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Quantitative stratigraphic analysis in a source-to-sink numerical framework

Xuesong Ding[1], Tristan Salles[1], Nicolas Flament[2], and Patrice Rey[1]

[1]Basin GENESIS Hub, EarthByte Group, School of Geosciences, The University of Sydney, Sydney, NSW 2006, Australia
[2]School of Earth and Environmental Science, University of Wollongong, Wollongong, NSW 2522, Australia

Correspondence: Xuesong Ding (xuesong.ding@sydney.edu.au)

Abstract.

The sedimentary architecture at continental margins reflects the interplay between the rate of change of accommodation creation (δA) and the rate of change of sediment supply (δS). As a result, stratigraphic interpretation increasingly focuses on understanding the link between deposition patterns and changes in $\delta A/\delta S$. Here, we use the landscape modelling framework *pyBadlands* to assess the respective performance of two well-established stratigraphic interpretation techniques: the trajectory analysis method and the accommodation succession method. In contrast to most Stratigraphic Forward Models (SFMs), *pyBadlands* provides self-consistent sediment supply to basin margins as it simulates erosion, sediment transport and deposition in a source-to-sink context. We present a landscape evolution that takes into account periodic sea level variations and passive margin thermal subsidence over 30 million years, under uniform rainfall. We implement the two aforementioned approaches to interpret the resulting depositional cycles at the continental margin. We first apply both the trajectory analysis and the accommodation succession methods to manually map key stratigraphic surfaces and define stratigraphic units from shelf-edge (or offlap break) trajectories, stratal terminations and stratal geometries. We then design a set of post-processing numerical tools to calculate shoreline and shelf-edge trajectories, the temporal evolution of changes in accommodation and sedimentation, and automatically produce stratigraphic interpretations. Comparing manual and automatic stratigraphic interpretations reveals that the results of the trajectory analysis method depend on time-dependent processes such as thermal subsidence whereas the accommodation succession method does not. In addition to reconstructing stratal stacking patterns, the tools we introduce here make it possible to quickly extract Wheeler diagrams and synthetic cores at any location within the simulated domain. Our work provides an efficient and flexible quantitative sequence stratigraphic framework to evaluate the main drivers (climate, sea level and tectonics) controlling sedimentary architectures and investigate their respective roles in sedimentary basins development.

1 Introduction

Since its introduction in the late 1970's, sequence stratigraphic architecture has been interpreted in terms of variations in eustatic sea level or relative sea level (*i.e.* accommodation change) (Vail et al., 1977a; Pitman, 1978; Posamentier et al., 1988; Posamentier and Vail, 1988; Jervey, 1988). With recognition of the role of sediment supply in affecting stratal geometries, changes in accommodation (δA) versus sediment supply (δS) - the $\delta A/\delta S$ ratio - has been widely accepted as the main control of sequence formation (Schlager, 1993; Muto and Steel, 1997; Catuneanu et al., 2009; Neal and Abreu, 2009; Neal et al., 2016). The $\delta A/\delta S$ ratio offers several advantages compared to other stratigraphic interpretation methods as it directly relates depositional patterns to the main contributing geological drivers (*e.g.* eustasy, tectonic and sediment supply). Yet, its practical application to stratigraphic interpretations remains challenging due to the inherent difficulties in accurately defining temporal variation of accommodation and, as a result, to quantify the $\delta A/\delta S$ ratio (Muto and Steel, 2000; Burgess et al., 2016). Insights into the links between depositional trends and changing $\delta A/\delta S$ can be obtained from physical observations of stratal architectures. For example, Helland-Hansen et al. (1994; 1996; 2009) proposed the trajectory analysis method that relates depositional units to the lateral and vertical migrations of the shoreline and shelf-edge trajectories. Neal et al. (2009; 2016) proposed a refined sequence stratigraphic method known as the accommodation succession in which sequence sets are interpreted based on offlap break trajectory and stratal geometries. The temporal evolution of accommodation change and sediment supply can then be derived from interpreted sequence sets and key stratigraphic bounding surfaces.

Over the past few decades, stratigraphic forward models (SFMs) has been widely used to investigate the interplay between major sequence-controlling factors (e.g. eustasy, tectonics, flexural isostasy, sediment supply, sediment compaction, basin physiography, etc.) and to quantify their influences on the development of sedimentary architecture (Reynolds et al., 1991; Posamentier and Allen, 1993; Steckler et al., 1993; Carvajal and Steel, 2009; Burgess et al., 2012; Granjeon et al., 2014; Csato et al., 2014; Sylvester et al., 2015; Harris et al., 2015, 2016). However, sediment supply in most SFMs is usually imposed and assumed to be constant in time, making it difficult to link model predictions with observations. In this study, we use the landscape evolution code *pyBadlands* that simulates sediment supply and routing from source to sink in a self-consistent manner (Salles, 2016; Salles and Hardiman, 2016; Salles et al., 2018). In *pyBadlands*, the erosion from upstream catchments is linked to sedimentation on basin margins through sediment routing resulting from a combination of channelling and hillslope processes. Sediment supply to continental margins is dynamically determined without user control; it results from the interaction of imposed tectonic, climatic and eustatic variations as well as autogenic changes in upstream catchment physiography.

The aims of this work are (1) to integrate the trajectory analysis method (Helland-Hansen and Hampson, 2009) and the accommodation succession method (Neal et al., 2016) within *pyBadlands* to derive quantitative interpretations; and (2) to assess the performance of these two methods for the interpretation of stratal architecture predicted with *pyBadlands*. To illustrate the workflow, we build a synthetic source-to-sink model that includes a mountain range (sediment source), an alluvial plain (sediment transfer zone) and a passive continental margin (sink area) where relatively well understood sequence-controlling drivers such as eustasy and thermal subsidence (Watts and Steckler, 1979; Bond et al., 1989; Steckler et al., 1993) are imposed.

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The synthetic stratal architecture is first interpreted following the workflow of the trajectory analysis and the accommodation succession methods. To automatise the definition of stratigraphic units, we then design a suite of numerical tools for the extraction of the shoreline and shelf-edge trajectories, the accommodation change and sedimentation evolution over space and time. These new capabilities make it possible to quickly interpret in a consistent manner synthetic depositional cycles using either the trajectory analysis or the accommodation succession method.

2 Methods of stratigraphic interpretations

Observation-based methods to interpret stratigraphic sequences have the advantage of being objective and independent of spatial and temporal scales. Hence, over the years, it has been recognised that stratigraphic interpretations should be guided by physical observations such as stratal terminations, stratal geometries and the trajectories of the shoreline and/or the shelf-edge (Abreu et al., 2014), and independent of depositional models and associated assumptions. Here, we focus on two such methods: (1) the trajectory analysis and (2) the accommodation succession method.

Helland-Hansen et al. (1994; 1996; 2009) designed trajectory analysis technique to define different trajectory classes based on the trajectories recorded at either shoreline or shelf-edge positions. Though both represents a break-in-slope, the shelf-edge evolves at larger spatial (Fig. 1) and over longer temporal scales than the shoreline, making it easier to define the shelf-edge on seismic data. By investigating the migration direction of the shoreline and the shelf-edge, four shoreline trajectory classes and three shelf-edge trajectory classes are used to characterise the successive depositional packages. The shoreline trajectory classes include the transgressive trajectory class (TTC), the ascending regressive trajectory class (ARTC), the descending regressive trajectory class (DRTC) and the stationary (*i.e.* non-migratory) shoreline trajectory class. The shelf-edge trajectory classes include descending trajectory class (DTC), ascending trajectory class (ATC), transgressive trajectory class (T) and stationary or flat trajectory class (Fig. 1).

Neal et al. (2009; 2016) presented a refined hierarchy framework, known as the accommodation succession method, in which the observations of depositional units are entirely based on the stratal geometry resulting from the evolution of accommodation change and sediment infill. Three stacking patterns and their bounding surfaces are defined and subsequently used to assess the changing history of accommodation and sediment supply (Fig. 1). These include the retrogradation stacking (R) for $\delta A/\delta S > 1$, the progradation to aggradation stacking (PA) for $\delta A/\delta S < 1$ and increasing, and the aggradation to progradation (even to degradation) stacking (AP or APD) for $\delta A/\delta S < 1$ and decreasing (and possibly negative). The three key surfaces bounding these stacking patterns are the sequence boundary (SB), the maximum transgressive surface (MTS) and the maximum regressive surface (MRS).

3 Building the stratigraphic architecture in *pyBadlands*

The workflow to build the stratigraphic architecture in *pyBadlands* is illustrated in Figure 2. In this study, we focus on the post-processing of model outputs. *pyBadlands* records the depth, the relative elevation and the thickness of each stratigraphic layer

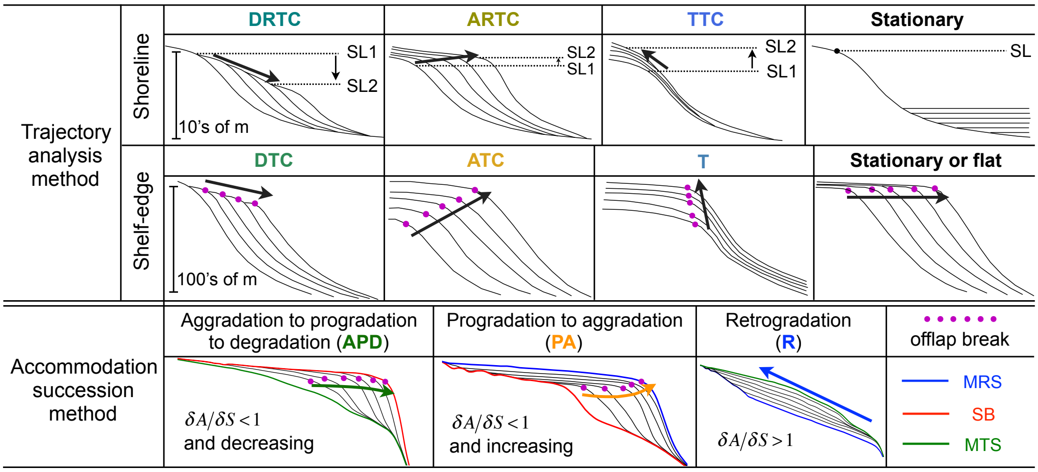

Figure 1. Stratigraphic sequence interpretation approaches used in this study. In the trajectory analysis method, four shoreline trajectory classes and three shelf-edge trajectory classes are delineated based on the lateral and vertical migrations of shoreline and shelf-edge. The shoreline trajectory classes include descending regressive trajectory class (DRTC), ascending regressive trajectory class (ARTC), transgressive trajectory class (TTC) and stationary trajectory class. The shelf-edge trajectory classes include descending (DTC), ascending (ATC), transgressive (T) and stationary shelf-edge trajectory classes (Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009). In the accommodation succession method, three types of stacking patterns and their bounding surfaces are defined based on observations of stratal terminations (e.g. onlap, offlap, etc) and stratal geometries, including aggradation to progradation to degradation (APD) stacking, progradation to aggradation (PA) stacking and retrogradation (R) stacking. The bounding surfaces are sequence boundary (SB), maximum transgressive surface (MTS) and maximum regressive surface (MRS). Each stacking pattern reflects changes in the rate of accommodation creation (δA) with respect to the rate of sediment supply (δS) at the shoreline. APD stacking corresponds to $\delta A/\delta S < 1$, with a decreasing trend that can be negative; PA stacking represents $\delta A/\delta S < 1$ and increasing; finally, R stacking occurs for $\delta A/\delta S > 1$ (Neal and Abreu, 2009; Neal et al., 2016).

through time. With these information, we are able to reconstruct the stratal stacking patterns, Wheeler diagrams and vertical stacking patterns (*i.e.* synthetic cores) at any locations.

We then interpret the synthetic depositional cycles in two ways. Firstly, we follow the workflow proposed in the trajectory analysis and the accommodation succession method. We manually mark the shelf-edge (or offlap break) trajectory and stratal terminations on the final output of stratal stacking pattern reconstructed from a simulated cross-section. Key stratigraphic surfaces and stacking patterns are then defined. Secondly, a series of post-processing tools are implemented in *pyBadlands* to numerically extract the shoreline and shelf-edge positions, and the temporal evolution of δA and δS through time and space (Fig. 3). The shoreline position is recorded by tracking the topographic contour equals to sea level. The shelf-edge is calculated by assuming a critical slope 0.025 degree in this case. Changes in relative sea level and sedimentation rate are used as proxies for δA and δS (Poag and Sevon, 1989; Galloway and Williams, 1991; Liu and Galloway, 1997; Galloway, 2001). Therefore, δA at any given location from time T1 to T2 integrates changes in eustatic sea level and basement subsidence, δS at any

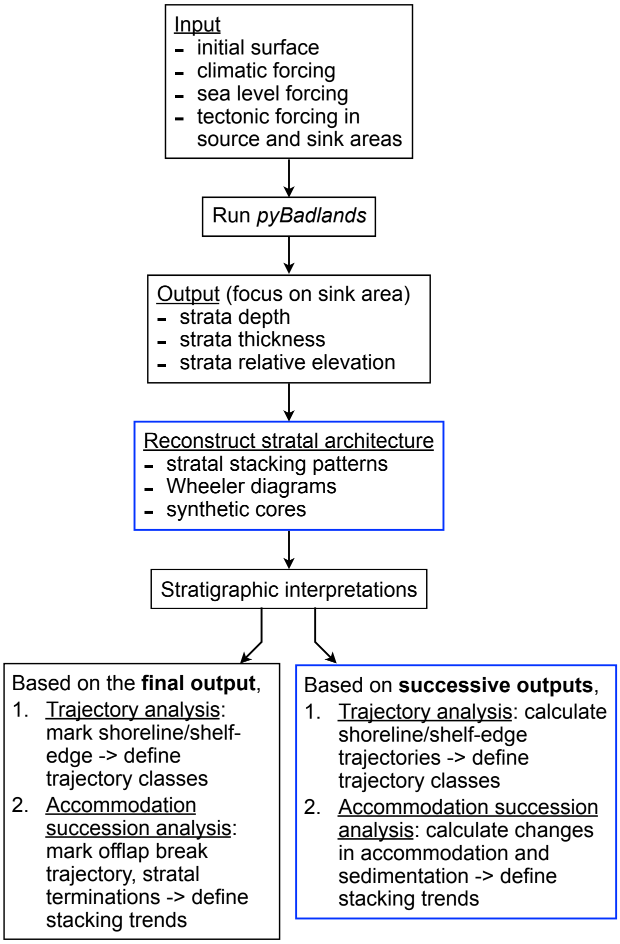

Figure 2. Workflow to build the stratigraphic architecture in *pyBadlands*. The new post-processing workflows designed to automatically interpret stratigraphic sequences are shown in the blue boxes.

given location between time T1 and T2 is given by deposited strata thickness. In this study, both δA and δS are in $\mathrm{m/Myr}$. Trajectory classes, stacking patterns and stratigraphic surfaces are defined automatically based on calculated shoreline, shelf-edge trajectories and time-dependent δA and δS.

4 Experimental setup, assumptions and simplifications

We provide an example to illustrate how our workflow can be used to automatically generate stratigraphic sequences and analyse them in an integrated numerical toolbox.

We create an initial synthetic landscape of dimensions 300 km by 200 km with a spatial resolution of 0.5 km. The region includes a mountain range, an alluvial plain and an adjacent continental margin consisting of a continental shelf, a continental

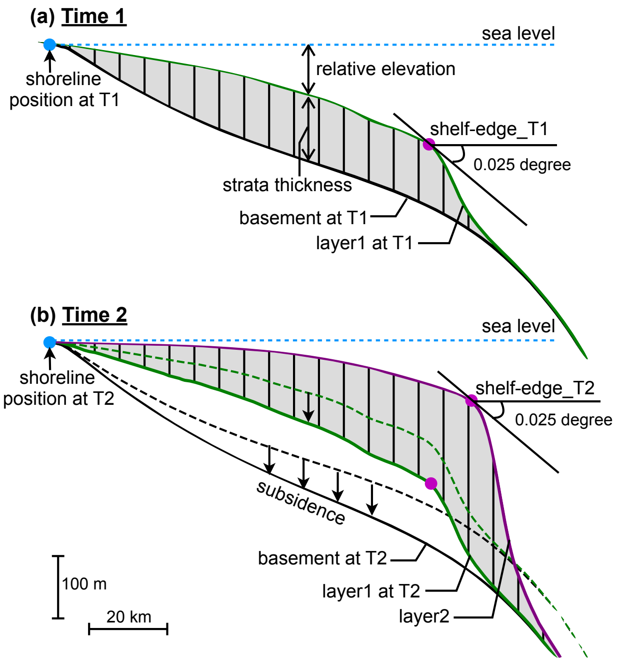

Figure 3. Schematic diagram showing the sedimentation from T1 to T2 under sea level variation and basement subsidence. The depth, the relative elevation and the thickness of stratigraphic layer are recorded at every time step. Post-processing tools extract the shoreline and shelf-edge positions, and calculate the rate of accommodation creation (δA) and the rate of sedimentation (δS) through time. The shoreline position is recorded by tracing the topographic contour equals to sea level. The shelf-edge is calculated by assuming a critical slope 0.025 degree. δA is calculated as changes in relative sea level over (T2-T1): (sea level change + subsidence)/(T2-T1); δS is calculated as deposited strata thickness over (T2-T1): (strata thickness)/(T2-T1).

slope and an oceanic basin. Details of the geometry are presented in Figure 4a. The model duration is 30 Myr, generating 300 stratigraphic layers with display intervals every 0.1 Myr. Our model setting mimics the first-order, long-term landscape evolution and associated stratigraphic sequence development along a passive continental margin, with forcing conditions including climate, sea level change and thermal subsidence.

In this study, we use a single flow direction, detachment-limited stream power law, and a simple downslope creep law to describe sediment erosion, transport and deposition. Detailed information can be found in Salles et al. (2016; 2018).

Considering that the present study is focused on long-term stratigraphic evolution, climatic forcing is assumed to be directly related to precipitation with a spatially and temporally uniform precipitation rate of 2.0 m/yr for the entire duration of the simulation (30 Myr).

Sea level fluctuations are a major driver of changes in accommodation and thus stratigraphic sequences development. They act at different temporal scales, resulting in various stratigraphic cycles with first-order cycles of duration around 200-300 Myr; second-order cycles of duration around 10-80 Myr; and third-order cycles of duration 1-10 Myr (Vail et al., 1977b). Here

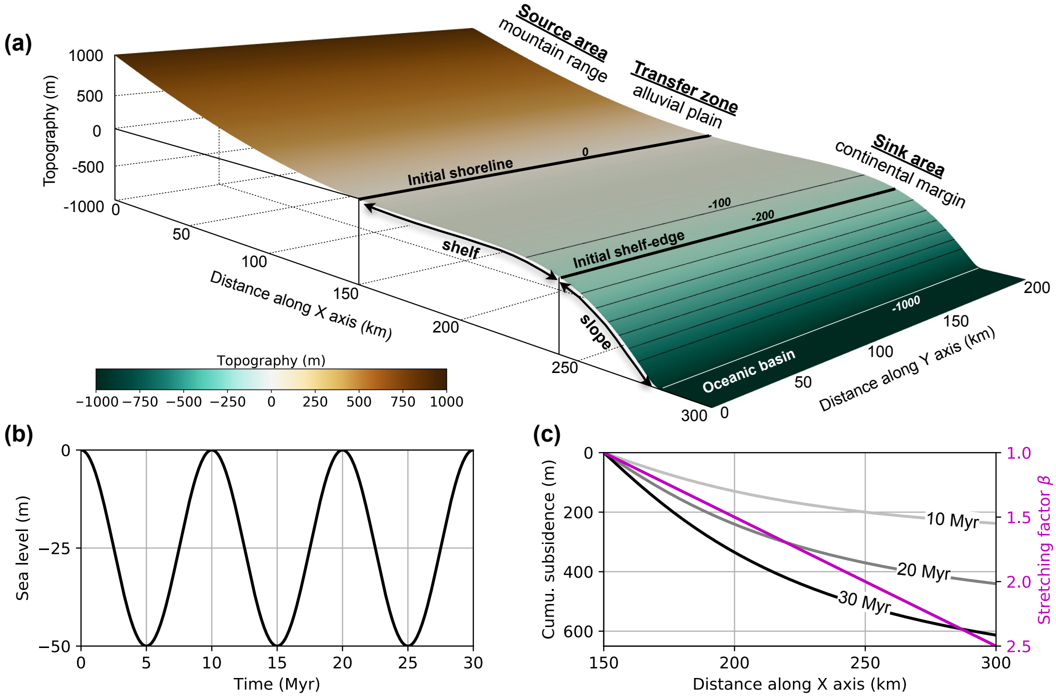

Figure 4. Model setup. (a) The initial surface elevation of the mountain region ranges from 200 m to 1000 m over a width of 100 km, while the elevation of the alluvial plain ranges from 0 m to 200 m over a width of 50 km. The sink area includes a continental margin in which the elevation of the continental shelf ranges from -250 m to 0 m over a width of 80 km, the elevation of the continental slope ranges from -1000 m to -250 m over a width of 40 km and a flat oceanic basin whose depth is -1000 m over a width of 30 km. Black lines are isobaths with an interval of 100 m. The initial elevations of shoreline and shelf-edge are 0 m and -200 m. (b) Eustatic sea level scenario modelled using a sinusoidal curve consisting of three 10 Myr cycles of peak-to-peak amplitude 50 m. (c) Distance-dependent stretching factor β and the resulting thermal subsidence at 10 Myr, 20 Myr, and 30 Myr across the continental margin.

we consider the effects of long-term eustatic cycles and assume that eustasy is independent of climate and local tectonics. For simplicity, eustatic sea level is modelled using a sinusoidal curve consisting of three 10 Myr cycles of 50 m amplitude (Fig. 4b), which correspond to second- to third-order eustatic fluctuations (Vail et al., 1977b).

Thermal subsidence is an important process leading to the deepening of basin floor due to isostatic adjustment during lithosphere cooling. A simple stretching model from McKenzie (1978) is applied in this study, in which subsidence is produced by thermal relaxation following an episode of extension. The equation to derive the subsidence at time t is:

$$S(t) = E_0 r - E_0 exp(-t/\tau) \tag{1}$$

where $E_0 = 4a\rho_0\alpha T_1/\pi^2(\rho_0 - \rho_w)$, $r = \frac{\beta}{\pi}sin(\frac{\pi}{\beta})$, $a = 125$ km is the thickness of lithosphere, $\rho_0 = 3300\ \mathrm{kg/m^3}$ the density of the mantle at 0°C, $\rho_w = 1000\ \mathrm{kg/m^3}$ the density of seawater, $\alpha = 3.28\times10^{-5}\ \mathrm{K^{-1}}$ the thermal expansion coefficient for both the mantle and the crust, $T_1 = 1333^o$ C the temperature of the asthenosphere, and $\tau = 62.8$ Myr the characteristic thermal diffusion time. The stretching factor β characterises the extension of the lithosphere. These parameters are taken from McKenzie (1978). In our experiments, thermal subsidence is imposed on the continental margin, starting from the initial shoreline (Fig. 4a), which experiences the least subsidence, to the outward edge where subsidence is maximum. We take β as distance-dependent and calculate the thermal subsidence accumulated at 10 Myr, 20 Myr and 30 Myr, respectively (Fig. 4c). The subsidence rate is constant at each single position but increases along the X-axis. In our model, relative sea level is the combined result of eustatic sea level and thermal subsidence, and thus varies spatially due to basement subsidence.

5 Results

5.1 Predicted stratal architecture

Our post-processing tools quickly extract simulated stratal stacking pattern as well as a Wheeler diagram and vertical stacking patterns in any region of the simulated domain. Figure 5 presents the stratal architecture generated along a cross-section through the middle of the domain. The stratal architecture is coloured based on depositional environments defined using six water depth windows. We infer depositional facies, changes in depositional trends, stratal terminations and stratal geometries from the development of stratal stacking patterns. This information is then used to define stratigraphic surfaces and systems tracts evolution (Van Wagoner et al., 1988). The Wheeler diagram displays the horizontal distribution of sedimentary layer sequences, as well as hiatuses in sedimentation, which is essential to recognise significant bounding surfaces such as unconformities or sequence boundaries, as well as transgressive and flooding surfaces (Payton et al., 1977; Miall, 2004). Vertical stacking patterns from synthetic cores show parasequences thickness and temporal depositional trends of specific sedimentary units. For example, progradation generates a coarsening-upward stacking pattern while retrogradation produces a fining-upward stacking (Van Wagoner et al., 1990).

The cross-section in Figure 5b displays the upstream erosion in the source area, the sediment packages deposited on the continental shelf and slope, as well as the deep-sea fan. Three successive cycles of lateral and vertical shifts of depositional packages occur in the continental shelf and slope area (Fig. 5a). For each depositional cycle, sediments first prograde and downlap to the basement during aggradation, and then onlap over previous stratal layers during retrogradation (Fig. 5a, Fig. 7a). The progradation, aggradation and following retrogradation represent a complete cycle of stacking succession. Three erosional surfaces (*i.e.* unconformity, cyan dashed lines in Fig. 5a) are present in the stratal stacking pattern that correspond to the deposition hiatus periods shown on the Wheeler diagram (Fig. 5c). Two condensed sections (pink dashed lines in Fig. 5a) that correspond to periods of retrogradation, indicate limited sediment supply into distal area during landward shoreline migration shifts. The Wheeler diagram also shows three depositional cycles corresponding to similar lateral shoreline migrations (Fig. 5c). As the model evolves, deposited layers prograde at least 10 km seaward between successive cycles, as shown on both the stratal stacking pattern (Fig. 5a) and on the Wheeler diagram (Fig. 5c). This results in increasing seaward migration rate (s.m.r.) and landward migration rate (l.m.r) (Fig. 5c). The three depositional cycles also show aggradation stacking patterns related to accommodation creation induced by the imposed continuous thermal subsidence (Fig. 5a).

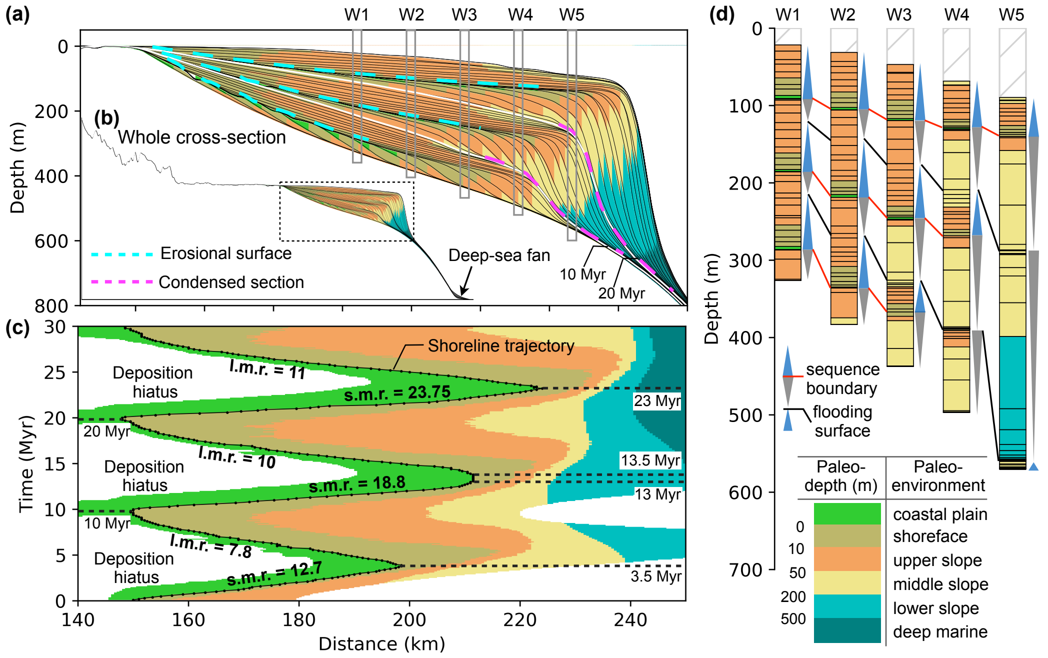

Figure 5. Predicted stratal architecture at 30 Myr. (a) Stratal stacking pattern for the cross-section shown on Fig. 3f. Black solid lines represent time lines at 0.5 Myr intervals. Dashed lines are erosional surfaces and condensed sections. Time lines at 10 Myr and 20 Myr are coloured in white. (b) Inset: whole cross-section with dashed box corresponding to the zoomed area presented in panel (a). (c) Wheeler diagram or chronostratigraphy chart. The solid line with black dots represents the shoreline trajectory. Dashed lines and the times indicate transitions in shoreline migration direction. Landward migration rates (l.m.r. in km/Myr) and seaward migration rates (s.m.r. in km/Myr) of shoreline are also shown for each migration cycle. (d) Vertical stacking patterns (or synthetic cores) extracted between 190 km (W1) to 230 km (W5) at 10 km intervals. The stratal stacking pattern, Wheeler diagram and vertical stacking patterns are coloured by paleo-water depth that can be used to represent different depositional environments. Assuming that grain size is determined by depositional environments, the facies successions can be defined, and in turn sequence boundaries and flooding surfaces can also be defined (Van Wagoner et al., 1990). Blue triangles represent upward-fining, gray triangles represent upward-coarsening. The paleo-depth and topography shown in this figure were directly produced by our post-processing tool.

Vertical stacking patterns (i.e. synthetic cores) are extracted at 10 km intervals from 190 km to 230 km (W1 to W5) along the cross-section (Figs 5a and d). Three cyclical vertical stacking are recognised for wells W1 to W3. Three sequence boundaries corresponding to extensive erosional surfaces as well as two flooding surfaces are apparent on these first three wells. The flooding surfaces extend down to wells W4 and W5, however, only the uppermost erosional surface is recorded in the vertical stacking pattern of the most distal core (well W5).

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5.2 Interpretations of depositional sequences

We now focus on the interpretation of the stratal architecture using both trajectory analysis and accommodation succession methods. We compare and contrast the interpretations resulting from the manual application of both methods, and from quantitative analysis using our post-processing tools.

5.2.1 Trajectory analysis

On the stratal stacking pattern extracted from the final output at 30 Myr, we manually pick the break-in-slope of the shelf-slope scale clinoforms as shelf-edge positions (magenta dots in Fig. 6a). Shoreline positions are difficult to be picked on the cross-section because shoreline clinoforms are not well developed with this model setting. We therefore focus on the analysis of shelf-edge trajectory evolution. According to its lateral and vertical shifts through time, descending shelf-edge trajectory classes are identified from 0 to 5 Myr, 10 to 14 Myr, and 20 to 23 Myr; ascending shelf-edge trajectory classes are recognised from 5 to 6.5 Myr, 14 to 17 Myr and from 23 to 26.5 Myr, and transgressive shelf-edge trajectory classes are defined from 6.5 to 10 Myr, 17 to 20 Myr, and 26.5 to 30 Myr (Fig. 6a).

In addition to manually picking the shelf-edge trajectory on the final output, we developed post-processing tools to extract time-dependent shelf-edge and shoreline positions from successive outputs and interpret predicted depositional cycles accordingly. Figure 6b displays the extracted lateral and vertical migrations of the shelf-edge position and interpreted shelf-edge trajectory classes. The descending shelf-edge trajectory classes (DTC) is identified from 0 to 3.5 Myr, 10 to 13 Myr, and 20 to 22.5 Myr; the ascending shelf-edge trajectory class (ATC) is identified from 3.5 to 6.5 Myr, 13 to 16.5 Myr and from 22.5 to 25.5 Myr, and the transgressive shelf-edge trajectory class is identified from 6.5 to 10 Myr, 16.5 to 20 Myr, and 25.5 to 30 Myr (Fig. 6b). The shelf-edge trajectory classes identified through time generally resemble the ones identified manually from the final output, with differences in the timing of transition from one class to another by up to 1.5 Myr, which is greater than the temporal resolution (0.5 Myr) used to represent stratigraphic sequences (Figs 6a and b).

We now use the post-processing toolbox to identify changes in shoreline trajectories that are difficult to pick manually for this case. Figure 6c displays the automatically-detected lateral and vertical migrations of the shoreline position and interpreted shoreline trajectory classes accordingly. The descending regressive trajectory class (DRTC) is identified from 0 to 4 Myr, 10 to 13.5 Myr, and 20 to 23 Myr; the transgressive trajectory class (TTC) is identified from 5 and 10 Myr, 15 and 20 Myr, and 25 to 30 Myr (Fig. 6c). The transition from DRTC to TTC is concomitant with a depositional hiatus and the formation of an erosional surface, whereas the transition from TTC to DRTC is related to condensed stacking sections in the distal area induced by limited sediment supply (Fig. 5c). We note that between 4 and 5 Myr, 13.5 and 15 Myr, and 23 and 25 Myr, the shoreline migrates landward even though sea level is falling, that we name the "descending transgressive trajectory class" (DTTC) as this shoreline evolution is not described in the literature. In our models, the DTTC occurs because the basement subsidence overrides the falling sea level and thus creates positive accommodation (Fig. 6e). This phenomenon is due to the model forcing conditions, and its identification directly linked to the time-dependent analysis of shoreline trajectory carried out here.

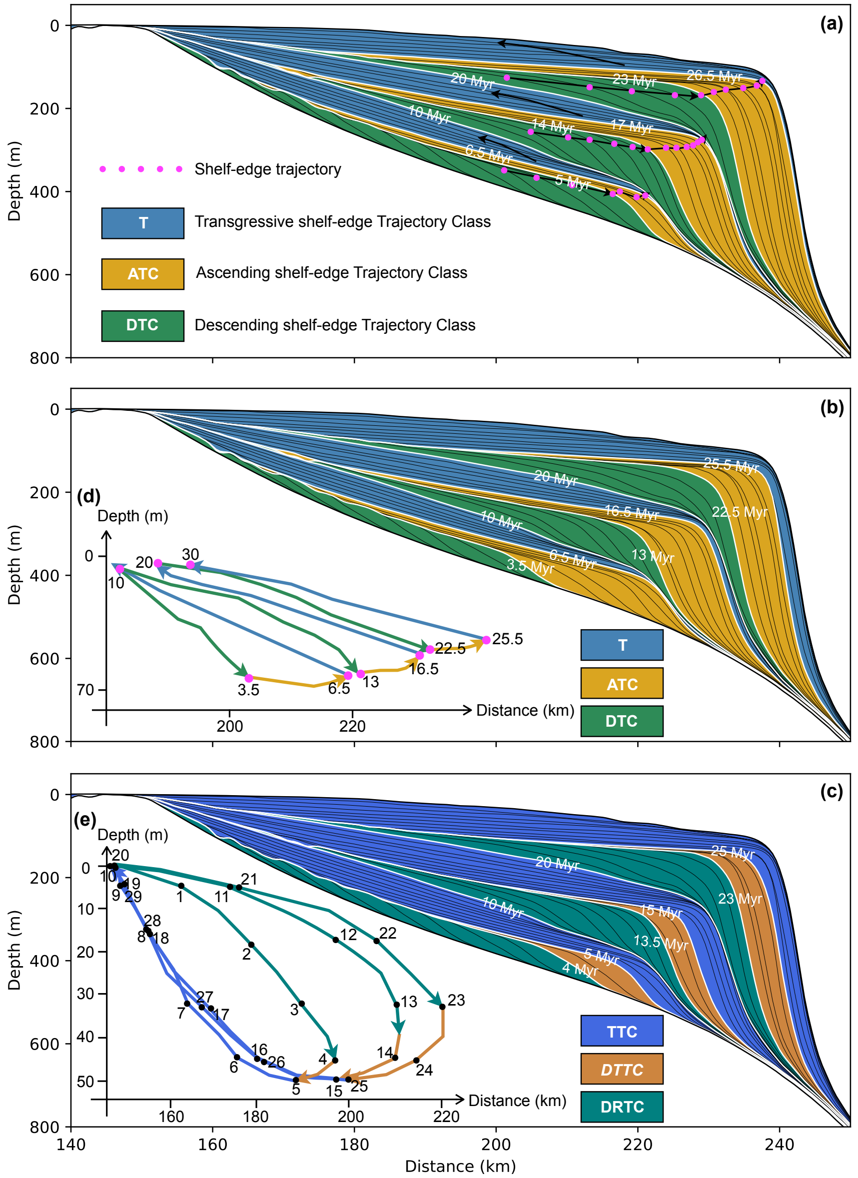

Figure 6. Interpretation of trajectory classes based on analysis of shoreline and shelf-edge trajectories (Helland-Hansen and Hampson, 2009). (a) Shelf-edge trajectory classes based on manually picking the shelf-edge trajectory (magenta dots) on the final output of stratal stacking pattern. (b) Automatically picking of shelf-edge trajectory classes based on calculated time-dependent shelf-edge positions in (d). (c) Automatically defined shoreline trajectory classes based on calculated time-dependent shoreline positions in (e). Time labels indicate the timing of each trajectory class formation. See Figure 1 for abbreviations.

5.2.2 Accommodation succession analysis

We then apply the accommodation succession method to analyze the sequence formation in terms of changes in accommodation and sedimentation. Following the workflow proposed by Neal and Abreu (2016), we first manually marked stratal terminations (*i.e.* onlap, downlap, toplap) and offlap breaks on the simulated stratal stacking pattern (Step 1 in Fig. 7a). Here, the offlap break is defined as the shelf-edge rather than the shoreline as shoreline scale clinoforms are not well generated in this model setting. Three stacking patterns and their bounding surfaces are then defined (Step 2 and Step 3 in Fig. 7a). For example, toplaps and downlaps are observed in the first 3.5 Myr and correspond to progradation (P) stacking. The stratal geometry associated with P stacking is characterized by either erosion or by a lack of topset deposition and relatively thick clinoform front. Though strata keep downlapping, onlap terminations start replacing toplap terminations after 3.5 Myr, which reflects successive phases of progradation and aggradation. This depositional trend is defined as progradation to aggradation (PA) stacking, which is characterized by thin topset deposits and thick clinoform fronts. The unconformity formed between P and PA stacking is interpreted as a sequence boundary (SB). Retrogradation (R) stacking corresponds to the onlapping of stratal deposits and landward shift of offlap break around 6.5 Myr. The thick topset deposit and condensed distal stacking characterize the stratal geometry deposited during this stage. Maximum regressive surfaces (MRS) are defined at the transition between PA and R stacking. At 10 Myr, the offlap break starts migrating seaward and downward. Toplap and downlap terminations are also observed after this time. The geometry of deposited strata also changes and is characterized by the formation of thicker clinoform fronts. This stacking corresponds to the AP class (aggradation to progradation). Maximum trangressive surfaces (MTS) separate R stacking from AP stacking. At 13 Myr, onlap terminations are visible and the offlap break starts migrating upward, corresponding to the transition towards PA stacking just above the SB surface. Following the same criteria, successive stacking of PA, R and AP as well as bounding surfaces (SB, MTS & MRS) are defined on the cross-section (Fig. 7b). Finally, the interpreted R, AP, and PA stacking patterns are used to assess the changing history of δA and δS (Step 4 in Fig. 7b).

Instead of calculating $\delta A/\delta S$ as a ratio (Neal et al., 2016), we compute $\delta A - \delta S$ at the shoreline over time (Fig. 7d), because δS can be equal to zero (Fig. 3). Under this approach, $\delta A - \delta S > 0$ corresponds to R stacking and is equivalent to $\delta A/\delta S > 1$; $\delta A - \delta S < 0$ and decreasing corresponds to APD stacking and is equivalent to $\delta A/\delta S < 1$ and decreasing; $\delta A - \delta S < 0$ and increasing corresponds to PA stacking and is equivalent to $\delta A/\delta S < 1$ and increasing. The stacking patterns can then be defined automatically (Fig. 7c), and are almost identical to the manually identified ones: differences in the timing of change of stacking pattern are 0.5 Myr at most, which is equal to the temporal resolution (0.5 Myr) with which stratigraphic sequences are represented on Figures 6 and 7.

6 Discussion

This study introduces quantitative interpretations of long-term stratal architectures predicted by the source-to-sink landscape modelling framework *pyBadlands*. Our interpretations follow both the shoreline and shelf-edge trajectory analysis (Helland-Hansen and Hampson, 2009) and the accommodation succession methods (Neal et al., 2016). Shoreline and shelf-edge represent the break-in-slope of clinoforms at different scales (Patruno et al., 2015, ; Fig. 1). For the considered model, shelf-slope

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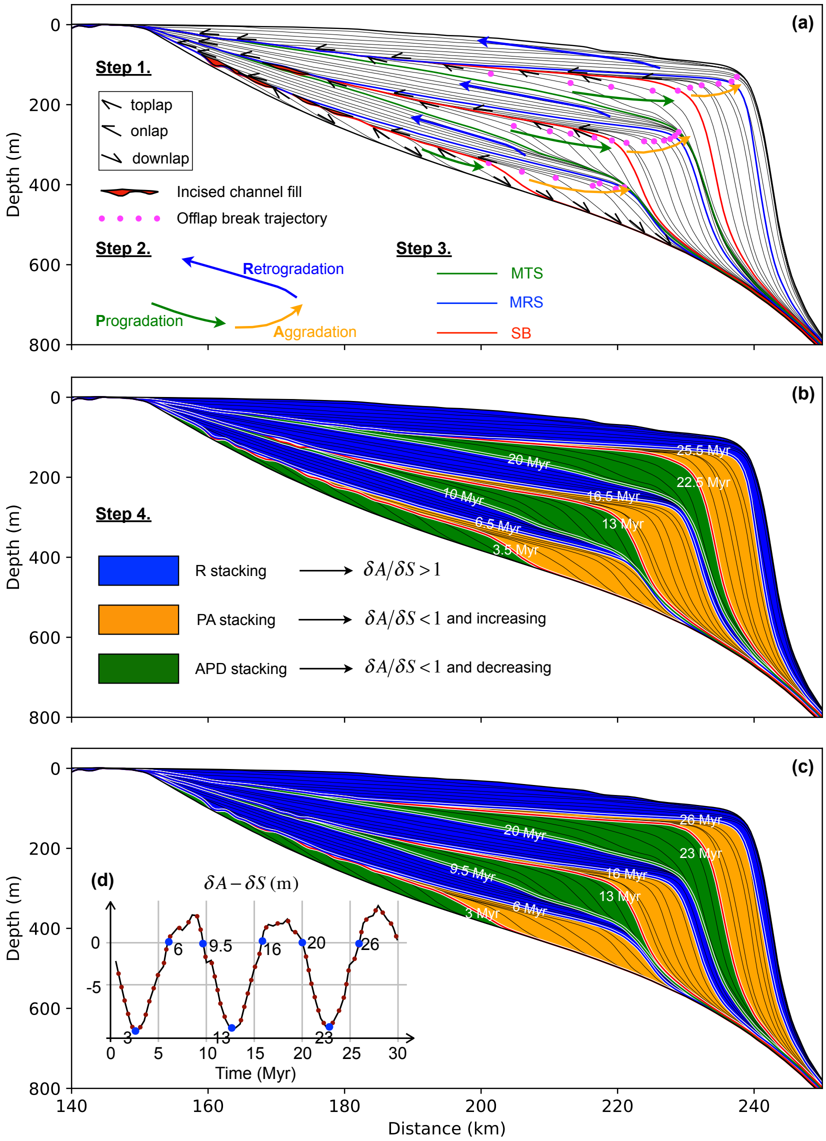

Figure 7. (a-b) Interpretation workflow based on the accommodation succession method (Neal et al., 2016). Step 1 includes marking stratal terminations (*i.e.* toplap, onlap and downlap represented using small arrows) and manually picking the break-in-slope as offlap break. The refilling of incised channels is shown in red, indicating erosional surfaces. Based on the marked stratal contacts, three stratal stacking trends (solid arrows) and three stratigraphic surfaces (colored solid lines) are then defined in Step 2 and Step 3. The three interpreted stacking patterns are filled with different colors, with their bounding times marked (Step 4). Each stacking pattern reflects the evolving ratio between rate of accommodation creation (δA) and rate of sediment supply (δS). (c) Automatically defined stacking patterns according to the calculated temporal evolution of $\delta A - \delta S$ (>0, <0 and decreasing, or <0 and increasing) (d).

clinoforms are well developed and the shelf-edge trajectory can be extracted from the final output (Fig. 6a). We introduce post-processing tools with which the positions of both the shoreline and the shelf-edge can be recorded from time-dependent output (Figs 6e and 6d). The shelf-edge trajectory picked from final output shows a different evolution from the shelf-edge trajectory extracted from successive outputs, due to imposed thermal subsidence on the continental margin (Fig. 4c). As shown on Figure 8, the shelf-edge trajectory appears to rise between 3.5 Myr and 6.5 Myr on the snapshot at 10 Myr (Fig. 8a), whereas it appears to fall between 3.5 Myr and 5 Myr on the snapshot at 20 Myr (Fig. 8b), because of ongoing thermal subsidence between 10 Myr and 20 Myr. As a consequence, identifying strata on the final output artificially extends the duration of descending trajectory class (Figs 6a and 8b). This should be kept in mind when identifying shelf-edge trajectories on seismic data, which are by nature a snapshot of the evolution of a basin. In comparison, the stratigraphic interpretations for the accommodation succession method indicate that there is no significant difference between analysing the final output and time-dependent outputs (Figs 7b and 7c). Therefore, the analysis of the presented model is more robust with the accommodation succession method than with the trajectory analysis method.

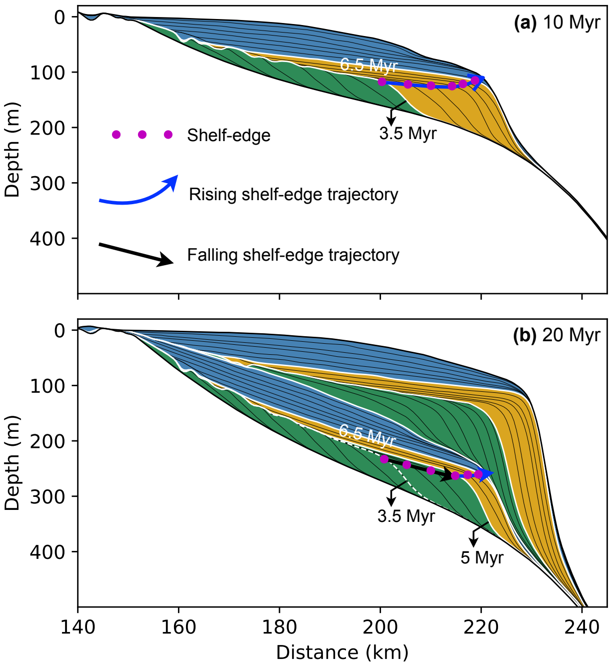

Figure 8. Stratal stacking pattern extracted at 10 Myr (a) and 20 Myr (b). Between 3.5 Myr and 5 Myr, the shelf-edge trajectory changes from rising at 10 Myr to falling at 20 Myr, as a result of basement subsidence. The descending trajectory class thus extends to 5 Myr.

A numerical implementation of the accommodation succession method requires to quantify changes in accommodation (δA) and sediment supply (δS). A common issue when calculating the ratio $\delta A/\delta S$ is the lack of unique approaches and common dimensional units to define these two metrics (Muto and Steel, 2000; Burgess, 2016). Both metrics represent changes in volume over a specific time interval and thus should be defined in m^3/yr. However, difficulties in delineating the potential

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space for sediment deposition require the use of proxies to quantify accommodation. Relative sea level, which combines the effect of sea level change and basement subsidence, is the most widely used metric for accommodation (Posamentier et al., 1988; Van Wagoner et al., 1988; Shanley and McCabe, 1994; Muto and Steel, 1997; Morad et al., 2000; Catuneanu, 2002). Time-dependent water depth has also been used to depict accommodation (Morad et al., 2000). The rate of relative sea level change or rate of water depth change thus defines δA, with units m/yr. Here, we used time-dependent water depth as a proxy for accommodation because it also takes into account the role of sedimentation. The quantification of $\delta A/\delta S$ ratio then requires that δS should also be expressed in m/yr. We therefore used the sedimentation rate by taking the stratal thickness deposited over a specific time to characterise δS. Although the sedimentation rate is often used as a proxy for δS (Poag and Sevon, 1989; Galloway and Williams, 1991; Liu and Galloway, 1997; Galloway, 2001), it only provides information about the deposition at a single location and does not reflect the spatial distribution of sedimentation (Petter et al., 2013). Furthermore, the distribution of sediment deposition is not determined solely by sediment supply, but is a combined result of the distance to sediment source, basin physiography and sediment transport efficiency (Posamentier et al., 1992; Posamentier and Allen, 1993). Recently, new methods have been proposed to improve the quantification of δS. Petter et al. (2013) proposed an approach that directly reconstructs sediment paleo-fluxes from stratigraphic records. Ainsworth et al. (2018) used a technique termed "TSF analysis" in which parasequence thickness (T) is used as proxy for accommodation at the time of deposition while parasequence sandstone fraction (SF) as proxy for sediment supply. Our work could be used to integrate and test these new quantitative interpretations based on the evolution of accommodation and sedimentation in a stratigraphic modelling framework. The quantification of δA and δS presented here could be extended in future work to investigate the interplay between accommodation change and sediment supply in 3D.

We have explored stratigraphic development in a source-to-sink context in which the dynamic sediment supply to the passive continental margin depends on climatic and tectonic evolution in the source area. Therefore, the physiographic evolution of the upstream region controls the depositional patterns in the sink area together with accommodation change (Ruetenik et al., 2016; Li et al., 2018). Most stratigraphic forward models (SFMs) focus on simulating sediment transport and deposition in the sink area, which limits the interpretation of the effect climatic and tectonic evolution on the stratigraphic record. In our framework, sediment transport and supply to the margin is dynamically related to autogenic and allogenic processes. As an example, though forced with uniform rainfall pattern in the source region, the rate of sediment supply to the sink area fluctuates with time (Fig. S1). This highlights the complex relationships between erosional signals and the preservation of a depositional record (Van Heijst et al., 2001; Kim et al., 2006; Kim, 2009). The source-to-sink numerical scheme used in *pyBadlands* makes it possible to explore important questions for the future of sequence stratigraphy, such as the role of sediment supply variations in the generation of stratigraphic sequences at different temporal scales (Burgess, 2016), and the importance of allogenic and autogenic processes in the formation and evolution of stratal record (Paola, 2000; Paola et al., 2009).

We modelled the formation of stratigraphic sequence over 30 Myr, which represents second to third order stratigraphic cycles (Vail et al., 1977b). Over this temporal scale, long-term eustatic sea level changes and dynamic uplift or subsidence induced by tectonics or deep Earth processes (e.g. mantle flow driven dynamic topography) might drive deposition (Burgess and Gurnis, 1995; Burgess et al., 1997), moderated by higher-frequency fluctuations in climate and sea level. The long-term stratigraphic record along continental passive margins thus potentially contains important constrains on the evolution of the structure of the deep Earth (Mountain et al., 2007; Braun, 2010; Flament et al., 2013; Salles et al., 2017). The framework we have introduced in this study integrates both long-term surface processes and stratigraphic modelling and can be used to quantitatively investigate the influences of long-term tectonics and deep Earth dynamics on stratal geometries and depositional patterns evolution as well as their feedback mechanisms (Jordan and Flemings, 1991; van der Beek et al., 1995; Rouby et al., 2013). Note that the tools we have introduced here are not specific to any temporal or spatial scale, and can also be used for short-term stratigraphic modelling.

7 Conclusions

We used *pyBadlands* to model sediment erosion, transport and deposition from source to sink, and to investigate the formation of stratigraphic sequences on a passive continental margin in response to long-term sea level change, thermal subsidence, and dynamic sediment supply. We analysed predicted stratigraphic architecture based on observations of shelf-edge or offlap break trajectory, stratal terminations and stratal geometries, following the workflow of two stratigraphic interpretation approaches: the trajectory analysis and the accommodation succession method. We introduced a set of post-processing tools to extract the temporal evolution of shoreline, shelf-edge, rate of accommodation change (δA) and sedimentation δS, based on which automatic interpretations can be obtained. Our results suggest that the stacking patterns defined with the accommodation succession method provide more robust reconstructions of the changing history of accommodation and sedimentation than the trajectory analysis method, because the interpretation of sequences with the trajectory analysis depends on time. In contrast, the accommodation succession method is not affected by the time-dependence of processes controlling the evolution of deposition. As a consequence, seismic data should be backstripped before stratigraphic sequences are intrepreted using the trajectory analysis method. Our work presents an integrated workflow that can be used to generate stratal architecture on basin margins and interpret 2D stratigraphic sequences produced by large-scale and long-term numerical experiments.

Code availability. *pyBadlands* is an open-source package distributed under GNU GPLv3 license. The source code is available on GitHub (http://github.com/pyBadlands-model). The easiest way to use the code is via our Docker container (pyBadlands-serial) which is shipped with the complete list of dependencies, the model companion and a series of examples. The code, inputs and post-processing functions used in this study are available on GitHub (https://github.com/XuesongDing/GMD-models).

Author contributions. Xuesong Ding designed the experiments and analysed the outputs with all co-authors. Tristan Salles developed the model code. Xuesong Ding prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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