

Deciphering the Interplay Between Tectonics and Eustatic Sea-Level in A Mixed Carbonate-Siliciclastic System: Insights from Stratigraphic Forward Modelling

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ABSTRACT

Sedimentary depositional systems are complex and sensitive to the interplay of various first-order controlling factors, including sea-level oscillations, tectonic re-arrangements, climate, and sediment supply. Hence, sedimentary depositional systems are heterogeneous and difficult to predict. In most cases, the spatial and temporal stratigraphic reconstruction is hindered by incompleteness of stratigraphic records, making quantification and prediction of factors controlling the dimension, shape, and distribution of sedimentary bodies challenging. Such limitations can have a costly impact on prediction of subsurface reservoir characterization, which are crucial for aquifer, hydrocarbon, and carbon capture storage applications. Here, we aim to overcome some of these challenges by providing quantitative insights on the spatiotemporal anisotropy of stacking patterns in a mixed carbonate-siliciclastic depositional system by implementing Stratigraphic Forward Modelling (SFM) using a Python-based Basin and Landscape Dynamics (Badlands). We evaluated 2 scenarios, with scenario A changes the rate of uplift and subsidence, whereas scenario B changes the periodicity of a hypothetical sea-level curve. The SFM was performed on a base model of 300 x 200 km and a gentle-sloped homoclinal ramp (0.03°) with a total of 10 MY simulation time. Our result shows two distinct sedimentary sequences whereby the tectonic-based scenario produced thicker HST deposit which could be a good target for petroleum exploration in a mixed carbonate-siliciclastic system. In contrast, the eustatic sea level-based scenario developed much thicker LST and MFS deposits which could be potential for source rock or seal. When combining the two first-order controls, our model signifies that tectonic rearrangement of a basin has a more pronounced effect on developing stratigraphic sequence compared to sea-level fluctuation. These findings may provide further guidance in predicting the reservoir quality in the subsurface when data is limited.

EXTENDED ABSTRACT

Introduction

Sedimentary depositional systems are complex and sensitive to the interplay of various first-order controlling factors, including sea-level oscillations, tectonic re-arrangements, climate, and sediment supply (e.g., Miall, 2013). Hence, sedimentary depositional systems are heterogeneous and difficult to predict. In most cases, the spatial and temporal stratigraphic reconstruction is compounded by incompleteness of stratigraphic records, making quantification and prediction of factors controlling the dimension, shape, and distribution of sedimentary bodies challenging (Straub et al., 2020). Such limitations can have a costly impact on prediction of subsurface sedimentary reservoir geometries, porosities, and permeability, which are crucial for aquifer, hydrocarbon, and carbon capture storage applications (Branets et al., 2009). Sequence stratigraphy concept (Posamentier and Vail, 1988) and stratigraphic forward model (SFM; Granjeon and Joseph, 1999) were developed to overcome these issues and provide qualitative and quantitative frameworks to predict sedimentary basin infill processes. Recent years, while advanced SFM models have been developed and most studies focused on the finer-scale variations in sedimentary architecture and heterogeneity, first-order processes governing the development of different sedimentary packages related to different sequence stratigraphic system tracts remain debatable, particularly in tectonically active basins. An SFM approach of mixed carbonate and siliciclastic continental shelves is presented to take a look into the relationship between the depositional process and stratigraphic responses at large spatial space and time (Quiquerez et al., 2004).

Here, we aim to overcome some of these challenges by providing quantitative insights on the spatiotemporal anisotropy of stacking patterns in a mixed carbonate-depositional system and its impact on reservoir heterogeneity. In this research, we investigate the impact of tectonic and sea-level change in a mixed siliciclastic and carbonate sequence stratigraphy by implementing SFM using an open-source, Python-based environment, Basin and Landscape Dynamics (Badlands; Salles et al., 2018). In this study, the impact of first-order sequence variables on the sedimentary packages are observed by changing the rate of uplift and subsidence and the periodicity of a hypothetical sea-level curve. This approach will allow us to assess and quantify the sensitivity of sedimentary systems to changes in first-order external controls and to numerically model how different sequence stratigraphy system tracks are developed, what controls the erosion and transportation of sediment, and what conditions favor the formation of laterally continuous reservoirs in the subsurface.

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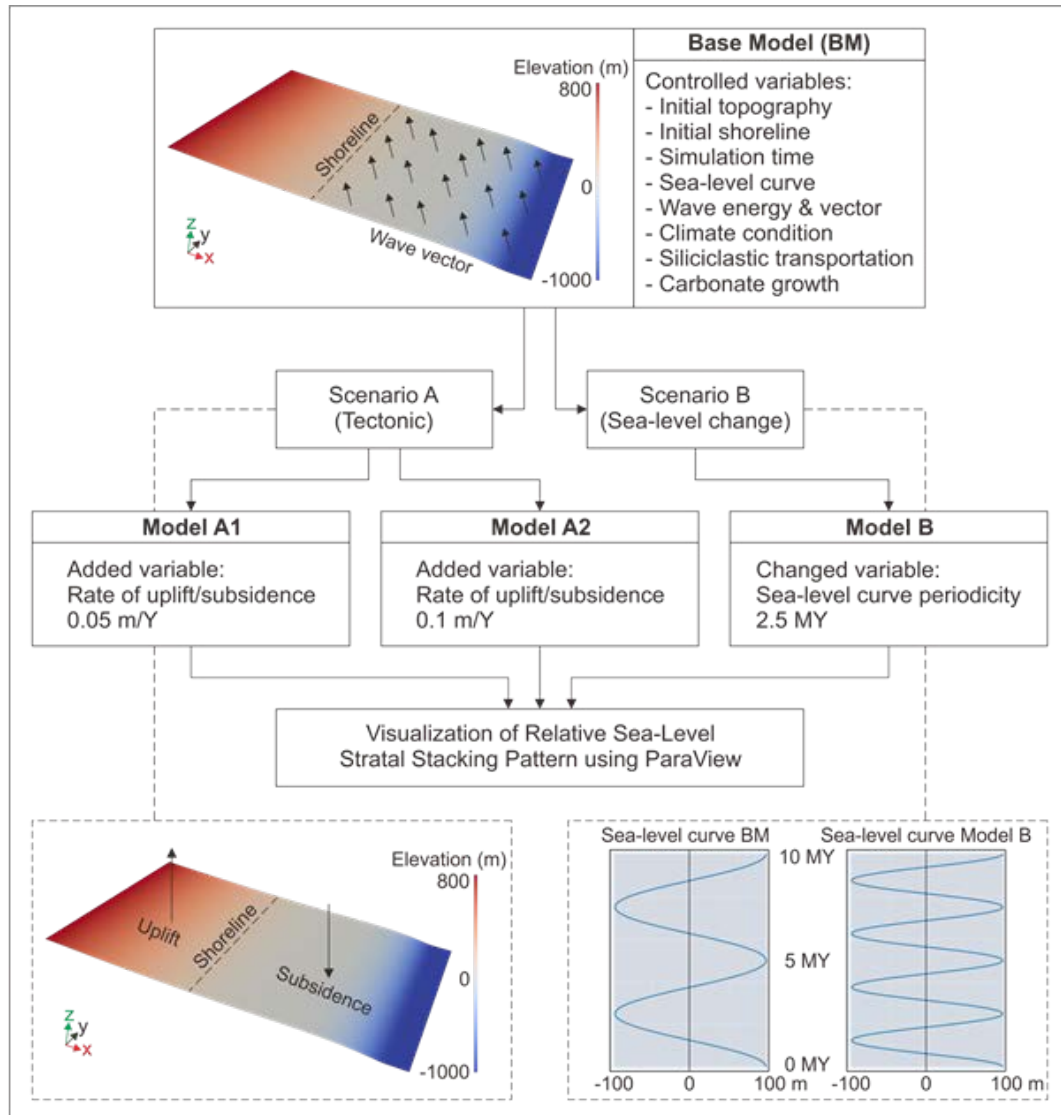


Figure 1. Workflow of this research. The dashed lines visually interpret the changed/added variable from the base model (BM).

Methodology

The SFM was performed with a total of 10 MY simulation time by using Badlands, accessed through Jupyter Notebook (Kluyver et al., 2016) and visualized in ParaView (Ahrens et al., 2005). The overall workflow follows the conventional SFM workflow proposed by Salles et al., 2016 (Fig. 1) and some modifications were performed to suit the primary objective of this study. We constructed a base model (BM) that served as the framework for the two different scenarios, with a dimension of 300 x 200 km and a gentle-sloped initial topography (0.03°). This surface geometry was chosen for its simplicity to highlight the impact of the imposed

variables. The initial shoreline was projected at precisely 0 m elevation. We generated wave energy and wave vector in a unidirectional SW-NE motion, with a maximum of 2 m wave height and -15 m for its maximum depth of wave influence, similar to the research of Arab-D homoclinal ramp (Zuhlke et al., 2015). Rate of precipitation was applied uniformly throughout all scenarios, with 1 m/m² value to generate a spatially uniform erosion for the siliciclastic sediments, providing a constant sedimentary transportation as long as the erosion persists throughout the simulation time. We enabled the carbonate growth in the entire initial topography surface, and will continue to grow as long as the surface is submerged. The carbonate consisted of two different grain sizes, which are grainstone (2 mm) and mudstone (0.002 mm). A hypothetical sea-level curve was applied to the base model, with an amplitude of 100 m and a periodicity of 5 MY.

The first scenario (scenario A) was simulated to see how regional tectonic will impact sequence stratigraphy throughout the sedimentary depositional environment. We created a land subsidence across the submerged initial topography surface (elevation below 0 m) and uplifting across the subaerial exposed surface (elevation above 0 m). The rate of uplift and subsidence are both uniform and constant throughout the simulation, with the first sub scenario (Model A1) of 0.05 m/yr and the second one (Model A2) of 0.1 m/yr. The second scenario (scenario B) increased the periodicity of sea-level curve to 2.5 MY, doubling the value from the base model (Model B). We extracted the stratal stacking pattern from relative sea-level of each model (BM, A1, A2, and B) to get the system tracts for each sedimentary package, and visualized them in 3D to see how each scenario will affect the SFM throughout the simulation time. We made a cross-section in the middle of Y axis across the entire X axis to observe and compare sediment thickness and the geometry of the sedimentary packages for each system tract (Fig. 2).

Results

Base model (BM) shows a falling stage system tract (FSST) deposited in the beginning of the simulation as the sea-level curve is started with a falling limb immediately from 100 m to -100 m, which are consistent with both scenarios. There are 3 maximum flooding surfaces (MFS) on the hypothetical sea-level curve, the initial 100m at 0 MY, at 5 MY, and at 10 MY by the end of simulation time. The sea-level curve is able to produce two complete stratigraphic sequence stacking patterns. The FSST is deposited for 2.4 MY, followed by a deposition of low-stand system tract (LST) for 0.8 MY, transgressive system tract (TST) for 1.2 MY, and finally a highstand system tract (HST) for 0.5 MY. The cycle continues for the next 5 MY, however, the thickness of each system tract deposit is relatively thicker than the first 5 MY.

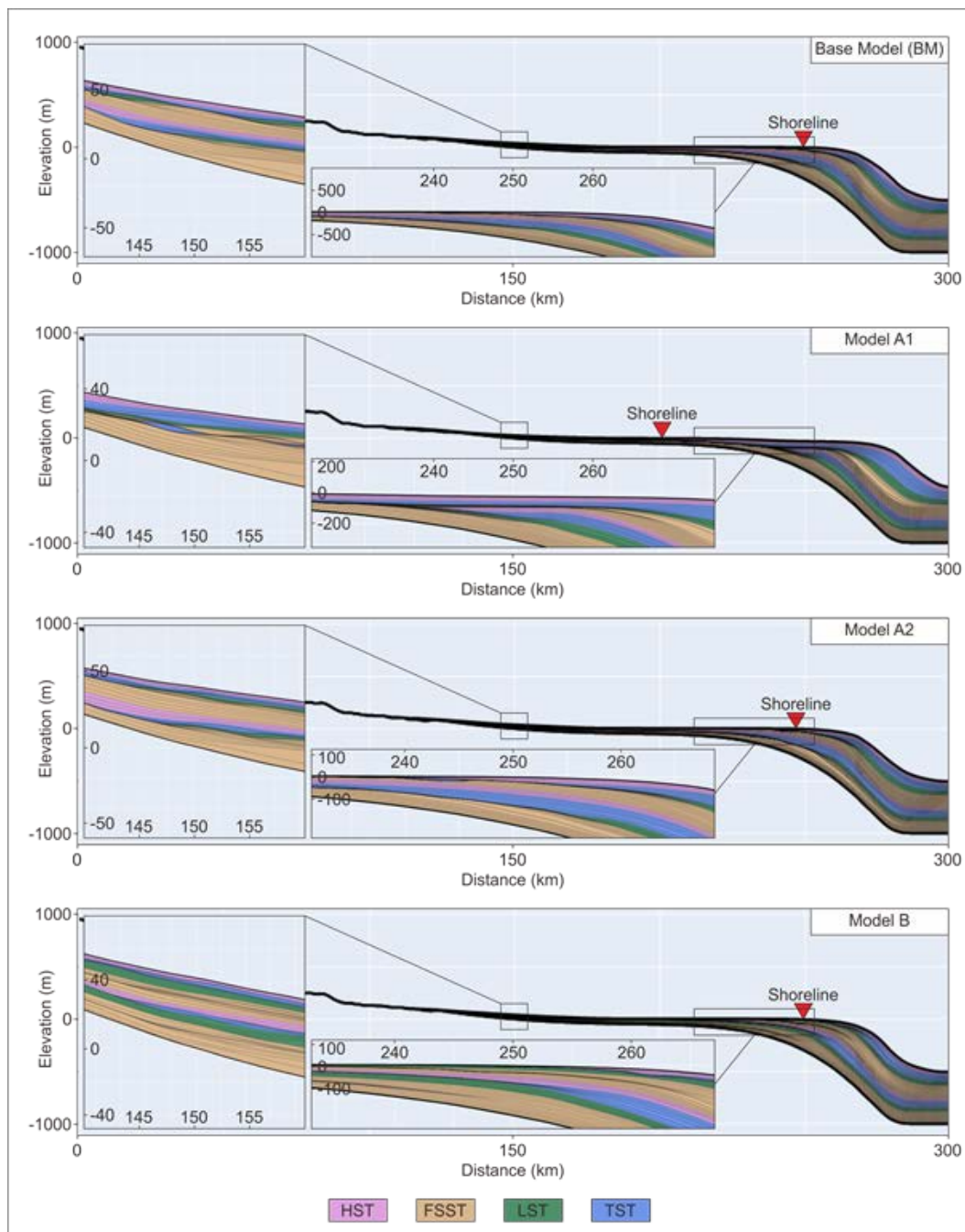


Figure 2. The compiled result of each model simulated in this SFM. The shoreline was taken from 0 m elevation at the end of simulation time for each model. Notice how the sedimentary succession of all system tracts are varying from each presented scenarios, and how far the progradation for each model.

In the Scenario A, model A1 shows a thicker total thickness of sediments basinward, and progrades further than BM. Model A2, however, does not exhibit the extent of progradation as far as A1, in fact, it has a relatively similar distance of progradation like BM. The shoreline at the end of simulation shows that model A1 has a closer distance with the initial shoreline, compared to BM and A2 that also shared a similar distance.

The Scenario B exhibits steeper clinoforms compared to the BM, and has a relatively thicker parasequence for each system tract at the first 5 MY. However, the second set of parasequence (5 – 10 MY) is thinner compared to BM, while retaining a relatively similar shoreline at the end of the simulation.

Discussion and Summary

The FSST sediments on BM is the thinnest amongst all simulated models. This is one of the key finding in our SFM, as the FSST sediments are all deposited at the beginning of the simulation. It highlights the influence of tectonic rearrangement and periodicity of sea-level fluctuations toward the thickness of the first sedimentary succession, which is a function of sedimentary supply and accommodation space. The added variables for scenario A provide a higher sediment influx due to uplifting in the source area, which result in higher eroded materials to source the basin. The subsidence at the basin created larger accommodation space compared to the base model, hence the sediments are relatively thicker. This is in agreement with how the thickness of TST in BM and scenario A are significantly different. The role of tectonic that uplifts the source area and subsides the basin is able to demonstrate a more pronounced starved basin. In the faster rate of uplift and subsidence (Model A2), the first TST succession (0 – 5 MY) is thicker than model A1, however, the second succession of TST shows the opposite. This suggests than an uplift and subsidence rate of 0.1 m/year in our model can provide a more balanced sediment supply and accommodation space for the initial topography, which is also supported by the relatively more prograded sediments at the end of the simulation time for A1.

In the scenario B, despite having twice the amount of MFS compared to the initial sea-level curve, the sediments deposited in model B shows only 2 complete stratigraphic sequence packages. It can be inferred that the total simulation time and the accumulation space provided in the BM and model B in our SFM are not sufficient to create additional packages. The thicker LST in model B suggests that an increased periodicity of sea-level fluctuation will create a thicker aggrading clinoform and a more pronounced backstepping pattern at the top of initial shoreline.

In the mixed siliciclastic-carbonate play, a thick and laterally continuous HST package is normally targeted for petroleum exploration (Snedden et al., 2003; Huang et al., 2016), exhibited by successful conventional explorations in Miocene Play, Gulf of Mexico (USA), Upper Jurassic Play (Norway), and Plio-Miocene Play, Kutei Basin (Indonesia), presented by “creaming curve” in exploration phase (Snedden et al., 2003). In our SFM, Model A2 has the

thickest HST deposit compared to the rest of the simulations, followed by model A1, all of which are tectonic-based scenarios. It means that tectonic rearrangement of a basin has a stronger effect on developing stratigraphic sequence compared to sea-level fluctuation, which are all in a good agreement with the presented case studies from the work of Snedden et al (2003).

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