GSA TODAY

THE GEOLOGICAL SOCIETY OF AMERICA®

VOL. 33, NO. 6 | JUNE 2023

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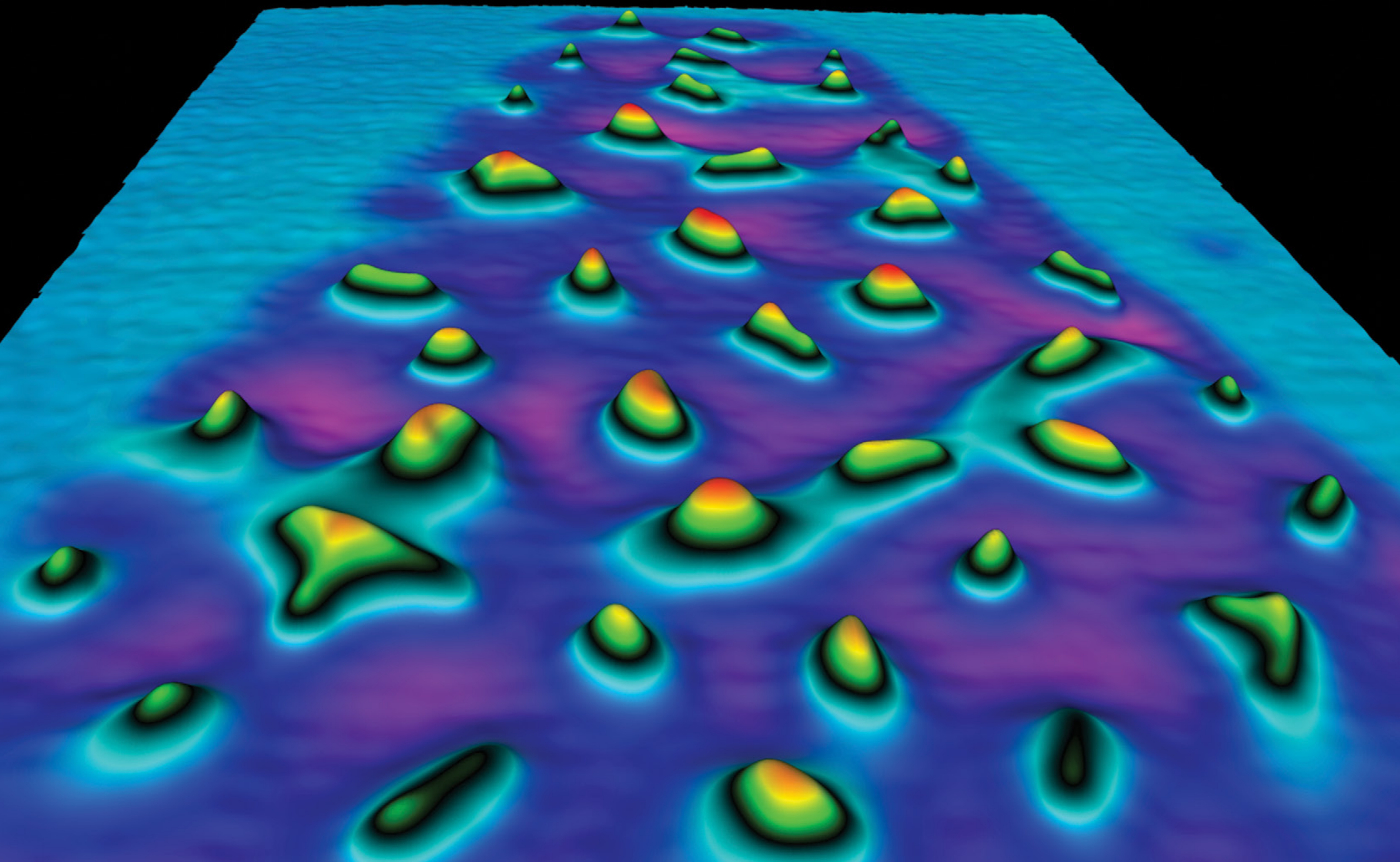

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Halokinetic Induced Topographic Controls on Sediment Routing in Salt-Bearing Basins: A Combined Physical and Numerical Modeling Approach

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ABSTRACT

Allogenic controls are frequently cited as key factors influencing basin evolution; however, fewer studies perform paleo-topographic reconstructions to examine the impact of topography in the development of stratigraphic sequences. Disentangling how allogenic versus autogenic controls affect the stratigraphic succession within a basin affected by salt tectonics is particularly challenging because decoupling the stratigraphic signature of lithospheric induced uplift and subsidence from salt tectonics is not a trivial exercise. We tackle this problem by integrating physical modeling results with a landscape numerical model and compare results with a case scenario from the subsurface. The physical model provides surface displacement data that are then used as inputs into the landscape numerical model to simulate the surface and stratigraphic evolution of a salt tectonic basin during a 25-m.y. timespan and within the context of a continental-scale source-to-sink (S2S) system. Results show that the evolution of salt structures impact the development and diversion of sedimentary routing systems within salt basins, thus influencing the character of the stratigraphic record independently of allogenic factors such as lithospheric induced uplift. Modeling results highlight the importance of reconstructing the paleo-topography of ancient depositional systems affected by salt tectonics to truly understand the nature of the final stratigraphic record.

INTRODUCTION

Basin-scale sediment distribution and its resulting stratigraphy are widely believed to be controlled by allogenic controls including changes in sediment supply, eustasy, and tectonics (e.g., Jervey, 1988; Heller et al., 1993). Changes in stratigraphy are often linked to variations associated with one or a combination of these allogenic controls; however, fewer studies have considered the effects that local topographic development can have in the imprinting of the stratigraphic record. In basins affected by salt tectonics, allogenic signatures within the stratigraphic record are overprinted by the influence of salt movement, and, as a consequence, decoupling the effects of sediment supply, eustasy, conventional tectonism, and salt tectonics becomes difficult. We believe that illustrating these relationships is important because salt basins are common in many regions of the world, including the Gulf Coast region of the United States and the deep-water Gulf of Mexico. Surprisingly, most geoscientists working outside the realms of industry or applied research have little exposure to knowledge associated with the complexities that salt basins pose when trying to untangle basin evolution and fundamental sedimentological, stratigraphic, and tectonic processes. By discussing some aspects of these complexities, using physical and numerical models coupled with observations from a real case study, we hope to bring attention to the importance of studying salt tectonic process and sediment interactions within salt basins as an important and often overlooked component of Earth's evolution.

In this study we present a novel methodology integrating inputs derived from physical modeling with landscape numerical modeling. The integrated model simulates the surface and stratigraphic evolution of salt-controlled basins within the context of a continental-scale source-to-sink (S2S) system covering the entire sedimentary profile from the upstream sediment source in the continental realm to the sediment sink in the marine realm. Such an approach benefits from using surfaces derived from a physical model that simulates the evolution of a salt basin containing numerous salt diapirs. Time steps of vertical movements derived from the physical model are the input for the numerical models. The input parameters from the physical model responded to well-known laboratory conditions constraining the evolution of the salt-tectonic topography (e.g., Dooley et al., 2013, and Supplemental Material[1]) and guiding the numerical approach. We use the numerical modeling approach to understand: (1) the level of influence that salt tectonics can insert in the development of sediment routing systems within the sink domain, and (2) how the evolution of local topography within salt basins influences the vertical development of stratigraphic patterns. Our study emphasizes the importance of reconstructing the

GSA Today, v. 33, no. 6, https://doi.org/10.1130/GSATG561A.1.

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[1]Supplemental Material. Explanations of seismic data acquisition, processing, and interpretation. Time-thickness map and seismic cross-sections of Lower Cretaceous Mississippi Salt Basin. Methodology of salt tectonics physical models, landscape, and stratigraphic numerical models. Table with input parameters for landscape and stratigraphic numerical model. Figure illustrating uplift and subsidence rates of the sink domain. Explanations for animations. Go to https://doi.org/10.1130/GSAT.S.22391062 to access the supplemental material; contact editing@geosociety.org with any questions.

paleo-topography of ancient depositional systems to better understand the imprinting of the stratigraphic section while taking into consideration the impact of an S2S configuration. Finally, we used learnings derived from this integration between physical and numerical models to establish parallels with observations from the Lower Cretaceous Mississippi Salt Basin (Fig. 1) to demonstrate the validity of the analogy between the modeling effort and a real case scenario.

METHODOLOGY

We integrated the results from a physical model and an S2S numerical model to better understand the sediment routing in salt-bearing basins. The physical model was designed to explore salt-tectonic processes within a salt-bearing basin punctuated by numerous salt structures similar to the ones observed in the Campeche Basin of the southern Gulf of Mexico (e.g., Davison, 2021, and references therein). It is important to highlight that results from physical models (aka. sandbox models) are agnostic, meaning that observations can be applied to other settings where particular processes form similar structures. Moreover, physical models of salt tectonics are not meant to exactly duplicate characteristics observed in a particular basin; instead, they are primarily designed to help understand processes associated with the formation of certain geological features (e.g., Dooley et al., 2012; Ge et al., 1997; Rowan and Vendeville, 2006).

It should be stressed that this first iteration of our numerical model doesn't take into consideration flexural subsidence as a response to sediment loading, taking only into consideration input from the physical model. This approach was adopted by design, given that we wanted our numerical models to start from a simpler baseline to progressively increase levels of complexity at later stages. We will incorporate sediment loading in our next iteration of numerical models, and we will compare results from different runs to weigh the influence of sediment loading versus pre-set geometric configurations exclusively derived from the physical model.

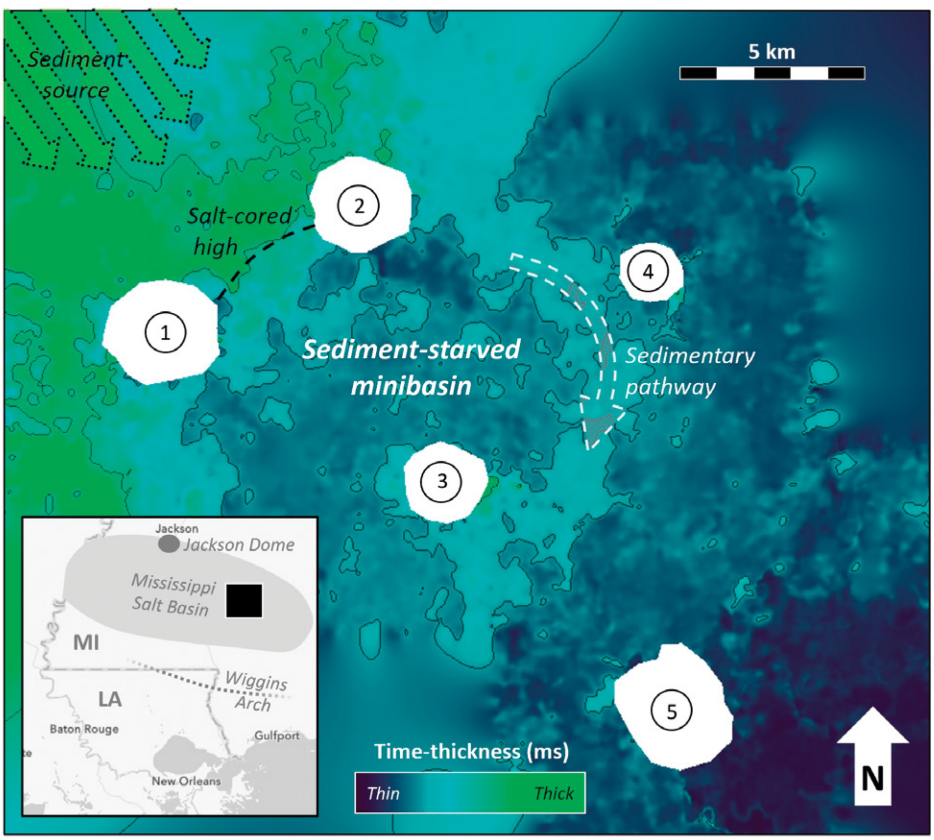

Figure 1. Time-thickness map from a Lower Cretaceous unit in the Mississippi Salt Basin (Thieling and Moody, 1997; Johnson et al., 2006). Regional sediment source is from the northwest. Numbers 1 to 5 in white areas denote locations of salt domes. Domes 1 and 2 acted as a salt-cored high blocking sedimentary input. A clockwise oriented sedimentary pathway developed around Dome 2. Contour interval is 50 ms. Map derived from seismic data courtesy of CGG. MI—Mississippi; LA—Louisiana.

The physical model utilized well-documented modeling materials, with a silicone polymer acting as our salt analog, and a mixture of silica sands and spherical cenospheres to simulate the siliciclastic overburden (e.g., Reber et al., 2020, and references therein). Salt diapirs and pillows with varying geometries were seeded by differential loading, as is typical for this style of physical modeling (e.g., Rowan and Vendeville, 2006; Dooley et al., 2013), and gradually grew upward as a series of diapirs, resulting in the localized drawdown of the autochthonous salt layer to feed these growing salt structures, leading to the formation of numerous salt-withdrawal basins (minibasins; Fig. 2A). As the diapirs grew, some linked as composite structures, forming salt-cored highs with the greatest structural relief above the crests of the original diapirs (Fig. 2A). The S2S numerical model uses height-change data through time from the physical model (i.e., the rates of subsidence and uplift, Fig. 2A) to constrain the evolution of the salt-related topography. The original parameters extracted from the physical model are upscaled to fit a continental-scale S2S system (Figs. 2A–2B). The pyBadlands software package is employed to simulate the evolution of topography and stratigraphy (Salles et al., 2018). The detailed description of the model parameters and governing equations of the landscape numerical modeling can be found in the supplemental material (see footnote 1). Even though the integrated physical and numerical modeling method proposed in this study is novel, the employed workflows of physical modeling of salt tectonics and S2S numerical modeling are well practiced in recent studies (e.g., Dooley et al., 2020; Duffy et al., 2021; Reber et al., 2020; Zhang et al., 2020; Ding et al., 2019).

The simulation time of the S2S numerical modeling is 25 m.y. The length and width of the entire numerical model from S2S are 1200 km and 500 km, respectively. The source domain is 250 km long with an initial 200-m-high topography and a constant uplift rate at 40 m/m.y. (Fig. 3). The source domain supplies sediments into the basin through a 250-km-long transfer zone that connects with a 700-km-long sink domain. The time duration, dimensions, and uplift rates used in the numerical model were defined based on analogies between the physical model and observations from the Campeche Basin (e.g., Davison, 2021).

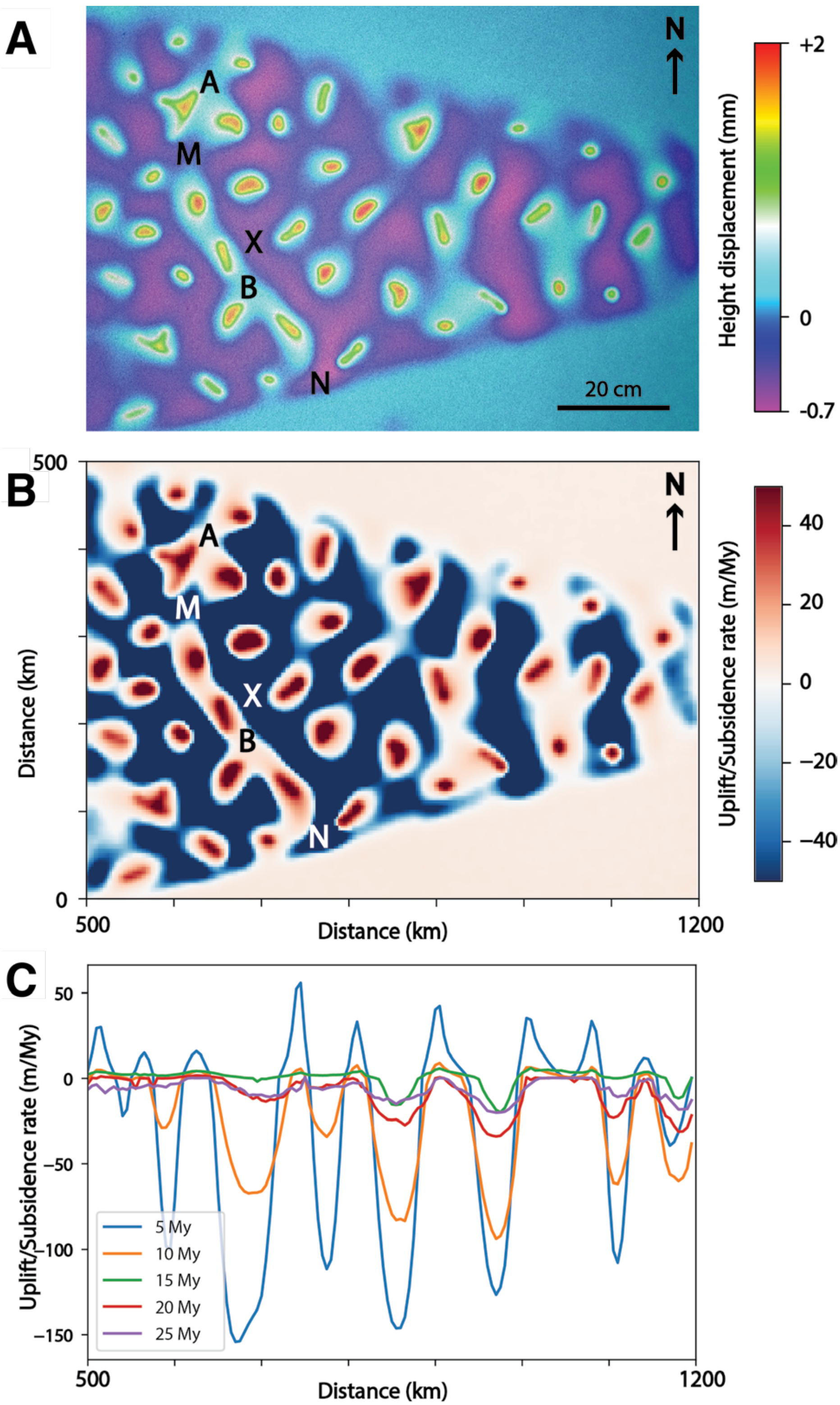

Figure 2. (A) Height displacements of our physical model from time-lapse stereo surface recordings and digital image correlation software. (B) Three-dimensional distribution of uplift/subsidence rates at 5 m.y. (upscaled from the data presented in Fig. 3A). (C) Cross section at basin axis showing the rates of uplift and subsidence at 5, 10, 15, 20, and 25 m.y. The cross section captures the high subsidence/uplift rates typically associated with the initial remobilization of in situ salt (blue and yellow lines for 5 and 10 m.y., respectively) versus later phases of evolution when most of the salt has already been remobilized (green, red, and purple for 15, 20, and 25 m.y., respectively). These trends are observed both in physical models and real case studies in the subsurface including the Mississippi Basin example that is presented in this work (see Fig. 1). Salt-cored highs are indicated by letters A and B in the map views, sedimentary pathways are indicated by letters M and N, and X represents location of starved minibasins.

The salt-tectonic movement within the sink domain in the numerical model is constrained by topographic inputs from the physical model by means of time-lapse stereo surface recordings and associated DIC (digital image correlation) software that captured incremental surface height changes (Fig. 2).

Finally, after obtaining results from our numerical model, we compare observations to a real subsurface case study in the Mississippi Salt Basin. The location of the 3-D seismic reflection survey that sourced the interpretations is shown in Figure 1. The prestack time-migrated seismic volume is situated over the east-central portion of the basin, has an area of ~533 km^2, and spans over five salt domes. Information on data acquisition, processing, and interpretation can be found in the supplemental material (see footnote 1).

RESULTS

Numerical Model

The numerical simulations showcased an S2S configuration that was active through 25 m.y. with the following characteristics: (1) sediment supply derived from the uplifting source domain, (2) a sediment transfer domain that bypassed sediments into the basin, and (3) a distal basin with local topography controlled by the effects of salt tectonics (Fig. 3 and Animation 2 in the supplemental material). The results reported herein focus on the description and interpretation of observations made within the sink domain. We use the terms sink and basin interchangeably.

The topography of the sink domain is defined by two stages of basin evolution. Stage 1 (0–15 m.y.) is influenced by the rapid rise of salt diapirs and high subsidence rates within proximal parts of the basin, while Stage 2 (15–25 m.y.) is characterized by a decrease in subsidence and the triggering of sediment bypass toward distal parts of the basin (Fig. 3). During Stage 1, the subsidence rate was 150 m/m.y.; this generated high accommodation in the proximal parts of the basin where extrabasinal sediments gradually infilled subsiding minibasins (Figs. 2 and 3). During Stage 2, subsidence rates fluctuated between 10–50 m/m.y., the proximal minibasins were already infilled, and sediments bypassed toward the east. Sediments infilled proximal minibasins during Stage 1 via line-sourced transport from fluvial systems that transited the transfer zone. Two salt-cored topographic highs (A and B in Fig. 3) partly blocked sediment transport within the sink domain during

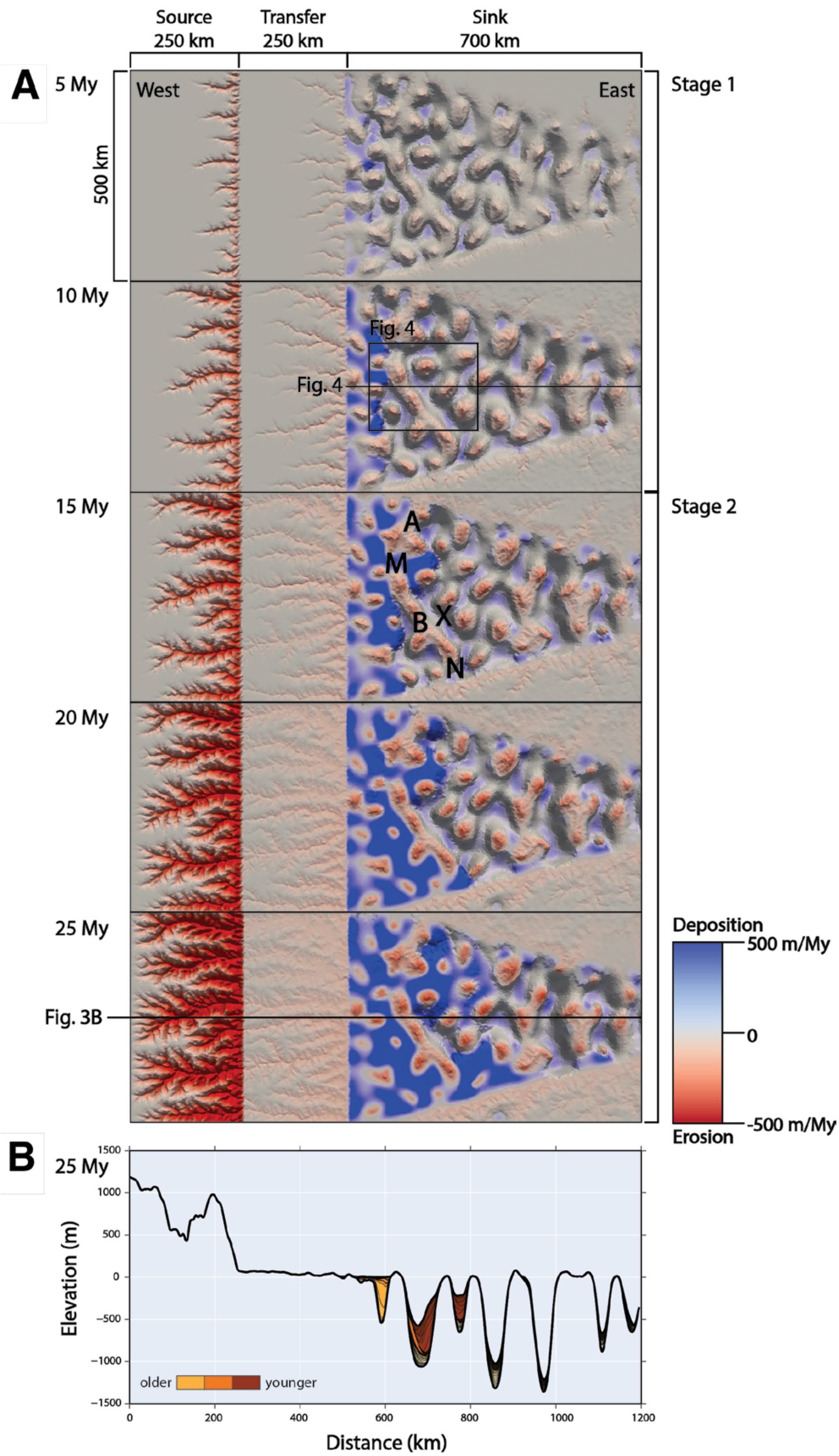

Figure 3. (A) Erosion/deposition maps of the source, transfer, and sink domains at 5, 10, 15, 20, and 25 m.y. Stage 1 (0–15 m.y.), active salt deformation controls basin accommodation and sediments infill the proximal minibasins. Stage 2 (15–25 m.y.) sedimentary pathways (M and N) bypass sediments around salt-cored highs A and B. Parts of minibasin X remain sediment starved. (B) Cross section along northern end of minibasin X showcasing modified stratigraphic patterns (see Fig. 4).

Stage 2 while proximal minibasins were completely infilled with sediments. During this time, the sediment dispersal system became point sourced with the development of two sedimentary pathways that delivered sediments into the central and distal portions of the basin (sediment pathways M and N in Fig. 3). In contrast, the minibasin located to the east of salt-cored high B (minibasin X, see Figs. 3 and 4) remains sediment starved during Stage 2 as salt-cored topographic highs block the free flow of sediments. Cross sections of basin stratigraphy in Figure 4 showcase how the minibasins are gradually filled from proximal to distal (see also Animation 2 in the supplemental material [see footnote 1]). In Stage 1, the depositional dip of strata infilling the minibasins is to the east, suggesting sediment supply from west to east; however, during Stage 2 the depositional dip reverses to the west within the central parts of the sink domain (minibasin X), implying an east to west sediment supply direction (Fig. 4).

Mississippi Salt Basin Case Study

In the Lower Cretaceous interval of the Mississippi Salt Basin, there is a clear heterogeneity of minibasin infills, with initial regional sediment supply as line-sourced from the northwest (Fig. 1). In this example, the salt-cored highs of domes 1 and 2 acted as barriers to sediment routing, generating a local sediment starved minibasin immediately to the southeast. As a consequence, a clockwise sedimentary pathway developed around dome 2 to feed downstream minibasins in an oblique pattern that is divergent from the initial line-sourced sedimentary input from the northwest (Fig. 1). The diversion of sedimentary sources and pathways as shown in the Lower Cretaceous Mississippi case study are common in basins affected by salt tectonics and are believed to be controlled by autogenic effects associated with salt deformation (e.g., Duffy et al., 2020). Despite the known influence of salt tectonics on the development of stratigraphic patterns, few studies have convincingly illustrated how these local topographic controls modify sedimentary pathways and how this impacts the rock record.

DISCUSSION

Tectonic and Local Topographic Controls on Sediment Distribution

Based on the dominant controls, basin evolution was divided into two stages: Stage

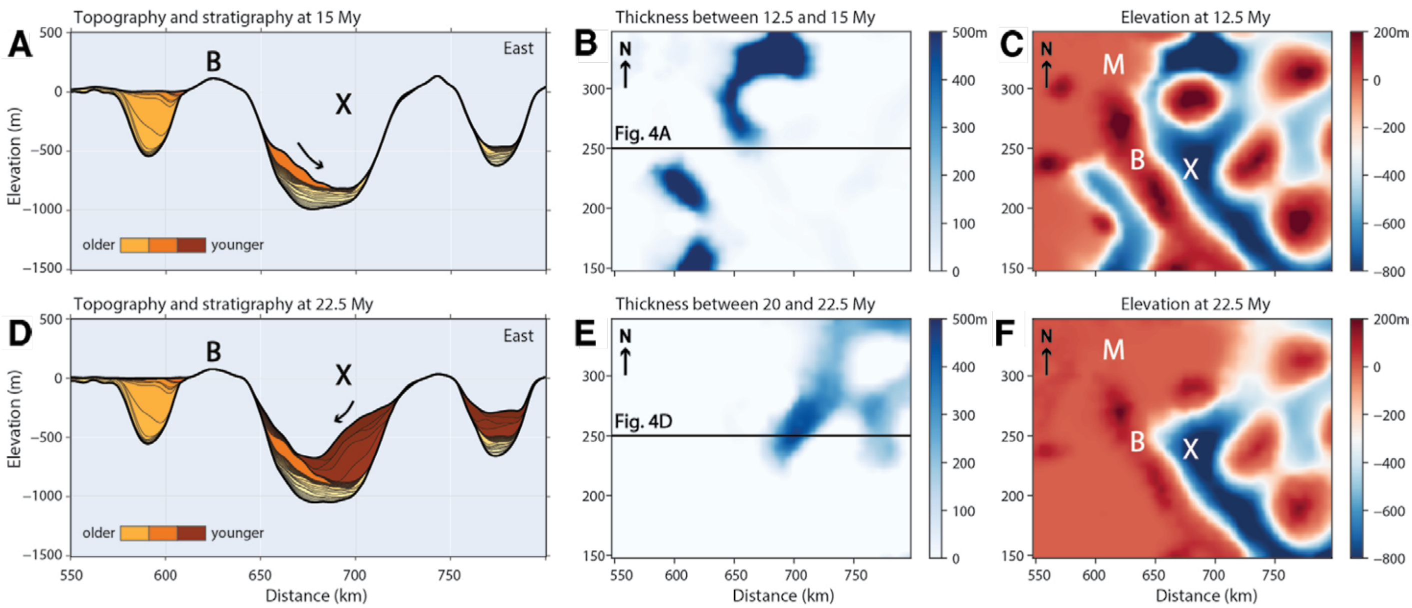

Figure 4. (A)–(C) Cross section, thickness map, and elevation map of a representative interval of Stage 1. B indicates location of salt-cored high, X location of minibasin, and M location of sedimentary pathway. The proximal minibasin to the west is completely infilled by this time; minibasin X is underfilled but stratigraphic bedding is predominantly dipping toward the east, indicating sediment supply from west to east if the cross section is taken as the only reference point for the interpretation. (D)–(E) Cross section, thickness map, and elevation map of representative interval of Stage 2. Minibasin X continues to be underfilled, but there is a change on the dip of stratigraphic beds toward the west, suggesting sediment supply from east to west if the cross section is taken as the only reference point for the interpretation. The thickness and elevation maps illustrate how sediment pathways (M) navigate salt-cored highs (B) to infill the northern portions of minibasin X from the north-northwest during Stage 1 and from the northeast during Stage 2.

1 (0–15 m.y.), which is controlled by active surface deformation associated with major salt movements; and Stage 2 (15–25 m.y.), which is controlled by the resultant local topography and sediment bypass toward the east. The rapid rise of salt-cored highs during Stage 1 (0–15 m.y.), including diapirs and irregularly shaped salt walls, is responsible for the overall basin configuration through time. During this early stage of basin evolution, the development of tortuous sedimentary pathways controlled sediment distribution within the proximal minibasins (Fig. 3A). During Stage 2, the basin relief evolved into a mature minibasin province flanked by salt-cored highs. Sediment dispersal patterns changed from line-sourced to point-sourced as the main depocenters moved basinward and were impacted by the local topography. The numerical model clearly illustrates how stratigraphic architectures varied from proximal to distal portions of the sink domain through time (Fig. 4). Figure 4 records the development of the stratigraphic infilling at different time steps in the model; the display clearly showcases how stratigraphic dips vary notably from east-dipping at 15 m.y. to west-dipping within the margins of minibasin X at 22.5 m.y. These drastic variations in depositional dip could be wrongly described as implying multidirectional sedimentary sources in real case scenarios where only seismic data is used to perform interpretations. However, our numerical model demonstrates that it is possible to explain these changes as due to readjustments of the sedimentary routing system as a response to the evolving mobile-substrate architecture (Fig. 4).

Using A/S Ratio to Predict Stratigraphic Patterns?

The balance or imbalance status between sediment supply (S) and accommodation (A), referred to as the A/S ratio, is widely used to predict stratigraphic patterns and serves as a conceptual basis for most sequence stratigraphic models. The increase of sediment supply or decrease of accommodation promotes regressive successions and basin fills. However, this theory does not hold when we look at the detailed evolution of composite minibasin X in the model (Fig. 4). Our results demonstrate that the stratigraphic patterns of minibasin X are mostly influenced by local, salt-controlled topography, rather than by allogenic changes on sediment supply or accommodation. The concept is rather simple once the numerical model is interrogated; however, in real case scenarios, where subsurface data is low quality or scarce and paleo-topographic reconstructions are not possible, these stratigraphic architectures could be easily misinterpreted. We plan to increase the complexity of the numerical model in future runs by adding flexural subsidence as a response to sediment loading; however, the current results demonstrate that paleo-topographic heterogeneities alone can significantly influence sedimentary pathways and resulting stratigraphic architectures that are preserved in the rock record.

Physical and Numerical Models as Analogs for Real Case Studies

In terms of basin evolution, in our numerical model Stage 1 can be defined as an underfilled and out of equilibrium phase while Stage 2 is trending toward equilibrium with proximal minibasins being infilled with sediments and sedimentary pathways actively developing toward the distal parts of the basin. Minibasin segmentation and sediment underfilling is still dominant in the distal basin during Stage 2 of our model. In the Mississippi Salt Basin, reactive and active diapirism took place from the Early–Late Jurassic to the Early Cretaceous (Johnson et al., 2006). This phase is analogous to Stage 1 in our model, a time period dominated by strong salt movement and uplift that helped define minibasin placement. A second phase of passive diapirism took place in the Mississippi Salt Basin from the Early to Late Cretaceous

(Johnson et al., 2006), and our analysis of subsurface data clearly showcases how during this time sedimentary pathways bypassed salt-cored highs following a trend that diverted from the original line-sourced pattern observed to the northwest (Fig. 1). Processes operating during the Early to Late Cretaceous in the Mississippi Salt Basin are analogous to Stage 2 of our model where proximal parts of the system are infilled by sediments while new sedimentary influx is rerouted around diapirs or salt-cored highs toward the distal basin (Figs. 1 and 3).

CONCLUSIONS

Our modeling results suggest that: (1) salt tectonics plays a key role in setting up the basin configuration and determining the sediment routing within the sink domain, (2) the evolution of local salt-related topography strongly controls the stratigraphic patterns within individual minibasins, and (3) it is possible to use physical and numerical models as analogs for real case subsurface case studies. The dramatic changes of stratigraphic patterns within a minibasin don't need to be linked to allogenic controls and can simply reflect a local response to salt tectonics. Our study emphasizes the importance of reconstructing paleotopography to understand sediment routing systems, especially in basins that developed above mobile substrates such as salt. Our methodology of integrating physical tectonic modeling and S2S numerical modeling provides new ideas on how to quantitatively predict the stratigraphic patterns preserved within salt-bearing basins. It is our intention to continue increasing the complexity of the numerical model by incorporating flexural subsidence as a response to sediment loading in our next batch of models. Salt tectonics, and the geological processes that operate within salt-bearing basins, have been predominantly the subject of study of geoscientists working in industry and applied research given the economic relevance that these basins have for oil and gas exploration. The overemphasis on proprietary resource assessment within these basins has left a gap in the understanding of some of the fundamental processes operating in salt-bearing basins that impacted Earth's evolution and therefore there is a need to pursue additional fundamental research using a more academic approach.

ACKNOWLEDGMENTS

This work was funded and directed by the State of Texas Advanced Resource Recovery (STARR) program in collaboration with the Applied Geodynamics Laboratory (AGL) consortia at the Bureau of Economic Geology, Jackson School of Geosciences at The University of Texas at Austin. Seismic data courtesy of CGG. We are grateful to Schlumberger for Petrel and to Eliis for Paleoscan University Grant software. We are also grateful for comments by two anonymous reviewers. Publication was authorized by the director of the Bureau of Economic Geology.

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Manuscript received 3 Jan. 2023
Revised manuscript received 29 Mar. 2023
Manuscript accepted 29 Mar. 2023