%)
Facies:
🟩 Terrestrial topset
🟦 Marine foreset
🟥 Subaerial hiatus
🟦 Marine hiatus
Shoreline trajectory
1 My EMT timeline
1.5 My EMT timeline
2 My EMT timeline
3 My EMT timeline
Terrestrial diffusion coefficient (k) :
Sand
Mud
Negligible thickness (< 2m) of topset aggradation between 1 and 2 My EMT.
e
RSL (m)
Sediment supply ($km^3My^{-1}$)
Terrestrial k ($km^2kyr^{-1}$)
EMT (My)
3
2
1
0
-50
0
+50
0
$10^3$
$20^3$
0
200
400
f
A2
B2
C2
D2
g
A2
B2
C2
D2
0
25
50
75
100
125
150
175
200
225
250
275
300
325
h
A2
B2
C2
D2
~500 m
1 My EMT
1.5 My EMT
2 My EMT
3 My EMT
250 km
Sequence boundary

FIGURE 3

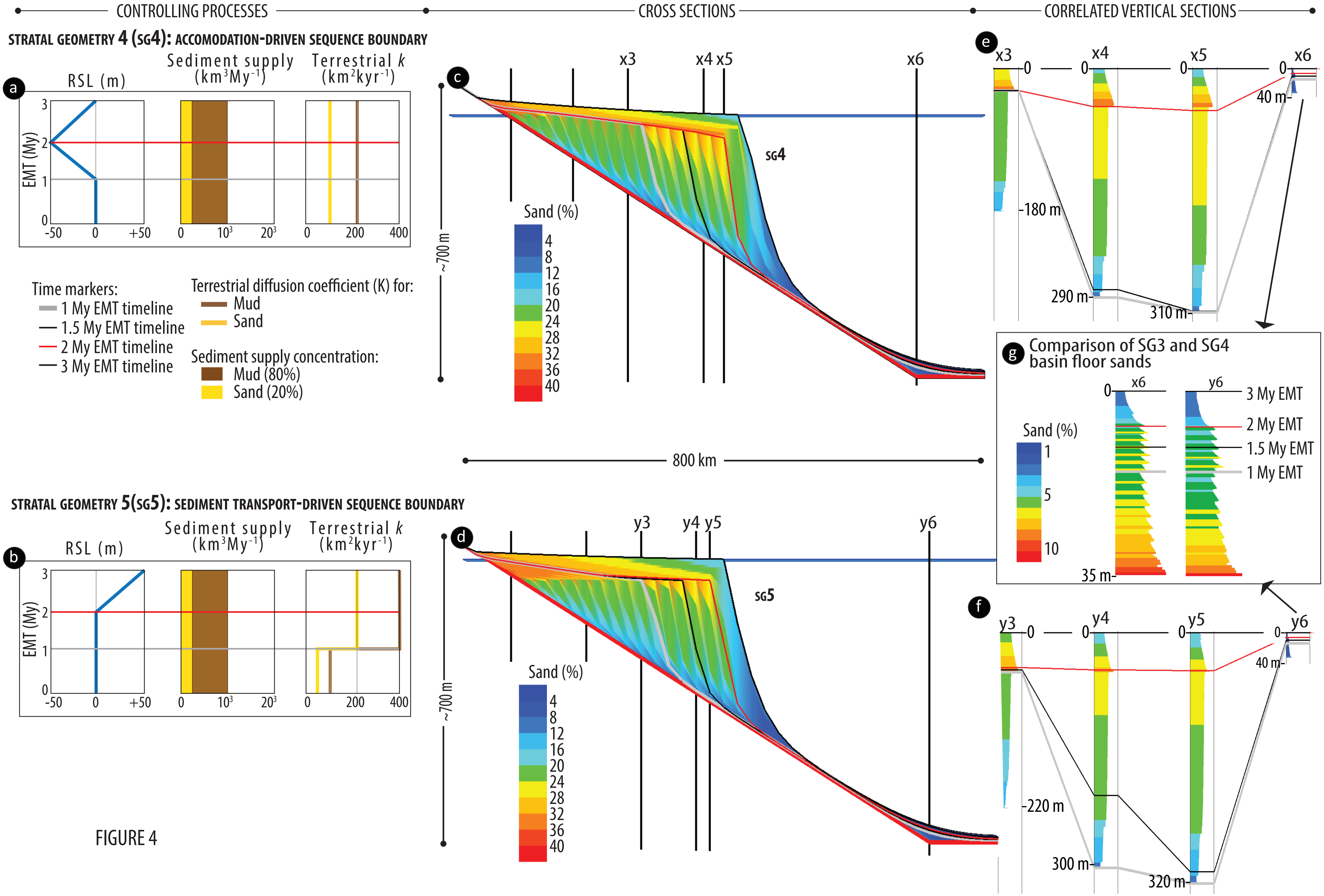
CONTROLLING PROCESSES
CROSS SECTIONS
CORRELATED VERTICAL SECTIONS
STRATAL GEOMETRY 4 (SG4): ACCOMODATION-DRIVEN SEQUENCE BOUNDARY
a
RSL (m)
Sediment supply (km³My⁻¹)
Terrestrial k (km²kyr⁻¹)
EMT (My)
3
2
1
0
-50
0
+50
0
10³
20³
0
200
400
Time markers:
1 My EMT timeline
1.5 My EMT timeline
2 My EMT timeline
3 My EMT timeline
Terrestrial diffusion coefficient (K) for:
Mud
Sand
Sediment supply concentration:
Mud (80%)
Sand (20%)
c
x3
x4 x5
x6
SG4
~700 m
Sand (%)
4
8
12
16
20
24
28
32
36
40
800 km
e
x3
x4
x5
x6
0
-180 m
290 m
310 m
40 m
g
Comparison of SG3 and SG4 basin floor sands
Sand (%)
1
5
10
x6
y6
0
35 m
3 My EMT
2 My EMT
1.5 My EMT
1 My EMT
STRATAL GEOMETRY 5(SG5): SEDIMENT TRANSPORT-DRIVEN SEQUENCE BOUNDARY
b
RSL (m)
Sediment supply (km³My⁻¹)
Terrestrial k (km²kyr⁻¹)
EMT (My)
3
2
1
0
-50
0
+50
0
10³
20³
0
200
400
d
y3
y4 y5
y6
SG5
~700 m
Sand (%)
4
8
12
16
20
24
28
32
36
40
f
y3
y4
y5
y6
0
-220 m
300 m
320 m
40 m

FIGURE 4

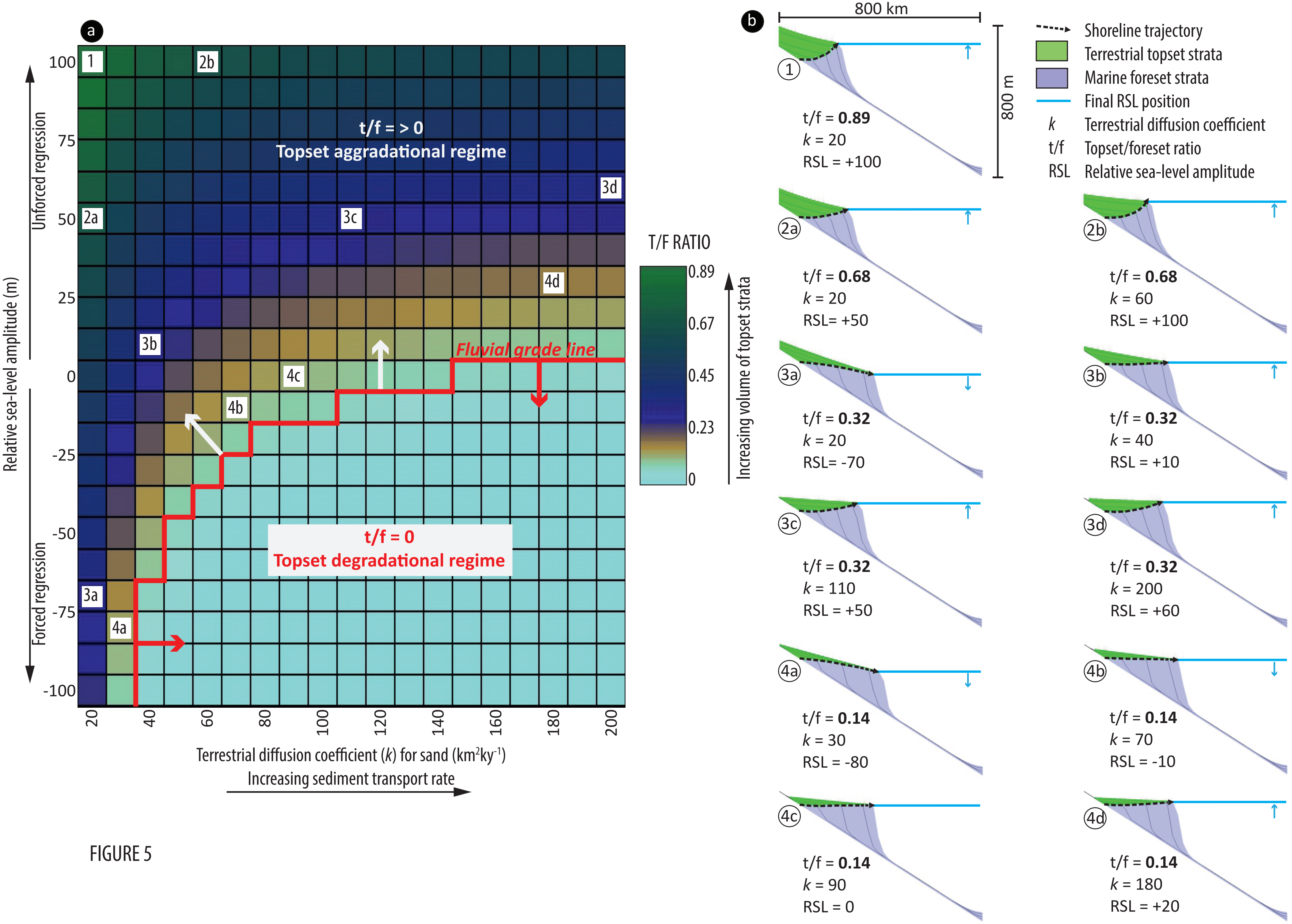
a
Relative sea-level amplitude (m)
Unforced regression
Forced regression
100
75
50
25
0
-25
-50
-75
-100
1
2a
2b
3a
3b
3c
3d
4a
4b
4c
4d
t/f = > 0
Topset aggradational regime
Fluvial grade line
t/f = 0
Topset degradational regime
20
40
60
80
100
120
140
160
180
200
Terrestrial diffusion coefficient (k) for sand (km²ky⁻¹)
Increasing sediment transport rate
T/F RATIO
0.89
0.67
0.45
0.23
0
Increasing volume of topset strata
b
800 km
800 m
Shoreline trajectory
Terrestrial topset strata
Marine foreset strata
Final RSL position
k Terrestrial diffusion coefficient
t/f Topset/foreset ratio
RSL Relative sea-level amplitude
① t/f = 0.89 k = 20 RSL = +100
2a t/f = 0.68 k = 20 RSL= +50
2b t/f = 0.68 k = 60 RSL = +100
3a t/f = 0.32 k = 20 RSL= -70
3b t/f = 0.32 k = 40 RSL = +10
3c t/f = 0.32 k = 110 RSL = +50
3d t/f = 0.32 k = 200 RSL = +60
4a t/f = 0.14 k = 30 RSL = -80
4b t/f = 0.14 k = 70 RSL = -10
4c t/f = 0.14 k = 90 RSL = 0
4d t/f = 0.14 k = 180 RSL = +20

FIGURE 5

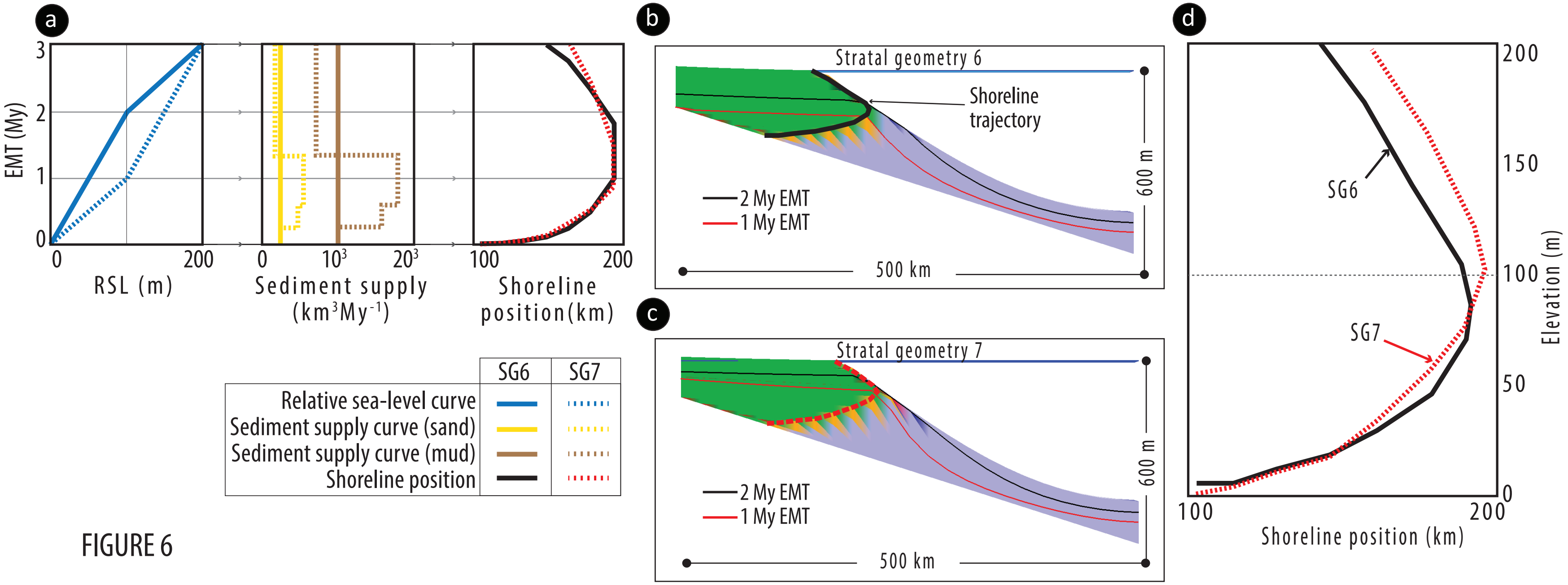
a
EMT (My)
3
2
1
0
0
200
RSL (m)
0
$10^3$
$20^3$
Sediment supply ($km^3My^{-1}$)
100
200
Shoreline position(km)
SG6
SG7
Relative sea-level curve
Sediment supply curve (sand)
Sediment supply curve (mud)
Shoreline position
b
Strata geometry 6
Shoreline trajectory
2 My EMT
1 My EMT
600 m
500 km
c
Stratal geometry 7
2 My EMT
1 My EMT
600 m
500 km
d
SG6
SG7
200
150
100
50
0
Elevation (m)
100
200
Shoreline position (km)

FIGURE 6

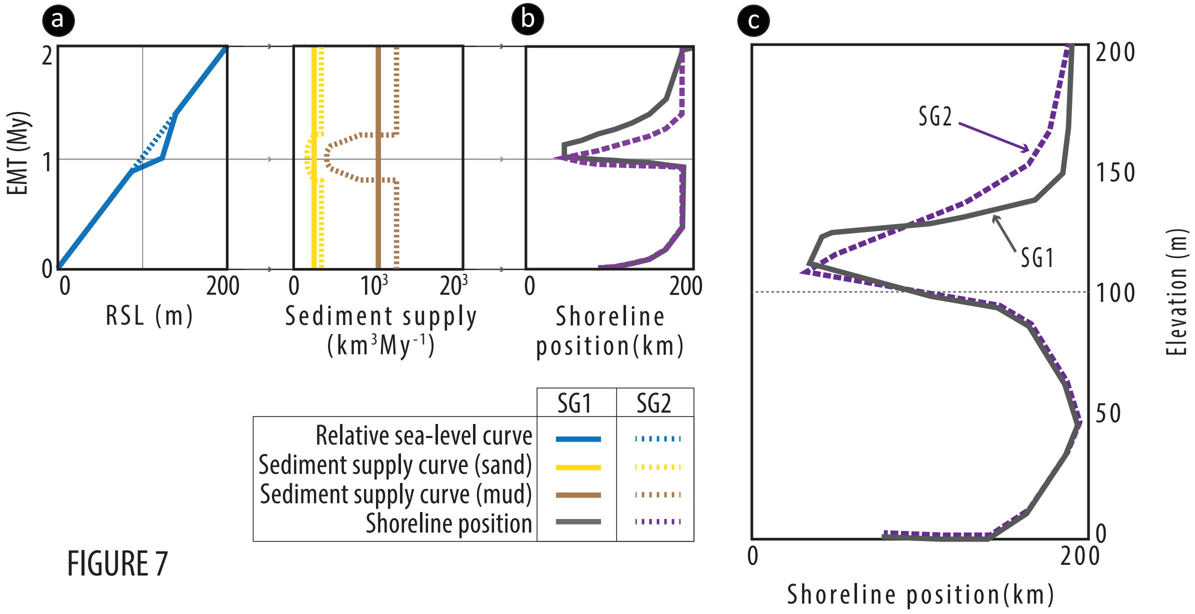
a
EMT (My)
0
1
2
0
200
RSL (m)
0
$10^3$
$20^3$
Sediment supply ($km^3My^{-1}$)
b
0
200
Shoreline position(km)
c
SG2
SG1
0
50
100
150
200
Elevation (m)
0
200
Shoreline position(km)
SG1
SG2
Relative sea-level curve
Sediment supply curve (sand)
Sediment supply curve (mud)
Shoreline position

FIGURE 7