Stratigraphic analysis of XES02: implications for the sequence stratigraphic paradigm

Bradford E. Prather[1,2], Oriol Falivene[3], and Peter M. Burgess[4]

[1]Department of Geology, 1414 Naismith Drive, University of Kansas, Lawrence, KS 66045, USA

[2]CarTerra, LLC, 715 Knox Street, Houston, TX 77007, USA

[3]Shell International Exploration and Production. 3333 Highway 6 South, Houston, Texas 77082, USA

[4]School of Environmental Sciences, University of Liverpool, Jane Herdman Building, Liverpool, L69 3GP, U.K.

Corresponding author E-mail: (bprather@ku.edu)

Short title – Stratigraphic Analysis of XES02

ABSTRACT

Sequence stratigraphy has the potential to provide a consistent method for integrating data, correlating strata, defining stratigraphic evolution, and generating quantifiable predictions. However, the consistent application requires a precise definition of concepts, stratigraphic units, bounding surfaces, and workflow. Currently no single generally accepted approach to sequence stratigraphic analysis exists, nor are there any robust tests of models and methods. Applying conventional sequence stratigraphic analysis to strata from an analog laboratory experiment (eXperimental EarthScape02, XES02) with known boundary conditions and chronology provides some initial robust testing of the models and methods. Despite stratigraphic architectures apparently consistent with those expected within the sequence stratigraphic paradigm, blind-test applications yield 1) deducted erroneous base-level curves, 2) systems-tract classification mismatches, 3) disconnected systems-tracts type and actual base level, 4) time-transgressive basin-floor fans and 5) missing systems tracts. Stratigraphic forward models using base-level curves derived from Wheeler diagrams cannot match the timing, redeposited-sediment volume, and depositional environments observed in the XES02 experiment. These mismatches result from common Wheeler diagram construction practice, producing poorly resolved base-level minima timing and base-level fall durations, hence inaccurate fall rates. Consequently, reconstructions of controlling factors based on stratal architectures remain uncertain, making predictions similarly uncertain. A reasonable path forward is to properly acknowledge these uncertainties while performing stratigraphic analysis and to address them through multiple scenario analysis and modeling.

KEYWORDS: sequence stratigraphy, eXperimental EarthScape, stratigraphic analysis, Wheeler diagram, stratigraphic forward model

INTRODUCTION

Sequence Stratigraphy: Evolution and Approaches

Sequence stratigraphy had slowly evolved from the late 1700s (Embry 2009) until the 1970s when the science went through a step change with the advent of seismic acquisition and processing schemes that showed arrangements of seismic reflectors amenable to stratigraphic interpretation. Over the past 40 years, the science of seismic stratigraphic has diverged into numerous sequence stratigraphy “schools of thought” all focused on various ways of defining a sequence boundary and the subsequent subdivision of a sequence into systems tracts (Frazier 1974; Mitchum et al. 1977; Haq et al. 1987; Posamentier et al. 1988; Van Wagoner et al. 1988; Galloway 1989; Van Wagoner et al. 1990; Embry and Johannessen 1993; Hunt and Tucker 1992; Helland-Hansen and Gjelberg 1994; Hunt and Tucker 1995; Neal and Abreu 2009; Catuneanu et al. 2011 Fig. 1). For an up-to-date summary of sequence stratigraphic concepts, we refer the reader to (Miall 2022) and the references therein.

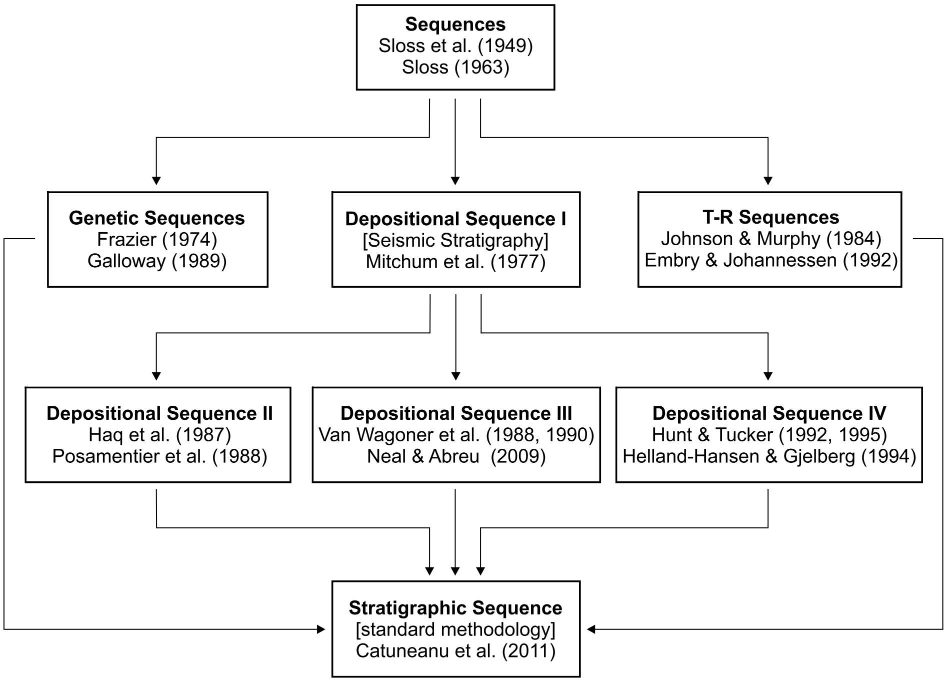

Fig. 1.– Evolution of approaches to sequence stratigraphy (Catuneanu 2019).

The divergent definitions have resulted in considerable confusion and miscommunication as different authors applied different sequence models and terminology in their study areas — see summaries by Catuneanu et al. (2009b), Embry (2009), and Catuneanu (2019). This culminated in a call for standardization of a sequence stratigraphic methodology, including the definition of concepts, stratigraphic units, bounding surfaces, and workflow (Catuneanu et al. 2009b). However, the publication of the plea from Catuneanu et al. only engendered continuing debate (Catuneanu et al. 2009a; Helland-Hansen 2009; Neal and Abreu 2009; Bhattacharya 2011; Henriksen et al. 2011). So, despite this and other calls for standardization over the years, there remains no generally accepted single approach to sequence stratigraphic analysis, nor any robust tests that prove these methods work.

Miall and Miall (2001) recognized these competing 'schools of thought' group into two paradigms, the global eustasy paradigm, which originated with Vail et al. (1977), and the complexity paradigm, which asserts that there are multiple causes of the accommodation changes that lead to the generation of sequences. Miall and Miall (2004) maintain that the scientific process in geology generally and sequence stratigraphic analysis specifically should be exemplified by the hermeneutic circle (Frodeman 1995), in which empirical observation, generalization, and theorizing (induction), are followed by the construction of a hypothesis (including models) and renewed observations to test and refine or abandon a theory (deduction). Ideally, this is a continuous and progressive process that tests theoretical assumptions. Still, history demonstrates that different and separate groups of stratigraphers have primarily followed the inductive and deductive approaches with various often quite divergent objectives (Miall and Miall 2004).

Sequence Stratigraphy Applications and Tests

In its broadest sense, there is consensus that sequence stratigraphy consists of recognizing and correlating stratigraphic surfaces, which represent changes in depositional trends in the rock record, and the description and interpretation of results, genetic stratigraphic units bounded by those surfaces (Embry 2009). The construction of a framework of systems tracts and bounding surfaces fulfills the practical purpose of sequence stratigraphy if the objective is to describe and interpret the depositional history of a stratigraphic succession (Embry 2009; Catuneanu 2020). Bhattacharya and Abreu (2016) maintain that without using a sequence stratigraphic approach, regardless of which “school” of sequence stratigraphy you prefer, it will be difficult to define reservoir–seal pairs and make accurate predictions about the updip and downdip limits of strata. The utility of the sequence stratigraphic approach is in its consistent application for the integration of data, correlation of strata, and definition of stratigraphic evolution in an area of study (Catuneanu et al. 2009a). However, simply interpreting data following a method with a few underlying model assumptions does not, on its own, test whether a model is correct or useful.

Another approach is to use the lithofacies distributions implicit in the various sequence stratigraphy models, supported only by limited and distant data points or indirect and low-resolution measurements in the exploitation of subsurface resource, as a framework for risk and uncertainty quantification in subsurface predictions. When this process culminates in drilling a well, the test is obvious. It compares the predicted stratigraphic succession, lithologies, and rock properties, represented by a well prognosis versus what is found from drilling. Currently, few or no tests of sequence stratigraphy of this type are published in the form of statistics on how well the predictions match the results of a blind test, as in this example we present here.

Barrell (1917) showed that when long-term and short-term curves of sea-level change are combined, the oscillations of base level provide only limited intervals when sea level is rising, and sediments can accumulate, such that “Only one-sixth of time is recorded” by sediments. Ager (1973, 1993) argued that “the sedimentary record is more gap than the record.” He suggested that many sedimentary units are deposited over very short periods of time and that the record is replete with gaps, the significance of which commonly goes unrecognized. Such gaps may, in total, represent more elapsed time than that of the preserved sediment, introducing uncertainty in any interpretation of depositional history based on stratigraphic architecture. To better address, this uncertainty, sedimentary geology and geomorphology are moving away from reasoning by analogy to reasoning by analysis (Paola et al. 2009). Laboratory experiments (Strong and Paola 2008; Martin et al. 2009; Cantelli et al. 2011) and stratigraphic forward modeling (Sylvester et al. 2011; Burgess 2012; Burgess et al. 2016; Falivene et al. 2019; Falivene et al. 2020) afford the geologist with the opportunity to observe and quantify how depositional history is recorded in strata.

However, aside from testing the lithology predictions, another key question remains: how often are the predicted processes that underpin these lithological predictions also tested? For example, these process predictions are assumed to be dominantly accommodation controlled, with a simple response to accommodation forcing providing predictive power even with limited data. Consequently, this is the element that most critically requires testing. One of the reasons for the paucity of tests of the validity of the sequence stratigraphic method is the difficulty of obtaining independent proxies for accommodation and sediment supply and a lack of suitable datasets in which stratigraphic architecture can be independently and unequivocally tied back to a specific set of accommodation and sediment supply (Burgess and Steel 2017). In addition, even the more detailed datasets with high-resolution three-dimensional seismic coverage of recent deposits usually have only limited chronostratigraphic and lithologic control. Therefore, an important alternative is to use laboratory experiments to test the sequence stratigraphic method.

Objectives

So, what are the practical consequences of a sequence stratigraphic interpretation from employing one or the other “schools”? This paper aims to conduct two types of stratigraphic analysis of the preserved deposits and stratigraphic architecture of the XES02 laboratory experiment, to test how well sequence-stratigraphic interpretations of line 1700 (Fig. 2, 3) can unravel the actual base-level controls of the experiment, and compare them to actual shoreline trajectories and systems tracts. To demonstrate how uncertainties in the derivation of base-level curves inherent in sequence stratigraphy methodologies affect stratigraphic architecture and sediment partitioning, we create a virtual flume using a previously calibrated reduced-complexity stratigraphic forward model described, validated, and tested in Falivene et al. (2019) and Falivene et al. (2020). We choose line 1700 because it is centrally located within the extent of the flume and has been the subject of recent studies (e.g., Martin et al. 2009; Granjeon 2014; Martin et al. 2017; Falivene et al. 2019; Aali et al. 2021).

Our conventional analysis applies the paradigm of Mitchum et al. (1977), Haq et al. (1988), and Posamentier et al. (1988), termed ***Depositional Sequence II*** (Fig. 1), using

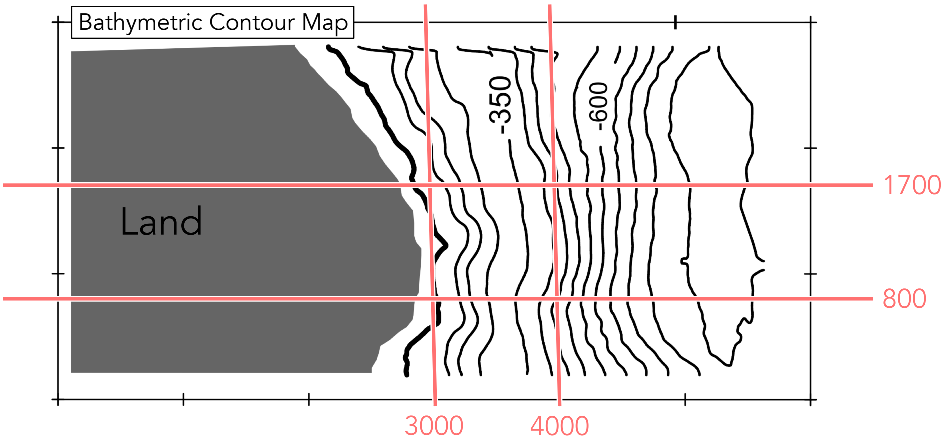

Fig. 2.— XES02 index map showing locations of lines used in this study to illustrate stratigraphy. Horizontal and vertical scales in mm.

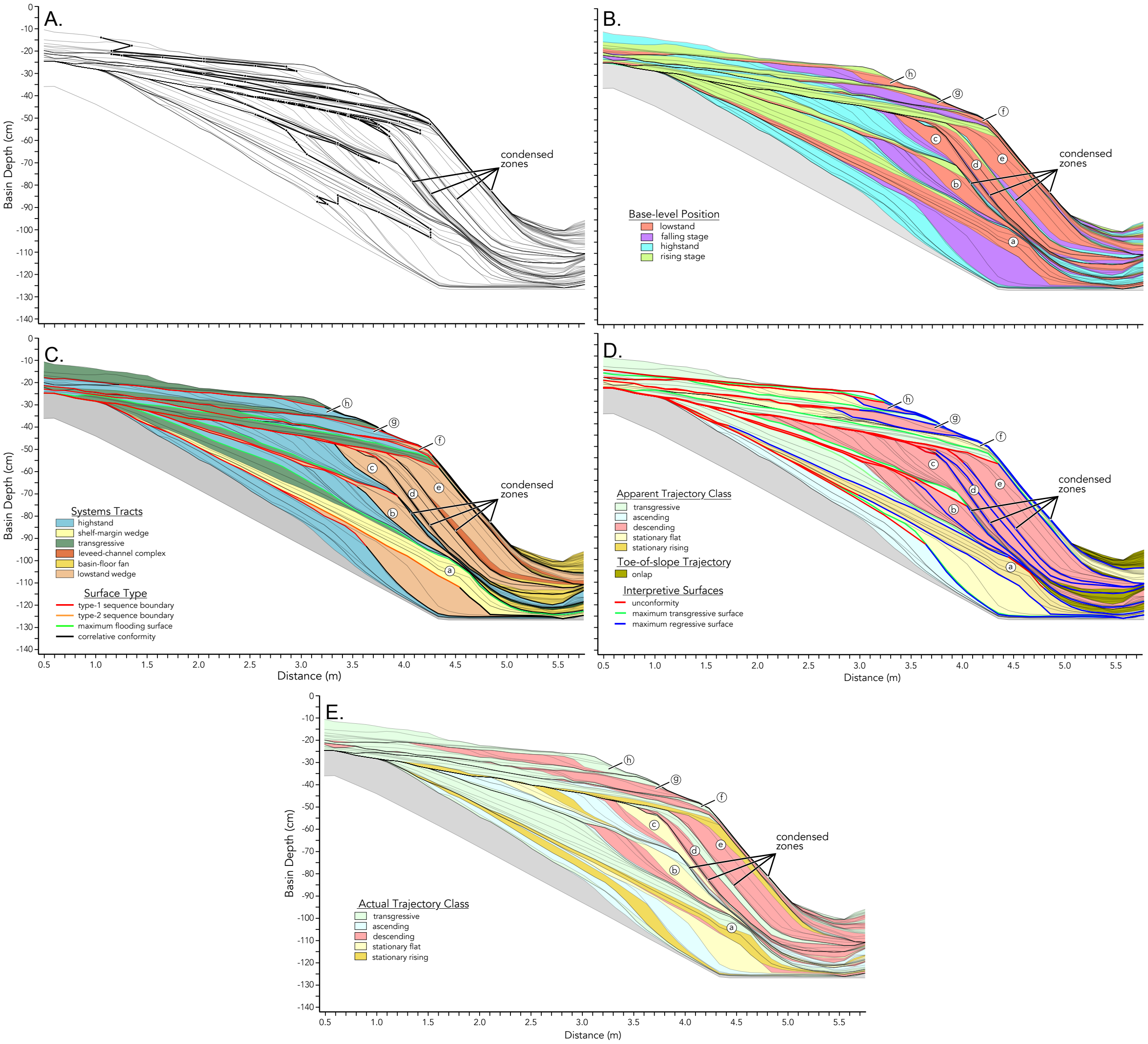

Fig. 3.— **A)** XES02 experiment architecture shows the scanned surfaces in final stratigraphic positions at a depositional dip slice around 1700 mm. The black dots denote shoreline positions, and connecting line denotes shoreline trajectory. Inset base map is from Martin et al. (2009). **B)** Stratigraphic analysis showing genetic units based on relative base level. **C)** Conventional sequence stratigraphic analysis showing systems tracts. **D)** units defined by apparent shoreline trajectory and **E)** units based on actual shoreline position (see Shoreline Trajectory Animation in Supplemental Files). Stratigraphic units a-h correspond to base-level *minima* (see Fig. 6).

Wheeler diagrams to reconstruct the base-level signal from the preserved architecture of XES02. This interpretational paradigm has been around for several decades, and the original systems-tracts terminology has recently been replaced with a scheme akin to that of Hunt and Tucker (1995) consisting of four almost universally accepted standard systems tracts: the highstand (HST), falling-stage (FSST), lowstand (LST) and transgressive (TST) systems tracts (Aali et al. 2021; Miall 2022). We choose Depositional Sequence II because we observe onlapping deposits at the toes of slopes in XES02 that appear to be below lowstand-stage prograding shelf-edge deltas, which is inconsistent with the standard systems-tract arrangement cited by Miall (2022) (see the section on Conventional Sequence Stratigraphic Analysis below), and Depositional Sequence II remains a “school of thought” commonly used in training exercises for universities and industry (e.g., Martin et al. 2017).

We also employ the trajectory-analysis approach of Helland-Hansen and Gjelberg (1994), termed here ***Depositional Sequence IV*** (Fig. 1). This “school” of thought is a common alternative to ***Depositional Sequence II*** analysis, favored by those who find the circular reasoning implied by the sea-level-linked systems-tracts terminology inherent in ***Depositional Sequence II*** objectionable. For simplicity, we assume that subsidence and sediment supply are known and constant, as it is in the experiment analyzed, even if this is not the case in natural systems. We choose these two ‘schools of thought’ as any seismic stratigrapher would have to when confronted with a regional seismic line from a frontier basin with no well data, a situation where the sequence stratigraphic method has perhaps the most potential to be useful.

XES02 EXPERIMENT

Boundary Conditions

The XES02 laboratory experiment was conducted in the eXperimental EarthScape facility (Saint Anthony Falls Laboratory, University of Minnesota), and designed to study long-term depositional patterns affected by spatially variable subsidence, time-variable eustasy, water discharge, and sediment supply. Boundary conditions and analysis of the resultant stratigraphy are briefly summarized below. For details, we refer readers to Kim et al. (2006a, 2006b), Strong and Paola (2008), Kim et al. (2009), and Martin et al. (2009) and for more complete treatments of the XES02 experiment.

The experiment started with progradation of a fan delta over a flat, wholly submerged initial topography with no subsidence, for approximately 60 hrs. The main experimental phase of 310 hrs follows; subsidence during this phase was basinward-increasing, representing a passive-margin-style subsidence profile. The subsidence rate was constant at an arbitrary location in the experimental domain (Martin et al. 2009).

Sediment was input through a point source at the center of the landward margin of the basin. Sediment supply was constant, set up at 0.0051 liters/second (including porosity, Martin et al. 2009). Assuming an initial porosity of 50%, the grain sediment supply rate approximates 0.92 x 10–2 m3/hour. The composition of the supplied sediment was 63% silica sand, 27% anthracite coal, and 10% kaolinite clay (Martin et al. 2009). Sand is the coarse-sediment fraction, and the lower-density coal is a more mobile fraction, mimicking the effect of mud (Martin et al. 2009). Kaolinite clay was initially added to enhance the mechanical strength during the sectioning of the experiment, but most of it accumulated in the distal marine part of the flume (Martin, personal communication).

The flume-tank water level (in effect, base level) followed a base-level curve with several sinusoidal fluctuations, including a) a single “slow” fall, followed by a rise in base level that lasted for 108 hrs (slow cycle; Fig. 4A), b) a single “rapid” fall, and rise (rapid cycle) with a subsequent base-level high stand lasting 18 hrs, and finally c) six “rapid” base-level cycles superimposed on a lower-order “slow” cycle to produce a “modulated” fall, and a lower-order rise to produce a modulated rise (Fig. 4C). The experiment was designed to study the geomorphic response of a transport system to “slow” and “rapid” allogenic forcing by base-level fluctuations (relative to the response time of the transport system itself) and its stratigraphic effects.

The experiment produced strata that resemble a typical passive-margin succession with multiple sets of clinothems (Fig. 3A). Subaerial topsets were dominated by one to multiple distributary channels that migrated laterally with multiple episodes of aggradation and incision. The non-cohesive sediment created a highly laterally mobile transport system and no persistent overbank deposits. Subaqueous sedimentation was dominated by grain fall and, to a lesser extent, by weak “turbidity” currents. Foreset over steepening and subsequent failures result in sediment bypass and accumulation as bottomsets. Base-level fluctuations strongly controlled the stacking patterns, shoreline position, and topset erosion (Kim et al. 2006b).

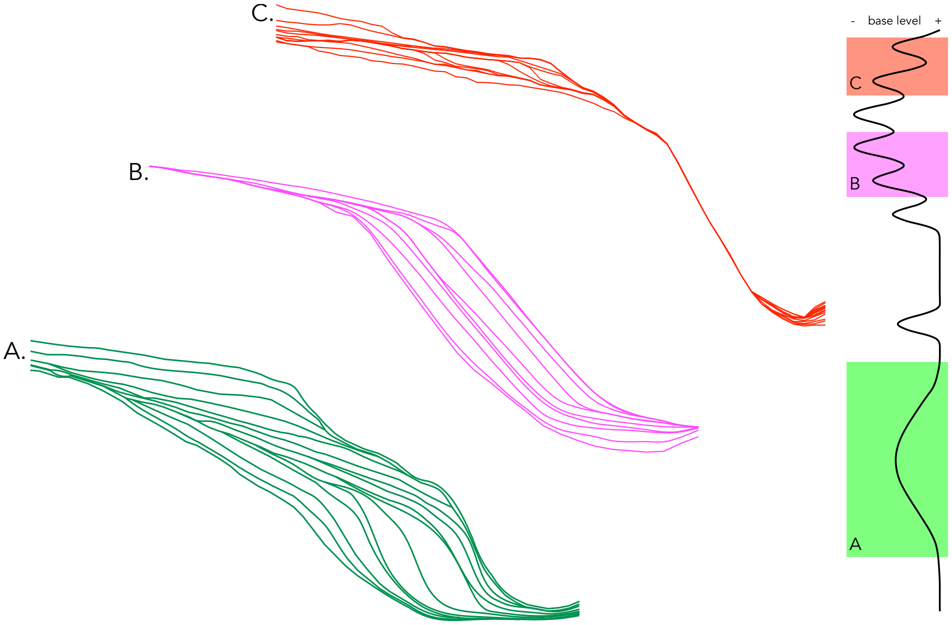

Fig. 4.— A) Stratigraphic-architecture styles resembling a low-frequency, low-amplitude slow-cycle base-level cycle, and B) composite high-frequency modulated base-level fall, and C) composite high-frequency modulated base-level rise (after Martin et al. 2008).

Data Collected from the Experiment

Topographic and bathymetric scans were collected at specific times during the experiment, creating 94 snapshots of surface topography through time (Kim et al. 2006a). The time surfaces were converted to their final stratigraphic position by migrating them downward and clipping them where eroded to account for postacquisition subsidence (Fig. 3A). This allows visualization of the resultant stratigraphy and sediment distribution in response to base level forcing and subsidence.

The shoreline position for each scanned surface was computed by intersecting topography with its corresponding base level at the time of deposition. Shoreline trajectory was then computed by connecting successive shorelines in consecutive snapshots (Fig. 3A). This approach is similar to Kim et al. (2006b). Subsidence increased basinward along the axis of the experiment, resulting in the rotation of the strata dipping towards the basin. Where younger topographic surfaces erode underlying stratigraphy, the shoreline position shifted vertically downward and was projected onto the corresponding unconformity. Automating trajectory analysis provided a complete history of actual shoreline migration at every time step before any later modification by erosion (see Supplementary files lines 800 and 1700 Shoreline Trajectory and Laboratory Experiment 3D Evolution Animations).

RESULTS: STRATIGRAPHIC ANALYSIS

Computed Time-Corrected Wheeler Diagrams

The chronostratigraphic or Wheeler diagram is a primary tool for understanding time preservation in the stratigraphic record (Wheeler 1958,1964a,1964b). Wheeler diagrams represent stratigraphic units and their bounding surfaces on plots with distance on the horizontal and relative time on the vertical axis (Fig. 5). If there are no absolute time constraints, the construction of these plots often assumes that the thickness of stratigraphic units to be a first-order approximation of elapsed time when plotted on a relative geological time scale (Fig. 5). Although this assumption is frequently used, caution is required since sedimentation rates can vary locally due to allocyclic (for example, variations in catchment denudation rates due to climate, uplift rates, or drainage reorganizations) or autogenic forcing due to avulsions.

Seismic reflection data can also be used to construct Wheeler diagrams by following the common assumption that seismic reflectors correspond to timelines, so that flattening the seismic reflectors and thereby converting two-way transit time into relative geologic time (Lomask et al. 2009; van Hoek et al. 2010, Qayyum et al. 2012; and Qayyum et al. 2014 Fig. 5). The units can be adjusted given available absolute time calibration for both thickness and two-way-transit-time approximations of elapsed time. As a result, Wheeler diagrams are only as reliable as available chronological data, and there is increasing recognition that new approaches are required to make progress, given this and other inherent uncertainties in the analysis of ancient strata (Sadler 1981; Burgess and Steel 2017; Miall et al. 2021).

Several options exist to automate the generation of Wheeler diagrams from a stack of stratigraphic surfaces of known or assumed age. For example, plots can be constructed by computing sedimentation rates for each location and stratigraphic position, masking

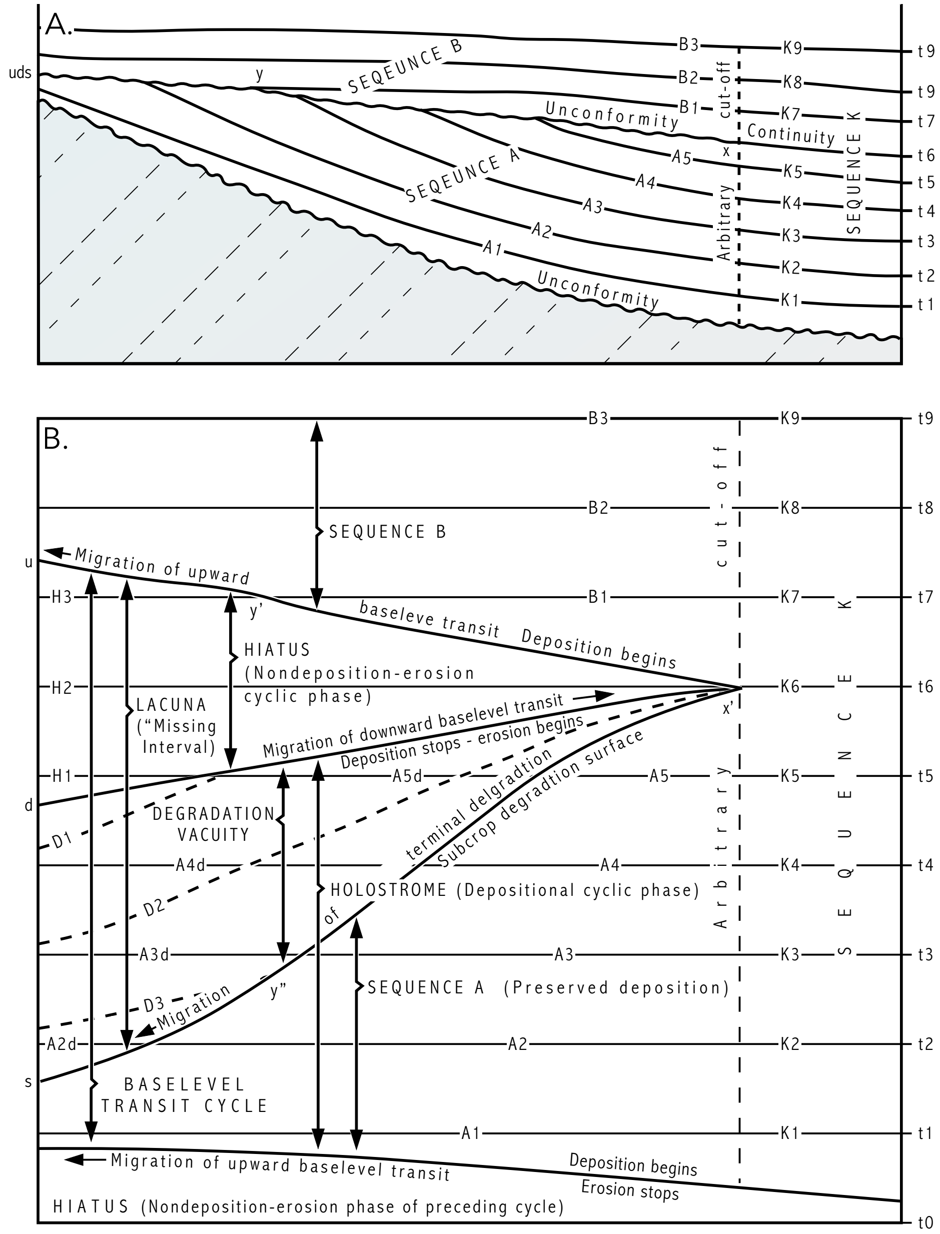

Fig. 5.— Classic Wheeler diagram redrawn from Wheeler (1964b) showing relationships of successive unconformity-bounded sequences and time stratigraphy. Note that in the absence of detailed chronostratigraphy, timelines are equally spaced.

zones with low sedimentation rates (Lomask et al. 2009), or plotting multiple interpolated truncated surfaces (Qayyum et al. 2012; Qayyum et al. 2014).

Another option is the so-called pseudo-Wheeler display method (van Hoek et al. 2010), which generates Wheeler plots that appear more similar to those manually constructed during conventional seismo-stratigraphic analysis. Using this method, we generate Wheeler displays for XES02 by considering the 94 surfaces scanned from the experiment, which in this case correspond to actual timelines of known age, for a specific section of the experiment (Fig. 6A). For each layer bounded by two consecutive stratigraphic surfaces, we flatten the top as a horizontal datum corresponding to the age of the top layer. The position of the base is proportionally distributed between the age of the previous layer and the age of the top. Zones with large relative unit thickness

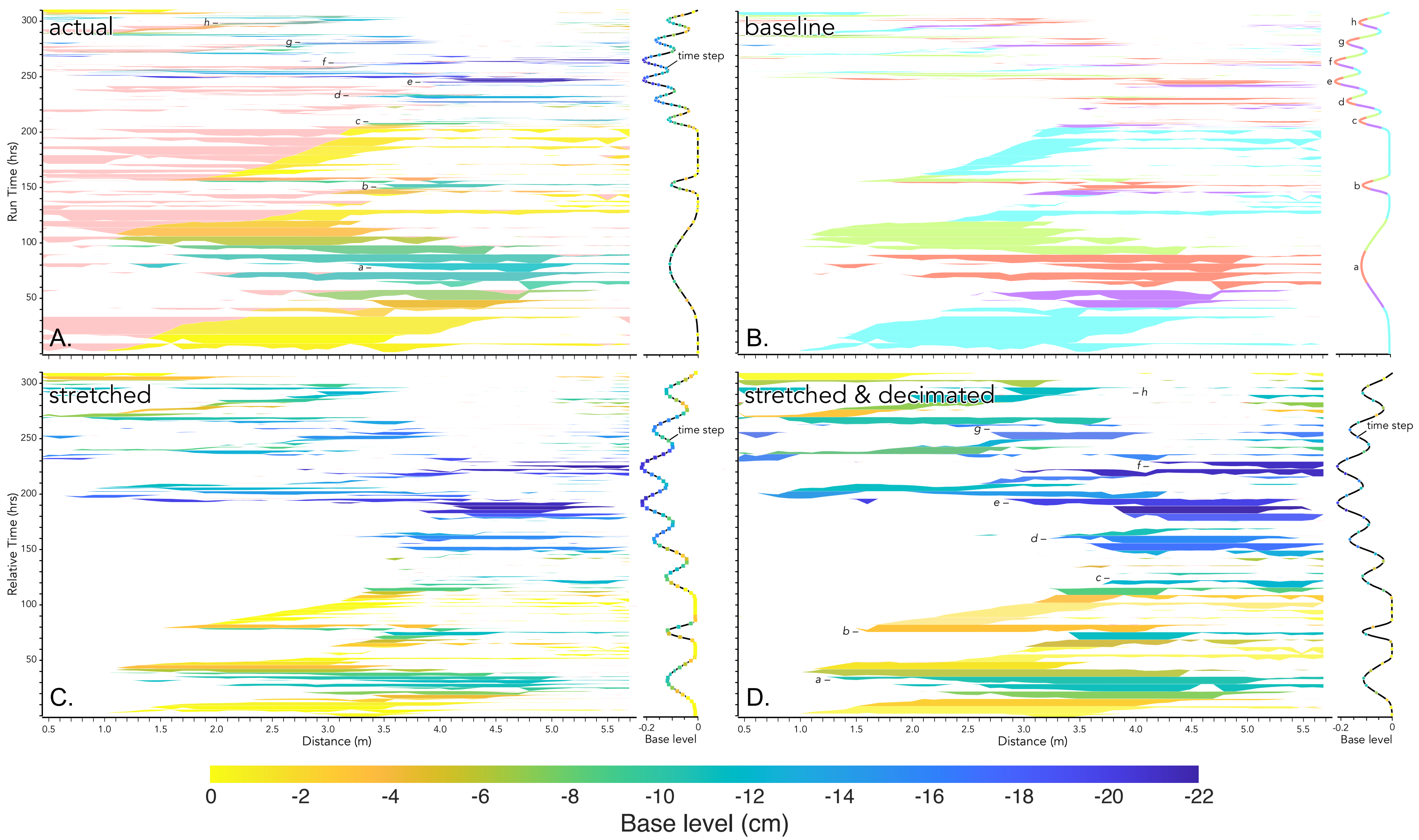

Fig. 6.— **A)** Actual Wheeler diagram from the final stratigraphic positions of surfaces scanned in the XES02 experiment following a depositional dip slice around 1700 mm. Each unit is color-coded for absolute base-level position except for the pink units, which represent degradational vacuity (***sensu*** Wheeler 1964b). **B)** Baseline diagram (see Fig. 3B for facies explanation); each unit is color-coded for relative base-level position and key stratigraphic events (base-level local ***minima***) a-h indicated. These are used to measure time offsets compared to various sequence stratigraphic analyses. **C)** Evenly spaced time steps (i.e., relative time) and resulting stretched base-level curve. **D)** Decimated time steps with correlative local base level and local ***minima*** events a-h. All time step indicators are color-coded for their absolute base-level position.

correspond to areas with high sedimentation rates, and therefore the base of the layer is at or near the age of the lower surface. Conversely, zones with small relative unit thickness correspond to areas with slow sedimentation rates, and therefore the base of the layer is at or near the age of the top surface (Fig. 6A). Sediment removed by erosion (degradation vacuity Fig. 5) during subsequent experiment evolution was also identified (pink areas as seen in Fig. 6A). A version of the Wheeler diagram with the eroded section not displayed was used for comparison purposes (compare Fig. 6A to B, C, and D).

Our baseline Wheeler diagram (Fig. 6B) provided a means of subdividing the XES02 stratigraphy into genetic units defined by relative base-level position at the time of deposition — these are comparable to depositional systems tracts as originally defined by Brown and Fisher (1977). These base-level-defined units are strictly observational and serve as a control for comparison with other forms of stratigraphic analysis described below. Genetic stratigraphic units in this analysis are defined relative to the XES02 base-level curve, where every base-level cycle was divided into rising, highstand, falling, or lowstand limbs (Fig. 6B). These time intervals can then be identified, and stratigraphic units color-coded accordingly on the corresponding depth section (Fig. 3B).

Conventional Sequence Stratigraphic Analysis

Martin et al. (2008, 2009, 2017) examined the experimental strata of XES02, focusing on stratigraphic surfaces defined by discordant contact geometries, and surfaces analogous to those delineated in the original work on seismic sequence stratigraphy (e.g., Posamentier and James 1992). Martin et al. highlight important aspects of sequence boundaries but include only a cursory classification of several systems tracts. In our conventional sequence stratigraphic analysis (e.g., Vail et al. 1977; Posamentier and Vail 1988; Van Wagoner et al. 1988; Van Wagoner et al. 1990), we purposely impose the sequence stratigraphic model on the entire XES02 fill (Fig. 3C). Our conventional sequence stratigraphic analysis was compared to a stratigraphic subdivision of XES02 stratigraphy using actual base level as a control (Fig. 6B) and a trajectory analysis (*sensu* Helland-Hansen and Gjelberg 1994 Fig. 3D) to define units, and Wheeler diagrams to reconstruct the base-level signal from the preserved stratigraphic architecture.

Once completed, the systems-tracts interpretation (Fig. 3C) was converted to a Wheeler diagram where stratigraphic unit thickness in the section was used as a first-order approximation of the duration of relative geologic time (e.g., Wheeler 1958, 1964a, 1964b; Lomask et al. 2009; Qayyum et al. 2012;). Individual stratigraphic units were further shaped using patterns of toplap and baselap and plotted against relative geologic time. An interpreted base-level curve was added by tracking the position of the maximum unit thickness (Haq et al. 1987; Jervey 1988; Posamentier et al. 1988 Fig. 7A).

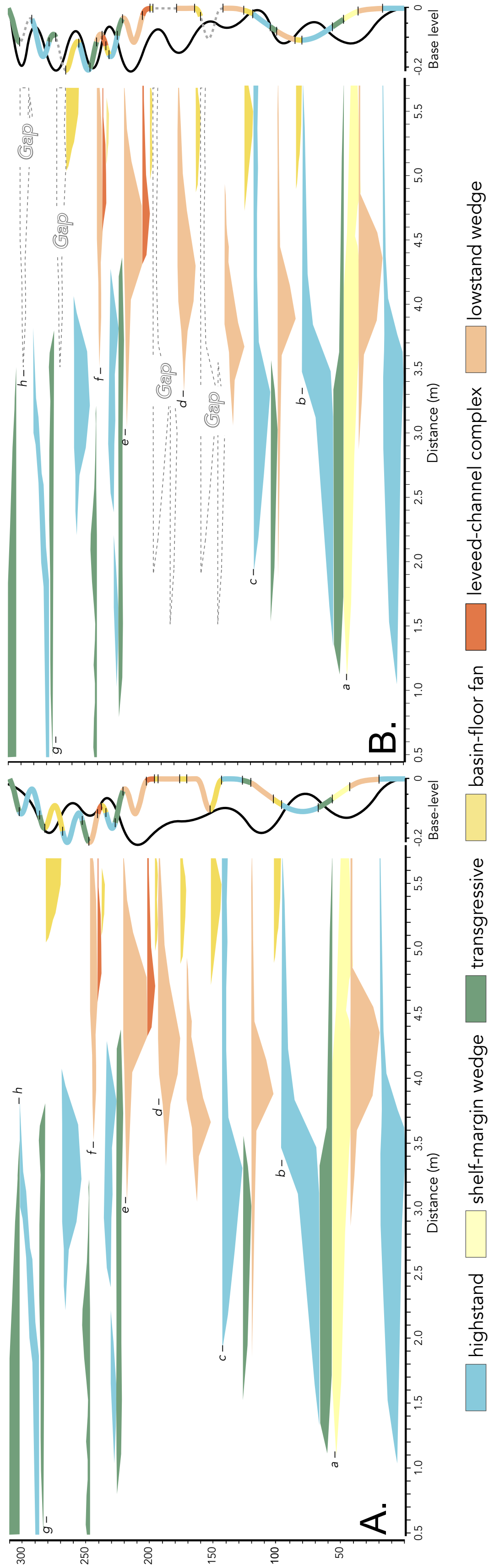

Fig. 7.— **A)** Wheeler diagram from conventional analysis (Fig. 3C) with the actual XES02 base level curve color-coded for systems-tracts positions and derived base-level curve. Note relative base-level *minima* events a-h from Fig. 6B. A summary of offset amounts is found in Table 1. **B)** Wheeler diagram based on sequence stratigraphic analysis but with restored systems tracts and correlative baseline *minima* a-h (Fig. 6B) and systems tracts are color-coded on the actual base-level curve.

The resulting stratigraphic succession does not fit the conventional sequence stratigraphic model. It is missing highstand and transgressive systems tracts associated with each of the shelf-margin wedges in the modulated falling-stage cycles between c-e base level *minima* (relative run times 160-200 hrs, Fig. 7A). This arrangement of systems tracts reflects deposition during three successive base-level falls, producing stacked shelf-margin wedges with eroded remnants of highstand and transgressive systems tracts on the shelf (Fig. 6B). The absence of these stratigraphic elements suggests that they might have been eroded, which in the case of XES02 is indeed true.

Stretched Wheeler Diagrams

As the accuracy of Wheeler diagrams in natural field settings is dependent on the availability of detailed chronostratigraphic control, short-term depositional cycles often remain unresolved, and unit boundaries or seismic reflectors are assumed to be equally spaced between points of age control (e.g., Wheeler 1964a, 1964b, 1958; Lomask et al. 2009; Qayyum et al. 2012).

The assumption of continuous deposition is fundamental to the construction of Wheeler diagrams plotted against relative geologic time. This interpretation inevitably follows from (1) assumed limited availability of high-resolution tightly constrained age dates and (2) the cryptic nature of most sedimentary hiatuses (Miall 2014). To judge the quality of our conventionally-constructed Wheeler diagram (Fig. 7A), we calculate from the XES02 data a Wheeler diagram where the duration between scanned surfaces is assumed as constant, stretching and squeezing the intervals between scanned surfaces throughout the duration of the experiment (Fig. 6C). This effectively converted the actual XES02 Wheeler diagram (Fig. 6A), where the stratigraphy is plotted against absolute time, to a Wheeler diagram that mimics an equivalent plotted against relative geologic time (Fig. 6C). We also created a decimated version of the stretched Wheeler diagram, to represent a lower time resolution and ease comparison with similar diagrams made through conventional sequence stratigraphic analysis (Fig. 6D). For both the stretched and decimated Wheeler diagrams, the base-level curve used in the experiment is stretched similarly, providing a new curve representing an objective representation of a poorly constrained base-level history.

Our stretched Wheeler diagram (Fig. 6D) has a poor match with the baseline stratigraphic events, which are offset an average of 47 hrs with respect to a total experiment duration of 310 hrs (Table 1). However, the stretched Wheeler diagram better matches the conventional Wheeler diagram (Fig. 7A); here, the baseline stratigraphic events are offset an average of 21 hrs (Table 2). The quality of the match reflects the assumption that evenly spaced timelines used to build the conventional Wheeler diagram was well executed.

Genetic Units Defined by Trajectory Analysis

We used a form of trajectory analysis (Helland-Hansen and Gjelberg 1994; Helland-Hansen and Martinsen 1996; Helland-Hansen and Hampson 2009) to define apparent descending, ascending, stationary rising, stationary flat, and in the special case of toe-of-slope deposits, onlapping trajectory classes to determine a succession of “genetic” units to complement our baseline and conventional sequence-stratigraphy analysis (Fig. 3D, E). In this scheme, trajectory descriptors replace sea-level descriptors in process explanations. The associated shelf-edge incision of flat or falling trajectory is commonly linked to sand-rich basin-floor deposition; rising and backstepping trajectory indicates shelf aggradation and sediment starvation of the slope and basin floor (Johannessen and Steel 2005; Henriksen et al. 2009; Ryan et al. 2009). Aali et al. (2021) use an automated geometrical breakdown approach (GBA) to classify XES02 systems tracts using trajectory analysis to reduce reliance on model-driven interpretations. Their approach differs from ours in that our analysis is manual only and is designed to reflect model-driven interpretations common to humans. Our trajectory analysis is later benchmarked using the actual shoreline trajectories automatically computed from the experiment data (Fig. 3A). We also did not attempt a sequential decompaction (*sensu* Beelen et al. 2019) or rotation of strata to define our apparent trajectory classes because these techniques, while almost certainly of great and underestimated importance, are not common in studies of frontier basins. However, we did examine the

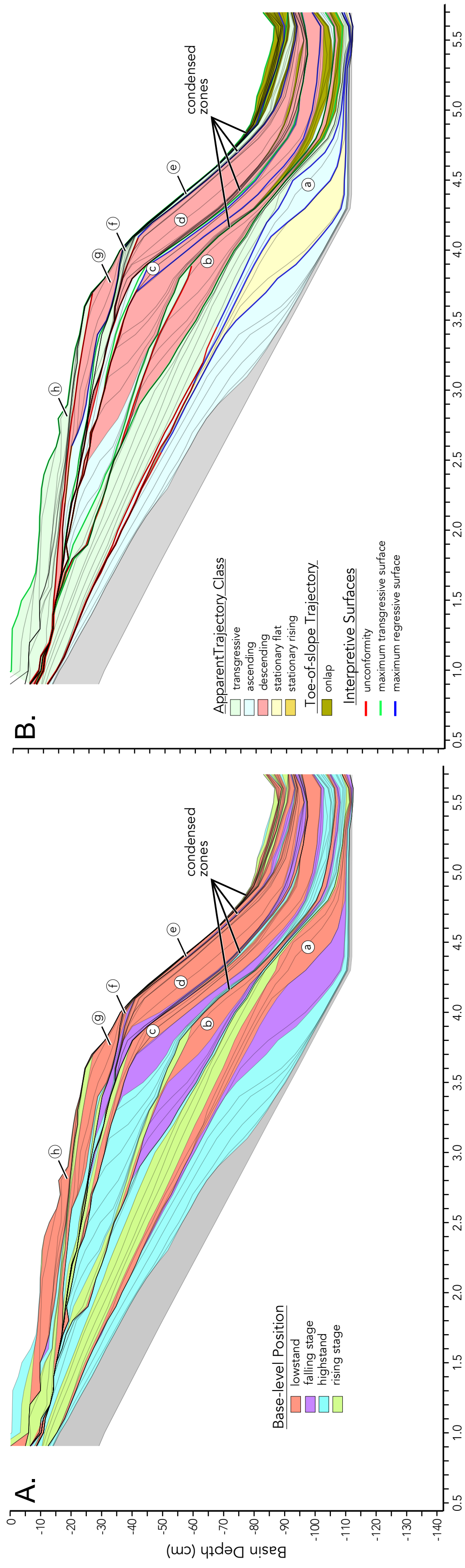

Fig. 8.— Line 800 analyses showing **A)** stratigraphic analysis showing relative base-level units identified in Baseline Wheeler diagram (Fig. 9B). **B)** Genetic units based on trajectory analysis. See Index Map (Fig. 2) for line location.

Table 1.— Timing of baseline stratigraphic events respect to the baseline.

	Baseline	Conventional (Fig. 6A)		Conventional /w Gaps		Stretched (Fig. 5D)	
Event	*t*	*t*	Δ|t|	*t*	Δ|t|	*t*	Δ|t|
a	60	54	6	44	16	33	27
b	150	96	54	80	70	76	74
c	210	142	68	118	92	125	85
d	230	193	37	173	57	160	70
e	245	219	26	218	27	192	53
f	265	244	21	238	27	225	40
g	280	281	1	273	7	259	21
h	300	303	3	298	2	292	8

actual topography and shoreline positions at all time steps to quality control our apparent trajectory product (see discussion of Trajectory Analysis below; also see Shoreline Trajectory Animation in the Supplementary Files).

Strike Variability

Testing whether one 2D transect is representative of base-level history for XES02 by analyzing other transects (Figs. 8, 9) along strike shows that there are generally small thickness variations and dip position changes of genetic units

Table 2.— Timing of baseline stratigraphic events respect to the Conventional interpretation Wheeler.

	Conventional (Fig. 6A)	Stretched (Fig. 5D)	
Event	*t*	*t*	Δ|t|
a	54	33	27
b	96	76	74
c	142	125	85
d	193	160	70
e	219	192	53
f	244	225	40
g	281	259	21
h	303	292	8

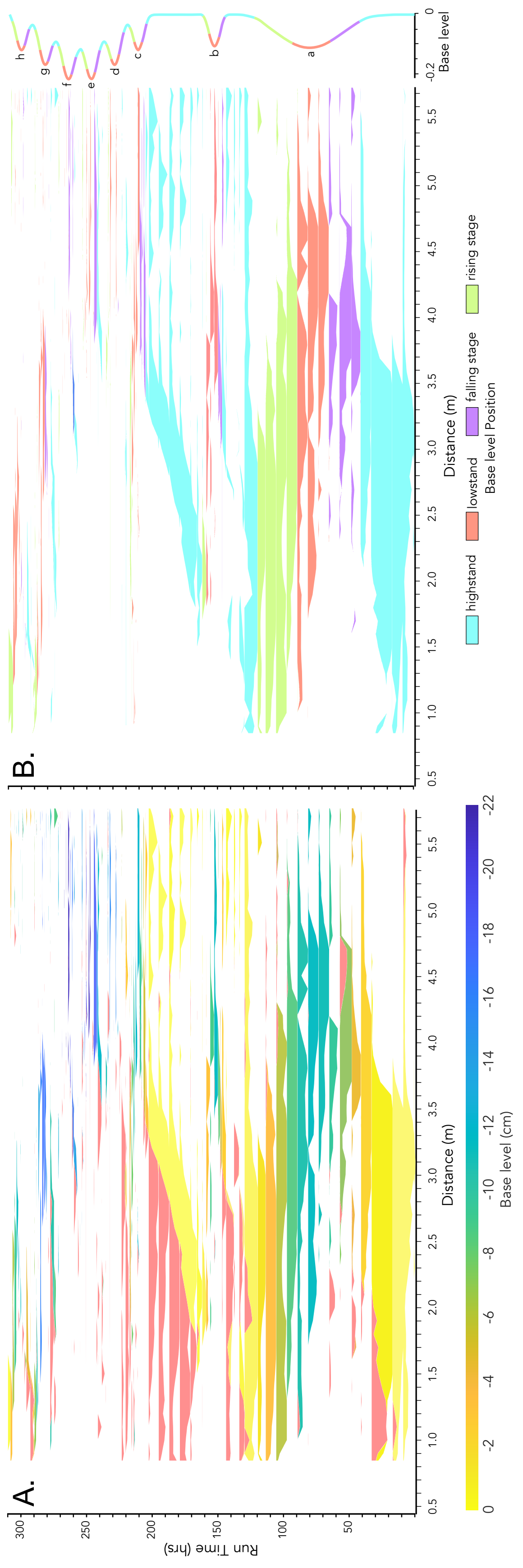

Fig. 9.— A) Actual Wheeler diagram from the final stratigraphic positions of surfaces scanned in the XES02 experiment at a depositional dip slice around 800 mm. Each unit is color-coded for absolute base-level position except for the pink units, which represent degradational vacuity (sensu Wheeler 1964b). B) Baseline diagram (see Fig. 3B for facies explanation) each unit is color-coded relative to its base-level position.

from one section to the next (Figs. 10, 11A). except for units between base-level *minima* events a–b (Fig. 11B), and b–c (Fig. 11C), which show significant differences in actual shoreline trajectory. Although the incised fluvial systems of XES02 are broad relative to the size of the tank, and the products of a single sediment-input point source that spreads uniformly across the tank, autogenic switching in the case of XES02 leads to significant differences in apparent trajectory class along strike (see section on Trajectory Analysis below for further discussion).

DISCUSSION

Sequence-Stratigraphy Analysis

Our conventional sequence stratigraphic analysis appears to be generally consistent with that expected within the sequence stratigraphic paradigm (Fig. 3C). This is not particularly noteworthy, because the XES02 experiment was designed to explore geomorphic responses to various base-level forcing, which is the underlying tenant of the sequence stratigraphic paradigm. However, we did encounter problematic interpretations and deviations from the conceptual model that are instructive when examined in detail. These include 1) systems-tract classification resulting in part from mismatches between systems tract type and actual base level, 2) artificial diachroneity within lowstand systems tracts, 3) time-

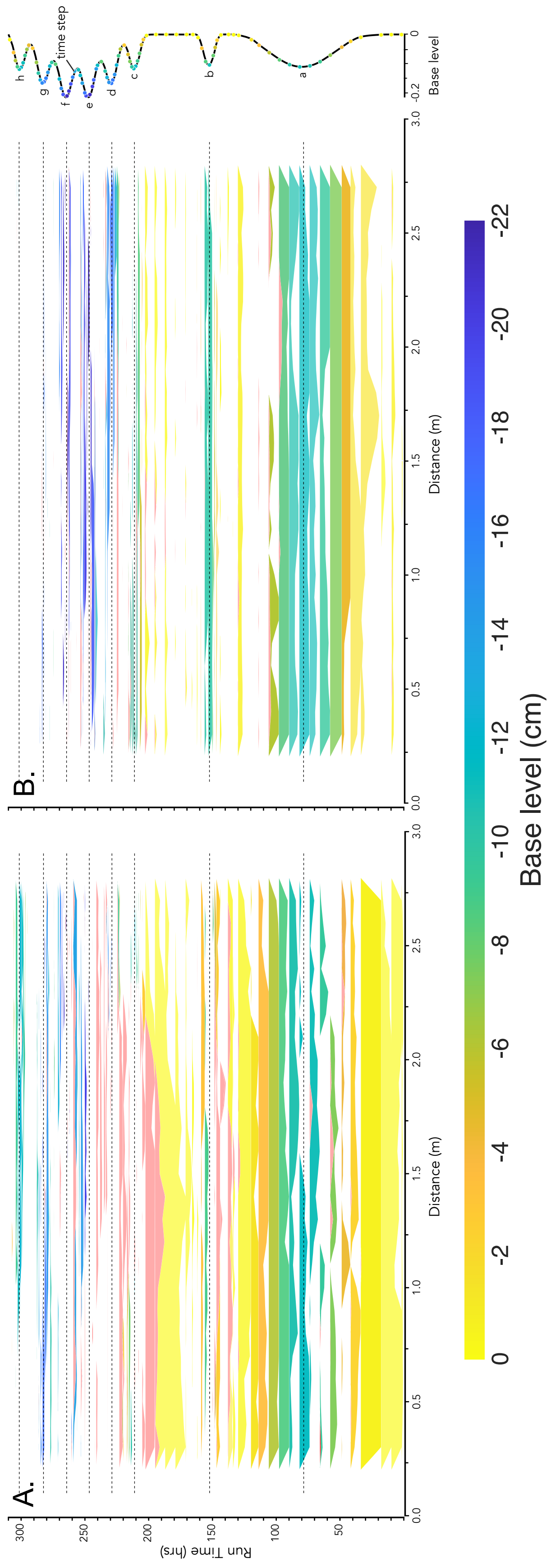

Fig. 10.— A) Strike Wheeler diagram at locations of 3000 mm and B) 4000 mm. See Index Map (Fig. 1) for line locations.

transgressive basin-floor fans, and 4) missing systems tracts, each topic of which is covered in the sections below.

Systems-Tracts Classification and Sequence Boundaries.— Assigning systems-tracts terminology was not always straightforward because identifying the sequence boundary was not straightforward, and the geometries of the sequence-bounded units in the conventional ***Depositional Sequence II*** model do not necessarily resemble those in the laboratory experiment. Still, the systems tracts can be easily made to resemble those of the ***Depositional Sequence II*** model in our conventional Wheeler diagram (Fig. 7A). Once done, it became clear that this approach did not accurately subdivide the strata into sediments deposited during the various base-level stages. Specifically, in our conventional analysis, highstand systems tracts correspond to strata deposited during both highstands and falling base level (compare Fig. 3B and Fig. 3C) due to our inability to accurately identify the sequence boundaries and their correlative conformities.

Sequence-boundary placement is dependent on which sequence stratigraphic school the interpreter chooses to use. In our case, we choose to use the concepts of Posamentier and Vail (1988), Posamentier et al. (1988), and Baum and Vail (1998), so we endeavored to find a sequence boundary corresponding with the beginning of sea-level fall, so coinciding with a subaerial unconformity on the shelf and upper slope, and with the base of submarine fan deposits in the basin.

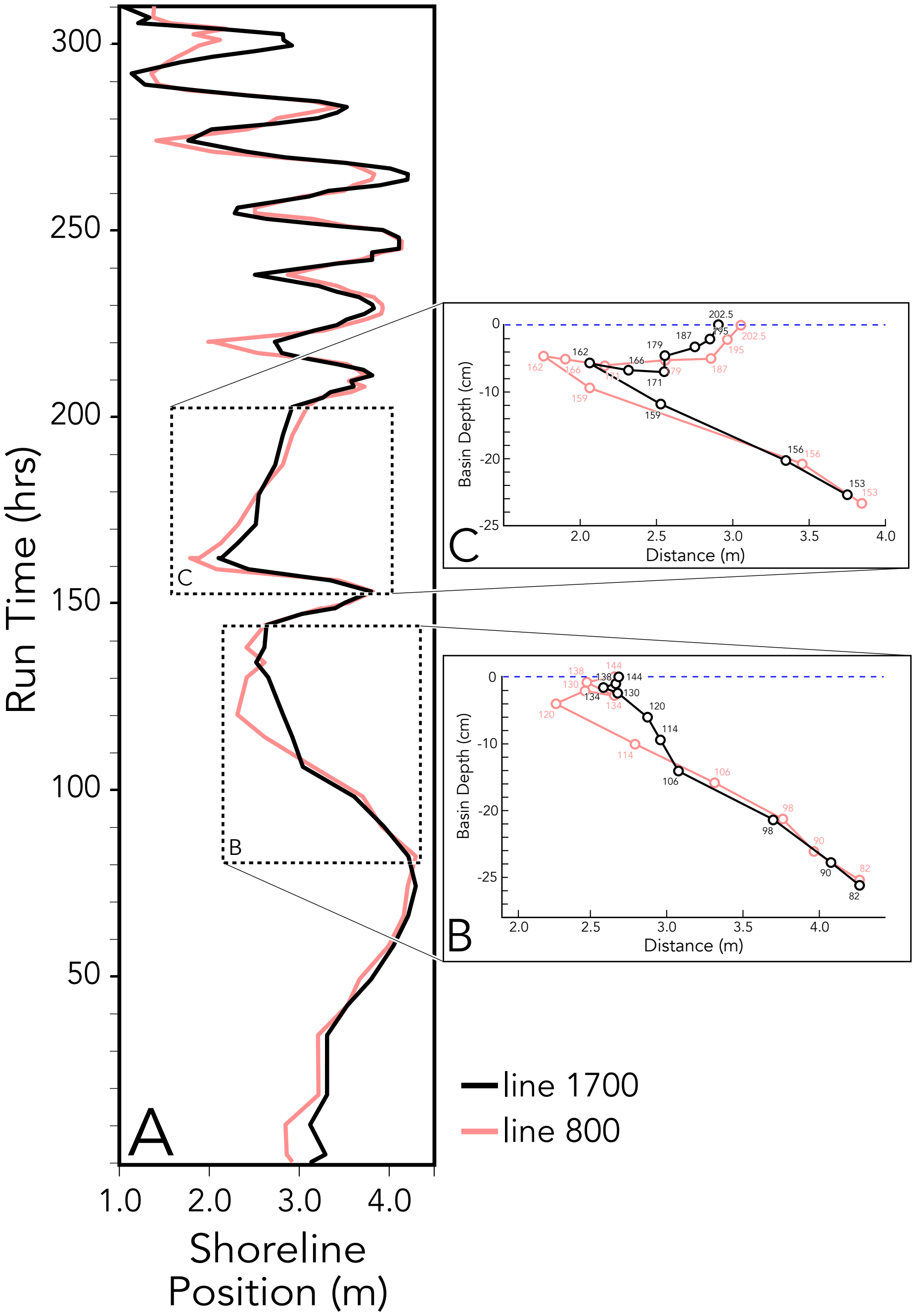

Fig. 11.— **A)** Comparison of actual shoreline trajectory histories of lines 800 and 1700**,** and **B)** actual shoreline positions in depth below the datum for time steps 153-202.5 hrs and **C)** 82-144 hrs.

However, the method used tended to place the sequence boundary within the lowstand, putting some of the falling-stage strata into the highstand (compare units b and c in Figs. 3B and C). Although we were able to identify the onlap surface at the base of submarine-fan deposits, the misinterpretation stems from our inability to accurately correlate the onlap surface through slope condensed zones and into the correct shelf clinoform (see the section on Time-Transgressive Basin-Floor Fans below). Correlating onlap surfaces is even more problematic in natural systems imaged by conventional seismic, in general, or by synthetic seismic, specifically, as is the case for XES02

(Lomask et al. 2009; Martin et al. 2017), due to constructive and destructive interference where seismic reflectors converge.

Classification of strata deposited during the slow-cycle lowstand, beginning at 66 hrs and ending at 82 hrs (unit a on Figs. 6A and 3C), was particularly problematic. The observed stacking pattern suggests deposition during stillstand implying $\delta A/\delta S \approx 1$, during the period of slow rate of base-level rise at the lowstand, suggesting a shelf-margin-wedge interpretation as it overlies a lowstand wedge as its position there is inconsistent with the models of Haq et al. (1987) where shelf-margin wedges form “when the rate of sea-level fall is slow, the withdrawal of the sea is more deliberate, and the whole shelf is not exposed.” Does having a lowstand wedge overlain by a shelf-margin wedge imply that there are missing transgressive and highstand systems tracts? The underlying lowstand wedge could be grouped with the highstand systems tract, ignoring the type-1 (?) sequence boundary separating it from the underlying highstand systems tract. Alternatively, one might consider lumping this unit with the overlying transgressive systems tract, which implies deposition of a transgressive systems tract at a lowstand. Unless some significance can be made for further arguing this point, it might be more prudent to call the unit a shelf-edge delta without trying to stick it into any particular systems-tract pigeonhole.

Identifying sequence-bounding surfaces and systems tracts for the individual units deposited during the modulated based-level cycles is not straightforward due to the numerous erosion surfaces bounding stratal packages on the shelf. Basin-floor-fan units converge into “slope” condensed zones, making the correlation with time-equivalent shelfal strata also problematic (Fig. 3C). Problems like these highlight just how uncertain many sequence-stratigraphic interpretations are likely to be and how difficult anyone's interpretation will likely be to reproduce rigorously.

Artificial Diachroneity within Lowstand Systems Tracts.— This interpretation process produced an arrangement of stratigraphic units that resembles systems tracts as depicted in the Exxon “slug” (Fig. 6A). However, it is possible to create them by imposing the model on the data (Fig. 7A). Ignoring base-level lowstand “a” base-level lowstands b–e (Fig. 3B) corresponds well with the position of lowstand-wedge systems tracts in our conventional interpretation (Fig. 3C). However, these lowstand wedge systems tracts are coeval with basin-floor fans producing the perception of diachroneity where there is none. For example, mapping of the Einstein-Fuji system (Sylvester et al. 2012; Prather 2020) shows the prograding complex and the channel–levee complexes of the lowstand wedge and the lowstand fan systems tracts are, within the limits of the seismic resolution, coeval.

We contend that the elements depicted in the sequence stratigraphic model result from poor resolution of thin beds on conventional seismic data (cf. Thorne 1992), where the ends of the seismic events are assumed to be the end deposition. This misconception goes back to the very beginning of the seismic-stratigraphy revolution and manifests as a marine hiatus in the Wheeler diagrams of Mitchum et al. (1977). This approach to stratigraphic analysis produces artificial discontinuity and diachronous systems tracts. In our conventional analysis of XES02, we encountered a similar situation where basin-floor units converge into condensed zones across the slope (Fig. 3C). Although recognized and rectified by Haq et al. (1987) with the addition of condensed zones into the standard model, it seems that the lowstand systems part of the standard model was never fixed, resulting in continued confusion, as evident when comparing Fig. 8–19 and 7.28 from Catuneanu (2006). The ideas of Mitchum et al. (1977) are so deeply embedded in the basic conceptual framework of the sequence stratigraphy that these conceptual flaws still manifest themselves, including in recent automated algorithms for Wheeler diagram construction (e.g., Lomask et al. 2009; Qayyum et al. 2012; Qayyum et al. 2014).

Time-Transgressive Basin-floor Fans.— Basin-floor fans produced in the flume tend to lump together into five discrete basin-floor systems tracts using our conventional sequence stratigraphic analysis (Fig. 3A). Each of the lumped basin-floor fans is strongly time-transgressive and corresponds to deposition during highstands, falling-stage, and lowstands of base level across multiple depositional cycles (compare Fig. 3B with Fig. 3C). The time-transgressive nature of XES02 basin-floor fans stems entirely from using onlap at the toe of slope as their sole recognition criterion. Their recognition is further complicated because these onlapping units converge into "slope" condensed zones. Martin et al. (2009) note that surfaces of widespread marine onlap ($O_{M,W}$ surfaces) strongly correlate to timelines near the inflection point of base-level fall and typically (though not always), when the rate of base-level fall is increasing, bypass to the basin floor. Furthermore, they note that several $O_{M,W}$ surfaces represent condensed intervals. Since the correlation of the onlap "surface" from the condensed internal and into coeval shelf stratigraphy is highly uncertain, basin-floor fans are placed at the base of the shelf-margin wedge *as* per the model (Fig. 3C) even though there is no reason to assume that basin-floor fans are exclusively a lowstand phenomenon (e.g., Burgess et al., 1998; Prather 2000; Covault et al. 2007; Falivene et al. 2020).

Also, poor resolution of thin beds in the coeval slope drape gives an interpreter the impression that this convergence occurs at an onlap surface. This is similar to problematic downlap-surface delineation, as pointed out by Thorne (1992), where the "surface" becomes recognizable only in settings of low bottomset aggradation or where the frequency of seismic is insufficient to resolve bottomset thin beds. Submarine fan convergence into slope condensed zones is a common problem for the interpretation of slope stratigraphy evident in high-resolution seismic data such as that used in studies of the Brazos–Trinity slope system in the Gulf of Mexico dating back to the early 2000s (e.g., Badalini et al. 2000; Beaubouef et al. 2003a, 2003b; Prather et al. 2012). These data show that onlap surfaces do not exist, especially as imaged by conventional seismic, but rather these surfaces have both "discrete" onlap (recognizable within the limits of high-resolution seismic data) and convergent lateral slope drapes, as pointed out by Prather (2020).

However, these observations are inconsistent with the conventional sequence stratigraphic paradigm that places basin-floor-fan deposits in the falling stage of base-level cycles (Haq et al. 1987). Generalizing XES02 observations to basin-scale systems remains dubious as slope and basin floor depositional processes in the flume are dominated by grain fall and, to a lesser extent, by weak turbidity currents due to foreset oversteepening and failure resulting in sediment bypass to bottomsets (Kim et al. 2006b). These flume-specific processes are unlike natural systems that have a wider variety of depositional processes and triggering mechanisms (e.g., Talling et al. 2012; Bailey et al. 2021).

Missing Systems Tracts.— Close examination of the actual Wheeler diagram above base-level *minima* events c and d (Fig. 6A) shows the presence of shelfal units now eroded. As a result of the above limitations, compounded by the limitations in chronostratigraphic resolution, our conventional Wheeler diagram (Fig. 7A) does not match the actual Wheeler diagram of XES02 (Fig. 6A). Here baseline events are offset by as much as 68 hrs (Table 1) compared to the actual Wheeler diagram (Fig. 6A). These correlation errors show that despite our best-effort interpretation, the conventional methodology of conventional sequence stratigraphic does not produce a match to the actual base-level curve used in the XES02 experiment, due mainly to the absence of chronostratigraphic dating in sufficient detail to resolve the high-frequency modulated base-level cycles that characterized the modulated part of the laboratory experiment.

Using a Wheeler diagram where these stratigraphic elements are missing will never work for reconstructing a valid XES02 base-level curve (Fig. 7A). So, an alternative is to add gaps of about equal duration to the underlying transgressive and highstand systems tracts (around a relative time of 145 hrs Fig. 7A) above each shelf-margin wedge between positions c and e to represent the missing systems tracts (Fig. 7B). Similarly, missing systems tracts are also inserted at positions g and h (Fig. 7B). The new Wheeler diagram is thicker than the total relative geological time interval, so we squeezed it to fit. This attempt to fit the model is highly uncertain, as we assumed at the beginning of this study that we have no age control, so we have no idea of the time interval represented by each gap. The match between this Wheeler diagram with restored systems tracts and the actual Wheeler diagram is worse, as stratigraphic events are offset by as much as 92 hrs (Table 1). Our estimated base-level curves based on the Wheeler diagram with restored systems tracts share some similarities with the stretched base-level curve in Fig. 6C in that they have a general match of amplitude and frequency across slow-cycle intervals as these have the best-preserved stratigraphy but do not resemble the stretched base-level curve across modulated base-level intervals as these intervals have the most incomplete strata.

Trajectory Analysis.— Genetic units defined through trajectory analysis vary significantly compared to conventional sequence stratigraphy and those defined by direct observation of shoreline position (compare Fig. 3C, D, and E). Apparent descending trajectories tend to define highstand and shelf-margin-wedge systems tracts. We were not able to differentiate multiple actual shoreline trajectories with units characterized by apparent descending trajectories below toplap unconformities. This is particularly evident with two periods of erosion ending at times 153 hrs and 248 hrs (Figs. 6B, 10A), producing incorrect trajectory classifications (Fig. 3E). Specifically, the transgressive and ascending regressive succession formed during time steps 106–144 hrs (Fig. 12A). The ascending unit formed during time steps 157–202 hrs appears as regressive units with descending trajectory after toplap erosion (Fig. 12B). Moreover, the presumed reservoir-prone topsets in both classes have been removed, creating a situation where associated reservoir presence risks would be misjudged. Identifying earlier periods of shelf bypass is challenging to recognize in an incomplete stratigraphic record of the shelf in highly erosional systems alone, a situation potentially rectifiable with sedimentological data from cores and wells.

The use of trajectory analysis for the prediction of the presence of submarine fans is justified in the case of XES02 for periods of modulated base-level cycles following 200 hrs when most of the deposits that onlap the toe of slope are associated with actual descending shoreline trajectories (Fig. 3D). This however is not the case for early intervals older than 200 hrs when most of the deposits that onlap the toe of slope are associated with stationary and ascending shoreline trajectories (Fig. 3D). Erosion of topsets as is the case of XES02 (Fig. 12) obscures these actual shoreline trajectories, producing apparent descending trajectories.

The stationary rising trajectory matches well with shelf-margin-wedge systems tracts, and the slow rate of base-level change during the slow cycle at the beginning of the experiment run. The toe-of-slope trajectories produce strongly time-transgressive basin-floor deposits that lump together multiple base-level cycles, as does the conventional sequence stratigraphic analysis because they have the same recognition criteria. In their GBA analysis of XES02, Aali et al. (2021) found it challenging to identify all eight base-level cycles in the preserved record, despite the well-controlled setting. Aali et al. (2021) is also show mismatches between the systems-tract terms and the actual base level of XES02. Although automating GBA seems a useful way to reduce reliance on model-driven interpretations, it still suffers from the incompleteness of the stratigraphic record. Miall (2014) stated that analyses of long-term processes, including mass-balance transport models and interpretations of shoreline trajectories through time, need to consider that far more time is likely missing from the stratigraphic record than is represented.

We find significant differences in shoreline trajectory along strike (Fig. 11A). An ascending trajectory between time steps 171–179 hrs along line 800, for example, changes along strike to stationary rising along line 1700 due to autogenic delta switching (Fig. 11B). Similarly, the ascending trajectory between time steps 120–130 hrs along line 800 changes to ascending along line 1700 (Fig. 11C, also see the Supplementary File: Laboratory Experiment 3D Evolution animation to observe the delta switching).

This is a recognized issue in the case of natural systems (e.g., Bhattacharya 2011; Madof et al. 2016). Using shoreline trajectories would result in a different relative-sea-level history unique to each line of section, but as in the case of XES02, erosion obscures this level of analysis (Fig. 12). As the observed strike variability occurs below our ability to detect, it was not critical to our interpretation. Still, it is easy to imagine

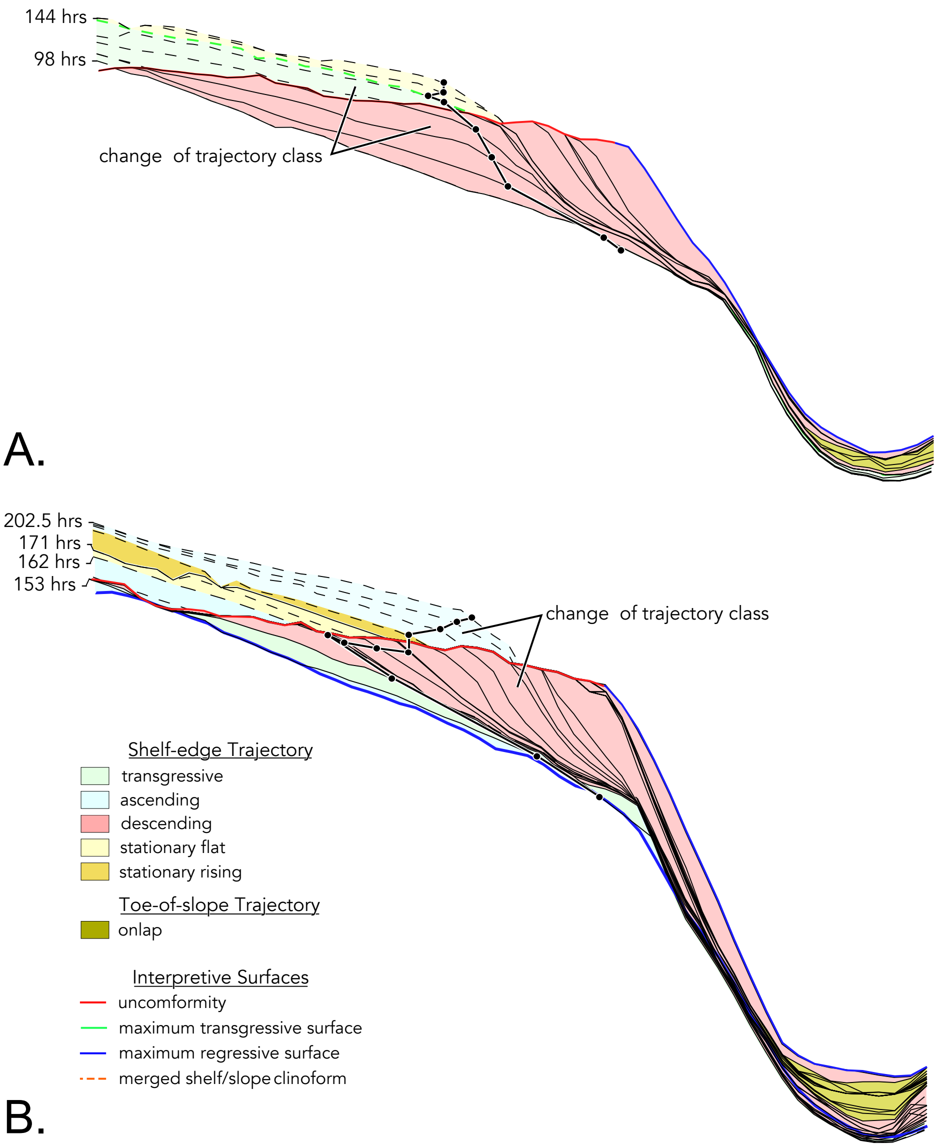

Fig. 12.— A) Genetic units between 98 and 144 hrs classified by actual shoreline trajectory and the resulting apparent trajectory classification after erosion ended at 153 hrs. B) Genetic units between 153 and 202.5 hrs classified by actual shoreline trajectory, and the resulting apparent trajectory classification after erosion ended at 232 hrs. Also, see highlighted apparent shoreline positions from XES02 in Fig. 3A.

settings where more pronounced strike variability across a continental margin, for example, could be more problematic (Madof et al. 2016).

As noted by Bhattacharya et al. (2019), and Miall et al. (2021) the construction of Wheeler diagrams from seismic sections of shallow marine deltaic successions shows that only a fraction of elapsed time is represented by sediment at any given location. Similar to those encountered in XES02 stratigraphy (Fig. 7B), these gaps are evident in the various Wheeler diagrams more due to delta switching and erosion, than to the poor stratigraphic resolution.

Knowing that this is to be expected, the best option to rectify the situation would be to build strike-oriented Wheeler diagrams (Fig. 10) to represent strike variability. As is the case for XES02, the gaps can be restored by forming a composite Wheeler diagram (Fig. 10), similar to restoring the gaps in our conventional Wheeler diagrams from XES02 (Fig. 7B). At this point, choices have to be made as to which of the various units evident on the dip-oriented Wheeler diagrams go into building the composite Wheeler diagram. This step can be problematic in practice because along-strike variability in environments of deposition invariably makes the process arbitrary since it is unknown in most cases how far along strike one needs to go to get a complete representation of all the missing units.

Scenarios of Stratigraphic Forward Models

Finally, we use a stratigraphic forward model to demonstrate how the base-level curves derived from our two sequence stratigraphic analyses impact stratigraphic architecture and sediment partitioning within a virtual XES02 experiment. We use the three-dimensional reduced-complexity stratigraphic forward model, previously tested and validated against the XES02 laboratory experiment by Falivene et al. (2019). This numerical model simulates the large-scale distribution of sand and mud between coastal-plain and cross-shelf paleo-valleys systems (Blum and Hattier-Womack 2009; Blum et al. 2013) and the coeval shelf-edge rollover (following the terminology in Poyatos-Moré et al. 2016) slope and basin floor.

Boundary Conditions and Tested Base-Level Curves.— Model boundary conditions are the position, supply, and composition of sediment input sources. This sediment's distribution is calculated by defining centerlines for each timestep that connects the sediment source point to the shoreline. Erosional and depositional surfaces bounding depositional domains are defined for each centerline, following geologic rules and ensuring mass balance with sediment input (Falivene et al. 2019). The model provides first-order predictions of sediment distribution controlled by simple geological parameters such as depositional profile angles and foreset failure angles that are all constrained by the experimental data (Falivene et al. 2019), so more robustly based on observation than most sequence stratigraphic models.

In addition to the numerical model using the XES02 base-level curve as a benchmark, we also test the following scenarios: 1) a scenario using the curve derived from the stretched Wheeler diagram (Fig. 5D), 2) a scenario with the conventionally deducted base-level curve (Fig. 6A) and 3) another scenario that includes the gaps corresponding to missing systems tracts (Fig. 6B).

Simulated Architectures and Sediment Partitioning.— Even using the actual subsidence and sediment supply, known from the original XES02 boundary conditions, and changing only base-level forcing, the resultant simulated architectures are quite different in all the scenarios modeled (Fig. 13). As subsidence and sediment supply in the numerical model (and the experiment) are constant, the shoreline position closely mimics base-level fluctuations. Using different base-level curves with different magnitude and relative position of base-level changes results in different shoreline evolution (Fig. 14) and, therefore, stratigraphic architectures.

All scenarios start with an initial zero-subsidence phase when the system experiences rapid progradation. The proportion of sediments accumulated in the marine domain

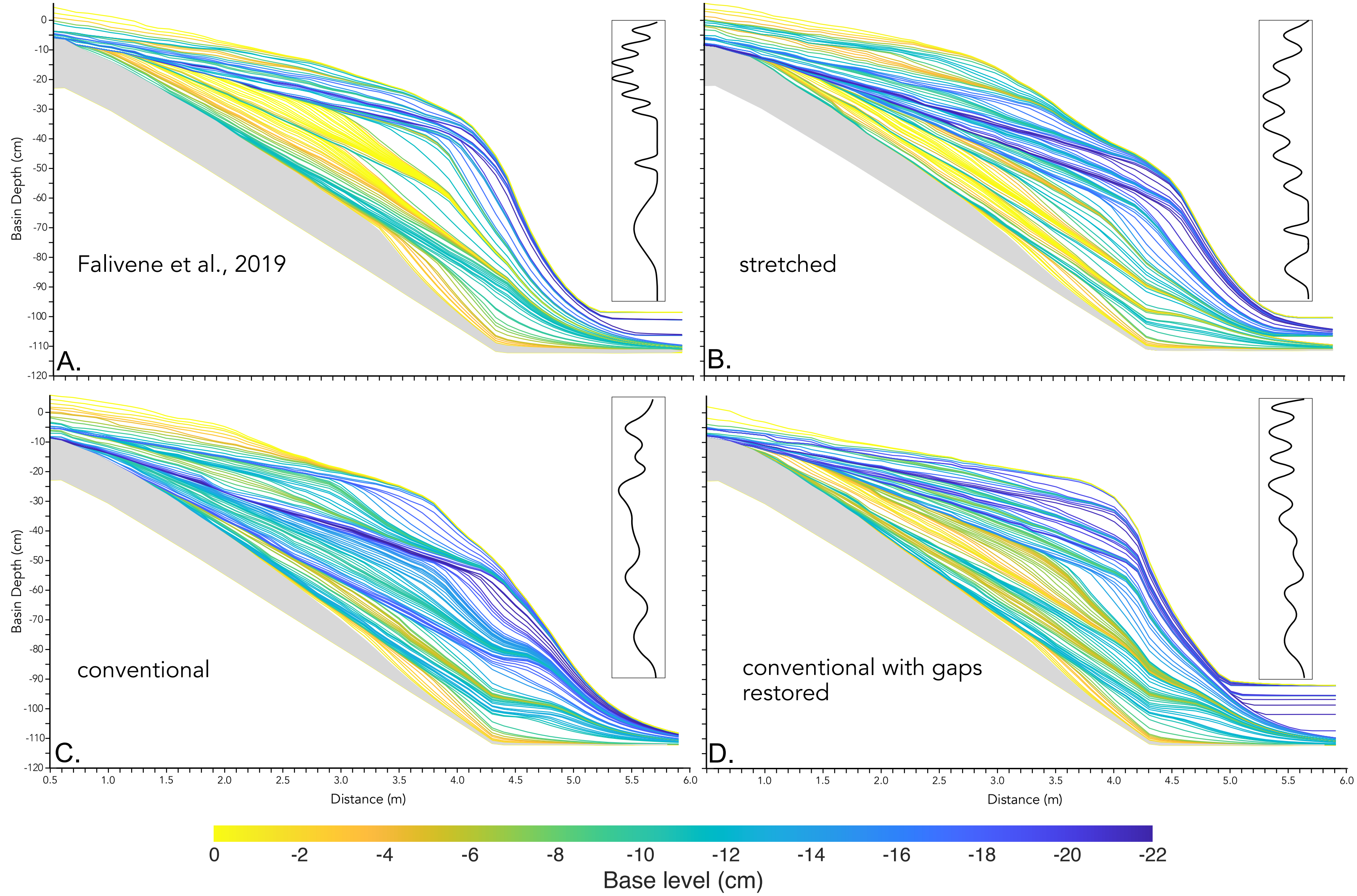

Fig. 13.— **A)** Stratigraphic architecture from the Falivene et al. (2019) forward model of XES02 key line 1700 mm Fig. 3A using input parameters equivalent to those of the laboratory experiment, Model realizations using the **B)** stretched, **C)** conventional, and **D)** conventional base-level curve with restored gaps. Timelines are shown every 2.5 hrs of simulated experiment time. The corresponding base-level curve is shown for each model scenario.

gradually decreases (Fig. 15) as the topset lengthens. This phase ends at around 60 hrs when subsidence starts. During the main phase of the experiment and the models, the A/S ratio remains close to equilibrium without considering the base-level fluctuations, making it an accommodation-dominated system (Zhang et al. 2019). Most topset strata are associated with the transgressive and highstand parts of some of the short cycles in the modulated fall (Fig. 15), so they are not identifiable in the Wheeler diagram (Fig. 6B).

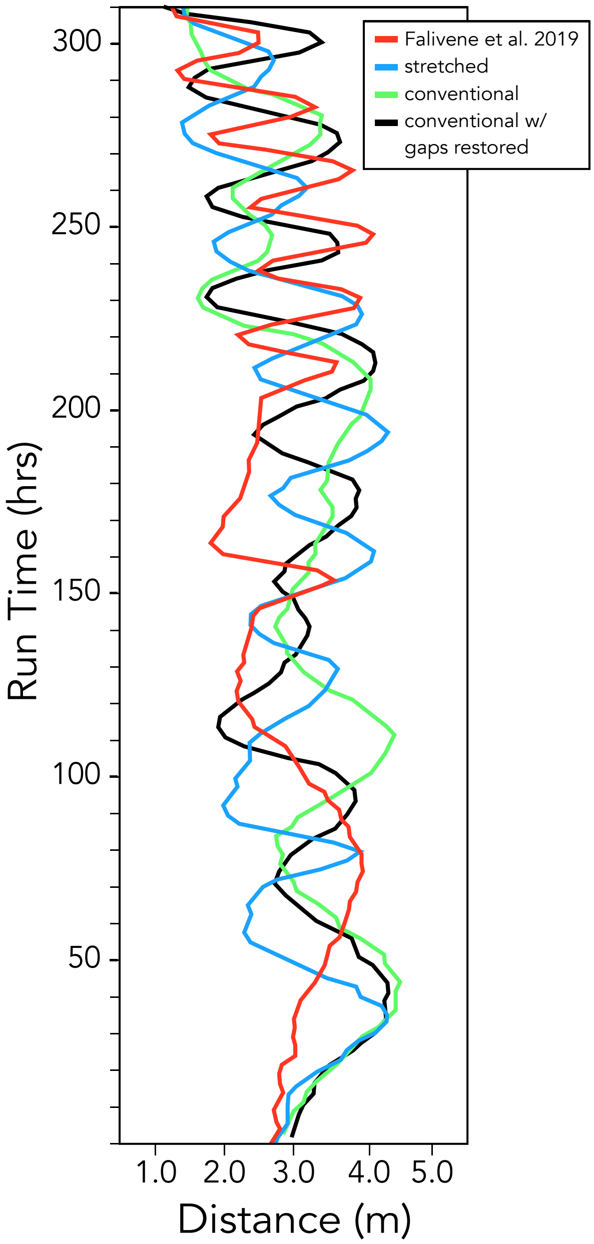

Fig. 14.— Modeled shoreline positions time-averaged along the depositional strike.

In the models and the original XES02 experiment, the development of sand-rich foresets and failed foresets is triggered mainly during base-level falls and, to a lesser extent, long periods of low base level with relatively little sedimentation in the topset (Fig. 15). These periods yield substantial increases in sediment accumulation rate compared to the sediment input rate to the system (up to fivefold, Fig. 15) due to the large volume of sediments eroded during the excavation of the incised valley. It is noteworthy, however, that the dimensions of fluvial valleys in the XES02 experiment and corresponding models are large relative to sediment supply, amplifying the contribution of eroded volumes compared to more natural systems where the sediment supply added by base-level-fall incision is negligible (Burgess and Hovius 1998; Blum and Aslan 2006; Falivene et al. 2020), so this experiment is not a perfect analog for a basin-scale system.

Nevertheless, it is clear from the models that using base level curves with different positions of base-level *minima* and durations of base-level falls, and hence base-level fall rates results in significant differences in timing, the volume of redeposited sediment, and preferential environment of deposition for their accumulation (Figs. 15, 16). For example, the model using the base level derived from a conventional sequence stratigraphic interpretation predicts significantly fewer sand-rich foresets and failed

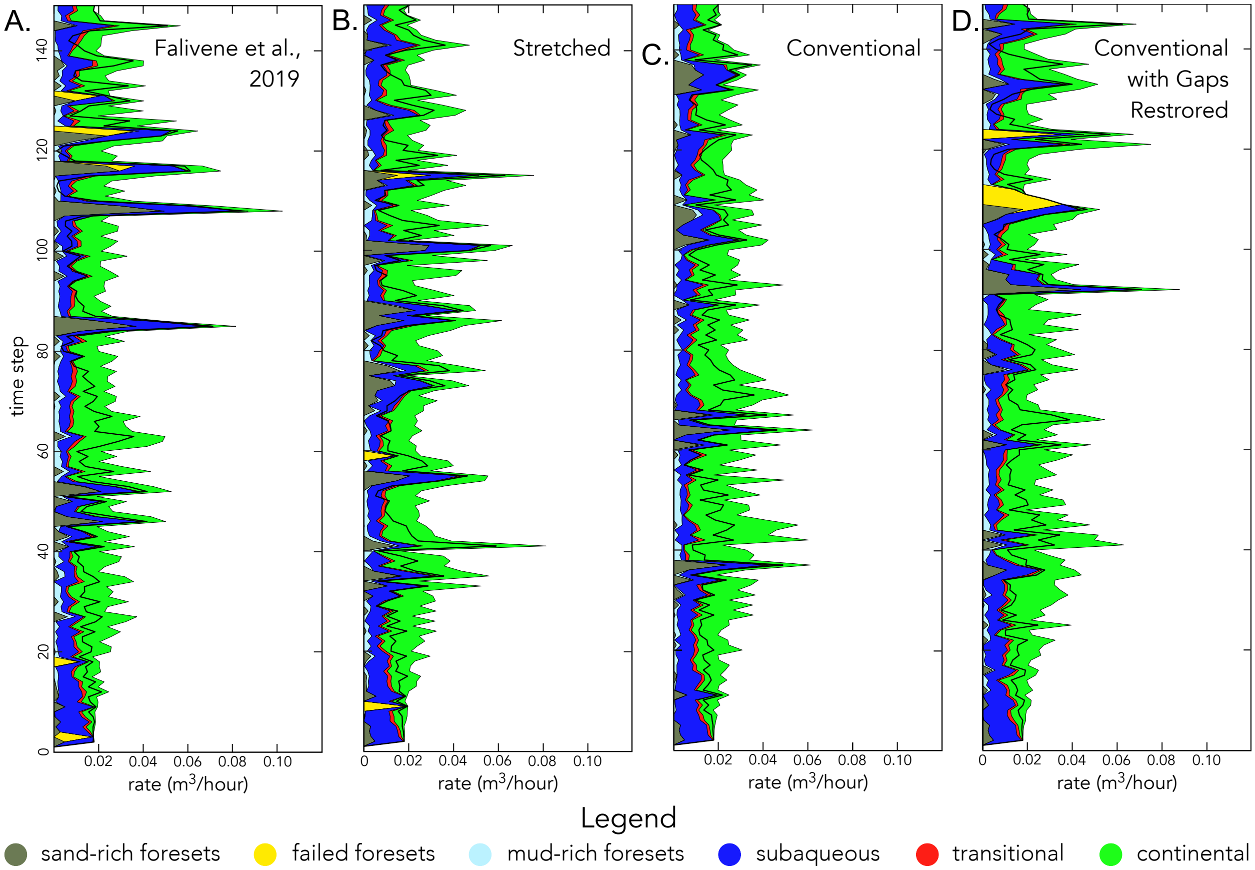

Fig. 15.— Mass balance and sediment partition through modeled time in **A)** Falivene et al. (2019), with boundary conditions comparable to the laboratory experiment from **B)** stretched, **C)** conventional, and **D)** conventional with restored gaps scenarios. Sediment above the black line was eroded and resedimented in subsequent timesteps. The sediment input rate to the experiment is around 0.018-0.019 m^3/hour, assuming an initial porosity of 50%

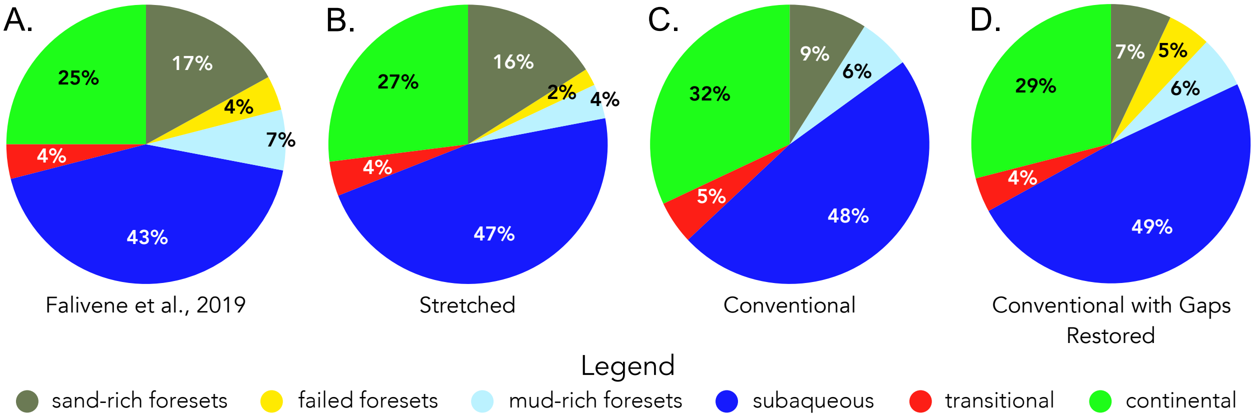

Fig. 16.— Distribution of sediment according to the environment of deposition **A)** baseline model from Falivene et al. (2019), **B)** stretched base level, **C)** conventional base level, and **D)** conventional base level with restored gaps.

foresets than the models using the original or even the stretched base-level curves because due to the missing systems tracts, the conventional base-level curve has significantly less time when base level is falling. Yet the development of sand-rich foresets and failed foresets is a critical predictive model output if we are trying to predict the potential for sand-rich sediment beyond the shelf edge.

It is worth emphasizing that the XES02 experiment represents a simplified case in which sediment supply and water discharge were simulated in the tank as constant through time. Henceforth, the models tested herein use boundary conditions accordingly. Nevertheless, Falivene et al. (2019) identify sediment supply as one of the most important parameters in controlling the resultant XES02 deposit architecture by testing models with different assumptions of sediment supply and other parameters controlling sediment transport. It is then likely that further testing more complex boundary conditions (which can be more representative of natural systems), including variable sediment supply input through different base-level positions, will result in more complex architectural variations. This will exacerbate the issues identified above related to the position of sequence boundaries and the correlation of basin floor fans and systems tracts with limited expression in the final deposits (Burgess and Prince 2015). Similar issues occur in systems that behave more three-dimensionally or include multiple sediment input sources (Burgess and Prince 2015).

Burgess and Prince (2015) 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 influencing factors that can plausibly explain their formation. For example, a maximum transgressive surface can occur in the model due to an increase in relative sea-level rise during constant sediment supply and a reduction in the rate of sediment supply during a continuous rate of relative sea-level rise. Sequence boundaries, topset aggradation, and shoreline trajectories are examples of non-unique stratal geometries.

IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

The Usefulness of Laboratory Experiments

Laboratory experiments do not contain the full range of dynamics or timescales observed in field settings (Paola 2000) due to unavoidable scaling issues or experiment-simplifying choices. For example, in XES02: 1) floodplain dynamics are absent due to the use of non-cohesive sediment, 2) wave- or current-driven subaqueous sediment transport is absent due to receiving basin waters being still, 3) sediment input volume (relative to discharge) is much larger than in natural systems, resulting in steeper fluvial slopes, 4) grainfall dominates slope and basin-floor depositional processes, with very limited development of turbidity currents due to scale and sediment cohesiveness, 5) sediment discharge and water discharge are decoupled from base-level controls, and 7) the relative contribution of fluvially eroded topset material to the shoreline flux is much greater than in most natural systems.

However, laboratory experiments demonstrate that geomorphic organization and stratigraphic architectures are largely scale-independent. The emergence of key processes in depositional systems, such as channelization, avulsion, compensation, and mass fractionation, occurs in both fields and experimental systems (Paola 2000). Paola et al. (2009) suggest that “unreasonable effectiveness” of experimental stratigraphy arises from this natural scale independence. Martin et al. (2017) maintain that sequence-stratigraphic methods are amenable to experimental stratigraphy, given that geomorphic organization and stratigraphic architectures are largely scale-independent. Using a well-constrained laboratory experiment for testing a sequence-stratigraphic method or model provides critical advantages compared to outcrop or poorly constrained seismic stratigraphic studies because the experiments have: 1) a three-dimensional comprehensive and exhaustive dataset, including also high-resolution chronologic constraints, that can be quantitively compared to model predictions, 2) unequivocal constraints on critical boundary conditions such as sediment input, subsidence, and base-level fluctuations, and 3) a complete record of depositional history.

Uncertainty in Sequence Stratigraphic Analysis and Stratigraphic Forward Models

Although dismissed by some practitioners of sequence stratigraphy, and although it is critical not to overgeneralize how applicable flume experiments are to natural systems, we must take an analysis of stratigraphy in laboratory experiments seriously because they are certainly reliable enough to point to possible sources of interpretive errors inherent in sequence stratigraphic analysis of field-scale deposits.

Our sequence stratigraphic analysis of XES02 revealed the following issues: 1) systems-tract classification mismatches, 2) systems-tracts type not determined by base-level changes, 3) time-transgressive basin-floor fans, and 4) missing systems tracts. In applied sequence stratigraphic analysis, it is fundamentally important to recognize the uncertainty these potential errors might produce in any interpretation of depositional history, correlation, or lithology prediction. In addition, in outcropping and subsurface settings (which are often much more complex than XES02), there are usually limited independent correlation timelines, and depositional geometries and stratal relations are used to correlate sedimentary units and assign them to specific intervals or ages within sea-level curves.

Such uncertainties in outcropping and subsurface settings can be addressed only by collecting more detailed chronostratigraphic constraints and by employing multiple scenarios in interpretations, especially where alternative processes produce similar stratigraphic architecture but could result in the prediction of different lithologic distributions or depositional histories (e.g., Burgess and Prince 2015). However, after investing much time deducing a combination of processes that provide a single reasonable reconstruction of depositional history, it is often difficult for interpreters to identify multiple scenarios that might match observed stratigraphic architecture or any new data just as well (i.e., anchoring bias).

A helpful solution is to use stratigraphic forward modeling to objectively explore a range of settings capable of producing similar stratigraphic architectures (e.g., Burgess et al. 2006), provided that the encoded depositional processes in the numerical model are capable of sufficient accuracy in simulating the natural processes controlling depositional geometry.

This approach has several advantages, including producing auditable and reproducible results in which strata are produced by well-documented, understandable algorithms and based on fundamental physical sedimentology and geologic principles. Input parameters for the models can be constrained by available regional or local knowledge and analog databases of typical geomorphic parameters. The parameters can also span a range that properly reflects the uncertainty arising from the lack of constraining data (Burgess 2012). This approach, which focuses on critical uncertainties and systematically tests a broad process-parameter space to get a range of likely outcomes, is very different from the standard sequence-stratigraphy approach, but as the numerical forward models and methods to apply them continue to develop (e.g., Burgess et al. 2006; Gervais et al. 2018; Hawie et al. 2019; Falivene et al. 2020; Nagle et al. 2021; Zhang et al. 2021) has significant potential to contribute to how we understand and predict strata.

How Accurate Are Sea-Level Curves Derived from Sequence Stratigraphic Methods?

The stratigraphic analysis of XES02 also highlights how difficult it is to construct accurate relative sea-level curves using a sequence stratigraphic methodology (e.g., Burton et al. 1987). Nevertheless, global sea-level curves (e.g., Haq and Schutter 2008; Haq 2014, 2018) might still be useful when coupled with stratigraphic forward-modeling studies, in which they can be adequately treated as one of several uncertain inputs to be tested or adjusted using a multiple scenario approach (e.g., Burgess et al. 2006; Charvin et al. 2009a; Charvin et al. 2009b; Charvin et al. 2011; Falivene et al. 2014).

CONCLUSIONS

We analyzed strata recorded in a laboratory experiment with well-defined boundary conditions. The experiment aims to reproduce a siliciclastic passive continental margin with sedimentation controlled by subsidence and base-level fluctuations (XES02). The analysis, following conventional sequence stratigraphic approaches, yielded: 1) erroneous base-level curves, 2) systems-tract classification mismatches, 3) disconnected systems-tracts types and actual base-level history, 4) time-transgressive basin-floor fans, 5) missing systems tracts, and 6) potential cognitive errors in the process of classifying strata. We also find little distinction between conventional sequence analysis and trajectory analysis as used in our analysis of XES02 stratigraphy, although is it often argued that trajectory analysis is superior at predicting reservoir-prone stratigraphy in deep water (e.g., Johannessen and Steel 2005; Helland-

Hansen and Hampson 2009; Henriksen et al. 2009; Wild et al. 2009). We recognize that using trajectory terminology produces less-circular reasoning, but the trajectory-analysis results are not superior to conventional sequence stratigraphy. Neither approach accounts for missing sections, resulting in spurious base-level curves and inaccurate depositional histories produced in either case.

We also computed Wheeler diagrams from the strata recorded in XES02 following approaches similar to those used when building Wheeler diagrams from seismic data. This requires an assumption that seismic reflections correspond to timelines. For seismic reflections or timelines in the XES02 experiment lacking precise absolute chronostratigraphic control, their ages are evenly spaced or proportional to the preserved thickness between known chronostratigraphic control points. The accuracy of such Wheeler diagrams is limited due to the limited chronological data available. Consequently, it (i.e., base-level curves derived from the stratigraphic analysis of XES02) can capture only general trends, with significant differences in the timing of base-level *minima* and henceforth base-level fall durations and rates. Due to the poorly resolved base-level curves, stratigraphic forward models using base-level curves derived from Wheeler diagrams constructed from the XES02 experiment are unable to match the timing, volume of redeposited sediment, and environments of deposition observed in the XES02 experiment, suggesting, in turn, that predictions from sequence stratigraphic analysis of this type are unlikely to be accurate.

The XES02 experiment results from a relatively simple set of forcing conditions with constant sediment supply, limited lateral variability, and a single sediment source. Despite this, and although analysis has been carried out using a perfectly recorded depositional record, the issues that we found in applying a sequence stratigraphic analysis to reconstruct the depositional history and controlling factors highlight the uncertainties inherent in analyses based only on stratal architectures. These uncertainties will only increase when dealing with limited or poorly resolved outcropping and subsurface datasets with limited chronostratigraphic constraints. The best approach to dealing with these uncertainties is to fully acknowledge them and evaluate them through multiple scenario analysis, for example, supported by the construction of multiple stratigraphic forward models. Accepting inherent uncertainty will ultimately provide more robust and useful ensemble-based probabilistic predictions.

ACKNOWLEDGMENTS

We knowledge and thank the National Center for Earth-Surface Dynamics (Saint Anthony Falls Laboratory, University of Minnesota) for making the XES02 data available through their Data Repository (http://www.nced.umn.edu/Data_Repository.html). The release of these data is a significant contribution to the advancement of the science of stratigraphy. We appreciate the comments on an earlier draft by J.P. Bhattacharya and O.J. Martinsen; their reviews helped us focus and improve the ideas presented herein. We are grateful for the remarks of JSR reviewers William Helland-Hansen, Gary Hampson, and Andrew Madof.

REFERENCES

Aali, M., Richards, B., Nedimović, M.R., Maselli, V., and Gibling, M.R., 2021, Geometrical Breakdown Approach to interpretation of depositional sequences: Geosphere. https://doi.org/10.1130/ges02371.1

Ager, D.V., 1973, The Nature of the Stratigraphical Record: New York, John Wiley, 151 p.

Ager, D.V., 1993, The New Catastrophism, Cambridge University Press, 231 p.

Badalini, G., Kneller, B., and Winker, C.D., 2000, Architecture and process in the Late Pleistocene Trinity-Brazos turbidite system, Gulf of Mexico, in Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., and Lawrence, D.T., eds., Deep-Water Reservoirs of the World: 20th Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference, Gulf Coast Section, SEPM, p. 16-34. https://doi.org/10.5724/gcs.00.15.0016

Bailey, L.P., Clare, M.A., Rosenberger, K.J., Cartigny, M.J.B., Talling, P.J., Paull, C.K., Gwiazda, R., Parsons, D.R., Simmons, S.M., Xu, J., Haigh, I.D., Maier, K.L., McGann, M., and Lundsten, E., 2021, Preconditioning by sediment accumulation can produce powerful turbidity currents without major external triggers: Earth and Planetary Science Letters, v. 562. 116845. https://doi.org/10.1016/j.epsl.2021.116845

Barrell, J., 1917, Rhythms and the measurements of geologic time: Geological Society of America Bulletin, v. 28, p. 745-904. https://doi.org/10.1130/gsab-28-745

Baum, G.R., and Vail, P.R., 1998, A new foundation for stratigraphy: Geotimes, v. 43, p. 31-35.

Beaubouef, R.T., Abreu, V., and Adair, N.L., 2003a, Ultra-high resolution 3-D characterization of deep-water deposits - I: A new approach to understanding the stratigraphic evolution of intra-slope depositional systems [abs.]: American Association of Petroleum Geologists Annual Convention.

Beaubouef, R.T., Abreu, V., and Van Wagoner, J.C., 2003b, Basin 4 of the Brazos-Trinity slope system, western Gulf of Mexico: the terminal portion of a Late Pleistocene lowstand systems tract, in Roberts, H.H., Rosen, N.C., Filton, R.H., and Anderson, J.B., eds., Shelf margin deltas and linked down slope petroleum systems: global significance and future exploration potential: 23rd Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference, Gulf Coast Section, SEPM, p. 45-66. https://doi.org/10.5724/gcs.03.23.0045

Beelen, D., Jackson, C.A.-L., Patruno, S., Hodgson, D.M., and Trabucho Alexandre, J.P., 2019, The effects of differential compaction on clinothem geometries and shelf-edge trajectories: Geology, v. 47, p. 1011-1014. https://doi.org/10.1130/g46693.1

Bhattacharya, J.P., 2011, Practical problems in the application of the sequence stratigraphic method and key surfaces: integrating observations from ancient fluvial-deltaic wedges with Quaternary and modelling studies: Sedimentology, v. 58, p. 120-169. https://doi.org/10.1111/j.1365-3091.2010.01205.x

Bhattacharya, J.P., and Abreu, V., 2016, Wheeler's Confusion and the Seismic revolution: How Geophysics Saved Stratigraphy: The Sedimentary Record, June 2016, p. 4-12. https://doi.org/10.2110/sedred.2016.2.4

Bhattacharya, J.P., Miall, A.D., Ferron, C., Gabriel, J., Randazzo, N., Kynaston, D., Jicha, B.R., and Singer, B.S., 2019, Time-stratigraphy in point sourced river deltas: Application to sediment budgets, shelf construction, and paleo-storm records: Earth-Science Reviews, v. 199. 102985. https://doi.org/10.1016/j.earscirev.2019.102985

Blum, M., Martin, J., Milliken, K., and Garvin, M., 2013, Paleovalley systems: Insights from Quaternary analogs and experiments: Earth-Science Reviews, v. 116, p. 128-169. https://doi.org/10.1016/j.earscirev.2012.09.003

Blum, M.D., and Aslan, A., 2006, Signatures of climate vs. sea-level change within incised valley-fill successions: Quaternary examples from the Texas Gulf Coast: Sedimentary Geology, v. 190, p. 177-211. https://doi.org/10.1016/j.sedgeo.2006.05.024

Blum, M.D., and Hattier-Womack, J., 2009, Climate change, sea-level change, and fluvial sediment supply to deepwater depositional systems, in Kneller, B., Martinsen, O.J., and McCaffery, B., eds., External Controls on Deep-Water Depositional Systems: SEPM, Special Publication 92, p. 15-39. https://doi.org/10.2110/sepmsp.092.015

Brown, L.F., Jr., and Fisher, W.L., 1977, Seismic-Stratigraphic Interpretation of Depositional Systems: Examples from Brazilian Rift and Pull-Apart Basins, in Payton, C.E., ed., Seismic Stratigraphy — Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 213-248. https://doi.org/10.1306/m26490c14

Burgess, P., Flint, S., and Hovius, N., 1998, Modern delta progradation rates: implications for relative sea-level control on timing of turbidite deposition with examples from the Jurassic of the Neuquen Basin, Argentina: American Association of Petroleum Geologists 1998 annual meeting: Tulsa, American Association of Petroleum Geologists and SEPM.

Burgess, P.M., 2012, A brief review of developments in stratigraphic forward modelling, 2000–2009, in Roberts, D.G., ed., Regional Geology and Tectonics: Principles of

Geologic Analysis: Amsterdam, Elsevier Inc., p. 379-404. https://doi.org/10.1016/B978-0-444-53042-4.00014-5

Burgess, P.M., Allen, P.A., and Steel, R.J., 2016, Introduction to the future of sequence stratigraphy: evolution or revolution?: Journal Geological Society of London, v. 173, p. 801-802. https://doi.org/10.1144/jgs2016-078

Burgess, P.M., and Hovius, N., 1998, Rates of delta progradation during highstands: consequences for timing of deposition in deep-marine systems: Journal of the Geological Society, v. 155, p. 217-222. https://doi.org/10.1144/gsjgs.155.2.0217

Burgess, P.M., Lammers, H., van Oosterhout, C., and Granjeon, D., 2006, Multivariate sequence stratigraphy: tackling complexity and uncertainty with stratigraphic forward modeling, multiple scenarios and conditional frequency maps: American Association of Petroleum Geologists, Bulletin, v. 90, p. 1883-1901. https://doi.org/10.1306/06260605081

Burgess, P.M., and Prince, G.D., 2015, Non-unique stratal geometries: implications for sequence stratigraphic interpretations: Basin Research, v. 27, p. 351-365. https://doi.org/10.1111/bre.12082

Burgess, P.M., and Steel, R.J., 2017, How to Interpret, Understand, and Predict Stratal Geometries Using Stratal-Control Spaces and Stratal-Control-Space Trajectories: Journal of Sedimentary Research, v. 87, p. 325-337. https://doi.org/10.2110/jsr.2017.19

Burton, R., Kendal, C.G.St.C., and Lerche, I., 1987, Out of our depth: On the impossibility of fathoming eustasy from the stratigraphic record: Earth-Science Reviews, v. 24, p. 237-277. https://doi.org/10.1016/0012-8252(87)90062-6

Cantelli, A., Pirmez, C., Johnson, S., and Parker, G., 2011, Morphodynamic and Stratigraphic Evolution of Self-Channelized Subaqueous Fans Emplaced by Turbidity Currents: Journal of Sedimentary Research, v. 81, p. 233-247. https://doi.org/10.2110/jsr.2011.20

Catuneanu, O., 2006, Principles of Sequence Stratigraphy: Amsterdam, Elsevier, 386 p.

CATUNEANU, O., 2019, Model-independent sequence stratigraphy: Earth-Science Reviews, v. 188, p. 312-388. https://doi.org/10.1016/j.earscirev.2018.09.017

Catuneanu, O., 2020, Sequence stratigraphy in the context of the ‘modeling revolution’: Marine and Petroleum Geology, v. 116. 104309. https://doi.org/10.1016/j.marpetgeo.2020.104309

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C., 2009a, Towards the standardization of sequence stratigraphy: Earth-Science Reviews, v. 92, p. 1-33. https://doi.org/10.1016/j.earscirev.2008.10.003

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and Winker, C., 2009b, Reply to the comments of W. Helland-Hansen on "Towards the standardization of sequence stratigraphy" by Catuneanu et al. [Earth-Sciences Review 92(2009)1-33]: Earth-Science Reviews, v. 94, p. 98-100. https://doi.org/10.1016/j.earscirev.2009.02.004

Catuneanu, O., Galloway, W.E., Kendal, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., and Tucker, M.E., 2011, Sequence stratigraphy: Methodology and nomenclature: Newsletters on Stratigraphy, v. 44, p. 173-245. https://doi.org/10.1127/0078-0421/2011/0011

Charvin, K., Gallagher, K., Hampson, G.L., and Labourdette, R., 2009a, A Bayesian approach to inverse modelling of stratigraphy, part 1: method: Basin Research, v. 21, p. 5-25. https://doi.org/10.1111/j.1365-2117.2008.00369.x

Charvin, K., Hampson, G.J., Gallagher, K., and Labourdette, R., 2009b, A Bayesian approach to inverse modelling of stratigraphy, part 2: Validation tests: Basin Research, v. 21, p. 27-45. https://doi.org/10.1111/j.1365-2117.2008.00370.x

Charvin, K., Hampson, G.J., Gallagher, K.L., Storms, J.E.A., and Labourdette, R., 2011, Characterization of Controls on High-Resolution Stratigraphic Architecture in Wave-Dominated Shoreface–Shelf Parasequences Using Inverse Numerical Modeling: Journal of Sedimentary Research, v. 81, p. 562-578. https://doi.org/10.2110/jsr.2011.48

Covault, J.A., Normark, W.R., Romans, B.W., and Graham, S.A., 2007, Highstand fans in the California borderland: The overlooked deep-water depositional systems: Geology, v. 35, p. 783-786. https://doi.org/10.1130/G23800A.1

Embry, A.F., 2009, Practical sequence stratigraphy, Canadian Society of Petroleum Geologists, The Reservoir, May 2008 and September 2009, 79 p.

Embry, A.F., and Johannessen, E.P., 1993, T–R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic–Lower Jurassic succession, Western Sverdrup Basin, Arctic Canada, in Vorren, T.O., Bergsager, E., Dahl-Stammes, O.A., Holter, E., Johansen, B., Lie, E., and Lund, T.B., eds., Arctic Geology and Petroleum Potential: Norwegian Petroleum Society Special Publication 2, p. 121-146.

Falivene, O., Frascati, A., Gesbert, S., Pickens, J., Hsu, Y., and Rovira, A., 2014, Automatic calibration of stratigraphic forward models for predicting reservoir presence in exploration: American Association of Petroleum Geologists, Bulletin, v. 98, p. 1811-1835. https://doi.org/10.1306/02271413028

Falivene, O., Frascati, A., Pittaluga, M.B., and Martin, J., 2019, Three-dimensional Reduced-Complexity Simulation of Fluvio-Deltaic Clastic Stratigraphy: Journal of Sedimentary Research, v. 89, p. 46-65. https://doi.org/10.2110/jsr.2018.73

Falivene, O., Prather, B.E., and Martin, J., 2020, Quantifying sand partition in icehouse continental margins: Numerical models from the Quaternary Brazos deltaic system: Basin Research, v. 32, p. 1711-1733. https://doi.org/10.1111/bre.12449

Frazier, D.E., 1974, Depositional episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf basin: Texas Bureau of Economic Geology Geologic Circular 74-1, University of Texas, Austin, 28 p.

Frodeman, R., 1995, Geological reasoning: Geology as an interpretive and historical science: Geological Society of America Bulletin, v. 107, p. 960-968. https://doi.org/10.1130/0016-7606(1995)107<0960:Grgaai>2.3.Co;2

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units: American Association of Geologists Bulletin, v. 73, no 2., p. 125-142.

Gervais, A., Ducros, M., and Granjeon, D., 2018, Probability maps of reservoir presence and sensitivity analysis in stratigraphic forward modeling: American Association of Petroleum Geologists, Bulletin, v. 102, p. 613-628.

Granjeon, D., 2014, 3D forward modelling of the impact of sediment transport and base level cycles on continental margins and incised valleys, in Martinius, A.W., Ravnås, R., Howell, J.A., Steel, R.J., and Wonham, J.P., eds., From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin: International Association of Sedimentologists, Special Publication 46, John Wiley & Sons, Ltd., p. 453-472

Haq, B.U., 2014, Cretaceous eustasy revisited: Global and Planetary Change, v. 113, p. 44-58. https://doi.org/10.1016/j.gloplacha.2013.12.007

Haq, B.U., 2018, Jurassic Sea-Level Variations: A Reappraisal: GSA Today, January 2018, v. 28, p. 4-10. https://doi.org/10.1130/GSATG359A.1

Haq, B.U., Hardenbol, J., and Vail, P., R, 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and van Wagoner, J.C., eds., Sea-Level Change: An Integrated Approach: SEPM, Special Publication 42, p. 71-108. https://doi.org/10.2110/pec.88.01.0071

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): Science, v. 235, p. 1156-1166. https://doi.org/10.1126/science.235.4793.1156

Haq, B.U., and Schutter, S.R., 2008, A Chronology of Paleozoic Sea-Level Changes: Science, v. 322, p. 64-68. https://doi.org/10.1126/science.1161648

Hawie, N., Marfisi, E., Saint-Ange, F., and MacDonald, A.W.A., 2019, Statistical analysis of forward stratigraphic models in complex salt provinces: The central Scotian Basin case study: American Association of Petroleum Geologists, Bulletin, v. 103, p. 433-467. https://doi.org/10.1306/07031817054

Helland-Hansen, W., 2009, Towards the standardization of sequence stratigraphy - Discussion: Earth-Science Reviews, v. 94, p. 95-97. https://doi.org/10.1016/j.earscirev.2008.12.003

Helland-Hansen, W., and Gjelberg, J.G., 1994, Conceptual basis and variability in sequence stratigraphy: a different perspective, Sedimentary Geology, v. 92, p. 31-52. https://doi.org/10.1016/0037-0738(94)90053-1

Helland-Hansen, W., and Hampson, G.J., 2009, Trajectory analysis: concepts and applications: Basin Research, v. 21, p. 454-483. https://doi.org/10.1111/j.1365-2117.2009.00425.x

Helland-Hansen, W., and Martinsen, O.J., 1996, Shoreline trajectories and sequences: description of variable depositional-dip scenarios: Journal of Sedimentary Research, v. 66, p. 670-688. https://doi.org/10.1306/D42683DD-2B26-11D7-8648000102C1865D

Henriksen, S., Hampson, G.J., Helland-Hansen, W., Johannessen, E.P., and Steel, R.J., 2009, Shelf edge and shoreline trajectories, a dynamic approach to stratigraphic analysis: Basin Research, v. 21, p. 445-453.

Hunt, D., and Tucker, M.E., 1992, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall: Sedimentary Geology, v. 81, p. 1-9. https://doi.org/10.1016/0037-0738(92)90052-S

Hunt, D., and Tucker, M.E., 1995, Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall-reply: Sedimentary Geology, v. 95, p. 147-160. https://doi.org/10.1016/0037-0738(94)00123-C

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, in Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H., Ross, C.A., and Van Wagoner, J.C., eds., Sea level changes:

An Integrated Approach: SEPM, Special Publication 42, p. 47-69. https://doi.org/10.2110/pec.88.01.0047

Johannessen, E.P., and Steel, R.J., 2005, Shelf-margin clinoforms and prediction of deepwater sands: Basin Research, v. 17, p. 521-550. https://doi.org/10.1111/j.1365-2117.2005.00278.x

Johnson, J.G., and Murphy, M.A., 1984, Time-rock model for Siluro-Devonian continental shelf, western United States: Geological Society of America Bulletin, v. 95, p. 1349-1359.

Kim, W., Paola, C., Martin, J., Perlmutter, M., Tapaha, F., Kneller, B., Martinsen, O.J., and McCaffrey, B., 2009, Net Pumping of Sediment into Deep Water Due to Base-Level Cycling: Experimental and Theoretical Results, Kneller, B., Martinsen, O.J., and McCaffery, B., eds., External Controls on Deep-Water Depositional Systems: SEPM, Special Publication 92, p. 41-56. https://doi.org/10.2110/sepmsp.092.041

Kim, W., Paola, C., Swenson, J.B., and Voller, V.R., 2006a, Shoreline response to autogenic processes of sediment storage and release in the fluvial system: Journal of Geophysical Research: Earth Surface, v. 111, F04013, https://doi.org/10.1029/2006JF000470

Kim, W., Paola, C., Voller, V.R., and Swenson, J.B., 2006b, Experimental Measurement of the Relative Importance of Controls on Shoreline Migration: Journal of Sedimentary Research, v. 76, p. 270-283. https://doi.org/10.2110/jsr.2006.019

Lomask, J., Francis, J.M., Rickett, J., Buursink, M.L., Gerber, T.P., Perlmutter, M., and Paola, C., 2009, New tools for seismic stratigraphic interpretation: Stratal convergence and instantaneous isochron attribute cubes derived from volumetric flattening of experimental strata: American Association of Petroleum Geologists, Bulletin, v. 93, p. 453-459. https://doi.org/10.1306/11200808104

Madof, A.S., Harris, A.D., and Connell, S.D., 2016, Nearshore along-strike variability: Is the concept of the systems tract unhinged?: Geology, v. 44, p. 315-318. https://doi.org/10.1130/g37613.1

Martin, J., Abreu, V., Neal, J.E., and Pratson, L., 2017, Chapter 13: Seismic stratigraphic concepts - learnings from experimental stratigraphy, in Abreu, V., Feldman, H.R., Pedersen, K.H., and Neal, J.E., eds., Sequence Stratigraphy of Siliciclastic Systems: SEPM, Concepts in Sedimentology and Paleontology 9, p. 123-126 and S95-S98.

Martin, J., Paola, C., Abreu, V., Neal, J., and Sheets, B., 2008, Sequence stratigraphic expression of an evolving experimental fluvial-to-marine depositional profile: American Association of Petroleum Geologists Annual Convention Extended, Abstracts, April 20-23, 2008, Search and Discovery Article #50121.

Martin, J., Paola, C., Abreu, V., Neal, J., and Sheets, B., 2009, Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level: American Association of Petroleum Geologists, Bulletin, v. 93, p. 503-533. https://doi.org/10.1306/12110808057

Miall, A., 2014, The Emptiness of the Stratigraphic Record: A Preliminary Evaluation of Missing Time In the Mesaverde Group, Book Cliffs, Utah, U.S.A: Journal of Sedimentary Research, v. 84, p. 457-469. https://doi.org/10.2110/jsr.2014.40

Miall, A.D., 2022, Stratigraphy: Chapter 5, Stratigraphy: A Modern Synthesis: Textbooks in Earth Sciences, Geography and Environment, p. 231-271. https://doi.org/ https://doi.org/10.1007/978-3-030-87536-7_5

Miall, A.D., Holbrook, J.M., and Bhattacharya, J.P., 2021, The Stratigraphy Machine: Journal of Sedimentary Research, v. 91, p. 595-610. https://doi.org/10.2110/ jsr.2020.143

Miall, A.D., and Miall, C.E., 2001, Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms: Earth-Science Reviews, v. 54, p. 321-348. https://doi.org/10.1016/S0012-8252(00)00041-6

Miall, A.D., and Miall, C.E., 2004, Empiricism and model-building in stratigraphy: Around the hermeneutic circle in the pursuit of stratigraphic correlation: Stratigraphy, v. 1, p. 27-46. https://doi.org/10.1.1.575.4606

Miller, K.G., Kominz, M., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293-1298.

Mitchum, R.M., Jr., Vail, P.R., and Sangree, J.B., 1977, Seismic stratigraphy and global changes of sea-level, part 6: Stratigraphic interpretation of seismic reflection patterns in depositional sequences, in Payton, C. E. ed., Seismic Stratigraphy–Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoir 26, p. 117-163.

Nagle, J., Marfisi, E., Piper, D.J.W., Pe-Piper, G., and Saint-Ange, F., 2021, How is stratigraphic modeling of frontier basins dependent on data: A case study of the Shelburne sub-basin, offshore SE Canada: Marine and Petroleum Geology, v. 132, 105227. https://doi.org/10.1016/j.marpetgeo.2021.105227

Neal, J.E., Abreu, V., Bohacs, K.M., Feldman, H.R., and Pederson, K.H., 2016, Accommodation succession (δA/δS) sequence stratigraphy: observational method, utility and insights into sequence boundary formation: Journal of the Geological Society. https://doi.org/10.1144/jgs2015-165

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47, p. 121-178. https://doi.org/10.1046/j.1365-3091.2000.00006.x

Paola, C., Straub, K., Mohrig, D., and Reinhardt, L., 2009, The “unreasonable effectiveness” of stratigraphic and geomorphic experiments: Earth-Science Reviews, v. 97, p. 1-43. https://doi.org/http://dx.doi.org/10.1016/j.earscirev.2009.05.003

Posamentier, H., and Vail, P., 1988, Eustatic controls on clastic deposition II- sequence and systems tract models, in Wilgus, C.K., Hastings, B.S., Kendal, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea level changes: an integrated approach: SEPM Special Publication 42, p. 125-154. https://doi.org/10.2110/pec.88.01.0125

Posamentier, H.W., and James, D.P., 1992, An overview of sequence stratigraphic concepts: uses and abuses, in Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P., eds., Sequence Stratigraphic and Facies Associations, The International Association of Sedimentologists, p. 3-18. https://doi.org/10.1002/9781444304015.ch1

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition I — sequence and systems tract models, in Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A., and van Wagoner, J.C., eds., Sea-Level change: An Integrated Approach: SEPM, Special Publication 42, p. 109-124. https://doi.org/10.2110/pec.88.01.0109

Poyatos-Moré, M., Jones, G.D., Brunt, R.L., Hodgson, D.M., Wild, R.J., and Flint, S.S., 2016, Mud-Dominated Basin-Margin Progradation: Processes and Implications: Journal of Sedimentary Research, v. 86, p. 863-878. https://doi.org/10.2110/jsr.2016.57

Prather, B.E., 2000, Calibration and visualization of depositional process models for above-grade slopes: a case study from the Gulf of Mexico: Marine and Petroleum Geology, v. 17, p. 619-638. https://doi.org/10.1016/S0264-8172(00)00015-5

Prather, B.E., 2020, Controls on Reservoir Distribution, Architecture and Stratigraphic Trapping in Slope Settings, in Scarselli, N., Adam, J., Chiarella, D., Roberts, D.G., and Bally, A.W., eds., Regional Geology and Tectonics (2nd Edition), Elsevier B.V., p. 481-515. https://doi.org/10.1016/B978-0-444-64134-2.00025-0

Prather, B.E., Pirmez, C., and Winker, C.D., 2012, Stratigraphy of Linked Intraslope Basins: Brazos Trinity System Western Gulf of Mexico, in Prather, B.E., Deptuck, M.E., Mohrig, D.C., van Hoorn, B., and Wynn, R.B., eds., Application of the Principles of Seismic Geomorphology to Continental-Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues: SEPM, Special Publication 99, SEPM (Society for Sedimentary Geology), p. 83-109. https://doi.org/10.2110/pec.12.99.0061

Qayyum, F., Groot, P., and Hemstra, N., 2012, Using 3 D Wheeler diagrams in seismic interpretation the HorizonCube method: First Break, v. 30, p. 103-109. https://doi.org/10.3997/1365-2397.30.3.56681

Qayyum, F., Groot, P.D., Hemstra, N., and Catuneanu, O., 2014, 4D Wheeler diagrams: concept and applications, in Smith, D.G., Bailey, R.J., Burgess, P.M., and Fraser, A.J., eds., Strata and Time: Probing the Gaps in Our Understanding: Special Publications, 404, p. 10. https://doi.org/10.1144/sp404.1

Ryan, M.C., Helland-Hansen, W., Johannessen, E.P., and Steel, R.J., 2009, Erosional vs. accretionary shelf margins: the influence of margin type on deepwater sedimentation: an example from the Porcupine Basin, offshore western Ireland: Basin Research, v. 21, p. 676-703. https://doi.org/10.1111/j.1365-2117.2009.00424.x

Sadler, P.M., 1981, Sediment Accumulation Rates and the Completeness of Stratigraphic Sections: The Journal of Geology, v. 89, p. 569-584. https://doi.org/10.1086/628623

Sloss, L., Krumbein, W.E., and Dapples, F., 1949, Integrated facies analysis. In: Sedimentary facies in geologic history, in Longwell, C., ed.: Geological Society America, Memoir 39, p. 91-124.

Sloss, L.L., 1963, Sequences in the Cratonic Interior of North America: Geological Society of America Bulletin, v. 74, p. 93-114. https://doi.org/10.1130/0016-7606(1963)74[93:sitcio]2.0.co;2

Strong, N., and Paola, C., 2008, Valleys That Never Were: Time Surfaces Versus Stratigraphic Surfaces: Journal of Sedimentary Research, v. 78, p. 579-593. https://doi.org/10.2110/jsr.2008.059

Sylvester, Z., Deptuck, M.E., Prather, B.E., Pirmez, C., and O'Byrne, C.J., 2012, Seismic Stratigraphy of a Shelf-Edge Delta and Linked Submarine Channels in the Northeastern Gulf of Mexico, in Prather, B.E., Deptuck, M.E., Mohrig, D.C., van Hoorn, B., and Wynn, R.B., eds., Application of the Principles of Seismic Geomorphology to Continental-Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues: SEPM, Special Publication 99, p. 31-59. https://doi.org/10.2110/pec.12.99.0013

Sylvester, Z., Pirmez, C., and Cantelli, A., 2011, A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture: Marine and Petroleum Geology, v. 28, p. 716-727. https://doi.org/10.1016/j.marpetgeo.2010.05.012

Talling, P.J., Masson, D.G., Sumner, E.J., and Malgesini, G., 2012, Subaqueous sediment density flows: Depositional processes and deposit types:

Sedimentology, v. 59, p. 1937-2003. https://doi.org/10.1111/j.1365-3091.2012.01353.x

Thorne, J.A., 1992, An analysis of the implicit assumptions of the methodology of seismic sequence stratigraphy, in Watkins, J.S., Zhiqiangm, F., and McMillen, K.J., eds., Geology and Geophysics of Continental Margins: American Association of Petroleum Geologists Memoir 53, p. 375-394.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 3: Relative changes of sea level from coastal onlap, in Payton, C. E. ed., in Payton, C. E. ed., Seismic Stratigraphy–Applications to Hydrocarbon Exploration, American Association of Petroleum Geologists, Memoir 26 p. 63-81. https://doi.org/10.1306/M26490C5

van Hoek, T., Gesbert, S., and Pickens, J., 2010, Geometric attributes for seismic stratigraphic interpretation: The Leading Edge, v. 29, p. 1056-1065. https://doi.org/10.1190/1.3485766

Van Wagoner, J.C., Mitchum, R.M., Jr., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Core, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies: American Association of Petroleum Geologists, Methods in Exploration Series no. 7, 55 p.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Jr., Vail, P.R., Sarg, J.F., and Loutit, T.S., 1988, An overview of sequence stratigraphy and key definitions, in Wilgus, C.K., Hastings, B.S., Kendal, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Changes – An Integrated Approach: SEPM, Special Publication 42, p. 39-45. https://doi.org/10.2110/pec.88.01.0039

Wheeler, H.E., 1958, Time-stratigraphy: American Association of Petroleum Geologists, Bulletin, v. 42, p. 1047-1063. https://doi.org/10.1306/0BDA5AF2-16BD-11D7-8645000102C1865D

Wheeler, H.E., 1964a, Baselevel transit cycle, in Merriam, D.F., ed., Symposium on Cyclic Stratigraphy – II: Kansas Geological Survey, Bulletin 169: Lawrence, p. 620-629.

Wheeler, H.E., 1964b, Baselevel, lithosphere surface and time-stratigraphy: Geological Society of America, Bulletin, v. 75, p. 599-610. https://doi.org/10.1130/0016-7606(1964)75[599:BLSAT]2.0.CO;2

Wild, R., Flint, S.S., and Hodgson, D.M., 2009, Stratigraphic evolution of the upper slope and shelf edge in the Karoo Basin, South Africa: Basin Research, v. 21, p. 502-527. https://doi.org/10.1111/j.1365-2117.2009.00409.x

Zhang, J., Flaig, P., Wartes, M., Aschoff, J., and Shuster, M., 2021, Integrating stratigraphic modeling, inversion analysis, and shelf-margin records to guide provenance analysis: An example from the Cretaceous Colville Basin, Arctic Alaska: Basin Research, v. 33, p. 1954-1966. https://doi.org/10.1111/bre.12543

Zhang, J., Kim, W., Olariu, C., and Steel, R., 2019, Accommodation- versus supply-dominated systems for sediment partitioning to deep water: Geology, v. 47, p. 419-422. https://doi.org/10.1130/G45730.1

SUPPLEMENTARY FILES

Blank Wheeler: Table-top version of a blank Wheeler diagram with streamwise distance on the x-axis, relative geologic time on the y-axis, and a blank panel on the right to record an interpreted base-level curve.

Laboratory Experiment 3D Evolution video files show the evolution of the topography and sedimentation rates through the XES02 experiment by successfully showing topography for each of the scanned surfaces with draped visualization of sedimentation/erosion rates.

Line 800 Shoreline Trajectory Animation

Line 800 black line. The black dots denote shoreline positions, and connecting line denotes shoreline trajectory.

Line 1700: Table-top version of line 1700 mm.

Line 1700 Shoreline Trajectory Animation