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Geometrical Breakdown Approach to interpretation of depositional sequences

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ABSTRACT

Seismic and sequence stratigraphic analyses are important methodologies for interpreting coastal and shallow-marine deposits. Though both methods are based on objective criteria, terminology for reflection/stratal stacking is widely linked to eustatic cycles, which does not adequately incorporate factors such as differential subsidence, sediment supply, and autogenic effects. To reduce reliance on model-driven interpretations, we developed a Geometrical Breakdown Approach (GBA) that facilitates interpretation of horizon-bound reflection packages by systematically identifying upward-downward and landward-seaward trajectories of clinoform inflection points and stratal terminations, respectively. This approach enables a rigorous characterization of stratal surfaces and depositional units. The results are captured in three-letter acronyms that provide an efficient way of recognizing repetitive stacking patterns through discriminating reflection packages objectively to the maximum level of resolution provided by the data. Comparison of GBA with selected sequence stratigraphic models that include three and four systems tracts and the accommodation succession approach shows that the GBA allows a greater level of detail to be extracted, identifying key surfaces with more precision and utilizing more effectively the fine-scale resolution provided by the input seismic data. We tested this approach using a synthetic analogue model and field data from the New Jersey margin. The results demonstrate that the geometric criteria constitute a reliable tool for identifying systems tracts and provide an objective and straightforward method for practitioners at all levels of experience.

INTRODUCTION

Sequence stratigraphy is the study of sedimentary units within a chronostratigraphic framework of genetically related strata bounded by surfaces of deposition (correlative conformities), nondeposition, and erosion (Van Wagoner et al., 1988). The discipline, which evolved from seismic stratigraphy (Vail et al., 1977), characterizes stratal stacking patterns and has been widely used to interpret the depositional history of sedimentary basins at multiple scales, as well as to infer the rate of sediment supply with respect to base-level change (Mitchum et al., 1977b; Posamentier et al., 1988; Helland-Hansen and Gjelberg, 1994), especially in coastal and shelfal environments (e.g., Csato et al., 2013; Eriksson et al., 2013; Fulthorpe et al., 1999; Mountain et al., 2007; Steckler et al., 1999; Pellegrini et al., 2017).

With a focus on shallow-marine strata, Sloss et al. (1949) defined six unconformity-bounded depositional cycles across the North American craton and attributed them to long-term (first-order) sea-level changes resulting from breakup and formation of supercontinents every 200–400 m.y. Researchers working on plate-tectonics theory observed second-order eustatic cycles at 10–100 m.y. time scales related to changes in the size of the oceans (Hallam, 1963). These changes are driven by fluctuations in the volume of magma produced at mid-ocean ridges (Hallam, 1963) and the relative speed of plate motion (Sheridan, 1987). With the advent of multichannel seismic imaging, surfaces of discontinuity in the sedimentary record were identified using physical properties (i.e., reflection terminations). Peter Vail and others at Esso Production Research (now ExxonMobil) proposed new concepts for interpreting the significance of stratal stacking patterns observed in two-dimensional (2-D) seismic data on continental shelves, attributing third-order cycles with 0.5–5 m.y. duration predominantly to glacio-eustasy (Vail et al., 1977; Mitchum et al., 1990). Advances in borehole logging, isotope geochemistry, and dating techniques led to the refinement of paleo–sea-level curves (Haq et al., 1987; Miller et al., 2005) and the recognition of fourth- and fifth-order cycles with durations of 0.1–0.5 m.y. and 0.01–0.1 m.y., respectively (Van Wagoner et al., 1990, 1988). These concepts have been extensively documented in American Association of Petroleum Geologists (AAPG) Memoir 26 (Payton, 1977), Society for Sedimentary Geology (SEPM; formerly known as the Society of Economic Paleontologists and Mineralogists) Special Publication 42 (Wilgus et al., 1988), and several other publications (Catuneanu et al., 2009; Embry and Johannessen, 2017; Miall, 2006; Miller et al., 2018; Posamentier and Allen, 1999; Zaitlin et al., 1994; Pellegrini et al., 2018).

A key advance was the recognition of systems tracts, i.e., genetically related stratigraphic units that are interpreted to be deposited at specific phases on the eustatic curve, even though the actual time of initiation is interpreted to be a function of the interactions among eustasy, sediment supply, and tectonics (Van Wagoner et al., 1988; Jervey, 1988; Hunt and Tucker, 1992; Posamentier and Allen, 1993; Plint and Nummedal, 2000). Figure 1 summarizes some of the main models that consider stacking patterns as the basic criteria with which to identify systems tracts within a depositional sequence. The proposed depositional sequence models (Hunt and Tucker, 1992; Miller et al., 2018; Van

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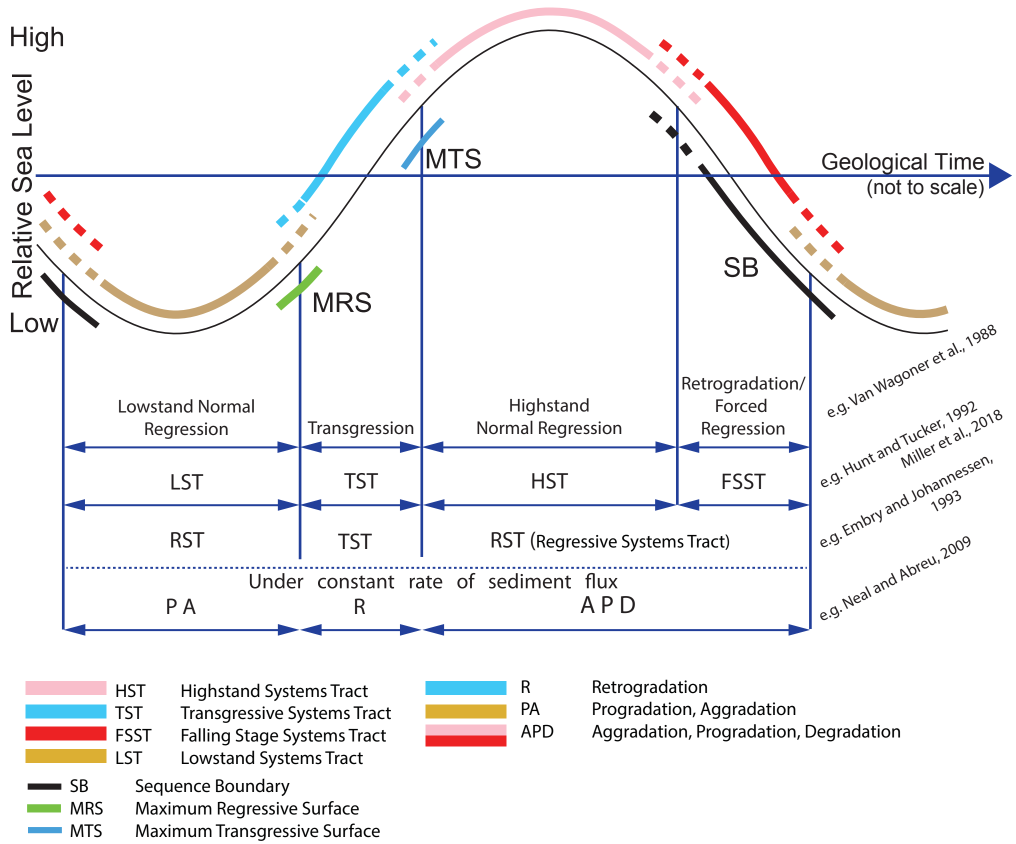

Figure 1. Schematic of the common approaches used in seismic sequence stratigraphic interpretation as a function of the relative sea-level cycle proposed by Van Wagoner et al. (1988), Neal and Abreu (2009), and Miller et al. (2018). These complementary approaches focus on different aspects of depositional architecture: (1) stratal stacking patterns like progradation (P), aggradation (A), degradation (D), and retrogradation (R) (Van Wagoner et al., 1988); (2) shoreline trajectories (Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009; Hunt and Tucker, 1992), such as the transgressive-regressive sequence model (Embry and Johannessen, 1993; and (3) accommodation succession stacking (Neal and Abreu, 2009; Neal et al., 2016). LST—lowstand systems tract, TST—transgressive systems tract, HST—highstand systems tract, FSST—falling stage systems tract, RST—regressive systems tract, SB—sequence boundary, MRS—maximum regressive surface, MTS—Maximum Transgressive Surface.

Wagoner et al., 1988) use the subaerial unconformity (a diachronous surface) and the top of its marine correlative conformity (synchronous surface) as a composite sequence boundary (Cohen, 1982; Goodwin et al., 1986). In these models, the formation of the subaerial unconformity is assumed to have been contemporary with the stage of base-level fall at the shoreline, and the correlative conformity is considered to be the seafloor at the end of forced regression, when the shoreline is forced to regress (i.e., to migrate seaward) by the falling base level irrespective of the sediment supply (Catuneanu, 2002). Depositional sequences used by Van Wagoner et al. (1988) and Miller et al. (2018) presented a similar concept, with the exception that a falling stage systems tract was recognized in the latter. The transgressive-regressive sequence model (Embry and Johannessen, 1993) is bounded by composite surfaces including subaerial unconformities, ravinement surfaces, and their correlative maximum regressive surfaces. In the transgressive-regressive model, the correlative conformity is replaced with the marine portion of the maximum regressive surface in shallow-marine settings on outcrop or subsurface data (Embry and Johannessen, 1993).

Precise seismic criteria for identifying the boundaries between systems tracts, however, are often lacking, leading to subjective interpretations and model results that fail to utilize the resolution (Sherriff, 1977) available in seismic data. For example, the boundary between the highstand systems tract and the falling stage systems tract is not defined by any specific surface in the four-systems-tract model due to the challenge in recognizing the onset of sea-level fall. In addition, orbital forces, eustasy, tectonic movements, rate of sediment supply, and autocyclicity (Muto et al., 2007) have all been understood to contribute to depositional cyclicity, leading to uncertainty as to whether, or to what degree, glacio-eustasy can be recognized in the sedimentary record (e.g., Matthews and Al-Husseini, 2010; Matthews and Frohlich, 1998; Strasser et al., 2000) and whether sequence stratigraphy is fractal, with a hierarchal or continuous pattern (e.g., Schlager, 2004).

In order to estimate the timing and partitioning of sediments within sequences, a sediment mass balance must be coupled with allogenic controlling mechanisms (e.g., Kendall et al., 1991; Martin et al., 2009; Perlmutter et al., 1997; Weimer and Posamentier, 1993). The accommodation succession method (Neal and Abreu, 2009) links accommodation creation and sediment fill with three observable stratal patterns: progradation-aggradation, during which the rate of accommodation creation is less than the rate of sediment fill; retrogradation, during which the rate of accommodation creation exceeds the rate of sediment fill; and aggradation-progradation-degradation, during which the rate of accommodation creation is less than the volume of supplied sediment, so that accommodation growth is negative. This model explains the initial condition necessary to deposit each stratal package but does not define precise criteria for identifying package boundaries.

The rapid development of seismic and sequence stratigraphy since 1977 has advanced sedimentary geology considerably but has also led to an abundance of overlapping terminology, methods, and models, which are often not clearly separated. We find that this makes the task of addressing fundamental scientific questions using large data sets difficult, particularly for new practitioners. This overall problem has been recognized by numerous studies (Catuneanu et al., 2009; Helland-Hansen and Hampson, 2009; Embry, 2009; Burgess et al., 2016; Miller et al., 2018). With a goal to further improve and simplify seismic and sequence stratigraphic work, we developed a new method for systematic identification, characterization, and interpretation of depositional units in seismic data that we name the Geometrical Breakdown Approach (GBA). The GBA examines the geometry of stratigraphic surfaces relative to older strata and defines objective geometric criteria that build on robust aspects of existing methods for analyzing stacking patterns and shoreline trajectories to generate an efficient and repeatable interpretation of clinothem external and internal structure. In essence, we characterize the relative position of each seismically resolvable depositional unit, from a single pair of reflections at close to tuning frequency to groups of reflections with similar geometry, with a three-letter acronym that combines the nomenclature for reflection terminations (Part 2 of AAPG Memoir 26; Mitchum et al., 1977b), seismic facies (Part 6 of AAPG Memoir 26; Mitchum et al., 1977a), and shoreline trajectories (Bullimore et al., 2005; Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009). These acronyms effectively characterize the relative spatial position of every depositional unit imaged (or group of similar units), and they immediately reveal cyclicity, although without any connotation regarding the origin of that cyclicity. The three-letter acronyms can then be used to assign depositional units to model-based interpretations of systems tracts (Posamentier et al., 1988; Plint and Nummedal, 2000) and accommodation successions (Neal and Abreu, 2009; Neal et al., 2016).

We first tested the GBA on a synthetic analogue model to evaluate its effectiveness in a known and controlled environment. This was followed by an application on 2-D seismic reflection data collected over the Miocene shelfal clinothems and across three Integrated Ocean Drilling Program (IODP) wells offshore the New Jersey margin, where variations in subsidence, sediment supply, and along-strike autocyclic processes (e.g., Martinsen and Helland-Hansen, 1995; Burgess et al., 2016; Madof et al., 2016; Chiarella et al., 2019) had a secondary impact on sediment deposition. Earlier results from seismic and sequence stratigraphic analysis of the same data (Katz et al., 2013; Miller et al., 2013) provided an excellent opportunity to evaluate the GBA approach. The main goal of this field test performed using 2-D seismic survey data was to identify and characterize depositional units objectively, without contamination by model-driven terms (Miller et al., 2018), and then to analyze eustatic cyclicity via a sequence stratigraphic model integrated with well data.

METHODS

The GBA is a streamlined methodology to interpret seismic reflection data in order to identify and characterize seismic stratigraphic packages that can then be incorporated into a sequence stratigraphic framework. The approach, which is an evolution of the accommodation succession method proposed by Neal and Abreu (2009), is based on the following procedure: (1) identify the landward and seaward terminations (i.e., the coastal or proximal onlap and the distal downlap) of each reflection within the interval of interest; (2) identify reflection packages with similar seismic facies (which can be defined following Vail et al., 1977) and geometry (clinothems), and locate the uppermost rollover point for each clinoform (or, if not evident, the midpoint; see definition of Patruno et al., 2015); (3) determine the direction of vertical shift in the uppermost rollover point (or midpoint) relative to the underlying package, and, likewise, the direction of horizontal shift of the uppermost landward and seaward terminations, and assign a three-letter acronym as described below; (4) use the upward succession of acronyms to identify stratigraphic patterns and cycles; (5) interpret underlying processes and mechanisms that governed the stratigraphic patterns using stratigraphic models selected by the interpreter (in our case, a conventional model of four systems tracts); and (6) apply steps 1–5 to multiple sequences to define sequence sets and composite sequences (sequences with a lower hierarchal order).

The spatial relationships for a package are defined, relative to the preceding package, by lateral shifts of stratal terminations and successive upward or downward movements of the rollover points for the upper surface. The rollover point typically up-steps (U) or down-steps (D), although there are instances where it maintains a static level (S), equivalent to toplap, or it may have been eroded (E) without obvious angularity. The landward and seaward terminations back-step (B) or fore-step (F) (onlap and downlap, as defined in previous studies but adding relative direction). In our study, U, D, B, and F were typically adequate, but S and E were added to maintain flexibility for different environments.

On this basis, the three-letter acronym for each reflection package is derived according to the geometry of its upper surface (Fig. 2). The first letter defines the relative position of the rollover point with respect to the underlying package, and the second and third letters define the relative positions of the landward and seaward terminations, respectively. The stacking patterns are then assigned

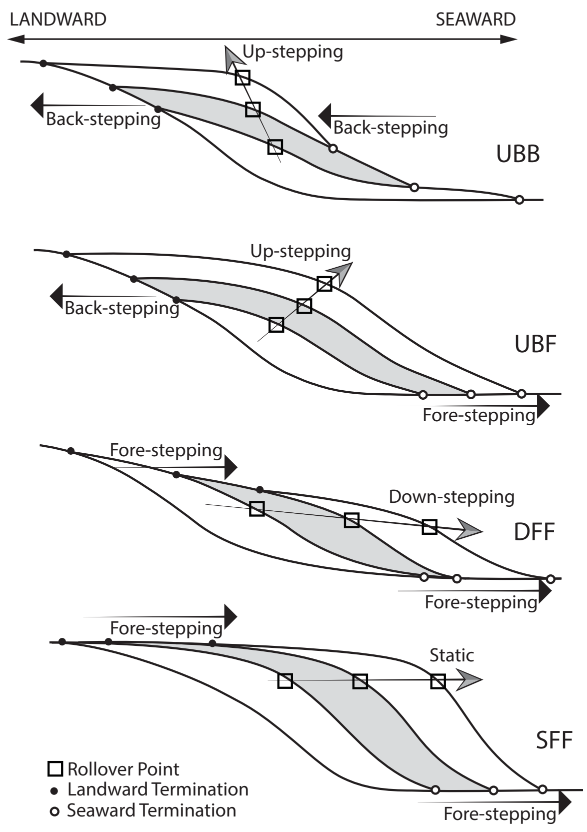

Figure 2. The four most common stratal geometries observed in a clinothem body in nature and their corresponding three-letter acronyms defined by the Geometrical Breakdown Approach (GBA). The first letter in the acronym indicates vertical movement (up/down) of the rollover point with respect to the older unit; the second letter defines movement (back-step/fore-step) of landward termination of the top surface, and the third letter defines movement (back-step/fore-step) of the seaward termination of the top surface.

to systems tracts based on the preferred stratigraphic model (Fig. 1). For a four-systems-tract model (Fig. 3), the stacking patterns are assigned as follows:

(1) Lowstand systems tract (LST): a pronounced DFB or DFF followed by one or more UBFs; the basal surface of the DFF or DFB defines the sequence boundary and the base of the LST; a forced regression, expressed by progradation and aggradation.

(2) Transgressive systems tract (TST): one or successive UBBs; the base of the TST is defined by the onset of back-stepping for both terminations (BB), with continued up-stepping of the rollover point (U); a transgression, expressed as retrogradation.

(3) Highstand systems tract (HST): two or more successive UBFs; the base of the HST is defined by the onset of fore-stepping for seaward termination (F) with continued back-stepping of the landward termination (B) and up-stepping of the rollover point (U); a normal regression, expressed as progradation and aggradation.

(4) Falling stage systems tract (FSST): two or more successive DFBs and/or DFFs; the base of the FSST is defined by the onset of down-stepping of the rollover point (D) and fore-stepping of the landward (and commonly the seaward) termination point (F); the beginning of a forced regression, expressed by degradation and commonly progradation.

(5) The maximum regressive surface (MRS) is marked by the change from UBFs to UBBs, and the maximum transgressive surface (MTS) is marked by the change from UBBs to UBFs.

(6) In the case of erosion and/or a complex system of sediment deposition (e.g., along-strike three-dimensional changes), DFB and UFB may be present in the stratal package; determining the systems tract should be performed on a case-by-case basis.

(7) Similarly, this style of combined geometric and positional characterization may be used and adapted to depositional systems where different interpretational models may apply or be developed, for example, mass transport deposits, turbidites, slopes, and basin floor systems.

The workflow described here identifies each package uniquely, and the sedimentary record emerges as repeated patterns of three-letter acronyms. By relating these patterns to models, it is then possible to integrate the different stacking patterns into the sequence stratigraphic model that best supports the interpretation of the data in the specific case. The clear advance of the proposed approach is that it follows simple rules, avoids complex terminology, is repeatable and easy to annotate, and makes the interpretation more methodical.

In essence, we have combined the key nomenclature of reflection terminations, seismic packages with consistent morphology (in multireflection packages, the acronym of the upper bounding surface is the same as each individual internal surface), and the spatial relationships of back-, fore-, up-, and down-stepping features while avoiding model-driven terminology. This makes the approach efficient, as only the upper bounding surface of each package needs to be correlated throughout a seismic survey, resulting in a set of single names that conveys the key geometric and spatial information. In practice, as is typical in interpretation procedures, the obvious packages and bounding surfaces tend to "jump out," and more subtle features become progressively more apparent.

An application of the GBA to the Miller et al. (2018) clinothem model shows that, while both approaches rely mainly on stratal geometry, the GBA incorporates the landward and seaward terminations to distinguish the interface between successive systems tracts (Fig. 4). When implementing a rigorous seismic analysis, the GBA does not require the introduction of additional data, such as the wireline measurements of petrophysical properties used in Miller

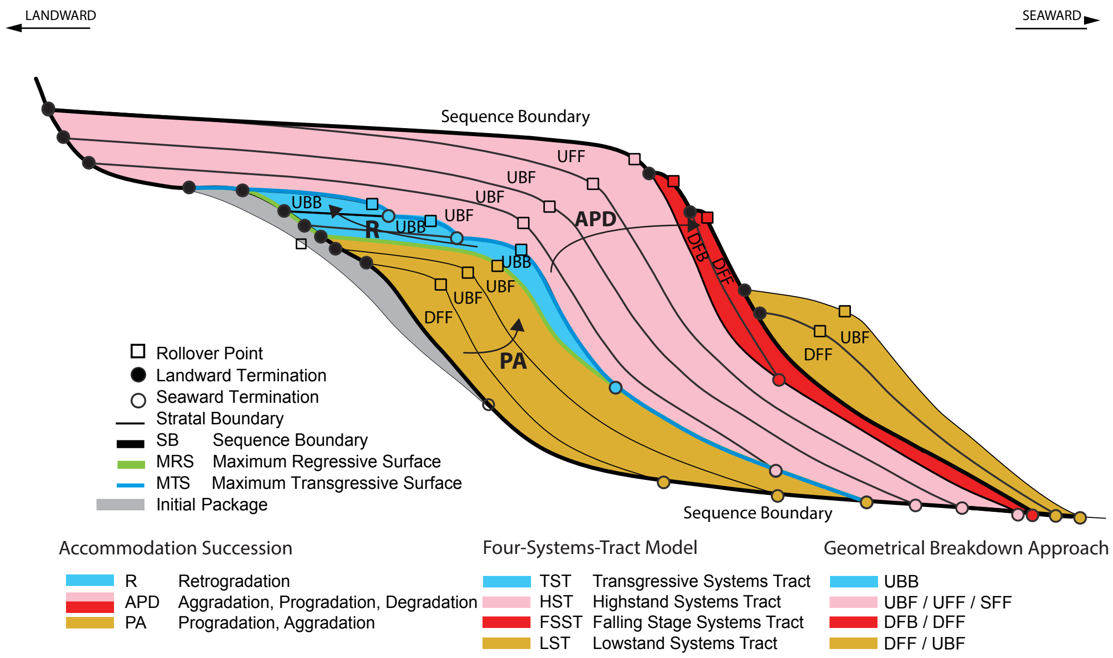

Figure 3. Slug diagram of idealized stratal geometries observed in seismic data. The diagram shows a full succession of systems tracts and their associated surfaces.

et al. (2018). However, these data can be incorporated if available as an independent data set to better correlate seismic facies with physical properties.

The GBA focuses on the spatial "stepping" relationships between depositional packages rather than their internal features. In other words, in this approach, while internal signatures are an important part of interpreting seismic data, it is the geometry of the upper and lower surfaces of each depositional unit on seismic sections that describes a discrete body of rock that is younger than the one below and older than the one above (Vail et al., 1977; Mitchum et al., 1977a). Where seismic artifacts are present, interpretational judgment may be needed to define the bounding reflections, but establishing a framework of interconnecting and truncating surfaces makes the rest of the procedure systematic. The question then arises of how much detail to invest in horizon interpretation. The workflow is applicable at multiple scales, down to the Rayleigh's limit of seismic resolution (half the wavelet width; Kallweit and Wood, 1982), which has been estimated through well calibration and forward modeling. However, separating signal from noise becomes harder as the level of detail increases.

DATA

We applied the GBA to high-resolution synthetic and field data to illustrate and test the approach in forward and inverse directions (i.e., known process to create stratigraphy vs. known stratigraphy to re-create process). We first used a synthetic data set, XES02, generated by the Experimental EarthScape Facility of St. Anthony Falls Laboratory at the University of Minnesota using programmable differential subsidence in a sedimentary basin under laboratory conditions (Paola et al., 2001). The experimental setup provided full control over influential input mechanisms of base-level change, subsidence, and rate of sediment influx, allowing an analysis of their effect on the depositional environment. Next, as a real-world example, we implemented the GBA to analyze Miocene clinothems offshore the New Jersey margin. In doing so, we incorporated the methodological approaches proposed by Neal and Abreu (2009) and Miller et al. (2018), and we identified key surfaces, sequences, systems tracts, and sequence sets only after all the three-letter acronyms had been determined.

XES02 Experiment

For the synthetic data test of the GBA, we used the stratigraphic section from the XES02 experiment shown in Figure 5A constructed by high-resolution laser and sonar tomography. The XES02 experiment (Figs. 5A and 5B) was designed to examine the stratigraphic response of a shallow-marine basin to slow, rapid, and superimposed cycles of base-level change under constant rates of subsidence, water supply, and sediment supply (Paola et

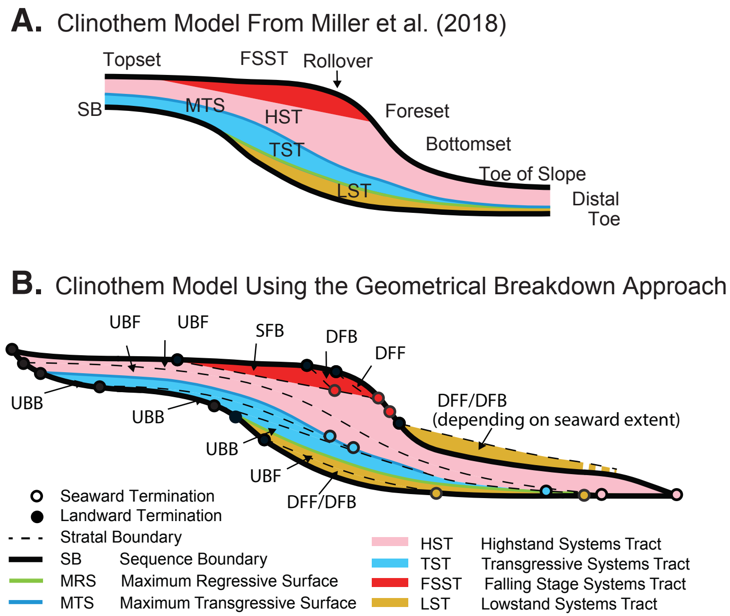

Figure 4. Schematic models of (A) clinothem presented by Miller et al. (2018), and (B) geometric breakdown of systems tracts using the Geometrical Breakdown Approach (GBA).

al., 2001). The slow removal of underlying material from the bottom of the apparatus allowed continuous sediment deposition to occur during 310 h of the experiment. Although constant through time at any one locality, the rate of subsidence increased downstream. In this setup, the trend in base-level change strongly influences the change in the ratio of accommodation creation to sediment flux.

The experiment had two phases (Fig. 5B). Phase 1 consisted of two base-level cycles, the first of which started with a steady base level and active subsidence to build an initial deposit, followed by the imposition of a slow cycle of base-level change and a short equilibrium period. A second, rapid base-level cycle was followed by a constant base level to promote a long equilibration period. Phase 1 was designed to study the stratigraphic response to base-level change for comparison with independent records of basin equilibrium time (Paola et al., 2001). Phase 2 consisted of six high-frequency base-level cycles that comprised one slow cycle with longer periodicity. It was designed to simulate natural conditions where recorded base-level cycles can have several major periodicities in response to external drivers and mechanisms (Strong and Paola, 2006; Martin et al., 2009). Because of the low overburden pressure, sediment compaction was negligible during the experiment. At the end of the experiment, some of the eight imposed cycles of base-level change had generated an incomplete suite of surfaces due to erosion, whereas other cycles had generated more than one sedimentary unit for the same discordance. As a result, it was challenging to identify all eight base-level cycles in the preserved record, despite the well-controlled setting. However, the sediment mass migration and shoreline movement curves were in phase with the base-level curve throughout the experiment (Fig. 5B).

New Jersey Rifted Continental Margin

For the field data test of the GBA, we used the offshore New Jersey seismic profile Oc270 line 529, with vertical resolution of ~5 m (Fulthorpe et al., 2000), which crosses IODP holes M27, M28, and M29 (Figs. 6 and 7). The New Jersey rifted continental margin is a prime location in which to investigate the history of eustatic changes since the Oligocene. High sediment influx (Poag and Sevon, 1989; Miller et al., 1998), tectonic stability (Miller et al., 2014), continuous subsidence due to lithospheric cooling, sediment compaction, and isostatic adjustment (Steckler and Watts, 1978; Watts and Steckler, 1979; Reynolds et al., 1991), and a wealth of available data (wells, seismic profiles, bathymetry) make it a natural laboratory in which to study paleoclimate and eustatic changes (Miller and Mountain, 1996). In a community effort to evaluate the relative influence of controlling mechanisms on the sedimentary record, series of boreholes (Fig. 6), including the most recent IODP holes M27, M28, and M29, were drilled along the New Jersey Sea-Level Transect, extending from the onshore New Jersey coastal plain across the continental shelf to the slope and rise (Miller and Mountain, 1994; Miller et al., 1998). The transect of boreholes made it possible to determine (1) the ages of sequence boundaries with a chronostratigraphic precision of ±0.25 m.y. to ±0.5 m.y. (Browning et al., 2013) to correlate the sequences with major eustatic events, and (2) the amplitude of relative sea-level changes associated with stratigraphic sequences (Miller and Mountain, 1994).

More than 30 seismic profiles and dozens of offshore boreholes, such as the IODP Expedition 313 and the New Jersey Sea-Level Transect, have greatly improved the resolution of the sequence stratigraphic model for the margin (e.g., Greenlee et al., 1992; Kominz et al., 2002; Miller et al., 2013; Mountain et al., 1996, 2007; Poag and Watts, 1987). Nearly continuous records from the Oligocene to middle Miocene form an excellent repository for evaluating chronostratigraphic and paleoenvironmental constraints (Steckler et al., 1999; Kominz et al., 2002; Browning et al., 2013; Katz et al., 2013; McCarthy et al., 2013). Previous studies of the New Jersey rifted margin showed that, since Oligocene times, eustasy, subsidence, sediment supply, and isostasy have contributed to the shoreline movement, with eustatic forcing being predominant (Grow and Sheridan, 1988; Mountain et al., 2010; McCarthy et al., 2013; Miller et al., 2014). Reconstruction of depositional setting through backstripping of the transgressive-regressive sequences deposited on the coastal plain (15–17 Late Cretaceous, 6 Paleocene, 12 Eocene, 7 Oligocene, and 18–20 Miocene

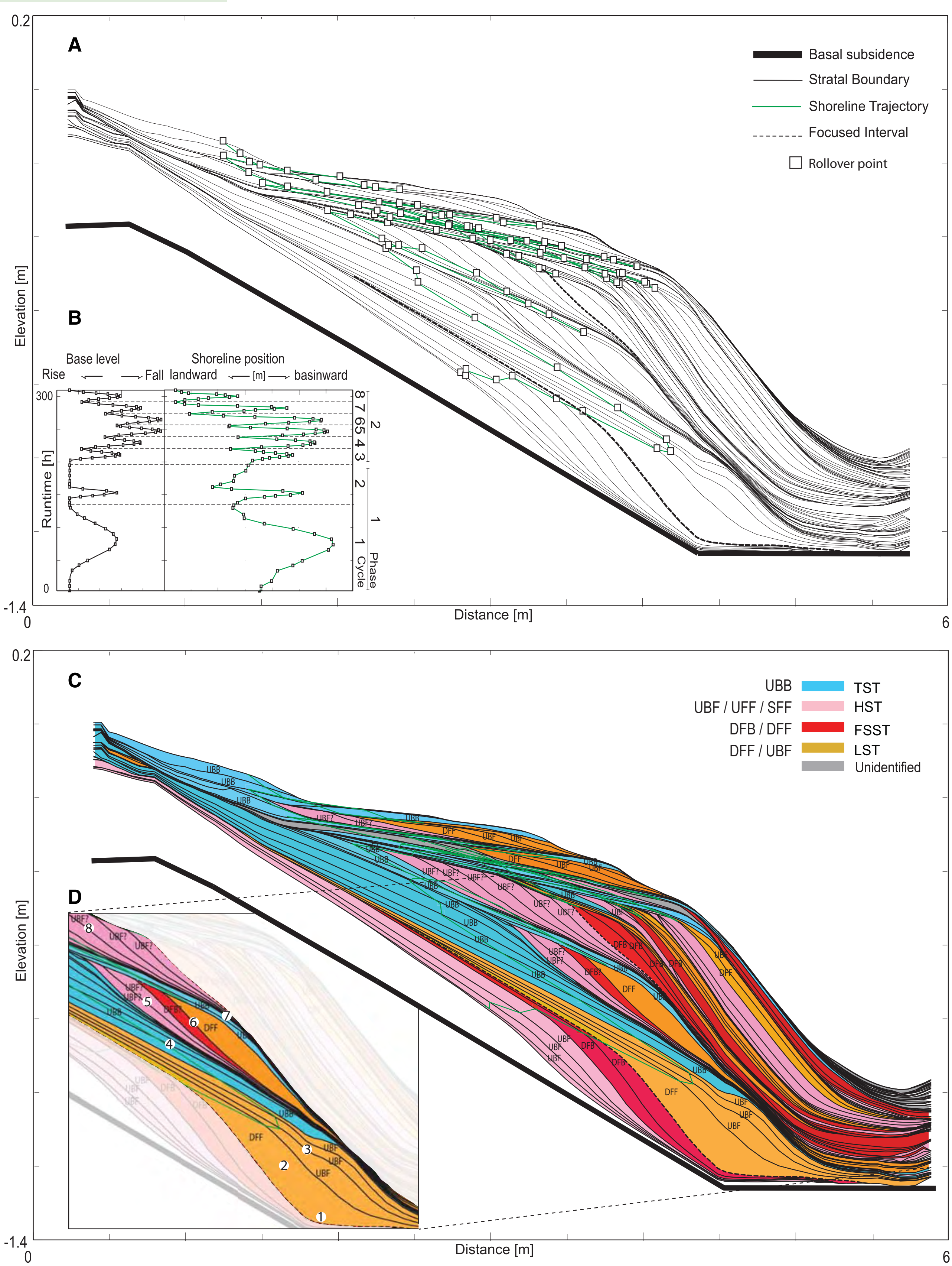

Figure 5. (A) Stratigraphic model of the XES02 experiment reconstructed from laser and sonar topographic measurements (image modified from Kim et al., 2014); (B) absolute base-level curve and corresponding shoreline position over the experiment run time; (C) XES02 laser and sonar topographic section shown with the overlain interpretation; and (D) shoreline trajectories (green line). Two dashed lines separate the zone described in the Results section. See Figure 3 for systems tract and Geometrical Breakdown Approach (GBA) abbreviations.

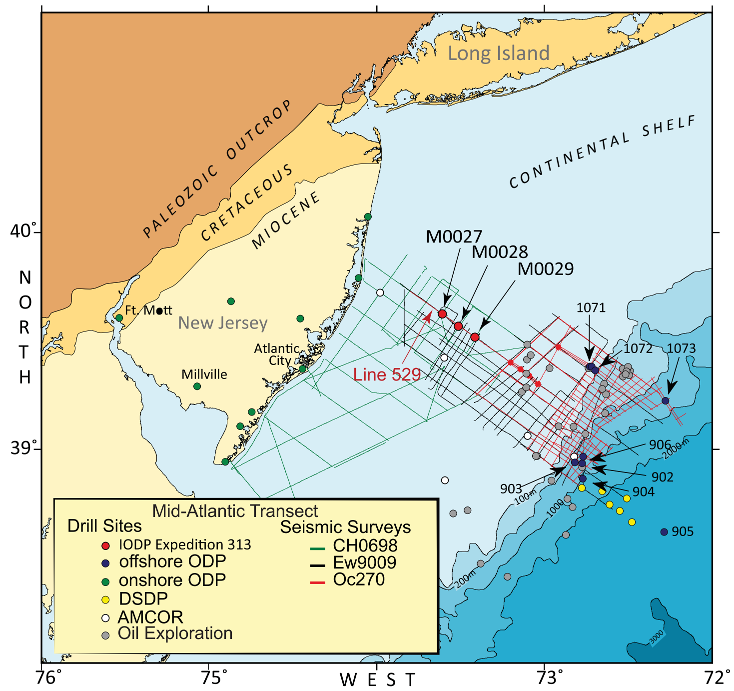

Figure 6. Map view of the study area offshore New Jersey continental margin. Seismic data crossing Integrated Ocean Drilling Program (IODP) wells M27, M28, and M29 were used for this study (base map from Mountain et al., 2010). ODP—Ocean Drilling Program; DSDP—Deep Sea Drilling Project; AMCOR—Atlantic Margin Coring Project.

sequences) has revealed numerous records of sea-level cycles (Greenlee et al., 1992; Miller and Mountain, 1994; Steckler et al., 1999; Miller et al., 2014).

RESULTS

Sequence Stratigraphy of Synthetic Strata under Known Conditions

The digitized section of Figure 5A comprises 101 surfaces formed during the 310 h of experiment (Paola et al., 2001; Kim et al., 2014). We focus the most detailed description on the part of the profile outlined by two dashed lines (Figs. 5C and 5D). Above the lower dashed line (Fig. 5D, part 1), which is an unconformity (sequence boundary) generated during phase 1 after the slow cycle, we observe a down-stepping unit (Fig. 5D, part 2) with both landward and seaward terminations that are fore-stepping relative to the lower sequence boundary (DFF). This stratum is followed by a series of up-stepping strata (Fig. 5D, part 3), with back-stepping landward terminations and fore-stepping seaward terminations (UBFs). At the top of this package, the UBF trend changes to a UBB trend (Fig. 5D, part 4). The boundary that marks this change in stratal geometry defines the MRS and marks the change from PA to R (or LST to TST). Following this set of UBB packages, an erosional surface seems to cut through the landward termination of packages with an up-stepping–back-stepping–fore-stepping (UBF) trend (Fig. 5D, part 5). As the seaward termination begins to fore-step, the bottom of the corresponding package marks the MTS and the change from TST to HST. Although the top of HST is eroded, the lower terminations continue to fore-step, indicating no change in environmental dynamics. An overlying series of partially eroded DFF and DFB strata (Fig. 5D, part 6) then represents an FSST. The last DFF, followed by a series of UBB strata (Fig. 5D, part 7), marks the end of the rapid cycle and beginning of the equilibrium period (upper dashed line, which indicates the end of the period chosen for detailed description). The erosional truncation, along with the remnant of the HST (UBF strata), marks the sequence boundary at the end of the rapid cycle (Fig. 5D, part 8).

During the long relaxation time of the second part of cycle 2 (Fig. 5), the base level does not change; however, continuous subsidence tips the basin (setup of the experiment) landward, which results in the deposition of new strata closer to the source. This means that the rollover point, landward termination, and seaward termination define UBBs. As deltas avulse, back-stepping of landward stratal termination (onlap) is associated with prograding packages on the shelf. Strong and Paola (2006) reported that the surface that ultimately served as the sequence boundary is more widespread than any other prograding up-stepping–back-stepping surface during the experiment, which increases the chance that the surface will be preserved in the stratigraphic record.

We also identified the geometry of sequences formed during phase 2, when high-frequency cycles were superimposed on one low-frequency cycle (except cycle 4, which was severely eroded; Fig. 5). The sequences show a distinctive progradational, aggradational, and retrogradational stacking pattern (Martin et al., 2009; Neal et al., 2016). On a regional scale, these sequence sets form a genetically related succession representing lowstand, transgressive, highstand, and falling stage packages, indicating a long-term fluctuation of the accommodation relative to the sediment flux (Mitchum and Van Wagoner, 1991; Neal and Abreu, 2009; Plint and Nummedal, 2000).

Sequence Stratigraphy of the New Jersey Rifted Continental Margin

Our analysis of seismic profile Oc270 line 529 (Fig. 6) focused on several sequences encompassing the early to late Miocene (Fig. 7), over an ~8-m.y.-long succession. We picked the rollover points and the landward and seaward terminations for each clinothem, and we grouped seismic packages characterized by similar geometry and facies using the three-letter acronyms (Fig. 7), which resulted in 53 systems tracts. At this stage, we did not consider the age model of the three wells, and thus we did not discuss any sequence hierarchy.

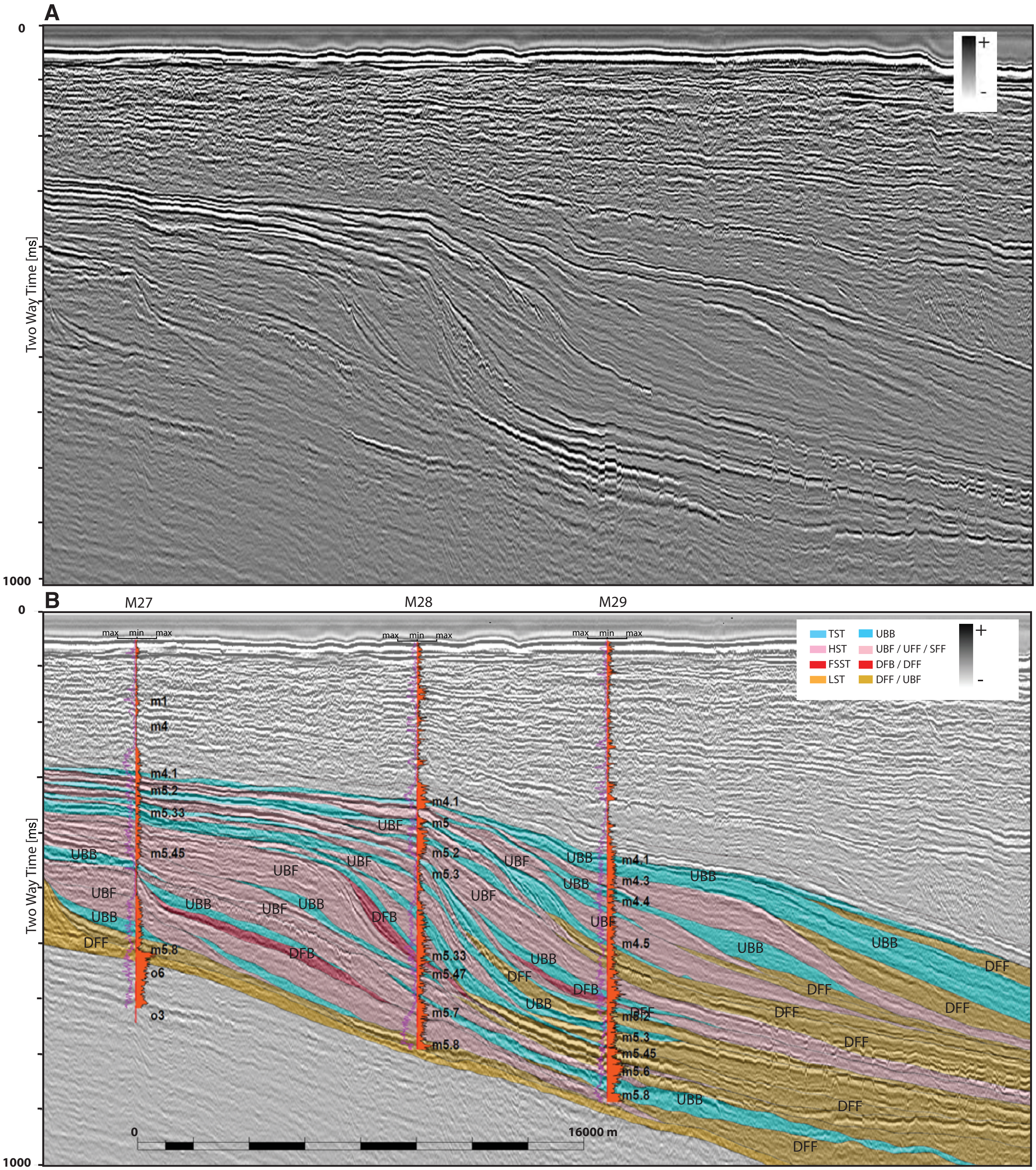

Figure 7. (A–B) Seismic profile Oc270 line 529 before (A) and after (B) interpretation. Spectral gamma-ray logs of thorium (purple log to left) and uranium (orange log to right) are displayed along the Integrated Ocean Drilling Program (IODP) wells M27–M29. See Figure 3 for systems tract and Geometrical Breakdown Approach (GBA) abbreviations.

TSTs, HSTs, and LSTs are observed in most of the identified sequences, with only three FSSTs, two of which are observed where the rollover point reaches the local maximum slope gradient. All three FSSTs are followed by relatively thick LSTs. Through time, the rollover point gradually migrates seaward, while the topset strata experience several periods of erosion. In the late Miocene, the record shows a succession of UBBs and UBFs with a continuous transgression landward. The spectral gamma-ray logs (Fig. 7) show an overall decrease in amplitude, which is attributed to the deposition of more sandy sediments in the late Miocene.

DISCUSSION

Applying the GBA to the synthetic XES02 chronostratigraphic units provided a framework for analyzing the identified seismic packages in the context of the controlling mechanisms that influenced sediment deposition, allowing the method to be evaluated in a controlled environment. Results from seismic and sequence stratigraphic analysis of field data from two previous studies of the New Jersey margin made possible a comparison with our interpretation based on the GBA. The outcomes of both the synthetic and the field data study provide a perspective on applying the GBA to shallow-marine stratigraphic analysis.

Evaluation of the Geometrical Breakdown Approach Application to Synthetic Data

We first analyzed the key surfaces and systems tracts from the XES02 results in the context of the most influential parameter that controlled sediment deposition: base level (Martin et al., 2009; Kim et al., 2014). Base level also controlled the rate of accommodation creation to sediment influx (δA/δS) under constant rates of subsidence and sediment influx (Fig. 8).

We used Equation 1 from Kim et al. (2014) to compute δA/δS, as it defines the rate of accommodation creation to sediment supply as a function of the stratal geometry. An assumption of the XES02 experiment is that the depositional environment experienced negligible loss or gain of sediment and negligible temporal variability in the rate of subsidence.

$$\frac{\delta A}{\delta S} = \frac{(u-s)\left[\frac{dZ_{bl}}{dt} + \sigma(s)\right]}{q_{so}} \quad (1)$$

In Equation 1, $u - s$ is foreset horizontal length, which is the distance from delta toe (u) to shoreline position or beginning of foreset slope (s), dZ_{bl}/dt is base-level change over time (if <0 base-level falls), $\sigma(s)$ is rate of subsidence, and q_{so} is sediment feed rate. Equation 1 implies that the rate of accommodation creation to sediment influx is directly proportional to (1) foreset horizontal length (i.e., the longer the delta toe to top-slope foreset, the more

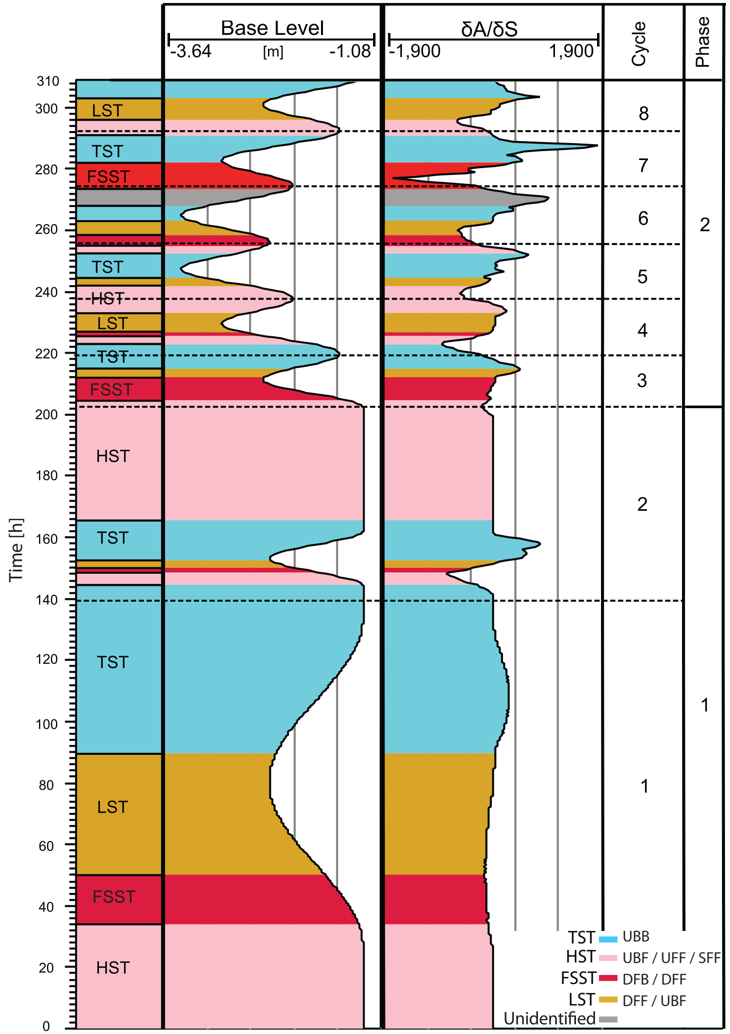

Figure 8. Stratigraphic interpretation of the XES02 experiment (color) bounded on the right by thin black lines showing the history of base-level change and the estimated ratio of the rate of accommodation creation to rate of sediment influx (δA/δS) as a function of time. Data are courtesy the National Center for Earth-Eurface Dynamics Data Repository (http://www.nced.umn.edu/Data_Repository.html, accessed March 2019). See Figure 3 for systems tract and Geometrical Breakdown Approach (GBA) abbreviations.

accommodation is available per unit of sediment influx), and (2) the cumulative sum of base-level change and total subsidence.

The stratigraphic section presented in Figure 8 shows that the basin preserved most of the sedimentary record from the slow (35–140 h) and fast (145–165 h) periods of base-level change in cycles 1 and 2 of phase 1. The identified systems tracts tie with the respective phases in a δA/δS cycle. During the initial equilibrium period (0–30 h), a small rate of subsidence caused a slightly positive δA/δS and, consequently, deposition of UBF strata. As the induced base-level fall reduced the accommodation, the negative δA/δS resulted in the deposition of DFBs and DFFs (35–50 h). Later, when the rate of accommodation creation matched the rate of sediment flux, UBF strata generated a lowstand systems tract (50–90 h) as the δA/δS value increased.

The phase 2 record of fast cycles superimposed on a long cycle repeats a similar set of systems tracts but with a time lag in relation to the δA/δS cycle. This time lag is as large as 4 h for some of the systems tracts, which indicates that short-period cycles may be challenging to identify in field data when superimposed on long-period cycles. Additional factors that are normally experienced in real situations, such as compaction and variable rate of sediment supply, had no influence on the experimental results. Additionally, the δA/δS log in Figure 8 was computed from the instantaneous change in accommodation and may not reflect the impact of the background slow cycle in phase 2. Nevertheless, observation of the relative shift in the location of the rollover point and seaward termination in cycles 4 and 5 (two out of three geometrical criteria for the GBA) seemed sufficient to identify the stacking patterns in partially eroded TSTs and HSTs. More severe erosion and incomplete records from cycles 6 and 7 led to uncertainty in identifying the rollover point and landward termination of strata.

Figure 9 summarizes the observed relationship between the timing of systems tract formation and the ratio of accommodation creation to sediment flux. When the rate of accommodation creation exceeds the rate of sediment flux, UBB strata result (TSTs). When the rate of accommodation creation matches the rate of sediment flux, UBF strata result, interpreted as HSTs or LSTs depending on the geometry of the stratal package below. When the rate of accommodation creation is less than the rate of sediment flux, DFF strata result (FSSTs). Whereas subsequent subaerial erosion or transgressive ravinement often remove the sedimentary record needed to identify FSSTs in field examples (Plint and Nummedal, 2000), we frequently (three quarters of all cycles) identified FSSTs in the synthetic data. This is largely due to the experiment's initial condition of a constant rate of sediment supply; in reality, climatic and tectonic conditions may not only shift the base level, but may also strongly affect the rate of sediment supply.

Comparison of Stratigraphic Interpretations on the New Jersey Shelf

Figure 10 compares the model based on implementing the GBA with the results from previous studies by Katz et al. (2013) and Miller et al. (2013), which benefited from a comprehensive data set that included biostratigraphy and lithology from cores, as well as seismic survey data. Using the criteria outlined in Miller et al. (2013), the core data indicated changes in water depth and shallowing and deepening stratal trends, confirming sequences and sequence boundaries identified by observing toplap, onlap, downlap, and erosional truncations in the seismic profiles. Miller et al. (2013) classified as TST a succession of deepening-upward reflection packages, between an initial transgressive surface and the MTS. Locating the MTS required observing downlap surfaces on seismic profiles and omission surfaces in cores, which can be ambiguous. Observation of benthic foraminifera and abundance of planktonic foraminifera were considered as the strongest evidence for maximum relative sea level (Katz

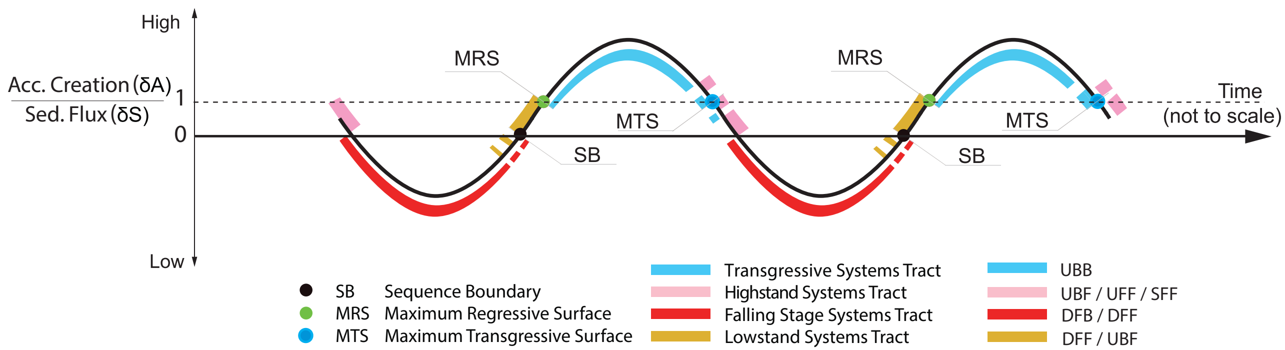

Figure 9. Timing of stratigraphic systems tracts formation and the associated surfaces in relation to the ratio of accommodation creation to sediment flux. The figure was made based on two core assumptions: (1) the coastal accommodation creation changes continuously and quasi-periodically at an inconsistent rate; (2) sediment potentially fills the space up to the base level, and any surplus is transported farther seaward, where excess accommodation is available (Helland-Hansen and Gjelberg, 1994; Neal et al., 2016).

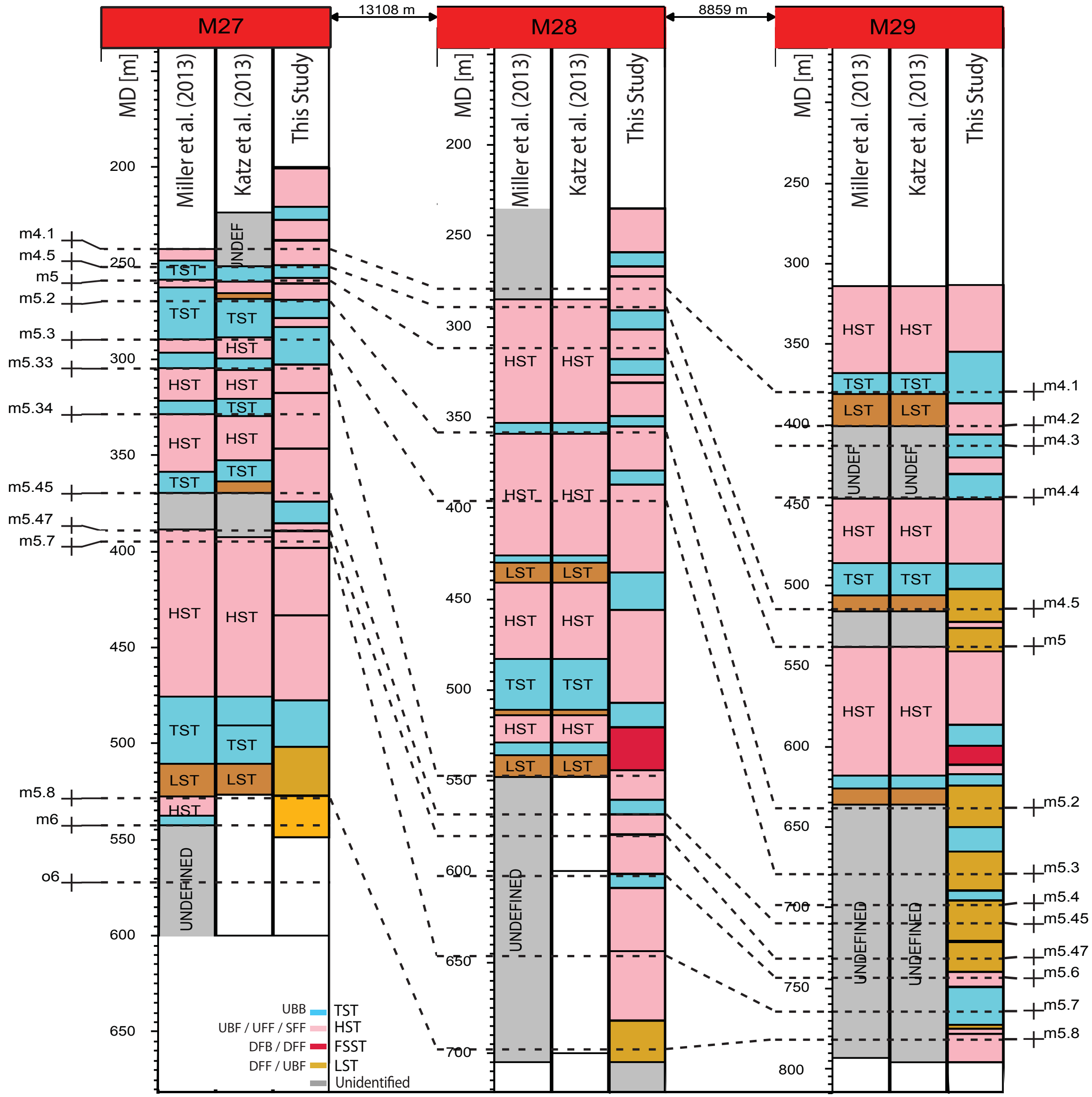

Figure 10. Sequence stratigraphic interpretation of the three Integrated Ocean Drilling Program (IODP) wells M27, M28, and M29 in measured depth (MD). Figure 6 shows the position of the three wells in a map view. The first letter of each layer stands for the geological epoch to which it belongs, with "o" standing for the Oligocene and "m" standing for the Miocene interval. Age data are from Browning et al. (2013). Site M27 was drilled at the topset of clinoforms where seismic data show signs of erosion and unconformity in the younger intervals. Site M28 had the worst coring recovery among three IODP wells (Mountain et al., 2010) due to the borehole instability and problems associated with drilling. Site M29 had an excellent core recovery (Mountain et al., 2010), and the majority of identified systems tracts have a thickness above the tuning thickness, which made them recognizable in both well and seismic data. See Figure 3 for systems tract and Geometrical Breakdown Approach (GBA) abbreviations.

et al., 2013) associated with MTS formation in the foreset of a clinoform. This technique has a low vertical resolution because it mainly identifies zones rather than the distinct surfaces designated as MTSs (Loutit et al., 1988). Identification of MTSs was based on a change from deepening-upward (retrogradational) to shallowing-upward (progradational) successions, which relied on the paleo–water depth and may have failed to recognize varied sediment flux, which is the other controlling parameter.

Comparison of the stratigraphic model based on the GBA with the results from previous studies revealed that, despite different approaches, the final interpretations are in general agreement. Figure 4 demonstrates the GBA applied to a model of the clinothem developed by Miller et al. (2013). Both clinothem models show a similar internal geometry, but the GBA forces the practitioner to incorporate rollover point and landward and seaward terminations in their seismic analyses. This makes the approach less dependent on well data and direct petrophysical measurements and age dating.

Figure 11 and Figure 12 show the GBA applied to sequences m5.2 and m5.8, respectively. We broke down the progradation of the strata in m5.8, formed in the late Miocene, into LST, TST, and HST using the acronym system, and our interpretation agrees with that of Miller et al. (2013) (Fig. 11). However, for sequence m5.2 (Fig. 12), the GBA provided a much greater level of detail, including the identification of an ~600 k.y. (Browning et al., 2013) cycle of LST, TST, and HST within strata previously interpreted as a thick HST (~100 m of sediments). The geometric features observed in seismic data were the primary criteria used to classify the sedimentary packages. The resolution of the input seismic survey data across the section constrained the spatial resolutions of the final interpreted model and the precision with which key surfaces, which delineate the onset of systems tracts, were picked.

Strengths and Limitations of the Geometrical Breakdown Approach

The variety of stratal analysis methods used to infer the driving mechanisms for the formation of depositional sequences and the lack of a universal observational seismic framework have been sources of controversy among practitioners (Neal et al., 2016). Linking the timing of stratigraphic sequence formation to sea-level cycles has contaminated systems tract nomenclature (Miller et al., 2018); in other words, systems tract names do not necessarily accurately reflect sea level and/or its variation during deposition. This has led to a need for a return to the basics of sequence stratigraphy using seismic, core, and well-log data to objectively categorize seismic reflection packages by observing their stratal geometries, stratal terminations, and vertical stacking patterns (Jervey, 1988).

The GBA focuses on the geometric characteristics of reflection packages observed in seismic survey data. The observed changes in a depositional sequence are attributed to the rate of accommodation creation relative to the rate of sediment flux (Neal et al., 2016), regardless of their driving geological mechanisms (Bohacs, 1998). Our synthetic and field test examples demonstrate

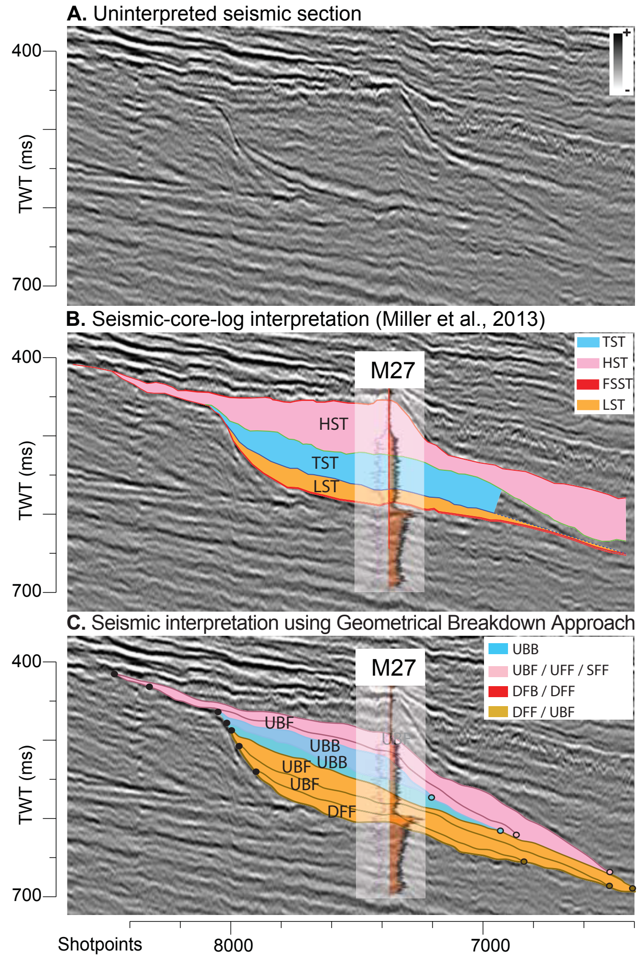

Figure 11. Comparison of seismic sequence stratigraphic interpretation in sequence m5.8. (A) Close-up of part of the seismic section of profile Oc270 line 529 prior to interpretation. (B) Sequence stratigraphic interpretation of part A from Miller et al. (2013) superimposed on log data. (C) Interpretation of the same sequence as in B but based on application of the Geometrical Breakdown Approach (GBA), which relies on the geometry of the reflection packages. TWT—two-way traveltime; M27—Integrated Ocean Drilling Program (IODP) well M27. See Figure 3 for systems tract and GBA abbreviations.

that the application of this method is a step forward in separating observation from interpretation, describing stratal surfaces (or packages of conformable surfaces) based on their relative spatial positions before applying systems tract, progradational-retrogradational-aggradational, or transgressive-regressive terminology.

The GBA is more resilient to the postdepositional tectonic deformation of strata than earlier interpretational approaches because it uses relative locations from three spatially removed points on each reflection package to identify corresponding systems tracts. For each reflection package, two out of the three points are boundary terminations rather than the structural configuration of reflection packages. Tectonic deformation is more likely to change the shape and attitude of reflection packages and, therefore, their internal reflection patterns, which are traditionally used to separate sequences and systems tracts. If clinothem geometry is absent, or rollover points are unrecognizable, it may still be possible to interpret up- or down-stepping of each reflection (stratal) package relative to the previous package by considering their overall geometry and midpoint locations, although this will inevitably introduce subjective judgment.

The GBA is designed to discriminate reflection packages at the maximum level of detail for the resolution provided by the seismic data, making the approach more sensitive to the quality of the input seismic data than other existing sequence stratigraphic approaches. The vertical resolution relates to how thick a bed must be to allow distinguishable reflections from the bed's top and bottom. The Rayleigh's limit of the input seismic data should be considerably higher than the smaller thickness of stratigraphic units to be investigated. This minimizes the mismatch between observed reflection terminations and stratal termination location due to seismic tuning (Widess, 1973). When the method is applied to investigate units with a thickness approaching the Rayleigh's limit of the input seismic data, separating the signal from noise becomes harder as the level of detail increases. Furthermore, the ability to distinguish the internal architecture of clinothems and accurate positioning of landward and seaward terminations inherently require more elongated seismic sections with high resolution.

Formation and preservation of strata require accommodation and supply of sediment in an environment that favors deposition and reduces sediment bypass or erosion. The sediment type and stratal geometry can be used to understand the balance between these factors, specifically in shallow-water environments, but it cannot be used to uniquely determine sea-level dynamics or the rate of sediment influx. Interpreting geometric change in sequences based on accommodation succession facilitates stratigraphic analysis away from data control points without speculation about the responsible mechanisms (Coe et al., 2003; Catuneanu et al., 2010; Obaje, 2013; Williams, 1993; Wilson, 1998).

Existing sequence stratigraphic approaches limit interpretation of the accommodation successions to the scale of a depositional sequence—the largest stratigraphic unit bounded by sequence boundaries (Neal et al., 2016) on a regional scale. The resolution of seismic data, which is independent of

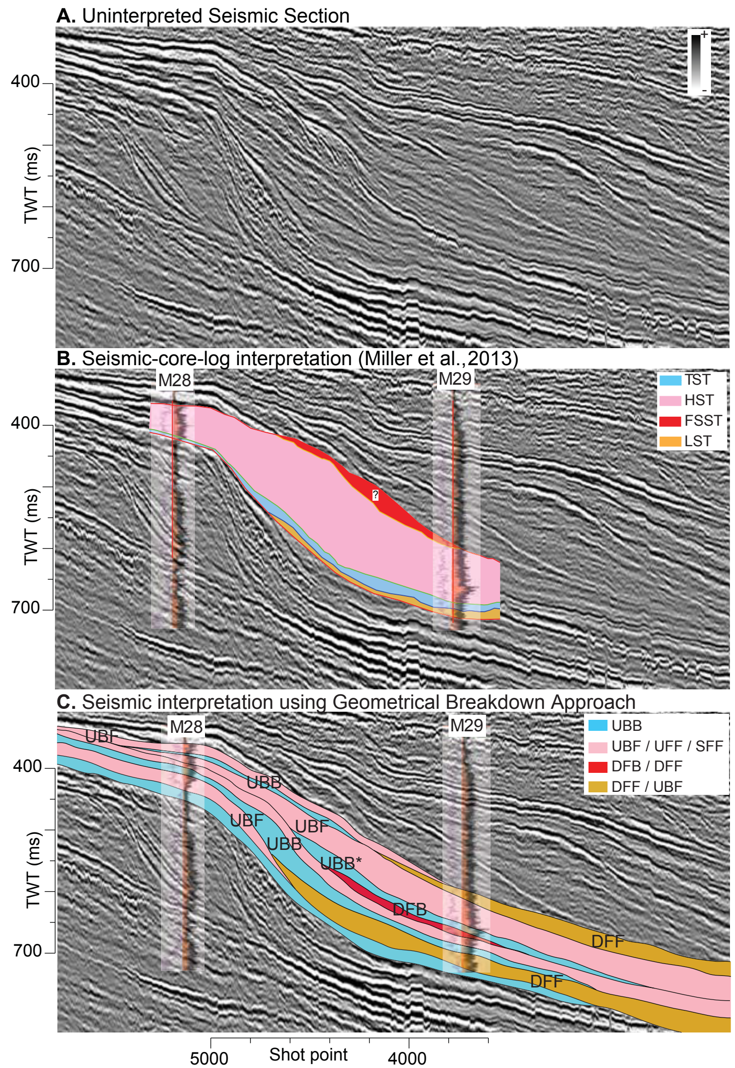

Figure 12. Comparison of seismic sequence stratigraphic interpretation in sequence m5.2. (A) Close-up of part of the seismic section of profile Oc270 line 529 prior to interpretation. (B) Sequence stratigraphic interpretation of part A from Miller et al. (2013) superimposed on log data. (C) Interpretation of the same sequence as in B but based on application of the Geometrical Breakdown Approach (GBA), which relies on the geometry of the reflection packages. The middle UBB package marked with an asterisk (*) in the figure was characterized based on the speculative position of packages assigned to DFF/UBF following the DFB package that ends farther seaward, beyond the edge of the seismic profile. TWT—two-way traveltime; M28/M29—Integrated Ocean Drilling Program (IODP) wells M28 and M29. See Figure 3 for systems tract and GBA abbreviations.

age or regional extent, controls the size of resolvable sedimentary packages (Mitchum et al., 1977b; Neal et al., 2016), but ambiguity and complexity in existing seismic stratigraphic approaches prevent this resolution from being reached. The GBA is applicable at multiple levels of detail, down to half-cycle amplitude and phase variations related to lithological changes that have been confirmed through well calibration and forward modeling.

Stratigraphic interpretation based on accommodation succession typically focuses on regional allocyclic changes. However, autogenic processes such as channel avulsion, delta-lobe switching, and autoretreat can induce local changes in accommodation and sediment flux. They may affect part of a conformable unit, in contrast to the regional trend represented by many sequences (Neal and Abreu, 2009; Neal et al., 2016). Interpreting such local events calls for a more detailed framework in which to categorize features that differ in scale but are the same in nature.

Future Application of the Geometrical Breakdown Approach

The along-strike variability in sedimentary records is challenging for existing sequence stratigraphic approaches. These models are governed by the assumption of uniform stacking in along-strike direction (Madof et al., 2016). Having explicit geometric criteria becomes critical in three-dimensional (3-D) analyses, where seismic packages gradually show up, deform, or disappear due to along-strike changes. The GBA forces the practitioner to notice and characterize the relative spatial locations of three points on individual seismic packages within their succession (assigning a three-letter acronym), which can be readily beneficial for analyzing along-strike changes in 3-D seismic volumes. How those changes are explained is a subsequent part of any analysis and is dependent on the ideas or models that the interpreter invokes.

Application of the GBA to mixed carbonate and clastic deposits requires several considerations. Clinoform geometries are common in carbonate and mixed clastic-carbonate environments, such as foreslopes outboard of reefs, platform margins, and basinal ramp carbonates (e.g., Moore and Wade, 2013; Patruno and Helland-Hansen, 2018). Whereas facies successions in clastic deposits are driven by the rate of accommodation to sediment supply, carbonates are commonly preserved in situ even in high-energy environments, often with minimal transportation. Clastic sediments are produced by weathering of bedrock and are transported long distances to the receiving basin (Lutgens et al., 2017), but carbonates form within the basin by biological and chemical processes (Marubini et al., 2001). Most modern carbonate-producing organisms are photosynthetic or dependent on other photosynthetic organisms (Marubini et al., 2001; Bosence, 2005), and carbonate production rates decrease with depth in accordance with the decrease in light intensity (Pomar, 2020). Consequently, the inundation of shallow shelves during transgression tends to enhance carbonate production and accumulation but causes sediment starvation and condensation in clastic systems. Although carbonate sediments are redistributed, transport is not as crucial as it is for clastic sediments. Carbonate sediment geometries are therefore governed not only by physical processes but also by factors that control ecosystem population and ecology. This should be taken into account when using the GBA to assess the ratio of accommodation creation to sediment influx in mixed carbonate-clastic successions.

Correlation of a stratigraphic record with its contemporary astronomical parameters requires surgical precision in stratigraphic interpretation. Numerous studies have shown that patterns of clinoforms suggest periodicity, and the average clinothem periods are estimated to be in the range of Milankovitch cycles (McCarthy et al., 2013; Miller et al., 1998, 2004). However, the impact of orbital control still needs quantitative support (Algeo and Wilkinson, 1988; Meyers, 2008). The geometric breakdown of sedimentary records based on the GBA leads to a time series of three-letter acronyms that codes the spatial changes in the stratigraphic succession with a level of detail unparalleled by existing stratigraphic approaches. This allows a more precise analysis of stratal rhythms.

CONCLUSIONS

For shallow-marine strata, the lack of clear separation between observation and model-driven interpretations in seismic analysis has frequently altered the understanding of stratigraphic sequences and their driving mechanisms. Historically, this has been a problem in analyzing the relative contributions of allogenic (the three S's: sea level, subsidence, and sediment supply) and autogenic processes. To mitigate this problem, we introduce the GBA, which follows a simple but rigorous classification of the spatial relationships of depositional units recognized in seismic profiles to identify systems tracts, without any connotation of controlling mechanisms. The approach builds on robust aspects of existing approaches to seismic stratigraphy while facilitating a more objective analysis of stratal patterns through systematic spatial description. These analytical observations can then be used to infer systems tracts, progradational-retrogradational-aggradational trends, and transgressive-regressive terminology.

By applying the GBA to depositional sequences generated in flume tank experiments and imaged by seismic data on the New Jersey margin, we demonstrated that the proposed geometric criteria are scale-independent and not influenced by a priori methodological assumptions, making them a reliable tool for accurate recognition of systems tracts. Comparison with previous approaches shows that, despite differing in methodology, the sequence interpretations are commonly in general agreement. However, the GBA can be used to objectively identify systems tracts and sequences down to the finest resolvable seismic units, a finer resolution than previously possible. While the GBA was tested on a 2-D cross-shelf transect that was sensitive to change in the rate of accommodation creation and sediment supply, its application is readily extendable to 3-D data and to more proximal and deeper-water settings because it relies simply on capturing the geometry and relative movement of depositional units before addressing their origin. This method could form a basis for automated interpretation of sequences and systems tracts once accurate identification of reflections, reflection connections, and terminations becomes possible through machine learning.

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